Indo-German Energy Forum

Decarbonising India -

Potential for Electrification across India's Economy & Assessment of Electricity Needs

Study by:

pwc

HEAT

On behalf of:

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MINISTRY OF POWER

Federal Ministry for Economic Affairs and Climate Action

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Key Findings

90 % electrification of India’s entire economy with adoption of mostly existing technologies possible.

~40 % emission reduction through energy efficiency gains mostly because of electrification of sectors which does not imply the huge thermal losses occurring when using fossil fuels.

~3300 GW of RE capacity required in 2050.

~5800 GW of RE capacity required in 2070 with the country's generation mix entirely dependent on RE sources.

~40 million tonnes of Green Hydrogen required in 2050.

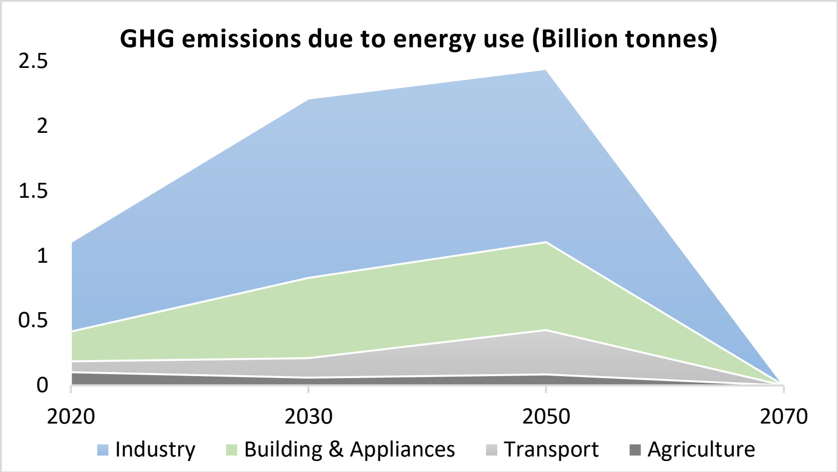
+3500 GWh battery storage required by 2070.

~4 % of available wasteland could be used to meet all land requirements for full decarbonisation of India's economy.

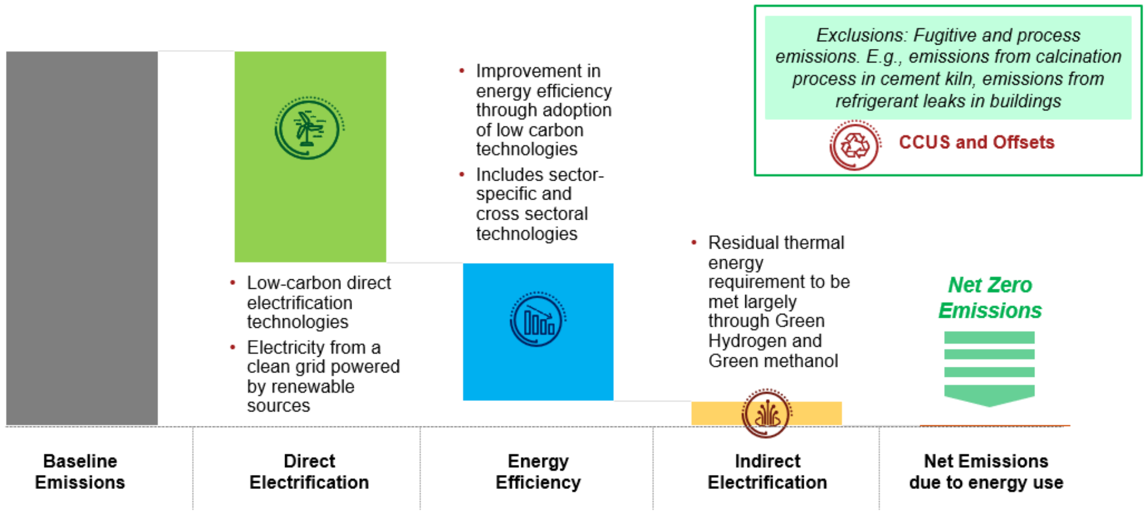
Decarbonisation of India’s economy leads to the decrease in imports of petroleum and natural gas, makes the country more self-reliant and assures energy security.

Executive Summary

This study offers technology recommendations for all sectors of India's economy to achieve net zero CO_2 emissions by 2070. The top priority is to switch to direct electrification using renewable energy to decarbonise industry, agriculture, transport, building, and appliances. Following direct electrification, using electricity based green hydrogen and other power-to-x requirements (PtX) solutions for indirect electrification is crucial. Additionally, exploring new low-carbon technologies can reduce reliance on high-emission ones. The study evaluates the technical feasibility and cost-effectiveness of these solutions, aiming to sustain the country's economic growth. Achieving a net zero carbon economy by 2070 is feasible but requires concerted action on multiple fronts. The study's key findings stress the need for immediate action to ensure India meets its goal of becoming a net zero emissions economy by 2070.



Due to efforts taken by Government of India and according to the Finance Ministry's Monthly Economic Review, the Indian economy is gearing up for unparallel growth. The increased spending by Government of India with increased private sector investment in infrastructure, manufacturing & other measures, indicate the growth of all sectors of the Indian economy. Despite ambitious efforts to reduce emissions, the increase in manufacturing, growth in infrastructure and growth in buildings & appliances, transport, and agriculture is foreseen to lead to increasing GHG emissions until 2050 in all sectors of the economy. Nevertheless, with increased penetration of direct and indirect electrification technologies it is feasible to reduce net emissions from energy use to zero by 2070.



In line with the objective of the study, our focus was to reduce emissions from energy use to a net zero level. This study estimates ~56% emission reduction as a result of replacing fossil fuels-based technologies with technologies based on efficient 'Direct Electrification' with renewable power.

Around 37% emission reduction can be achieved as a result of 'Energy Efficiency' improvement. This again is largely due to technology switches to technologies based on electrification. Residual thermal energy requirement can be electrified by indirect electrification route. The study does not include fugitive and process emissions (e.g. CO_2 release due to calcination in cement and fugitive emission as a result of refrigerant leaks in buildings). Carbon Capture, Utilization, and Storage (CCUS) and offsets will play a vital role in the mitigation of these emissions.

1 Energy efficiency improvement due to electrification

Electrification and energy efficiency are two of the most important parameters for the energy transition. It can also be said that electrification and energy efficiency are two sides of the same coin. In most of the sectors, electrification with renewables leads to an inherent increase in energy efficiency, resulting in reduced energy consumption.

Typically, more than 60% of energy used for electricity generation is lost in the conversion of coal to power. There are hardly any losses involved in power generation with renewables. This also means that the primary energy demand based on fossil fuels requires far less renewable power to entirely replace them.

Industrial manufacturing processes are a focal point for driving efficiencies. Energy supply to processes in industrial manufacturing currently relies heavily on the combustion of fossil fuels, which are either used directly to supply heat or indirectly through utility systems. As per this analysis, the industrial sector would be electrified by 31% in 2030, 75% in 2050, and 89% in 2070 in the ambitious scenario.

There are several benefits related to electrification of processes in industrial sectors. Electric systems tend to have a relatively superior design, yield, process controllability, and flexibility compared with existing systems. Additionally, electric systems have a higher performance lifetime.

The highly efficient fossil fuel-based industrial boilers that typically fall within the efficiency range of 75% to 85% are still inefficient as compared to an electric boiler. Electric boilers waste minimal energy, ensuring that their performance is fully optimized. Efficiencies of electrode type electrical boilers are in the range of 97% to 99%.

Induction cookstoves are generally considered more energy efficient and easier to use than other cookstoves, not only because of the amount of energy consumed, but also because they don't heat up the air around it. This provides better cooking comfort. The typical efficiency of an induction cookstove is ~76%, which is more than double the efficiency of a gas-based cookstove i.e. 30%.

Electric vehicles (EVs) are also a case which offer the benefit of both electrification and energy efficiency. EVs are highly energy efficient when compared with internal combustion engines. EVs typically convert ~77% of the electrical energy input to power output at wheels. However, conventional internal combustion engine-based vehicles convert just about 12 to 30% of the energy stored in fuel to power output at wheels. Moreover, EVs do not have any tailpipe emissions.

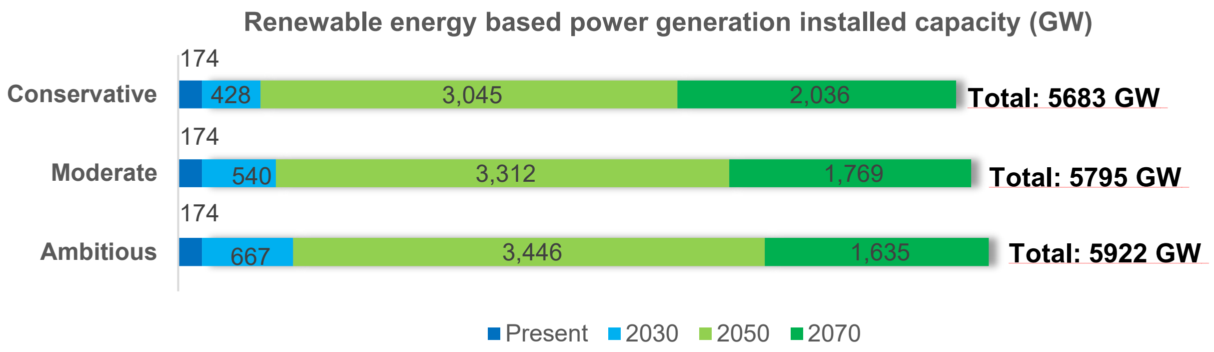
There are several other decarbonisation technologies that offer energy efficiency improvement from conventional technologies. An illustration of energy efficiency improvement of such direct electrification technologies is presented below, and details are provided in respective sections of the sub-sectors.

Technology Name	Sector	Typical EE improvement potential
Electrolysis High Temperature Molten Oxide	Iron & Steel	46%
Electrowinning	Iron & Steel	70%
Evaporator	Pulp & Paper	17%
Pulp Machine	Pulp & Paper	45%
Electric Thermic Oil Heater	Textile	16%
Electric Heat Setting Machine	Textile	38%
Electrified Drying Process	Textile	25%
Electric Boiler	Cross-cutting	17%
Heat Pump	Cross-cutting	50%
Electric Pressure Calcination with MVR	Aluminium	60%
Electrolysis in reduction pots	Aluminium	30%
Electric Kilns	Brick	25%
Electric Kilns	Cement	30%

2 Unprecedented drive towards renewable energy (RE) is required to achieve net zero by 2070

Achieving net zero GHG emissions requires a fully decarbonized electrical power system. The effectiveness and pace of electrification pathways in decarbonizing all of the sectors will depend on the rate of decarbonization of the Indian electricity sector. This requires immediate and massive deployment of renewable energy (RE) technologies such as solar photovoltaics, wind power generation technologies, hydro and biomass. Reaching the target in a scenario (see section 1.5) with focus on maximum electrification wherever possible, requires an addition of ~598 GW of solar photovoltaic, ~57 GW of wind, ~21 GW of hydro power and ~4 GW biomass-based power by 2030. This amounts to **~4 times** the present RE installations. In its *Panchamrit* goal, India has committed itself to install 500 GW of non-fossil fuel-based capacity by 2030. A recently updated bidding trajectory for renewable energy power projects published by Govt. of India already foresees an increase in public tenders for RE power capacities to 50 GW per year which will support achieving this goal. In a scenario with focus on maximum electrification wherever possible and 5 million metric tons of green hydrogen production, **the RE capacity will be further increased by around 23%** to meet the RE capacity requirement by 2030. In the moderate decarbonisation scenario this is in line with official goals, considering the goal to achieve 125 GW additional renewable energy capacities for green hydrogen production under the National Green Hydrogen Mission of India. The CEA report[1] on optimal generation capacity for 2029-30 indicates an emphasis on renewable energy and energy storage systems for energy transition through decarbonization of the power sector. The report projects a total installed capacity of about 777.14 GW in the year 2030 with battery storage of about 41.65 GW, which is in line with our estimation in a moderate scenario, i.e. the requirement of 757 GW of installed capacity. The share of non-fossil fuel-based sources is going to increase to 64% in 2029-30 from the present level of 43% of total installed capacity. Whereas in the ambitious scenario, the share of non-fossil fuel-based installed capacity increases to **68% by 2030 from 43% of present capacity**.

Our analysis under different scenarios indicates that aggressive efforts would be required, especially to enhance installed capacity for power generation through wind and solar photovoltaic, to meet the expected electricity requirement through rapid electrification of various sectors of the economy.



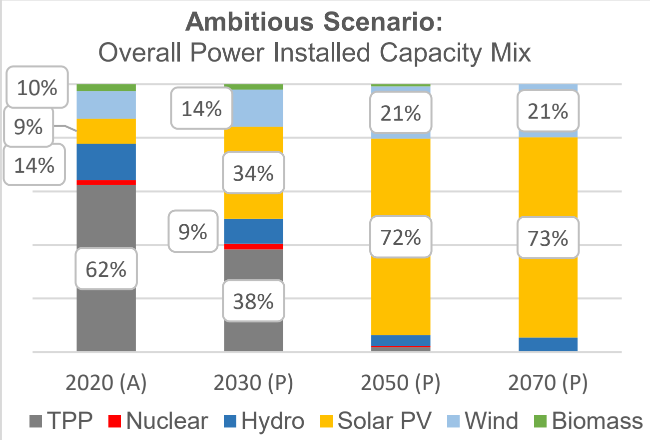
[1] *Report on optimal generation capacity mix for 2029-30, Version 2.0, April 2023, CEA, Ministry of Power, GoI*

To meet the entire country's electricity requirement, including electricity requirements for the generation of green hydrogen, the required capacity of renewable energy in 2030, 2050, and 2070 is ~**841 GW**, **4287 GW**, and **5922 GW,** respectively. Whereas in **2050, the** total installed capacity requirement for solar would be **3,344 GW**, **730 GW** of wind energy, **145 GW** of hydro power, and the remaining energy requirement would be met by other sources like biomass and nuclear. Similarly, the total installed capacity requirement for **2070** is also estimated, i.e. **3835 GW** of solar power, **996 GW** of wind energy, and **250 GW** of hydro power.

The World Meteorological Organization forecasts that the average global temperature will rise by 1.5°C by 2030. This already means the depletion of the global carbon budget under Paris Agreement. Global emissions need to be zero much prior to 2050 for limiting temperature to 2°C. Achieving climate neutrality will require unprecedented drive. To put the numbers in perspective, world's total RE installed capacity including hydro power at present stands at +4 TW, by 2070 India alone would need ~6 TW.

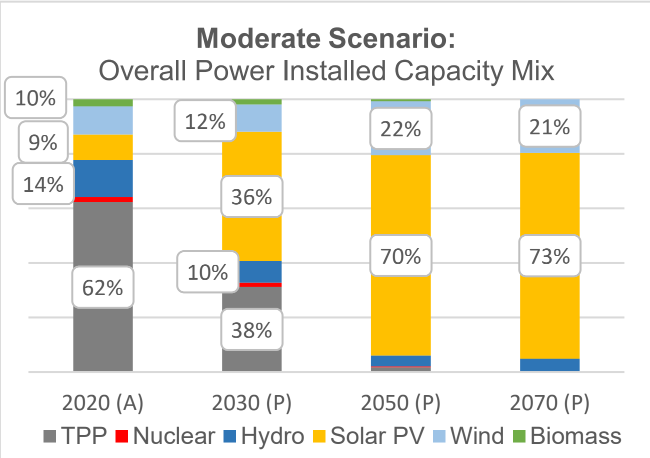
An accelerated push towards the use of more RE technology is required. There is a need to limit or discourage the use of fossil fuels especially in power plants. The phase-out of fossil fuel subsidies, carbon pricing, and other market changes are foreseen to assure proper price signals. Further incentives for massive infrastructure investment, including smart transmission and distribution grids are required. Adopted framework conditions addressing the increased renewable energy capacity needs will create the enabling ecosystem required to mobilise private sector funding.

3 Change in installed capacity mix: Phasing down of thermal power plants (TPP)

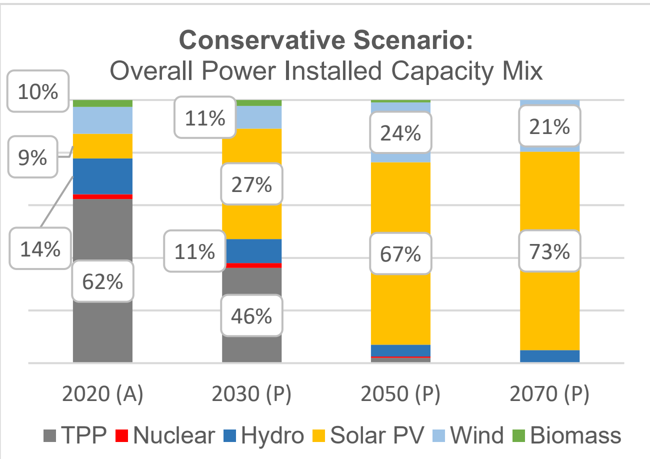


Electricity is one of the most critical enablers of the nation's economic and social development. The power demand rises in response to economic development. Power generation capacity augmentation is the most important component used to meet the demand for electricity in order to cater to the growth rate.

Towards realising the objective of GHG emission-free energy, India has set a target to reach 500 GW of non-fossil fuel-based capacity and a contribution of power from these sources accounting for 50% of total installed capacity by 2030. In this study, an analysis has been done to identify the optimal mix of the installed capacity for different scenarios and different timelines. To reach net zero by 2070 the contribution of non-fossil fuel-based sources increases, and the contribution of fossil fuel-based sources decreases. In the ambitious scenario, it can be witnessed that the contribution of fossil fuel-based plants is **68%** by 2030, **2%** by 2050 and by 2070, there will be no fossil fuel-based electricity generation. The illustration shown presents the values for each scenario. A detailed description of the installed capacity mix is presented in Section 6 of the report.



As per CEA projection, by 2030, India would have a contribution of 276.51 GW thermal power plants (251.7 GW coal-based, 24.8 GW gas-based) in the installed capacity mix. In line with the Government target of phasing down thermal power plant generation (TPP), it is estimated that by 2050, all the old TPP (211.9 GW coal-based) installed before 2030 would be retired as a result of the end of useful life, whereas the new installation of ~40 GW would continue to operate by 2050. Along with new installations, old gas-based power plants would also continue to operate as natural gas is a comparatively cleaner fuel than coal. By 2070, all the coal and gas-based power plants would be phased out and the entire country's demand would be met by the RE installed capacity.



By 2070, the country's generation mix would be completely dependent on RE as source of power. This would be achievable by realizing full wind and hydro power potential with 27% of the total grid mix in 2070. Solar will contribute with 73% in the capacity mix. Utilizing a mere **~4%** of available wasteland is estimated to meet necessary land requirements.

4 Massive technological leaps to achieve "Net Zero" by year 2070

Net zero needs the widespread usage of both commercially available technologies as well as the deployment of technologies that are demonstrated but not yet commercially accessible. While technologies with high technical readiness levels will need to be deployed sector-wide, fundamental and applied research & development (R&D) for lower technical maturity levels technologies must also proceed in parallel. Major advancements in early-stage technologies across all decarbonization pillars will be needed in the coming decades to reach net zero emissions by the year 2070. The major innovation potential lies in the development of advanced batteries and electrolysers for green hydrogen. While these two technologies are crucial to the decarbonization journey from the supply side, there needs to be a significant focus on top demand side electrification technologies with the highest potential towards decarbonization across all the sectors of the economy. An analysis of the technology penetration and electrification potential of each sub-sector has been divided into two phases.

Phase 1 (2023-30): Promotion of high-maturity technology in the near-term scenario

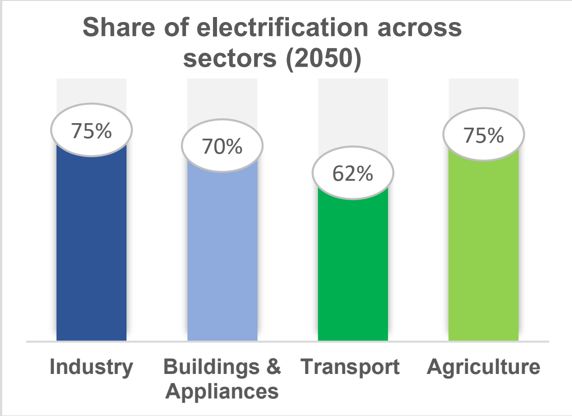
In the near-term scenario, there should be a policy push for the promotion of the technologies having high TRL (technology readiness level), i.e., TRL 7-9. It requires the below listed activities.

- Dissemination of the benefits of the technology amongst the wide industrial stakeholder
- Financial incentive for the uptake of the technology
- Stringent targets for the designated consumers (DCs) under Performance Achieve and Trade (PAT) schemes to adopt high mature technologies.

Top electrification technologies until 2030
(Based on TRL level i.e., TRL 7-9)

1	Electric Melting Furnace (Glass)	6	Electric Thermic Oil Heater (Cross-sectoral)
2	Electrical Conditioning and Forming (Glass)	7	Radio Frequency based Dryer (Paper)
3	Electrical Post Forming & Annealing	8	Electric Heat Setting Machine (Textile)
4	Electric Boilers (Cross-sectoral)	9	Electric Vehicle (Road Transport)
5	Electric Induction Cookstove (Appliances)	10	Fuel switch to PtX (Shipping & Aviation)

Phase 2 (2030-50): Integration of existing decarbonization technologies while encouraging breakthrough technologies



Promoting the penetration of existing as well as low-TRL[2] (Technology Readiness Level) net zero technologies requires an ecosystem that includes the below-listed activities,

- **Pilot demonstrations** of mature low-carbon technology and leveraging these to tap the downstream replication potential.
- Unlocking the next generation of low-carbon technologies requires more **clean energy R&D, academia, industry and international collaboration.** Government R&D spending needs an exponential boost with a reprioritization in critical areas such as electrification, green hydrogen, and bioenergy.
- There is a need for **policy-level initiatives and directives** for penetration of these commercially available decarbonisation technologies in the initial phase of net zero pathways.

The graph above presents the percent share of possible electrification across all sectors of the Indian economy. It can be noted that by 2050, **75%** of industrial & agriculture sectors would be electrified followed by buildings and transport.

Top electrification technologies after 2050
(Based on energy and CO_2 emission reduction potential)

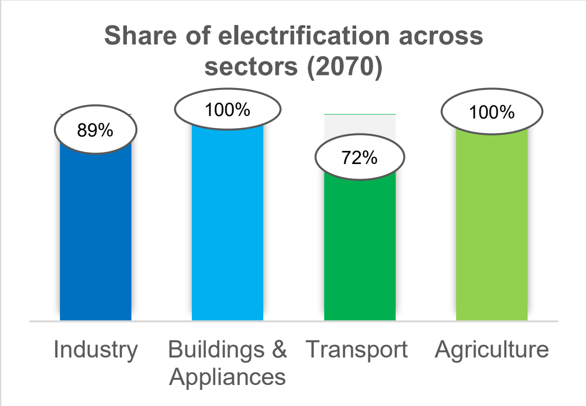
1	Electric Kiln (Cement)	5	Sole GH2 or Blending with Natural Gas (I&S)
2	Electrolysis in the Reduction Pots (Al)	6	Radio Frequency based Dryer (Paper)
3	Oxy-fuel and Hydrogen (Cross-sectoral)	7	Electric Kiln (Bricks)
4	Electric Boilers (Cross-sectoral)	8	Electric Vehicles (Transport)

As per the analysis, technologies mentioned below in the box have been evaluated based on their energy intensity and emission-saving potential. All the mentioned technologies are comparatively more mature and available across some of the developed economies.

[2] *Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. TRL 1 (scientific research is beginning) is the lowest and TRL 9 (commercialised) is the highest.*

Phase 3 (2050-70): Indigenization and Integration of breakthrough technologies

After Phase 1, there is an overarching need to deploy those technologies which have been through the R&D stage in phase 1, have achieved better technology readiness levels, and are now being manufactured in India and readily available at scale. Also, there should be a continued focus on implementing the existing technologies with due support at policy and operational levels as required. Actions to take this goal forward are:



- Development of breakthrough technologies and **commercialization of low-TRL level technologies.** There should be a focus on **manufacturing these technologies in India** to make them cost-effective.
- **Pilot demonstrations** of breakthrough/innovative technologies and development of case studies.
- **Policy level** initiatives and mandates for net zero.

The transport sector would be electrified **72%** by 2070, because sub-sectors like shipping and aviation would be highly dependent on sustainable alternate fuels other than electrification. Meanwhile, the industry sector will be electrified **89%** by 2070. The technologies listed below in the box would act as key pillars to decarbonise all the sectors of the Indian economy. They have been evaluated based on their energy intensity and emissions saving potential.

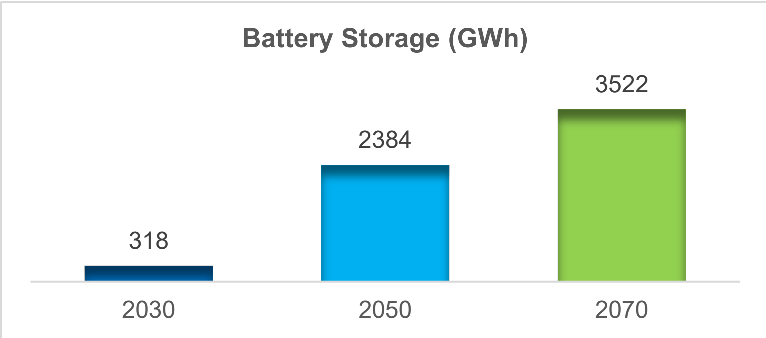
Top electrification technologies beyond 2050 (Based on energy and CO_2 emission reduction potential)			
1	Heat pump (Cross-sectoral)	4	Electric Tractor (Agriculture)
2	Electrification of Brick Kiln (Brick)	5	Electric Pressure Calcination with MVR (Al)
3	Electrolysis: Low Temp. Alkaline Electrowinning (I&S)	6	Electrical Pulping & Paper Processing (Paper)
		7	Electric Shipping & Aviation

5

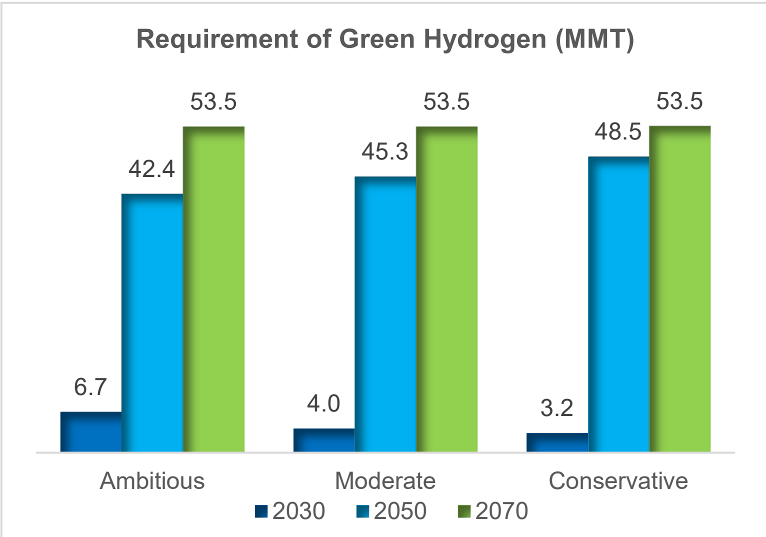
Addressing existing energy security concerns, while minimizing the emergence of new ones

As per analysis conducted, in the future scenario, there will be increased dependence on carbon-free electricity, so there will be a substantial decrease in the import of petroleum and natural gas products, over the timeframe. This step will address the current Indian energy security concerns and make the country more self-reliant in its energy usage.

This transition would require a substantial amount of critical minerals to meet the energy requirement of the country. Increasing RE installation capacity would lead to an increased need for battery energy storage capacity, as presented in the illustration, and this will increase the dependence on critical minerals such as copper, cobalt, manganese, lithium and various rare earth metals.



The import of critical minerals for batteries will emerge as a new energy security concern. As per a report from the Geological Survey of India, till February 2023, India has identified **~6 million tonnes** of (inferred resources) of Lithium. These recent developments give a fresh air of breath and enhanced confidence in the potentially reduced dependence on the import of Lithium. While in recent times, India has imported Li-ion batteries worth **USD 1.23 billion** in 2018 and 2019, international reports on economically feasible recycling rates of above 99 % are encouraging.

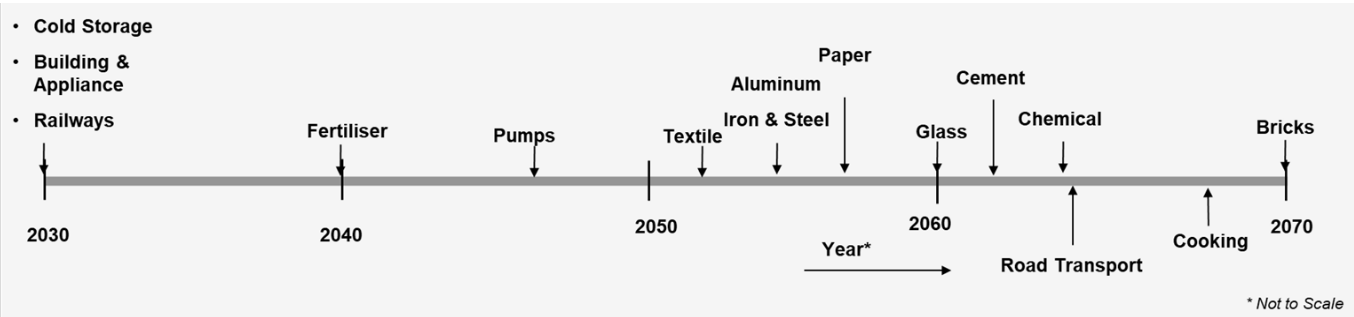


As per the national green hydrogen mission, India would produce **5 MMT** of green hydrogen, with and additional potential to export **5 MMT** of green hydrogen. This adds an estimated requirement of **~112 GW** of electrolyser and ~**211 GW** of solar PV by 2030. Whereas, as per the analysis in an ambitious scenario, the country would be requiring **6.7 MMT** of green hydrogen by 2030 and **53.5 MMT** of green hydrogen, leading to a demand of **~423 GW** of electrolysis capacity and ~**705 GW** of solar PV capacity by 2070 in the ambitious scenario. Details of RE requirements from green hydrogen are mentioned in Chapter 6 of the report.

At present the production of electrolysers is more centric to China and the western countries of the globe. Companies like Nel ASA, Norway, John Cockerill, Belgium, H-Tec Systems, Sunfire, Thyssen Nucera, Germany and others are the leading manufacturers of green hydrogen electrolysers. Ohmium launched India's first green hydrogen electrolyser facility. To promote more facilities like this, India has announced the National Green Hydrogen Mission and committed to manufacturing 5 MMT of green hydrogen by 2030. This points to a strong need for emphasis on an **international collaboration** with technology suppliers and a policy push for the manufacturing electrolysers domestically. India has already initiated steps in the same line. They have a budget outlay of INR 19,744 Crore for the National Green Hydrogen Mission and will also introduce a production-linked incentive (PLI) scheme to give impetus to the manufacturing of green hydrogen and its key component – the electrolyser.

6 Phase-wise electrification scenario of sectors of India's economy

Depending on the degree of penetration and availability of technologies related to each sub-sector, the analysis indicates the tentative timeline of the electrification potential of the individual sub-sectors. The electrification potential of the sub-sectors is determined based on the TRL level of the technologies and the commitment of the respective line ministries. A tentative timeline of complete electrification is as follows.

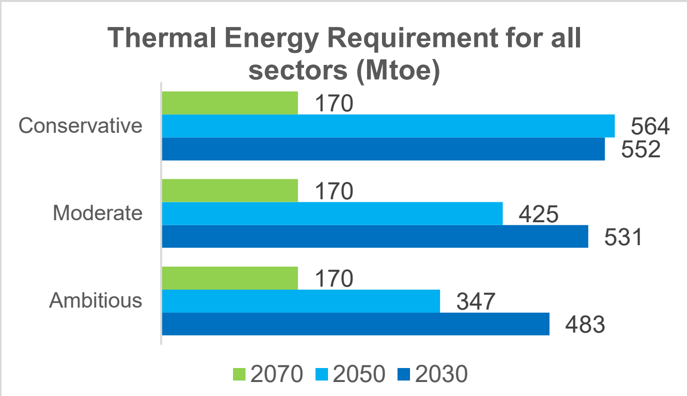


Indian Railways has committed to be completely electrified by 2030. Building and appliances (excluding cooking) as well as cold storage can be 100% electrified by 2030. According to the model used here, the fertiliser sector can achieve to be 100% carbon-free by 2040. This is in line with estimates by Niti Aayog and RMI. There is an immense potential to electrify the Iron & Steel sector. As per current technology readiness levels, it is expected that 90% of the sector can be electrified by 2050. The conventional Direct Reduction Iron – electric arc furnace (DRI-EAF) route of steelmaking would transition to H_2DRI-EAF route. Whereas the blast furnace – basic oxygen furnace (BF-BOF) route would transition to direct electrolysis of steel technology, i.e., Molten oxide electrolysis and Electrowinning. Ultratech Cement, contributing to 33% share of India's cement manufactured, commits to be net zero by 2050 and led by the pathway of its largest player, the entire Indian cement industry would be net zero by 2060. Some sectors such as cooking and bricks are highly unorganized and dependent on biomass and fossil fuels, due to which these sub-sectors are expected to be carbon-free by 2070. In order to achieve decarbonization in respective sectors and sub-sectors of the economy in a phased manner as estimated above, in line with respective decarbonization potential, the following series of actions are suggested:

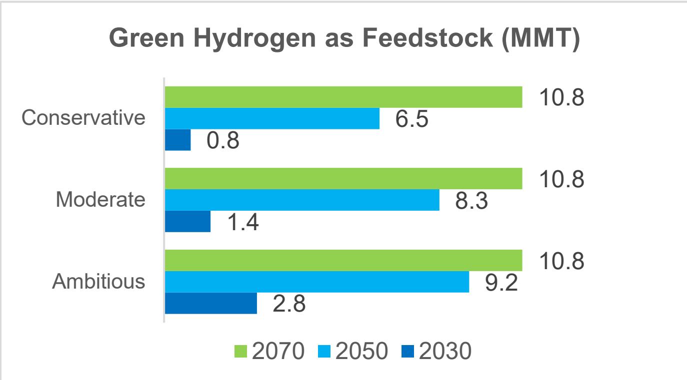
- Policy mandates to be put in place for increased usage of electrification technology.
- Stringent targets for the PAT participating industries to promote these technologies.
- Introduction of a carbon tax for large industries to promote clean technologies.
- Fiscal and Taxation policies to incentivize uptake of electrification technologies.
- Financial incentives to increase the uptake of these technologies in medium and small-scale industries.

7 Addressing the remaining thermal energy and feedstock needs by green hydrogen and other sustainable alternate fuels (SAF)

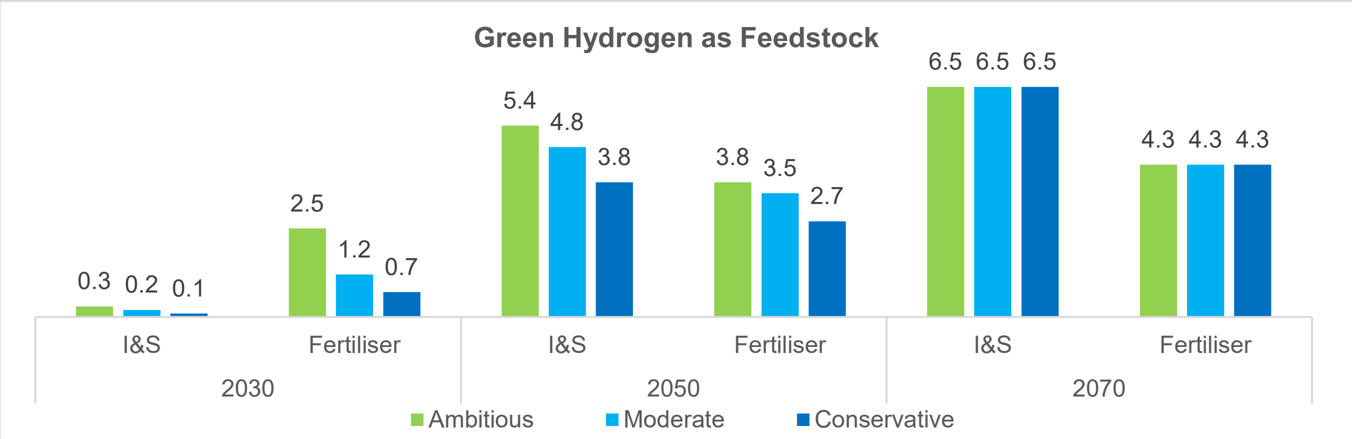
In line with the objective of the study, the focus has been on the increase in electrification in all sectors of the economy. At the same time, there is going to be a considerable residual thermal energy requirement, which can't be electrified. Hence, this report covers the need for residual thermal energy for the country across the timeline until 2030, 2050, and 2070. **170.4 Mtoe of thermal energy** (as a fuel) is required by the year 2070. The remaining thermal energy (as fuel) requirement by 2070 would be met by **82 mn kL of green methanol** and **43 million tonnes of green hydrogen** (~482 GW of electrolyser capacity). There should be a push towards allocating budget for R&D related to green hydrogen technology and electrolyser and other technologies for the production of sustainable alternate fuels. Policy mandates are required for the deployment of these technologies at scale and a mandate has to be made to use the carbon-free fuel rather than fossil fuels.



In addition, our analysis estimates the use of Green Hydrogen (GH_2) as feedstock in select industrial sub-sectors. **Fertilizer and iron & steel** are two prominent sectors catering to the use of GH_2 as feedstock. In an ambitious scenario, we anticipate the demand for **GH2 as feedstock from fertiliser and iron & steel sector to be 2.8, 9.2 and 10.8 MMT** by the years 2030, 2050 and 2070, respectively.



In the ambitious scenario of the model, consumption of green hydrogen as a feedstock in iron & steel would increase by 18 times between 2030 and 2050 and ~21 times between 2030 and 2070. Whereas the GH_2 consumption as feedstock in fertiliser sector would increase by ~1.5 times and ~1.7 times in 2050 and 2070, respectively. The year-on-year increase in consumption of GH_2 as feedstock in fertiliser sector is marginal between 2050 and 2070. This is due to a potential commitment, that the fertiliser sector would be net zero by 2040.



At the same time, there would be an exponential increase in consumption of GH_2 as feedstock in the iron & steel sector, largely due to two factors, i.e. growth in overall demand for steel in the country and the priority of the Ministry of Steel in greening the sector.

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BAU	Business-as-usual
BEE	Bureau of Energy Efficiency
BEV	Battery electric vehicles
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalents
CUF	Capacity utilization factor
DAC	Direct air capture
DCs	Designated customers
EVs	Electric vehicles
FY	Financial year
GH2	Green hydrogen
GHG	Greenhouse gas
GW(h)	Gigawatt(hours)
INR	Indian Rupees
IRENA	International Renewable Energy Agency
MMT	Million metric tonnes
Mn kL	Million kilolitres
MNRE	Ministry of New and Renewable Energy
MOSPI	Ministry of Statistics and Programme Implementation
Mtoe	Million tonnes of oil equivalent
MW(h)	Megawatt(hours)
PAT	Perform, Achieve and Trade
PLI Scheme	Production Linked Incentive Scheme
PV	Photovoltaic
R&D	Research and development
RE	Renewable energy
TRL	Technology readiness level
TTP	Thermal power plants
UV	Ultraviolet

1 Introduction

Heat stress, reductions in freshwater supply, soil drying, more intense tropical cyclones, monsoons, and sea-level rise, amongst other impacts pose a serious threat to the Indian economy. At the same time, the global climate crisis unveils economic opportunities for India as new decarbonisation technologies and industries are required to be developed, manufactured, and deployed at scale. This study identifies a specific and concrete roadmap for deep decarbonisation in India. It emphasises the electrification potential of all the sectors of the Indian economy.

1.1 India's Goal of Decarbonisation

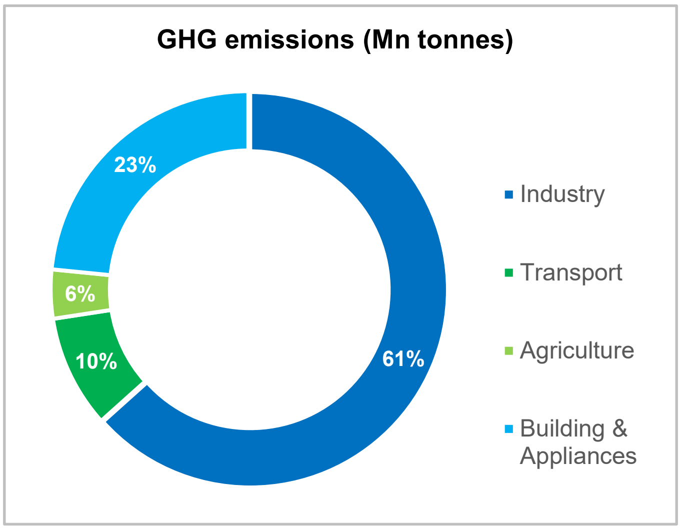
India, at COP26 held in Glasgow, UK, announced its ambition to become a net zero emitter by 2070: an important milestone in the fight against climate change. Despite low per-capita emissions (2.47 tCO_2)[3], India is the 3rd largest emitter globally, emitting a net 3.4 gigatonnes of CO_2 equivalent ($GtCO_{2-e}$) every year as of 2021[4]. India has updated their Nationally Determined Contribution (NDC) goals by presenting to the world 'five nectar elements' (*Panchamrit*) of the country's climate actions, which will lead towards achieving India's long-term goal of net zero by 2070.

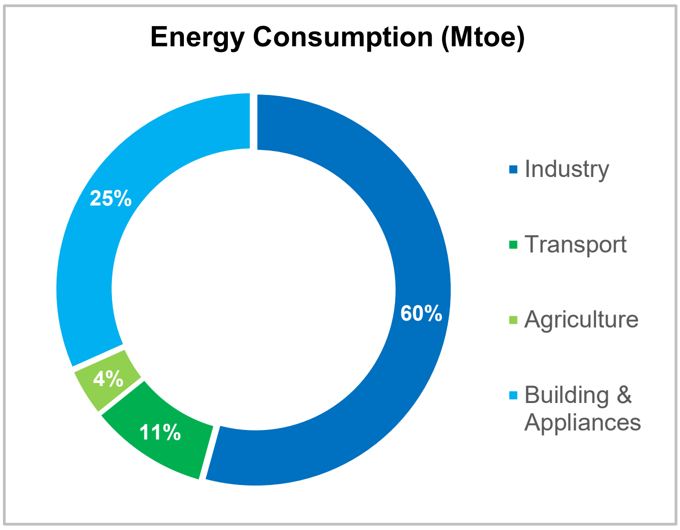
As per the updated NDC, Government of India has committed to **reducing the emission intensity of its GDP by 45%** by 2030 from the 2005 level. India would install **additional non-fossil fuel-based power capacities of 500 GW** by 2030 and also committed that **50% of its energy requirement** would be **fulfilled by these energy sources**. India has also committed to the **reduction** of total projected **carbon emissions by one billion tonnes** from 2021 to 2030.

In line with the commitments of the central government, first line ministries have committed to sector specific net zero goals. **Indian Railways** has committed to be **100% electrified by 2030,** which alone would lead to the reduction of CO_2 emissions by **60 million tonnes** annually. Niti Aayog and RMI were proposing for the **fertiliser sector** to become **carbon-free by 2040.**[5]

1.2 Sectoral Overview

India now ranks fifth in the global ranking of GDP, having a GDP of ~3.5 trillion USD and committed to becoming the third largest economy by 2037 with a GDP of 10 trillion USD. The country is broadly





[3] *UNEP 2023*
[4] *Reserve Bank of India 2023, https://www.rbi.org.in/SCRIPTs/PublicationsView.aspx?id=21769*
[5] *Niti Aayog & RMI, https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf*

categorized into 4 sectors, i.e., industry, agriculture, building and appliances, and transport and all the mentioned sectors are contributing to India's economy. As presented in the illustrations, the most major energy-consuming sector is industry, i.e., 60% of the total energy consumption, followed by building and appliances, transport, and agriculture. Industry is the leading sector in GHG emissions, followed by building & appliances, transport, and agriculture sector.

1.3 Direct electrification Vs Hard to abate sectors

Hard-to-abate sectors are those sectors where emission mitigations are either costly or impossible to reduce with currently available technologies. These emissions are usually categorized into two categories: emissions due to the usage of fossil fuel in thermal applications and emissions due to the processes involved in the manufacturing operations. Usually, there are two streams of hard-to-abate sectors, first is **heavy industries,** which include cement, steel, and chemical manufacturing. Another is heavy-duty transport, which includes majorly shipping[6] and aviation.

Coal is being used as both a source of heat and as part of the chemical process of converting iron ore to elemental iron. Both of the applications produce carbon dioxide. Eliminating CO_2 emissions from steelmaking requires a change in process, which is discussed in detail in the Iron and Steel section. Hydrogen can be used as the fuel (heat source) and as a chemical reducing agent. Thus, green hydrogen has immense potential to eliminate CO_2 emissions. Steel can also be recycled and melted with Electric Arc Furnaces powered by renewables without CO_2 emissions, but the demand for steel is too large to be met with recycled steel alone.

Cement production also releases CO_2 as part of the chemical process. In this case, when limestone is heated to a very high temperature to produce calcium oxide "clinker," the cement's primary component. Other substances can be mixed with clinker while still maintaining cement quality, but the primary method of decarbonising the sector is to capture the CO_2 and store or find a use for it. In today's scenario, carbon capture utilization and storage (CCUS) is costly technology for being deployed at a scale in the country.

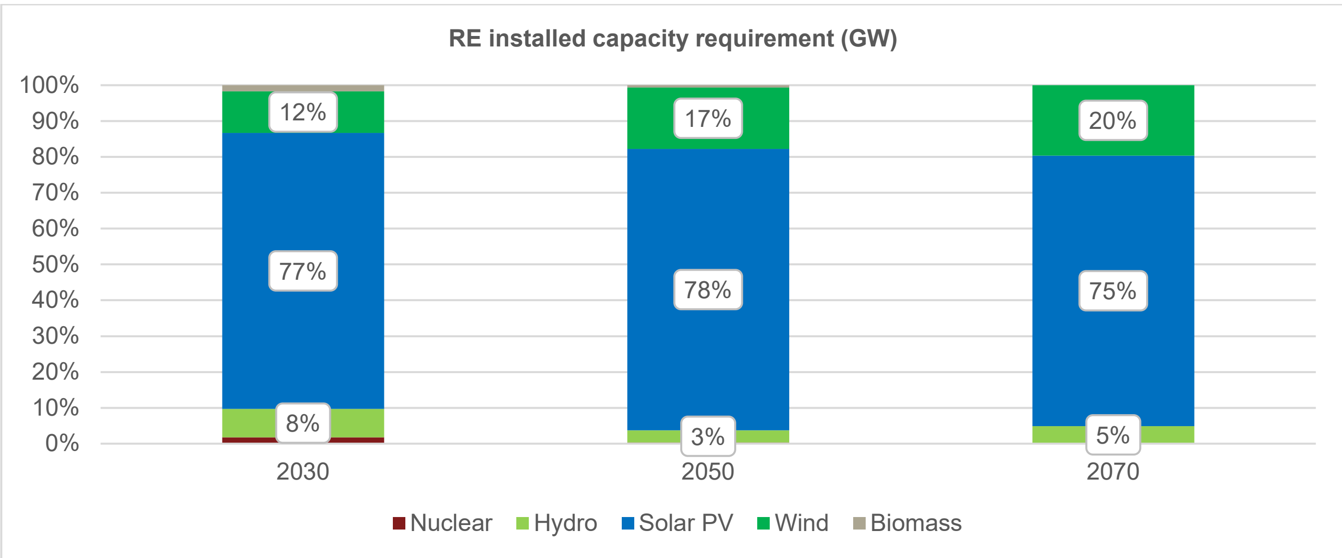
To keep India on track reaching the target of net zero by 2070, there is a dire need of transition of all the sectors of the economy towards carbon-free energy. In this study, all sectors of the economy, including most sub-sectors[7], have been covered. As part of the analysis, there are many sub-sectors which can be completely electrified through direct electrification[8] technologies. Sectors which would be requiring thermal energy for their production processes by 2070 and sectors having emissions from their processes are categorised under the hard-to-abate category. Sectors like iron and steel, cement, chemicals, MSMEs, non-specified industries, shipping, and aviation are categorized under hard-to-abate sectors. The illustration presented below classifies the sectors under the direct electrification category and hard-to-abate sectors with a long-term perspective (i.e., by 2070).

[6] https://energytracker.asia/cop26-and-hard-to-abate-sectors/
[7] *Sectors like Petroleum Refining are consciously avoided since we are targeting an economy free of fossil fuels*
[8] *Direct Electrification – It means energy requirement of any particular sectors are completely met by the electricity supplied through grid*

Directly Electrified Sectors		
Glass	Paper	Textile
Cold Storage	Fertiliser	Aluminium
Harvesters	Tractor	Bricks
Food Processing	Buildings	Road Transport
Railways	Pump	
Hard-to-Abate Sectors		
Iron & Steel	Cement	Chemical
Shipping	Aviation	MSME
Others (Non-specified) Industry		

1.4 Required RE installed capacity

In the net zero roadmap, the energy demand of India would be primarily met by electricity. Instead of fossil fuels, the energy sector will be largely based on renewable energy. In the ambitious scenario, India would require RE capacity of 841 GW by 2030, 4287 GW by 2050, and 5922 GW by 2070. Distribution of solar, wind, hydro, nuclear and biomass energy is determined based on the maximum availability of RE through these sources, and the capacity utilization factor (CUF) inherent to the respective RE technologies.



Capacity utilization factors for the respective RE technologies for the years 2030, 2050, and 2070 are estimated based on the past trend of technology improvements. CUF thus estimated, is shown in the below table. Improvement in the capacity utilization factor of solar PV is due to three main reasons a) the trend towards greater deployment in regions with higher irradiation levels, b) increased use of tracking systems, and c) improvements in the performance of systems as losses have been reduced, for e.g. Through improvements in inverter efficiency.

Capacity Utilisation Factor	Solar[9]	Wind[10]	Biomass	Hydro	Nuclear
Year 2030	20%	30%	83%	40%	80%
Year 2050	32%	40%	86%	40%	80%
Year 2070	45%	50%	-	40%	-

1.5 Outcomes of the Study

As part of the study, we have built a user-interactive model. The model presents the various parameters such as (a) power requirement to electrify the sectors (in GW), (b) renewable energy requirement (GW), (c) energy consumption base and proposed (thermal and electrical) in Mtoe, (d) GHG emission reduction potential, (e) green hydrogen, and (f) green methanol requirement. All the mentioned parameters have been calculated for all the sub-sectors and for the overall country for each of the three timelines, i.e. 2030, 2050, and 2070. It has been modelled to estimate the above-mentioned parameters based on different scenarios, i.e., conservative, moderate, and ambitious.

These scenarios are the forward-looking scenarios for the country to transition to net zero emissions. Scenarios are being classified based on the level of effort to implement or the pace to deploy the decarbonisation technologies in each sector. The highest effort scenario is categorized as "ambitious" whereas the lowest effort is "conservative" scenario. The level of effort for each scenario is tabulated below, where the level of effort is the percent of the penetration level of each technology in each sub-sector.

Year →	2030	2050	2070
Scenarios ↓	Level of effort		
Conservative Scenario	30%	70%	100%
Moderate Scenario	50%	90%	100%
Ambitious Scenario	100%	100%	100%

Explanation of scenarios: For instance, XYZ technology is considered for any sub-sector with a penetration level of for example 10% in 2030, 50% in 2050, and 100% by 2070.

In the conservative scenario referring to % level of efforts from the above table, the penetration of the XYZ technology in the conservative scenario by 2030 would be 3% (i.e., 30% level of efforts of 10% of technology penetration). Similarly, for 2050, penetration would be 35% (70% level of efforts of 50% of technology penetration) and by 2070, penetration in the conservative scenario would be 100% (100% level of efforts of 100% of technology penetration).

In the moderate scenario, penetration of XYZ technology in the sector would be 5% by 2030 (50% level of efforts of 10% of technology penetration), 45% of penetration by 2050 (90% level of efforts of 50% of technology penetration) and 100% by 2070.

In an ambitious scenario, the level of effort is maximum, so technology penetration by 2030 would be 10% (100% level of effort of 10% of technology penetration). By 2050, penetration will be 50% (100% level of efforts of 50% of technology penetration) and by 2070, penetration will be 100%.

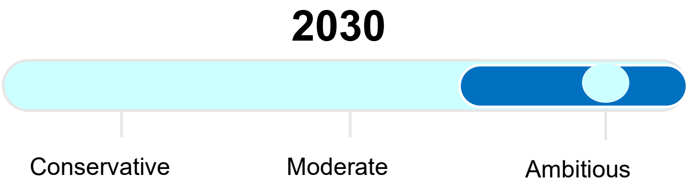
[9] https://atb.nrel.gov/electricity/2021/utility-scale_pv
[10] https://www.dnv.com/energy-transition-outlook/rise-of-renewables.html

The main results of the study, including the findings of all three scenarios, are illustrated below for the years 2030, 2050, and 2070. The analysis includes the following key result areas:

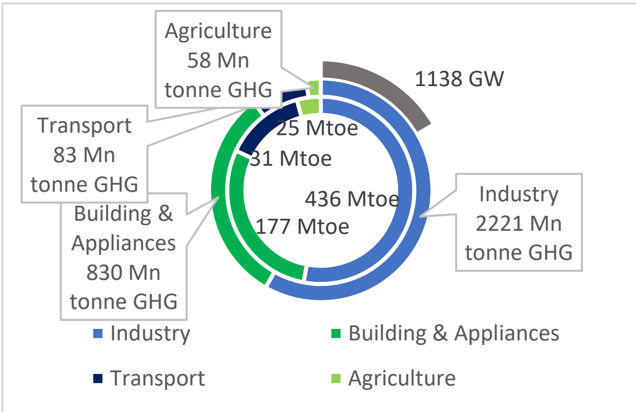
- Sectoral Energy Consumption (Mtoe)
- Sectoral GHG Emission Intensity (mn tonnes)
- Sectoral Electrification Potential (%)
- Total installed electricity generation capacity required (GW)

Explanation of the Illustration

The illustrations shown below present the above-mentioned parameters for each timeline and different scenarios.

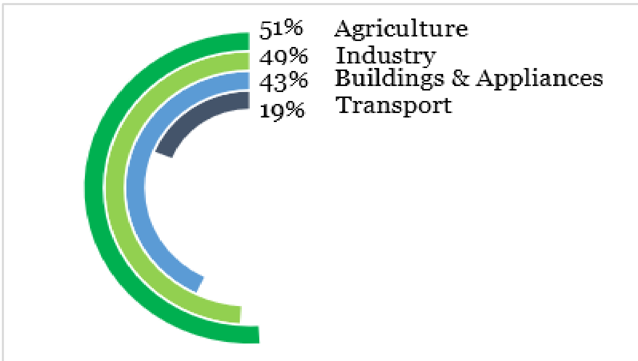


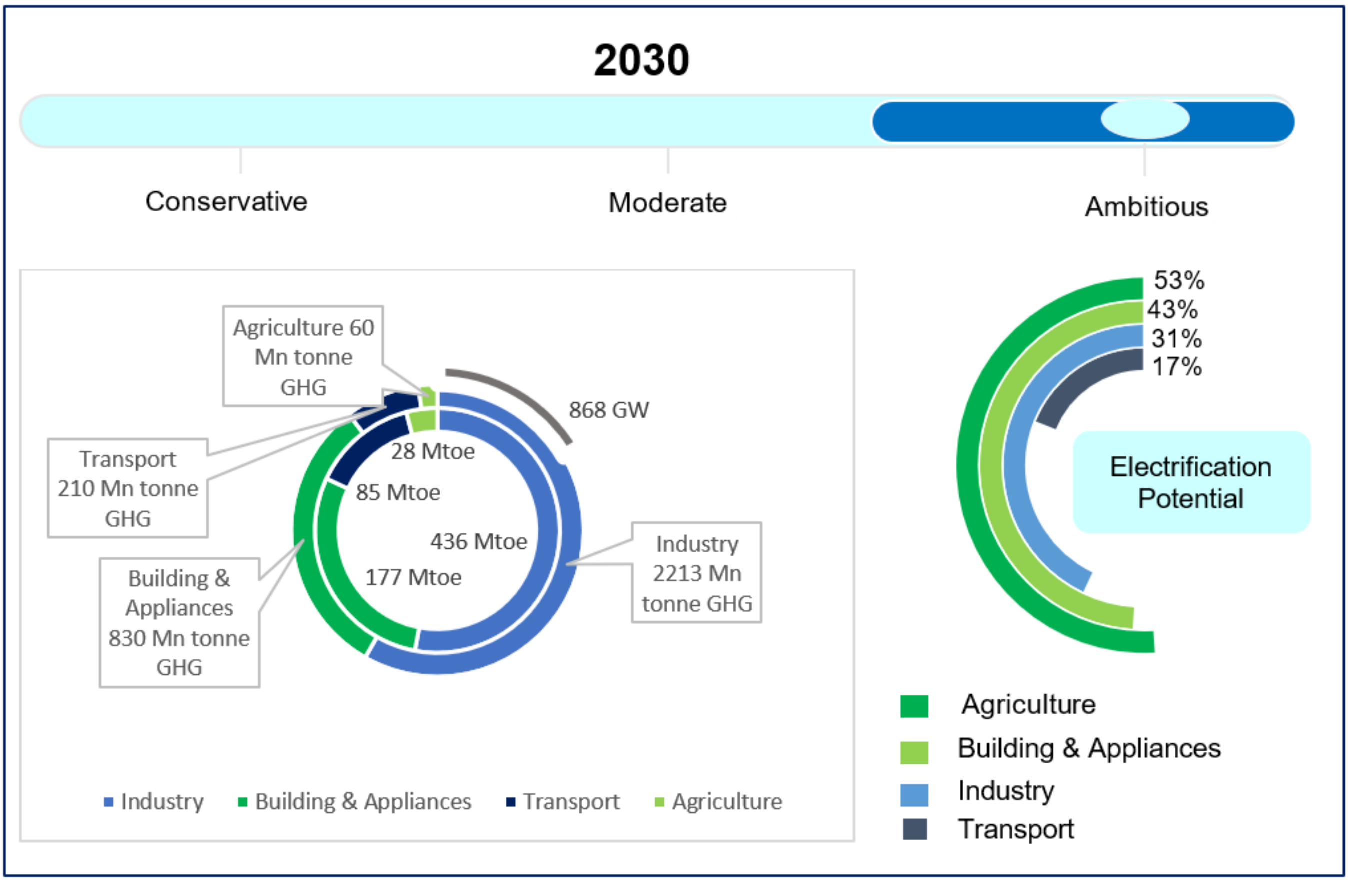
The toggle point above represents the scenario for which an analysis has been covered.



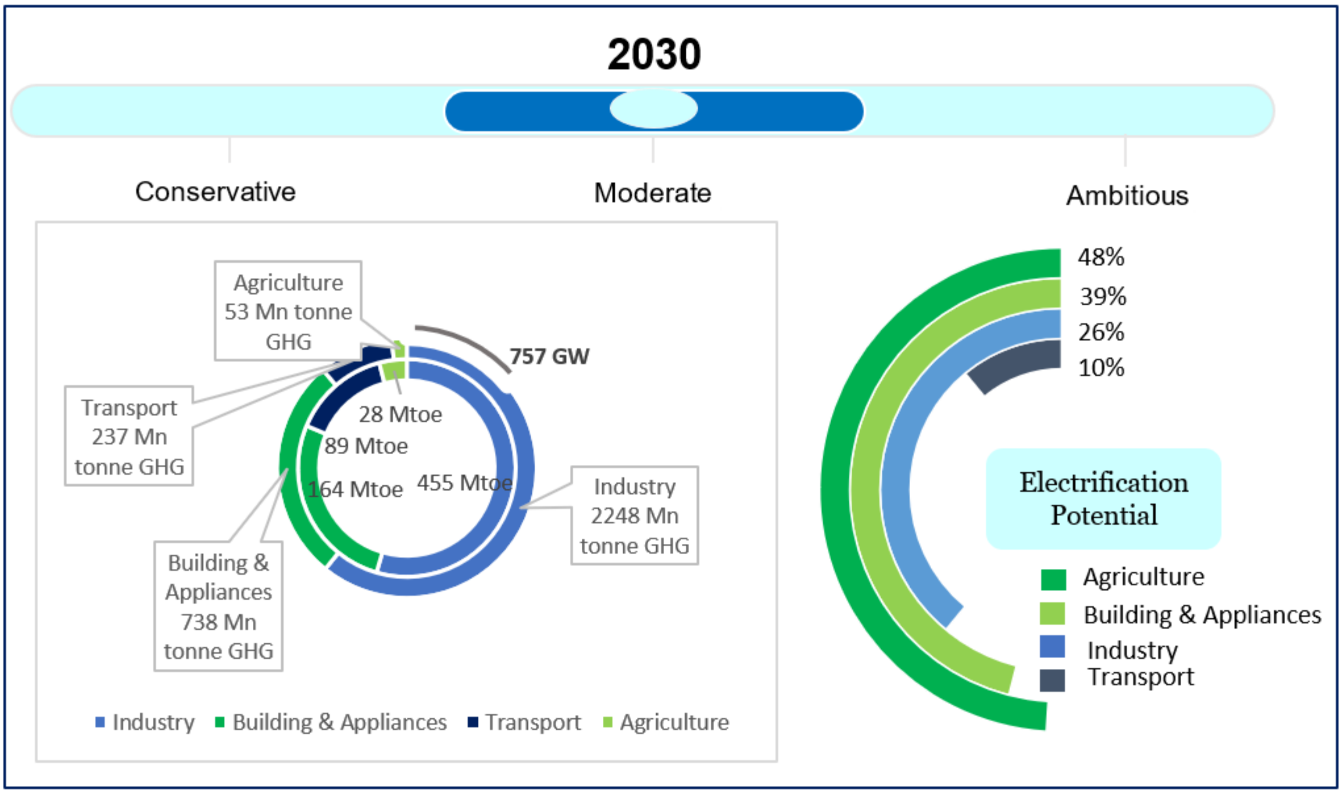
This illustration has three concentric rings, the outer most concentric ring represents the total installed electricity generation capacity required (GW) which is 1138 GW. Middle concentric ring represents the sectoral GHG emission intensity (mn tonnes), and the inner most ring presents the sectoral energy consumption in Mtoe.

The illustration to the right has concentric rings representing the percent electrification of each sector i.e., 51% electrification in agriculture sector, 19% electrification in transport sector and so on.

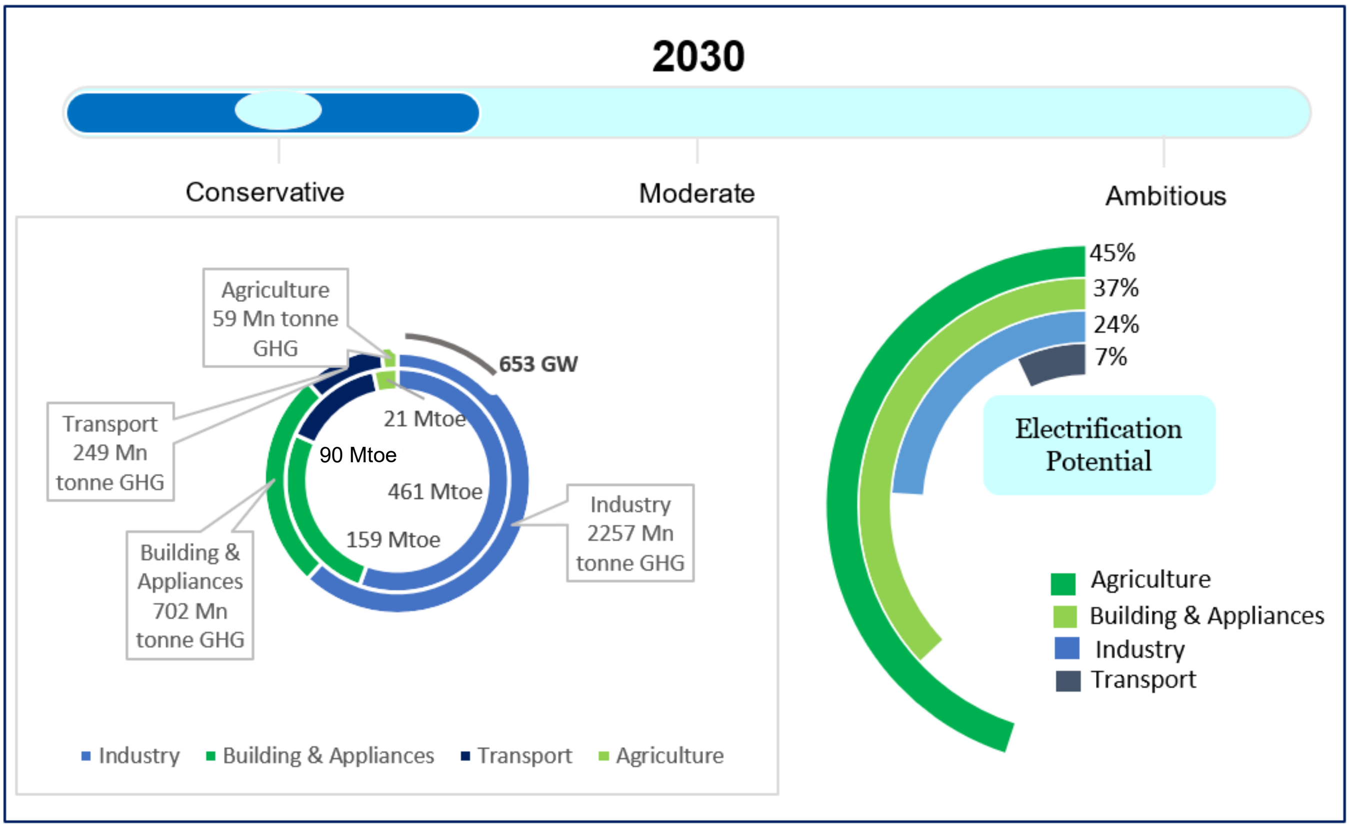


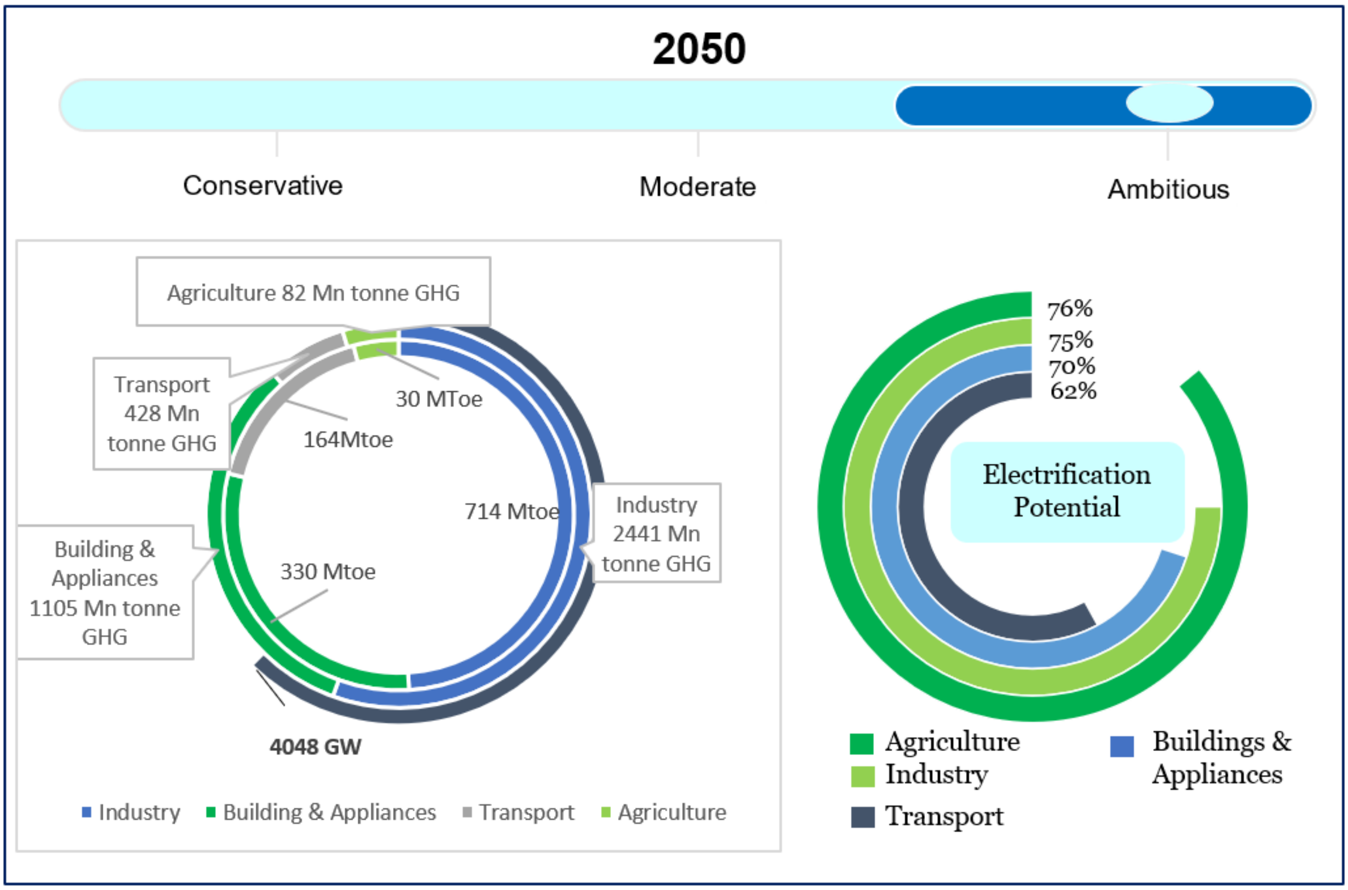


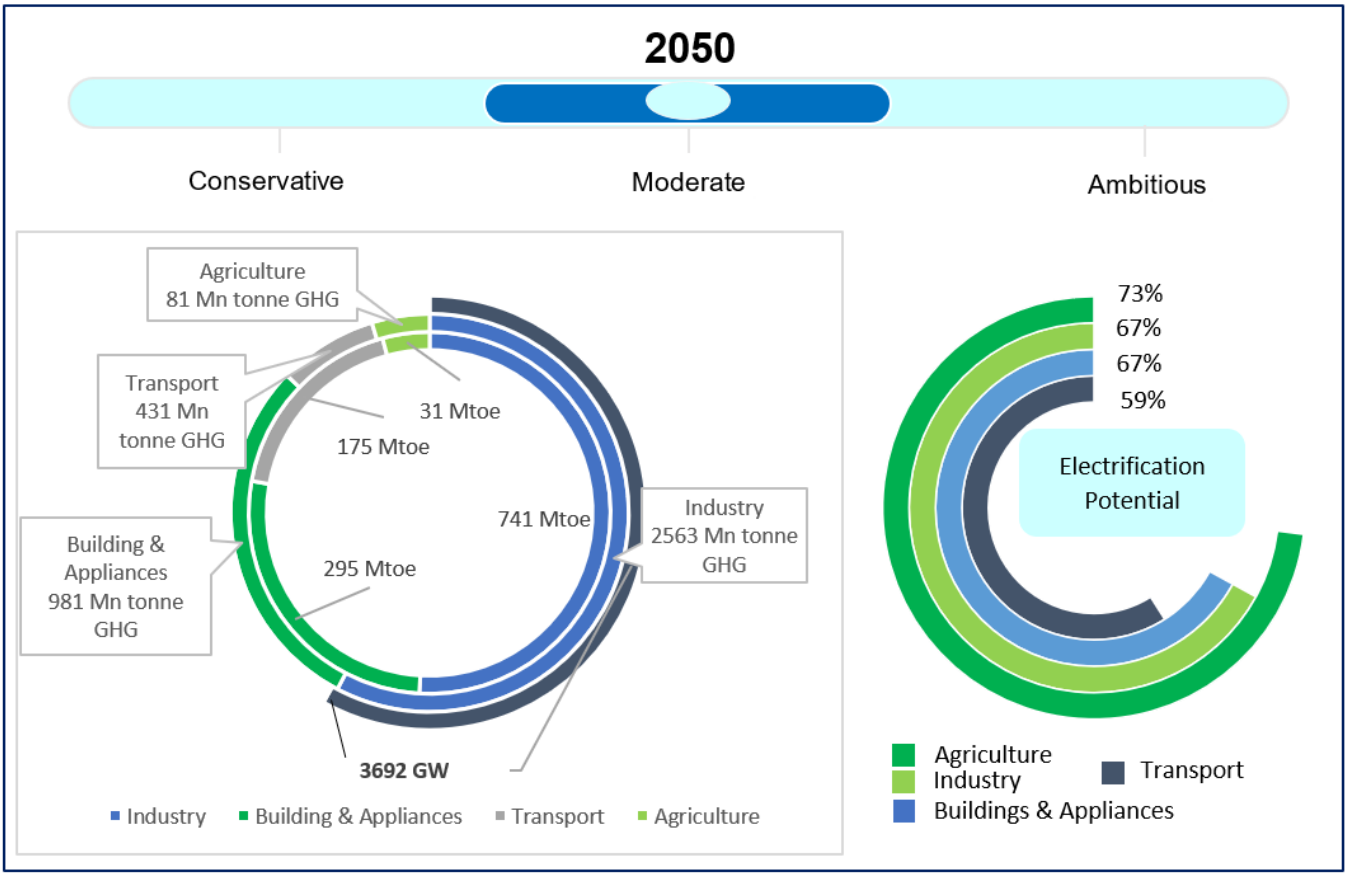
2030
Conservative
Moderate
Ambitious
Agriculture 60 Mn tonne GHG
868 GW
Transport 210 Mn tonne GHG
28 Mtoe
85 Mtoe
436 Mtoe
177 Mtoe
Industry 2213 Mn tonne GHG
Building & Appliances 830 Mn tonne GHG
Industry
Building & Appliances
Transport
Agriculture
53%
43%
31%
17%
Electrification Potential
Agriculture
Building & Appliances
Industry
Transport

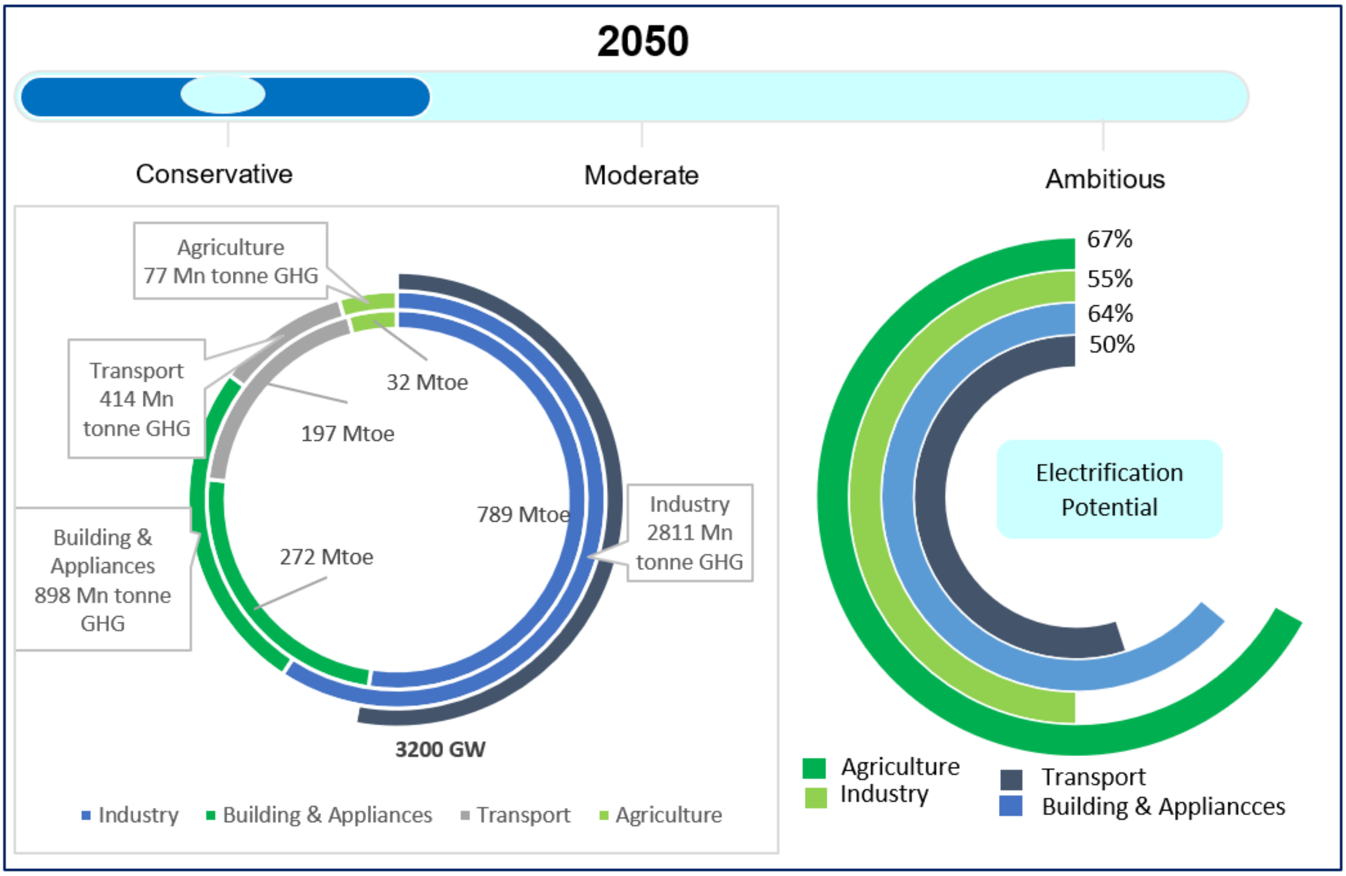


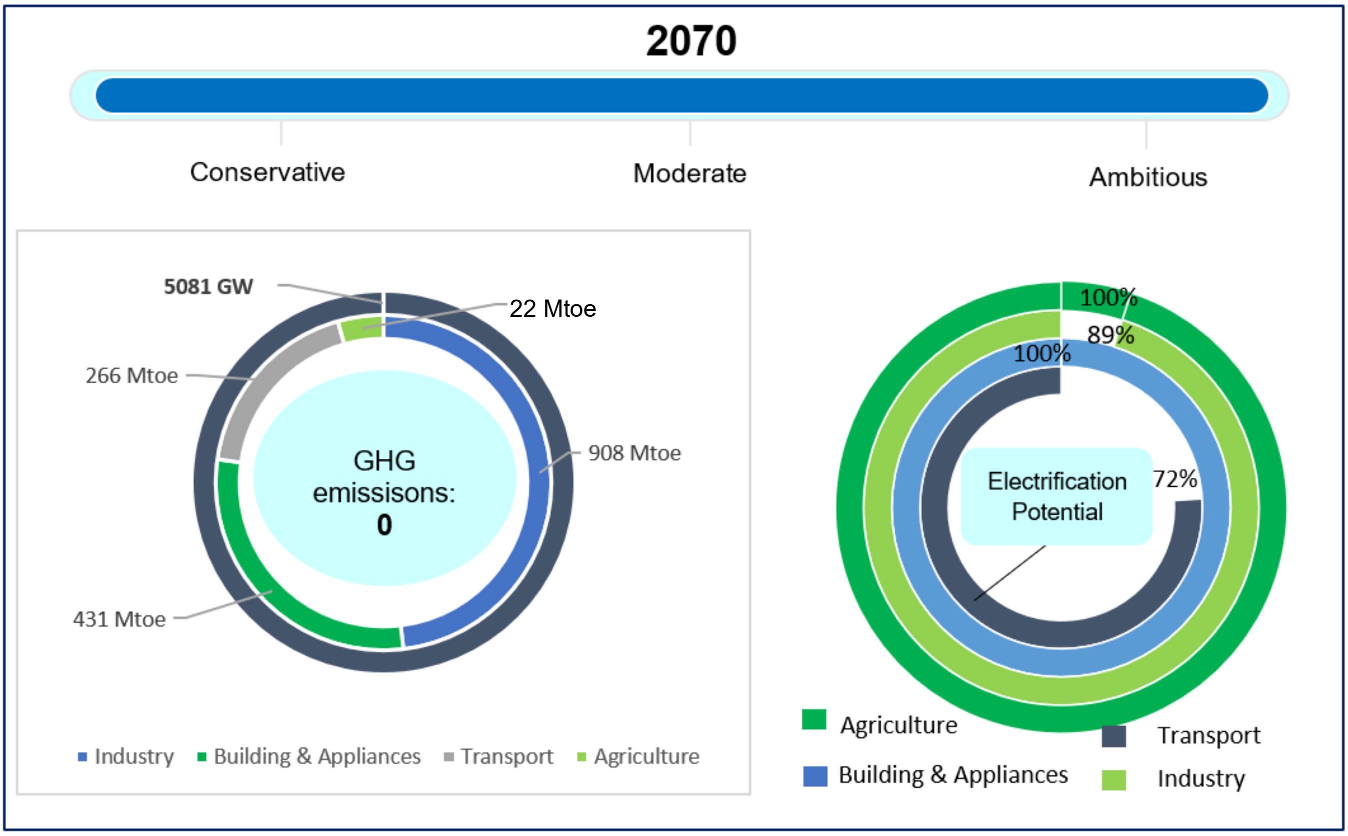
2030
Conservative
Moderate
Ambitious
Agriculture 53 Mn tonne GHG
757 GW
Transport 237 Mn tonne GHG
28 Mtoe
89 Mtoe
164 Mtoe
455 Mtoe
Industry 2248 Mn tonne GHG
Building & Appliances 738 Mn tonne GHG
Industry
Building & Appliances
Transport
Agriculture
48%
39%
26%
10%
Electrification Potential
Agriculture
Building & Appliances
Industry
Transport


2030
Conservative
Moderate
Ambitious
Agriculture 59 Mn tonne GHG
653 GW
Transport 249 Mn tonne GHG
21 Mtoe
90 Mtoe
461 Mtoe
159 Mtoe
Industry 2257 Mn tonne GHG
Building & Appliances 702 Mn tonne GHG
Industry
Building & Appliances
Transport
Agriculture
45%
37%
24%
7%
Electrification Potential
Agriculture
Building & Appliances
Industry
Transport


2050
Conservative
Moderate
Ambitious
Agriculture 82 Mn tonne GHG
Transport 428 Mn tonne GHG
30 MToe
164Mtoe
714 Mtoe
Industry 2441 Mn tonne GHG
Building & Appliances 1105 Mn tonne GHG
330 Mtoe
4048 GW
Industry
Building & Appliances
Transport
Agriculture
76%
75%
70%
62%
Electrification Potential
Agriculture
Industry
Transport
Buildings & Appliances


2050
Conservative
Moderate
Ambitious
Agriculture
81 Mn tonne GHG
Transport
431 Mn
tonne GHG
Building &
Appliances
981 Mn tonne
GHG
Industry
2563 Mn tonne
GHG
31 Mtoe
175 Mtoe
741 Mtoe
295 Mtoe
3692 GW
Industry
Building & Appliances
Transport
Agriculture
73%
67%
67%
59%
Electrification
Potential
Agriculture
Industry
Buildings & Appliances
Transport


2050
Conservative
Moderate
Ambitious
Agriculture
77 Mn tonne GHG
Transport
414 Mn
tonne GHG
Building &
Appliances
898 Mn tonne
GHG
Industry
2811 Mn
tonne GHG
32 Mtoe
197 Mtoe
789 Mtoe
272 Mtoe
3200 GW
Industry
Building & Appliances
Transport
Agriculture
67%
55%
64%
50%
Electrification
Potential
Agriculture
Industry
Transport
Building & Appliancces


2070
Conservative
Moderate
Ambitious
5081 GW
22 Mtoe
266 Mtoe
908 Mtoe
431 Mtoe
GHG emissisons: 0
Industry
Building & Appliances
Transport
Agriculture
100%
89%
100%
72%
Electrification Potential
Agriculture
Transport
Building & Appliances
Industry

2 Electrification of Industry

2.1 Electrification of Iron & Steel

There is a dire need to decarbonise the steel industry, and it has ample technical options to decarbonise and increase process efficiency. There is huge potential to implement technologies like heat recovery in sinter cooling and to use this heat to generate power, thereby, reducing the energy intensity of the process. Another instance of possible intervention in the Indian context would be coal moisture control to increase the calorific value of the coke used for iron making. This can increase the competitiveness of domestic steel industries in terms of resource consumption and carbon footprint. It is worth noting that a major share of these technologies can be implemented by modifying existing process chains.

Process efficiency measures and energy-efficient technologies would simply not suffice to eliminate carbon-based energy sources from the steel industry. Legacy coal-based capacities can be decarbonized by transitions to green hydrogen routes and carbon-free electricity, in addition to fuel-switching technologies and breakthrough technologies like Electrowinning, Carbon Capture and Storage (CCS), etc.

With the implementation of the above-mentioned technologies, 79% of the energy consumption can be electrified. The remaining 21% of the energy need would be met by green hydrogen, as per our analysis. This implementation would lead to reaching net zero target of the steel industry and there would be a significant drop (i.e. by 56%) in the energy consumption of the sector. Steel sector energy consumption could come down from 245 Mtoe in the base scenario to 109 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions.

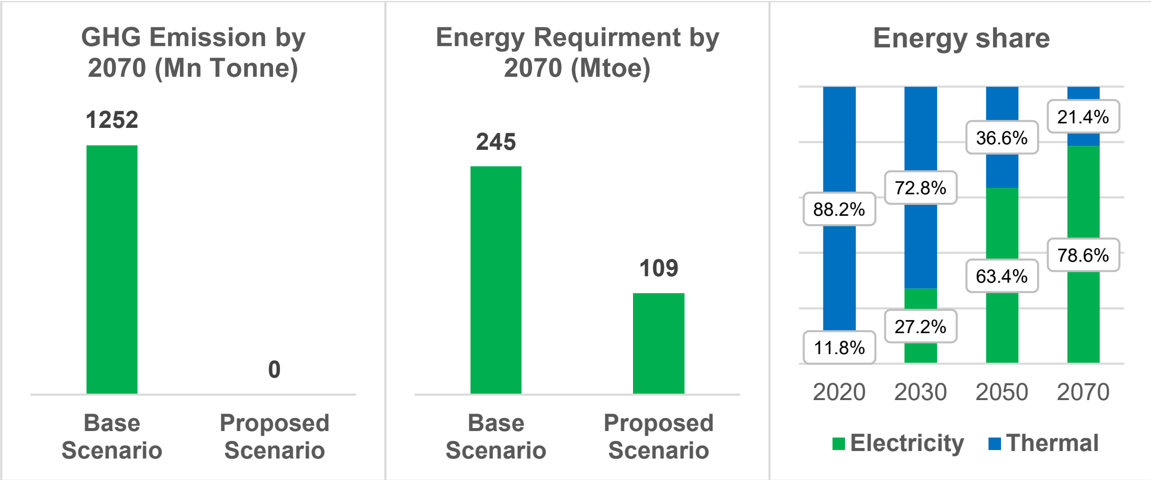
109 Mtoe of Energy Demand by 2070 from the sector

Reduction of **1252 Mn tonne CO_{2e}** by 2070

Requirement of **247 GW** of power demand by 2070

Requirement of **168 GWh** of battery storage capacity by 2070

Our analysis indicates about a 10% reduction in GHG emissions by 2030, 70% by 2050, and 100% by 2070. Key findings of the ambitious scenario of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.



The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e. level of efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[11].

Outlook for Decarbonisation

The Iron and steel sector is one of the backbones of economic development due to its applications to almost all other sectors. In India, the iron and steel industry has been developing for over a century since the first Tata Iron and Steel Company plant in Jamshedpur. India is the second-largest producer of crude steel and 2nd largest consumer of finished steel in the world as of 2022[12].

The Indian steel industry ranks among the most energy-intensive in the world, using more than 40 percent more energy than the global average[13]. In India, the blast furnace – basic oxygen furnace (BF-BOF) process contributes to 45% of the steel production, whereas 30%[14] of the production is through the direct reduced iron (DRI) route, and the remaining 25% is from scrap. Given the increased production trajectory set by the Ministry of Steel (MoS), i.e. production of 300 million tonnes of crude steel by 2030 and the net zero by 2070 commitments, there is a dire need to decarbonise the steel industry. As per the estimation, emissions from the sector are ~250 million tonnes of CO_2 equivalent. And it is expected to reach the level of 608 million tonnes CO_{2e} by 2030, 1000 million tonnes CO_{2e} by 2050, and 1259 million tonnes CO_{2e} by 2070.

Production Process

Iron ore is converted into steel through one of two process routes. The most common route is integrated steel making where iron (called pig iron) is first produced in a blast furnace and then refined into crude steel in a basic oxygen furnace. Direct reduction iron – electric arc furnace (DRI-EAF) steelmaking is an alternative process route. Direct reduced iron is transformed into crude steel in an electric arc furnace.

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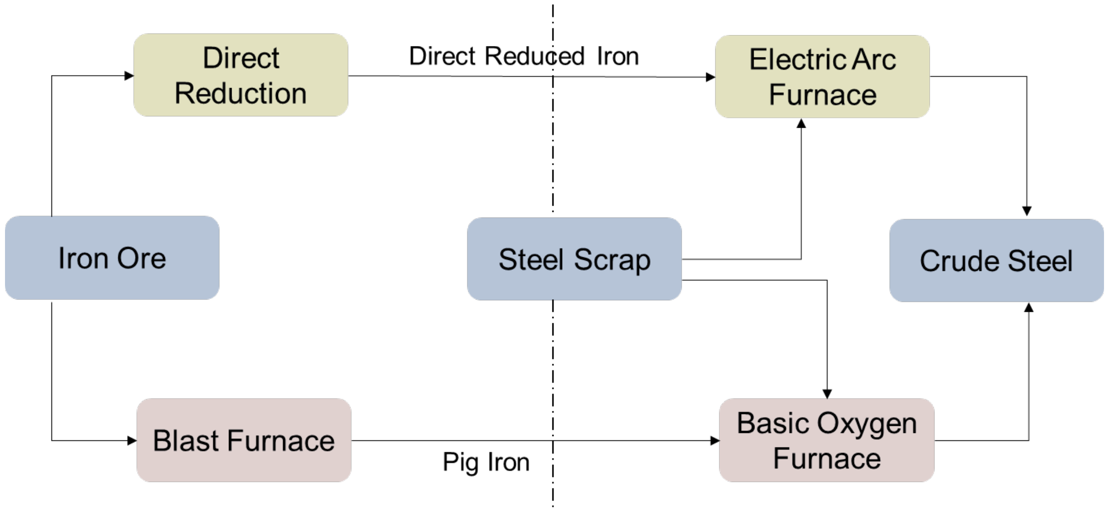
[11] *Refer to Annexure 1 – Methodology, assumptions, and references for baseline projections*

[12] *pib.gov.in/PressReleaseIframePage.aspx?PRID=1896882*

[13] *"Energy and Environment Management in Iron & Steel Sector | Ministry of Steel | GoI." 2019. Steel.gov.in. 2019 available at https://steel.gov.in/technicalwing/energy-and-environment-management-iron-steel-sector .*

[14] *BEE Study – "Assessment of various industrial sectors of economy to meet NDC targets, January 2022"*

Seventy-five percent of the world's steel is made via the integrated steel-making route, involving a blast furnace and basic oxygen furnace. The principal energy source in this process is coking coal which must first be converted into coke. Integrated steel making requires, on average, 1,400 kg of



iron ore, 700 kg of coal, 300 kg of limestone and 120 kg of recycled steel to produce 1,000 kg of crude steel. The average energy use, taking into account the manufacture of raw materials, is nearly 20 GJ per tonne of liquid steel, or 5,489 kWh.

Key Steps of BF-BOF Route

Sintering

Iron ore fines (small, grained iron ore) are mixed with clay and sometimes a flux (limestone), and heated to 1,300°C to produce a hard pellet. The larger particle size of pellets means they allow better circulation of oxygen or air in the blast furnace and melting is more efficient.

Coke-making

High-grade coal, called coking coal, is converted into almost pure carbon by prolonged heating in an oven in the absence of oxygen. In recent years, there has been a significant reduction in the coke consumption in the blast furnace due to increased injection of pulverized coal.

Lime production

Limestone is converted to lime for use as a flux to remove impurities. About 7.7% of direct emissions arise from the decomposition of limestone for use in blast furnaces.

Blast furnace

Coke, iron ore pellets and flux are fed into the top of the furnace while coal dust and hot, oxygen-rich air are blown in at the bottom. As the material falls downward, the reactions occur that turn iron ore to pig iron.

Coke plays three vital roles in a blast furnace:

i. Burning coke provides heat to drive chemical reactions and melt the iron
ii. Upon combustion, coke converts to carbon monoxide, which reduces iron ore to iron
iii. Coke provides a strong but permeable support to allow a free flow of gases in the furnace

Basic oxygen furnace

Molten pig iron is fed from the blast furnace into the basic oxygen furnace along with steel scrap. At this stage, the pig iron contains impurities and too much carbon. Most of this carbon is removed by blowing oxygen through the molten pig iron. Molten steel flows out of the basic oxygen furnace.

DRI-EAF Route

A significant percentage of primary steel is made via an alternative process: direct reduction. One advantage of direct reduction is that it does not require the iron to melt, and so the reduction occurs at a lower temperature (≈900°C) than in a blast furnace, and therefore uses less energy. Direct reduction usually uses syngas (carbon monoxide, hydrogen, carbon dioxide, and methane) as both reductant and fuel. Worldwide, nearly 60 million tonnes of direct reduced iron are produced every year.

TECHNOLOGIES FOR DECARBONIZATION

In line with the objective of the study focusing on direct electrification, we have covered three technologies in detail: **molten oxide electrolysis (MOE)**, **electrowinning**, and **electrolysers for green H_2 generation**. MOE and electrowinning technologies have potential for direct electrification and can completely replace crude steel production by BF-BOF route and lead to a reduction in specific energy consumption by 30%. Whereas, in H_2 DRI-EAF route, hydrogen can be produced through green routes rather than the conventional processes. A comparative analysis of the different routes of steel production is explained in the table below.

Table 1: Comparative analysis of different routes of steel production[15] [16]

Process	BF-BOF	Scrap-EAF	H_2 DRI-EAF	Steel by Electrolysis
Main Production Process	1. Sintering/palletisation 2. Coke Making 3. Blast Furnace 4. Basic Oxygen Furnace 5. Casting, rolling and finishing	1. EAF 2. Casting, rolling and finishing	1. H_2 Production 2. DRI production 3. EAF 4. Casting, rolling and finishing	1. Electrolysis of Iron Ore 2. Casting, rolling and finishing
Electrical Demand (kWh/tonne)	621	710	3500	3300
Thermal Demand (kWh/tonne)	4861	667	667	556
Total (kWh/tonne)	5482	1377	4167	3856

[15] https://www.globalefficiencyintel.com/electrifying-us-industry
[16] https://bze.org.au/wp-content/uploads/2020/12/electrifying-industry-bze-report-2018.pdf

Table 2: Details of Direct and Indirect Technology

Name of Technology	Type of Electrification	TRL	Technology Provider / Demonstrated Project (Country)
MOE (Molten Oxide Electrolysis)	Direct	TRL 6 (Laboratory testing of prototype component or process)	1)Boston Metals (USA)
Electrowinning	Direct	TRL 4 (Prototype system verified)	1) ArcelorMittal (Luxembourg) 2) John Cockerill (Belgium) 3) EDF (UK)
Electrolysers for H_2 generation	Indirect	TRL 8-9 (System completed and proven in operational environment)	1) Plug Power (USA) 2) ITM Power (UK) 3) Nel Hydrogen (Norway) 4) John Cockerill (Belgium) 5) SunFire (Germany) 6) Bloom Energy (USA) 7) Thyssenkrupp (Germany) 8) Cummins New Power (USA)

INDIRECT: ELECTRIFICATION OF THE STEEL MAKING

Hydrogen DRI-based EAF steel-making

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, and reducing agents. The majority of DRI production worldwide is based on natural gas and takes place in shaft furnaces, retorts, and fluidized bed reactors. The iron ore is reduced in a solid state in the DRI furnace before being melted in the EAF. Hydrogen and carbon monoxide are the reducing agents in the DRI-EAF route. DRI-EAF facilities mainly use natural gas to generate the reducing syngas (carbon monoxide, hydrogen, carbon dioxide, and methane) via catalytic processes based on dry reforming of methane (DRM), steam reforming of methane (SRM), and partial oxidation of methane (POM). Gasified coal is also used in the generation of hydrogen. Instead of using coal/natural gas to produce hydrogen, it can be produced by electrolysis using (renewable) electricity. Using electrolytic hydrogen as the primary reducing agent in DRI production, where electricity is generated from low or zero-carbon sources, can substantially reduce the GHG emissions of steel production. Using GH_2 as a reducing agent enables achieving higher reduction degrees from iron ore. Hydrogen could be used as the single reducing agent in the DRI process. In this case, the top gas is principally composed of water, and no reformer would be required. Instead, a gas heater would be attached to the system to preheat the gases to the required temperature. The hydrogen-based DRI is currently being piloted under the project name 'HYBRIT' in Sweden (HYBRIT, 2020).

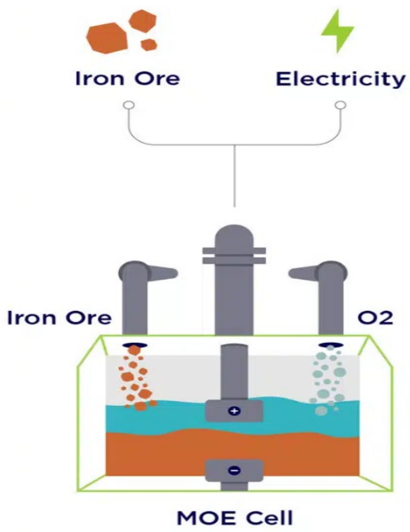
Global Example: HYBRIT – Zero carbon hydrogen in Sweden

Sweden has both iron ore reserves and significant resources of renewable energy. This has inspired a joint venture called HYBRIT to explore making steel with renewable hydrogen. HYBRIT aims to develop an existing method of natural gas-based direct reduction to run on pure hydrogen.

HYBRIT is already designing a pilot plant near the country's iron ore fields and plans to build a commercial-scale plant by the late 2020s. The Swedish Energy Agency is funding half the costs of the pilot plant. HYBRIT estimates that steel made using hydrogen would cost 20-30% more than conventional steel. However, they expect this difference to disappear as renewable electricity prices fall and the cost-penalty for carbon emissions rises.

DIRECT: STEEL MAKING BY ELECTROLYSIS OF IRON ORE

Electrolysis of iron ore in steelmaking is an emerging technology. Electrolysis of iron ore allows the transformation of iron ore into metal and gaseous oxygen (O2) using only electrical energy. Adoption of electrolysis technology would eliminate coke-making and blast furnaces and emissions associated with them.



$$2\,Fe_2O_3 + e^- \longrightarrow 4\,Fe + 3\,O_2$$

There are two main types of electrolysis processes that are being developed for steelmaking:

- The low-temperature electrolysis of iron ore in alkaline solution at 110 °C is known as electrowinning. This is currently being developed by ArcelorMittal in the SIDERWIN project. The SIDERWIN project is working towards developing a pilot-scale plant in the next few years (IEA, 2020). TRL – 4 and the timeline for full penetration is 2070.
- The high-temperature reduction of iron ore in a molten oxide environment at 1,600 °C was pioneered at MIT and is currently being developed by the start-up Boston Metal. It is being further developed into a pilot-scale plant (Boston Metal, 2020). In the cell, an inert anode is immersed in an electrolyte containing iron ore and then electrified. When the cell heats to 1600 °C, the electrons split the bonds in the iron ore. TRL is 5-6, and the timeline for full penetration is 2050.

Compatibility with currently used technologies

This technology is a new technology, and the process of production of this technology is completely different than the conventional process. So, this technology is not compatible with the existing technologies. This route of steel production has the potential to completely replace the existing BF-BOF route of steel production.

OTHER TECHNOLOGIES

There are several other technologies related to process and energy efficiency which can lead to a reduction of specific energy consumption of the sector. Detailed analysis of all the technologies has been done on parameters like energy savings, potential of GHG emission reduction, TRL, and deployment case is explained in the table shown below.

This study primarily focuses on identifying prospective opportunities for electrification (direct/indirect) of different sectors of the Indian economy. While assessing the emerging technologies for electrification, which may play a prominent role in achieving the objective of the study, we find that certain breakthrough technologies are at a nascent stage of commercialization. Going forth, in the short run, energy efficiency may support in reducing the specific energy consumption initially, but to up to a certain limit. However, with the focus on a net zero economy, a detailed assessment of emerging and breakthrough technologies has been emphasized in this study. Molten oxide electrolysis, Electrowinning (direct electrification of the core processes), green H_2-based DRI – EAF (indirect electrification) etc., will play a pivotal role in decarbonizing the iron and steel sector hence the detailed analysis in the next section is projected for the integration of technologies during the timeline till 2070.

Table 3: Details of other technologies

Name of Technology	Electricity Savings (kWh per tonne of product)	Fuel Savings (GJ per tonne of product)	CO2 Reduction (kg CO2 per tonne of product)	TRL	OEMs (Country of Origin)
Sintering					
Heat recovery from sinter cooler	-	0.25	23.85	TRL 9 (system proven in operational environment)	1) JP Steel Plantech Co. (Japan) 2) Nippon Steel & Sumikin Engineering Co. Ltd. (Japan) 3) ME Energy Private Limited (India)
Sinter Plant Heat Recovery (Power Generation from Sinter Cooler Waste Heat)	22.1	-	18.12*	TRL 9 (system proven in operational environment)	
High Efficient (COG) Burner in Ignition Furnace for Sinter Plant	-	0.01	0.44	TRL 9 (system proven in operational environment)	1) JP Steel Plantec Co (Japan), 2) Nippon Steel & Sumikin Engineering Co. Ltd. (Japan) 3) Sekyung Corporation (South Korea)
Cokemaking					
Coke Dry Quenching (CDQ)	-	1.9	97.51	TRL 9 (system proven in operational environment)	1) JP Steel Plantec Co (Japan), 2) Nippon Steel (Japan) 3) Paul Wurth India Private Limited (Luxembourg)
	150	-	123*		
Coal moisture control (CMC)	-	0.29	27.56	TRL 9	1) Nippon Steel (Japan)

				(system proven in operational environment)	2) Kawasaki Heavy Industries Ltd. (Japan)
Ironmaking (BF)					
Top pressure recovery turbine (TRT)	50	-	41*	TRL 9 (system proven in operational environment)	1) Paul Wurth India Private Limited (Luxembourg), 2) Mitsui E&S Machinery Co. Ltd. (Japan), 3) Kawasaki Heavy Industries (Japan)
Pulverized coal injection (PCI)	-	1.39	132.1	TRL 9 (system proven in operational environment)	1) Claudius Peters (Germany), 2) Danieli India Limited (Italy), 3) JP Steel Plantec Co (Japan) 4) Nippon Steel (Japan)
Hot stove waste heat recovery	-	0.083	7.89	TRL 9 (system proven in operational environment)	1) Nippon Steel (Japan)
Ironmaking (DRI)					
Use of iron ore pellets in DRI kiln	-	1.44[17]	136.23	TRL 9 (system proven in operational environment)	1) Electrotherm (India) Ltd. (India), 2) Concast (India) Ltd. (India)
Steelmaking (BOF)					
LD/converter gas recovery system	-	0.84	79.8	TRL 9 (system proven in operational environment)	1) Primetals Technologies India Private Limited (UK) 2) JP Steel Plantech (Japan) 3) Nippon Steel & Sumikin Engineering Co., Ltd. (Japan)

[17] *Morrow, William R., Ali Hasanbeigi, Jayant Sathaye, and Tengfang Xu. 2014. "Assessment of Energy Efficiency Improvement and CO2 Emission Reduction Potentials in India's Cement and Iron & Steel Industries." Journal of Cleaner Production 65 (February): 131–41.* https://doi.org/10.1016/j.jclepro.2013.07.022

LD/converter gas sensible heat recovery system	-	0.126	11.97	TRL 9 (system proven in operational environment)	1) Primetals Technologies India Private Limited (UK) 2) JP Steel Plantech (Japan) 3) Nippon Steel & Sumikin Engineering Co., Ltd. (Japan)
Steelmaking (EAF)					
Waste heat recovery in electric arc furnace	132		108.24*	TRL 9 (system proven in operational environment)	1) Primetals Technologies India Private Limited (UK) 2) JP Steel Plantech (Japan) 3) ME Energy Pvt. Ltd. (India) 4) First ESCO India Pvt. Ltd. (India)
Processing/Rolling					
Reheating Furnace with Re-Generative Burner	-	0.19	10.66	TRL 9 (system proven in operational environment)	1) Bloom Engineering (USA) 2) ENCON Thermal Engineers (P) Ltd. (India) 3) Shenwu Thermal engineering co ltd (China) 4) Entec Industrial Furnaces Pvt. Ltd (India)
Direct rolling of hot billet	-40 (an increase in electricity use because of billet heating)	1.45	116*	TRL 9 (system proven in operational environment)	1) Electrotherm (India) Ltd. (India), 2) Concast (India) Ltd. (India)
Variable speed drives for flue gas control, pumps, fans in integrated steel mills	11.11			TRL 9 (system proven in operational environment)	1) Amtech Electronics (India) Limited (India) 2) Grundfos India (Denmark)

					Major electric equipment suppliers
Cogeneration for use of untapped coke oven gas, blast furnace gas, & basic O_2 furnace-gas in integrated steel mills	97.22	NA	NA	TRL 9 (system proven in operational environment)	1) Thermax group (India) 2) GE (USA) Major power plant suppliers

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for production

Detailed desk research and analysis has been conducted to project the production demand of the sector for the years 2030, 2050, and 2070. Production demand projection for the sector is derived based on the GDP manufacturing growth rate and past trend of annual production of each sector. Detailed A detailed list of assumptions, values and references is annexed in Annex 1.

Also, production demand has been aligned with the target of the Ministry of Steel (MoS) to reach 300 million tonnes production capacity by 2030. Considering the above correlation, the Government target production of crude steel in the country would be 249 Mn tonne by 2030, and 428 Mn tonne, and 515 Mn tonne by 2050 2070, respectively.

Production Demand

Year	2020	2030	2050	2070
Production (Million tonnes)	102.6	249.0	428	515.6

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering India's target of net zero by 2070, which means the complete transition to a green hydrogen route and carbon-free electricity by 2070.

Molten oxide electrolysis and Electrowinning technology have the potential to directly replace the BF-BOF route of steelmaking. These two technologies are direct electrification technology, and they have low TRL, i.e., 4-5, but they have been successfully deployed as pilot projects in the industries and over a period of time, they would be commercially available. Penetration of both these technologies is low for the year 2030 due to its low TRL. Technology penetration will gradually increase by the year 2050 and 2070. Molten oxide electrolysis technology can be replaced by Electrowinning because the energy consumption of Electrowinning is comparably low, and it has an energy efficiency potential of ~60%.

Green hydrogen can be used both as a reducing agent and as fuel in the conventional DRI-EAF route of steelmaking. Penetration of the green hydrogen is also estimated based on the TRL of the technology, i.e., TRL 9. This GH_2 DRI-EAF route has the potential to completely replace the conventional DRI route of steelmaking by 2070. Steel production through the scrap route amounts to a 30% share of the total steel production in the country. This relative share of steel production through the scrap route, and hence the penetration of corresponding technology, is considered to remain constant over the years up to 2070.

The correlation between production share and penetration of technology is presented in the image shown below.

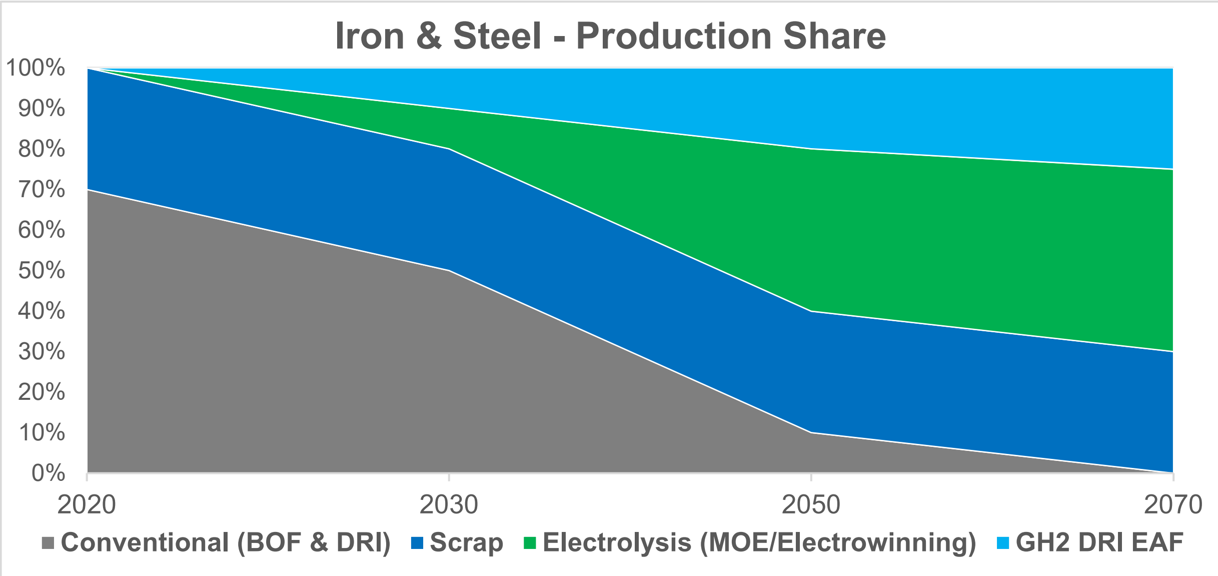


Figure 1: Penetration level of technologies

Projected Energy Consumption for Decarbonization

The penetration of each technology varies depending on the decarbonization scenario considered (conservative, moderate and ambitious). In other words, the decarbonization scenarios represent varying levels of effort of technology implementation over the years till 2070. This would lead to changes in energy consumption in each decarbonization scenario.

Energy requirement for the sector is projected, considering the different scenarios of decarbonisation.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	114	144	109

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050, and 100% by 2070. The energy demand of the steel sector would reduce by 4% in 2030, 29.4% in 2050, and 55% in 2070 over the base scenario.

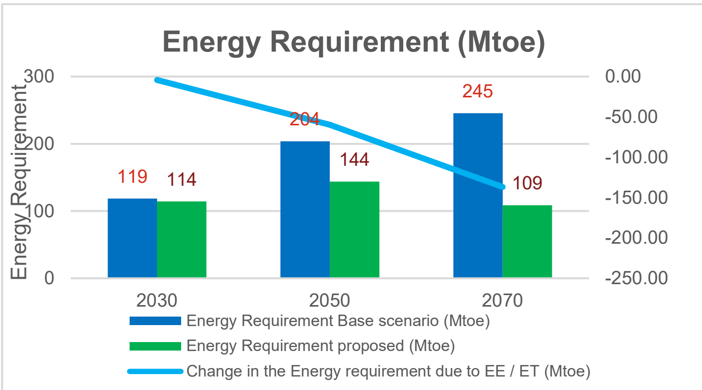


Figure 2: Energy requirement (Conservative - Iron and Steel)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	111	127	109

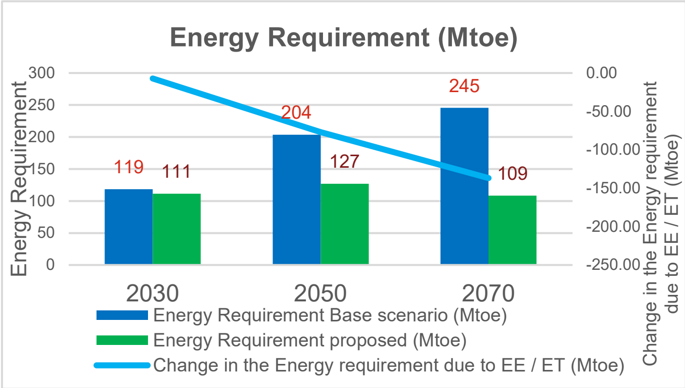


Figure 3: Energy requirement (Moderate - Iron and Steel)

In the moderate scenario, efforts to penetrate the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. A reduction in energy demand of the steel sector would be the same as the conservative scenario for the year 2070. Due to the increase in the efforts corresponding to the moderate scenario, energy demand reduction (over base year) in the years 2030 and 2050 would be more than that of the conservative scenario (7% reduction in 2030, 38% in 2050)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	104	118	109

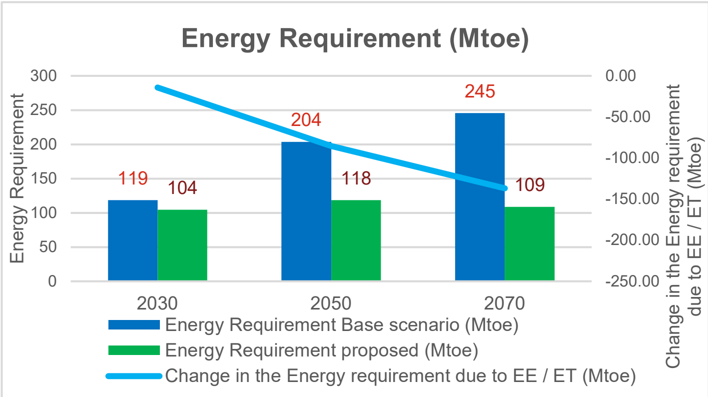


Figure 4: Energy requirement (Ambitious - Iron and Steel)

In the ambitious scenario, efforts to penetrate the technology are being considered at high levels, i.e., 100% by 2030. Reduction in energy demand of the steel sector would be the same as of conservative and moderate scenario for the year 2070. Due to relatively higher efforts in the ambitious scenario, energy demand reduction (over base year) in the years 2030 and 2050 would be more than that of the other two scenarios (12.6% reduction in 2030, 42% in 2050)

Projected RE installed capacity for Decarbonization

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy (including fossil and non-fossil fuel-based sources). In the ambitious scenario, the power installation requirement for the sector would be **91 GW** by 2030, **284 GW** by 2050**, and 247 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand for one one-day autonomy period in case of any seasonal disruption for RE hybrid power. Battery storage capacity for the sector would vary in the range of **7 – 13 GWh** for 2030 across different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Year	2030	2050	2070
Ambitious Scenario			
RE hybrid installed capacity (GW)	62	280	247
Battery Storage (GWh)	13	136	168
Moderate Scenario			
RE hybrid installed capacity (GW)	51	262	247
Battery Storage (GWh)	11	123	168
Conservative Scenario			
RE hybrid installed capacity (GW)	39	224	247
Battery Storage (GWh)	7	101	168

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach, for years 2030, 2050, and 2070, 604 million tonnes CO_{2e}, 1040 million tonnes CO_{2e}, and 1252 million tonnes CO_{2e}, respectively, in the base scenario. Under the ambitious scenario, net zero is estimated to be achieved by 2070 as the majority of the production would be electrified ,electricity would come from green energy sources and remaining thermal requirement would be met by the green hydrogen, which is an indirect route of green energy source. Since this adoption of technology and transition to different routes will materialize over the period, there will also be a significant drop in emissions by 2050, leading to net zero emissions by 2070. GHG emissions reduction for all the scenarios are calculated and presented in the graph below.

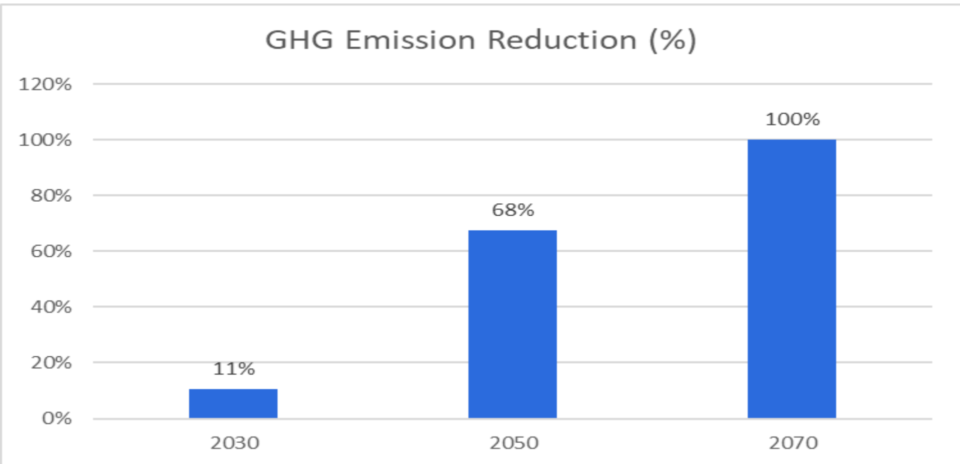


Figure 5: Ambitious Scenario - GHG emission reduction

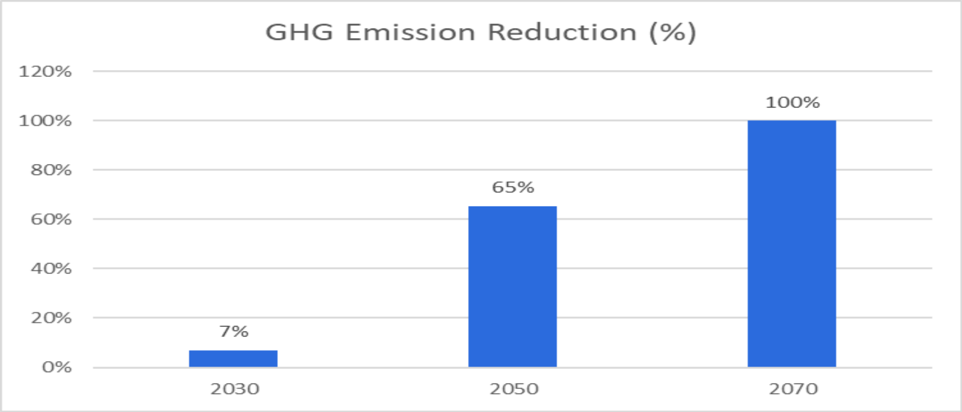


Figure 6: Moderate Scenario - GHG emission reduction

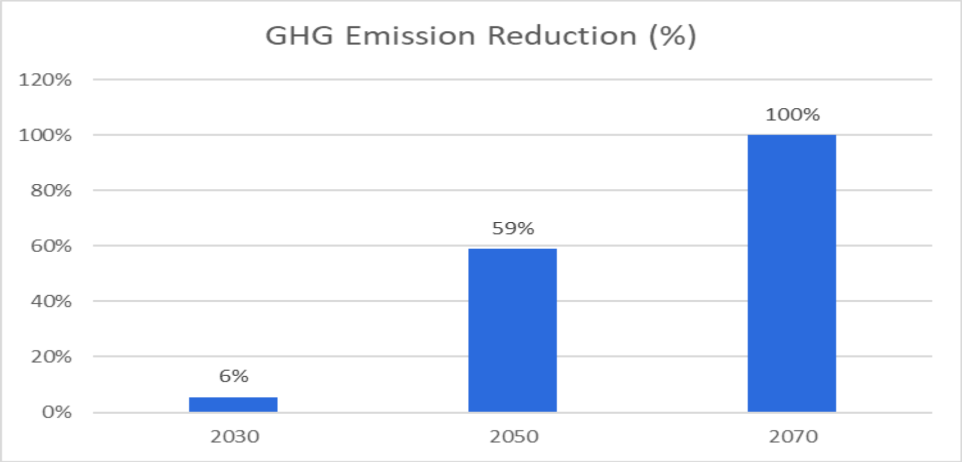


Figure 7: Conservative Scenario - GHG emission reduction

2.2 Electrification of Pulp and Paper

The pulp and paper sector comes in top five most energy intensive industries globally and contributes to ~1% of the net GHG emissions in India.[18] As pulp and paper production is projected to grow, there is a need for identification and deployment of decarbonization measures in the pulp and paper industry. Technologies such as electric boilers, radio frequency paper dryers and heat pumps will have a major role to play in the electrification of the pulp and paper sector.

With the implementation of the above-mentioned technologies, 100% of the energy consumption of the sector can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 12% i.e., from 75 Mtoe in the base scenario to 66 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions: 30% by 2050, and 100% by 2070. Key findings of the ambitious scenario of the model are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

66 Mtoe of Energy Demand by 2070 from the sector

Reduction of **340 Mn tonne CO_{2e}** by 2070

Power demand of **191 GW** by 2070

Requirement of **132 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e. level of decarbonization efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[19].

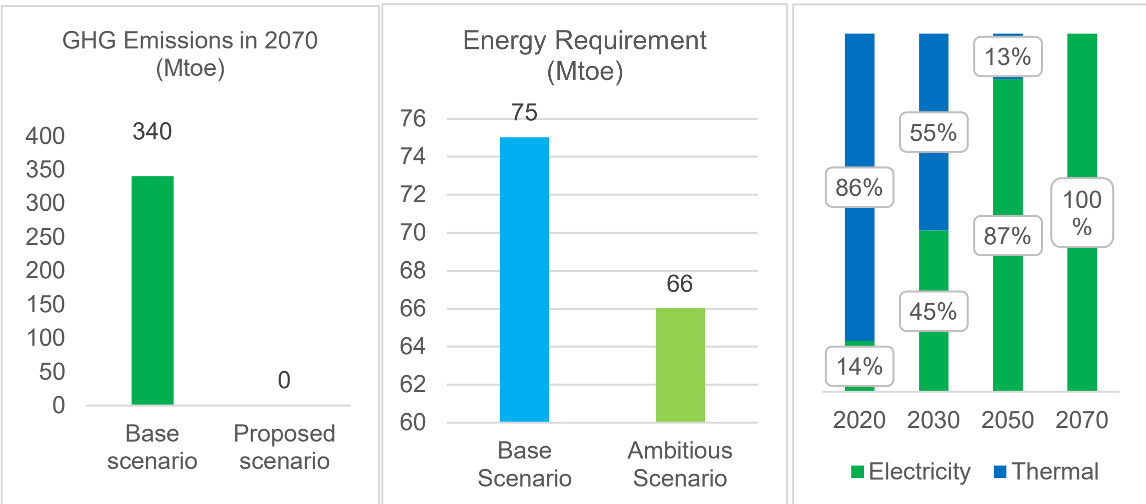


Figure 8: Improvement in GHG emission, energy requirement and electrification potential by 2070

[18] https://ippta.co/wp-content/uploads/2023/03/62-65.pdf
[19] *Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections*

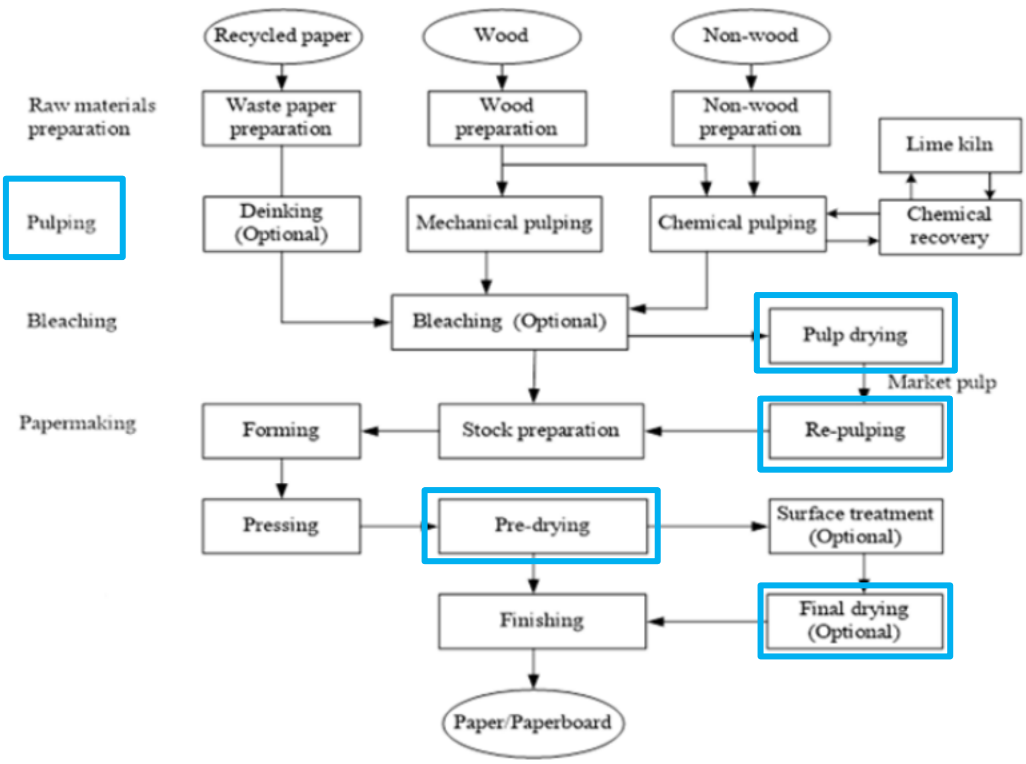
SECTOR OVERVIEW

Outlook for Decarbonisation

Globally, the paper Industry is one of the high priorities because of its significant contribution in economic development and high energy intensity. In India, too this industry plays a vital role in the overall industrial growth. The Indian paper industry is one of the world's fastest-growing industries. It grew at a compounded annual growth rate of 6-7%[20]. Among the top producers of paper, India ranks at fourth[18] position with an estimated production of 20 Mtpa. The Indian pulp and paper sector accounts for about 4% [18] of the global production, estimated at 500 Mtpa. In 2012, India recorded a paper consumption of 9.3[21] kg/capita vis-à-vis the global average of 58 kg/capita and the energy consumption of the Indian paper industry is 11.1 Mtoe. The domestic demand for paper consumption is on the rise due to increasing population, literacy rate, and growth in GDP, leading to generally improving living standards of individuals. Also the ban on plastic leads to an increase in paper consumption for packaging material.

The Indian paper Industry has a highly fragmented structure consisting of small, medium and large-sized paper mills having capacities ranging from 10 to 1150 tonnes per day employing wood, agro-residues and recycled wastepaper as major raw materials.

Process Flow Diagram



The key processes that drive pulp and paper manufacturing are the preparation of raw materials, pulping, recovery of chemicals, bleaching, drying of pulp, and producing paper. The **pulping and paper drying processes** are associated with the highest energy consumption.

[20] https://www.unido.org/sites/default/files/files/2020-07/INDIA_PAPER.pdf
[21] https://static.psa.gov.in/psa-prod/publication/Report_on_Opportunities_for_Green_Chemistry_Initiatives_in_Pulp_Paper_Industry_India.pdf

- **Pulping Process**: The pulping process employs three types of raw materials a) hardwood, b) agro-residues, and c) recycled fibre/wastepaper. Generally, two approaches are employed for pulping in the Indian context: chemical pulping and chemi-mechanical pulping.
  - **Chemical Pulping - Kraft Sulphate process**: The Kraft/sulphate process is the most versatile method of pulp production. It results in strong and long fibre as well as low lignin content pulp. In this process, the wood chips are cooked at a temperature of **165-170°C** with sodium hydroxide (caustic soda) and sodium sulphide to separate lignin and wood resins from the pulp. The pulp is then washed and bleached, if necessary. About 92-95 % of the chemicals (sodium hydroxide, sodium sulphide and lime) are recovered and reused by operating in a closed-loop system.
  - **Chemical Pulping – Soda process**: The Soda pulping process is employed for pulping of agro-residues like wheat and rice straw and bagasse. In this process these raw materials are cooked with caustic soda at a temperature of **150-160°C** to separate lignin from the raw material. The pulp is then washed and bleached, if necessary, to make a bleached pulp.
  - **Chemi-mechanical pulping (CMP):** In the chemi-mechanical process, the wood chips are first impregnated with mild caustic soda-based chemicals to extract resin and lignin from the fibre prior to mechanical refining.

Table 4: Energy Intensity of different processes

Process Steps	Equipment	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)
Liquor evaporation and pulping chemical preparation	Evaporator	996	46
	Pulp Machine	567	40
	Cooking Machine	656	95
Bleaching	Conventional bleaching plant	312	75
Drying	Steam/fuel-based dryer	1245	128
Papermaking	Papermaking machine	310	296
Total Energy		**4086**	**680**

All the thermal needs of the plants are being fulfilled by the steam generated using fossil fuel-based boilers.

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Electric Boiler (Electrode Type)

Electric boilers are being used in the drying process of the sector to meet their steam requirement. A detailed description of the technology is given in section *8.1 Cross-cutting technologies*.

Radio Frequency Paper Dryer

Radio-frequency heating is a form of dielectric heating with systems operating in the 10-30 MHz frequency and 10-30 meters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material. Since the entire thickness of the material is heated simultaneously, the process offers uniform heating at low temperatures. This technique works well with materials that are poor conductors of heat and electricity due to its greater

depth of penetration and is much more efficient than conventional heating processes. Radio-frequency systems heat material more uniformly and with greater depth of penetration, and work best with objects of a regular, simple shape.
The key advantage of dielectric heating is its ability to heat large volumes of material efficiently.


Photo by RF Systems

Global Example

RF Systems, Italy, is one of the manufacturers of radio frequency paper dryers and it is commercially available.

Technology Readiness Levels (TRL)

Due to good pre-existing adoption, this technology has a TRL of 9.

Heat Pump

An electric heat pump is a technology for producing hot air, hot water, or steam. It does this very efficiently by extracting thermal energy from a convenient source of heat. It is particularly useful for reusing heat wasted by many industrial processes. In the paper and pulp industrial sector, a heat pump is used in the drying process to generate the steam and dry the output of the processes. A detailed description of the technology is given in section 8.1 Cross-cutting technologies.

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Process Flow Diagram

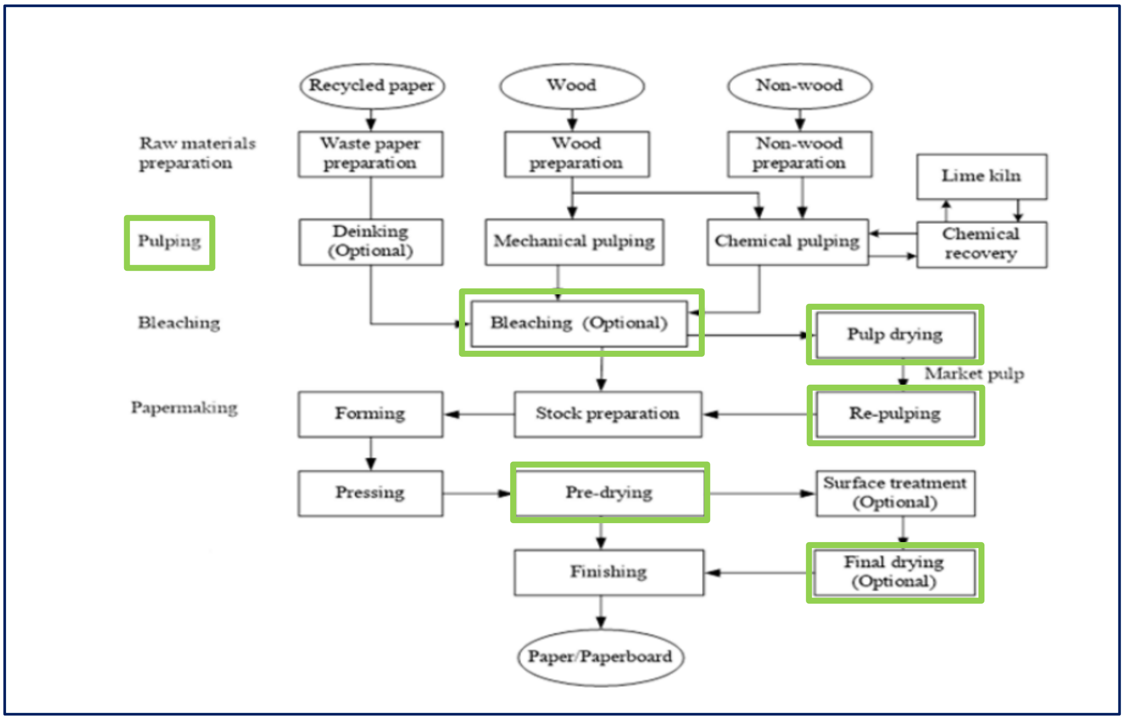


Table 5: Energy Intensity of different processes (Electrified Scenario)

Process Steps	Equipment	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)
Liquor evaporation and pulping chemical preparation	Evaporator	0	885
	Pulp Machine	0	517
	Cooking Machine	0	647
Bleaching	Conventional bleaching plant	0	338
Drying	Steam/fuel-based dryer	0	1176
Papermaking	Papermaking machine	0	557
Total Energy		**0**	**4120**

Current and projected demand for production

Detailed desk research and analysis have been conducted to project the production demand of the sectors for the years 2030, 2050, and 2070. Production demand projection for the sector is derived based on the GDP manufacturing growth rate and past trend of annual production of each sector. A detailed list of assumptions, values and references is annexed in Annex 1.

Based on the analysis, production of paper in the country would be 34 Mn tonne by 2030, 87 Mn tonne, and 105 Mn tonne by 2050 and 2070 respectively.

Production Demand

Year	2019	2030	2050	2070
Production (Million tonnes)	18	34	87	105

Suitable technology mix

Technologies are evaluated primarily based on their TRL level and potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering India's target of net zero by 2070. The correlation between technology share and penetration of technology is presented in the image below.

Technologies like electric steam dryers (electrode boiler/heat pump) are at TRL 9. So, these technologies can be deployed at scale in the near and in long-term scenarios. The efficiency level of the above-mentioned technologies is also higher than the conventional technologies[22] , thus giving them an upper edge for implementation. Other technologies like evaporators, bleaching plants, and pulp machines are also at decent TRL levels, i.e., TRL 8 and these technologies also have the potential to be deployed by 2030-2035. The image shown below represents that the pulp and paper sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector.

[22] Explained in Section 8: Cross-cutting Technologies

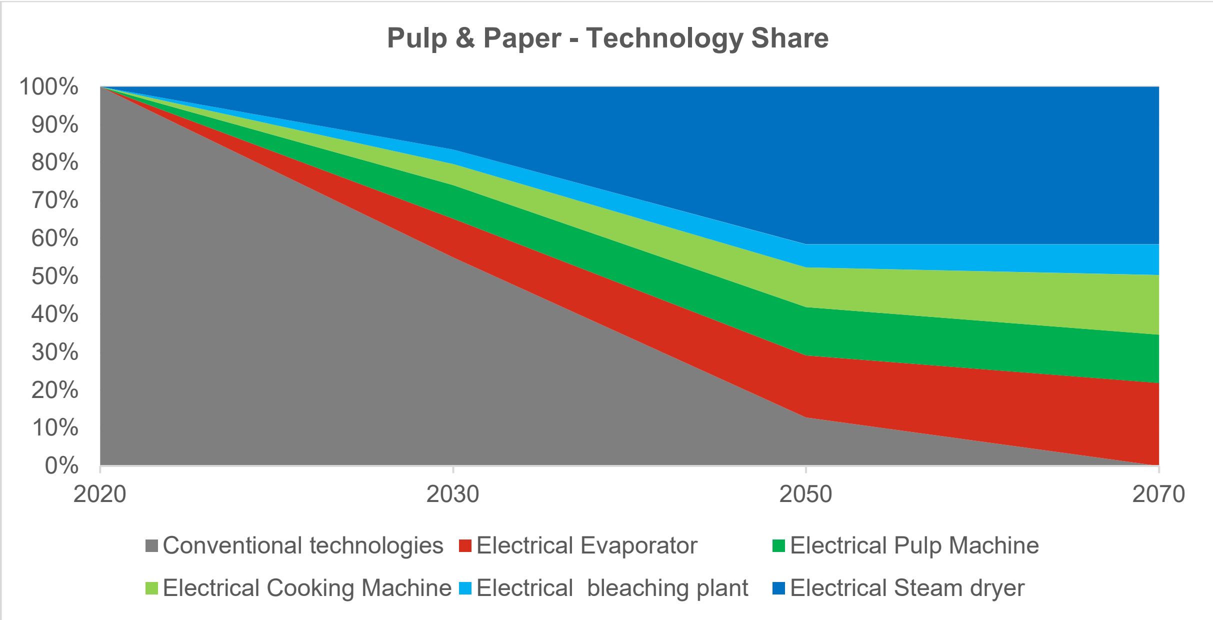


Figure 9: Penetration of technology

Projected Energy Consumption for Decarbonization

Energy consumption is projected, considering the different scenarios of decarbonisation (conservative, moderate and ambitious). Technology penetration of each technology varies depending on the scenarios, i.e., the effort of implementation would lead to changes in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	23.8	58	66

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e. 30% by 2030, 70% by 2050, and 100% by 2070. The energy demand of the paper sector would reduce by 2% in 2030, 6% in 2050, and 12% in 2070 over the base scenario.

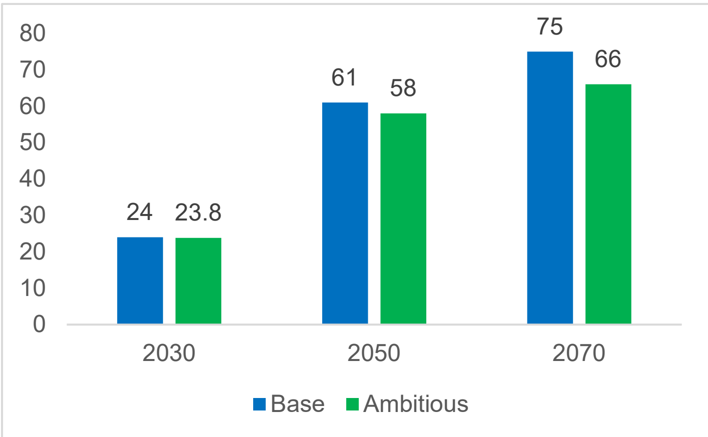


Figure 10: Energy requirement (Conservative – Paper)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	23.5	56.6	66

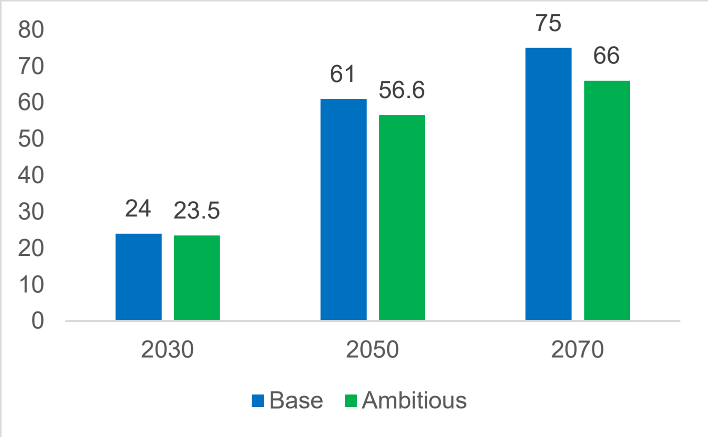
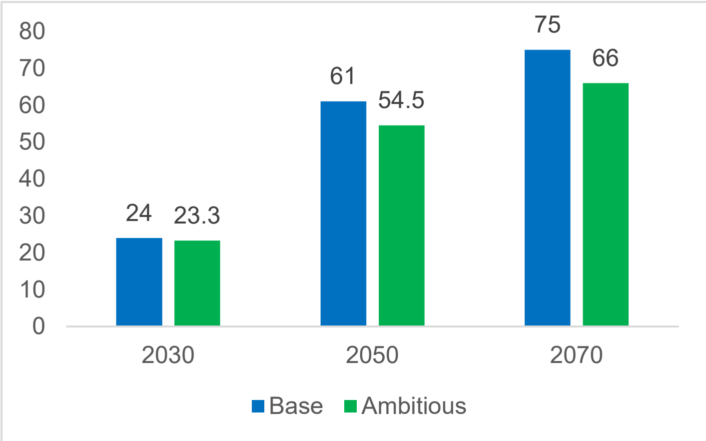


Figure 11: Energy requirement (Moderate scenario - Paper)

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels i.e., 50% by 2030, 90% by 2050, and 100% by 2070. A reduction in energy demand in the paper sector would be the same as in the conservative scenario for the year 2070. Due to the increase in the efforts in the moderate scenario, the reduction in the years 2030 and 2050 would be more than that of the conservative scenario (3% reduction in 2030, 8% in 2050)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	23.3	54.5	66



In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e. 100% by 2030, 100% by 2050, and 100% by 2070. Reduction in energy demand of the paper sector would be the same as of conservative and moderate scenario for the year 2070. Due to the increase in the implementation efforts in the ambitious scenario, the reduction in the years 2030 and 2050 would be more than that of the other two scenarios.

Projected RE installed capacity for Decarbonization

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilization factor is calculated for the different timelines based on the mix of different sources of energy, including fossil and non-fossil fuel-based sources). In the ambitious scenario, the power installation requirement for the sector would be **24 GW** by 2030, **180 GW** by 2050**, and 191 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand for one day autonomy period in case of any seasonal disruption for RE hybrid power. Battery storage capacity for the sector would vary in the range of **2 – 7 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Year	2030	2050	2070
Ambitious Scenario			
RE hybrid installed capacity (GW)	16	177	191
Battery Storage (GWh)	7	94	132
Moderate Scenario			
RE hybrid installed capacity (GW)	12	128	191
Battery Storage (GWh)	5	66	132
Conservative Scenario			
RE hybrid installed capacity (GW)	6	92	191
Battery Storage (GWh)	2	46	132

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach, for years 2030, 2050, and 2070, 110 million tonnes CO_{2e}, 279.5 million tonnes CO_{2e}, and 339.8 million tonnes CO_{2e} in Business-as-usual (BAU) scenario, respectively. Under the ambitious scenario, net zero is estimated to be achieved by 2070 as the majority of the production would be electrified and electricity would come from green energy sources. Since this adoption of technology and energy transition will materialize over the years, there would also be a significant drop in emissions by 2050 and net zero emissions by 2070. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below. In all three scenarios GHG emissions of the sector increase till 2030. This is because the ongoing electrification of the sector in consequence boosts electricity demand. Due to the consistent high percentage of non-renewables the emission factor of the grid will still be at around 780 grams of CO_2 per unit of electricity in 2030.

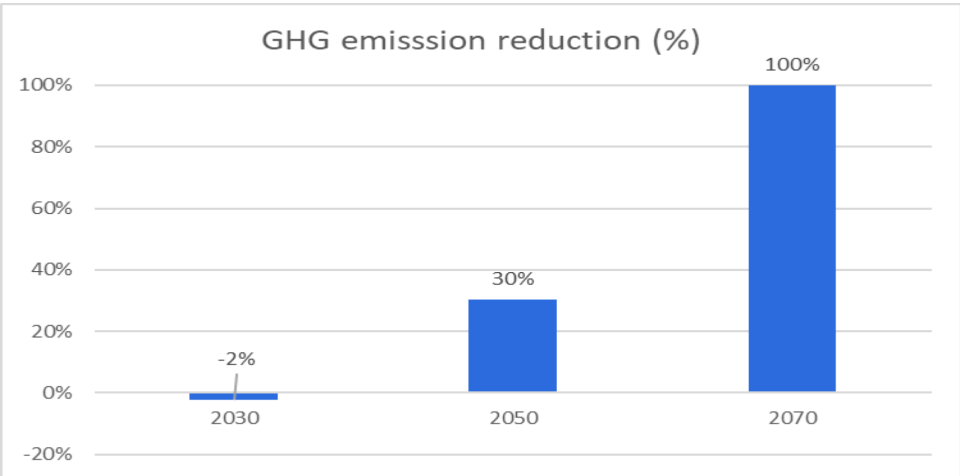


Figure 13: Ambitious Scenario - GHG emission reduction

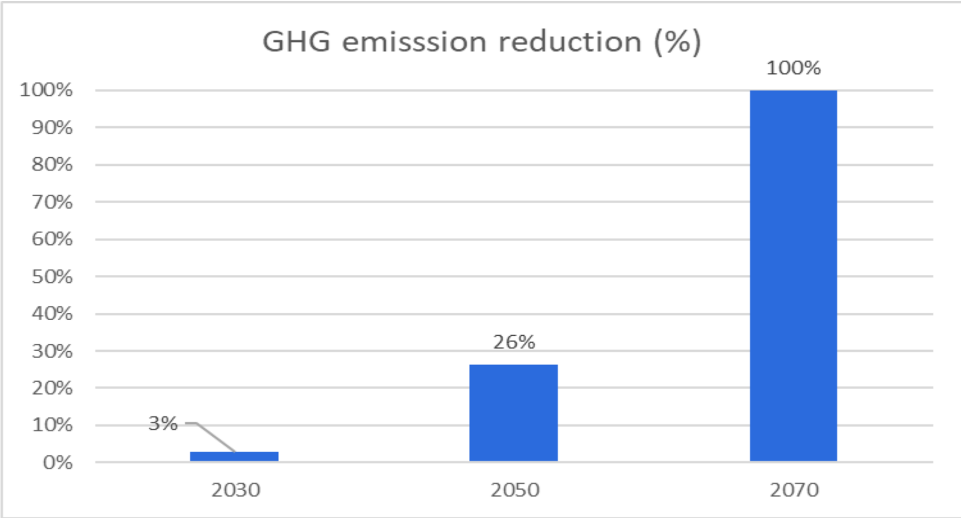


Figure 14: Moderate Scenario – GHG emission reduction

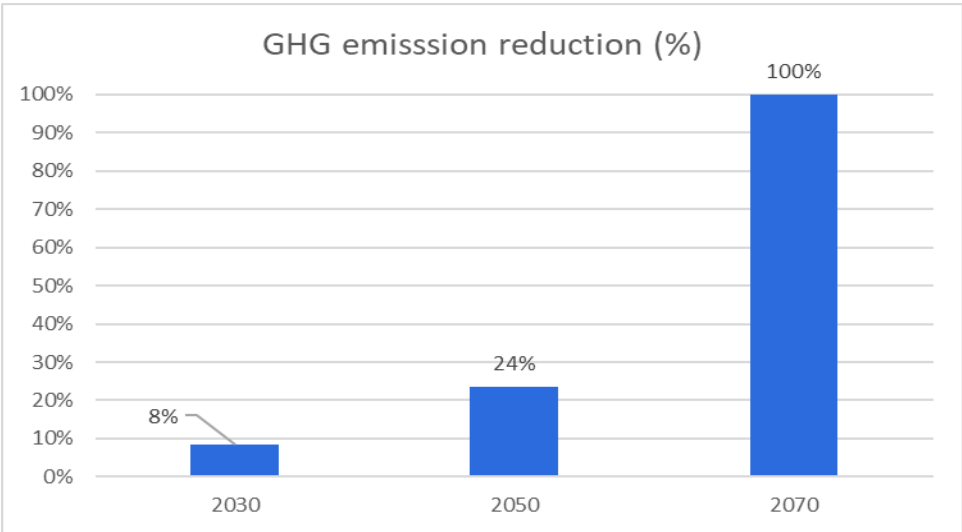


Figure 15: Conservative Scenario – GHG emission reduction

2.3 Electrification of glass industry

Glass production is an energy intensive process involving sub processes such as fossil fuel-based melting which is a major source of GHG emissions. Moving to electrified processes such as electric heating has several benefits like improved energy efficiency, more flexible control, and less combustion-related emissions. Electrification technologies such as electric furnace, electric forehearths and electric annealing oven can electrify the existing melting, conditioning, and forming and post forming and annealing processes respectively.

With the implementation of the abovementioned technologies, 100% of the sector's energy consumption can be electrified. This implementation would result in a significant drop in the energy consumption of the sector in the ambitious scenario by 20%, i.e. from 3.5 Mtoe in the base scenario to 2.8 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions: 46.3% by 2030, 75.5% by 2050, and 100% by 2070. Key findings of the scenario analysis model (ambitious scenario) are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

2.8 Mtoe of Energy Demand by 2070 from the sector

Reduction of **14.52 Mn tonne CO_{2e}** by 2070

Power demand of **8.3 GW** by 2070

Requirement of **5.7 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology which varies with the scenario used in the model (i.e. level of effort – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector, for consecutive years up to 2070 based on corresponding GDP projections[23].

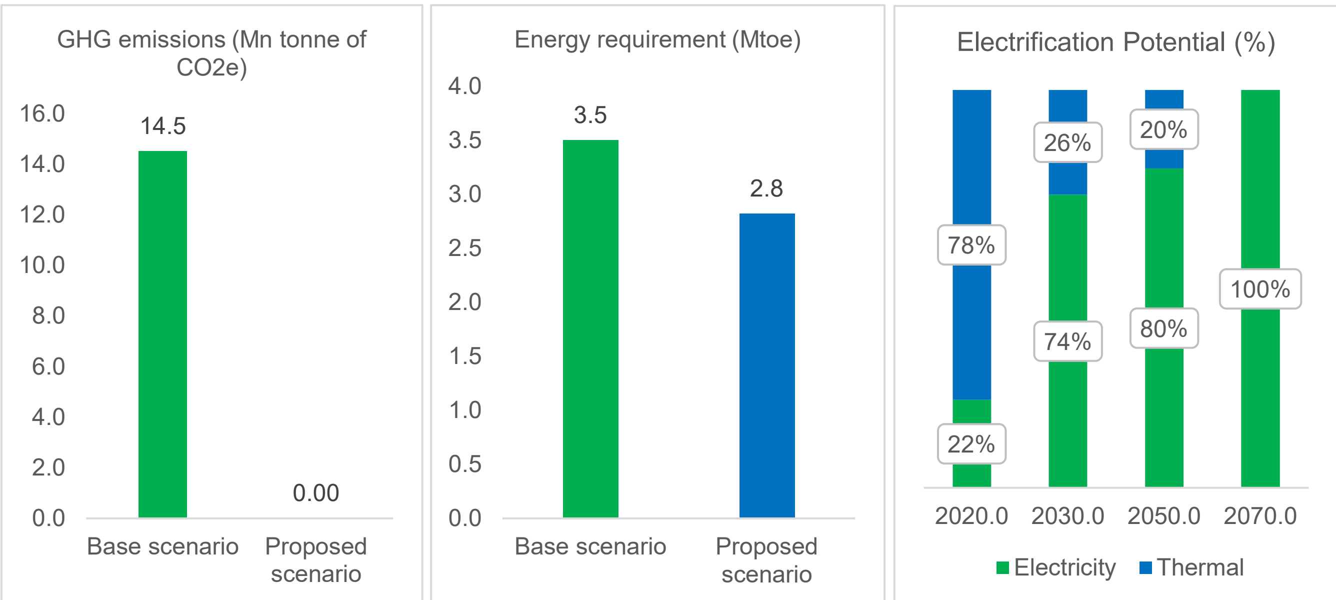


Figure 16: GHG emissions, energy requirement and electrification potential in proposed scenario

[23] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

SECTOR OVERVIEW

The glass industry manufactures a wide range of products used across various key sectors, including construction, household, markets, and automotive. The four major glass products are flat glass, pressed or blown glass, glass containers, and products made from purchased glass.

In 2019, annual glass production in India was 2.7 million tonnes and energy consumption was around 0.56 Mtoe. By 2030, glass production is projected to increase by 6 million tonnes.

Process Flow

1. **Batching** — Mixing and homogenizing of raw materials
2. **Melting/Refining** — The mixed batch is melted in a furnace and subsequently refined and conditioned
3. **Forming** — Molten glass is formed into desired shapes
4. **Finishing** — Finishing processes influence specific characteristics and performance

Mixing: the raw materials for glass (mainly sand, soda ash, limestone, and often recycled glass) are mixed, crushed and transported using electrically powered equipment

Melting: the materials are melted by heating them to 1550°C in a gas-fired regenerative end-port furnace.

Conditioning: molten glass is transferred from the furnace to the forehearth where it is heated evenly to the right temperature for forming

Forming: the conditioned glass is sent to a forming machine, where it is cut to the right size and shaped into containers using compressed air and/or a mechanical plunger

Annealing & cooling: The glass enters an oven (called an 'annealing lehr') where it is cooled in a controlled manner from 600°C to room temperature

Finishing: coatings are applied to provide additional scratch resistance

Packaging: containers are packaged, normally on pallets, for shipment

Conventional Thermal Equipment

Melting Furnace: The most energy-intensive step in glassmaking is melting the raw materials. This accounts for around 75% of the energy requirement. Modern glass furnaces now have an efficiency of around 50%, with a maximum of 60%.

Forehearth: To maintain an even temperature throughout the molten glass, forehearths heat and cool simultaneously, leading to heat loss and inefficiency. The forehearth consumes 6% of the energy in a typical container glass system

Annealing Lehr: In order to cool glass in a gradual and controlled manner, the lehr initially applies heat. The lehr consumes 12% of energy in a typical glass plant

Table 6: Energy intensities of different processes[24]

Process Stage	Temperature Requirement	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)
Mixing	Room Temperature		161
Melting	1550°C	1150	204
Conditioning and Forming	up to 1100°C	105	26
Post Forming and annealing	up to 600°C	210	25
Total		**1465**	**416**

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Three main applications of electric heating in glass production are: 1) electric boosting of fuel-fired furnaces, 2) all-electric melting and refining, and 3) electrically heated temperature conditioning.

Electric Furnace

An electric furnace is mainly composed of a refractory lined box supported by a steel frame with electrodes inserted either from the side, the top or the bottom of the furnace. The melting process is mainly powered by resistive heating as current flows through the molten glass. However, the furnace is dependent on fossil fuel usage for kickstarting the melting process. The furnace operates without interruption and has a typical service lifetime of up to seven years. A layer of batch material is placed on top of the molten glass, which results in its gradual melting from the bottom up. A conveyor system that moves over the entire surface of the furnace is utilized to deposit a fresh layer of batch material on the top surface. Most electric furnaces are equipped with bag filter systems which collect unutilized batch material and feed it back to the melter. Electric furnaces are typically able to achieve higher melt rates per surface area of the furnace, and the thermal efficiency of these furnaces (on energy delivered to the furnace basis) is almost twice or three times that of fossil fuel-fired furnaces.

Global Example

Several manufacturers offer electric glass melters capable of melting over 100 tonnes of glass per day. UK company **Electroglass** has built a 280-tonne-per-day electric furnace.

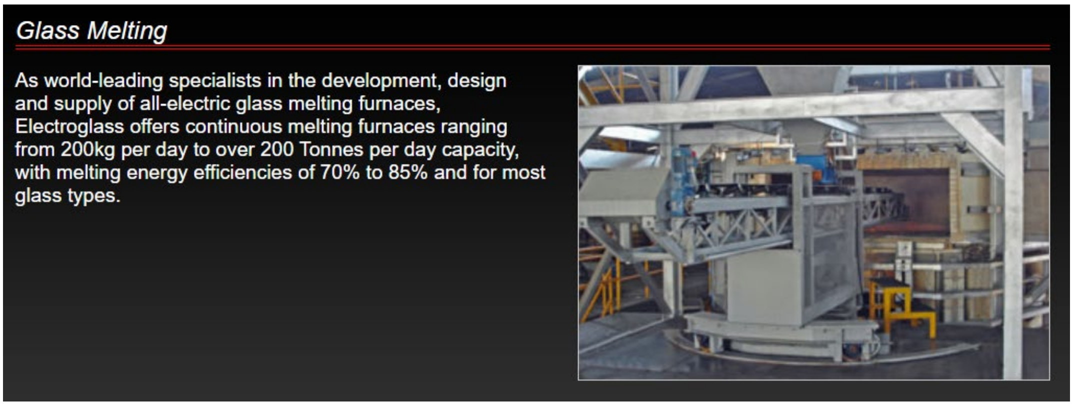


Photo by Electroglass

[24] https://www.globalefficiencyintel.com/electrifying-us-industry
https://bze.org.au/wp-content/uploads/2020/12/electrifying-industry-bze-report-2018.pdf

Technology Readiness Levels (TRL)

Electric glass melting furnaces are commercially available. There are several technology providers available across the globe. TRL is 9.

Efficiencies

The efficiency of an electric glass-melting furnace is 87%

Compatibility with currently used technologies

The transition to an electrified glass container manufacturing process is quite viable due to the commercial availability of electric melting.

Electric Forehearths

Highly efficient All-Electric Forehearths cool and condition non-volatile glass types, providing precise temperature control and consistent thermal homogeneity. The forehearth is completely electrically heated during normal operation and initial heat up. Actual case histories show operating cost savings of up to 80% when compared to equivalent gas-fired forehearths. All-electric forehearths offer extremely high thermal efficiency due to low thermal mass superstructure and insulation.

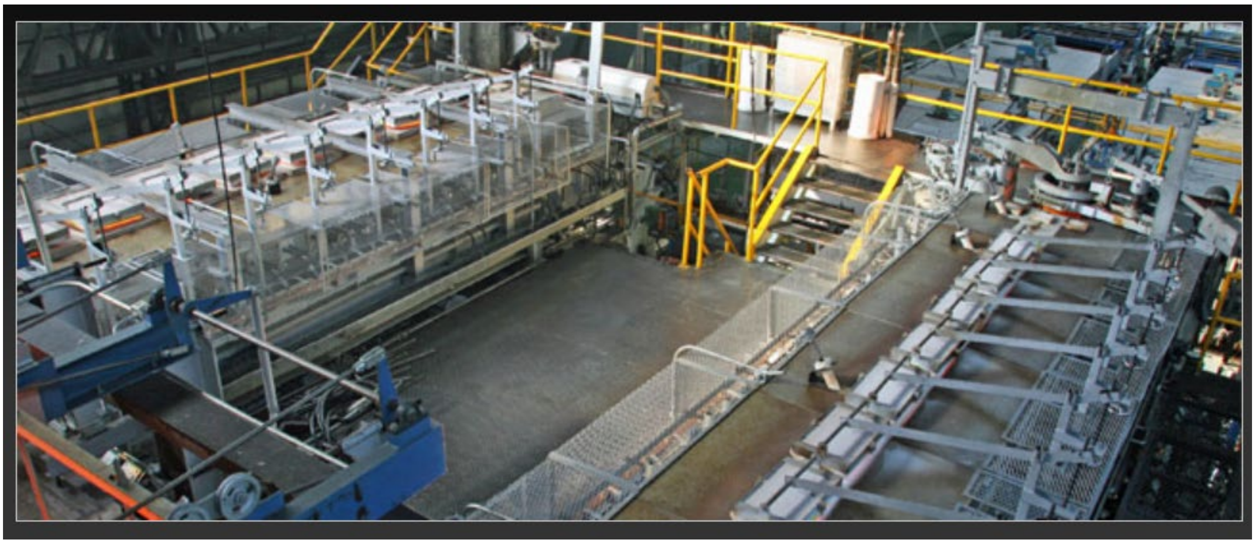


Photo by Electroglass

Technology Readiness Levels (TRL)

Electric forehearth is commercially available and there are several technology providers like Electroglass, UK. The TRL for such technologies is 9.

Electric Annealing Lehr

In an electric annealing lehr, the glass enters the lehr at a temperature of approx. 600°C and is cooled to approx. 70°C.

Technology Readiness Levels (TRL)

Electric annealing lehr is commercially available, and there are many technology providers like CNUD, Pennekamp, etc. Hence, the TRL for this technology is 9.

Photo by Pennekamp

Electrified Glass Manufacturing

Process Stage	Conventional			All Electrified	
	Equipment	Thermal Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Electrical Demand (kWh/tonne)	Equipment
Mixing	Mixer/crusher		161	161	Mixer/crusher
Melting	Gas-fired furnace	1150	204	860	Electric furnace
Conditioning and Forming	Forehearth and forming equipment	105	26	104	Electric Forehearth
Post Forming and annealing	Gas fired annealing oven	210	25	183	Electric annealing oven
Total		**1465**	**416**	**1308**	

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for production

Detailed desk research and analysis have been conducted to project the production demand of the sectors for the years 2030, 2050, and 2070. Production demand projection for the sector is derived based on the GDP manufacturing growth rate projection and past trend of annual production of each sector. A detailed list of assumptions, values and references is annexed in Annex 1.

Considering the above analysis, production of glass in the country would be 6 Mn tonne by 2030, and 18 Mn tonne, and 22 Mn tonne by 2050, 2070, respectively.

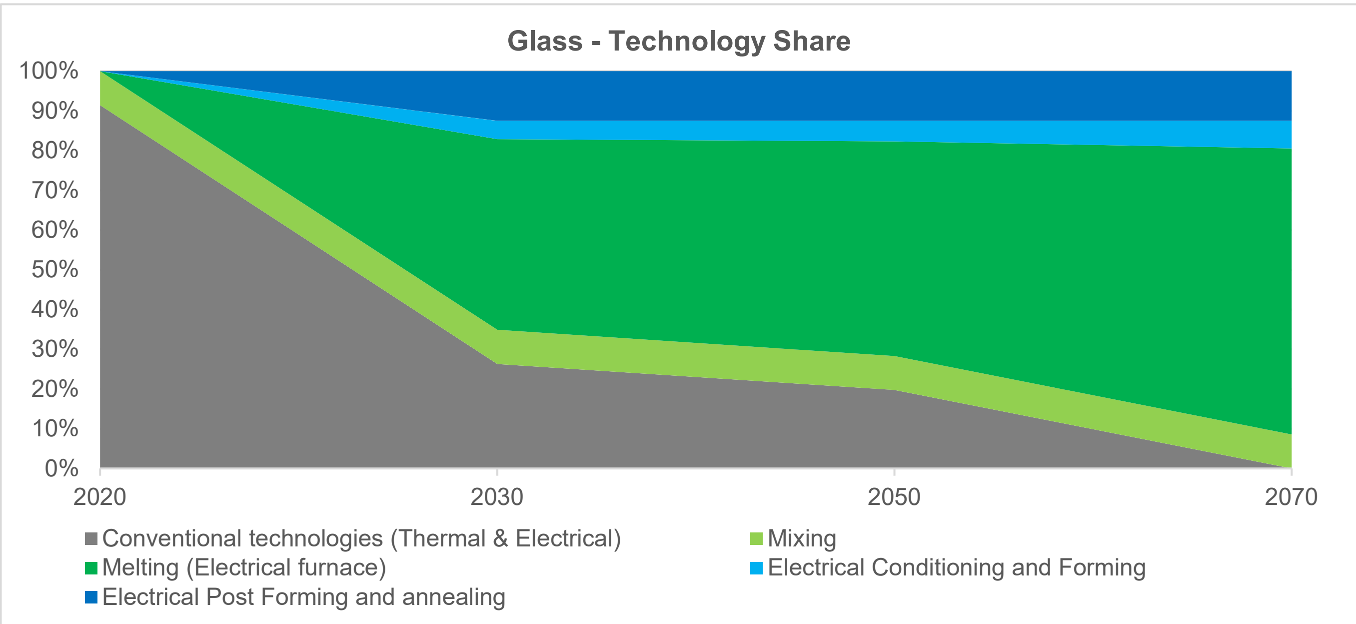
Production Demand

Year	2019	2030	2050	2070
Production (Million tonnes)	3	6	18	22

Suitable technology mix

Technologies are evaluated primarily based on their TRL level potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering India's target of net zero by 2070. The correlation between technology share and penetration of technology is presented in the image below. The image shown below represents that the glass sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals, and this would lead to direct electrification of the sector.

In this sector, technologies that are being considered are at the TRL 8-9. Most of the technologies have already been deployed globally. Electric melting furnaces are at a high technology readiness level, and it would penetrate by 75% in the entire glass sector. Whereas technology like electric post forming and annealing has the potential to completely penetrate by 2030 due to their availability and cost-effectiveness.



Projected Energy Consumption for Decarbonization

Energy consumption is projected, considering the different scenarios of decarbonisation (conservative, moderate and ambitious). Technology penetration levels for the various technologies vary depending on the scenarios, i.e., level of effort towards technology implementation would lead to changes in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.9	2.6	2.8

In the conservative scenario, efforts towards penetration of the technologies are being considered at lower levels during initial years, i.e., 30% by 2030, 70% by 2050, and 100% by 2070.

The energy demand of the glass sector would reduce by 4.1% in 2030, 7.5% in 2050, and 19.3% in 2070 over the base scenario.

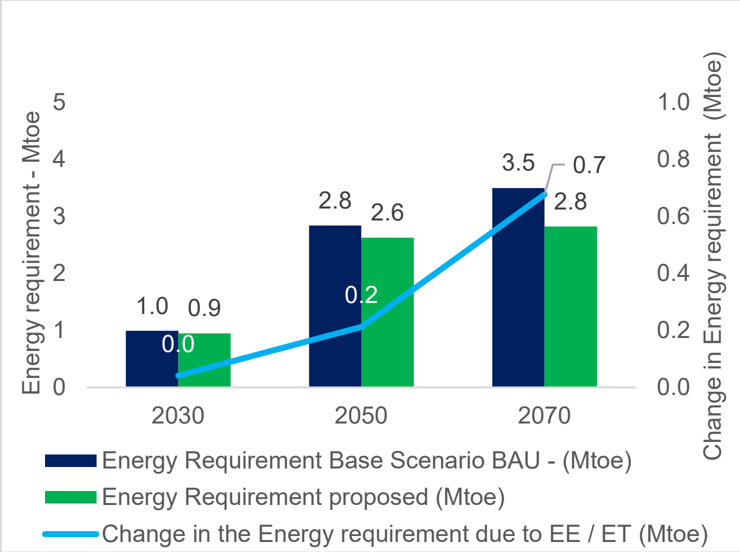


Figure 18: Energy requirement (Conservative - Glass)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.9	2.5	2.8

In the moderate scenario, efforts towards penetration of the technologies are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. The reduction in energy demand in the glass sector would be the same as per the conservative scenario for the year 2070.

Due to the increase in efforts over the moderate scenario, the reduction in the years 2030 and 2050 would be slightly more than that of the conservative scenario (6.7% reduction in 2030, 10.3% in 2050).

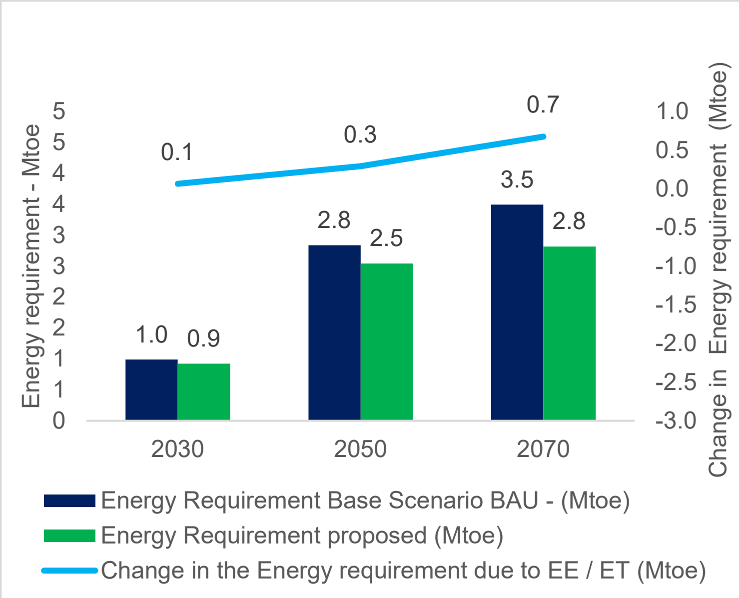


Figure 19: Energy requirement (Moderate - Glass)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.9	2.4	2.8

In the ambitious scenario, efforts towards technology penetration are being considered at high levels, i.e., 100% by 2030, 100% by 2050, and 100% by 2070. A reduction in energy demand in the glass sector would be the same as the conservative and moderate scenario for the year 2070.

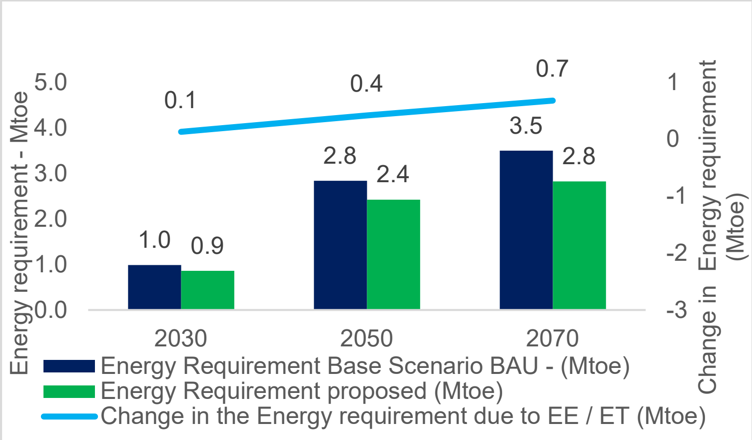


Figure 20: Energy requirement (Ambitious - Glass)

Due to the increase in the efforts in the ambitious scenario, the reduction in the years 2030 and 2050 would be more than that of the other two scenarios (13% reduction in 2030, 14.6% in 2050)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **2 GW** by 2030, **7 GW** by 2050, and **8 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand on a day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.3 – 0.6 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Year	2030	2050	2070
Ambitious Scenario			
RE hybrid installed capacity (GW)	1.4	6.9	8
Battery Storage (GWh)	0.6	3.7	5.7
Moderate Scenario			
RE hybrid installed capacity (GW)	0.69	5.9	8
Battery Storage (GWh)	0.4	3.1	5.7
Conservative Scenario			
RE hybrid installed capacity (GW)	0.64	4.9	8
Battery Storage (GWh)	0.3	2.6	5.7

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 4.1 million tonnes CO_{2e}, 11.8 million tonnes CO_{2e}, and 14.5 million tonnes CO_{2e} for the years 2030, 2050, and 2070 in BAU scenario, respectively. Under the ambitious scenario, net zero is estimated to be achieved by 2070 as the majority of the production would be electrified and electricity would come from green energy sources. Since this adoption of technology and transition to the different routes will take over the period, there would also be a significant drop in emissions in the mid-year, i.e., 2030 and 2050 (1.9 million tonnes

CO_{2e} in 2030, and 8.9 million tonnes CO_{2e} in 2050). GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

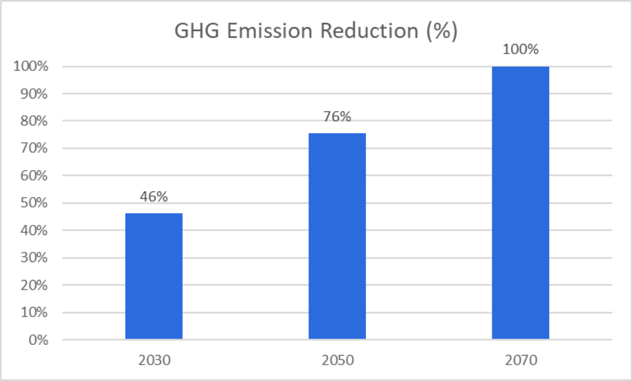


Figure 21: GHG emission reduction (Ambitious – Glass)

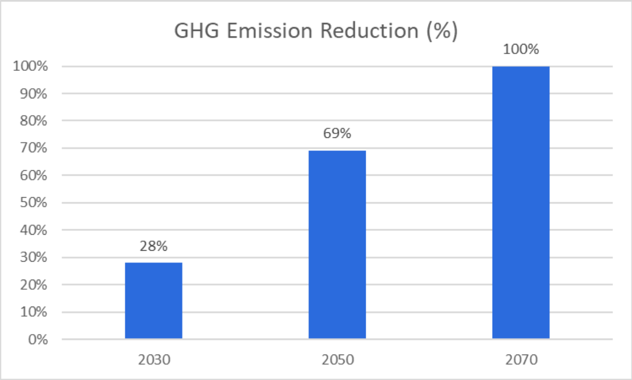


Figure 22: GHG emission reduction (Moderate – Glass)

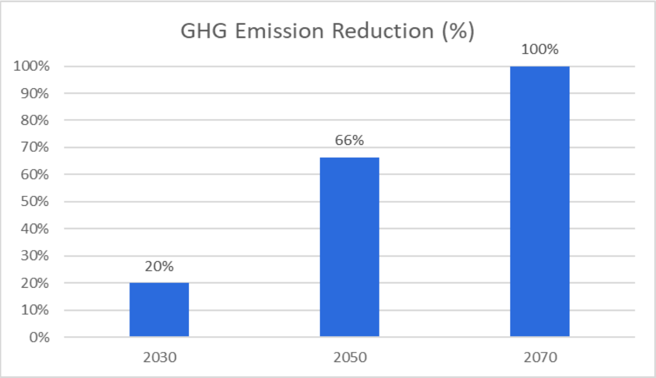


Figure 23: GHG emission reduction (Conservative – Glass)

2.4 Electrification of Aluminium Sector

The carbon intensity of aluminium production in India is higher compared to global benchmarks. The smelting process for extracting aluminium from its oxide, alumina, done mostly by the Hall-Heroult process, is a major consumer of electricity and, hence a major source of GHG emission.

Electrification technologies such as electric furnaces, electric calcination, MVR powered by renewable energy for process heating requirements, electric melting, and heating, among others, can be deployed for electrifying the sector.

With the implementation of the above mentioned technologies, 100% of the sector's energy consumption can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 37.2%, i.e., from 106 Mtoe in the base scenario to 66.45 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions: 33% by 2050 and 100% by 2070. Key findings of the scenario analysis model (ambitious scenario) are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

66.45 Mtoe of Energy Demand by 2070 from the sector

Reduction of **479.4 Mn tonne CO_{2e}** by 2070

Power demand of **193 GW** by 2070

Requirement of **133 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e.level of effort – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector, for consecutive years up to 2070 based on corresponding GDP projections[25].

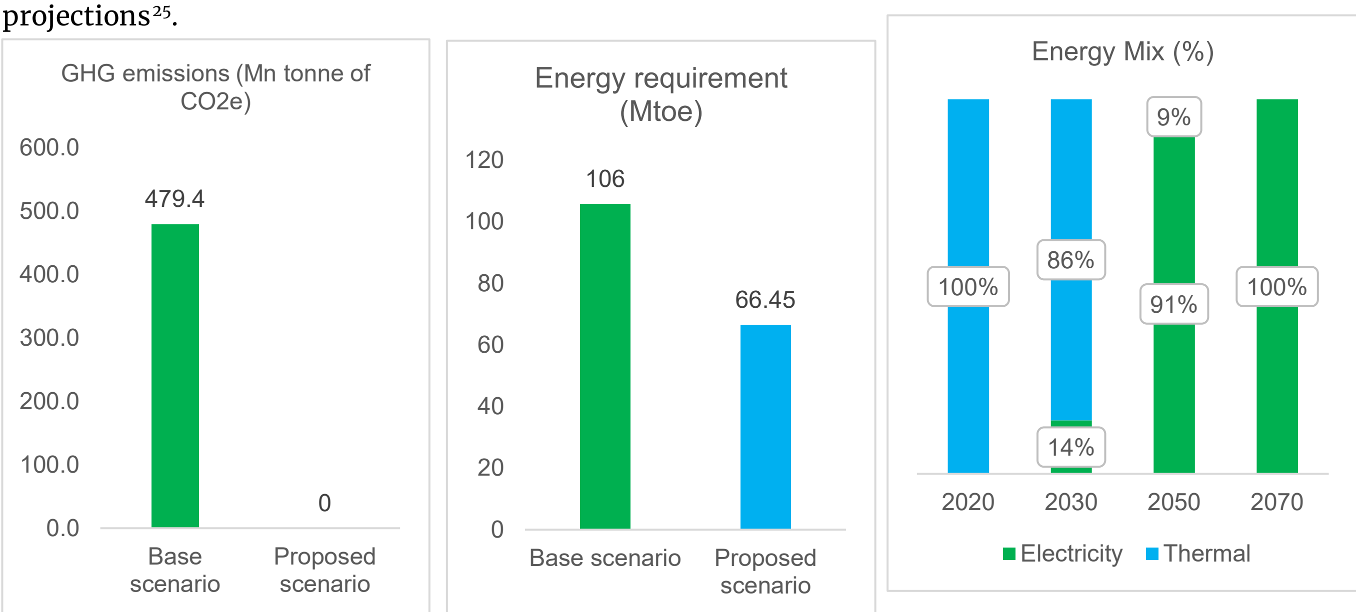


Figure 24: GHG emissions, energy requirement and electrification potential in proposed scenario

[25] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

SECTOR OVERVIEW

The aluminium sector is one of the most energy-intensive industries globally, with a significant carbon footprint. In India, the aluminium industry is one of the largest consumers of electricity, accounting for nearly 5-6% of the total power demand[26] in the country. The production of aluminium requires a significant amount of energy, primarily in the form of electricity, to extract aluminium from bauxite ore. This energy-intensive process results in a high carbon footprint, making decarbonization of the industry a pressing need.

Aluminium is often referred to as the 'metal of the future' due to its versatility and importance in strategic industries such as defence, aerospace, electrical, automotive, and infrastructure. India is one of the largest producers of aluminium globally, with a production capacity of over 4 million tonnes per year[27]. However, the industry's high carbon intensity poses a significant challenge to India's commitment to reducing greenhouse gas emissions under the Paris Agreement. Despite the challenges, the demand for aluminium is expected to increase globally, driven by the growing demand for lightweight and high-strength materials in various industries such as automotive, construction, and packaging.

Furthermore, aluminium is critical to the success of emerging green sectors such as renewable energy and electric vehicles, which will see an increased intensity of aluminium consumption. As a result, demand for cost-effective aluminium may rise exponentially, moving from 4 MTPA at present to 10 MTPA by 2030[27]. This highlights the importance of developing a sustainable and efficient aluminium industry in India to meet the growing demand for this critical raw material.

According to ICRA, India's domestic aluminium manufacturers have the highest carbon intensity among global producers, with emissions of nearly 17-20t CO_2e per tonne of aluminium due to their significant use of coal in generating captive power. To achieve their ambitious targets of a 25% reduction in carbon emissions in the next 5-7 years and achieve net zero status by 2050, the industry will require significant investment in renewable energy (RE) or low carbon-intensive power sources. This investment could cost up to $5 billion by 2030 and $20 billion by 2050, depending on the RE mix used. Entities may choose to sign power purchase agreements to secure RE power instead of making upfront capital expenditures, but the cost of metal production is still expected to rise significantly.[28]

However, aluminium entities operating in western economies have gradually switched to lower carbon-intensive hydropower, with almost 60% lower carbon intensity compared to their Asian counterparts. Additionally, increasing the share of secondary production through higher usage of scrap is another lever for decarbonization. However, this will require an improvement in domestic aluminium scrap collection, as a significant part of the scrap source is currently imported.

In the medium term, global demand for greener aluminium is expected to increase significantly, especially from automotive OEMs with ambitious carbon abatement targets. The recent agreement by the European Union to impose a tax on imports of most energy-intensive industries, like aluminium and steel, from January 2026, is expected to increase demand for low-carbon aluminium. However, India's export competitiveness could be significantly impacted if the emission level remains unabated, as India exported around 0.5 million metric tonnes of primary aluminium to European countries in FY2022[28].

[26] https://www.reuters.com/world/india/india-aluminium-producers-draw-costly-power-grid-hurting-utilities-low-coal-2021-10-19/
[27] https://timesofindia.indiatimes.com/business/budget/union-budget-2023-address-roadblocks-that-restrict-indias-aluminium-industry/articleshow/97050744.cms
[28] https://www.icra.in/Media/OpenMedia?Key=72ba47ae-0b28-44fd-8a2a-2ae3741844af

Although aluminium production is energy-intensive, it is important to recognize the industry's significant progress in reducing specific energy consumption (SEC) over the past decade. The aluminium sector has achieved a reduction of 1-1.5 % per year in SEC. The results of the Perform, Achieve & Trade (PAT) scheme of the Bureau of Energy Efficiency (BEE) since 2012 for the aluminium sector highlight the actions taken by many large aluminium producers in India through energy efficiency measures and technology upgrades.

Overall, the aluminium industry plays a central role in national security and the success of various government programs in India. It is also a key player in emerging green sectors, making it a critical component of India's sustainable development. Therefore, it is essential to prioritize promoting the aluminium sector and investing in innovative technologies and sustainable practices to ensure its long-term growth and success.

Process Flow

The production of primary aluminium (from ore) can be divided into four main stages: mining of raw bauxite, Bayer refining, primary smelting, and metal finishing.

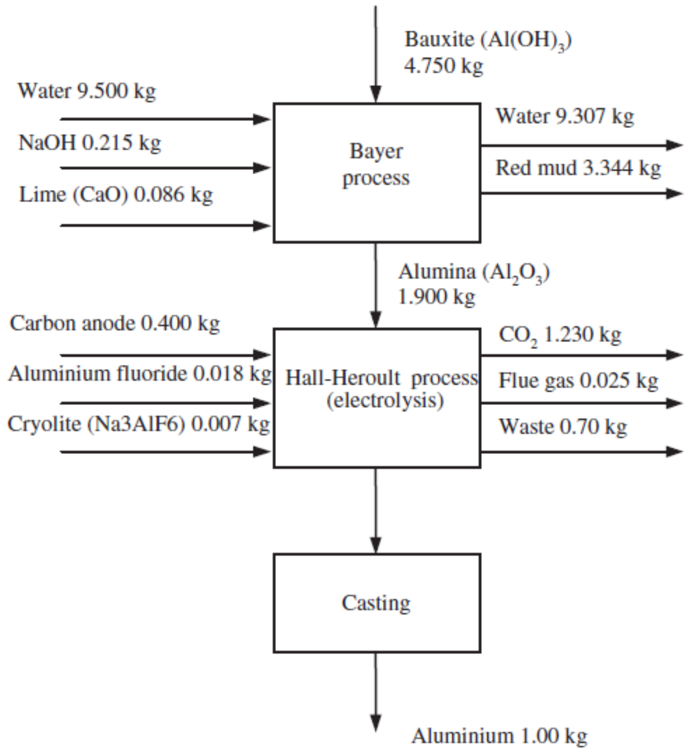


Figure 25: Primary aluminium production from raw material

Alumina is refined from bauxite using the Bayer refining process. The process involves dissolving crushed, ground, and sized bauxite under pressure with a hot solution of sodium hydroxide and sodium carbonate to form green liquor. The aluminium oxides in the bauxite react to form soluble sodium aluminate.

$Al_2O_3{\cdot}H2O + 2NaOH = 2NaAlO_2 + 2H2O$, and

$Al2O_3{\cdot}3H_2O + 2NaOH = 2NaAlO_2 + 4H_2O$

The green liquor is clarified to remove impurities like sand, undissolved iron oxides, titanium oxides, silica, and others. The remaining insoluble materials, called "bauxite residue" or "red mud," are thickened, washed, and dewatered to recover sodium hydroxide. The clarified liquid is cooled and seeded with crystals of gibbsite to aid the precipitation of alumina trihydrate. Alumina trihydrate is then calcined in a fluid bed or rotary kiln at about 980°C to 1,300°C to remove the water of crystallization and produce the dry white powder, alumina. The calcining rates and temperatures are carefully controlled and vary depending on the final physical properties specified for the alumina. The Bayer process consumes energy equivalent to 39.2 MJ/kg.

The metallic aluminium is produced from the alumina through the Hall-Heroult process, commonly referred to as smelting. It involves the reduction of alumina to aluminium metal using electricity in a reduction cell. The reduction cell is a large vessel made of steel or other materials that is lined with carbon or other materials that can withstand high temperatures. The reduction cell is filled with a molten mixture of alumina and cryolite, which acts as the electrolyte in the process. The cell also contains a series of graphite or carbon anodes and a cathode made of carbon.

A direct current (DC) is passed through the reduction cell, causing a chemical reaction that reduces the alumina to aluminium metal. The electric current is supplied by large rectifiers that convert the alternating current (AC) from the power grid into direct current (DC). At the cathode, the aluminium ions in the molten cryolite are reduced to aluminium metal, which accumulates at the bottom of the cell. At the anode, the carbon is oxidized to form carbon dioxide, which is released as a gas. The carbon anodes are gradually consumed during the process and must be periodically replaced. The aluminium metal that accumulates at the bottom of the cell is periodically tapped off and collected. The collected aluminium metal is typically impure and must be further refined to remove any remaining impurities.

Hall-Heroult is an energy-expensive process that consumes energy equivalent to 162.1 MJ/kg. The last step is the casting of molten aluminium into blocks or ingots, having an embodied energy value of 26.1 MJ/kg. The production process of secondary or recycled aluminium is simple and requires only 5 - 7% of the energy needed for primary aluminium. Aluminium's capacity to be recycled easily has been one of its key advantages. In its first incarnation,, it was a comparatively expensive material, partly because of the large amounts of energy consumed in smelting the alumina into aluminium. Aluminium can be recycled repeatedly without any deterioration in quality. The more often the metal is recycled, the more competitive its lifetime cost becomes. Aluminium requires a great deal of energy to be produced. This energy consumption brings environmental burdens besides the large amounts of pollutants released during the production process.[29]

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Electric Calcination

Electric calcination, also known as electro-calcination or electro-decalcification, is an innovative technology that uses electricity to calcine alumina in the refining phase of aluminium production. Calcination is the process of heating alumina to high temperatures to remove impurities and convert it into pure aluminium oxide.

Traditional calcination processes use fossil fuels such as natural gas or fuel oil to provide the heat required for the process. However, electric calcination uses electricity as the primary energy source, which can be sourced from renewable energy sources such as hydropower, wind power, or solar power. This makes electric calcination a more sustainable and environmentally friendly option compared to traditional calcination processes.

The process of electric calcination involves passing an electric current through a bed of alumina, which causes the alumina to heat up and undergo a series of chemical reactions. This process is typically

[29] https://www.researchgate.net/publication/228954617_Sustainability_analysis_of_window_frames

carried out in a fluidized bed reactor, where the alumina particles are suspended in a fluidized gas stream that carries the heat generated by the electric current.

Electric calcination has several benefits over traditional calcination processes, including:

- Lower emissions - Electric calcination produces significantly lower emissions of greenhouse gases and other pollutants compared to traditional calcination processes that use fossil fuels.
- Lower operating costs - Electric calcination has lower operating costs compared to traditional calcination processes, as it does not require the use of fossil fuels or the associated infrastructure.
- Improved quality - Electric calcination can produce alumina with higher purity and uniformity compared to traditional calcination processes.

Overall, electric calcination is a promising technology that has the potential to reduce the environmental impact of alumina refining in the aluminium production process. The adoption of electric calcination by leading aluminium producers demonstrates the industry's commitment to sustainability and environmental responsibility.

Technology Readiness Levels (TRL)

Electric calcination is a relatively new technology that is still in the development and demonstration phase, and its Technology Readiness Level (TRL) can be in the range of 5 to 6.

Several companies are currently involved in the development and commercialization of electric calcination technology, including Alcoa Corporation, Rusal, and Emirates Global Aluminium (EGA). These companies have invested heavily in research and development to improve the efficiency and effectiveness of the technology and to bring it to market.

While electric calcination has been demonstrated to be a promising technology with several potential benefits, further research and development are needed to bring it to a higher TRL level. This includes scaling up the technology to a commercial scale, optimizing the process for efficiency and cost-effectiveness, and addressing any technical challenges or limitations that may arise.

Energy Efficiency

Electric calcination has been demonstrated to be more energy-efficient compared to traditional calcination processes that use fossil fuels such as natural gas or fuel oil to provide the heat required for the process. The use of electricity as the primary energy source reduces energy consumption and improves the overall efficiency of the process.

There are several factors that contribute to the energy efficiency of electric calcination, including:

- **Direct heating** - Electric calcination uses direct heating to calcinate the alumina, which is more efficient compared to traditional calcination processes that use indirect heating. Direct heating reduces heat loss and improves the overall efficiency of the process.
- **Efficient energy transfer** - Electric calcination uses electricity to generate heat, which is transferred directly to the alumina particles. This results in more efficient energy transfer and reduces energy consumption.
- **No fuel consumption** - Electric calcination does not require the use of fossil fuels, which reduces energy consumption and eliminates the associated emissions and operating costs.

- **Renewable energy sources** - Electric calcination can be powered by renewable energy sources such as hydropower, wind power, or solar power, which further enhances its energy efficiency and sustainability.

The energy efficiency of electric calcination has been demonstrated in several research studies and pilot projects. Overall, electric calcination has the potential to significantly improve the energy efficiency of alumina refining in the aluminium production process.

Compatibility with currently used technologies

Electric calcination is compatible with the currently used technologies in alumina refining, as it can be easily integrated into the existing process without major changes to the infrastructure or equipment. In fact, electric calcination can replace the traditional calcination process that uses fossil fuels such as natural gas or fuel oil to provide the heat required for the process. Electric calcination uses direct heating to calcinate alumina, which is more efficient compared to traditional calcination processes that use indirect heating. Direct heating reduces heat loss and improves the overall efficiency of the process, making it more compatible with existing technologies.

Foreseen cost of development

Alcoa is investing about $20 million[5] to prove the technical and commercial viability of electric calciners powered by renewable energy to reduce greenhouse gas emissions in the alumina refining process. The project will provide valuable insights into the commercialization and technology development pathway for electric calcination and facilitate the decarbonization of a sector that is difficult to decarbonize.

Global adoption of electric calcinators

In April 2022, Australian Renewable Energy Agency (ARENA) announced funding of $8.6 million to Alcoa of Australia Limited (Alcoa) for investigating and trailing electric calcination in the alumina refining process. Alumina refining is an energy-intensive process that traditionally relies on the combustion of fossil fuels for process heating. Alcoa aims to demonstrate the technical and commercial feasibility of using electric calciners powered by renewable energy to decarbonize the alumina refining process. The project will be delivered in two stages, and the first stage will involve the study, selection, engineering, and testing of technologies until the end of 2023. The second stage will begin in the first quarter of 2024 and continue into mid-2026 with detailed design, construction, and pilot testing of this emerging technology at Alcoa's Pinjarra Alumina Refinery in Western Australia. Integrating electric calcination with mechanical vapor recompression (MVR) and powering the process with renewable energy could potentially reduce emissions from alumina refining by about 98%. This will be a first-of-its-kind project in the global aluminium industry.[30]

[30] https://arena.gov.au/news/world-first-pilot-to-electrify-calcination-in-alumina-refining/

Use of renewable energy for electrolysis in the reduction pots

The use of renewable energy for electrolysis in the reduction pots in aluminium production is being explored to reduce greenhouse gas emissions and make the industry more sustainable. The conventional electrolysis process for aluminium production requires a significant amount of energy, which is typically generated by burning fossil fuels. However, the use of renewable energy sources such as hydropower, wind power, and solar power can provide a more sustainable and environmentally friendly alternative.

Technology Readiness Levels (TRL)

The TRL of using renewable energy for electrolysis can be assigned a level of around 8-9.

Energy Efficiency

The energy efficiency of using renewable energy for electrolysis in the reduction pots in aluminium production can vary depending on the specific implementation of the technology and the type of renewable energy source used. However, in general, using renewable energy sources for electrolysis in aluminium production has the potential to improve energy efficiency and reduce the amount of energy required for the process.

Compatibility with currently used technologies

The potential to integrate renewable energy sources into existing infrastructure and processes with minimal modifications is a key advantage of using renewable energy in aluminium production, as it can help to reduce the costs and disruption associated with implementing new technologies.

The electricity generated by RE source can be transmitted to the aluminium smelter through the existing electrical grid. In some cases, it may be required to modify the electrical infrastructure at the aluminium smelter to accommodate the new source of electricity, but these modifications can typically be made with minimal disruption to the existing facility.

Foreseen cost of development

The cost of developing renewable energy sources such as solar, hydropower, and others for electrolysis in the reduction pots in aluminium production in India can vary depending on several factors. However, in general, the cost of renewable energy sources in India has been decreasing in recent years, making it an increasingly attractive option for the aluminium production industry.

Global adoption of RE for aluminium production

Rio Tinto operates an aluminium plant in Saguenay-Lac-Saint-Jean, Quebec, Canada, that relies on hydropower to produce aluminium. Rio Tinto's aluminium plant in Quebec is a prime example of the use of renewable energy and energy efficiency measures in the production of aluminium. By relying on hydropower and implementing energy efficiency measures, the plant can reduce its environmental impact and improve its economic sustainability.[31]

Emirates Global Aluminium (EGA) has introduced CelestiAL, a new type of solar aluminium which is produced using solar power from Dubai's electricity grid. To ensure that the energy used to make CelestiAL solar aluminium comes entirely from the sun, EGA tracks and verifies their sourcing of solar power through the International Renewable Energy Certification System. EGA has also announced plans to increase its use of renewable energy to power its aluminium production facilities. The

[31] https://www.riotinto.com/en/operations/canada/saguenay#:~:text=In%20November%202021%2C%20we%20announced,Lac%2DSaint%2DJean%20region.

company aims to reduce its carbon footprint and improve its environmental sustainability by shifting to renewable energy sources such as solar and nuclear power. EGA is considering building nuclear power plants in the UAE and is also exploring the use of solar energy to power its aluminium production facilities in the region.[32]

Figure 26: EGA markets its solar aluminium under the product name CelestiAL

Norway's Hydro uses hydroelectric power at its pilot plant in Karmøy, Norway. It also uses innovative technology to achieve stability and control in the electrolytic bath, reducing energy consumption to 12.3 kWh per kilo of aluminium produced. This is well below the world average of 14.1 kWh and Hydro's own average of 13.8 kWh. The new technology also saves the global environment from 1 million tonnes of CO2 emissions and produces 60,000 fewer tonnes of CO2 emissions per year compared to the world average.[33]

Eti Aluminyum, a subsidiary of Cengiz Holding and the only integrated aluminium mining and production complex in Turkey, is expanding its solar park to produce clean and green aluminium and achieve net zero emissions. The company is building two photovoltaic plants with a combined capacity of 104.2 MW, and with its existing two plants, the total capacity will reach 163 MW. This, combined with Eti Aluminyum's 540 MW Oymapinar hydropower plant, will cover all the consumption in the aluminium production plant, including the energy-intensive electrolysis process, which makes up a large share of overall expenses. The company aims to produce "clean and green aluminium" and reduce its net greenhouse gas emissions to zero, with an annual output of 80,000 tons.[34]

Figure 27: Eti Aluminyum's Solar Park to supply electricity to the production plant

[32] https://www.ega.ae/en/products/celestial
[33] https://www.hydro.com/en/about-hydro/stories-by-hydro/the-worlds-most-energy-efficient-aluminium-production-technology/
[34] https://balkangreenenergynews.com/turkish-aluminum-producer-building-solar-power-plants-to-reach-net-zero-emissions/

Tomago Aluminium, the largest electricity user in New South Wales, is actively seeking help to transition to 100% renewable energy sources for its aluminium production, ending its reliance on coal-fired power generation, in September 2022. The company sought proposals for renewable generation and storage products. It is looking for expressions of interest from outside parties to develop or invest in long-term traceable renewable energy and dispatchable firm power generation projects or contracts. The company's sustainability goals are supported by its owners, who are committed to transitioning the business to a low-carbon future[35].

Renewable electricity-powered MVR (Mechanical Vapour Recompression)

In the alumina refining process, steam is generated during the Bayer process (process used to extract alumina from bauxite ore). Steam is typically considered waste and is released into the atmosphere. However, MVR technology can be used to recover the energy from the waste steam and reuse it in the refining process. The MVR process involves mechanically compressing the waste steam, which increases its temperature and pressure, and then condensing it to provide process heat. The compressed steam can be used in various parts of the refining process, such as in the digestion stage, where bauxite ore is mixed with caustic soda to dissolve the alumina.

In the refining process, around 70% of GHG emissions come from fossil fuel-driven process heating in the Bayer refining circuit.[36]

Displacing the fossil fuels used for this process heating with a renewable energy source would possibly reduce the emissions by approximately 10 Mt $CO2\text{-}_e$ per annum.[36]

Technology Readiness Levels (TRL)

Although MVR is a proven technology in other industries, particularly in single-stage evaporators, its application in powering an alumina refinery has not yet been fully demonstrated. The compression ratios required for MVR technology to be effective in low-temperature alumina refineries are 60:1, and even higher for high-temperature refineries. At present, these ratios have not been shown to enable short-term commercialization, and additional demonstrations are still necessary following the MVR evaporation demonstration.

To achieve commercialization, a full-sized demonstration of the MVR precipitation compressor train system is required. It would capture waste energy as vapour and deliver compressed vapour as live steam to the refinery, demonstrating that the technology can achieve the required compression ratio and reliability. Successful execution of the full-sized demonstration will provide technical and commercial certainty with respect to large-scale MVR implementation.

The TRL of MVR technology in the alumina refining process can be assigned a level of around 5-6. While the technology has been demonstrated in other industries, additional testing and demonstrations are still required to prove its effectiveness and commercial viability in the context of alumina refining.

Energy Efficiency

MVR requires about one third the power of an electric boiler to achieve the same outcome.[37]

Compatibility with currently used technologies

[35] https://reneweconomy.com.au/tomago-aluminium-smelter-seeks-partners-in-shift-to-100-pct-renewables/
[36] https://arena.gov.au/knowledge-bank/mvr-retrofit-and-commercialisation-report/
[37] https://arena.gov.au/knowledge-bank/mvr-retrofit-and-commercialisation-report/

Mechanical Vapour Recompression (MVR) technology has the potential to be applied in various scenarios, including new refinery builds, existing refinery expansions, and retrofitting of existing refineries to replace fossil fuel powered process heating. The principle of MVR remains the same across all applications: low-grade wastewater vapour from the refining processes is compressed to produce steam that can be used as process heat. However, retrofit designs may face practical limitations due to the need to repurpose and tie in existing infrastructure, and there may be some technical uncertainty around MVR application in high-temperature alumina production.

For new installations, both brownfield expansions and greenfield, MVR offers lower design and operating costs compared to conventional fossil-fuel technology. The capital cost of MVR is offset by capital cost savings in the boiler, making it an already economic option.

Foreseen cost of development

The estimated capital cost of implementing MVR technology is approximately $220 per annual tonne of alumina production for low-temperature refineries and $260 per annual tonne for high-temperature refineries.[37] Retrofitting existing fossil-fuel facilities with MVR technology is more challenging in the short term, as it requires integration with existing equipment and the sunk cost of the existing process heat generating systems, which become largely redundant. However, in the medium to long term, retrofits are likely to become commercially competitive as carbon markets become fully established and trading at the true long-term cost of carbon abatement.

The capital cost of implementing MVR technology will vary depending on the type of refinery and retrofitting existing facilities can present challenges in the short term. However, as carbon markets continue to develop and the true cost of carbon abatement is realized, the economic viability of retrofitting existing facilities with MVR technology is likely to improve. Overall, MVR technology remains a promising option for reducing greenhouse gas emissions and improving energy efficiency in the alumina refining process.

Global adoption of RE-powered MVR

Alcoa is conducting an MVR evaporation project that will define the feasibility of installing additional evaporator capacity at its Wagerup Alumina Refinery using MVR technology to drive a 65 tonnes per hour single stage Falling Film Evaporator (FFE).

This Low Carbon Alumina Refining project will electrify steam production in the alumina refining process, thus displacing fossil-fuel boiler steam. [38]

Evaporation capacity is typically provided by multi-stage flash evaporation trains that use steam for heating, where the steam is generated by fossil fuel combustion. This demonstration installation will generate additional evaporation by recompressing exhaust water vapour from an existing FFE with an electrically powered MVR and using the recompressed steam to heat the evaporator. When the electricity for the MVR is generated from renewables, this additional evaporation capacity does not contribute any GHG emissions. The MVR evaporation demonstration, aimed for completion in 2025, will provide the required technical information to proceed to a large-scale trial using MVR to produce process heat from waste energy. Successful demonstration of this means significant decarbonisation of the alumina industry becomes possible if renewable energy is available.

MVR technology is currently used in alumina refineries in China.

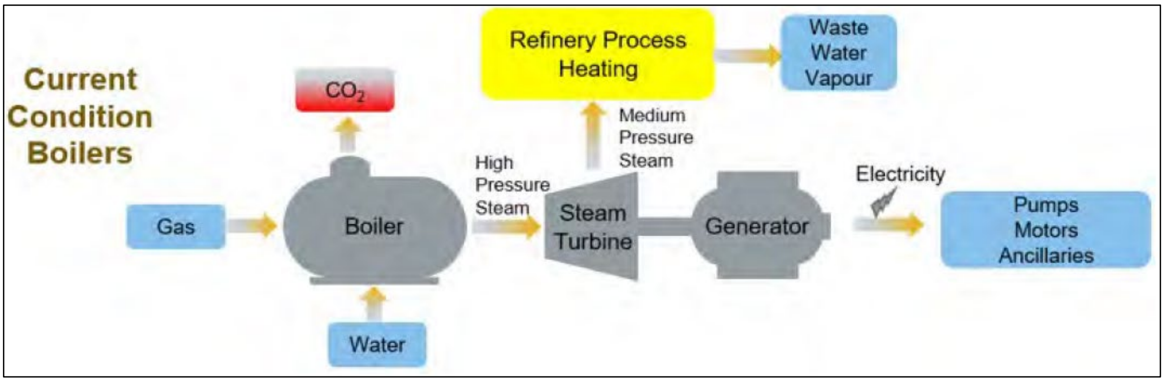


Figure 28: Current condition - process heat from fossil fuels

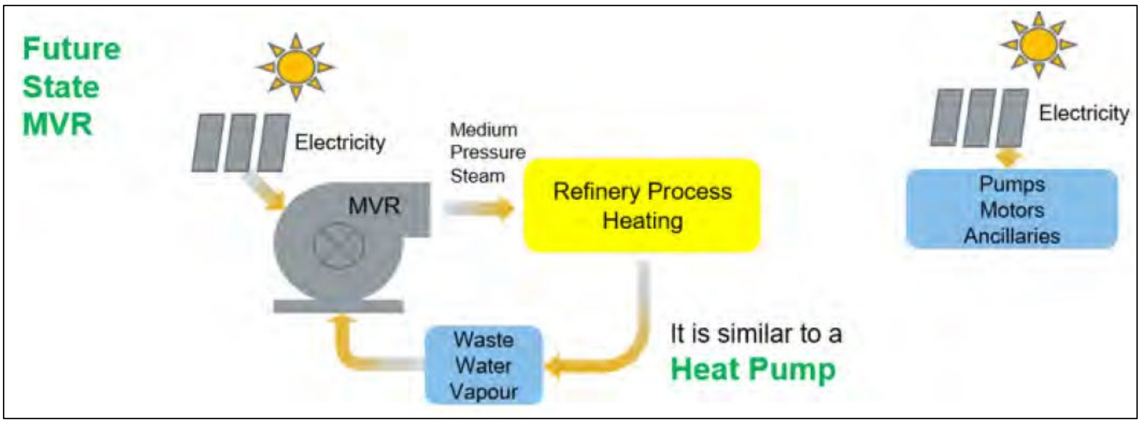


Figure 29: Future state - process heat from renewable power and MVR

[38] https://aluminium.org.au/news/mechanical-vapour-recompression-for-low-carbon-alumina-refining/

Electric anode baking furnace

In the aluminium industry, the production of one ton of aluminium requires the consumption of approximately 0.4 tons of carbon anodes in the reduction cell. These anodes require heat treatment (baking) to obtain specific mechanical, thermal, and electrical properties suitable for use in the aluminium production process. The anode baking process typically takes between 390 and 480 hours and involves several phenomena.

The electric anode baking furnace is a technology that has been developed to replace the traditional gas-fired anode baking furnace used in the production of aluminium. The electric anode baking furnace uses electricity to heat the anodes, which are used in the aluminium production process, instead of burning natural gas. The use of electric anode baking furnaces has several benefits over traditional furnaces, including:

- **Lower emissions** - Electric anode baking furnaces produce significantly lower emissions of greenhouse gases and other pollutants, making them more environmentally friendly than traditional furnaces.
- **Lower operating costs** - Electric anode baking furnaces have lower operating costs and require less maintenance, making them more cost-effective in the long run.
- **Renewable energy** - Electric anode baking furnaces use electricity as the primary energy source, which can be sourced from renewable energy sources such as hydropower, wind power, or solar power. This makes them a crucial component of the aluminium industry's efforts to reduce its carbon footprint and achieve sustainability goals.
- **Improved quality** - Electric anode baking furnaces can produce anodes with higher quality and consistency, which can result in improved efficiency and cost savings in the electrolytic process of producing aluminium.

Electric anode baking furnaces are typically designed to be highly efficient, with features such as regenerative burners, preheating systems, and waste heat recovery systems. These features help to further reduce energy consumption and improve the environmental performance of the furnace.

They use a large amount of electricity, which is typically sourced from renewable energy sources such as hydropower, wind power, or solar power. This makes them a crucial component of the aluminium industry's efforts to reduce its carbon footprint and achieve its sustainability goals. Electric anode baking furnaces work by heating the anode raw materials, which are typically a mixture of petroleum coke and pitch, to high temperatures of around 1200-1300°C. The mixture is heated in the furnace for several hours to bake the anodes, which are then cooled and stored until they are needed in the electrolytic process.

Technology Readiness Levels (TRL)

Although electric kilns or electric burners are not novel technologies, electric furnaces for large-scale use, such as for baking anodes, are not yet available/developed. Hence, a low TRL level of 2-3 can be assigned for this technology.

Energy Efficiency

Electric anode baking furnaces are highly energy-efficient compared to traditional anode baking furnaces that use fossil fuels such as coal or natural gas. The energy efficiency of electric anode baking furnaces is achieved through several design features and operational strategies, such as using regenerative burners, preheating systems, and waste heat recovery systems. These features help to reduce energy consumption and improve the environmental performance of the furnace. Electric anode baking furnaces can also be equipped with advanced control systems that can help optimize furnace performance and reduce energy consumption. These control systems use sensors and data analytics to monitor the furnace and adjust its operations in real time.

The energy efficiency of electric anode baking furnaces is typically measured by their specific energy consumption (SEC), which is the amount of energy required to produce one metric ton of anodes. The actual SEC value may vary depending on factors such as the size and design of the furnace, the use of renewable energy sources, and the efficiency of the heating and control systems.

Compatibility with currently used technologies

It may be possible to retrofit existing furnaces to accommodate the electric anode baking technology. Retrofitting would involve modifying the existing furnace to accommodate the electrical heating system, which may require changes to the furnace burners and infrastructure. Alternatively, aluminium producers may choose to install new electric burners alongside their existing gas-fired burners.

Foreseen cost development

The cost depends on the size of the furnace and can range from several million dollars to tens of millions of dollars. While the cost of electric furnaces can be higher than traditional gas-fired furnaces, they may offer long-term cost savings through improved energy efficiency and reduced maintenance costs.

Global adoption of electric anode baking furnaces

None of the major aluminium producers have adopted the use of electric furnaces for baking anodes yet. However, as the demand for sustainable and low-carbon aluminium production grows, the adoption of electric furnaces may become more cost-competitive, further driving down costs and increasing adoption rates.

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Hydrogen as an alternative fuel for thermal energy generation

About

There are several methods used to generate clean hydrogen, including blue hydrogen (splitting natural gas into hydrogen and CO_2). However, the most sustainable long-term option is green hydrogen, which uses renewable energy-powered electrolysers to produce hydrogen from water. Hydrogen does not produce smoke, so when it burns, only steam is produced. The steam produced can be captured and used further in the refining process. For example, if the steam from the hydrogen-fired calciner can substitute fossil fuels in the refining process, then 50% of the operation will be decarbonized. Details of the technology are explained in section 8.1 Cross-cutting technologies

Global adoption of hydrogen as alternative fuel

In June 2021, Rio Tinto teamed up with the Australian Renewable Energy Agency (ARENA) to study whether hydrogen can replace natural gas in alumina refining to drive down carbon dioxide emissions. Rio Tinto plans to conduct an AUD$1.2 million (£860,000) feasibility study into using clean hydrogen instead of natural gas in the calcination process of refining at its Yarwun alumina refinery in Gladstone, Queensland, Australia. It will simulate the calcination process using a lab-scale reactor at its Bundoora Technical Development Centre in Melbourne, Victoria. A preliminary engineering and design study will also be conducted at Rio Tinto's Yarwun refinery to understand the construction and operational requirements of a potential demonstration project.[39]

Norwegian aluminium producer Norsk Hydro ASA is exploring opportunities to develop its hydrogen facilities, aiming to offer renewable energy sources to third parties while enhancing the production of low-carbon aluminium. Hydro aims to strengthen its hydrogen production and usage by 2025, allowing it to increase its share in the low-carbon aluminium market. Developing and operating hydrogen resources aligns with Hydro's current slate of hydrogen pipeline projects, which could lead to switching from natural gas to hydrogen in several of its Norwegian plants, contributing to the target of reducing its own CO2 emissions by 30% by 2030. Hydro has unique capabilities due to its renewable power positions and large internal demand for gas that can be replaced by green hydrogen solutions, enabling the company to build and develop a complete value chain for green hydrogen in Norway. Hydro's 2050 net-zero roadmap includes a pilot project to use hydrogen for calcination at the Alunorte alumina refinery in Brazil.

Battery-Electric vehicles (BEVs)

Battery-operated vehicles can be used in various stages of the aluminium production process to reduce emissions and improve efficiency. Some of the areas where battery-operated vehicles can be used include:

Mining: Battery-operated vehicles can be used for the transportation of personnel and materials in underground mines. These vehicles are emission-free and can improve worker safety by reducing exposure to exhaust fumes.

Refining: Battery-operated forklifts and other material-handling equipment can be used in alumina refineries to transport materials and products. This can reduce emissions and improve efficiency compared to traditional diesel-powered equipment.

Smelting: Battery-operated vehicles can be used for the transportation of materials and equipment in aluminium smelting plants. This can reduce emissions and improve efficiency compared to traditional diesel-powered vehicles.

Logistics: Battery-operated vehicles can be used for the transportation of finished aluminium products within the plant or to external locations. This can reduce emissions and improve efficiency compared to traditional diesel-powered vehicles.

Technology Readiness Levels (TRL)

BEVs have higher TRL levels (8-9) as the technology is readily and commercially available.

Energy Efficiency

Typically, electric vehicles have an energy efficiency of about 80-85%.

[39] https://arena.gov.au/news/renewable-hydrogen-could-reduce-emissions-in-alumina-refining/

Compatibility with currently used technologies

There are some original equipment manufacturers (OEMs) that offer retrofitting technology for converting diesel vehicles to electric vehicles. This can be a cost-effective way for companies to transition their existing fleet to electric power without having to purchase new vehicles.

However, it's important to note that electric vehicles will require the installation of charging infrastructure. The installation of charging infrastructure can be a significant investment, particularly for larger fleets.

Foreseen cost development

The cost of an electric haul truck typically ranges from $1.5 to 3 million, and there are additional costs associated with setting up the necessary charging infrastructure.

Global adoption of battery-operated vehicles

In June 2022, Vedanta Aluminium, India's largest producer of aluminium, commissioned India's largest electric fleet of 27 forklifts, powered by lithium-ion batteries, in partnership with GEAR India. The forklifts are being operationalized at the company's aluminium smelter at Jharsuguda, in Odisha, which is the world's largest single-location aluminium smelter, ex-China. The Smart Fleet Management system uses IOT technology to integrate the data collected by intelligent terminals, providing Vedanta Aluminium insights in real-time with respect to forklift speed, access to operate, collision avoidance, optimization analysis for operational efficiency and equipment maintenance.

Figure 30 - 27 lithium-ion battery-powered electric forklifts deployed at Vedanta's Aluminium Smelter at Jharsuguda (Odisha), in partnership with GEAR India

The electric forklifts also have forward and reverse cameras, red-zone lights, blue spotlights, and an automatic deceleration mechanism while turning. Benefits include reducing diesel consumption by more than 2.5 lakh litres annually, GHG emission savings of nearly 690 tonnes of CO_2 equivalent, and increased productivity of operations through longer working cycles via rapid charging. The company is committed to achieving Net Zero Carbon by 2050 and is leveraging this avenue to increase women's participation in core operations by training women drivers to operate these smart forklifts.[40]

OTHER TECHNOLOGIES

Inert anodes

Inert anode technology is an alternative to traditional carbon anodes used in the production of aluminium. In traditional aluminium production, carbon anodes are consumed during the electrolysis process, producing CO_2 emissions and other pollutants. Inert anode technology, on the other hand, uses anodes made of materials that are not consumed during the process, such as ceramic or metal.

[40] *https://vedantaaluminium.com/media/press-releases/list/vedanta-aluminium-commissions-indias-largest-fleet-of-electric-lithium-ion-forklifts/*

The inert anode technology has the potential to significantly reduce greenhouse gas (GHG) emissions in the aluminium production process. In traditional aluminium production using carbon anodes, the anodes are consumed during the electrolysis process, producing CO_2 emissions and other pollutants. Inert anode technology, which uses anodes made of materials that are not consumed during the process, has the potential to eliminate these emissions. In addition to reducing GHG emissions, the use of inert anode technology could also reduce other pollutants associated with traditional aluminium production, such as particulate matter and sulphur dioxide.

There are several types of inert anode technology currently under development, including:

- Ceramic anodes: Ceramic anodes are made from materials such as yttria-stabilized zirconia (YSZ) or lanthanum chromite and are designed to resist degradation during the electrolysis process. Ceramic anodes have the potential to significantly reduce CO_2 emissions and improve energy efficiency in the aluminium production process.
- Metal anodes: Metal anodes are made from materials such as titanium, zirconium, or nickel, and are designed to resist corrosion and degradation during the electrolysis process. Metal anodes have the advantage of being more conductive than ceramic anodes, which can improve the efficiency of the electrolysis process.
- Sulphide anodes: Sulphide anodes are made from materials such as copper sulphide or silver sulphide and are designed to be stable in the high-temperature and corrosive environment of the aluminium production process. Sulphide anodes have the potential to significantly reduce greenhouse gas emissions and improve energy efficiency in the aluminium production process.

The development and commercialization of this technology face several challenges, including the high cost of materials and the need for further research and development to improve the durability and performance of the anodes. Despite these challenges, there is growing interest in inert anode technology among aluminium producers and stakeholders in the industry, as it offers the potential for a more sustainable and low-carbon aluminium production process.

Technology Readiness Levels (TRL)

RUSAL has successfully produced low-carbon aluminium using its proprietary inert anode technology at its Krasnoyarsk (KrAZ) aluminium smelter, demonstrating the feasibility and reliability of the technology at a commercial scale. However, further testing and validation are needed to demonstrate the long-term durability and performance of the anodes, as well as to optimize the technology for wider commercial adoption. Hence, inert anode technology can be assigned a TRL level of 6 to 7 at this moment.

Energy Efficiency

Inert anodes may improve the energy efficiency by up to 25%.[41]

Compatibility with currently used technologies

It could be used in both new and existing aluminium smelters.

[41] https://elysis.com/en/start-of-construction-of-commercial-scale-inert-anode-cells

Foreseen cost development

Recent estimates suggest that the capital costs for cell replacement range from $1-2 million for retrofitting and up to $1-2 billion for greenfield projects incorporating inert anode technology. Adoption of inert anode technology could result in a 3% reduction in operating costs and a 2% improvement in return on investment for greenfield installations, based on these figures. To be financially competitive with conventional carbon anodes, the overall costs of inert anodes need to be at least equal to or lower than the cost-price of conventional carbon anodes, which typically range from $110 to $120 per ton. In cases where inert anodes provide direct energy savings, a slightly higher cost- price may be feasible.[42]

Global adoption of inert anodes

Figure 31 – RUSAL Inert Anodes

In 2021, UC Rusal, a subsidiary of En+ Group, developed low-carbon aluminium using its proprietary inert anode technology, achieving a carbon footprint of less than 0.01 tonnes of CO_{2e} per tonne of aluminium. The aluminium was produced at Rusal's Krasnoyarsk aluminium smelter, using experimental industrial operations and next-generation inert anode technology. The technology replaces carbon anodes with inert, non-consumable materials, resulting in a significant reduction of emissions from the smelting process. The aluminium was produced at Rusal's Krasnoyarsk (KrAZ) aluminium smelter, where the company has constructed experimental industrial operations and is developing the next-generation inert anode technology for the electrolysis process. The capacity of the new inert anode electrolysis cell is about 1 tonne of aluminium per day at a current rate of 140,000 A. In addition to its low carbon footprint, the purity of the aluminium produced using inert anode technology is higher than 99%, making it suitable for use in a wide range of applications. The technology also offers a range of other benefits, including the release of oxygen in the process of aluminium production. In comparison to full-scope industry average emissions, metal produced with inert anodes has an 85% lower carbon footprint.[43]

Figure 32 – ELYSIS Inert Anodes

ELYISIS is a joint venture company led by Alcoa and Rio Tinto that is developing inert anodes. The inert anode prototype cells are designed to operate on a commercial scale typical for large modern aluminium smelters, using an electrical current of 450 kiloamperes (kA). In June 2021, Alcoa and Rio Tinto started construction on the first commercial-scale prototype cells of ELYSIS' inert anode technology, located at Rio Tinto's Alma smelter in Saguenay-Lac-Saint-Jean, Quebec. The Government of Canada has also announced a further $20 million financial contribution to support the project. ELYSIS is working to complete the technology demonstration by 2024, followed by commercialization activities. The ELYSIS technology has the potential to significantly reduce GHG emissions in the aluminium production process in Canada, with an estimated reduction of 7 million tons of CO_{2e}, equivalent to removing 1.8

[42] https://www.ctc-n.org/technologies/inert-anode-technology-aluminium-smelters
[43] https://www.lightmetalage.com/news/industry-news/smelting/rusal-produces-low-carbon-aluminum-using-inert-anode-technology/

million cars from the roads. In addition to reducing emissions, ELYSIS will also sell next-generation anode and cathode materials, which will last more than 30 times longer than traditional components, offering significant cost savings and efficiency improvements.[44]

Carbon Capture, Usage and Storage (CCUS)

CCUS technologies can be applied to the smelting process in the aluminium industry to capture and store carbon dioxide (CO2) emissions. Smelting is a critical stage in the aluminium production process and is responsible for a significant portion of the industry's greenhouse gas emissions. Details of the technology are explained in section *8.1 Cross-cutting technologies.*

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand of production

Detailed desk research and analysis have been conducted to project the production demand of the sectors for the years 2030, 2050, and 2070. Production demand projection for each sector is derived based on the correlation between the GDP manufacturing growth rate projection and the past trend of annual production of each sector. Considering the above correlation, production of aluminium in the country would be 8 Mn tonne by 2030, 23.6 Mn tonne, and 29.1 Mn tonne by 2050, 2070 respectively. A detailed list of assumptions, values and references is annexed in Annex 1.

Production Demand

Year	2019	2030	2050	2070
Production (Million tonnes)	3.7	8.0	23.6	29.1

Suitable technology mix

Technologies are evaluated primarily based on their TRL level potential of decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering India's target of net zero by 2070. The corelation between technology share and penetration of technology is presented in the image shown below.

This study was primarily focused on direct electrification, and the technology opted in the model is also in line with the study objective. All the selected technologies will lead to the complete direct electrification of the sector. Breakthrough technology like CCUS is not considered in this model because it would not directly electrify the sector. Electric anode baking is one of the technologies that has a low TRL, i.e., 3 when compared to other sectoral technologies of the model and due to this, penetration of this technology is not considered in the year 2030 and only 50% penetration is considered by 2050. Other technologies like electric casting, electrolysis in the reduction pots and electric pressure calcination are a comparatively mature technology and are considered to have significant penetration by 2050. The image shown below represents that the aluminium sector can be transitioned to net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector.

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[44] https://www.ctc-n.org/technologies/inert-anode-technology-aluminium-smelters

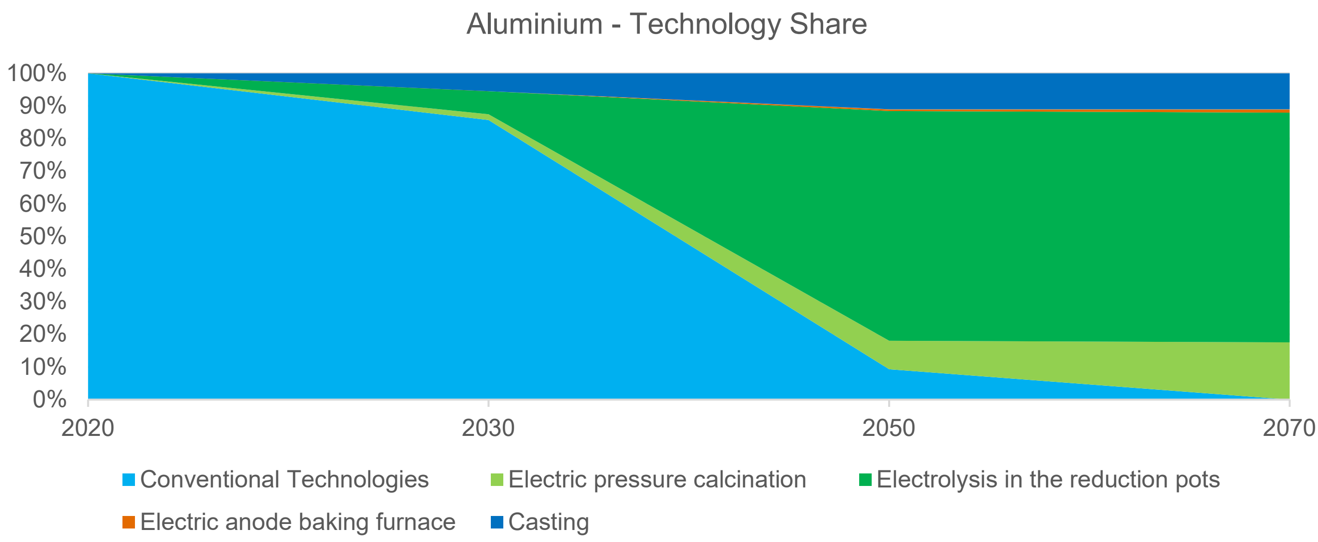


Figure 33: Penetration level and TRL of electrification technologies - Aluminium

Projected Energy Consumption for Decarbonization

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration of each technology varies depending on the scenario, i.e., the effort of implementation causing changes in energy consumption in each scenario.

Conservative Scenario

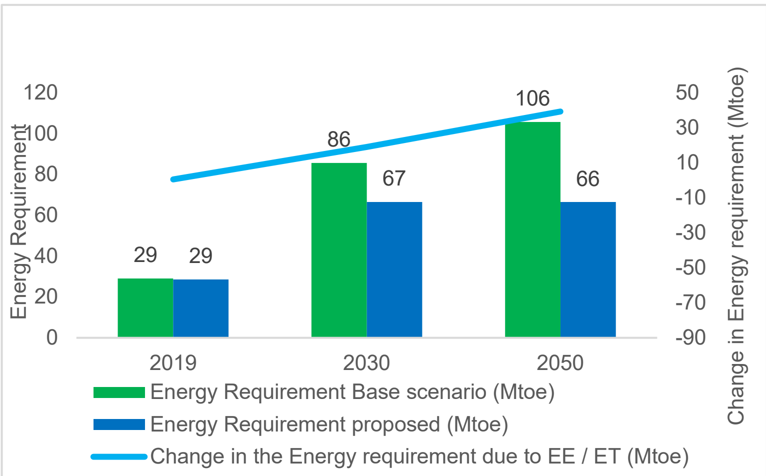


Figure 34: Energy requirement (Conservative - Aluminium)

Year	2030	2050	2070
Energy Demand (Mtoe)	28.61	66.50	66.45

In the conservative scenario, efforts to penetrate the technology levels are being considered at lower i.e., 30% by 2030, 70% by 2050, and 100% by 2070. The energy demand of aluminium sector would reduce by 1.8% in 2030, 22.3% in 2050, and 37.2% in 2070 over the base scenario.

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	28.27	61.04	66.45

In the moderate scenario, efforts to penetrate the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. A reduction in energy demand of the paper sector would be the same as the conservative scenario for the year 2070. Due to the increase in the efforts in the moderate scenario, the reduction in the years 2030 and 2050 would be slightly more than that of the conservative scenario (3% reduction in 2030, 28.7% in 2050).

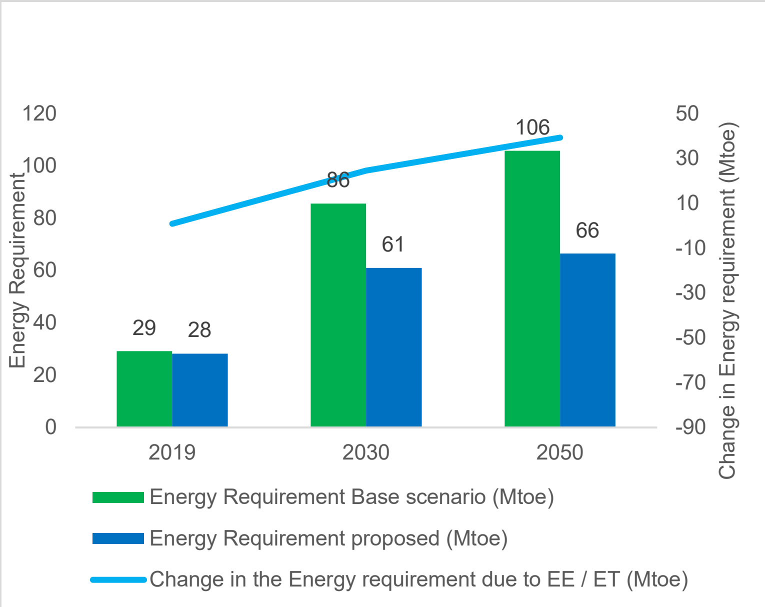


Figure 35: Energy requirement (Moderate - Aluminium)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	27.40	58.31	66.45

In the ambitious scenario, efforts to penetrate the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050, and 100% by 2070. Reduction in energy demand of aluminium sector would be the same as of conservative and moderate scenario for the year 2070. Due to the increase in the efforts in the ambitious scenario, the reduction in the years 2030 and 2050 would be more than that of the other two scenarios (5.9% reduction in 2030, 31.9% in 2050)

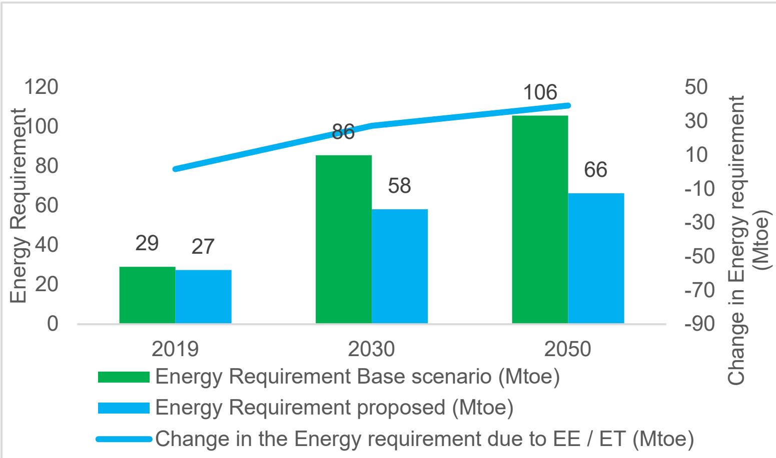


Figure 36: Energy requirement (Ambitious - Aluminium)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **13 GW** by 2030, **200 GW** by 2050 and **193 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand on one day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **1.2 – 3.8 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Year	2030	2050	2070
Ambitious Scenario			
RE hybrid installed capacity (GW)	8.8	196	193
Battery Storage (GWh)	3.8	102	133
Moderate Scenario			
RE hybrid installed capacity (GW)	4.8	184	193
Battery Storage (GWh)	2	96	133
Conservative Scenario			
RE hybrid installed capacity (GW)	2.5	154	193
Battery Storage (GWh)	1.2	81	133

Projected GHG emission reduction

The total energy emissions for the sector is estimated to reach 132.1 million tonnes CO_2e, 388.2 million tonnes CO_2e, and 479.4 million tonnes CO_2e for the years 2030, 2050 and 2070 in BAU scenario, respectively. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the production would be electrified and electricity would come from green energy sources. Since this adoption of technology and transition to different routes will take over the period, there would also be significant drops in emissions in the mid-year, i.e., 2050 (176.1 million tonnes CO_2e in 2050). GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below. In all three scenarios GHG emissions of the sector increase till 2030. This is because of the ongoing electrification of the sector leads to an increase in the electricity demand. Due to the high percentage of non-renewable power capacities, the emission factor of the grid will still be at around 780 grams of CO_2 per unit of electricity in 2030.

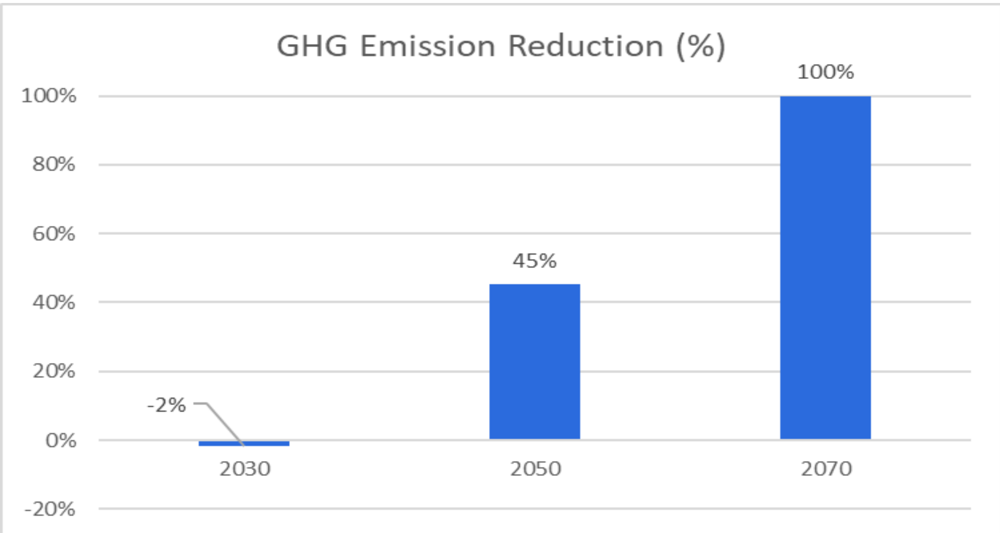


Figure 37: GHG emission reduction (Ambitious – Aluminium)

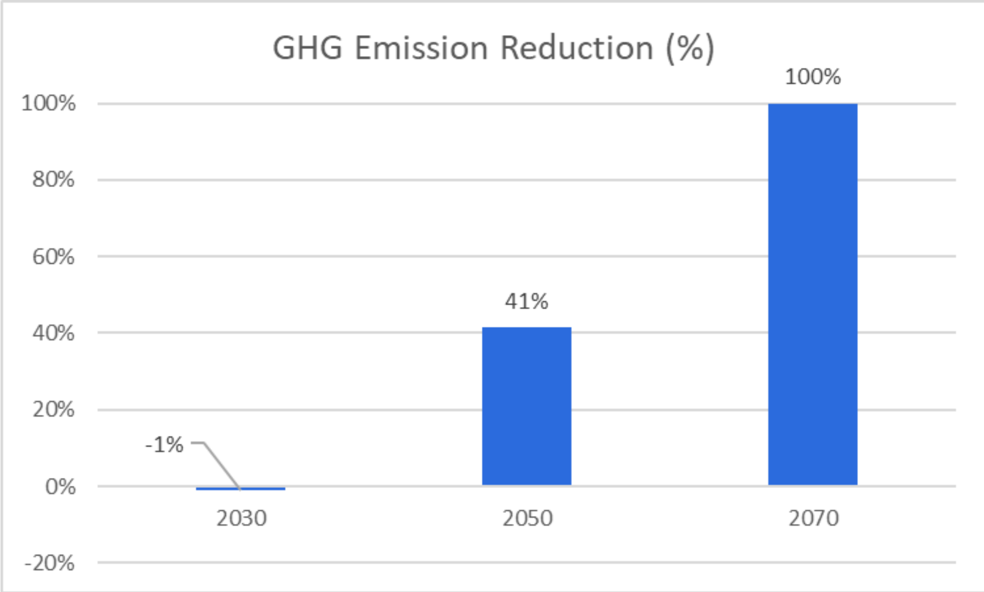


Figure 38: GHG emission reduction (Moderate – Aluminium)

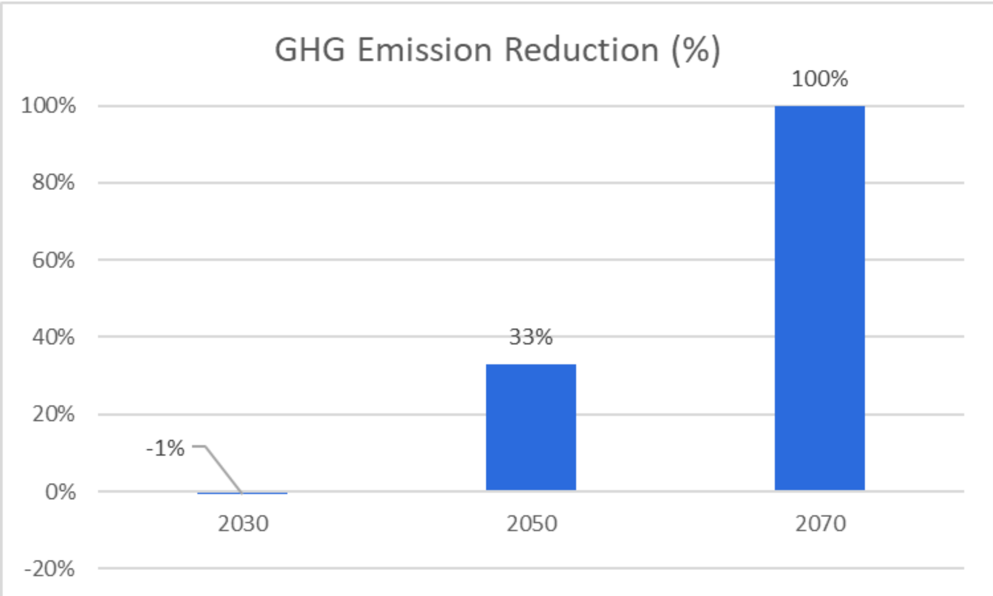


Figure 39: GHG emission reduction (Conservative – Aluminium)

2.5 Electrification of Chemical Sector

Electrification technologies such as electric boilers, electric heat pumps, and other electrified technologies powered by renewable energy for process heating requirements, electric melting, and heating, among others can be deployed for electrifying the sector.

One of the key components of direct electrification in the chemical industry could be the electrification of steam crackers, which are critical to the supply chains of various chemicals, including the most widely used types of plastics, such as polyethylene and polypropylene. Alongside direct electrification, a significant portion of the industry's future electricity demand will arise from the need to produce green hydrogen through water electrolysis.

With the implementation of the above-mentioned technologies, 100% of the energy consumption of the sector can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 42%, i.e., from 67 Mtoe in the base scenario to 39 Mtoe in the ambitious effort scenario. A reduction in energy consumption would also lead to a reduction in GHG emissions, i.e., 100% by 2070. Key findings of the ambitious scenario are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

39 Mtoe of Energy Demand by2070 from the sector

Reduction of **210 Mn tonne CO_{2e}** by 2070

Power demand of **194 GW** by 2070

Requirement of **132 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e., level of effort – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[45].

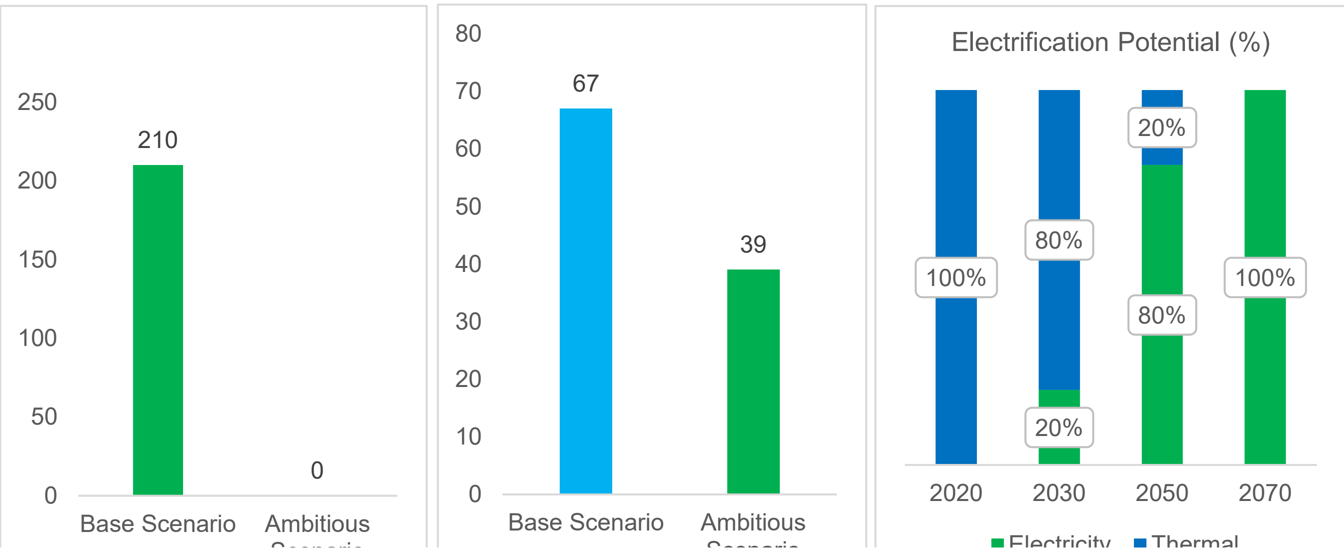


Figure 40: GHG emissions, energy requirement and electrification potential in proposed scenario

[45] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

Sector Overview

The chemical industry is highly diversified and covers an extensive range of over eighty thousand commercial products. It is the backbone of industrial and agricultural development in the country, providing essential building blocks for a multitude of downstream industries, such as textiles, papers, paints, varnishes, soaps, detergents, pharmaceuticals, and more.

With initiatives such as the "Make in India" program, the chemical industry is set to experience significant growth, with investments, innovation, and infrastructure development becoming the major focus areas for industry players. Despite being one of the most important industries in the country, the per capita consumption of chemical products in India is currently only one-tenth of the world average, indicating that the demand potential for chemical products is yet to be realized.

Globally, the chemical sector is the largest industrial energy consumer and the third-largest industry subsector in terms of direct CO2 emissions.[46] This is primarily because around half of the chemical subsector's energy input is consumed as feedstock – fuel used as a raw material input rather than as a source of energy.

Despite its energy consumption and environmental impact, the chemical industry remains a vital contributor to economic growth and development worldwide, providing essential products and materials for a broad range of industries and applications. With ongoing efforts to optimize processes, reduce emissions, and promote sustainability, the industry is poised to continue to play a significant role in the global economy for years to come.

Chemicals can be broadly divided into the following sub-groups.

[46] https://www.iea.org/fuels-and-technologies/chemicals

Basic Chemicals

Chemicals, such as organic and inorganic chemicals, bulk petrochemicals, other chemical intermediates, plastic resins, synthetic rubber, man-made fibres, dyes ,pigments and printing inks, are basic chemicals. These are also known as commodity chemicals.

Specialty Chemicals

Specialty Chemicals, also known as performance chemicals, are low-volume but high-value compounds. These chemicals are derived from basic chemicals and are sold based on their functions. For example, paints, adhesives, electronic chemicals, water management chemicals, oilfield chemicals, flavors and fragrances, rubber additives, paper additives, industrial cleaners and fine chemicals, sealants, coatings, catalysts etc., come under this category.

Pesticides

Chemicals which essentially are meant for protecting agriculture crops against insects and pests, are covered under this sub-group. Fertilizers and Pesticides played an important role in the "Green Revolution" during the 1960s and 1970s.

Heat energy is the primary form of energy used in chemical industry production processes, followed by electricity. The heating infrastructure is primarily designed for the use of fossil fuels, notably natural gas and oil. The processes used to produce hydrogen, ammonia, and other fundamental chemicals are well-established, and significant investments have been made in their associated infrastructures.

In India, the production of alkali chemicals (soda ash, caustic soda, and liquid chlorine) accounted for approximately 71% of the total production of major chemicals in the year 2021-2022.[47] A significant proportion of CO_2 emissions in the chemical industry can be attributed to the use of fossil fuels as a source of heat energy for thermochemical reactions. Moreover, the production of hydrogen through chemical reactions also results in significant process-related CO_2 emissions, which are not caused by fuel use for energy but rather by the thermochemical processes involved.

To align with international climate targets, the chemical industry needs certain infrastructural developments for electrification. These include the accelerated deployment of new renewable electricity generation capacity and the upgrading of transmission grids to transport power to chemical clusters. Additionally, more flexible operations of power-intensive processes and distributed storage capacity for energy and chemical intermediates are necessary to compensate for fluctuations in energy supply at different temporal scales.

The expansion of renewable-electricity-driven chemicals in the market will significantly reduce the carbon footprint of the chemical industry. Electrochemical production offers unique advantages over conventional thermal-driven processes, including the ability to operate at small and medium scales while maintaining high throughput, making them applicable for modular systems and distributed on-site productions, particularly for unstable and hazardous chemicals.[48]

Additionally, electrochemical reactions can be controlled directly by the applied potential rather than high temperature and pressure, making them inherently safer and more flexible, which benefits selective reduction and oxidation conversion. Finally, the electrification of chemical production is an efficient solution for maximizing the utilization of renewable energy by directly converting it into chemical energy. Increasing the electrification of chemical production has the potential to enhance

[47] https://chemicals.gov.in/sites/default/files/Reports/Annual_report_hi-2022-23.pdf
[48] https://pubs.acs.org/doi/10.1021/jacsau.2c00138#

the penetration rate of renewable energy in the electricity market, further reducing the dependence on fossil resources. [48]

PROCESS FLOW

Soda Ash

Sodium carbonate (Na_2CO_3) or soda ash can be found naturally or manufactured from natural salt, such as sodium chloride (common salt). It has numerous applications, but one of its most notable uses is in the production of glass. Additionally, it is a key chemical used in soap production, paper making, baking soda production, and bleaching fabrics and paper.

The Solvay Process, also known as the ammonia-soda process, is the primary industrial process for producing sodium carbonate (Na_2CO_3) or soda ash. Salt brine, which can be easily sourced from both inland and ocean sources, provides salt and water as feedstocks for this process. Limestone and ammonia are also used as feedstocks.

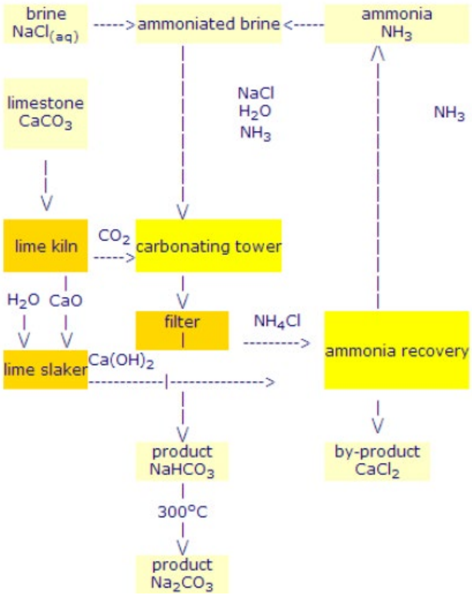


Figure 41 - Manufacturing steps in Solvay Process[5]

The Solvay process involves several steps, including -

1. Brine purification
2. Ammoniation of brine
3. Reactions in Solvay Tower
4. Reactions in Kiln / Separation of solid sodium hydrocarbon
5. Formation of sodium carbonate
6. Ammonia Recovery

The brine is purified by precipitation of alkaline earth metal ions. Ammonia gas is absorbed in concentrated brine to give a solution containing both sodium chloride and ammonia. The ammoniated brine is then purified by removing impurities using a process called brine purification. The pH of the brine is adjusted to around 9.5 using milk of lime, which causes the precipitation of magnesium and calcium ions as magnesium hydroxide and calcium carbonate, respectively. [49]

Limestone is calcined in a lime kiln at a temperature of 900°C to produce quicklime (CaO). Coke burns in a counter-current of pre-heated air to provide the heat of combustion, and the resulting carbon dioxide (CO_2) is sent to the carbonating (Solvay) towers. The residue, calcium oxide, is used in ammonia recovery. [49]

In the Solvay/Carbonating Tower, CO_2 dissolves in the ammoniated brine and reacts with the dissolved ammonia to form ammonium hydrogen carbonate. The solution now contains ions Na+(aq), Cl-(aq), NH_4+(aq), and HCO_3-(aq). Of the four substances that could be formed by different combinations of these ions, sodium hydrogen carbonate ($NaHCO_3$) is the least soluble. It precipitates as a solid in the lower part of the tower, which is cooled. The temperature and pressure in the tower are carefully controlled to ensure the proper formation of sodium hydrogen carbonate. [49]

[49] *https://www.worldofchemicals.com/440/chemistry-articles/manufacturing-of-sodium-carbonate-by-solvay-process.html*

Suspended sodium hydrogen carbonate is removed from the carbonating tower and heated at 300°C to produce sodium carbonate:

$2NaHCO_3(s) \rightarrow Na_2CO_3(s) + H_2O\ (g) + CO_2\ (g)$

Ammonia recovery occurs using calcium hydroxide ($Ca(OH)_2$) produced by reacting quicklime with water. The calcium hydroxide is then reacted with the ammonium chloride separated out of the carbonating tower by filtration:

$Ca(OH)_2(aq) + 2NH_4Cl(aq) \rightarrow CaCl_2(aq) + 2H2O(l) + 2NH_3(g)$

The temperature and pressure in the ammonia recovery process are carefully controlled to maximize the yield of ammonia gas. The ammonia gas is then recycled back into the ammoniation step of the Solvay process. [49]

Caustic soda and liquid chlorine

Caustic soda is a widely used inorganic bulk chemical that is strongly alkaline and odourless and is applied in several fields such as pulp and paper manufacturing, viscose yarn, staple fibre, aluminium, textiles, soaps, and detergents.

The demand for caustic soda in India is expected to rise due to the increasing demand from the textile and alumina sectors. Most of the caustic soda plants in India operate at around 80-85% efficiency, resulting in a surplus production volume. [50]

The traditional chlor-alkali process, which is based on Membrane Cell Technology, is responsible for approximately 99.5% of caustic soda production worldwide. This process simultaneously generates chlorine and hydrogen gas and is considered energy-efficient due to its lower power requirement.[50]

$2NaCl + 2H_2O + electricity \rightarrow 2NaOH + Cl_2(g) + H_2(g)$

The electrolytic cell consists of two electrodes, the anode and cathode, which are submerged in the liquid brine. When electricity is applied to the solution, the anode acquires a positive charge, while the cathode acquires a negative charge, causing electrons to flow from the anode to the cathode. A selectively permeable membrane is placed between the electrodes, allowing only positive ions, such as hydrogen (H+) and sodium (Na+), to pass through while keeping the final products, caustic soda and chlorine gas, physically separated. The anode's positive charge attracts negatively charged chloride ions, which undergo oxidization upon contact with the anode, losing two electrons. This process instantly leads to the formation of Cl2 gas, which covalently bonds with itself and is removed from the electrolytic cell.

To remove oxygen contamination from chlorine gas, the gas is cooled to produce a liquid while the oxygen remains in gaseous form, allowing for separation. This process is referred to as liquefaction.

Sodium hydroxide solution may contain residual salt, which can be removed by heating the mixture of sodium hydroxide and brine solution to evaporate water. This results in more concentrated solution, with the salt precipitating out and being recovered to produce more brine. The sodium hydroxide solution is then concentrated up to 50%.

In practice, the chlor-alkali membrane process consumes around 2.10-2.15 kWh_e/kg NaOH of electrical energy and 0.128-0.196 kWh_t/kg NaOH of thermal energy. On the other hand, the chlor-

[50] https://kemicalinfo.com/articles/caustic-soda-manufacturers-in-india/#:~:text=The%20Caustic%20Soda%20Market%20Scenario,based%20on%20Membrane%20Cell%20Technology

alkali diaphragm process tends to use less thermal energy (0.038-0.047 kWh_t/kg) at the cost of slightly higher energy usage (1.94-2.51 kWh_e/kg NaOH). [51]

Thermal energy is used in caustic soda production in the form of steam for various processes, such as heating and evaporating the brine solution, drying the caustic soda, and providing heat for other reactions in the process.

The brine solution is heated to a high temperature to improve the efficiency of the electrolysis process. The heat required for this is typically supplied by steam generated from a boiler using fossil fuels or other sources of energy.

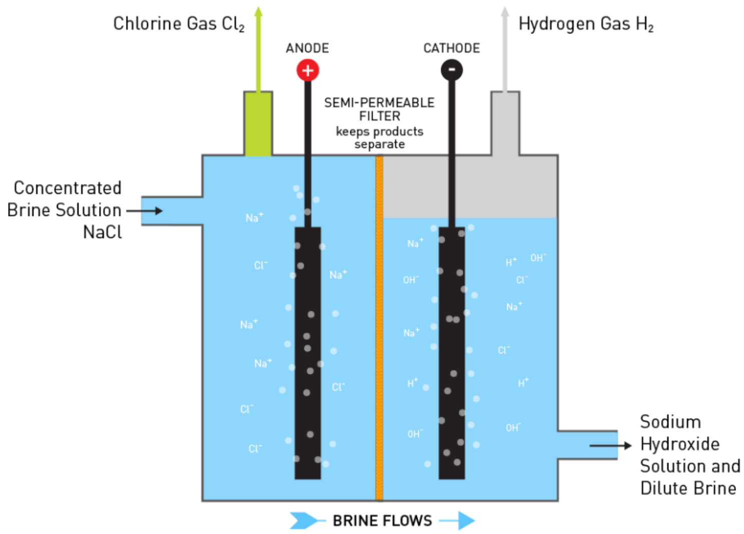


Figure 42 - Chlor alkali manufacturing from electrolysis[52]

The drying process for caustic soda also requires thermal energy, which is typically supplied by a steam-heated drying system. The caustic soda is first filtered to remove impurities, and then it is heated and dried to a specific moisture content, which is necessary for proper handling and storage. When considering only the electrical part, the energy efficiency of conventional chlor-alkali processes amounts to around 75%[51]

[51] https://pubs.acs.org/doi/10.1021/acsenergylett.1c01827
[52] https://www.chlorine.org/what-is-chlorine/manufacturing/

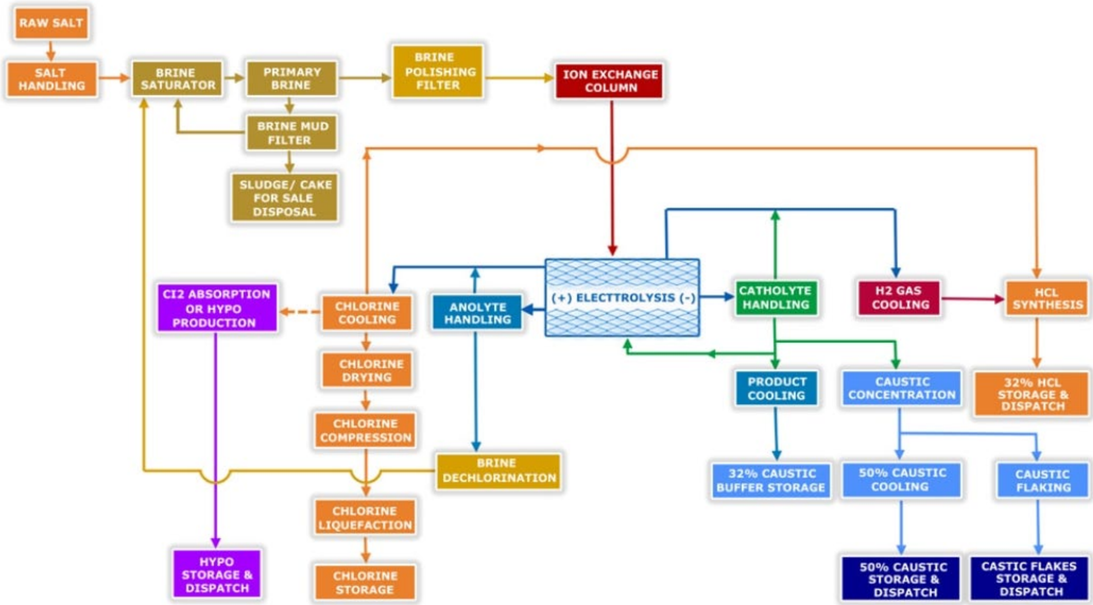


Figure 43 - Caustic Soda Plant Process Flow Diagram[53]

To liquefy the chlorine gas, it is first cooled to a very low temperature of around -33°C (-27°F) by compressing it and reducing its temperature. The cooling process causes the chlorine gas to condense into a liquid form.

The chlorine gas is purified post liquefication to remove any remaining impurities such as moisture, hydrochloric acid, and other gases. This purification stage is important to ensure the quality and purity of the final product.

The purified liquid chlorine is then stored in specially designed containers, such as cylindrical tanks or railcars, and transported to various industrial users. Liquid chlorine is used for a variety of industrial applications, including the production of plastics, solvents, and chemicals, as well as for water treatment and disinfection.

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Industrial heat pumps

In chemical production, heat pumps can be used for a variety of purposes, such as process heating and cooling, solvent recovery, and distillation. These processes often require high-temperature differentials and large amounts of energy. Hence, heat pumps can cover only around a quarter of process heat demand. However, low-temperature processes can benefit from substantial amounts of waste heat from other processes on the same site.

The utilization of heat pumps in the chemical industry has gained significant attention in recent years owing to increasing demand for sustainable practices. In particular, the application of heat pumps in the production of salts proves to be highly beneficial, as they aid in the concentration of salt solutions and in treating the effluent process.

[53] *https://www.nubergepc.com/caustic-soda-chlorine-plant.html*

Electric boiler

In the chemical manufacturing industry, electric boilers can be used for a variety of applications, including heating reactors, distillation columns, and other process equipment. They can also be used for clean steam generation, which is required for applications such as sterilization and cleaning. Electric boilers can also provide significant cost savings for chemical companies. They have a lower operating cost than traditional boilers since they do not require fuel storage or handling, and they have a longer lifespan, which reduces maintenance costs.

OTHER TECHNOLOGIES

Biomass steam boilers

Biomass-based steam boilers work by burning biomass fuel in a combustion chamber, which produces hot gases that transfer heat to water in a boiler vessel. The heated water then generates steam, which can be used for various industrial processes, including heating, cooling, and electricity generation.

One of the primary advantages of biomass-based steam boilers is their sustainability. Biomass is a renewable energy source that can be replenished much faster than fossil fuels. Additionally, the combustion of biomass produces greenhouse gas emissions, but it is less than the combustion of fossil fuels.

Biomass-based steam boilers also have a high energy efficiency rate, which allows them to produce steam using less fuel compared to traditional boilers. This results in cost savings for industrial users, as well as reduced environmental impact.

Technology Readiness Levels (TRL)

Biomass steam boilers have a long history of use and are widely regarded as a well-established and mature technology. Based on their successful deployment in commercial applications, they are typically assigned a TRL of 9, which denotes a fully mature technology that has been thoroughly tested and proven effective.

Energy Efficiency

Biomass boilers are generally considered to be less efficient than those fuelled by fossil fuels. In fact, the first law analysis shows that the energy efficiency of biomass boilers is only around 76%, while the exergy efficiency is 25% at a production steam rate of 4 tons/hr.[54]

Compatibility with currently used technologies

Biomass-based steam boilers can generally be integrated with existing fossil fuel-based steam boilers to provide a more sustainable and efficient solution for steam generation. This approach is often referred to as co-firing or co-combustion.

Co-firing involves the simultaneous combustion of biomass and fossil fuel in the same boiler, while co-combustion involves the combustion of biomass in a separate boiler that is connected to the existing fossil fuel boiler system. In both cases, the biomass is used to supplement or replace a portion of the fossil fuel, reducing the overall consumption of fossil fuel and associated emissions.

The compatibility of biomass-based steam boilers with existing fossil fuel-based steam boilers largely depends on the specific details of the existing system, including the type of fossil fuel being used and the design of the boiler system. Retrofitting an existing fossil fuel-based steam boiler to include

[54] https://www.researchgate.net/publication/303992505_Energy_Analysis_for_steam_boiler_burning_with_biomass

biomass can be a complex process that requires careful consideration and planning to ensure compatibility and optimal performance.

Foreseen cost development

The capital cost for the biomass boiler can be around 580 USD/kW, which represents the cost of installing the boiler, including equipment, construction, and associated costs. The O&M costs for the biomass boiler can be around 14.5 USD/kW/yr, which includes expenses associated with fuel, labour, and maintenance.[55]

Global adoption of biomass steam boilers

In 2021, Solvay became the first company in the world to use 100% renewable power at its soda ash plant in Rheinberg, Germany, after it switched from burning coal to biomass. The company installed two biomass boilers, which used scrap waste wood chips as fuel to produce steam and electricity. The switch to biomass was part of Solvay's plans to eliminate the use of coal wherever renewable alternatives exist, and it reduced CO_2 emissions at the Rheinberg plant by 65% relative to 2018. While the use of biomass as a renewable fuel has proven divisive, Solvay's move demonstrated the potential for biomass-based boilers to provide a sustainable and efficient solution for steam generation in the chemical industry.[56]

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand of production

Detailed desk research has been conducted to project the production demand of the sectors for the years 2030, 2050, & 2070. Production demand for sector is projected based on the correlation between the GDP manufacturing growth rate projection and past trend of annual production each sector. Considering the above correlation, production of chemicals in the country would be 19.7 Mn tonne by 2030, and 48.2 Mn tonne and 58.3 Mn tonne by 2050 and 2070 respectively. Detailed list of assumptions, values and references is annexed in Annex 1.

Production Demand

Year	2019	2030	2050	2070
Production (Million tonnes)	11.6	19.7	48.2	58.3

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, and potential of decarbonisation and suitability of the technologies. Penetration level of the selected technologies is estimated considering India’s target of net zero by 2070. Technologies used for steam generation like electrode boiler or heat pump are at TRL 9. So, these technologies can be deployed at scale in the near and in long term scenario. Efficiency level of the above mentioned technologies are also higher than the conventional technology (explained in Section 8) gives them an upper edge for implementation. Corelation between technology share and penetration of technology is presented in the image shown below. The image shown below represents that the chemical sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector.

[55] https://www.irena.org/-/media/Files/IRENA/REmap/Methodology/IRENA_REmap_2030_technology_cost.ashx
[56] https://www.sustainable-carbon.org/germany-solvay-switches-soda-ash-plant-from-coal-to-biomass/

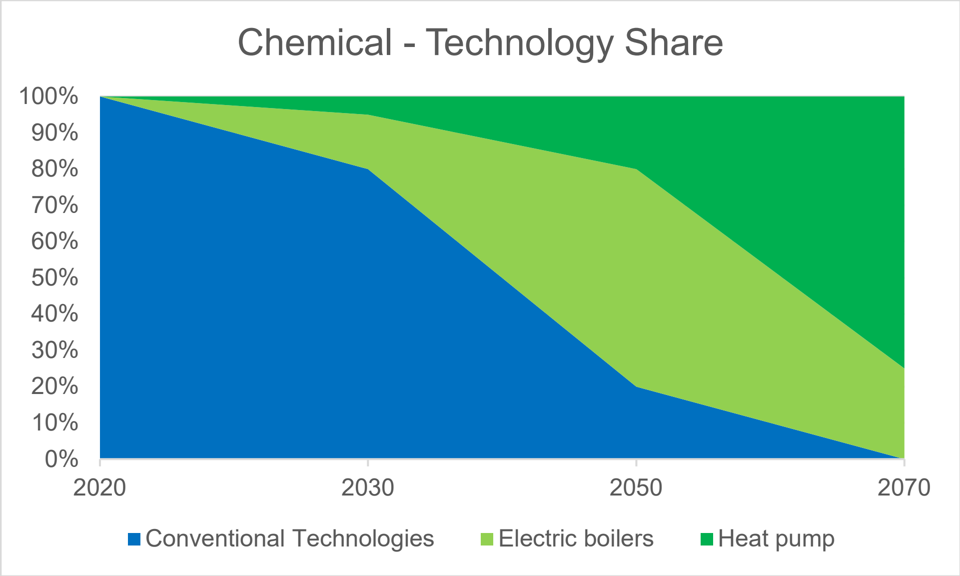


Figure 44: Penetration level and TRL of electrification technologies - Chemical

Projected Energy Consumption for Decarbonization

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration of each technology varies depending on the scenarios: the effort of implementation resulting a change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	22	48	39

In the conservative scenario, efforts to penetrate the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050, and 100% by 2070. The energy demand of the chemical sector would reduce by 1.5% in 2030, 13 % in 2050, and by 42% in 2070 over the base scenario.

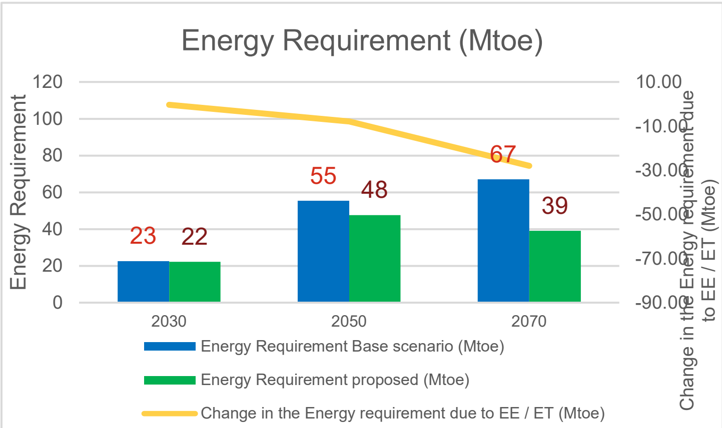


Figure 45: Energy requirement (Conservative - Chemical)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	22	45	39

In the moderate scenario, efforts to penetrate the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. A reduction in energy demand in the paper sector would be the same asthe conservative scenario for the year 2070. Due to the increase in the efforts in the moderate scenario, the reduction in the years 2030 and 2050 would be slightly more than that of the conservative scenario (2% reduction in 2030, 18% in 2050).

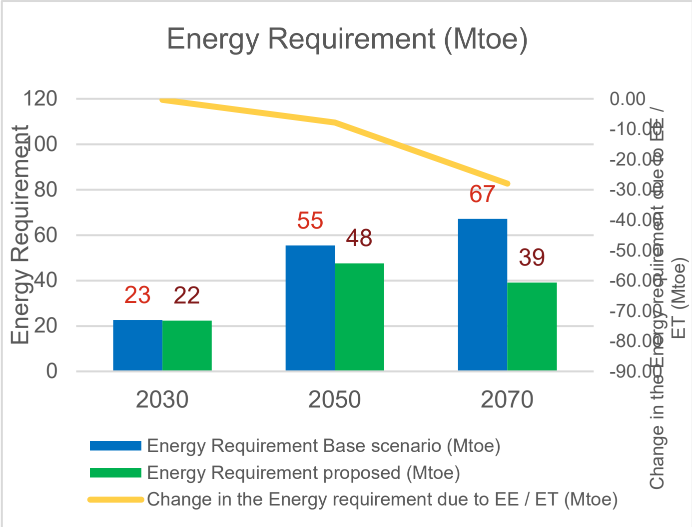
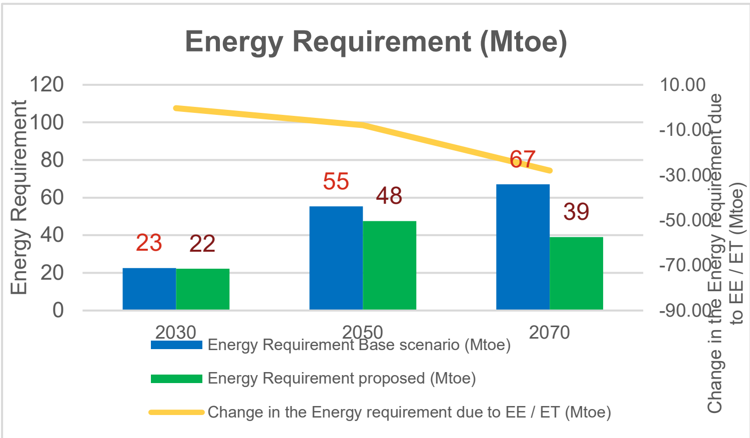


Figure 46: Energy requirement (Moderate - Chemical)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	21.47	44.21	39

In the ambitious scenario, efforts to penetrate the technology are considered at high levels,, i.e., 100% by 2030, 100% by 2050, and 100% by 2070. A reduction in energy demand in the paper sector would be the same for conservative and moderate scenarios for the year 2070.



Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity has been estimated for the different timelines 2030, 2050 and 2070 average capacity utilisation factor is calculated for the different timeline based on the mix of different sources of energy i.e., fossil and non-fossil fuel-based source of electricity. In the ambitious scenario, the power installation requirement for the sector would be **15 GW** by 2030, **168 GW** by 2050 and **194 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand on one day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.6 – 2.1 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Year	2030	2050	2070
Ambitious Scenario			
RE hybrid installed capacity (GW)	10	165	194
Battery Storage (GWh)	2	77	132
Moderate Scenario			
RE hybrid installed capacity (GW)	5	148	194
Battery Storage (GWh)	1.1	70	132
Conservative Scenario			
RE hybrid installed capacity (GW)	2.5	114	194
Battery Storage (GWh)	0.6	56	132

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 70.7 million tonnes CO_{2e}, 173.2 million tonnes CO_{2e}, and 209.7 million tonnes CO_{2e} for the years 2030, 2050, and 2070 in BAU scenario, respectively. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the production would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below. In all three scenarios GHG emissions of the sector increase till 2030. This is because of the ongoing electrification of the sector which in consequence boosts the electricity demand. Due to the high percentage of non-renewables in the capacity mix, the emission factor of the grid will still be at around 780 grams of CO_2 per unit of electricity in 2030.

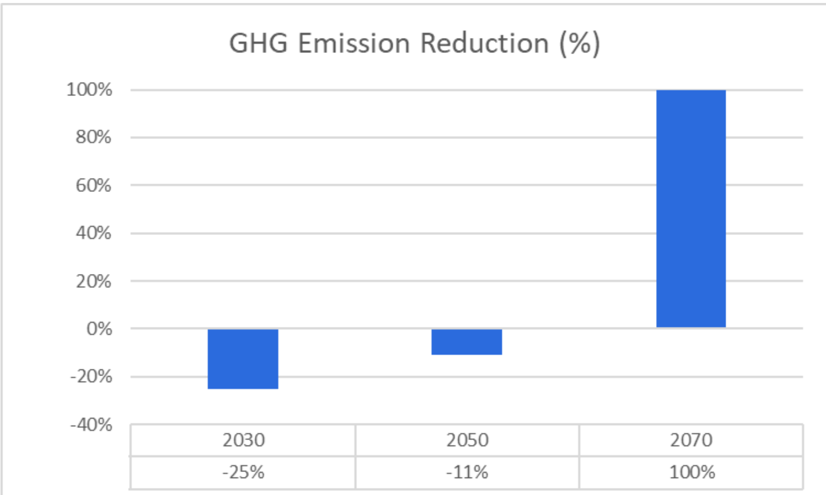


Figure 48: GHG emission reduction (Ambitious – Chemical)

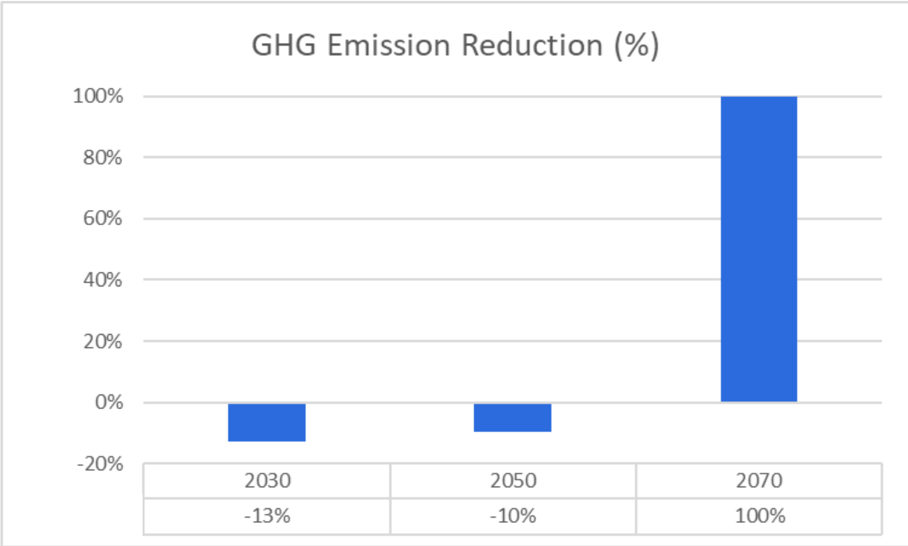


Figure 49: GHG emission reduction (Moderate – Chemical)

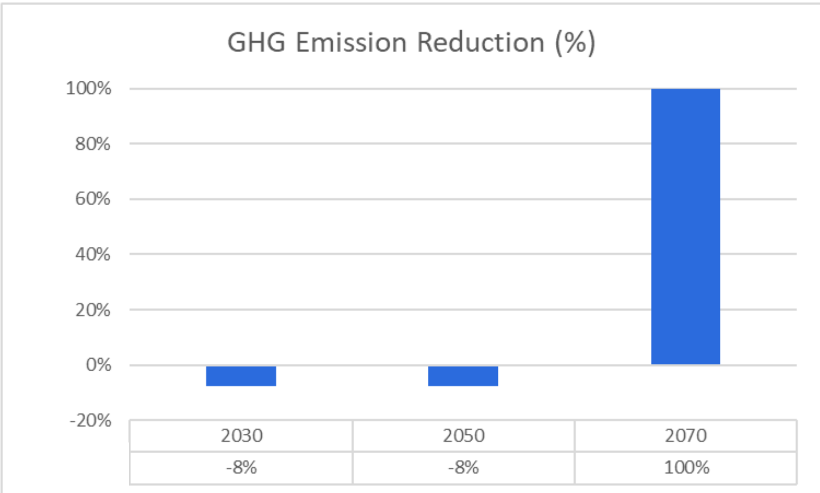


Figure 50: GHG emission reduction (Conservative – Chemical)

2.6 Electrification of Cement Sector

Electric kiln technology will massively replace the conventional boilers in the cement sector in 2070 in electrification scenario. As the major energy consumption in the cement industry is of kin, kiln comprises of 70-75% of total energy consumption of the cement plant. With the deployment of this technology, 100% of the energy consumption of the sector can be electrified from the existing 0% level. This implementation would result in a drop in the energy consumption of the sector by 37%, i.e., from 109 Mtoe in base scenario to 69 Mtoe in ambitious effort scenario by 2070. Reduction in energy consumption would also lead to a reduction in GHG emission: 100% by 2070. Key findings of the scenario analysis model (ambitious scenario) are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

69 Mtoe of Energy Demand by 2070 from the sector

Reduction of **499 Mn tonne CO_{2e}** by 2070

Power demand of **200 GW** by 2070

Requirement of **139 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e.level of effort – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[57].

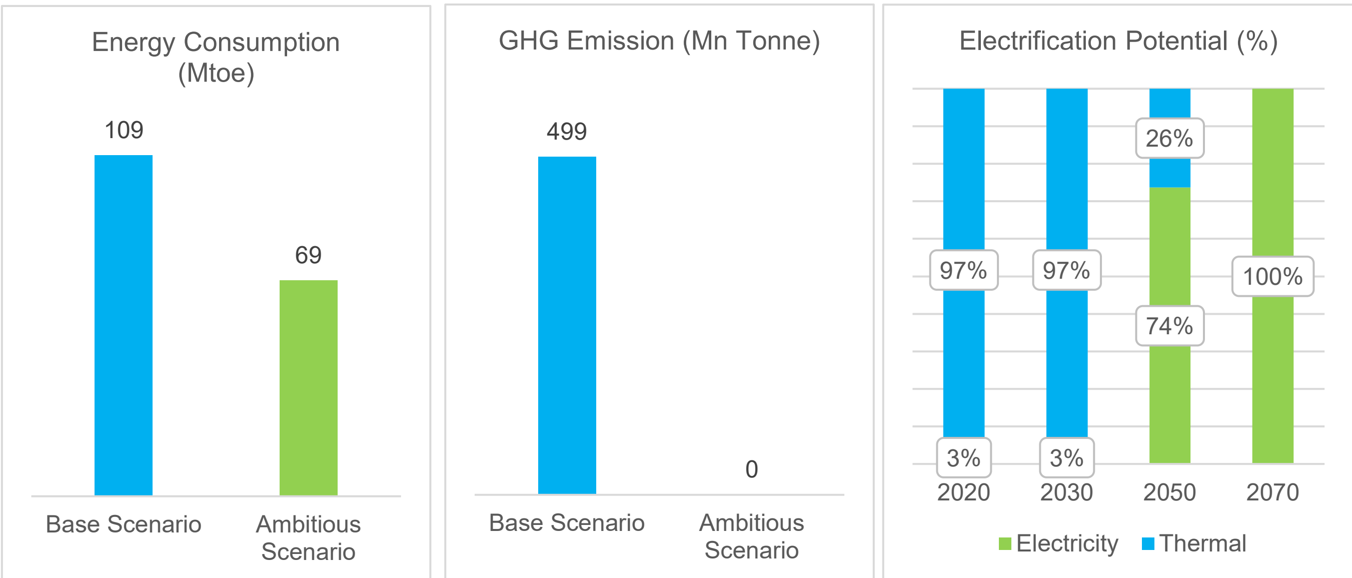


Figure 51: GHG emissions, energy requirement and electrification potential in proposed scenario

[57] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

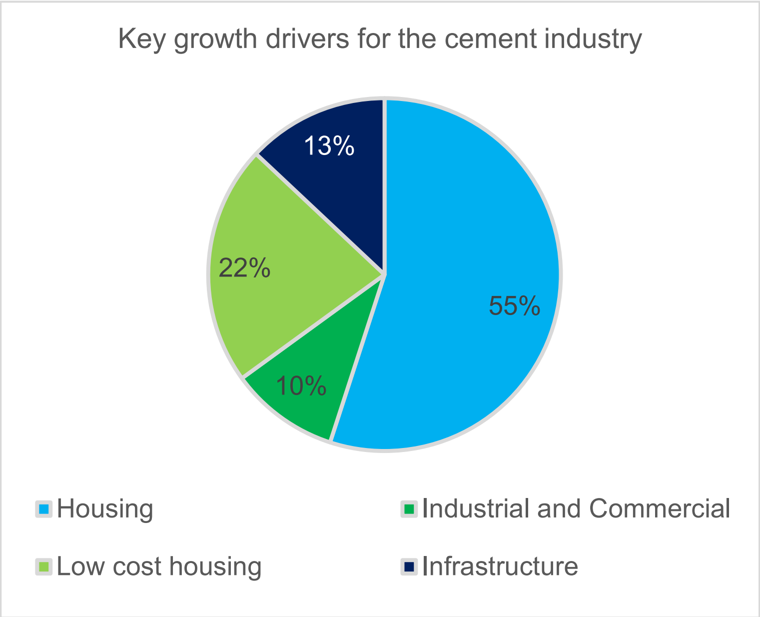
Sector Overview

India accounts for around 8 percent[58] of the installed capacity globally and is the second-largest cement producer in the world after China, accounting for about 55 percent of global production[59]. In the country, there are 210 large cement plants with an installed capacity of 410MT, while 350 mini cement plants contribute the rest. The private sector holds 98 per cent of the production capacity in the country. India's overall cement production capacity is approximately 545MT in FY22. The Indian cement sector stands second to China in both its production and consumption of cement. The cement production in FY13 was 247 MT, which has now increased annually by around 5.3 percent. The overall cement production in FY22 is estimated at 381 MT.

As a result of the outbreak of the global Covid-19 pandemic, cement production was down by almost 18 percent in FY21 as compared with the same period last year. Production has exceeded pre-pandemic levels over the course of April 2021 to December 2021. It increased by around 3 percent from 247MT in FY20 to 254MT[60].

The consumption of cement in India has grown at a CAGR of 5.68 percent from FY16 to FY22. The demand for the cement industry is expected to reach 550-600MT per annum (MTPA) by 2025[61]. India's cement production in February 2021 rose by 7.8 percent compared to February 2020.

The direct CO_2 intensity of cement production increased by 1.8 percent per year during 2015-2020[59]. In 2018, The CO_2 emission intensity of the Indian cement industry was 576 kg CO_2/ton of cement produced, whereas the global average stood at 634 kgCO_2/ton of cement produced[62].



While India is the second-largest cement producer in the world, the per capita cement consumption is 195 kg[63] , which is far less than China's per capita consumption of 1000 kg and also less than the world average of 500 kg. Despite this fact, cement demand and supply in India have shown an increasing trend. The cement industry has the potential to grow rapidly in a fast-growing economy like India.

There are five large cement plants recorded, which are owned by various State Government Undertakings like Tamil Nadu Cement, Malabar Cements, J&K Ltd and Mawmluh-Cherra Cement Ltd, Shillong, Meghalaya. Increasing demand from housing and construction work for other Government infrastructure projects like roads, metros, airports, irrigation, etc., are demand drivers that support cement demand. The private sector holds 98 percent of the production capacity in the country.

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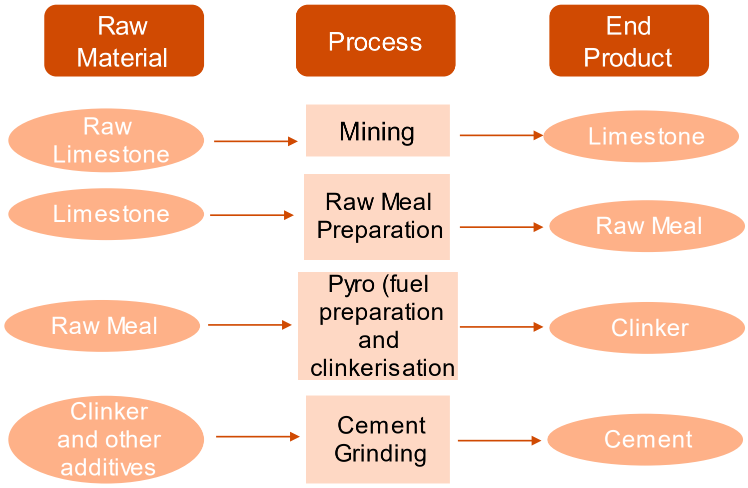
[58] CMA India
[59] https://www.iea.org/reports/cement
[60] https://www.careratings.com/Uploads/media/24022022024752_CareEdge_Research_-_Cement_Industry_Update_.pdf
[61] https://www.ibef.org/industry/cement-presentation
[62] https://aeee.in/emission-reduction-approaches-for-the-cement-industry/#:~:text=Thepercent20CO2percent20emissionpercent20intensitypercent20of,kgCO2percent2Ftonpercent20ofpercent20cementpercent20produced.
[63] https://beeindia.gov.in/en/cement#:~:text=The%20per%20capita%20consumption%20of,and%201000%20kg%20of%20China.

PROCESS FLOW

Production of Cement, which includes energy sources, type of feedstock and low carbon measures required for the production process



Step 1: Raw Meal Preparation:

Quarrying raw materials & Crushing

- Natural occurring calcareous deposits such as limestone, marl, or chalk provide calcium carbonate ($CaCO_3$) and are extracted from quarries, often located close to the cement plant.
- Very small amounts of 'corrective' materials such as iron ore, bauxite, shale, clay, or sand may be needed to provide extra iron oxide (Fe_2O_3), alumina (Al_2O_3), and silica (SiO_2) to adapt the chemical composition of the raw mix to the process and product requirements.
- The raw material is quarried and transported to the primary and secondary crushers and broken into 10cm large pieces.

Pre homogenization and raw meal grinding

- Takes place in which different raw materials are mixed to maintain the required chemical composition, and the crushed pieces are then milled together to produce a 'raw meal'.
- To ensure high cement quality, the chemistry of the raw materials and raw meal is very carefully monitored and controlled.

Step 2: Clinker Making

Preheating

- The preheater is a series of vertical cyclones through which the raw meal is passed, coming into contact with swirling hot kiln exhaust gases moving in the opposite direction.
- In these cyclones, thermal energy is recovered from the hot flue gases, and the raw meal is preheated before it enters the kiln, so the necessary chemical reactions occur faster and more efficiently.
- Depending on the raw material moisture content, a kiln may have up to six stages of cyclones with increasing heat recovery with each extra stage.

Pre-calcining

- Calcination is the decomposition of limestone into lime.
- Part of the reaction takes place in the 'precalciner', a combustion chamber at the bottom of the preheater above the kiln, and part in the kiln.

Clinker production in the rotary kiln

- The pre-calcined meal then enters the kiln. Fuel is fired directly into the kiln to reach material temperatures of up to 1,450°C.
- As the kiln rotates, about 3-5 times per minute, the material slides and tumbles down through progressively hotter zones towards the 2,000°C flame. The intense heat causes chemical and physical reactions that partially melt the meal into clinker.
- Typically, 35 percent of the fuel is combusted in the kiln.

Step 3: Grinding and Storing

Cooling and Storing

- From the kiln, the hot clinker falls onto a grate cooler where it is cooled by incoming air, the heated air is generally recovered for use as combustion air or raw material drying, thereby minimizing energy loss from the system.
- A typical cement plant will have clinker storage between clinker production and grinding.

Cement Grinding

- The cooled clinker and gypsum mixture is ground into a grey powder - OPC 33, 43, 53 with mineral components and additives to make blended cement PPC and PSC.
- All cement types contain around 4-5 percent gypsum to control the setting time of the product. Traditionally, ball mills have been used for grinding.

Blending

- If significant amounts of slag, fly ash, limestone, or other materials are used to replace clinker, the product is called "a factory-made composite cement or blended cement".
- These composite and blended cements can be made at the site that produced the clinker, but they can also be produced remotely at grinding and blending or just blending sites.
- These blending sites typically consume OPC to produce other cement types, e.g., PPC or PSC.

Storing

- The final product is homogenized and stored in cement silos and dispatched from there to either a packing station (for bagged cement) or to a silo truck for dispatch to customers.

Emission sources

- During calcination or calcining, calcium carbonate ($CaCO_3$) (limestone) is heated in a cement kiln to form lime, a process that emits CO_2 as a byproduct. This accounts for about 50-55 percent of all emissions from cement production. The resulting lime reacts in the kiln with silica, aluminum, and iron oxides present in the raw material to produce clinker. Clinker, an intermediate product, is mixed with a small amount of gypsum and/or anhydrite to make Portland cement.

- Indirect emissions from the burning of fossil fuels used to heat the kiln account for about 35-40 percent of emissions from cement.
- Finally, electricity used to power additional machinery and the transportation of cement account for the remaining 8-10 percent of the industry's emissions.

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Electric Kiln

Modern Electric energy powered kilns help in providing the solutions for the decarbonization of the energy requirement for the sector. Electric kilns are being operational in the European countries, and electricity can be generated from Solar. RE Hybrid installations can be wheeled from the RE generators to ensure carbon-neutral energy usage.

Calix LEILCA has developed a new, CO_2-neutral production line for the cement industry with an electric kiln.

CO_2-neutral cement production uses new and highly advanced technologies to cut down on material use, implement closed cycles, shorten building industry transportation distances and reduce CO_2 emissions. The new, cutting-edge moulding process is distinct from earlier techniques, which were totally dependent on fossil fuel energy consumption.

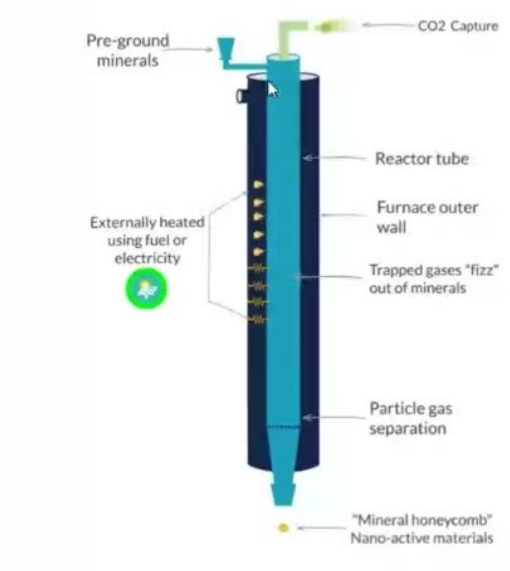


Figure 52: Electric Kiln section

Technology Readiness Levels (TRL)

The electric kiln is a relatively new technology in the Indian context, but globally, there are demonstrations in Belgium and other European countries, and its Technology Readiness Level (TRL) can be commercialized in other countries range of 7-8 based upon a scale of kiln operations.

While the electric kiln has been demonstrated to be a promising technology with several potential benefits, further research and development are needed to bring it to a higher TRL level. This includes scaling up the technology to a commercial scale in manufacturing units of the country, optimizing the process for efficiency and cost-effectiveness, and addressing any technical challenges or limitations that may arise.

Energy Efficiency

It has been demonstrated to be more energy-efficient compared to traditional processes that use fossil fuels such as natural gas or fuel oil to provide the heat required for the process. The use of electricity as the primary energy source reduces energy consumption and improves the overall efficiency of the process.

There are several factors that contribute to the energy efficiency of electric calcination, including:

- Direct heating - Electric calcination uses direct heating to calcinate the alumina, which is more efficient compared to traditional calcination processes that use indirect heating. Direct heating reduces heat loss and improves the overall efficiency of the process.
- Efficient energy transfer - Electric calcination uses electricity to generate heat, which is transferred directly to the alumina particles. This results in more efficient energy transfer and reduces energy consumption.
- No fuel consumption - Electric calcination does not require the use of fossil fuels, which reduces energy consumption and eliminates the associated emissions and operating costs.
- Renewable energy sources - Electric calcination can be powered by renewable energy sources such as hydropower, wind power, or solar power, which further enhances its energy efficiency and sustainability.

Global Adoption of Electric Kiln

- Electric Kiln has already been installed in one of the factories in Australia in 2013, with a scale of 25 kTpa and a required process temperature of 760 ^{0}C. Capital cost was Euro 11 million, and maintenance is also minimal in the range of less than 5% of capital cost or ~ Euro 60k per annum.


Figure 53: Calix LEILAC implementation in Australia and Belgium

- Similar installation has been done in Belgium in 2019, with capital cost of Euro 8 million, with same capacity as mentioned in the above example but the temperature requirement is higher than that of above.

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Green Hydrogen as fuel with oxy-fuel burner

Coal is the fuel that is most widely used in cement production, representing 70%[64] of the global cement thermal energy consumption. Oil and natural gas jointly contribute 24% to the thermal energy demand in global cement production, and biomass and waste contribute just above 5% of the global thermal energy use in the sector. Switching to fuels that are less carbon-intensive, like green hydrogen enables a major reduction of GHG emissions from the base scenario. Detail description of green hydrogen and its production process is explained in section *8.1 Cross-cutting technologies.*

The use of hydrogen as a fuel can reduce the CO_2 emissions by 100%. In the operation, hydrogen can be used in oxyfuel burners for a flameless operation as a standalone fuel or in a mixture with other fuels.

New production processes are exploring the use of hydrogen gas instead of coal and natural gas. A hydrogen-fired oxyfuel burner under operation is shown in Figure 54: Hydrogen-fired oxy fuel burner.

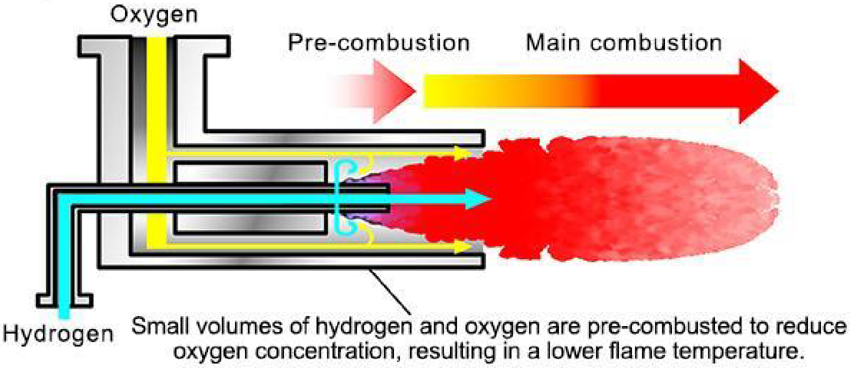


Figure 54: Hydrogen fired oxy fuel burner

The comparison of different burner systems is presented in the below table.

Table 7 : Comparison of different burner

System Considerations	Cold Air	Hot Air (Recuperative)	Regenerative	Oxy-fuel
Thermal Efficiency	Low	Medium	High	High
Fuel Usage	High	Medium	Low	Low
CO_2 Emissions	High	Medium	Low	Low
Maintenance Required	Low	High	High	High
Initial Cost	Low	Medium	High	Medium
Operating Cost	High	Medium	Low	Medium

OTHER TECHNOLOGIES

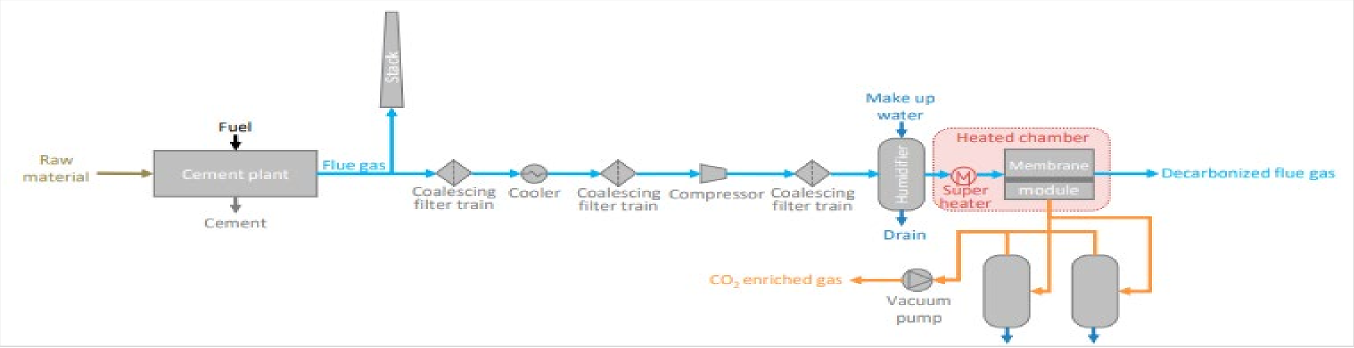
There are several other technologies related to process and energy efficiency which can lead to a reduction of specific energy consumption in the sector. Detailed analysis of all the technologies has

[64] https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf

been done on parameters like TRL, year availability of the technology, GHG emission reduction, and deployment case is explained in Table 8: Other Technologies - Cement.

Carbon Capture, Utilisation and Storage (CCUS)

Conventional kilns of existing and new cement plants could be retrofitted with post-combustion CO_2 capture technologies relatively easily, without substantially modifying the cement manufacturing process. There are different post-combustion technologies that can be used to capture the CO_2 from the kiln-off gas: chemical absorption, membranes, and sorption with solids. Details of CCUS are explained in section *8.1 Cross-cutting technologies*



- **Chemical Absorption:** processes have been commercially used as part of core operations in other industrial sectors for a long time. Chemical absorption in the post–combustion capture technology is the most advanced and enables up to 95%[65] capture yields. Thermal energy is required for the regeneration of the sorbent (amine-based sorbents are most commonly used in CO_2 -separating processes), and electricity is needed to operate the capture unit.

- Using **membranes** as a CO_2 separation technique could theoretically produce a yield of more than 80%. However, membranes have only been proven on small or laboratory scales where up to 60-70%[50] recovery yields were achieved. Membranes do not have energy requirements for regeneration but can be sensitive to sulphur compounds and other potential contaminants and, in some cases, to high temperatures.

- **Calcium Looping**: separates the CO_2 contained in flue gases from sorbents based on calcium oxide through sequential carbonation-calcination cycles (carbonation is the reaction of calcium oxide and CO_2 to give calcium carbonate). A pilot plant using calcium looping to capture one tCO_2[66] per hour was commissioned in 2013 in Chinese Taipei. The Zero Emission of Carbon with MIXed Technologies research infrastructure in Italy is investigating the calcium looping process to capture CO2 from coal gasification and steam methane reforming processes[67].

Advanced Grinding

As grinding circuits have been improved over the past few years, new technologies have been developed, such as high-pressure grinding rolls (HPGR) (roller presses), Horomills, high-efficiency classifiers, and vertical roller mills (VRM) for clinker grinding, all of which are more energy efficient than traditional equipment, such as tube mills. Cement grinding is done using energy-efficient equipment such as high-pressure grinding rolls, vertical roller mills, CKP pre-grinders, Cemex mills, and Horo mills because conventional multi-compartment ball milling circuits consume more energy. This technology has an emission reduction potential of 10 $kgCO_2$ per tonne of cement.

[65] https://iea.blob.core.windows.net/assets/cbaa3da1-fd61-4c2a-8719-31538f59b54f/TechnologyRoadmapLowCarbonTransitionintheCementIndustry.pdf
[66] Chang et al., 2014
[67] Stendardo et al., 2016

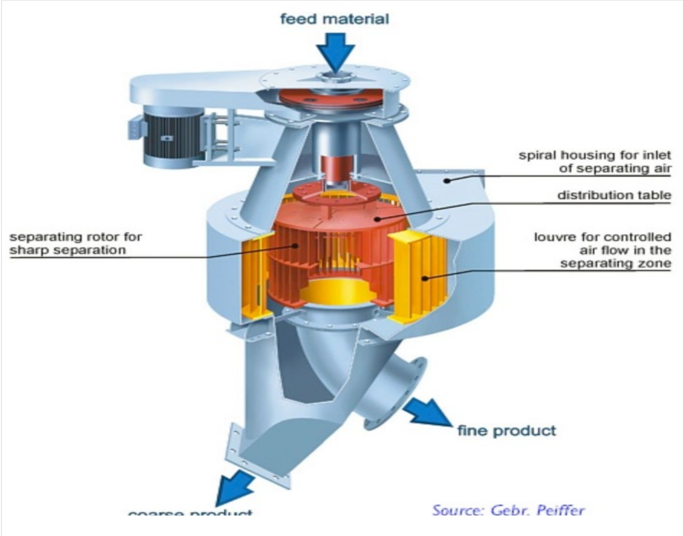


Figure 55: Advanced Grinding

Electrical and thermal energy efficiency improvements in kilns and preheater

By adding a precalciner and, where possible, an extra preheater, an existing preheater kiln may be converted to a multi-stage preheater precalciner. By adding a precalciner to the plant, the plant's capacity will be increased while the specific fuel consumption will be lowered, and NOx emissions will decrease (due to lower combustion temperatures in the precalciner). To convert existing plants, various manufacturers have developed special precalciners, for example, Pyroclon®-RP by KHD in Germany. Older calciners can also be retrofitted for energy efficiency improvement and NOx emission reduction[68]. This technology has an emission reduction potential of 9 $kgCO_2$ per tonne of cement.

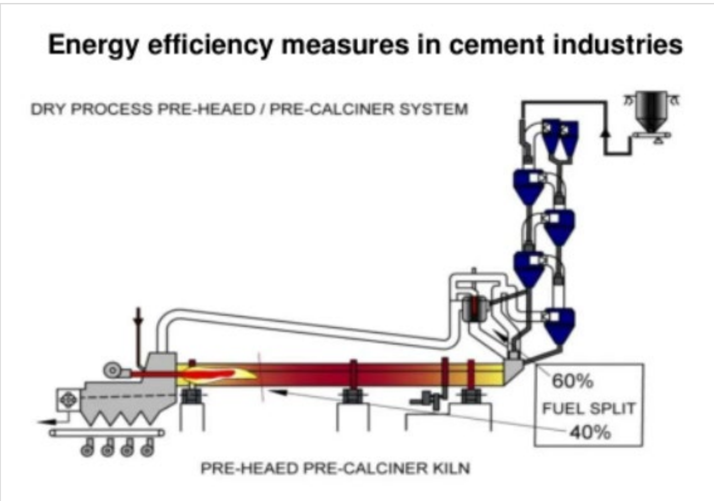


Figure 56: Electrical and thermal energy efficiency improvements in kiln and preheater

Waste Heat Recovery

Power can be generated from rotary kiln preheaters (PH) and the exhaust of cement plants using waste heat recovery power plants (WHR). These hot gases are used to generate steam in a steam generator (Boiler), which is further used to generate electricity/power through a steam turbo

[68] https://www.osti.gov/servlets/purl/927882

generator (STG). Using waste heat for power generation can fulfill up to 30% of the cement plant's power requirements, resulting in substantial savings/reductions in production costs.

There are three processes by which WHR-based power plants are installed in the cement industry globally.

- Steam Rankine Cycle System (SRC)
- Organic Rankine Cycle System (ORC)
- Kalina-based system

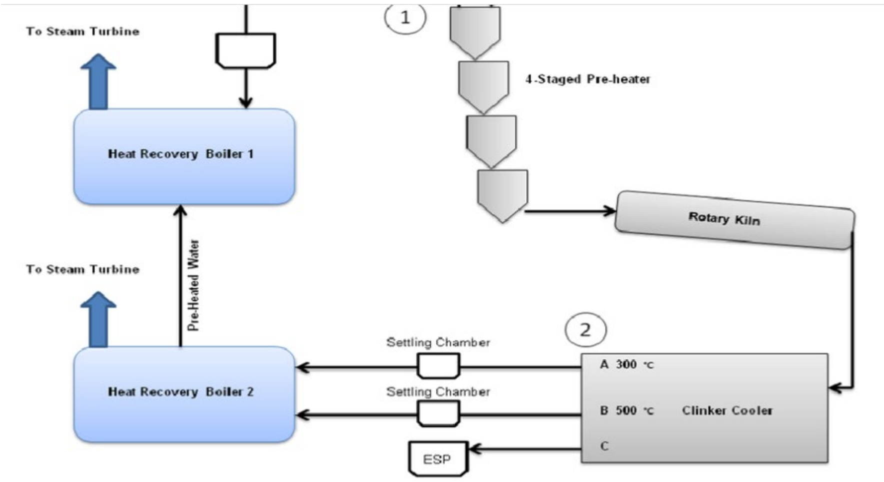


Figure [illegible] Waste heat recovery in Cement processes

Table 8: Other Technologies - Cement

Technology	TRL	Year available (importance for net zero emissions)	Deployment status	Energy/Emission Reduction	Country
Novel physical adsorption (using silica or organic-based adsorption)	6	2035 (High)	• The CO2MENT project in Canada launched trials in 2019 of Svante's CO2 capture technology at a LafargeHolcim cement plant; it will trial using the CO2 for low-carbon fuels and concrete (LafargeHolcim, 2019; Financial Post, 2019). • In early 2020, several companies announced a joint study to assess the design and cost of a commercial facility (0.725 MtCO2/yr) at the Holcim Portland cement plant in Colorado, United States (Total, 2020).		
Direct separation	6	2030 (High)	• Successful pilot-scale demonstration at the Heidelberg Cement plant in Belgium by the LEILAC project in 2019, targeting large-scale demonstration in 2025 (0.1 MtCO2/yr) (LEILAC, 2019; Perilli, 2020).		
Other capture technologies	4 or 5	--- (Medium)	• Various other capture technologies could be applied to cement, including membrane separation, chilled ammonia process and cryogenics. Some laboratory and small-scale trials have taken place, but these technologies remain in relatively early		

			development stages (ECRA, 2017; Sayre et al., 2017; Pérez-Calvo, 2018).		

Technology	TRL	Year available (importance for net zero emissions)	Deployment status	Energy/Emission Reduction	Country
Sequester/ mineralise CO2 in concrete and other inert carbonate materials	9	Today (Medium)	• Multiple commercial-scale plants using CO2 for producing aggregates or in concrete curing (Carbon8, 2020; CarbonCure, 2020; Blue Planet, 2020). • Sinoma International and CNBM completed a project in 2016 in China that uses CO2 to produce precipated barium carbonate (50 kt/yr).* • CO2Min, led by HeidelbergyCement and RWTH Aachen University, has proven the ability of olivine and basalt to absorb CO2 (Beumelburg, 2017; Stopic et al., 2019). • The FastCarb project in France is investigating accelerated carbonation in recycled concrete aggregates; research is currently at the lab scale (FastCarb, 2020).	unknown; only limited amounts of CO2 can be injected as it changes the alkalinity of cement and attacks steel in concrete	
Calcined clay	9	Today (High)	• Currently used in a limited number of countries in low proportions; developed by collaboration between researchers in Cuba, India and Switzerland (Scrivener et al., 2018; UNEP, 2016; LC3 cenent). • A large-scale flash calciner that would	Reducing up to 40% CO2 emission compared to Ordinary Portland cement	Switzerland, India, Cuba,

			considerably improve the energy efficiency of calcinating clay is under development in China, with two 300 t/day lines already built (Sui, 2020).		

Technology	TRL	Year available (importance for net zero emissions)	Deployment status	Energy/Emission Reduction	Costs	Country
Carbonation of calcium silicates	8	Today (Medium)	• First produced in 2014 by Solidia Technologies at a Lafarge plant in the United States, with production now at an additional plant in Hungary; in 2019, a first commercial venture was announced to supply a paver plant (Aggregates Business, 2019).			
Magnesium silicates (MOMs)	3	--- (Medium)	• R&D largely remains in university labs; at present, largely on hold after a venture (Novacem in the United Kingdom) ended in 2012 due to lack of funding (Majcher, 2015).			
Alkali-activated binders (geopolymers)	9	Today (Medium)	• Some cements already commercially available, but primarily used in nonstructural applications. An example is Vertua Ultra Zero developed by CEMEX in Switzerland (CEMEX, 2020). Others are at earlier stages of development.			
Direct Electrification						
Concentrated solar power direct heating	6	--- (Medium)	The SOLPART project in France successfully commissioned a pilot-scale calcination solar reactor in mid-2019; it aims to open a partially solar powered cement plant by 2025 (SOLPART, 2019). • US-based start-up Heliogen proved in 2019 at its test facility in the Mojave Desert the possibility of generating heat above 1 000°C using concentrated solar power (Heliogen, 2019). • The Paul Scherrer Institute, ETH Zurich and LafargeHolcim are performing a study using concentrated solar power in kilns (LafargeHolcim, 2015).	<50% emissions.		Spain
Technology Performance						

Advanced grinding	6 to 9	Today (Medium)	• Various technologies are at different stages of development, some nearing commercialisation (ECRA, 2017; 2020b).	5% power savings		Europe

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for production

Production demand projection for the cement sector is derived based on the correlation between the GDP, manufacturing growth rate projection and past trends for annual production of cement. The detailed list of assumptions and values is annexed in Annex 1.

Production Demand

Year	2020	2030	2050	2070
Production (Million tonnes)	334.37	496.5	1115.2	1335.6

Suitable technology mix

Technologies are evaluated primarily based on their TRL level potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated, considering India's target of net zero by 2070. The correlation between technology share and penetration of technology is presented in the image below. The image shown below represents that the cement sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector.

Technologies like direct electrification of kiln are at the mature readiness level, and they have already been deployed in many places. So, the penetration of this technology would be crucial for electrifying the cement sector and it has a high energy efficiency potential of 30% when compared to conventional technologies. Advanced grinding is also one of the electrification technologies to electrify the grinding process in cement operations with a low energy efficiency potential of 5%, and it is estimated to be completely penetrating in the cement operation by 2030. The use of hydrogen as a fuel with an oxy-fuel burner is also considered in the model to transition the sector from carbon-intensive fuel to low-carbon fuel. Its penetration is estimated till 2050 because green hydrogen is currently at a higher readiness level and it can be deployed at scale. By 2050, it is estimated the electrified kiln would be commercially viable in India and it would completely replace the use of green hydrogen as a fuel.

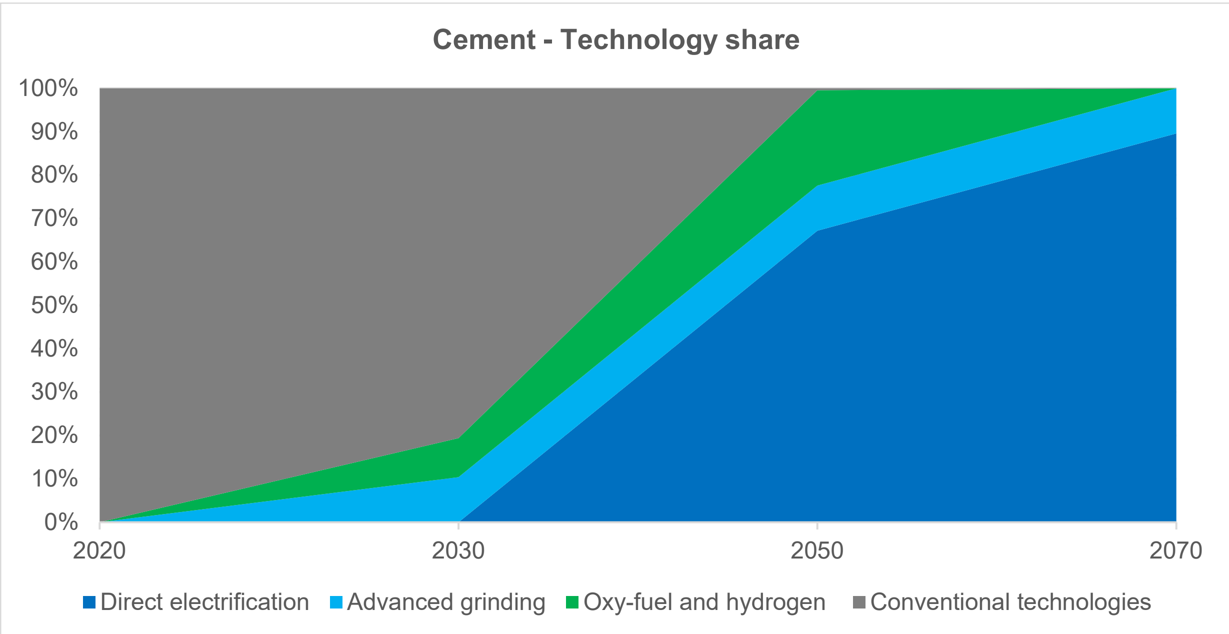


Figure 58: Penetration level of technologies (Ambitious Scenario)

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration of each technology varies depending on the scenarios: the effort of implementation resulting in a change in energy consumption in each scenario.

Table 9: Projected energy requirement (Mtoe) till 2070 in different scenarios

Scenarios ↓ / Year →	2030	2050	2070
BAU	40	91	109
Conservative	39	68	69
Moderate	38	64	69
Ambitious	36	62	69

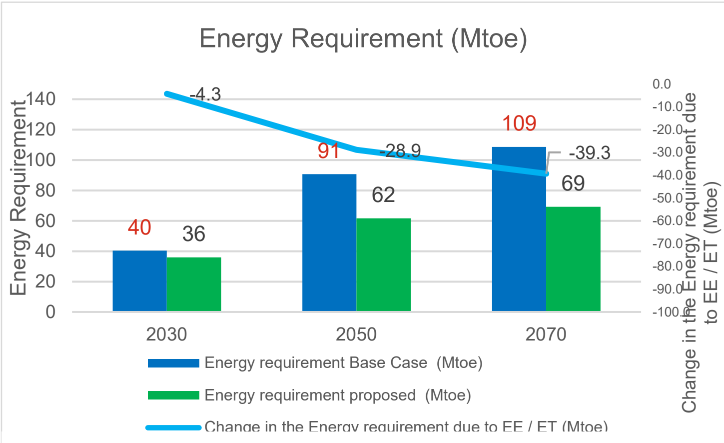


Figure 59: Energy Requirement - Conservative

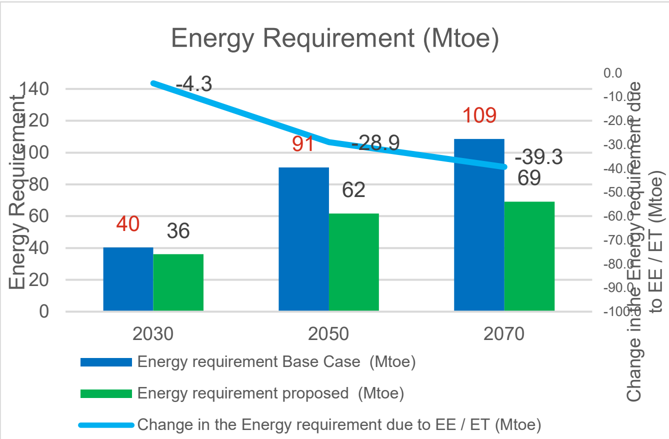


Figure 61: Energy Requirement - Moderate

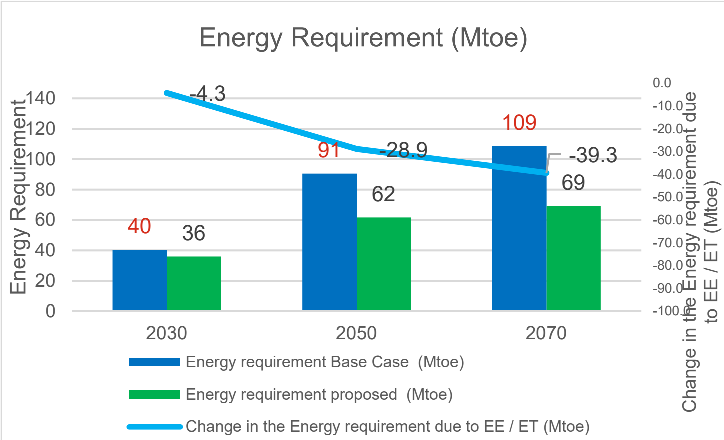


Figure 60: Energy requirement - Ambitious

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy i.e.,, fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **4 GW** by 2030, **166 GW** by 2050 and **200 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand on one day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **1.2 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 10: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070

Conservative	2.5	116	200
Moderate	2.7	148	200
Ambitious	2.7	163	200

Table 11: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	1.2	61	139
Moderate	1.2	77	139
Ambitious	1.2	85	139

Projected GHG emission reduction

The total GHG emissions for this sub-sector under industries are estimated to reach 186 million tonnes CO_{2e} in 2030, 417 million tonnes CO_{2e} in 2050 and 499 million tonnes CO_{2e} in 2070 in the base scenario. Under the ambitious scenario, it is estimated to be 0 in 2070, 246 million tonnes CO_{2e} in 2050, and 171 million tonnes CO_{2e} in 2030. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

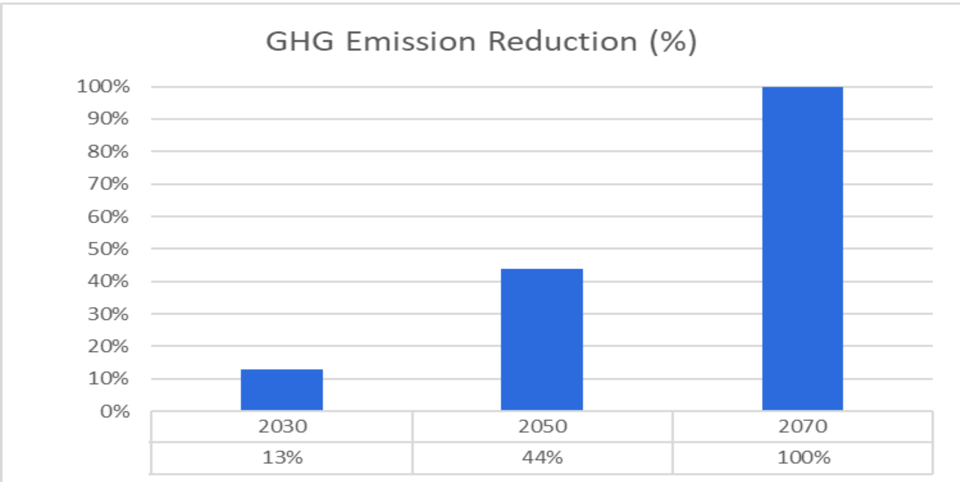


Figure 62: GHG Emissions Reduction (Ambitious)

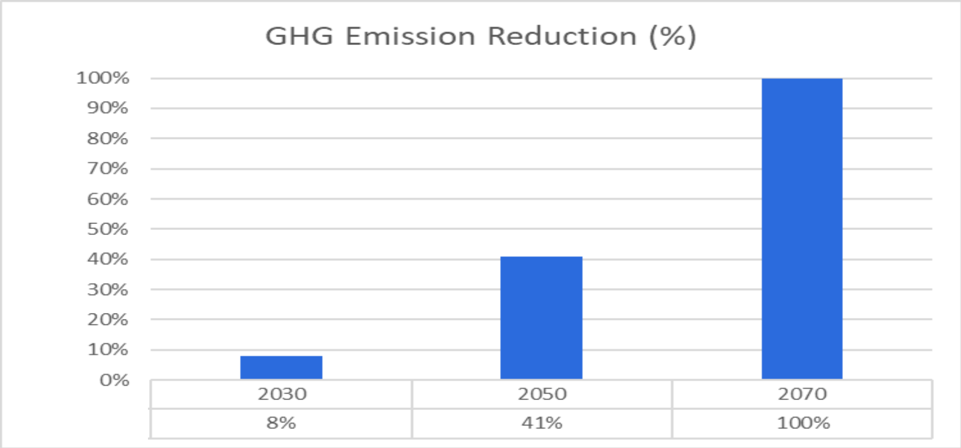


Figure 63: GHG Emissions Reduction (Moderate)

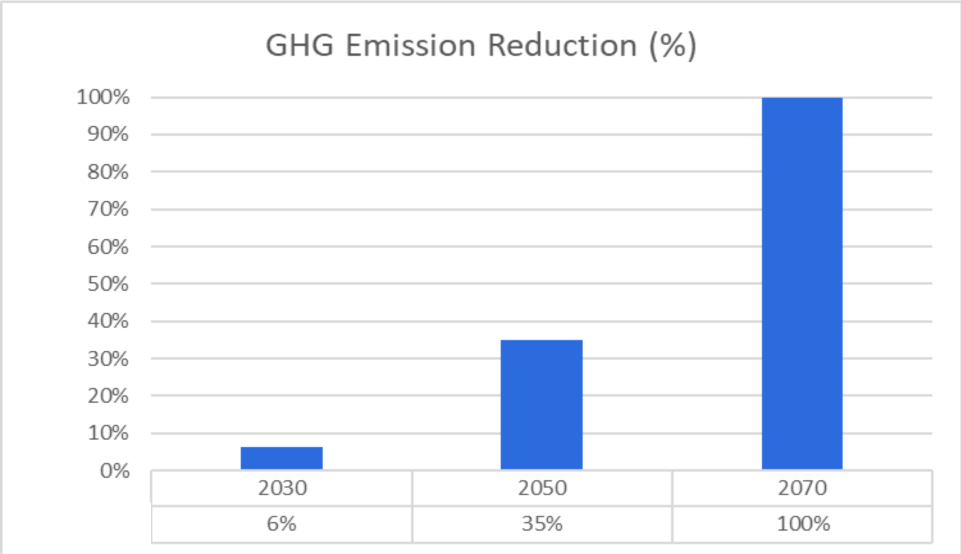


Figure 64: GHG Emissions Reduction (Conservative)

2.7 Electrification of the Textile Sector

Electric boilers, heat pumps, electric stenter and other electrified technology, will massively replace the conventional boilers in the textile sector in 2070 in the electrification scenario. As the major energy consumption in the textile industry is of conventional boiler and heat setting machines, it comprises ~ 60% of the total energy consumption of the textile plant. With the deployment of this technology, 100% of the energy consumption of the sector can be electrified from the existing level. This implementation would result in a drop in the energy consumption of the sector by 44%, i.e., from 16 Mtoe in the base scenario to 9 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions - 100% by 2070. Key findings of the scenario analysis model (ambitious scenario) are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

9 Mtoe of Energy Demand by 2070 from the sector

Reduction of **79 Mn tonne CO_{2e}** by 2070

Power demand of **25 GW** by 2070

Requirement of **18 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e. level of efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[69].

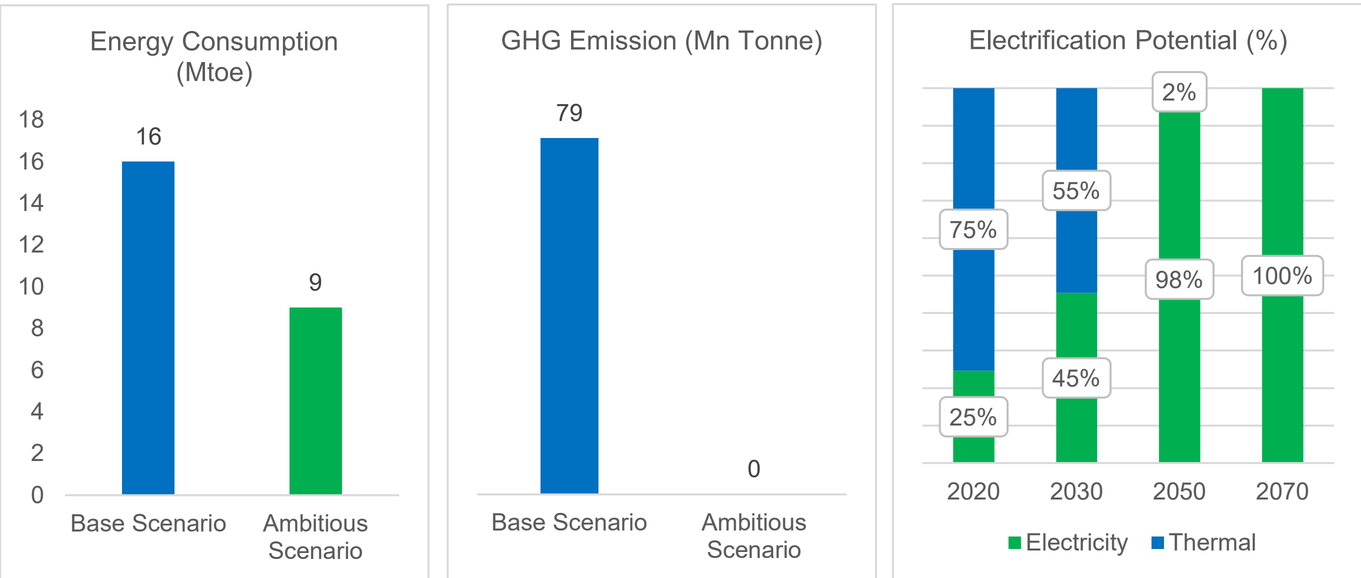


Figure 65: GHG emissions, energy requirement and electrification potential in proposed scenario

SECTOR OVERVIEW

[69] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

India's textile sector is one of the oldest industries in the Indian economy, dating back several centuries. The industry is extremely varied, with hand-spun and hand-woven textiles sectors at one end of the spectrum and the capital-intensive sophisticated mills sector at the other end. The fundamental strength of the textile industry in India is its strong production base of a wide range of fibre/yarns, from natural fibres like cotton, jute, silk and wool to synthetic/man-made fibres like polyester, viscose, nylon and acrylic.

The Indian textile and apparel industry is expected to grow at 10% CAGR from 2019-20 to reach US$ 190 billion by 2025-26. India has a 4% share of the global trade in textiles and apparel.

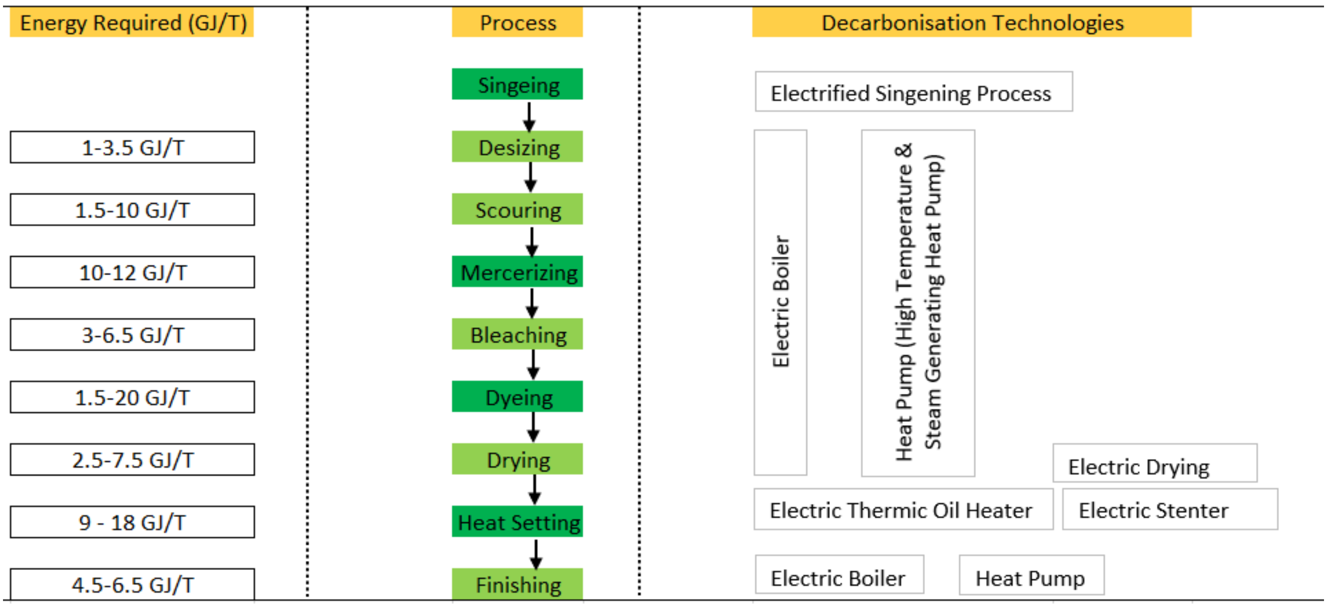
India is the world's largest producer of cotton. Estimated production stood at 362.18 lakh bales during the cotton season 2021-22. Domestic consumption for the 2021-22 cotton season is estimated to be 338 lakh bales. Cotton production in India is projected to reach 7.2 million tonnes (~43 million bales of 170 kg each) by 2030, driven by increasing demand from consumers. In FY23, exports of readymade garments (RMG) cotton, including accessories, stood at US$ 7.68 billion till January 2023. It is expected to surpass US$ 30 billion by 2027, with an estimated 4.6-4.9% share globally.

Production of fibre in India reached 2.40 MT in FY21 (till January 2021), while for yarn, the production stood at 4,762 million kgs during the same period. Natural fibres are regarded as the backbone of the Indian textile industry, which is expected to grow from US$138 billion to US$195 billion by 2025.

India's textile and apparel exports (including handicrafts) stood at US$ 44.4 billion in FY22, a 41% increase YoY. During April-October in FY23, the total exports of textiles stood at US$ 21.15 billion. India's textile and apparel exports to the US, its single largest market, stood at 27% of the total export value in FY22. Exports of readymade garments, including cotton accessories stood at US$ 6.19 billion in FY22.

PROCESS FLOW

The production of textile consists of many processes.The below mentioned process flow diagram is of the typical wet processing industry. This process flow diagram includes the specific energy consumption of each sub-process and also the available decarbonization technology.



Major Textile Processes

Singeing

Fabrics from the weaving and knitting section contain some loose fibers protruding or struck out from the surface. Singeing removes those loose, hairy fibers by burning them off. This is typically the first process in the wet-processing unit. The objective is to generate an even surface without a fuzzy appearance, which will not tend to pill. Singing of fabric can be achieved in various arrangements. Plate singeing machine uses heated plates, roller singeing machine uses rotating cylinders, and the most commonly used gas singeing machines uses gas burners. As a result, a smooth surface appears. This also helps to achieve uniform dyeing afterwards.

Mercerising and Washing Process

Mercerization is a chemical treatment applied to cotton fibers or fabrics to improve their dyeing properties, tensile strength, absorbency, and luster. The treatment consists of immersing the yarn or fiber in a solution of sodium hydroxide for short periods (usually less than four minutes) and then treating it with water or acid to neutralize the sodium hydroxide. If the material is held under tension during this stage, it will be less likely to shrink. Higher-quality cotton goods are usually mercerized; mercerized cloths take brighter, longer-lasting colors while using a lower amount of dye.

Dyeing Process

Dyeing is the application of color to the whole body of textile material with some degree of colorfastness. Textiles are dyed using continuous and batch processes and dyeing may take place at any of several stages in the manufacturing process (i.e., before fiber extrusion, while the fiber is in staple form, to yarn, to fabrics, and garments). Various types of dyeing machines are used for both continuous and batch processes. Every dye system has different characteristics in terms of versatility, cost, the tension of the fabric, use of carriers, weight limitations, etc. Dyeing systems can be aqueous, non-aqueous (inorganic solvents), or use sublimation (thermosol, heat transfer). Hydrophilic fibers, such as cotton, rayon, wool, and silk, are typically easier to dye as compared with hydrophobic fibers, such as acetate, polyesters, polyamides, and polyacrylonitrile. Dyeing is an energy-intensive process since it requires heat, which is provided by steam. The steam is usually generated in combustion steam boilers.

Drying Process

Fabric drying is done to get rid of moisture and impart a wrinkle-free smooth surface to the fabric. Contact drying using cylinder dryers is mainly used for intermediate drying rather than final drying (since there is no way of controlling fabric width) and for pre-drying before stentering. Fabric is passed around a series of cylinders, which are heated by steam supplied at pressures. Cylinders can be used to dry a wide range of fabrics. However, since the surface of the fabric is compressed, the process is not suitable for fabrics with a raised surface effect. Cylinder dryers are heated by steam. Other types of dryers, such as hot air dryers, are also used for drying fabrics during wet processing. These conventional hot air dryers are also often heated by steam.

Heat Setting Process (Stenter Machine)

After dyeing and printing, heat-setting of fabric is done to make sure that the fabric retains its shape afterwards. The process is very important, especially for the knit fabric to control the fabric shrinkage, It also helps to impart wrinkle/crease resistance to the fabric. A stenter machine is often used for heat setting. Stenters are mainly used in textile finishing for heat-setting, drying, thermosol processes, and finishing. It can be roughly estimated that, in fabric finishing, the fabric is treated on average 2 – 3 times in a stenter. Fabric can be processed at speeds from 10 – 100 m/minute and temperatures of more than 200°C. Stenters can be heated in a variety of ways, such as direct gas firing and through the use of thermal oil systems. Gas-fired stenters are highly controllable over a wide range of process temperatures.

Thermal oil heating for stenters requires a small thermal oil boiler and its associated distribution pipeline. This system is less efficient than direct gas firing and has higher capital and running costs. Finally, there are several steam-heated stenters. Because of their low-temperature limits (usually up to a maximum of 160°C), these stenters can only be used for drying; they are not suitable for heat setting or thermo-fixing of fabrics.

AVAILABLE TECHNOLOGIES FOR DIRECT POTENTIAL

Electric Boiler and Heat Pump

The textile industry has a large steam demand and, therefore, requires a steam boiler for its production process. Textile industries have very high requirements for the quality of steam and the amount of steam produced.

Requirement of steam and hotter at different processes of textile manufacturing:

Pre-processing of textiles: In textile manufacturing, the pre-processing of textiles is an essential part of the production process. It involves preparing raw materials for dyeing and finishing by removing impurities that can harm the finished fabric. This requires hot water and steam.

Printing Process: It involves the addition of colors or colorings to fabrics to give them color. While dyeing can be done at any stage of cloth manufacturing, it's most generally performed during the yarn product or fabric woven stages. This is a pivotal step in achieving the ideal appearance of fabrics. The color must be transferred to the cloth with a specific quantum of heat and humidity, which brume provides.

Finishing of textile: Steam boilers are essential for the finishing process of textiles. To give fabrics a finishing look, burning of fabrics and elimination of wrinkles are done. Pressure, on the other hand, is the best-considered option for some fabrics, making a boiler an essential part of the process. Not only do they provide the necessary steam, but they also provide the necessary heat to dye fabric. Since steam is relatively hot, the right temperature is essential for dyeing and printing textiles. To maximize the use of steam boilers, textile factories should choose the right ones based on their needs. Cross-cutting technologies like **electric boilers and electric heat pumps** are explained in detail in section *8.1 Cross-cutting technologies*.

Electric Thermic Oil Heater (Electric Stenter)

Conventional Scenario

A **thermic fluid heater** is industrial heating equipment used where only heat transfers are desired instead of pressure. In this equipment, a thermic fluid is circulated in the entire system for heat transfers to the desired processes. The combustion process heats up the thermic fluid, and this fluid carries and rejects this heat to the desired fluid for concluding the processes. After rejecting it, this fluid comes back again to the thermic fluid heater and this cycle goes on.

Working Principle

Electrically powered thermal fluid heating systems use an electric circulation heater and a low-watt density immersion bundle. It's a simple, robust, and reliable system that allows for the use of electricity instead of natural gas, fuel oil, or coal sources. Configurations vary from 30kW to 800kW, and custom configurations from 800kW to 4MW or higher.

Compatibility

Electric thermic fluid heaters can be used to fulfil the thermal requirement of stenter machines. It fully replaces the use of fossil fuel in conventional thermo pack.

Technology Readiness Level (TRL)

TRL level of this technology is 9 and it is commercially available across many countries in the world. Sigma Thermal USA[70] and Pirobloc[71], are one of the leading suppliers.

Electrified Heat Setting Machine

Conventional Scenario

Stenters are mainly used in textile finishing for heat-setting, drying, thermosol processes, and finishing. It can be roughly estimated that, in fabric finishing, the fabric is treated on average 2 – 3 times in a stenter. Fabric can be processed at speeds from 10 – 100 m/minute and temperatures of more than 200°C. Stenters can be heated in a variety of ways, such as direct gas firing and through the use of thermal oil systems. Thermal oil heating for stenters requires a small thermal oil boiler and its associated distribution pipeline.

Working Principle

Several stenter manufacturing companies offer choices for the type of heating system in the machine. Many stenter manufacturers offer machines with electric heating systems.

Compatibility

Stenter with electric heating instead of a direct gas-fired or thermal oil stenter reduces the total energy consumption of the process because of a reduction in energy losses in the system.

Technology Readiness Level (TRL)

TRL level of this technology is 9 and it is commercially available across many countries in the world. Zhejiang, China[72] is one of the leading suppliers.

[70] https://www.sigmathermal.com/products/thermal-fluid-systems/shots-electric-thermal-fluid-heater/
[71] https://www.pirobloc.com/en/products/thermal-oil-heaters/
[72] https://www.hotairstenter.com/product/hot-air-stenter.html

Photo by Licheng with model ZCMD768 - Hot Air Stenter

Electrified Singeing Process

Conventional Scenario

Singeing is a preparation method for textiles; it is applied more commonly to woven textiles and cotton yarns where a clean surface is essential. Singeing in textiles is a mechanical treatment or finish to obtain a neat surface of the fabric or less hairy yarn. In a singeing machine, the yarns or fabrics are exposed to direct flames or to the heated plates to burn the protruding fibers.

Working Principle

Conventional singeing machines use heat from fuel combustion to remove fluff. However, this heat can also be provided through electrical energy. Electric cylinder singeing machines use high-temperature industrial electrical heating elements (such as silicon carbide rods) as heating sources. Silicon carbide heating rods are high-temperature, non-metal electrical heating elements that have many advantages over other metal elements, such as a high working temperature, oxidation resistance, longer life, and corrosion resistance.

Compatibility

The electrified singeing process is a completely new process and it cannot be retrofitted with the existing technology.

Technology Readiness Level (TRL)

TRL level of this technology is 8-9 and it is available in some of the countries in the world. HUARUI, China[73] is one of the leading suppliers.

Photo by Huarui

[73] https://textilemachinery.en.made-in-china.com/product/vZFAgcGPnRYC/China-Supply-of-Electric-Heating-Singeing-Machine-Woven-Fabric-Singeing-Machine-Knitted-Fabric-Singeing-Machine-Made-in-China-Hot-Selling-Model.html

Electrified Drying Process

Working Principle

One of the most prominent electrification technologies for the drying process in the textile industry is infrared machines. Infrared heating is radiant heating and it differs from conduction and convection because it transfers heat to objects directly, without heating something else in between (air, water, metal, etc.). Infrared is a proven source of heat in textile processing, as infrared sends high heating power in extremely compact times. This helps to lessen energy consumption, to expand production speeds, and to lower production costs.

Compatibility

The electrified drying process is a completely new process and it cannot be retrofitted with the existing technology.

PLUFIX Electr. Heated Model

Model	Belt Width	Conveyor Infeed & Outfeed	Heat Chamber	Total Lenght	Heating Power	Electrical Requirements	IR Heating Option
PLUFIX Single Belt PLX-1	160 cm (63") 170 cm (67") 180 cm (71") 190 cm (75") 200 cm (79")	1.500 mm (59")	4.800 mm (16')	7.800 mm (26')	48 kW	380 / 415 VAC, 3 ph, 80 A, 50/60 Hz, 52 kW	9 kW
PLUFIX Double Belt PLX-2	2 x 81 cm (32") 2 x 91 cm (36") 81 cm + 121 cm (32") + (48")	1.500 mm (59")	4.800 mm (16')	7.800 mm (26')	48 kW	380 / 415 VAC, 3 ph, 80 A, 50/60 Hz, 52 kW	9 kW

Technology Readiness Level (TRL)

TRL level of this technology is 8-9 and it is available in some of the country in the world. Ansal, Turkey[74] is one of the leading suppliers.

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand of production

Production demand projection for the textile sector is derived based on the correlation between the GDP, manufacturing growth rate projection and past trends of annual production of textiles. The detailed list of assumptions and values is annexed in Annex 1.

Production Demand

Year	2020	2030	2050	2070
Production (Million tonnes)	6.1	8.4	16.9	19.9

Suitable technology mix

Technologies are evaluated primarily based on their TRL level and potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated, considering India's target of net zero by 2070.

The purpose of technologies like electric boilers and heat pumps is the same, i.e., to generate steam or to generate hot water to meet the thermal energy requirement of the textile manufacturing process.

[74] http://www.textiledryer.com/blog/plufix

The electrode boiler is fairly at an advanced stage of commercialisation than heat pumps, so initially, the penetration of electric boilers is estimated at a fast pace, i.e., 30% by 2030 and 70% by 2050, and in the last timeline, 2070, there is 0% penetration of electric boiler. On the other hand, the penetration of heat pumps is increasing in the projected timeline. It is estimated to penetrate 10% by 2030, 30% by 2050, and 100% by 2070.

Similarly, other technologies like electric drying, electric stenter, and electric thermic fluid heaters are all direct electrification technologies and TRL is in the range of 7-9. So, the penetration of the above mentioned technologies is based upon its readiness level and commercialisation. Corelation between production share and penetration of technology is presented in the image shown below. The image shown below represents that the textile sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector.

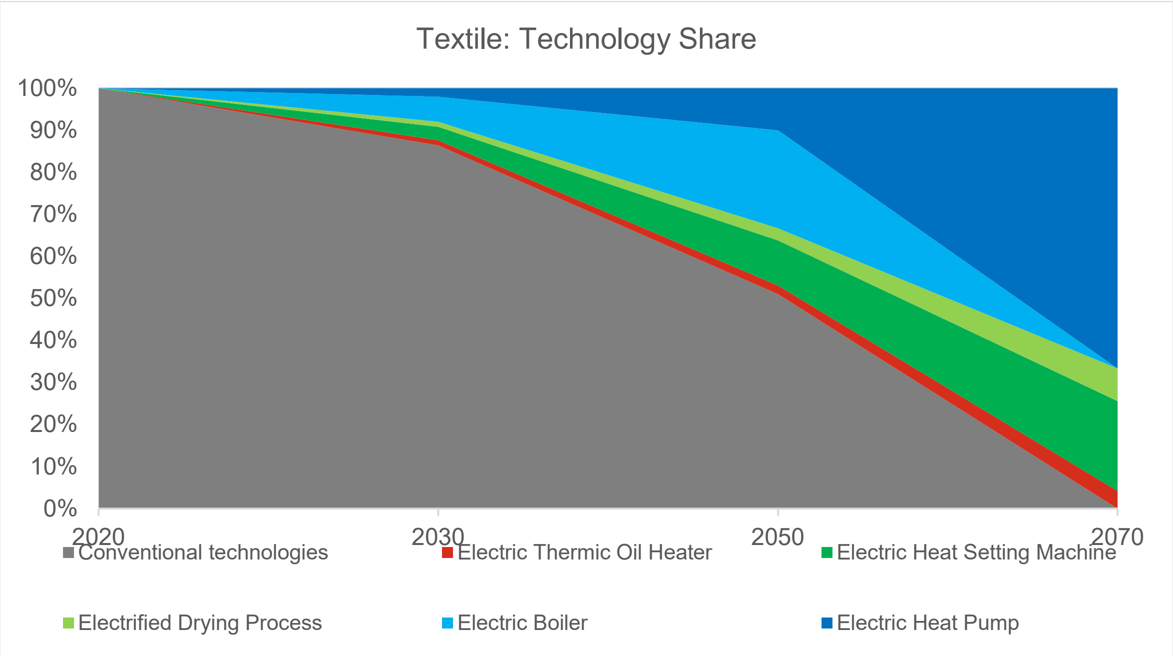


Figure 66: Penetration level of technol/ogies (Ambitious Scenario)

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration of each technology varies depending on the scenarios: effort of implementation resulting a change in energy consumption in each scenario.

Table 12: Projected energy requirement (Mtoe) till 2070 in different scenarios

Scenarios ↓ / Year →	2030	2050	2070
BAU	7	13	16
Conservative	6	11	9
Moderate	6	11	9
Ambitious	6	10	9

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **9 GW** by 2030, **36 GW** by 2050 and **25 GW** by 2070. Whereas the renewable energy requirement for the sector is depicted in the table shown below. Additional battery storage capacity is also estimated to meet the demand on one day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.9 - 2.6 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 13: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	3	21	25
Moderate	5	28	25
Ambitious	9	36	25

Table 14: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	0.9	10.8	17.6
Moderate	1.4	14.2	17.6
Ambitious	2.5	18.7	17.6

Projected GHG emission reduction

The total GHG emissions for this sub-sector under industries is estimated to reach 33 million tonnes CO_{2e} in 2030, 67 million tonnes CO_{2e} in 2050 and 79 million tonnes CO_{2e} in 2070 in the base scenario. Under the ambitious scenario, it is estimated to be 0 in 2070, 41 million tonnes CO_{2e} in 2050, and 26 million tonnes CO_{2e} in 2030. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

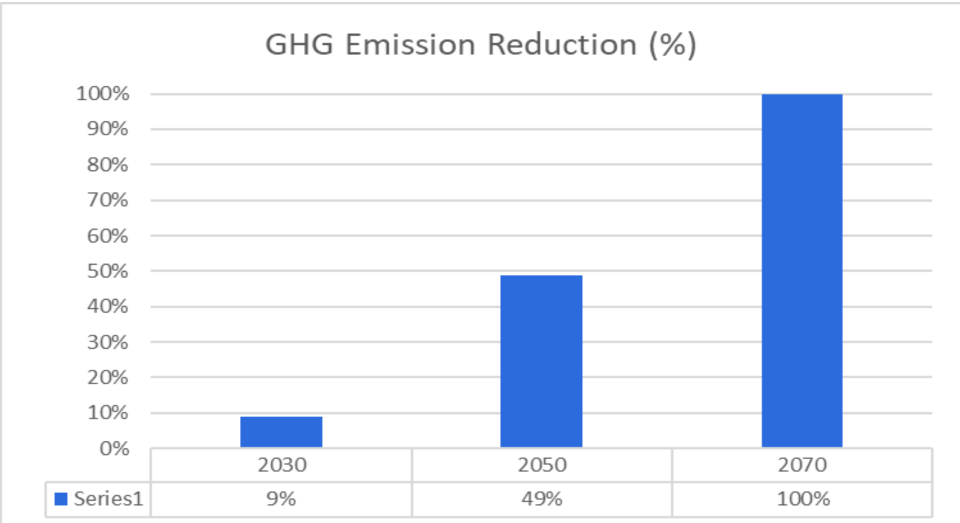


Figure 67: GHG Emissions Reduction (Ambitious)

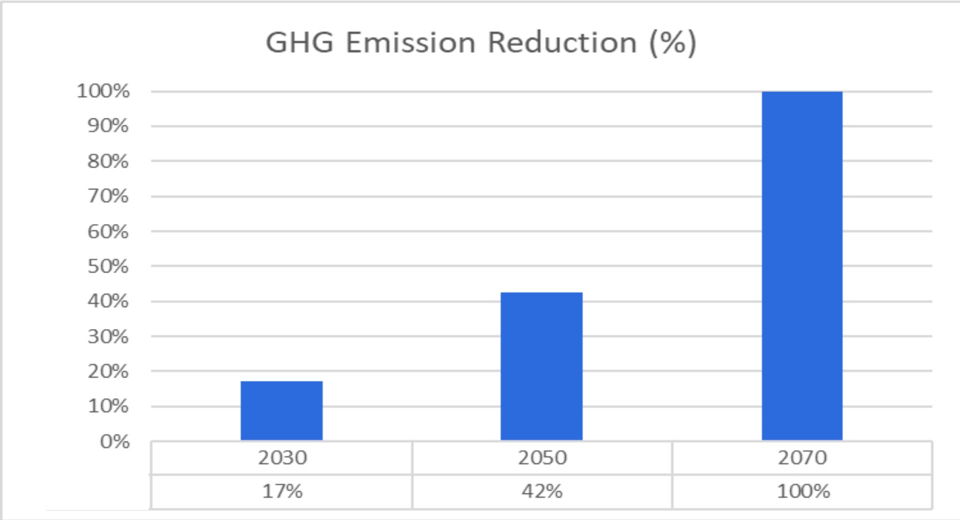


Figure 68: GHG Emissions Reduction (Moderate)

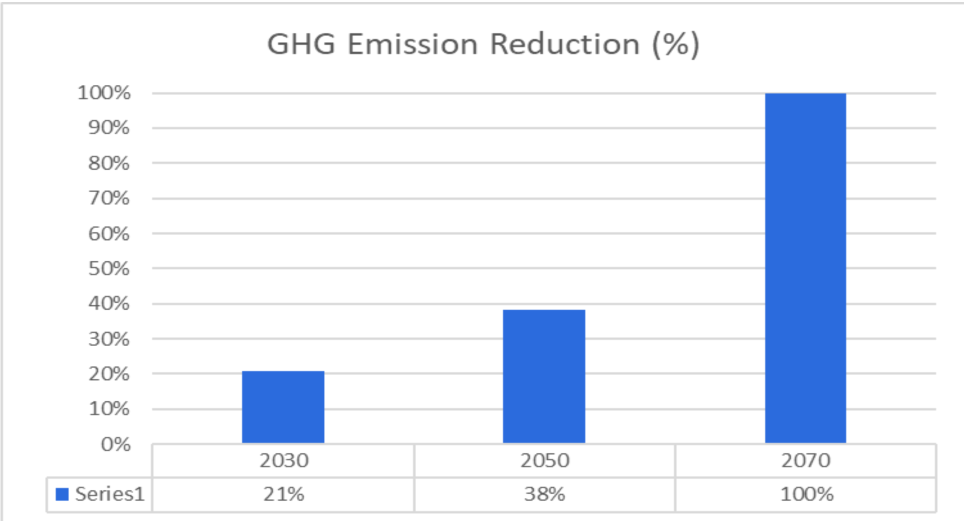


Figure 69: GHG Emissions Reduction (Conservative)

2.8 Electrification of Brick Sector

Electric kiln technology will completely replace the conventional kilns in the brick sector in 2070 in the electrification scenario. With the deployment of this technology, 100% of the energy consumption of the sector can be electrified from the existing 0% level. This implementation would result in a drop in the energy consumption of the sector by 24%, i.e., from 68 Mtoe in the base scenario to 50 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in

50 Mtoe of Energy Demand by 2070 from the sector

Reduction of **312 Mn tonne CO_{2e}** by 2070

Power demand of **146 GW** by 2070

Requirement of **166 GWh** of battery storage capacity by 2070

GHG emissions: 2% by 2030, 33% by 2050 and 100% by 2070. Key findings of the ambitious scenario of the model are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

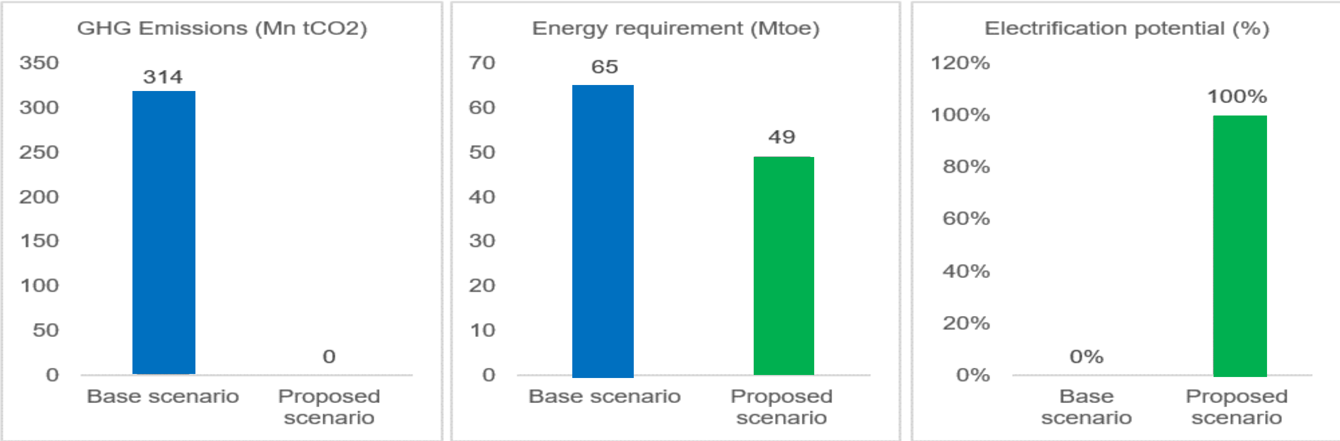


Figure 70: GHG emissions, energy requirement and electrification potential in proposed scenario

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e.level of efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[76].

SECTOR OVERVIEW

India is the second-largest brick producer in the world, producing 250 to 300 billion bricks annually (or 440 to 530 million m^3). The demand for bricks is anticipated to expand by three to four times over the next 20 years, reaching 750–1000 billion bricks per year due to the significant projected growth in the building stock in India. Over 10 million people can find seasonal work in the sector, which provides nearly 0.7% of the nation's GDP[77]. The growing brick sector also has a significant impact on other economic sectors like transportation and construction. Brick kilns[78] globally use 375,000,000 tonnes of coal annually, and India ranks third on the list.

Since 6000 B.C., bricks have been made by combining crushed clay with water, shaping the mixture into the appropriate shape and size, drying it, and then firing it at a temperature of about 1100 degrees Celsius to give it resilience and weather resistance. The clay produces bricks with varied densities, strengths, water absorption, and thermal conductivity depending on its mineral content and geological distribution. FCBKT is the most widely used traditional technology in India.

This traditional method of making bricks has an impact on the environment since it releases greenhouse gases (GHG) when fuel is burned in brick kilns, which causes climate change and raises questions about the exploitation of clay and topsoil. There are more recent man-made materials that have an emphasis on either aesthetics, upkeep, building time or effort, etc. The emphasis on immediate benefits, such as cost savings, frequently ignores factors like thermal comfort or the long-term sustainability of new technology, such as end-of-life difficulties. The utilization of clay bricks

[76] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections
[77] https://beeindia.gov.in/sites/default/files/Brick%20Sector%20Market%20Transformation%20Blueprint_BEE%281%29.pdf
[78] https://hablakilns.com/the-brick-industry/the-brick-market/

has evolved during the past ten years, resulting in less energy and clay consumed. The newly developed clay product, often hollow and perforated clay bricks and blocks, has lower densities & uses less clay and energy.

With the potential to lead India towards a more sustainable route for infrastructure development, a technical transformation of conventional solid bricks to porous and hollow goods would offer both energy and raw material efficiency. Also, hollow and perforated products enable the use of clay other than topsoil, which can be preserved.

To reduce carbon emissions and move towards the carbon economy, a shift from conventional technologies to cutting-edge ones like electric-operated kilns and zig-zag kilns is essential.

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Electric Kiln

Modern Electric energy powered kilns help in providing the solutions for the decarbonization of the energy requirement for the sector. Electric kilns are being operational in the European countries, and electricity can be generated from Solar. RE Hybrid installations or can be wheeled form the RE generators to ensure the carbon neutral energy usages.

Wienerberger has developed a new, CO_2-neutral production line for brick slips with an electric kiln at the Kortemark site in Kortemark, Belgium.

At Kortemark's CO_2-neutral brick slip production is to use new and highly advanced technologies to cut down on material use, implement closed cycles, shorten building industry transportation distances and reduce CO_2 emissions. The new, cutting-edge moulding process is distinct from earlier techniques that created brick slips by slicing bricks, which usually resulted in some waste. The new moulding method is exceptional because it yields soft-mud brick slips with exceptional dimensional stability and accuracy.

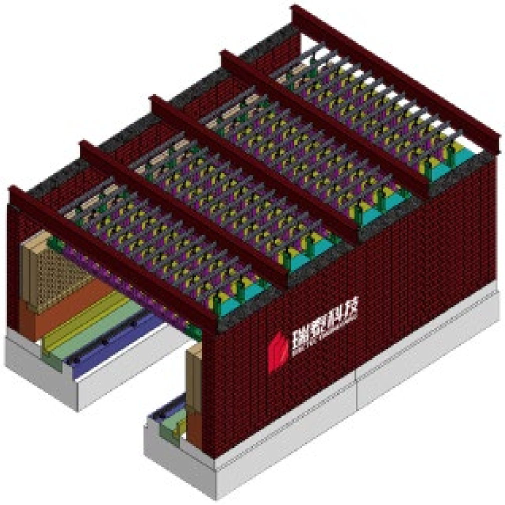


Figure 71: Electric Kiln section

An electrically heated oven is used for the baking of the bricks and thus does not require any other thermal fuel for heating applications. The heating is controlled with automation to ensure the highest quality. The brick slips are perfect for the construction of prefabricated buildings since geometric deviations are prevented. Both the dryer and the kiln run fully on electricity with Wienerberger's system hence no fossil fuel is required.

Technology Readiness Levels (TRL)

Electric brick kiln is a relatively new technology in the Indian context, but globally, there are demonstrations inBelgium and other European countries, and its Technology Readiness Level (TRL) can be commercialized in the other countries range of 6-9 based upon the scale of the kiln operations.

While an electric kiln has been demonstrated to be a promising technology with several potential benefits, further research and development are needed to bring it to a higher TRL level. This includes scaling up the technology to a commercial scale (based upon the small and mid-size brick manufacturing units in the country), optimizing the process for efficiency and cost-effectiveness, and addressing any technical challenges or limitations that may arise.

Energy Efficiency

Electric calcination has been demonstrated to be more energy-efficient compared to traditional calcination processes that use fossil fuels such as natural gas or fuel oil to provide the heat required for the process. The use of electricity as the primary energy source reduces energy consumption and improves the overall efficiency of the process.

There are several factors that contribute to the energy efficiency of electric calcination, including:

- Direct heating - Electric calcination uses direct heating to calcinate the alumina, which is more efficient compared to traditional calcination processes that use indirect heating. Direct heating reduces heat loss and improves the overall efficiency of the process.
- Efficient energy transfer - Electric calcination uses electricity to generate heat, which is transferred directly to the alumina particles. This results in more efficient energy transfer and reduces energy consumption.
- No fuel consumption - Electric calcination does not require the use of fossil fuels, which reduces energy consumption and eliminates the associated emissions and operating costs.
- Renewable energy sources - Electric calcination can be powered by renewable energy sources such as hydropower, wind power, or solar power, which further enhances its energy efficiency and sustainability.

OTHER TECHNOLOGIES

Zigzag Firing Technology

Energy requirement in the Zig Zag kiln is mainly used for irreversible chemical reactions and losses such as trench bottom, periodic heating and cooling of kiln structure and due to un-burnt carbon in ash. Other uses are removal of the water in the brick and losses from the furnace. SEC[79] for the optimally operated ZIG-ZAG kiln lies in the range of 1150-1250 MJ/ tonne of the fire clay. Details of the energy consumption are presented next.

[79] https://sidhiee.beeindia.gov.in/pdf/bricks/6.pdf

Processes / Losses	Energy consumption (MJ/tonne of fired clay)
Heat required for removal of mechanically held water in green bricks	86
Surface heat loss from kiln	120
Heat loss in flue gases	130
Heat loss due to partial conversion of C to CO	6
Sensible heat loss in unloaded bricks	10
Irreversible chemical reaction and kiln structure	803

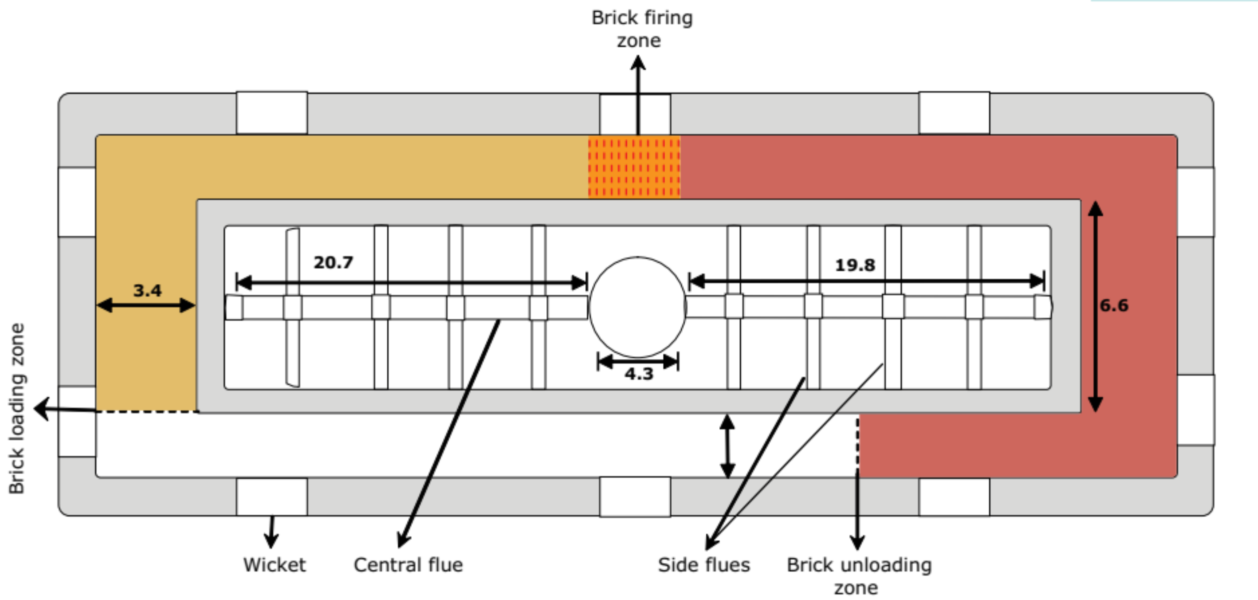


Figure 72: Schematic of the Zig -Zag Kiln (BEE Demonstration in Varanasi) [80]

Conventional kilns require the energy in range of 1400-2500 MJ/tonne based upon the scale of operations and type of the technologies. Adopting this technology will help the in reduction of the 15-30% of the energy consumption.

BEE Varanasi Case Study (Brick manufacturing 3lakh/ month)

Investment required for retrofitting 15.4 Lakh INR

Total monetary savings annually 25.8 Lakh INR

Simple Pay back 7-8 months

[80] https://beeindia.gov.in/sites/default/files/Case%20Study%20-%20Varanasi%20Cluster_0.pdf

K-Brick manufacturing

K-Brick creates a tenth of the CO2 emissions of a traditional burnt brick and uses less than a tenth of the energy in its production because it is created from over 90% recycled demolition and building waste materials. This process does not involve cooking bricks at 1200 degrees centigrade. Therefore, it has < 5% carbon footprint of a traditional clay brick. K-bricks may be made in seconds, whereas clay bricks take 10 to 40 hours. K-brick also helps improving energy efficiency and promotes the circular economy.

Photo by KHL Group

Company - Kenoteq (Scotland). The K-Brick is in its final stages of BBA certification in the UK allowing its commercial use from Spring 2023. Its Environmental Product Declaration (EPD) certificate and Design Guide will also be available in the coming years.

To reduce energy needs, it is crucial to choose building materials that naturally regulate temperature. Because of this, the K-Brick was designed with a large thermal mass that retains heat in the winter and keeps buildings cool in the hotter summers, lowering the cost of heating and cooling the finished construction.

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for production

Production demand projection for the brick sector is derived based on the correlation between the GDP, manufacturing growth rate projection and past trends of the annual production of textiles. The detailed list of assumptions and values is annexed in Annex 1.

Production Demand

Year	2020	2030	2050	2070
Production (Million tonnes)	840	1315	3018	3625

Suitable technology mix

Technology like electric kilns is the only technology that would directly electrify the sector. The electric kiln has been successfully deployed in European countries and it is commercially available also. In India, the brick sector is highly unorganised and small. Therefore, the penetration of kilns in the near term scenario, i.e., 2030, is estimated to be 0%. Its penetration is expected to start from 2050 and by 2070, it can completely replicate all the other technologies. Corelation between technology share and penetration of technology is presented in the image shown below. The image shown below represents that the brick sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector.

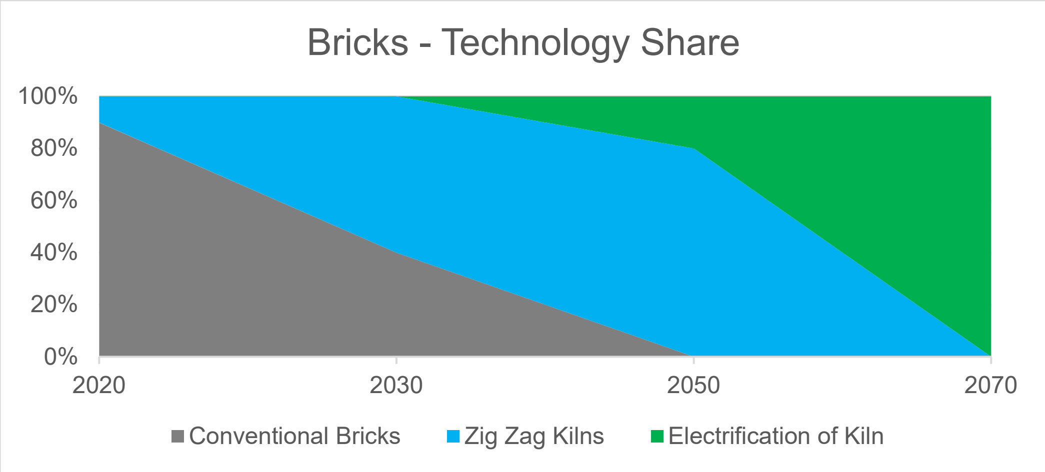


Figure 73: Penetration level of technologies (Ambitious Scenario)

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration of each technology varies depending on the scenarios: the effort of implementation resulting in the change in energy consumption in each scenario.

Table 15: Projected energy requirement (Mtoe) till 2070 in different scenarios

Conservative Scenario

Scenarios ↓ / Year →	2030	2050	2070
BAU	25	57	68
Conservative	24	45	50
Moderate	23	45	50
Ambitious	22	45	50

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based source of electricity. In the ambitious scenario, the power installation requirement for the sector would be **10 GW** by 2030, and it is expected to increase by **52 GW, 146 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **5-6 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 16: Projected RE hybrid (GW) requirements till 2070 [81]

Scenarios ↓ / Year →	2030	2050	2070
Conservative	7	43	146
Moderate	7	48	146
Ambitious	7	51	146

[81] *Projected at 45% PLF*

Table 17: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	5.7	37	166
Moderate	5.6	41	166
Ambitious	5.2	44	166

Projected GHG emission reduction

The total GHG emissions for this sub-sector under industries are estimated to reach 113.8 million tonnes CO_{2e} by 2030, 259.7 million tonnes CO_{2e} by 2050, and 479 million tonnes CO_{2e} by 2070 in the base scenario. Under the ambitious scenario, it is estimated to be 0 in 2070, 177 million tonnes CO_{2e} in 2050, and 118 million tonnes CO_{2e} in 2030. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

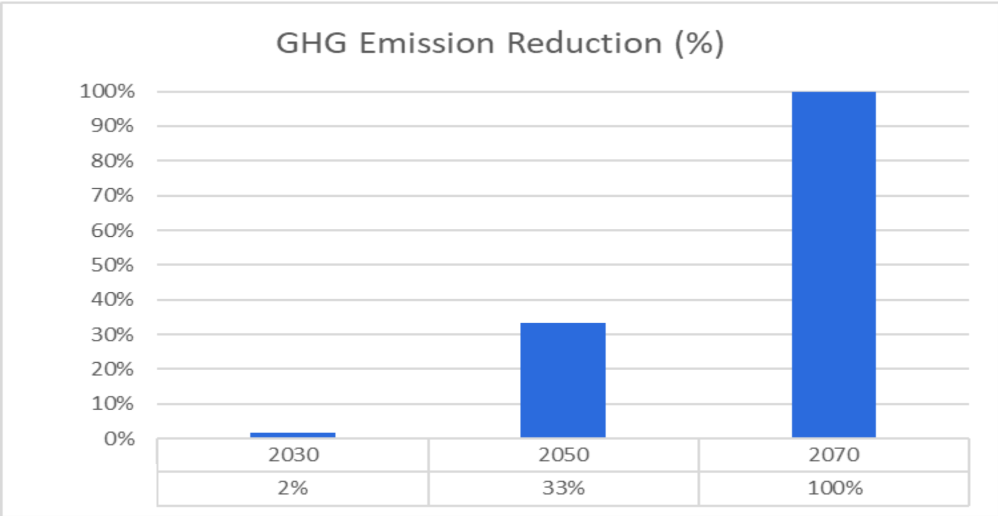


Figure 74: GHG Emissions Reduction (Ambitious - Bricks)

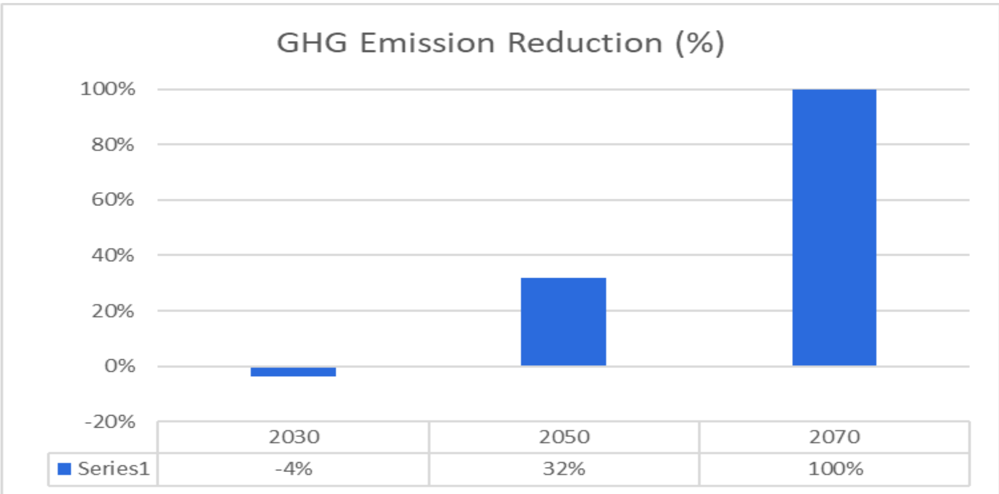


Figure 75: GHG Emissions Reduction (Moderate - Bricks)

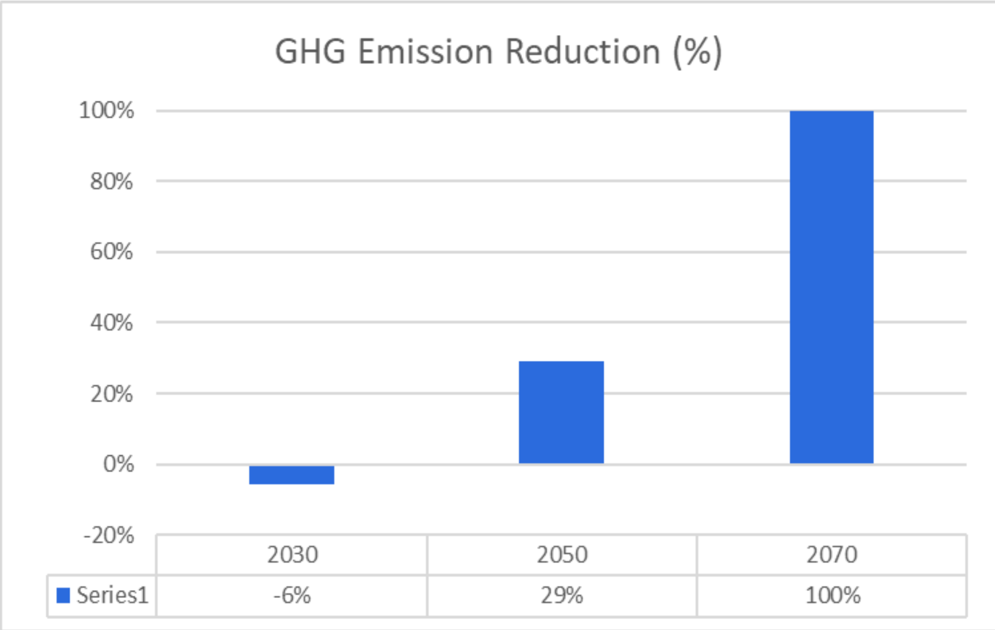


Figure 76: GHG Emissions Reduction (Conservative - Bricks)

2.9 Electrification of MSMEs & Others (Non-specified Industry)

SUMMARY

The MSME (micro, small and medium enterprises) sector, is a heterogeneous sector in terms of the products manufactured, sizes, manufacturing processes, output and technology used in manufacturing. MSMEs engaged in manufacturing account for about 33%[82] of India's manufacturing output and around 28% contribution to the GDP as a whole. The MSME sector accounts for a quarter of the total industrial energy consumption in India.[83] They are the backbone of the OEMs and with the projected growth in the large industries sector, the MSMEs are also projected to grow in terms of their economic output. MSMEs typically are characterised by a high degree of heterogeneity within the manufacturing processes across various geographic locations, even for similar product offerings.

The MSMEs in India are around Sixty-Three million – and a majority of them have not implemented any energy efficiency (or) decarbonisation technology measures since they commissioned and continue to depend on obsolete, low-efficiency technologies that result in wasteful energy consumption, also reducing profitability and competitiveness of MSMEs sector in India. The sector holds immense potential in fostering energy efficiency and upgradation to decarbonisation technologies in routine processes.

In this section, we have covered all the MSMEs and non-specified industries, industrial sectors covered I this section are ceramics, machine tools, brass, lime kilns, secondary steel, tiles, refractories, petrochemicals, refineries, automotive, pharma, consumer durables, defence manufacturing, electronics manufacturing, real estate construction, oil and gas, mining, and telecom. There is a dire need to decarbonise the industrial sector by decoupling the sectoral growth and sectoral carbon footprint. Thermal energy equipment used in the industrial sectors mentioned above is generally fossil fuel-based boilers, furnaces, kilns, etc. Electrification technologies such as electric boilers, induction furnaces, and heat pumps, among others, will have a role to play in this decarbonisation. Clean energy fuel substitution, like green hydrogen in place of existing fossil fuels used, will complement the decarbonisation pathway.

With the implementation of the above-mentioned technologies, 85-90% of the energy consumption of the sector can be electrified from the existing level. This implementation would result in a significant drop in the energy consumption of the MSME sector by 22%, i.e., from 310 Mtoe in the base scenario to 241 Mtoe in the ambitious effort scenario. Similarly, there is a reduction in the non-specified industry sector of 27% by 2070 in the ambitious scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions, i.e., a 100% reduction by 2070. Key findings of the ambitious scenario of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

MSME

241 Mtoe of Energy Demand by 2070 from the sector	Reduction of **2200 Mn tonne CO_{2e}** by 2070
Power demand of **619 GW** by 2070	Requirement of **856 GWh** of battery storage capacity by 2070

[82] https://beeindia.gov.in/sites/default/files/Annexure%201.pdf
[83] https://www.oecd.org/environment/cc/cefim/india/roadmap/CEFI-Roadmap-MSME-Energy-Efficiency-Workshop-Summary.pdf

218 Mtoe of Energy Demand by 2070 from the sector

Reduction of **1634 Mn tonne CO_{2e}** by 2070

Power demand of **513 GW** by 2070

Requirement of **1028 GWh** of battery storage capacity by 2070

Others (Non-specified Industry)

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Induction Furnace

The foundry industry supplies products to the automobile, machinery and utility sectors. More than 50% of the existing casting produced in India is through the coke-fired cupola furnace route. As a result, this sector consumes huge quantities of coal, approximately 50% of which is imported ,also leading to significant carbon dioxide emissions. This coke-fired cupola furnace used in the melting process can be replaced with an electric induction furnace. The electric induction furnace is more energy efficient compared to the cupola furnace and produces fewer carbon dioxide emissions as a result of grid electricity use. As the grid is transitioning to greener sources of power, the emissions through induction furnaces will gradually decrease over a period of time.[84]

An Induction Furnace is based on the theory of electromagnetic induction and hence uses the induction heat to heat the metal to its melting point. They can be divided into three types depending on the frequency (50 Hz – 250 kHz), i.e., high frequency, medium frequency, and low frequency type of furnaces. These furnaces are used for the re-melting of iron & steel (steel scrap), copper, aluminium, precious metals and alloys and come in capacities ranging from less than 1kg to 100 MT. This technology has its own advantages and disadvantages, as mentioned below.[85]

Advantages[85]

- As it does not use electrodes and electric arcs the production of steel and alloys is low in carbon and occluded gases and hence is without any quality problem.
- Melting losses are low.
- Less alloying elements are needed
- High power efficiency and hence cost-effective
- Precise control over operating parameters

Disadvantages[85]

- Refining in an induction furnace is less effective compared to an electric arc furnace (EAF)
- The life of refractory lining is low as compared to EAF
- Removal of S & P is limited, so selection of charges with less impurity is required.

Global Best Practice Examples[Error! Bookmark not defined.]

[84] https://www.teriin.org/sites/default/files/2021-07/potential-for-electrifying-Indian-msme.pdf
[85] https://www.idc-online.com/technical_references/pdfs/mechanical_engineering/Induction_Furnace.pdf

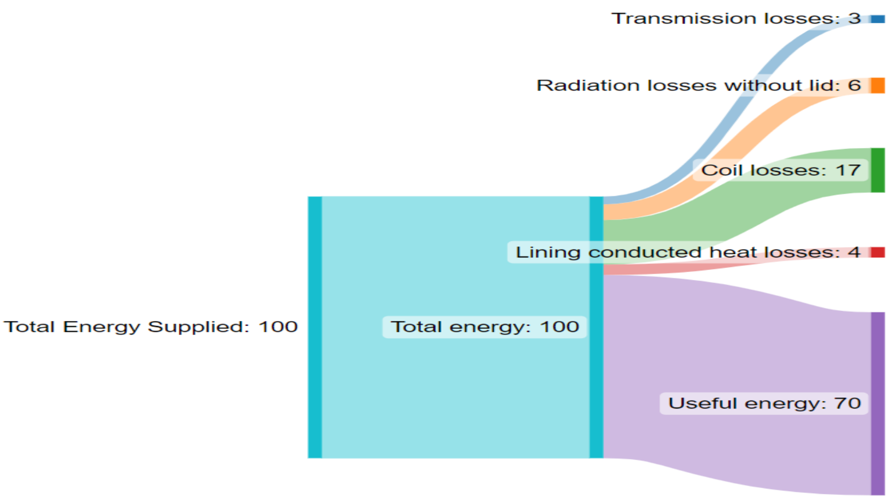
A foundry unit in Kolhapur, India manufactures graded cast iron castings. The unit produces about 1976 tonnes of castings per annum and has an annual energy bill of Rs 174 lakhs. The unit replaced its inefficient, small-capacity cupola furnace with a 1250 kW induction furnace having a crucible capacity of 500 kg, 1500 kg and 2500 kg and capable of supplying power to all three crucibles at the same time. The specific energy consumption of the melting operation was reduced by 53% post-implementation of the induction furnace. Additionally, the GHG savings from this intervention are about 265 tonnes CO_2 per year. The simple payback period for this investment was 2.1 years.

Figure 77: Energy efficient induction furnace in foundry unit in Kolhapur, India[1]

Technology Readiness Level

This technology is commercial and in use in many foundries. Hence, the TRL for this technology is considered at 9.

Energy Efficiency[86]



The energy loss in a typical induction furnace is in the range of 100 to 130 kWh per tonne. In old models of induction furnaces, the furnace efficiency comes out at around 65 – 75%. However, with the development of energy efficient coils, new refractory material, reduction of converter losses and reduction in transformer losses, the energy losses in state-of-the-art furnaces are reduced to 60 to 90 kWh per tonne. Hence, the new furnaces have an efficiency between 81 – 87 %.

Compatibility with currently used technologies

The existing cupola furnace needs to be completely replaced with a new induction furnace. Using an induction furnace for melting operation will demand a reliable power supply.

Electric Boiler/ Heat Pump

A detailed description of the technologies is explained in section *8.1 Cross-cutting technologies.*

Compatibility with currently used technologies

A large number of MSMEs rely on conventional boilers, which generate heat using coal, natural gas, oil, etc. These steam boilers can be replaced with Electric Boilers. There is a demand for low-

[86] *https://beeindia.gov.in/sites/default/files/BOP-Belgaum.pdf*

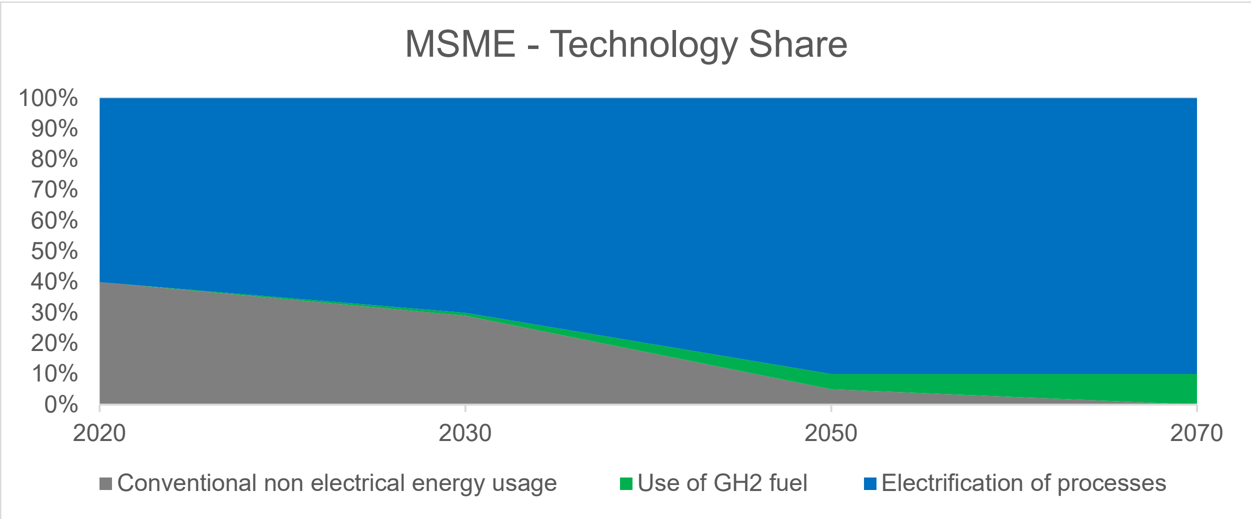
temperature process heat in industries such as paper, food, chemicals, etc. Industrial Heat Pumps can be used for these applications.

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

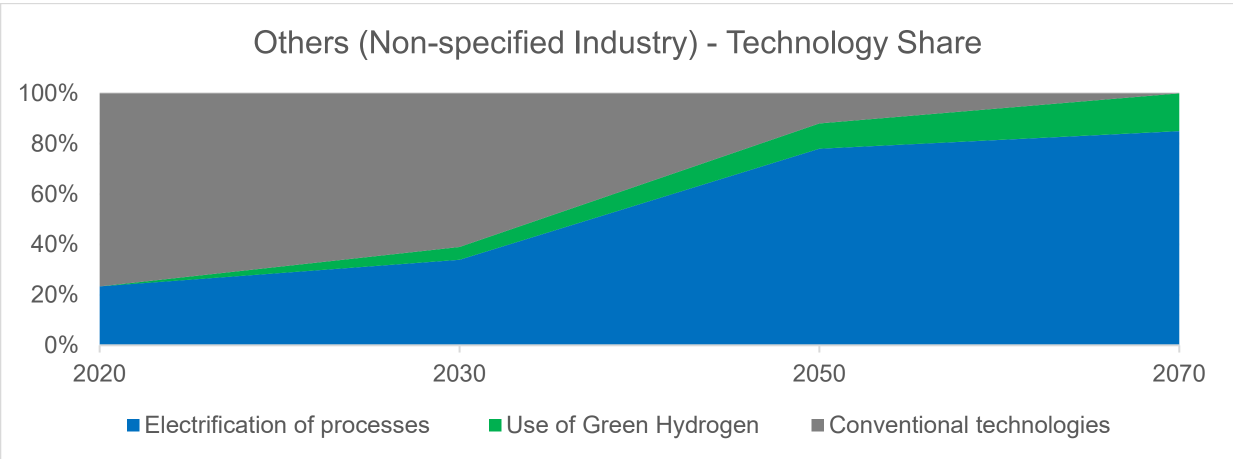
Suitable technology mix

Technologies are evaluated primarily based on their TRL level potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated, considering India's target of net zero by 2070. Corelation between technology share and penetration of technology is presented in the image shown below. The image shown below represents that MSME and other non-specified industry sectors can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector to an extent of 85-90% of the total sectoral energy consumption.

MSME



Others (Non-specified Industry)



Projected Energy Consumption for Decarbonisation

The energy consumption until 2070 in the base scenario is estimated by considering a year-on-year growth same as the MSME and other sector' growth in past years. Energy consumption is also projected, considering the scenario of decarbonisation (conservative, moderate and ambitious).

Penetration of each technology varies depending on the scenarios, i.e., the effort of implementation resulting in a change in energy consumption in each scenario.

MSME

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	75	130	241

In the conservative scenario, efforts to penetrate the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050, and 100% by 2070. The energy demand of the chemical sector would reduce by 1% in 2030, 16% in 2050, and 22% in 2070 over the base scenario.

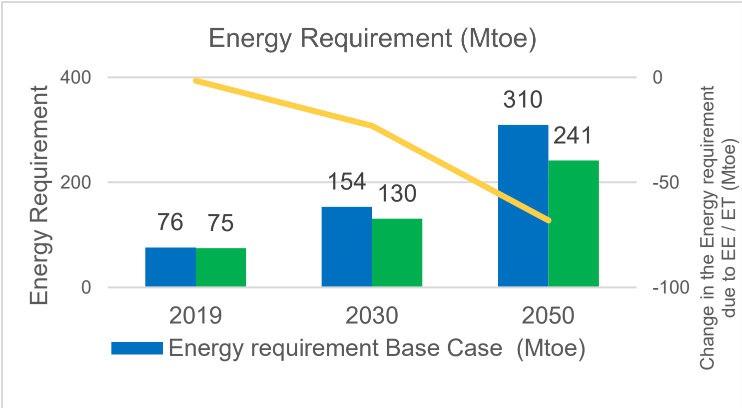


Figure 78: Energy requirement (Conservative - MSME)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	74	124	241

In the moderate scenario, efforts to penetrate the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. The reduction in energy demand of the MSME sector would be the same as that of the conservative scenario for the year 2070.

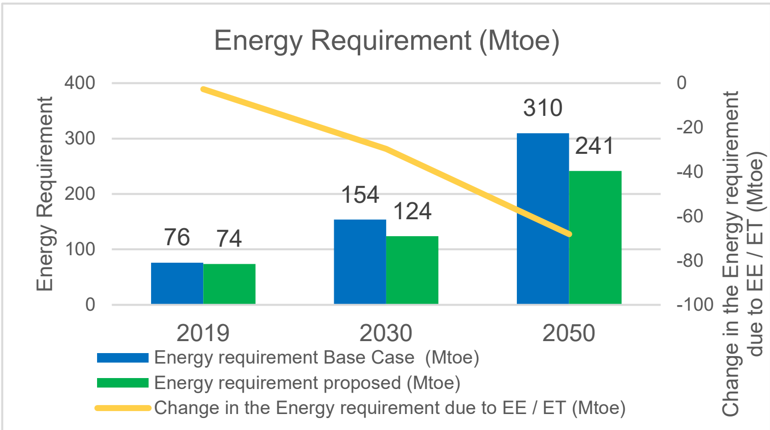


Figure 79: Energy requirement (Moderate - MSME)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	57	112	225

In the ambitious scenario, efforts to penetrate the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050, and 100% by 2070. Reduction in energy demand of the MSME sector would be the same as that of the conservative and moderate scenarios for the year 2070.

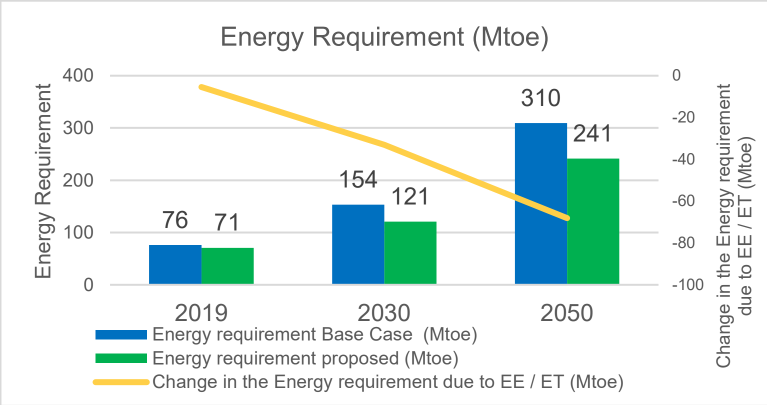


Figure 80: Energy requirement (Ambitious - MSME)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **257 GW** by 2030, and it is expected to increase by **860 GW, 1132 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **91-94 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

MSME

Table 18: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	94	374	619
Moderate	103	386	619
Ambitious	106	395	619

Table 19: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	91	391	856
Moderate	92	402	856
Ambitious	94	407	856

Others (Non-specified Industry)

Table 20: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	51	367	513
Moderate	62	423	513
Ambitious	69	450	513

Table 21: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	78	719	1028
Moderate	90	827	1028
Ambitious	99	881	1028

Projected GHG emission reduction

The total GHG emissions for the MSME and anon-specified industry sector are estimated to reach 1138 million tonnes CO_{2e}, 2306 million tonnes CO_{2e}, and 3834 million tonnes CO_{2e} for years 2030, 2050, and 2070, respectively, in the BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the production would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

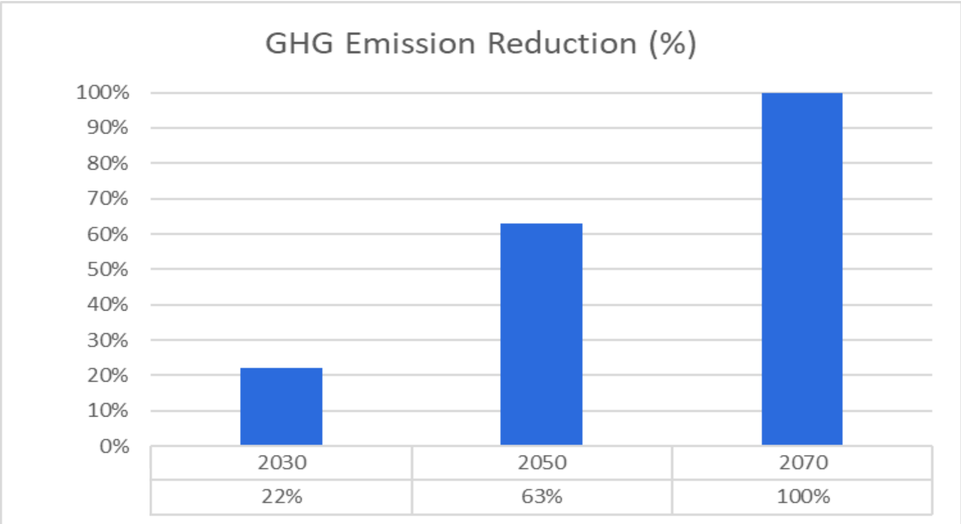


Figure 81: GHG emission reduction (Ambitious – MSME)

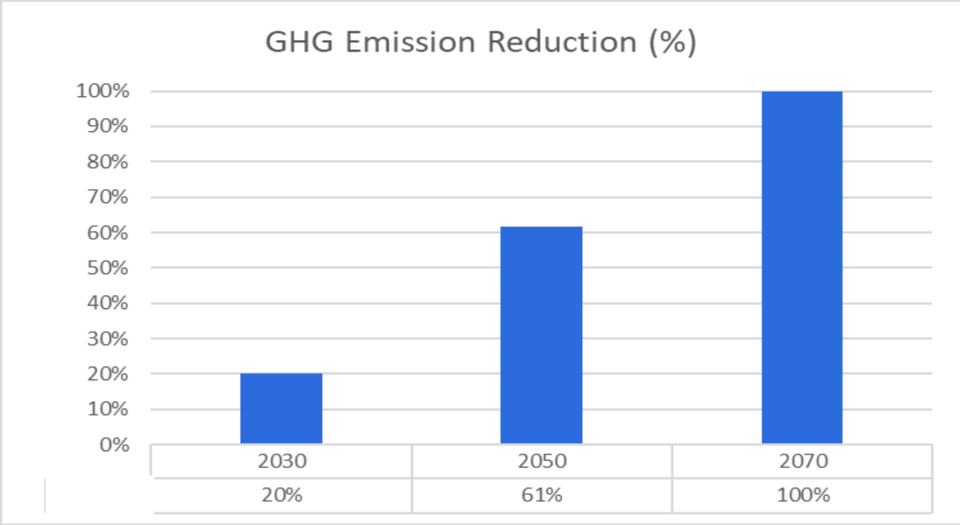


Figure 82: GHG emission reduction (Moderate – MSME)

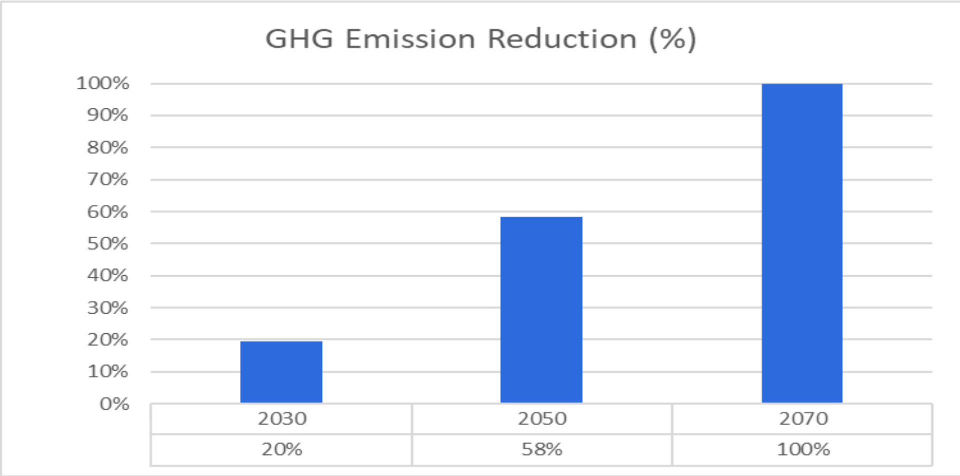


Figure 83: GHG emission reduction (Conservative – MSME)

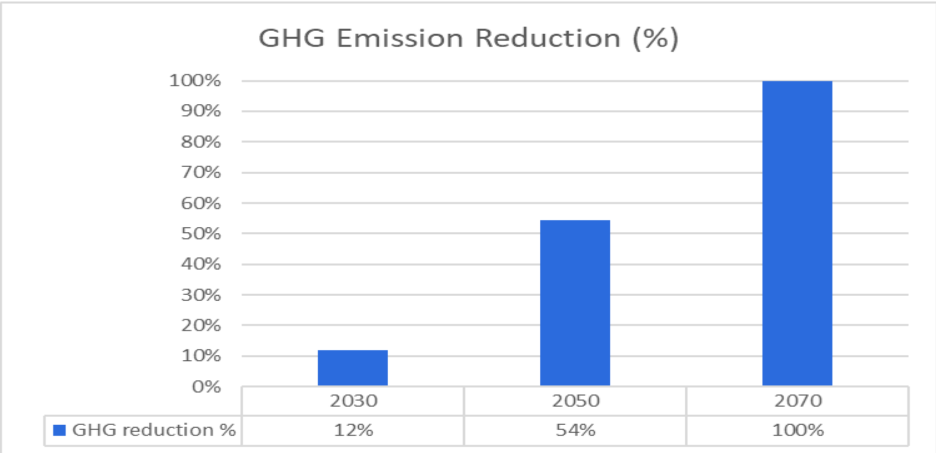


Figure 84: GHG emission reduction (Ambitious – Others)

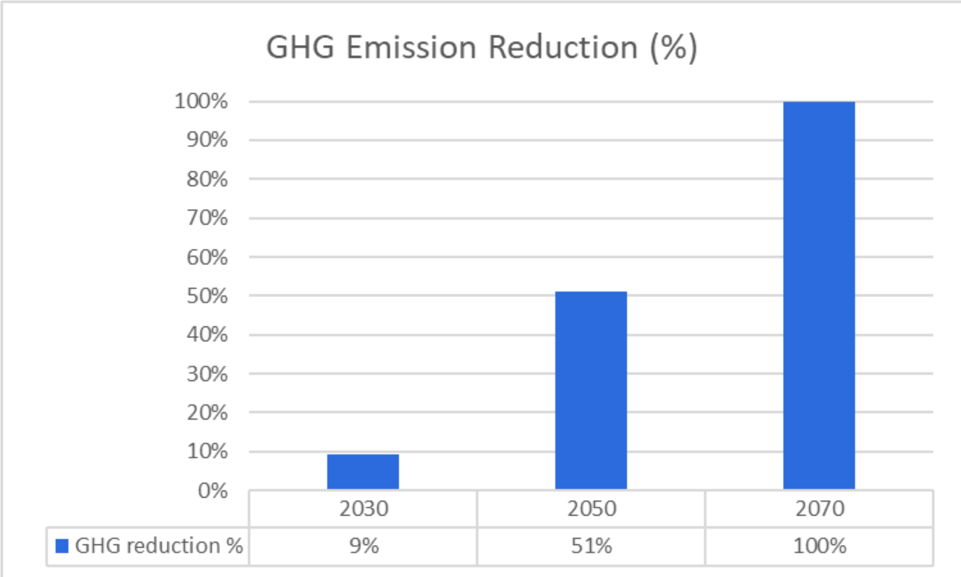


Figure 85: GHG emission reduction (Moderate – Others)

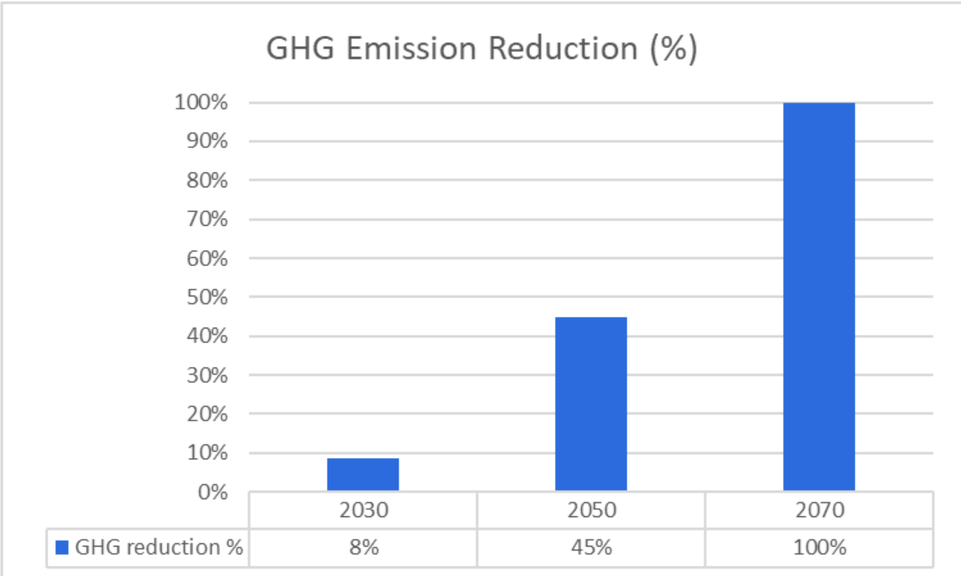


Figure 86: GHG emission reduction (Conservative – Others)

3 Electrification of Agriculture

3.1 Electrification of Fertiliser Sector

Existing Goals

The Fertiliser sector had a share of 57% in the total hydrogen demand in 2020 (NITI Aayog). At present, the hydrogen production for ammonia is fossil fuel based with natural gas and coal as the raw materials for feedstock. However, the domestic production of natural gas is unable to meet the demand, and hence, India imported natural gas worth INR 58,328.94[87] crore in FY 22, a share of which is used by the fertiliser industry. In addition, India imported 2.3 MMT of ammonia and 9.3 MMT of ammonia in the form of imported fertilisers, together which accounted for a share of 42% in the total ammonia use in India in FY 22 (Fertiliser Association of India). To achieve net zero targets and reduce hydrogen and ammonia imports, the Government of India launched the Hydrogen Policy, with proposed targets of 15% of the fertiliser production in 2025 and 70% of the fertiliser production in 2035 to be from green hydrogen.

Potential (%) for net zero through electrification

The fertiliser sector has the potential to transition to 100% electrified production by 2040 from the existing 2% level of electrification. The major contribution will be through replacing the steam methane reforming sub-process used for producing hydrogen, which is a significant consumer of fossil fuels at present, with green hydrogen. The fossil fuel-based hydrogen production can be replaced by electrolysis-based hydrogen gas production.

Electrolysis technologies like Alkaline Electrolysers and Polymer Electrode Membrane (PEM) Electrolysers will have a major role to play in this transition as these are mature technologies. Subsequently, technologies such as Solid Oxide Electrolyser Cell (SOEC) and Anion Exchange Membrane (AEM) electrolysers will supplement this electrolysis based hydrogen transition.

With the implementation of the above-mentioned technologies, 100% of the energy consumption of the sector can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 18.3%, i.e., from 29 Mtoe in the base scenario to 24 Mtoe by 2070 in the ambitious effort scenario. Reduction in energy consumption would also lead to reduction in GHG emission: 6.7% by 2050 and 100% by 2070. Key findings of the ambitious scenario of the model are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

24 Mtoe of Energy Demand by 2070 from the sector

Reduction of **91.6 Mn tonne CO_{2e}** by 2070

Power demand of **81 GW** by 2070

Requirement of **48 GWh** of battery storage capacity by 2070

[87] *Ministry of Commerce and Industry*

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e. level of efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[88].

Figure 87: GHG emissions, energy requirement and electrification potential in proposed scenario

PROCESS FLOW

In India, urea dominates fertiliser production with a 65% share in the total production, followed by diammonium phosphate (DAP) at 10% and complex fertilisers such as ammonium nitrate, ammonium phosphate, nitro-phosphate-potash and muriate of potash (MOP) at 25% (WRI). Urea requires 570 kg[89] of ammonia for 1 tonne of production, whereas DAP requires 200 kg of ammonia.

The conventional method of manufacturing fertilisers such as urea and DAP involves three basic steps: production of hydrogen from methane source, production of ammonia from hydrogen, and production of fertiliser from ammonia.

Hydrogen Production through Steam-Methane Reforming

In this step, a source of methane, such as natural gas, undergoes a reaction with steam at temperatures between 700°C to 1,000°C in the presence of air to produce hydrogen gas (H_2) along with carbon monoxide (CO) and a small amount of carbon dioxide (CO_2). The waste heat produced in this reaction is utilised for feedstock preheating and steam generation. To generate energy needed to drive the reaction, there is a need to burn a portion of methane. The next step is to convert the CO to CO_2 and H_2 through a water gas shift reaction.

$$CO + H_2O \xrightarrow{700°C \text{ to } 1000°C} CO_2 + H_2 + \text{small amount of heat}$$

The CO_2 from syngas is then removed through CO_2 stripper either by the Benfield method or the MDEA (methyl di-ethanol amine) process. This CO_2 is either supplied to the urea plant as a feedstock or is released into the atmosphere. The CO and CO_2 gas eventually left is converted to methane as they both are hazardous for catalysts used in ammonia synthesis.

[88] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections
[89] https://wri-india.org/blog/emission-reduction-potential-green-hydrogen-ammonia-synthesis-fertilizer-industry#:~:text=Each%20ton%20of%20ammonia%20production,naphtha%2C%20or%20coal%20are%20employed.

The steam methane reforming reaction is endothermic and is therefore favoured by a higher temperature. Typical reformer outlet temperatures fall in the range of 810–900°C. As the temperature increases, the hydrogen yield increases, which is observed as a reduction in the methane concentration in the reformer effluent, this leads to the occurrence of methane leakage.

Ammonia Production

A mixture of one volume of nitrogen & three volumes of hydrogen compressed to 250 atmosphere and at a temperature of about 500° C in the presence of catalysts such as powdered iron or platinized asbestos are reacted to form ammonia.

$$N_2 + 3H_2 \xrightarrow[\text{Catalyst Fe, Mo}]{500° \text{ C}} 2NH_3 + 24400 \text{ cal.}$$

Urea Production

The carbon dioxide and urea react in a liquid state in a converter at a temperature between 160-200° C and a pressure of about 400 atmospheres. The NH_3 and CO_2, which remain unreacted, are removed with the help of the evaporator still and are again used in the process.

$$2NH_3 + CO_2 \xrightarrow[\text{400 Atm.}]{160\text{-}200° \text{ C}} NH_2COONH_4$$

Ammonium carbamate

The urea solution is then pumped to the crystalliser for cooling and crystallisation. Further, the crystals of urea are centrifuged and dried. The urea solution, which is evaporated to less than 1% moisture, i.e. the molten urea, is sprayed down in a tower against a counter flow of dry air to get pellets or prilled urea.

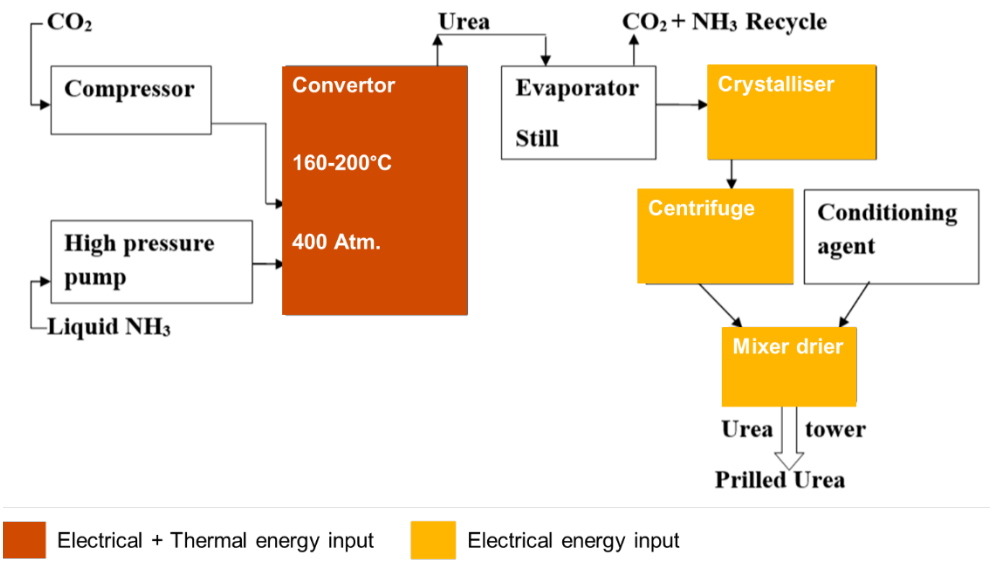


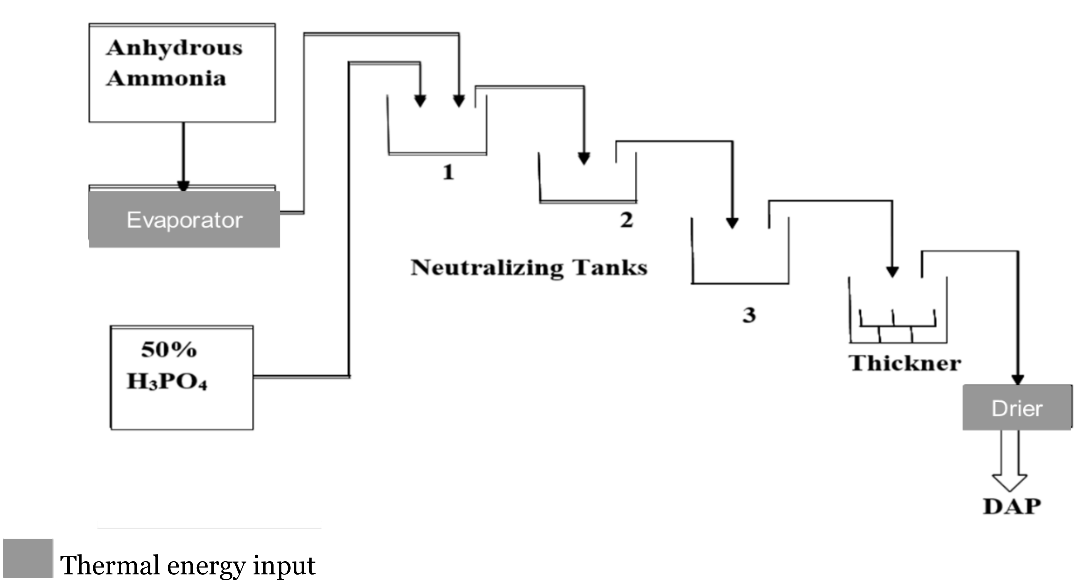
Figure 88: Manufacturing process of urea

Diammonium Phosphate (DAP) Production

DAP is produced by reacting excess amounts of ammonia with phosphoric acid. The phosphoric acid used here is synthesised from rock phosphate and crude phosphoric acid. A series of neutralising tanks, also called as agitators, lined with acid-proof bricks and lead, are used for carrying out the reaction. The DAP slurry produced is converted to paste and an almost solid mass on cooling. The product is further dried and granulated.

$$2NH_3 + H_3PO_4 \longrightarrow (NH_4)_2 HPO_4$$

Ammonia OPA DAP



Thermal energy input

Figure 89: Manufacturing process for diammonium phosphate

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Replacing Natural Gas with Green Hydrogen in Feedstock

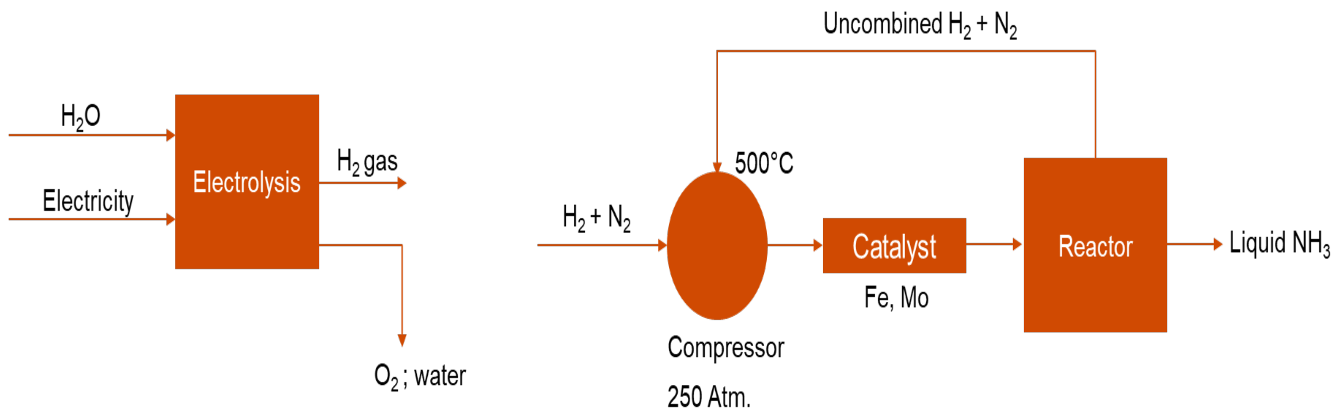
In fertiliser production, the production of ammonia has an approximately 80% share of the total energy consumption. Conventionally, ammonia is produced from fossil fuel-based hydrogen, as discussed above. This hydrogen can be produced through electrolysis, wherein the electricity requirement is met through renewable electricity, resulting in low-emission hydrogen production. The next section describes the types of electrolysers at different stages of commercial development along with their TRL, efficiency, emissions, and cost, among other parameters. Details of the green hydrogen generation and electrolysis process are explained in section *8.1 Cross-cutting technologies*

Electrifying Steam Use

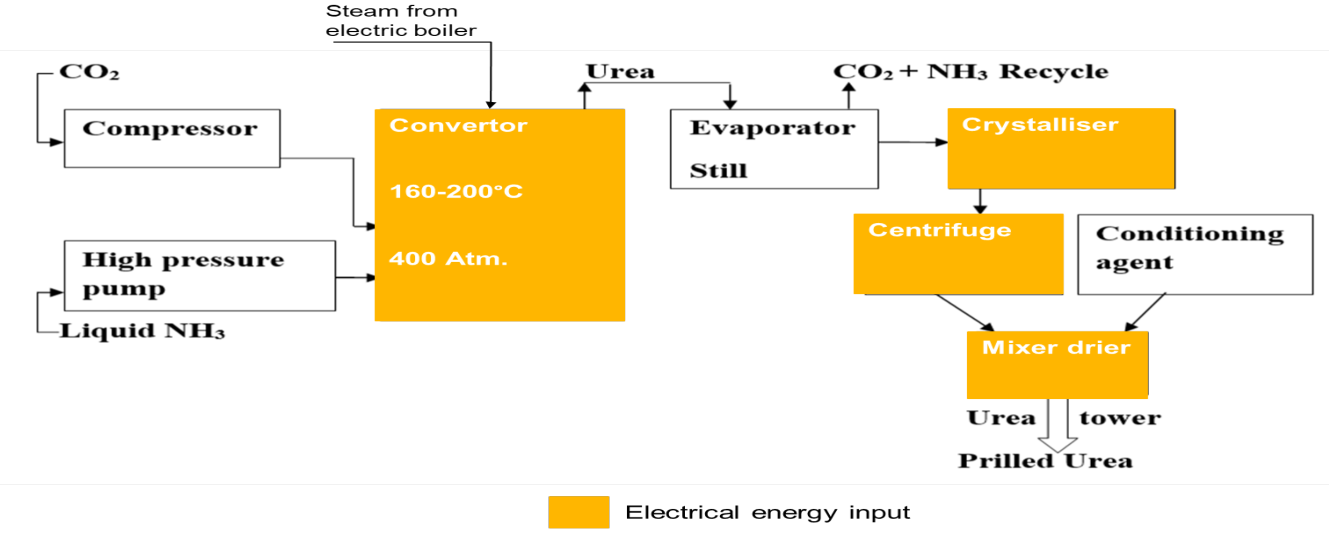
In the case of Urea production, there is a need to maintain the temperature of the converter between 160 to 200 °C, which is done by using steam. Also, in the case of DAP production, the anhydrous ammonia goes through an evaporator to remove the excess water, which also requires steam. This steam requirement in Urea and DAP production can be met through electric boilers. Details of an electric boiler are explained in section *8.1 Cross-cutting technologies.*

Electrification of fertiliser manufacturing

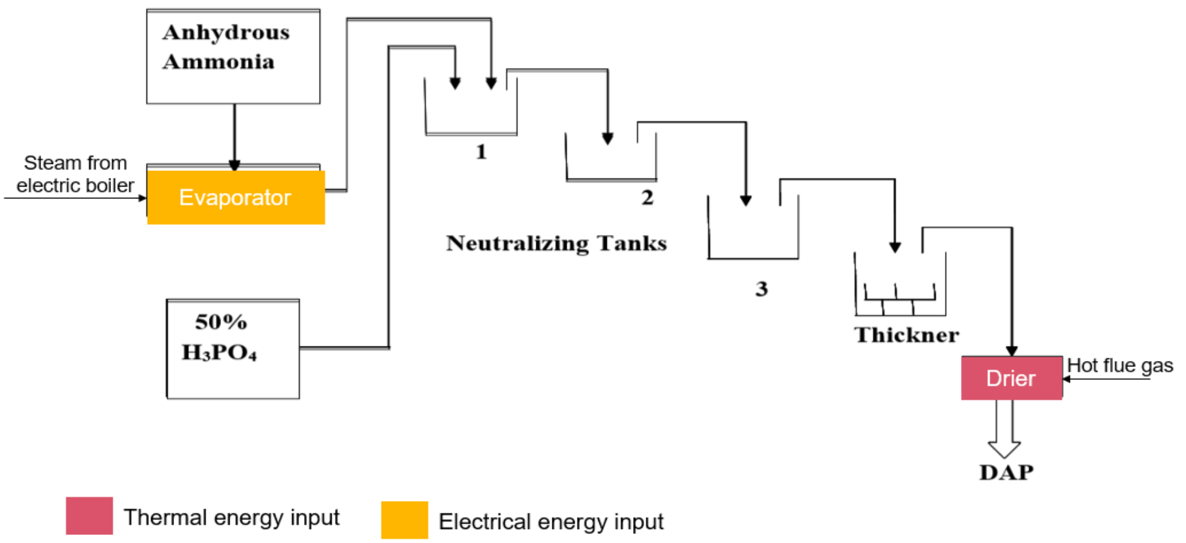
Ammonia Production



Urea Production



DAP Production



ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for production

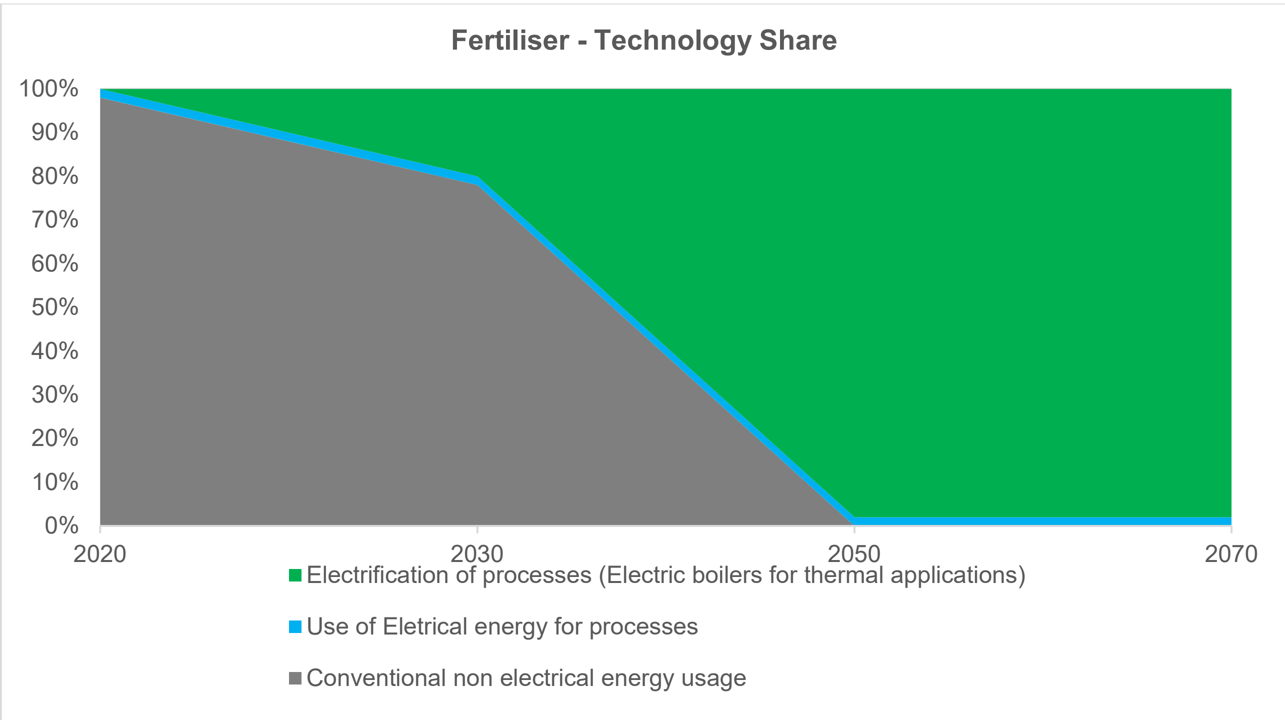
Detailed desk research and analysis have been conducted to project the production demand of the sector for the years 2030, 2040, 2050, and 2070. Production demand projection for the sector is derived based on the correlation between the GDP growth rate projection and the past trend of annual production of the sector. Considering the above correlation, production of fertilisers in the country would be 29.1 Mn tonne by 2030, and 36.5 Mn tonne, 45 Mn tonne and 50.8 Mn tonne by 2040, 2050, and 2070, respectively. The detailed list of assumptions, values and references is annexed in Annex 1.

Production Demand

Year	2019	2030	2040	2050	2070
Production (Million tonnes)	24.0	29.1	36.5	45.0	50.8

Suitable technology mix

Technologies are evaluated primarily based on their TRL level and potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated, considering India's target of net zero by 2070. Corelation between production share and penetration of technology is presented in the image shown below. The image shown below represents that the fertiliser sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector to an extent.



Projected Energy Consumption for Decarbonisation

Energy consumption is projected considering the ambitious scenario of decarbonisation, i.e., 100% electrification by 2040. The ambitious scenario is considered as part of the Government of India's Hydrogen Policy, which has a target to produce 70% of fertilisers from green hydrogen in 2035.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	17	21	24

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050 and 100% by 2070. The energy demand of the chemical sector would reduce by 1% in 2030, 19% in 2050, and 20% in 2070 over the base scenario.

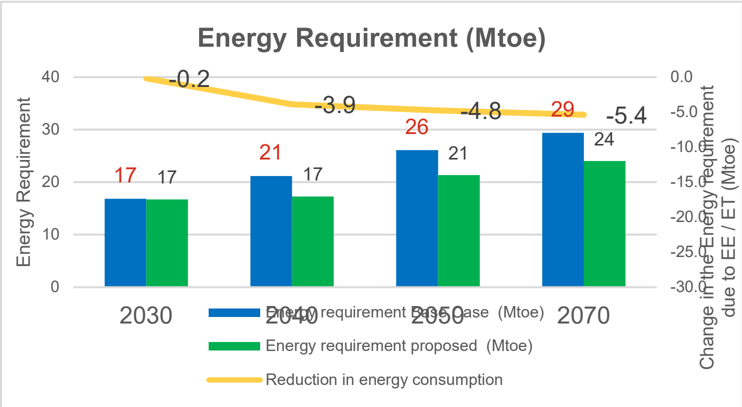


Figure 90: Energy requirement (Conservative)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	17	21	24

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050 and 100% by 2070. The reduction in energy demand of the MSME sector would be the same as that of the conservative scenario for the year 2070.

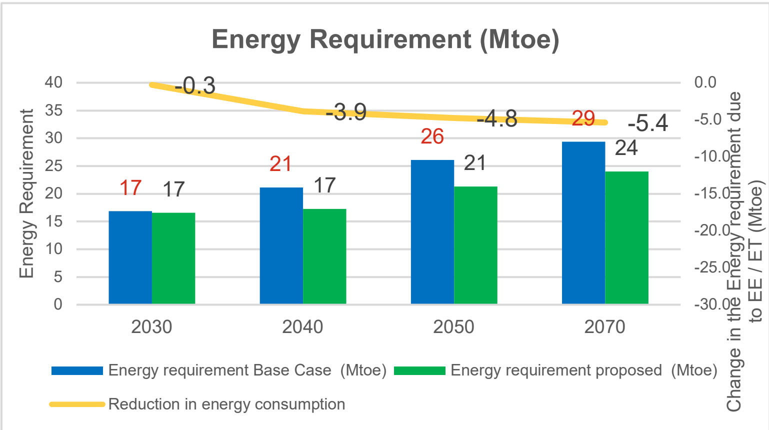


Figure 91: Energy requirement (Moderate)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	16	21	24

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070. The reduction in energy demand of the MSME sector would be the same as that of the conservative and moderate scenario for the year 2070.

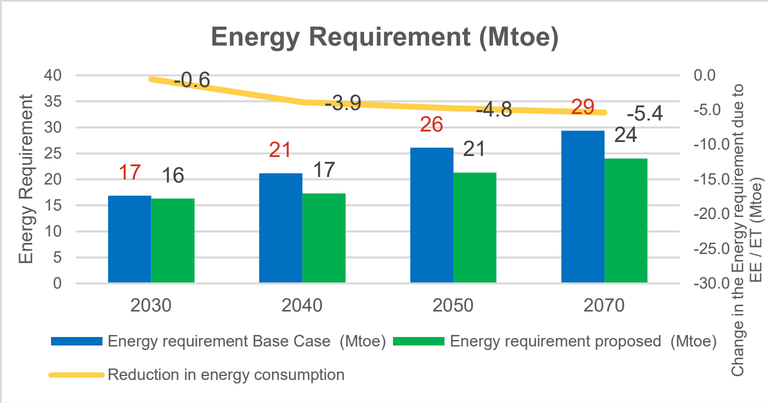


Figure 92: Energy requirement (Ambitious)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **10 GW** by 2030, and it is expected to increase by **60 GW, 81 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **1-3 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 22: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	2	56	80
Moderate	4	59	80
Ambitious	7	59	80

Table 23: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	1.1	41	48
Moderate	1.7	41	48
Ambitious	3	41	48

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 52.4 million tonnes CO_{2e}, 65.7 million tonnes CO_{2e}, 81.1 million tonnes CO_{2e},, and 91.6 million tonnes CO_{2e} for years 2030, 2040, 2050, and 2070, respectively in BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070, as the majority of the production would be electrified and powered by green energy sources. GHG emissions reduction, in this case, is calculated and presented in the graph shown below. GHG emission reduction is negative for all the scenarios because there is penetration of the electrification technology in all the scenarios and this leads to an increase in the electricity consumption of the sector. The grid emission factor of the electricity in 2030 is at the high end due to less contribution of RE technology in the electricity generation mix of the country, i.e., 780 grams of CO_2 per unit of electricity when compared to future timelines.

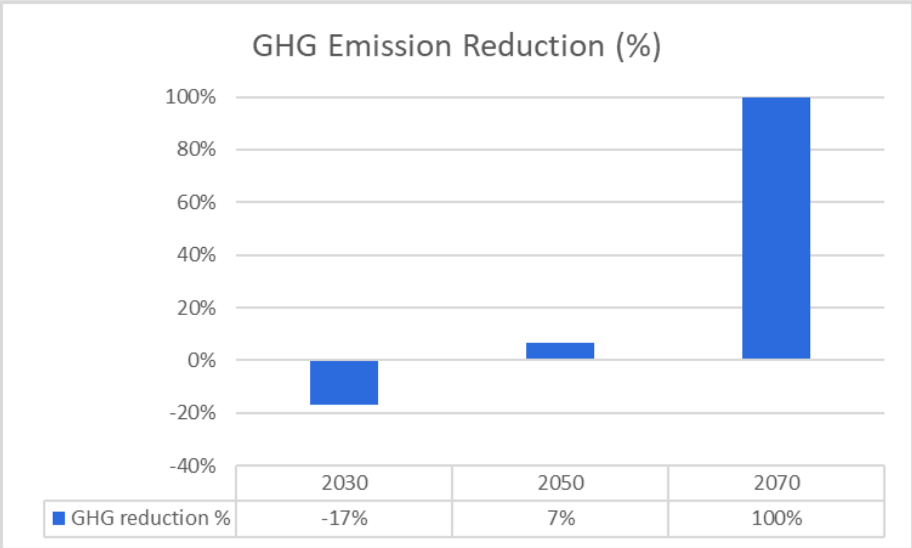


Figure 93: GHG emissions reduction (Ambitious)

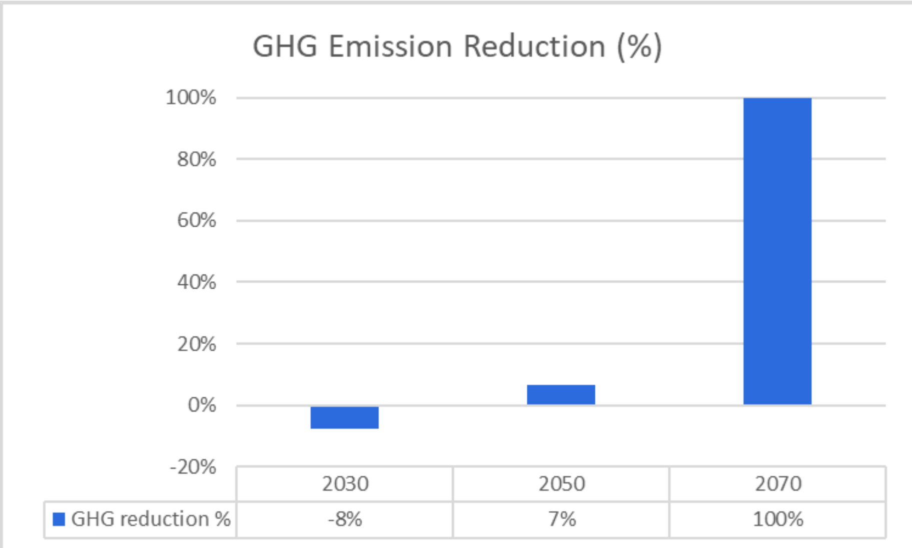


Figure 94: GHG emissions reduction (Moderate)

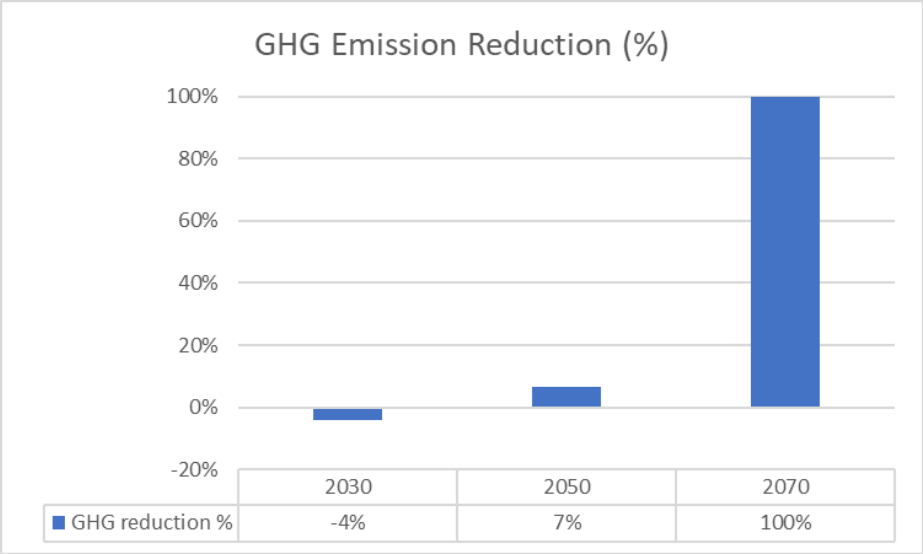


Figure 95: GHG emissions reduction (Conservative)

3.2 Electrification of Food Processing Industry

The Food Processing sector in India is referred to as "A Sunrise sector" as it offers good business opportunities supported by retail sector growth, favorable economic policies, and attractive fiscal incentives. The food processing sector is very diverse in nature as it caters to a range of products, including fruits, grains, confectionery and bakery, fats and oils, spices and salts, among others. India's food processing market is projected to be valued at $ 535 Bn by 2025, growing at a CAGR of 15.2%.[90] With a projected growth of the food processing sector, energy consumption will also grow significantly. Hence, there is an urgent need to decouple this economic growth and energy growth by implementing electrification technologies that are more energy efficient than conventional fossil fuel-powered processing technologies.

Currently, as per the estimation, the share of electrical energy is at ~ 17% of the total food processing sector's energy consumption and is projected to be 90% by 2070. Technologies such as electrification of heating (i.e. microwave, induction, radio frequency), high-pressure processing, ultrasonic pasteurisation of liquid foods, pulsed electric field pasteurisation, industrial heat pumps, mechanical vapour recompression evaporator, ultraviolet radiation processing, among others, will need to be deployed to achieve the required emission reduction goals. In addition, the use of clean energy fuels for processing needs will complement the decarbonisation efforts.

With the implementation of the above-mentioned technologies, 90% of the energy consumption of the sector can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 47.8%, i.e., from 26 Mtoe in the base scenario to 13 Mtoe by 2070 in the ambitious effort scenario. A reduction in energy consumption would also lead to a reduction in GHG emissions by 14% through 2050 and 98% through 2070. Key findings of the scenario analysis model (ambitious scenario) are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

13 Mtoe of Energy Demand by 2070 from the sector

Reduction of **39 Mn tonne CO_{2e}** by 2070

Power demand of **27 GW** by 2070

Requirement of **37 GWh** of battery storage capacity by 2070

[90] https://www.investindia.gov.in/sector/food-processing#:~:text=The%20FDI%20equity%20inflow%20in,at%20a%20CAGR%20of%2015.2%25.

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e. level of efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[91].

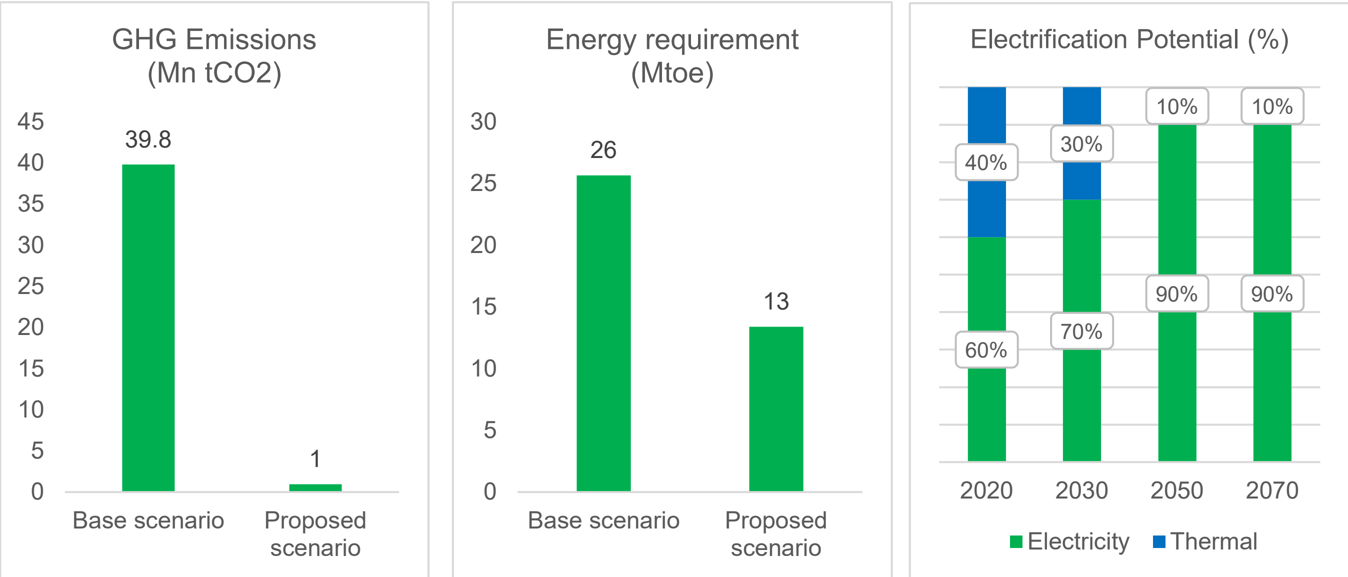


Figure 96: GHG emissions, energy requirement and electrification potential in proposed scenario

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

ELECTRIFICATION OF HEAT

Microwave Heating

Working Principle

In this type of oven, microwaves are produced through a magnetron and are reflected from the metal in the interior of the oven. These microwaves are then absorbed by the food and cause the water molecules in the food to vibrate. This vibration of water molecules produces heat, which cooks the food. As a result, foods with high water content, like fresh vegetables, cook quickly in a microwave oven. In the case of foods with thick layers, the outer part of the food gets heated and cooked with microwaves, whereas the inner part is cooked through conduction heat transfer from the outer layer to the inner layer. This technology for cooking food is more energy efficient than conventional technologies as the cooking time is comparatively less and the energy is directly used to heat food rather than some portion being wasted in heating the oven compartment. As microwave ovens cook food quickly and also reduce the need for additional water for cooking, there is less loss of vitamins and minerals from the food. The containers used for microwave cooking are made of materials such as glass,

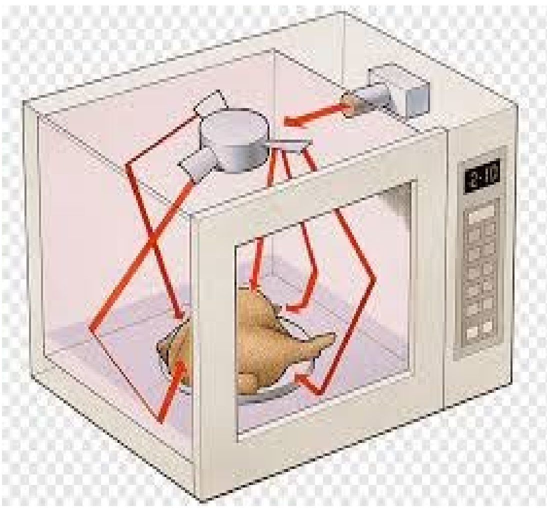


Figure 97: Microwave oven (Source: PNGWing)

[91] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

ceramic, and plastic, among others, as the microwaves can transfer through them. Microwave heating finds application in cooking, drying and tempering in addition to limited use in pasteurisation and sterilisation of foodstuffs.

Global Best Practice Example[92]

Anchor Foods Ltd. has installed a Microwave Splitter using 3 dB couplers. As shown in the figure, the energy from the magnetron is split equally in four ways and is radiated sequentially from the four sides on blocks of butter for tempering. In this process, the temperature of foodstuffs is increased from the cold store temperature to a few degrees below zero. In this particular case, the temperature of 25 kg blocks of butter is raised from -14°C to about -2°C. For this tempering process, three separate lines operating at 896 MHz are used.

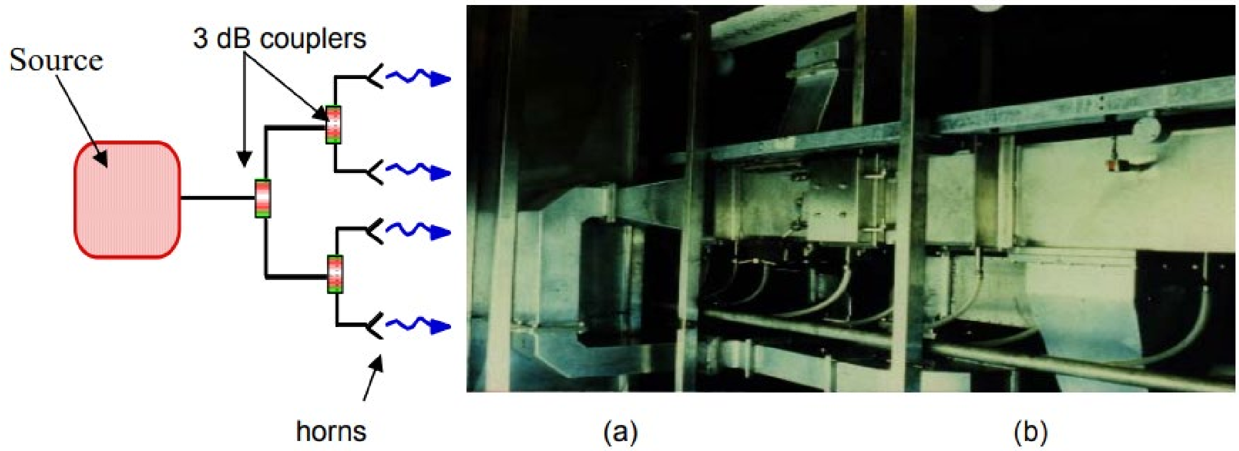


Figure 98: (a) Microwave splitter using 3 dB couplers and (b) continuous microwave butter tempering lines (Source: Anchor Foods Ltd, Dr A C (Ricky) Metaxas)

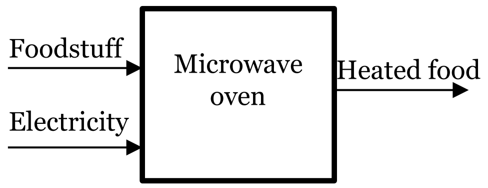
Technology Readiness Level (TRL)

Microwave heating is a commercial technology and has a technology readiness level of 6-8, depending on the application[93]. There are some challenges to deploying microwave technology in the near term, such as high capital cost, changes in dielectric properties that may have some effects on heating pattern quality, etc. Microwave heating will be fully deployed by 2050.

Efficiencies

The energy efficiency of microwaves is 50-70%[93].

Inputs – Outputs



Compatibility with currently used technologies

[92] https://www.pueschner.com/downloads/MicrowaveHeating.pdf
[93] https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf

This is a new technique of heating food that is different from conventional technology, which uses thermal energy input for cooking, drying, and other processes. As a result, there is a need for the installation of new equipment with microwave heating setup.

Foreseen cost development

The input power of microwave ovens for food processing applications ranges from 5 kW to 300 kW. The cost of a 50 kW and 50 kg Microwave Prawn Shrimp Cracker Puffing Machine is USD 30000 – 42000.[94]

Induction Heating

Working Principle[95]

The induction hob contains a copper coil beneath the ceramic plate. When a cooking pot made of ferromagnetic material such as cast iron or stainless steel is placed on top of the induction plate, an alternating current is passed through the copper coil. As a result, an oscillating magnetic field is produced, which induces flux, resulting in eddy current flow in the cooking pot. This eddy current flows through the resistance of the pot, producing heat. This heat from the pot is then transferred to the food through conduction and convection. This technology has applications in various cooking processes, including boiling, steaming, and frying, among others.

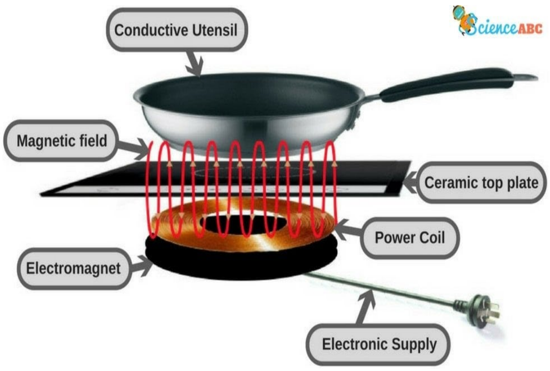


Figure 99: Induction cooking stove (Source: Science ABC)

Global Best Practice Example

Induction ovens are in use in various food processing industries like ITC, MTR, Suhana, Himalaya, Food Solution (India) Ltd, GRB, Bambind, and Almond House, among others.[96]

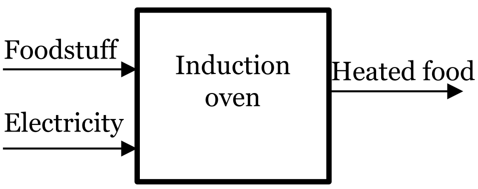
Technology Readiness Level

The induction cooking technique is a commercial technology and hence stands at TRL 9. Induction heating can be fully deployed by 2035.

Efficiencies

The induction type of cooking method is highly energy efficient and has an efficiency of about 70-90%.[97] There are ohmic losses in the induction system.

Inputs – Outputs



Compatibility with currently used technologies

[94] https://www.joyangmachinery.com/sale-13914946-50-kw-50-kg-h-microwave-prawn-shrimp-cracker-puffing-machine.html
[95] https://www.cda.eu/hobs/how-does-induction-cooking-work/
[96] Lorman Kitchen Equipments Pvt. Ltd.
[97] https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf

This is a new technique of heating food that is different from conventional technology, which uses thermal energy input for cooking, drying, and other processes. As a result, there is a need for the installation of new equipment with induction heating setup.

Foreseen cost development

The capacity of induction ovens ranges from 3 to 100 kW and the average price is around INR 10 lakhs.[98]

Radio Frequency Heating

Working Principle

Radio Frequency heating is successfully used in processes including drying, baking and thawing of frozen meat with limited application in continuous pasteurisation and sterilisation of food.[99] This is a volumetric process of heating dielectric materials like foodstuffs through radio waves released by magnetron. The dielectric substance is placed within the cavity between electrodes and the high radio-frequency voltage is applied across the electrodes. The produced radiations penetrate within the food and interact with the protein, fat, salt, etc., resulting in molecular vibration which produces heat within the food. Because of the low frequency and larger wavelength of radio frequency waves than microwaves, radio frequency waves penetrate deeper into the food, resulting in more uniform heating of product compared to microwave-heated ones.

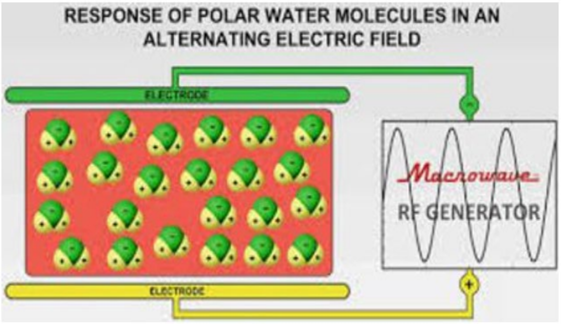


Figure 100: Radio Frequency Heating

Global Best Practice Example[100]

Pepperidge Farm, on its Goldfish line, has installed Radio Frequency drying equipment. The installation of this new RF equipment has doubled the throughput of the Goldfish line, which was not possible earlier due to high moisture content in the final product affecting the cracker's texture as a result of an increase in the oven's throughput. As this dryer reduces the moisture content to half without impacting the baking characteristics, the plant is able to double its production capacity without adding a new Goldfish line.

Technology Readiness Level

This technology is commercial and has a TRL of 4-8, depending on application.[101] This technology can be fully deployed by 2050.

Efficiencies

The energy efficiency of RF generators is around 50-70%[101].

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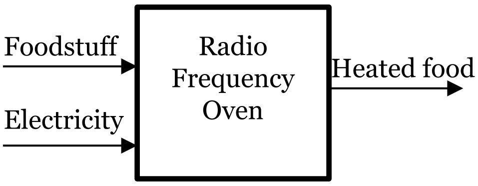
[98] https://www.lormantechnologies.com/commercial-induction-cooking-equipments.html

[99] https://pubmed.ncbi.nlm.nih.gov/14669879/#:~:text=Radio%20frequency%20heating%20has%20been,of%20foods%20is%20rather%20limited.

[100] https://radiofrequency.com/pepperidge-farm-tour/

[101] https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf

Inputs – Outputs



Compatibility with currently used technologies

This is a new technique of heating food that is different from conventional technology, which uses thermal energy input for cooking, drying, and other processes. As a result, there is a need for the installation of new equipment with a radio frequency heating setup.

Foreseen cost development

The current costs of RF dryers ranges from INR 18 to 25 lakhs for power input ranging from 75 to 100 kW.[102]

High-Pressure Processing

Working Principle[103]

High Pressure Processing (HPP) is a non-thermal technique to preserve food by inactivating pathogens and microorganisms harmful to food. This is done by using intense pressure of about 400–600 MPa at chilled or mild process temperatures (<45°C). This process has minimal effects on the physical characteristics of food, like texture and appearance, as well as on taste and nutritional value. Both liquid and high-moisture-content solid food can be processed with the help of HPP technique. HPP technique does not break the covalent bonds, so the food chemistry remains unaffected. This technique can be applied to the processing of milk, fruit juices, smoothies, and already processed food like sliced cooked meat products and RTE meals.[104]

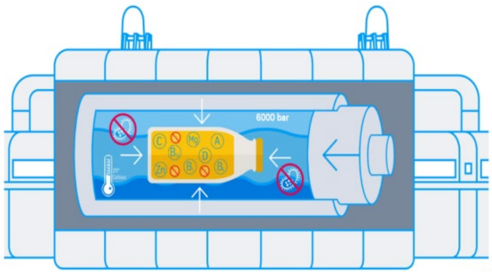


Figure 101: High Pressure Processing (Source: thyssenkrupp)

Global Best Practice Example

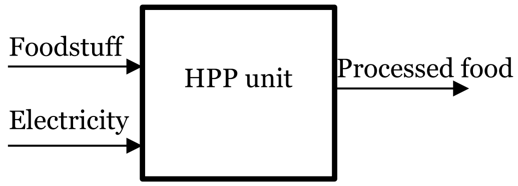
In India, juice and beverage manufacturers *Second Nature* and *Suri Agro Fresh Private Limited* are using HPP technology in their process.[105]

Technology Readiness Level

This technology is commercially available and is at TRL 8.[106] This technology can be fully penetrated by 2035.

Inputs – Outputs

[102] https://www.indiamart.com/
[103] https://www.ift.org/news-and-publications/food-technology-magazine/issues/2008/november/features/preserving-foods-through-high-pressure-processing
[104] https://www.efsa.europa.eu/en/news/high-pressure-processing-food-safety-without-compromising-quality#:~:text=HPP%20can%20be%20used%20at,meat%20products%20and%20RTE%20meals.
[105] https://www.hiperbaric.com/en/hpp-technology/customers/
[106] https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf



Compatibility with currently used technologies

This is a new technique of inactivating food spoiling pathogens and microorganisms. Conventional technology uses thermal energy for same. As a result, there is a need for installation of new equipment with high pressure processing technology.

Foreseen cost development

The cost of an HPP unit ranges from $500,000 to more than $3 million per machine.[107]

Ultrasonic Pasteurization of Liquid Foods

Working Principle[108]

Ultrasonic pasteurisation is a non-thermal technique to destroy or deactivate food-spoiling microorganisms and enzymes. It can be used for pasteurisation of canned foods, milk, dairy, eggs, juices, beverages with low alcohol content, and other liquid foods. Ultrasound alone or ultrasound together with elevated heat and pressure, also known as thermo-mano-sonication, can be used for the effective pasteurisation of food products. A sophisticated ultrasonic pasteurisation technique is superior to conventional pasteurisation methods as it does not adversely affect the nutrient content and physical characteristics of food. Ultrasonic pasteurisation occurs due to acoustic cavitation, which generates very intense shear forces, liquid jets and turbulences. Intense damage to microbial cells is caused by these extensive forces.

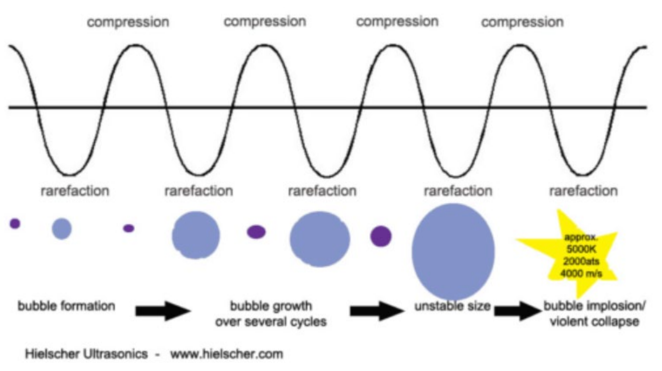


Figure 102: Ultrasonic Cavitation (Source: Hielscher Ultrasonics)

Technology Readiness Level

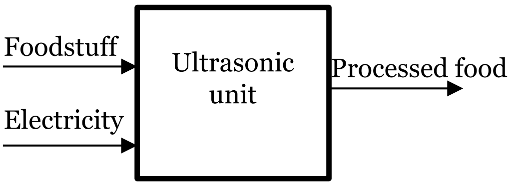
This technology is in the development stage, as there is a need to conduct further research with equipment manufacturers for the evaluation of resistant materials for sonotrodes.[109] The TRL for this technology is 7, but this technology is commercially available.[110] This technology can be fully penetrated by 2040.

Efficiencies

[107] https://www.foodengineeringmag.com/articles/98497-hpp-equipment-trends-and-the-science-behind-the-technology#:~:text=The%20Equipment,are%20JBT%20Avure%20and%20Hiperbaric.
[108] https://www.hielscher.com/ultrasonic-pasteurization-of-liquid-foods.htm
[109] https://www.mdpi.com/2076-3417/12/20/10416/pdf
[110] https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf

In an experiment conducted by The University of Melbourne to evaluate the effectiveness of ultrasound in dairy processing, it was observed that ultrasound is most effective in the deactivation of microbes when combined with other treatments, such as pressure and/or temperature.[111]

Inputs – Outputs



Compatibility with currently used technologies

This is a new technique for processing liquid foods and includes components such as an electric power generator, transducer and emitter for producing ultrasonic waves. As a result, there is a need for the installation of new equipment for producing ultrasonic waves.

Foreseen cost development

The cost of an Ultrasonic Milk Pasteuriser unit ranges from $530 - $1,500.[112]

Pulsed Electric Field Pasteurisation

Working Principle[113]

Pulsed Electric Field (PEF) technology is used for the pasteurisation of pumpable foods. When food enters the PEF chamber and flows between the electrodes, it is subjected to pulses with a higher electric field for a few micro to milliseconds. This application of high voltage results in the inactivation of microorganisms present in food. Food contains several ions, which gives them electrical conductivity, making the transfer of electric pulses from food possible. This technique is preferred with liquid foods as the flow of electric current in liquid food is more efficient.

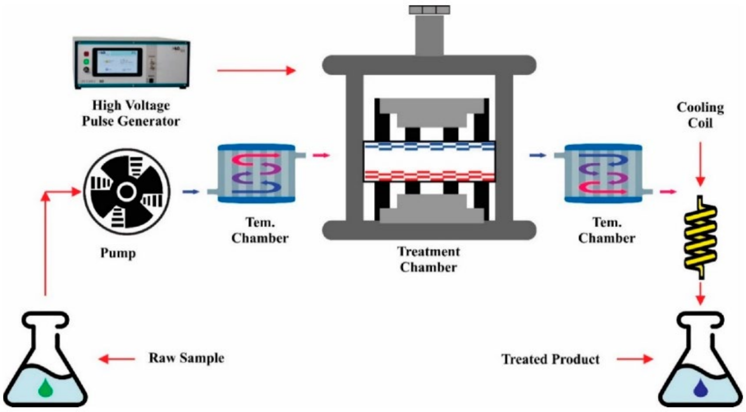


Figure 103: Non-thermal pasuteurisation of food using Pulsed Electric Field (Source: MDPI)

Technology Readiness Level

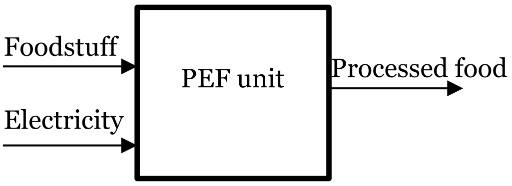
Pulsed Electric Field processing technology is commercially available for processing liquid foods and hence is considered at TRL 8-9.[114] This technology can be fully penetrated by 2035.

[111] https://cdn-prod.dairyaustralia.com.au/dairynsw/-/media/project/dairy-australia-sites/national-home/resources/2020/12/03/the-effects-of-ultrasound-in-dairy-processing-webinar-content/the-effects-of-ultrasound-in-dairy-processing-webinar-content.pdf?rev=80e87925262d473d8aca93a7f98c9133
[112] https://www.alibaba.com/product-detail/Ultrasonic-100-Litres-Milk-Pasteurizer-50_1600732114883.html
[113] https://medcraveonline.com/JNHFE/pulsed-electric-field-technology-in-food-preservation-a-reviewnbsp.html
[114] https://elea-technology.com/

Efficiencies[115]

A PEF treatment results in 5-log inactivation of relevant microorganisms in orange juice, and if pre-heated to a temperature of 45 °C, the efficacy of PEF treatment improves.

Inputs – Outputs



Compatibility with currently used technologies

This is a new technology for inactivating microorganisms and hence requires the installation ofnew equipment.

Foreseen cost development

The processing costs, including CAPEX and OPEX for liquid foods treated using PEF technology, are in the range of $0.02/L of product.[116]

Industrial Heat Pumps

Details in the section – *8.1 Cross-cutting technologies*

Mechanical Vapour Recompression (MVR) Evaporator

Working Principle

MVR evaporators operate on the same principle as heat pumps. The evaporated water vapor is recompressed by a low-speed centrifugal fan or compressor to increase the saturation temperature of the vapor. This recompressed vapor can then be used as heating steam as it releases its latent heat through heat transfer surface during condensation. MVR can be used for drying, evaporation, cooking and baking processes.

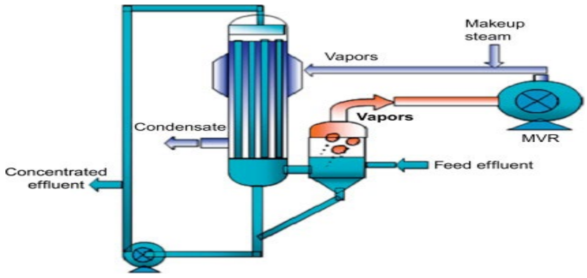


Figure 104: MVR Evaporator (Source: ScienceDirect)

Global Best Practice Examples[117]

A facility in Tianjin, China, has installed MVR technology for treating its high salt-content wastewater.

Technology Readiness Level

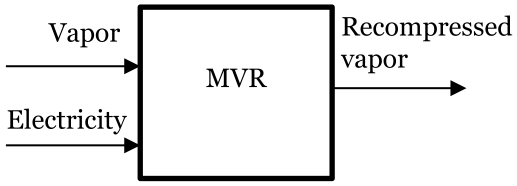
MVR is a commercial[118] technology and hence stands at TRL 9. This technology can be fully penetrated by 2030.

Efficiencies

115 https://www.ingredients-insight.com/contractors/manufacturing/elea-technology/
116 https://www.ingredients-insight.com/contractors/manufacturing/elea-technology/
117 https://www.lhevaporator.com/case-studies/mvr-evaporating-crystallizer#productsinvolved
118 https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf

The COP of this technology is 10-30[118].

Inputs – Outputs



Compatibility with currently used technologies

An MVR evaporator system can replace an existing boiler or contribute to reducing the boiler's capacity.

Foreseen cost development

The cost of evaporation by MVR evaporator is $7-8[119]/ton.

Ultraviolet (UV) Radiation Processing

Background[120]

UV light is an alternative to traditional thermal processing in the food industry. The US Food and Drug Administration (FDA) and US Department of Agriculture (USDA) have concluded that UV irradiation is safe to use. The UV source types, such as continuous UV low-pressure and medium-pressure mercury lamps, pulsed UV, and excimer lamp technologies, can be used in the food industry. The applications for UV light may include pasteurization of juices and beverages, post-lethality treatment to control microbial contamination on meats and shelled eggs surfaces, and increasing the shelf life of fresh produce.

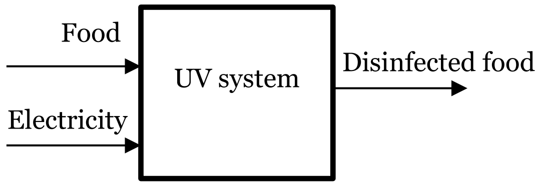
Global Best Practice Examples[121]

In Scotland, Loch Fyne Oysters, a seafood and meat company, uses two medium-pressure UV disinfection systems for treating depuration water in the oyster and mussel depuration tanks at the oyster farm. The capacity of the lamps to treat water is up to 150 m^3 per hour. This UV lamp treatment has resulted in a reduction in E.coli by 99.99%. The requirement of chemicals is not there, and also the pH of water remains unaffected.

Technology Readiness Level

This technology is at present at TRL 8[122] and is expected to be fully penetrated by 2035.

Inputs – Outputs



[119] https://www.lhevaporator.com/case-studies/mvr-evaporating-crystallizer
[120] https://uvsolutionsmag.com/stories/pdf/archives/100403Koutchma_Article.pdf
[121] https://www.foodprocessing-technology.com/projects/uvdissinfection/
[122] https://backend.orbit.dtu.dk/ws/portalfiles/portal/284071559/ECOS_Paper_Technology_catalogue_revised_final_1_.pdf

Compatibility with currently used technologies

There is a need to replace the existing thermal based disinfection system with UV light based disinfection.

Foreseen cost development

The cost of a UV Disinfection system for treating commercial wastewater with a capacity of 48000 LPH is INR 15000.[123]

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Green Hydrogen as fuel with oxy-fuel burner

Natural gas/furnace oil is the fuel that is most widely used in food processing industries. Switching to fuels that are less carbon-intensive, like green hydrogen, enables a major reduction of GHG emissions from the base scenario. A detailed description of green hydrogen and its production process is given in section *8.1 Cross-cutting technologies.* The use of hydrogen as a fuel can reduce CO_2 emissions by 100%.

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for production

Detailed desk research and analysis have been conducted to project the production demand of the sector for the years 2030, 2040, 2050, and 2070. Production demand projection for the sector is derived based on the correlation between the GDP growth rate projection and the past trend of annual production of the sector. Considering the above correlation, the production demand for processed food in the country would be 386 Mn tonne by 2030, and 784 Mn tonne and 930 Mn tonne by 2050 and 2070, respectively. The detailed list of assumptions, values and references is annexed in Annex 1.

Production Demand

Year	2020	2030	2050	2070
Production (Million tonnes)	274	386	784	930

Suitable technology mix

Technologies are evaluated primarily based on their TRL level and potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated, considering India's target of net zero by 2070. Corelation between technology share and penetration of technology is presented in the image shown below. The image shown below represents that the food processing sector can be transitioned to a net zero scenario with the penetration of the mentioned technologies at different time intervals and this would lead to direct electrification of the sector to an extent.

[123] https://www.indiamart.com/proddetail/food-and-beverages-uv-disinfection-system-21121308530.html

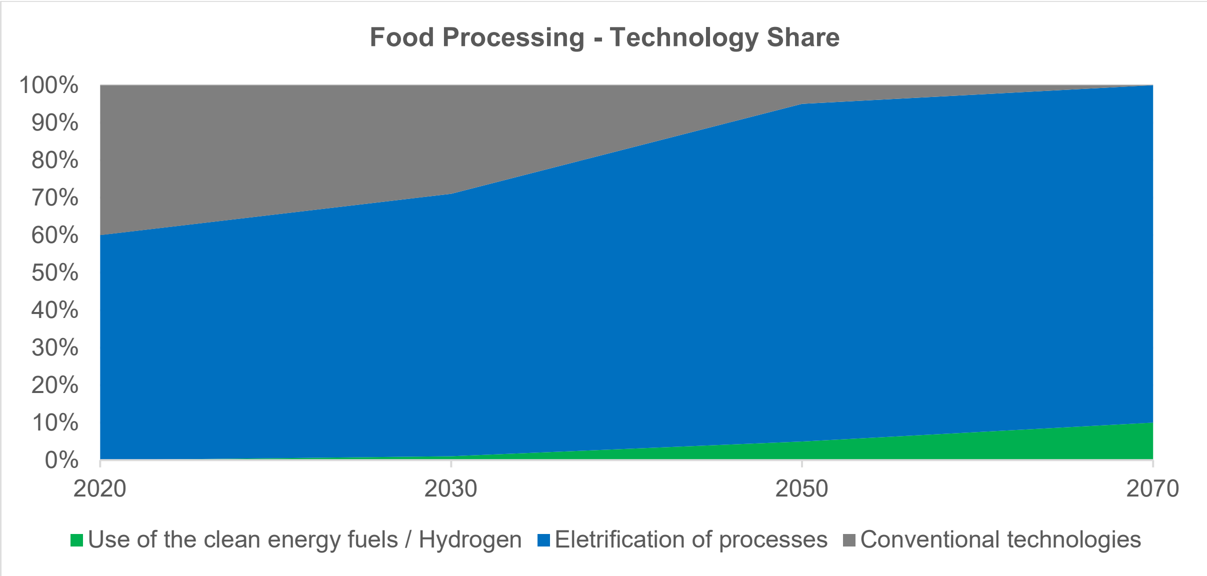


Figure 105: Technology penetration and TRL (Food Processing)

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the ambitious scenario of decarbonisation.

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	6	11	13

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels i.e., 100% by 2030, 100% by 2050, and 100% by 2070. The energy demand of the food processing sector would reduce by 51.1% in 2030, 51.9% in 2050, and 47.8% in 2070 over the base scenario.

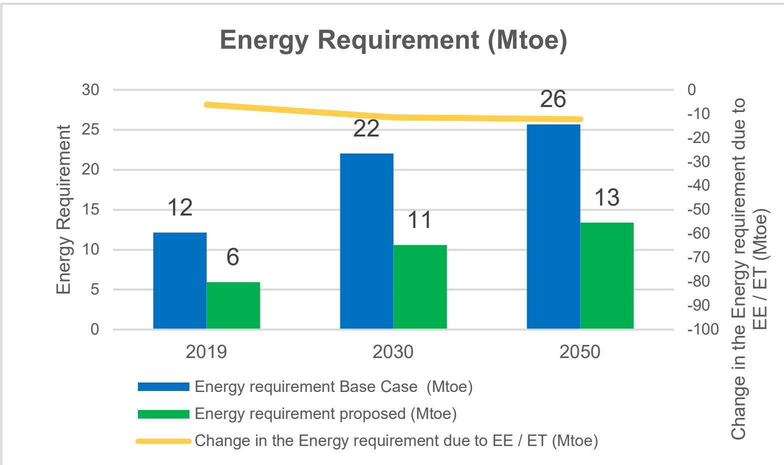


Figure 106: Energy requirement (Ambitious - Food Processing)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	6	11	13

In the moderate scenario, efforts to penetrate the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. Reduction in energy demand of sector would be same as that of the ambitious scenario for the year 2070.

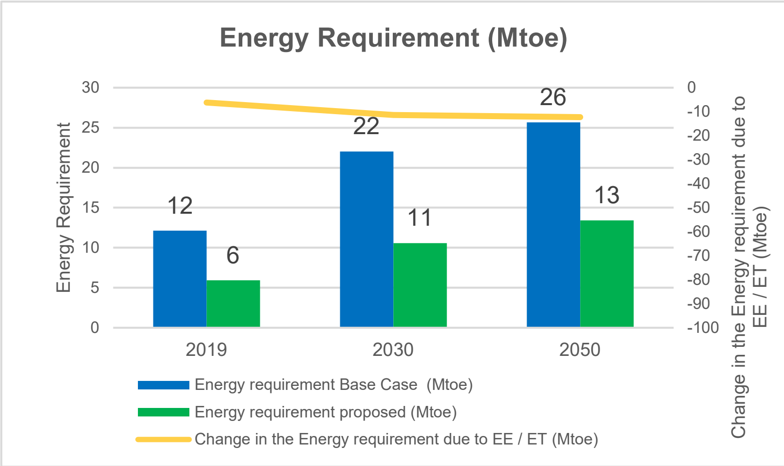


Figure 107: Energy requirement (Ambitious - Food Processing)

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	6	11	13

In the conservative scenario, efforts of penetration of the technology are being considered at the lowest levels, i.e., 30% by 2030, 70% by 2050, and 100% by 2070. The reduction in energy demand of sector would be the same as that of the ambitious scenario for the year 2070.

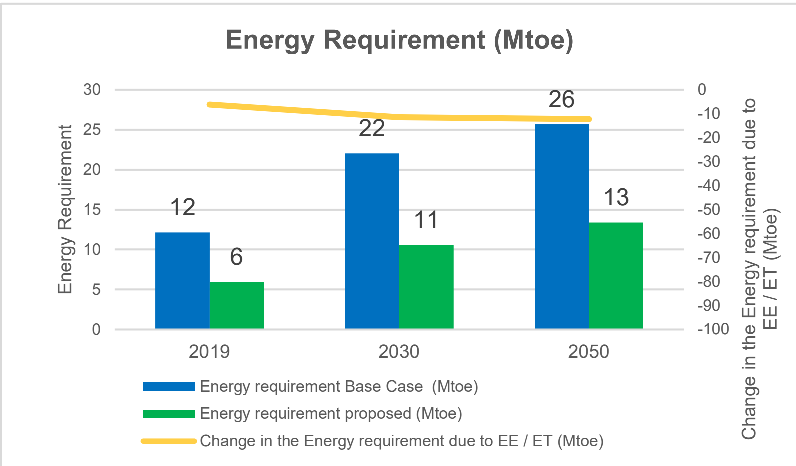


Figure 108: Energy requirement (Ambitious - Food Processing)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **9 GW** by 2030, and it is expected to increase by **30 GW, 27 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **4.5-5.5 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 24: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	4.5	25	27
Moderate	5	27	27
Ambitious	6	29	27

Table 25: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	4.5	25	37
Moderate	4.8	29	37
Ambitious	5.5	30	37

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 15.8 million tonnes CO_{2e}, 33.2 million tonnes CO_{2e}, and 39.8 million tonnes CO_{2e} for the years 2030, 2050, and 2070, respectively, in BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the production would be electrified and electricity would come from green energy sources. GHG emissions reduction for the ambitious scenario is calculated and presented in the graph shown below.

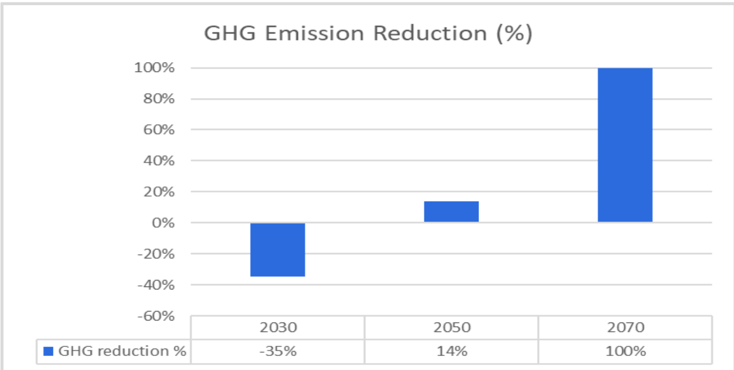


Figure 109: GHG emission reduction (Ambitious – Food Processing)

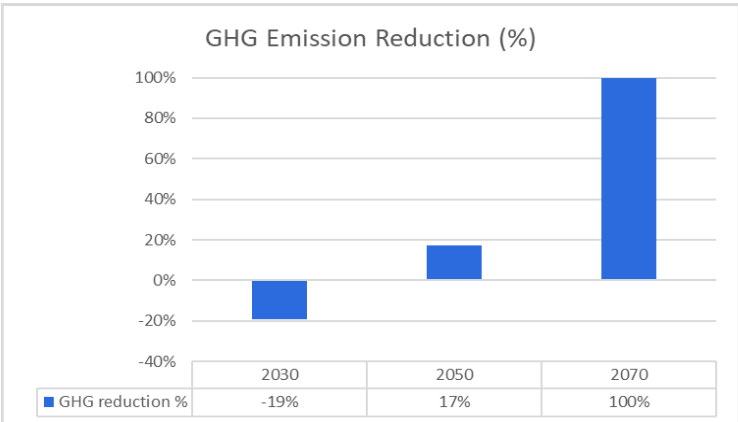


Figure 110: GHG emission reduction (Moderate – Food Processing)

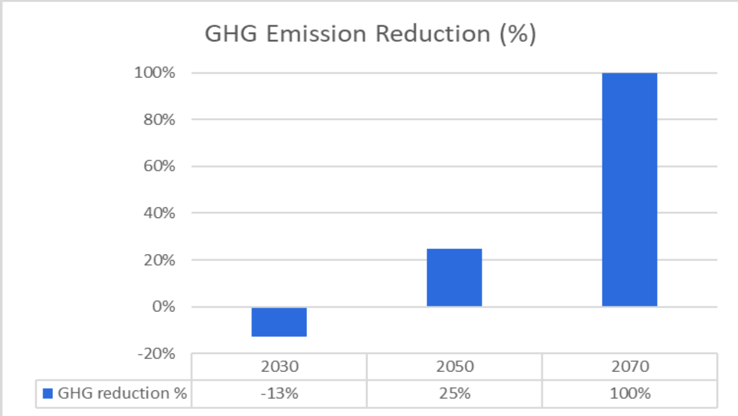


Figure 111: GHG emission reduction (Conservative - Food Processing)

3.3 Electrification of Cold Storages

The cold storage capacity in India is projected to surpass 100 million metric tonnes in 2070. At present, electricity is the primary energy consumption in this sector, accounting for a share of 87% of total energy demand. A small share of 13% is contributed by diesel used in backup generators in case of power outage. It is projected that this 13% diesel energy use will be replaced by electricity powered through the grid (as the grid connectivity to villages improves) and through renewable sources such as solar photovoltaic till 2030.

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Solar Cold Storage with Thermal Energy Storage Backup System

This type of storage enables effective use of solar energy for preserving perishable food items such as fruits, vegetables, etc. In the case of off-grid operation, the cold storage primarily runs on solar energy, which can be switched to grid electricity on cloudy days. During sunshine hours, the electricity provided through a solar photovoltaic system is used to provide cooling energy to the cold room via a vapor compression refrigeration cycle and store excess cooling energy in a Thermal Energy Storage (TES) system. In the TES system, the cold energy is stored in phase change material such as water or water salt eutectic mixture and is discharged and supplied to the cold room on a need basis. As during non-solar hours, the energy needs of the cold room are met through the TES system, the dependency on the grid and diesel generators for electricity can be eliminated. The system comprises components including a Cold Room, SPV System, Solar Controller, Refrigeration System, Thermal Energy Storage (TES), System, and Batteries for Auxiliary Load.

Global Best Practice Example

Figure 112: Solar powered cold storage at Nochad Subhiksha coconut production centre, Kozhikode[124]

1. The Agency for Non-Conventional Energy and Rural Technology (ANERT) has set up a solar-powered cold storage project at Nochad Subhiksha Nalikera Ulpadaka Kendram, under Perambra block panchayat. The cold storage will store coconut and related products and has a capacity of 5 tonnes. The cold storage is equipped with a 5 HP compressor motor and solar panels with a capacity of 6 kW. As a result, in case of a power outage, the cold storage can maintain its temperature up to 30 hours.[125]

2. The Jacobs & Cushman San Diego Food Bank, which is the largest hunger relief organisation in San Diego County, CA, serving an average of 4,00,000 people per month, has installed a TES-integrated rooftop solar photovoltaic system. The food bank relies on solar PV during the day and a TES system during the night and hence has achieved net zero energy usage and electric grid independence for their refrigeration and cold storage energy needs. The food bank achieved increased temperature stability and reduced its carbon footprint and cost. Their night-time energy consumption dropped by 95%, from 168 kWh to 8.1 kWh.[126]

Figure 113: Solar panels installed at San Diego Food Bank[127]

[124] https://www.eqmagpro.com/anert-launches-solar-powered-cold-storage-in-kozhikode/
[125] https://www.saurenergy.com/solar-energy-news/anert-inaugurates-keralas-first-solar-powered-cold-storage-project
[126] https://www.vikingcold.com/downloads/San-Diego-Food-Bank-Case-Study.pdf
[127] https://sandiegofoodbank.org/about/green-initiatives/

Technology Readiness Level

The solar photovoltaic system is a mature technology with TRL 9. However, the development of phase change material (PCM) technology for storing heat is not yet at a fully commercial level. A number of players are currently investing in R&D efforts for heat storage applications using PCM. For cold storage applications, this technology can be considered currently at a TRL 7-8.[128]

Energy Efficiency

Improving the energy efficiency of PCM-based thermal energy storage systems will require improving the efficiency of individual system components, such as heat exchanger technology, among others. The PCM-TES system efficiency is 75-90%.[128]

Foreseen cost development

- The cost of a five-metric-ton solar-powered cold storage unit ranges from ₹1.20 million to ₹1.50 million, excluding the cost of thermal energy storage.[129]
- The cost of a 6MT solar-powered cold storage with a Thermal Storage System consisting of components including an external body of cold storage, PV array, mounting structure, refrigeration unit, solar controller for powering condensing unit, thermal storage system, solar and electric battery system for auxiliary components, temperature set controller, and remote monitoring system is INR ~20 lakhs per kW.[130]

ELECTRICITY REQUIRED FOR FULL DECARBONISATION

Current and projected cold storage capacity

Detailed desk research and analysis have been conducted to project the cold storage capacity for the years 2030, 2050, and 2070. Firstly, a correlation between the past trend of GDP and cumulative cold storage capacity was obtained. Based on this correlation factor and GDP projection, the cold storage capacity was projected until 2070. Considering the above correlation, cold storage capacity in the country would be 49 Mn tonnes by 2030, 91.9 Mn tonnes, and Mn tonnes by 2050, and 107.6 Mn tonnes by 2070, respectively. The detailed list of assumptions, values and references is annexed in Annex 1.

Production Demand

Year	2019	2030	2050	2070
Cold storage capacity (Million metric tonnes)	36.8	49	91.9	107.6

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation and suitability of technologies. The penetration level of the selected technologies is estimated considering the share of diesel energy in cold storage energy consumption and India's target of net zero by 2070. Technology penetration level of electrification technology, i.e. renewable energy sources in this case, is at 9.

[128] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/545249/DELTA_EE_DECC_TES_Final__1__.pdf
[129] https://www.mercomindia.com/switching-to-solar-could-halve-electricity-bills-of-cold-storage-units
[130] http://upneda.org.in/MediaGallery/Solar_24May22_8.pdf

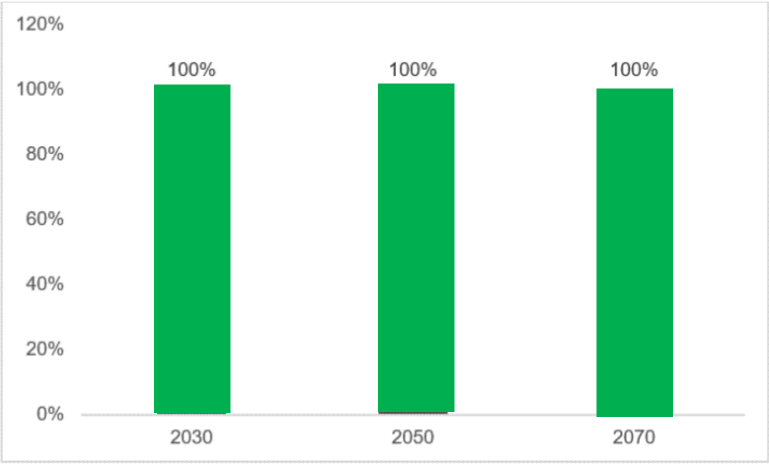


Figure 114: Penetration level of electrification technologies – Cold Storage

Projected Energy Consumption for Decarbonisation

Energy consumption is projected considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenarios, i.e., the effort of implementation resulting a change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.13	0.25	0.30

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050, and 100% by 2070. The reduction in energy consumption is 11% in 2030, 8% in 2050 and 6% in 2070, over the base scenario.

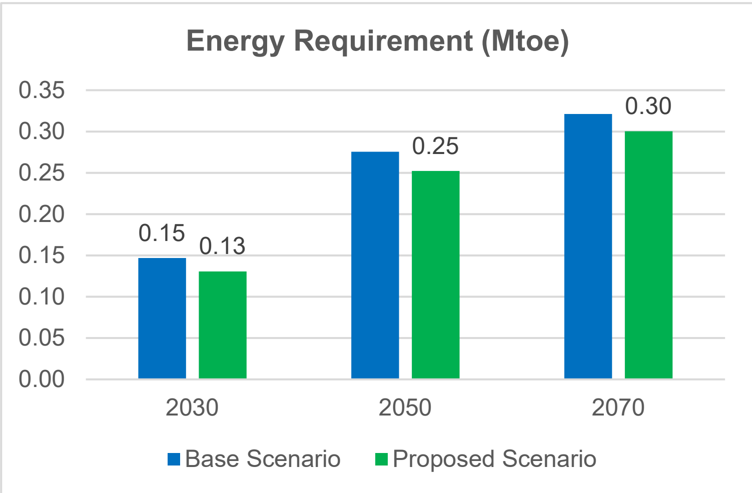


Figure 115: Energy requirement (Conservative - Cold storage)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.13	0.26	0.30

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070. The reduction in energy consumption is 10% in 2030, 7% in 2050 and 6% in 2070 over the base scenario.

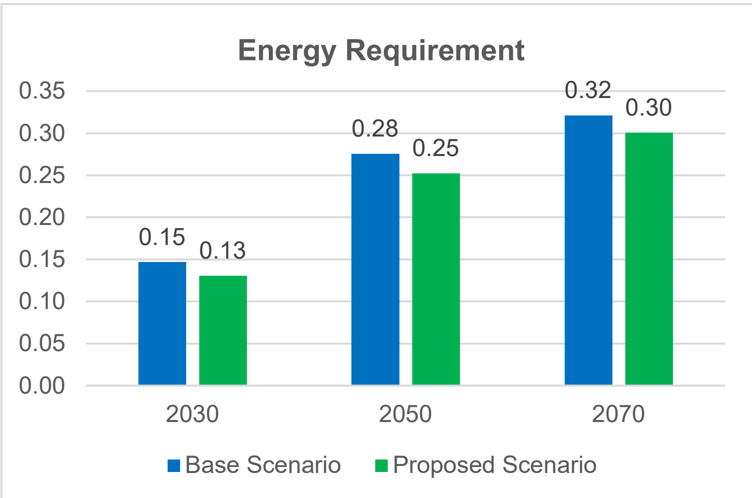


Figure 116: Energy requirement (Moderate - Cold Storage)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.14	0.26	0.30

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050, and 100% by 2070. The reduction in energy demand is 6% in 2030, 2050 and 2070.

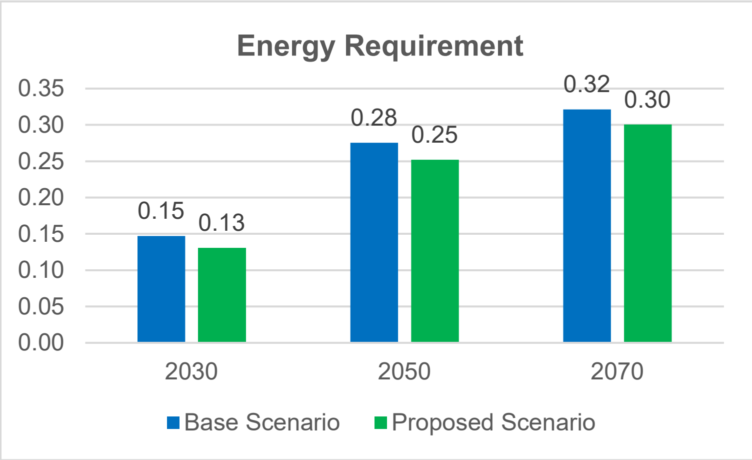


Figure 117: Energy requirement (Ambitious - Cold Storage)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **0.4 GW** by 2030, and it is expected to increase by **1 GW, 0.9 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.1 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 26: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	0.4	0.9	1
Moderate	0.4	0.9	1
Ambitious	0.4	1	1

Table 27: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	0.1	0.5	0.6
Moderate	0.1	0.5	0.6
Ambitious	0.1	0.5	0.6

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 1.2 million tonnes CO_{2e}, 2.3 million tonnes CO_{2e}, and 2.7 million tonnes CO_{2e} for the years 2030, 2050, and 2070 respectively, in BAU scenario. Under the ambitious scenario, the sector is estimated to be net zero in 2070 as the majority of the pumps would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

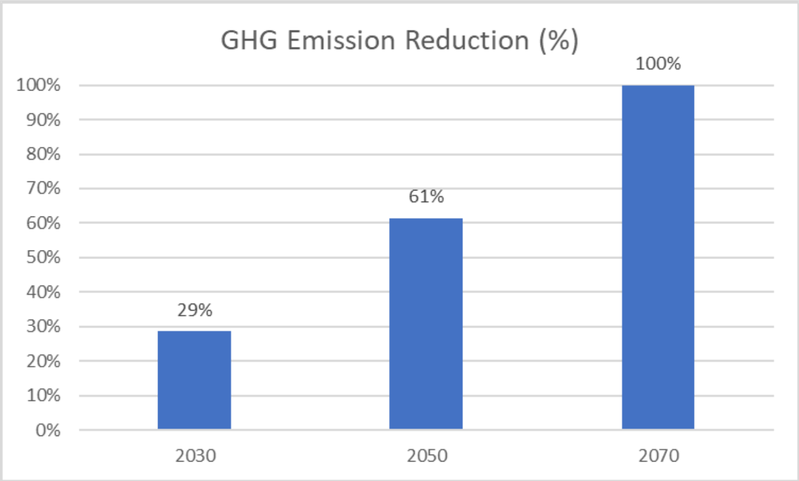


Figure 118: GHG emission reduction (Conservative – Cold Storage)

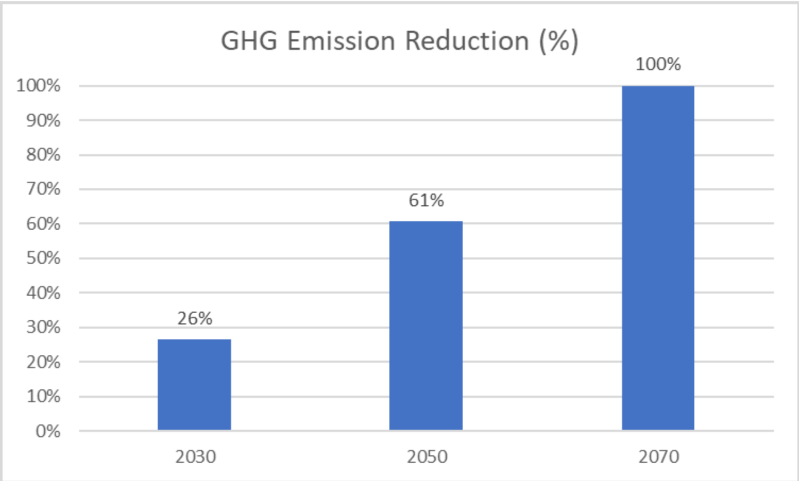


Figure 119: GHG emission reduction (Moderate – Cold Storage)

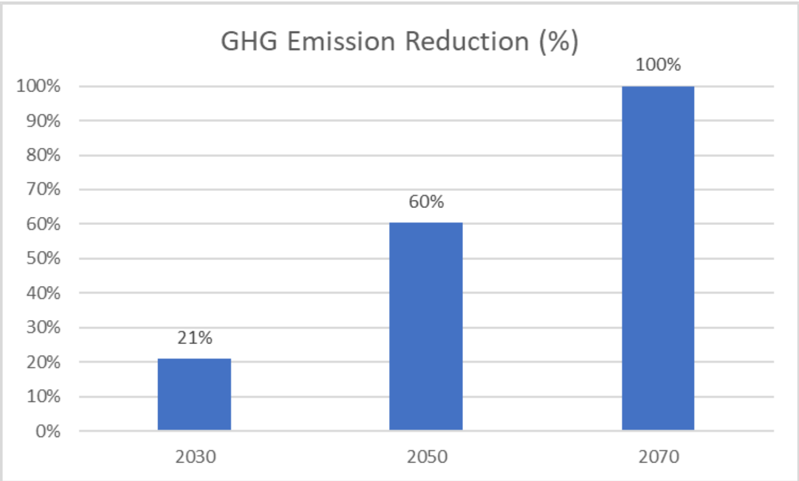


Figure 120: GHG emission reduction (Ambitious – Cold Storage)

3.4 Electrification of Agriculture Machineries

PUMPS

With an aim to ensure energy security for Indian farmers government of India has achieved 40% of installed electric power capacity from non-fossil fuel powered sources by 2030 as part of its INDC, the GOI launched the PM KUSUM scheme. Launched in 2019 this scheme has 3 components, Component A: 10,000 MW of solar capacity through installation of small Solar Power Plants of individual plants of capacity up to 2 MW, Component B: Installation of 20 lakh standalone Solar Powered Agriculture Pumps, and Component C: Solarisation of 15 Lakh Grid-connected Agriculture Pumps. However, there is a need to make more ambitious efforts to align with the net zero by 2070 target. As of now, approximately 30% of the pumps are powered by diesel. In spite of that, there is a potential to electrify 100% of the pumps by 2050, wherein the electricity used to power these pumps will be solar-based.

With the implementation of the above-mentioned technologies, 100% of the energy consumption of the sector can be electrified. This implementation would lead to a reduction in GHG emissions by 84% in 2030, 68% in 2050, and 100% in 2070. Key findings of the ambitious scenario of the model are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

16 Mtoe of Energy Demand by 2070 from the sector

Reduction of **241 Mn tonne CO_{2e}** by 2070

Power demand of **47 GW** by 2070

Requirement of **174 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology, which varies with the scenario used in the model (i.e. level of efforts – ambitious, moderate or conservative). The base scenario is constructed by projecting the production levels (manufacturing / service output) of the sector for consecutive years up to 2070 based on corresponding GDP projections[131].

[131] Please refer to Annexure 1 – Methodology, assumptions, and references for baseline projections

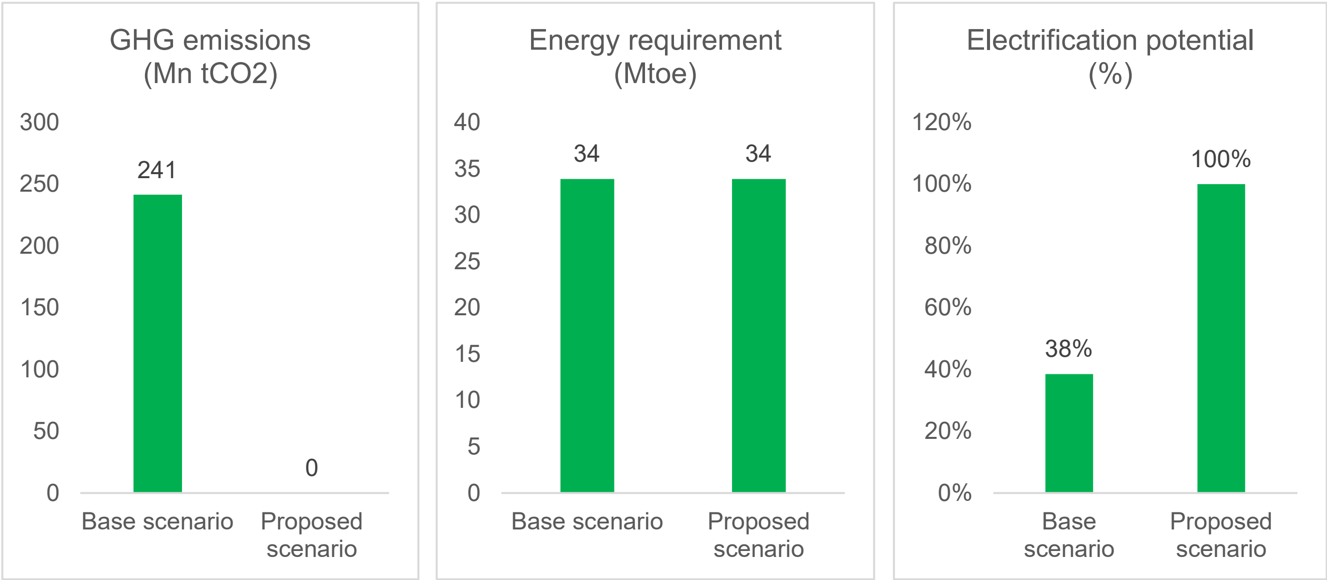


Figure 121: GHG emissions, energy requirement and electrification potential in proposed scenario

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Electric Pumps

Global Best Practice Examples

As of 2022, an estimated 20.3 million grid-connected electric pumps have been installed in India.[132]

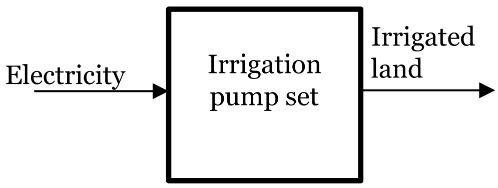
Technology Readiness Level

This technology is commercial and mature and, hence, is at TRL 9. Electric pumps can be fully penetrated by 2030.

Efficiencies

The energy efficiency of BEE star-rated irrigation pumps lies within 35-60%.[133]

Inputs – Outputs



Compatibility with existing technologies

A replacement of the existing diesel-powered pump with an electric pump is needed.

Foreseen cost development

[132] https://www.iea.org/data-and-statistics/charts/estimated-stock-of-agricultural-irrigation-pumps-in-india-2010-2022
[133] https://www.cstep.in/drupal/sites/default/files/2019-02/IPSets_GoK_ppt.pdf

The cost of a 5 HP pump is INR 50,000 in addition to the O&M cost, which is 2.5% of the project cost.[134]

Solar Irrigation Pumps

Global Best Practice Examples

A total of 3.84 lakhs of standalone solar pumps are installed in India till June 2022.[135]

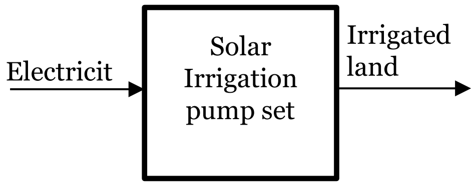
Technology Readiness Level

Solar-powered irrigation pump sets are commercially available and hence stand at TRL 9. Solar irrigation pumps can be fully penetrated by 2035.

Efficiencies

The pumping efficiency of a solar pumping system consisting of 32 modules of 255.8 watts each and a 7.5 hp DC centrifugal monoblock pump was observed between 56-66% in noon conditions in Karnataka.[136]

Inputs – Outputs



Compatibility with existing technologies

An existing electric pump can be powered by solar electricity, and in the case of diesel-powered pumps, there is a need for the installation of new equipment.

Foreseen cost development

The cost of a solar pumping system varies from INR 3.08 - 7.67 lakhs for pump capacity varying from 1.5 to 4 HP.[137]

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for pumps

Detailed desk research and analysis have been conducted to project the demand for pumps for the years 2030, 2050, and 2070. Firstly, a correlation factor between GDP and pump stock was obtained based on the respective values for the past few years. Based on this correlation factor, the number of agriculture pumps was projected up to FY 2070. Considering the above correlation, the demand for pumps in the country would be 34.4 Mn by 2030 and 53.2 Mn and 72.6 Mn by 2050 and 2070, respectively. The detailed list of assumptions, values and references is annexed in Annex 1.

[134] https://www.cstep.in/drupal/sites/default/files/2019-02/IPSets_GoK_ppt.pdf
[135] http://164.100.24.220/loksabhaquestions/annex/179/AS275.pdf
[136] https://www.ijcmas.com/7-5-2018/Priyanka,%20et%20al.pdf
[137] https://agricoop.nic.in/sites/default/files/SolarPumpsetModel_0.pdf

Production Demand

Year	2020	2030	2050	2070
Pump stock (Million)	30.2	34.4	53.2	72.6

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation, and suitability. The penetration level of the selected technologies is estimated considering the increased demand for solar pumps through the KUSUM scheme and India's target of net zero by 2070. Technology penetration levels are presented in the graph below.

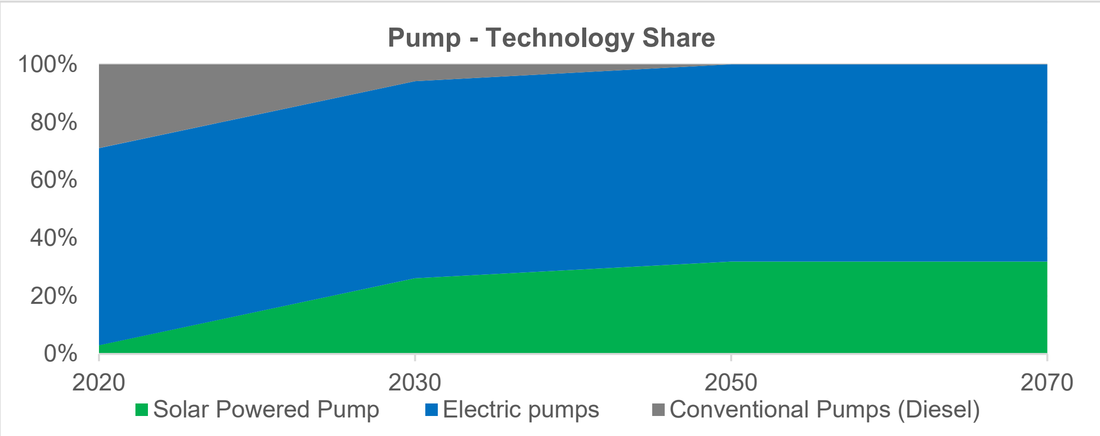


Figure 122: Penetration level of electrification technologies - Pumps

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenarios, i.e., effort of implementation resulting in a change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	9	25	34

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 70% by 2030 and 100% by 2050 and 2070.

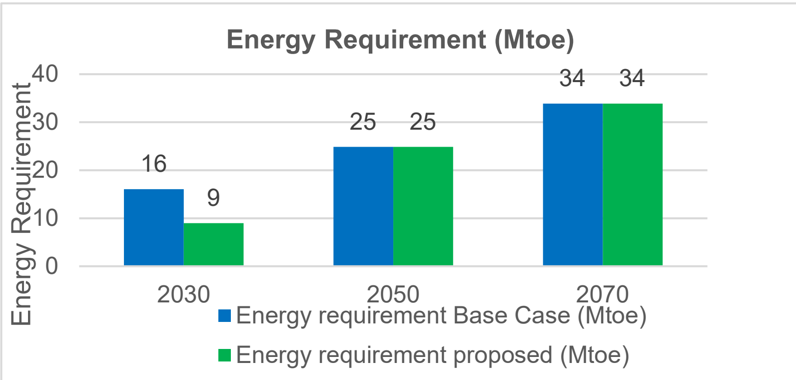


Figure 123: Energy requirement (Conservative - Pumps)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	13	25	34

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 100% by 2030, 2050 and 2070.

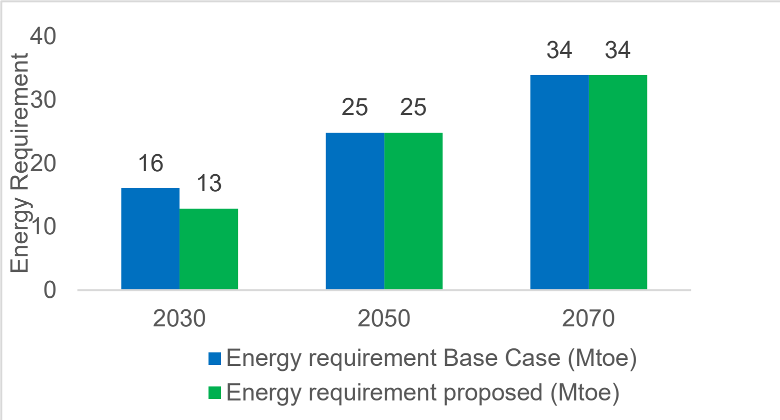


Figure 124: Energy requirement (Moderate - Pumps)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	13	25	34

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050, and 100% by 2070.

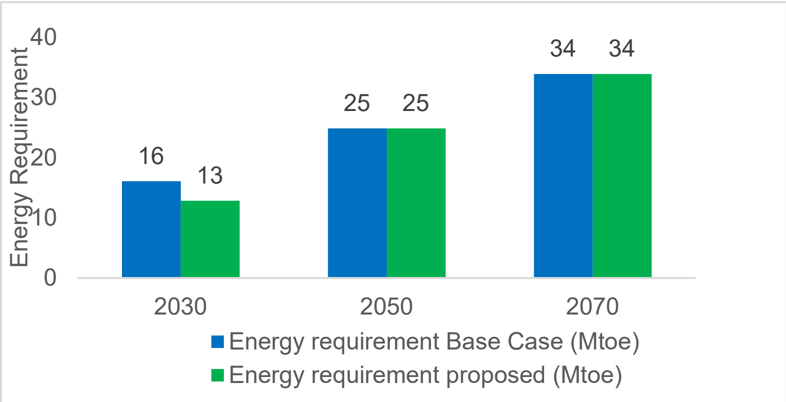


Figure 125: Energy requirement (Ambitious - Pumps)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **39 GW** by 2030, and it is expected to increase by **61 GW, 47 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **31-48 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 28: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	15	59	47
Moderate	27	60	47
Ambitious	27	60	47

Table 29: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	31	159	174
Moderate	48	159	174
Ambitious	48	159	174

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 114 million tonnes CO_{2e}, 177 million tonnes CO_{2e}, and 241 million tonnes CO_{2e} for years 2030, 2050, and 2070 in the BAU scenario, respectively. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the pumps would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

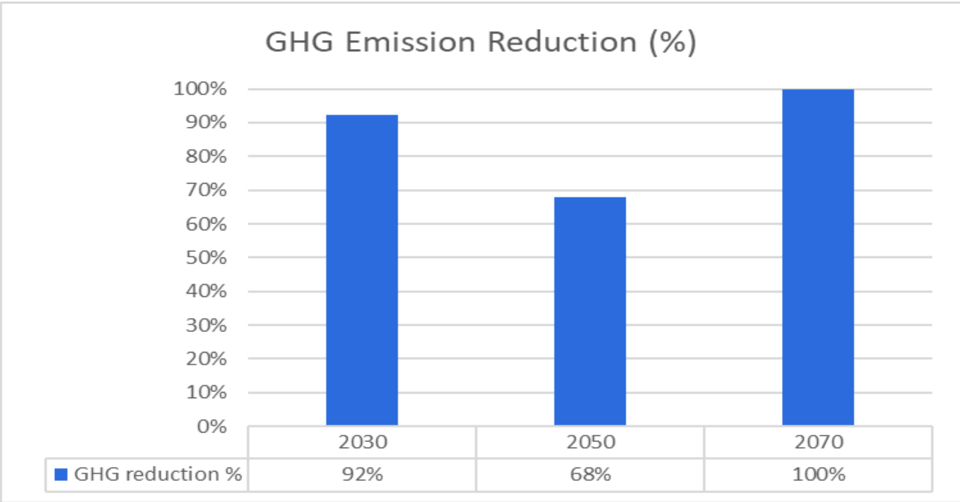


Figure 126: GHG emission reduction (Ambitious– Pumps)

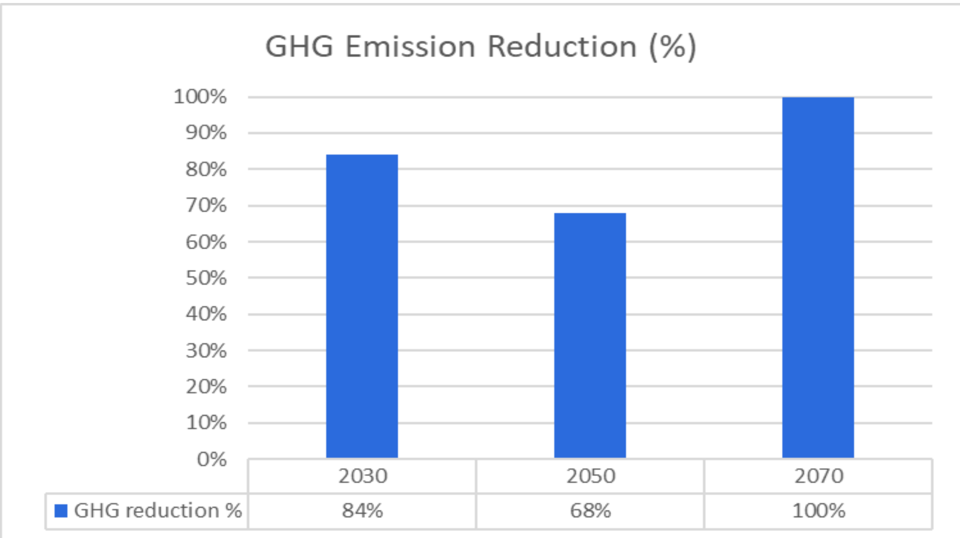


Figure 127: GHG emission reduction (Conservative– Pumps)

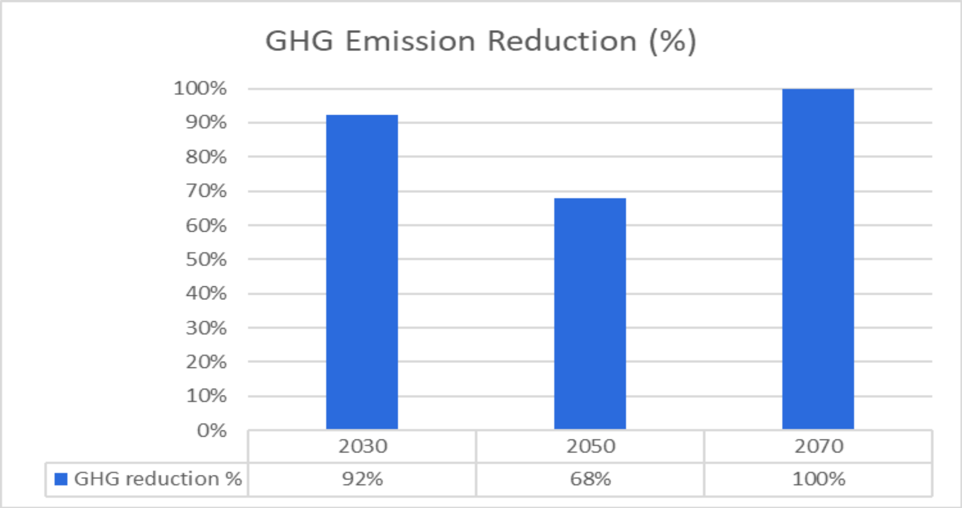


Figure 128: GHG emission reduction (Ambitious – Pumps)

TRACTORS

There is an urgent need to reduce emissions from tractors, which are entirely powered by diesel at present. Fuel switching to electricity, H2 fuel cell and methanol will be critical for decarbonising tractor usage in farms. Due to the low energy density of electric batteries, the potential level of electrification can be 50% by 2070. H2 fuel cell-based and methanol-based tractors will complement the decarbonisation of tractors having a share of 40% and 10% respectively in the total stock of tractors by 2070.

With the implementation of the above-mentioned technologies, 100% of the energy consumption of the sector can be electrified. This implementation would lead to a reduction in GHG emissions by 100% by 2070. Key findings of the scenario analysis model (ambitious scenario) are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

5 Mtoe of Energy Demand by 2070 from the sector

Reduction of **90 Mn tonne CO_{2e}** by 2070

Power demand of **16 GW** by 2070

Requirement of **1.5 GWh** of battery storage capacity by 2070

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Full Battery Electric

The main challenge associated with the full battery-electric variant is the energy density of Li-ion batteries. An average tractor requires 400[138,139] litres of energy reserve. Whereas a full electric variant weighs 9-10 tonnes and takes 5000 litres in volume to do the same 8 hours of work.[140] Hence, this technology is most suitable for small tractors as large tractors will exceed the acceptable weight limit, resulting in soil compaction and reduced operation time.

Global Best Practice Examples

The e25 Compact Electric Tractor by Solectrac is in use at the Kōkua Hawaiʻi Foundation.[141]

Technology Readiness Level

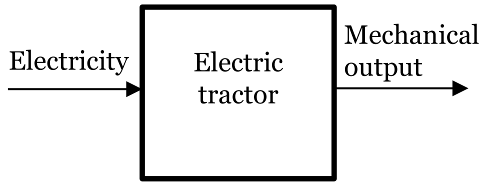
Small electric tractors are commercially available and hence stand at TRL 9. Some of the manufacturers of electric tractors include Sonalika, Mahindra, John Deere, and Celestial, among others. Electric tractors can be fully penetrated in small farms by 2030.

[138] https://www.fendt.com/de/geneva-assets/article/94968/592540-fendt700vario-2002-td-de.pdf
[139] https://www.volkswagenag.com/de/news/stories/2018/10/powerful-andscalable-the-new-id-battery-system.html
[140] https://www.cema-agri.org/images/publications/position-papers/CEMA_decarbonising_agriculture_27-04-22.pdf
[141] https://solectrac.com/cet-electric-tractor

Efficiencies

The energy efficiency of electric tractors is a minimum of 80%.[142]

Inputs – Outputs



Foreseen cost development

The base price of a 25 HP electric tractor is $ 29,249.[143]

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Fuel Cell Electric Tractor

Fuel cell electric tractors are powered by hydrogen, which can be made from renewable electricity using electrolysis technology. The energy density of hydrogen is higher than that of electric batteries but lower than that of diesel fuel. As a result, the range provided by fuel cell electric tractors is less compared to diesel tractors. Additionally, there are issues related to tank and fuelling infrastructure and logistics. This technology performs better in terms of size and weight compared to the full electric type. However, the high demand for cooling decreases its efficiency.

Global Best Practice Examples[144]

A hydrogen-powered tractor developed by a specialist vehicles manufacturer, *Terberg,* in association with a hydrogen fuel cell systems company *zepp.solutions,* is being tested in the Port of Rotterdam. The tractor is equipped with four 350 bar hydrogen fuel tanks containing a total of 14.4 kg of hydrogen, sufficient for a whole day's work in the port. The image shown below is the platform to test the tractor.

[142] *Hashemnia, Nasser, and Behzad Asaei. "Comparative study of using different electric motors in the electric vehicles." In 2008 18th International Conference on Electrical Machines, pp. 1-5. IEEE, 2008.*

[143] https://solectrac.com/cet-electric-tractor

[144] https://trans.info/en/rotterdam-port-s-new-hydrogen-powered-tractor-how-does-it-compare-to-its-diesel-counterpart-209144

Figure 129: Fuel Cell Electric Vehicle being tested in the port of Rotterdam (Source: zepp.solutions, Trans.INFO)

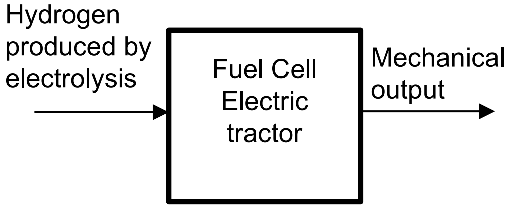
Technology Readiness Level

The prototypes of fuel cell-hydrogen tractors are developed but are currently commercially not viable.[145] Hence, this technology stands at TRL 7. Fuel cell hydrogen tractors can be fully deployed by 2040.

Efficiencies

Fuel cell electric tractors are 10-12% more energy efficient compared to equivalent diesel tractors at tank-to-wheel level.[146]

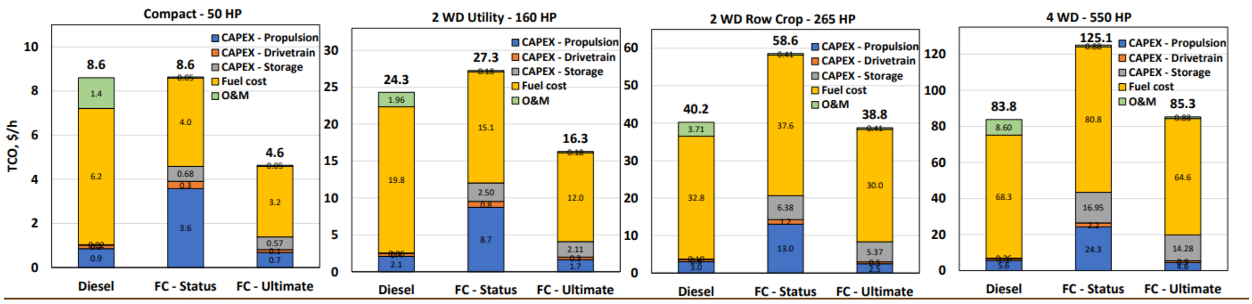
Inputs – Outputs



[145] https://www.cema-agri.org/images/publications/position-papers/CEMA_decarbonising_agriculture_27-04-22.pdf
[146] https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/

Compatibility with existing technologies

Foreseen cost development[147]



ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Baseline energy consumption

In the case of tractors, the historical trend of share of the agriculture sector in the country's total GDP was considered for projecting the agriculture sector GDP values till FY 2070. For FY 2020 to FY 2030, India's historic trend was considered, for FY 2030 to FY 2050, China's historic trend was considered and for FY 2050 to FY 2070, considering India as a developed economy by then, the US's trend was considered. A correlation between agriculture sector GDP and fuel consumption by tractors (considering data for the past few years) was determined for projecting the fuel consumption by tractors till FY 2070 in the baseline scenario.

[147] https://www.energy.gov/sites/default/files/2021-12/922-9-mission-innovation-ANL.pdf

Suitable technology mix

Technologies are evaluated primarily based on their TRL level and potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering India's target of net zero by 2070. Technology penetration levels and TRL are presented in the graph presented above.

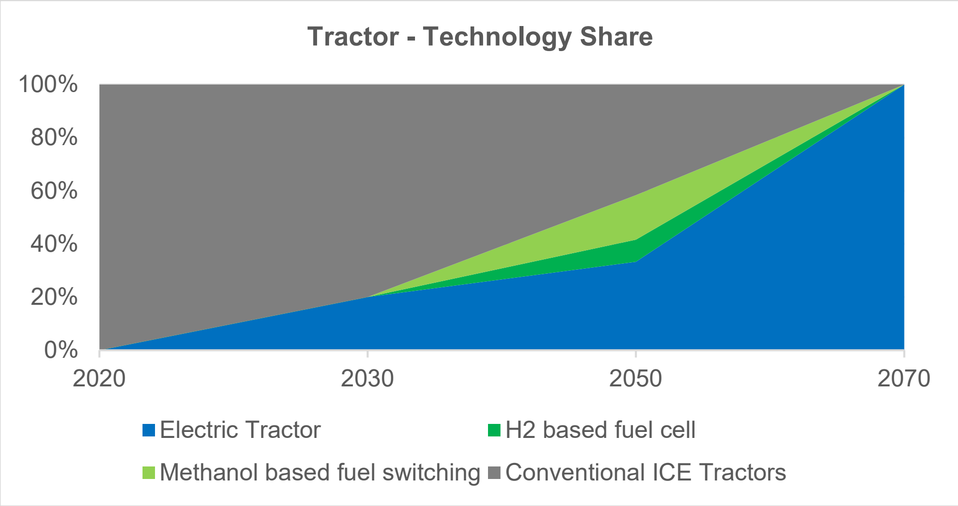


Figure 130: Penetration level and TRL of electrification technologies - Tractors

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenarios – the effort of implementation leads to change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	12.17	20.81	29.66

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050, and 100% by 2070.

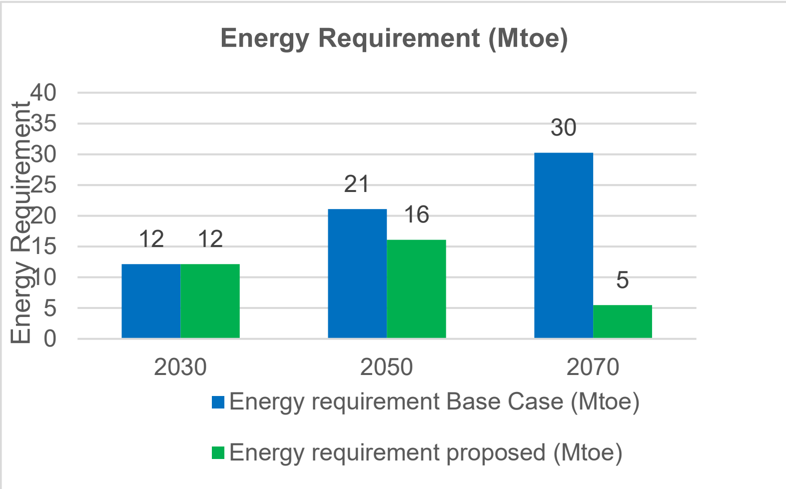


Figure 131: Energy requirement (Conservative - Tractors)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	12	15	5

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050, and 100% by 2070.

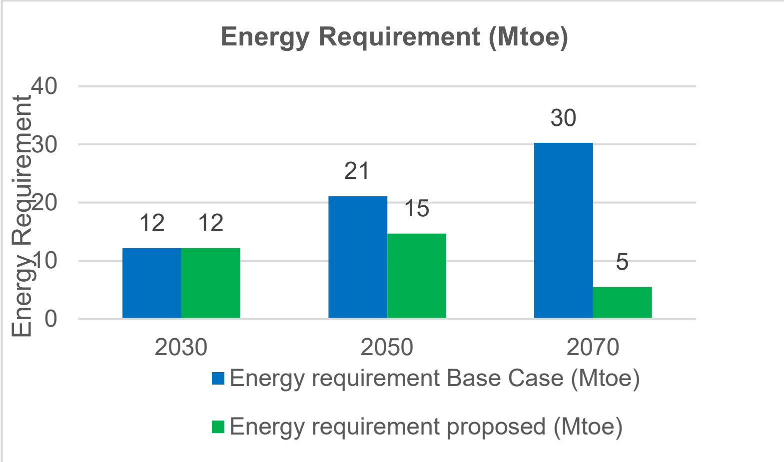


Figure 132: Energy requirement (Moderate - Tractors)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	12	14	5

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050, and 100% by 2070. A reduction in energy demand for tractors would be the same as of conservative and moderate scenarios for the year 2070.

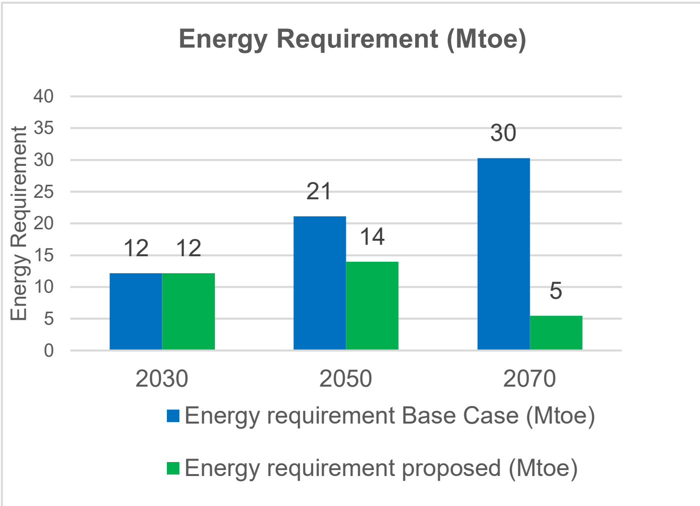


Figure 133: Energy requirement (Ambitious - Tractors)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070 average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based source of electricity. In the ambitious scenario, the power installation requirement for the sector would be **8 GW** by 2030, and it is expected to increase by **26 GW, 16 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.2-0.7 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios is presented in the table shown below.

Table 30: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	1.2	21	16
Moderate	3	24	16
Ambitious	5	25	16

Table 31: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	0.2	1.5	1.5
Moderate	0.3	1.8	1.5
Ambitious	0.7	1.9	1.5

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 36 million tonnes CO_{2e}, 63 million tonnes CO_{2e}, and 90 million tonnes CO_{2e} for years 2030, 2050, and 2070 in BAU scenario, respectively. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the tractors would be electrified, wherein the electricity would come from green energy sources. The remaining tractors would be H_2 fuel cell-based and methanol fuel-based, wherein the hydrogen for H_2 fuel-based tractors will be produced using renewable electricity. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

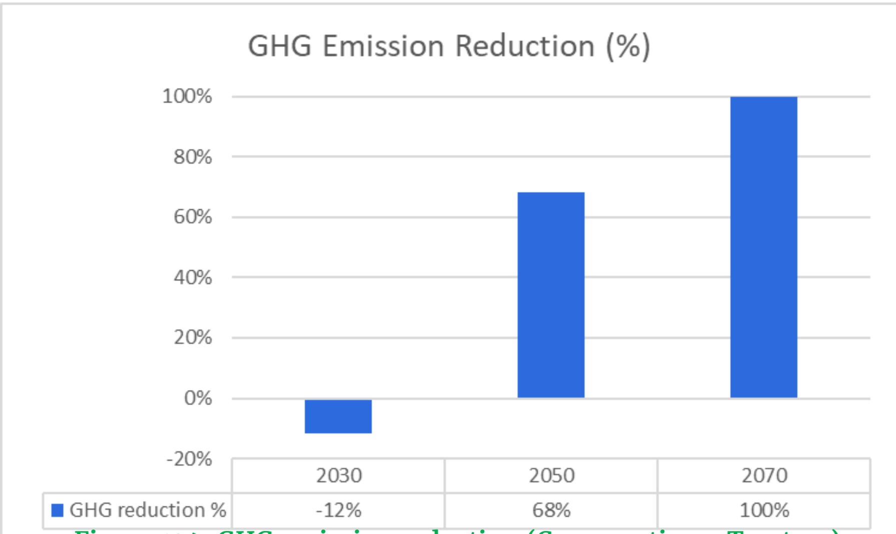


Figure 134: GHG emission reduction (Conservative – Tractors)

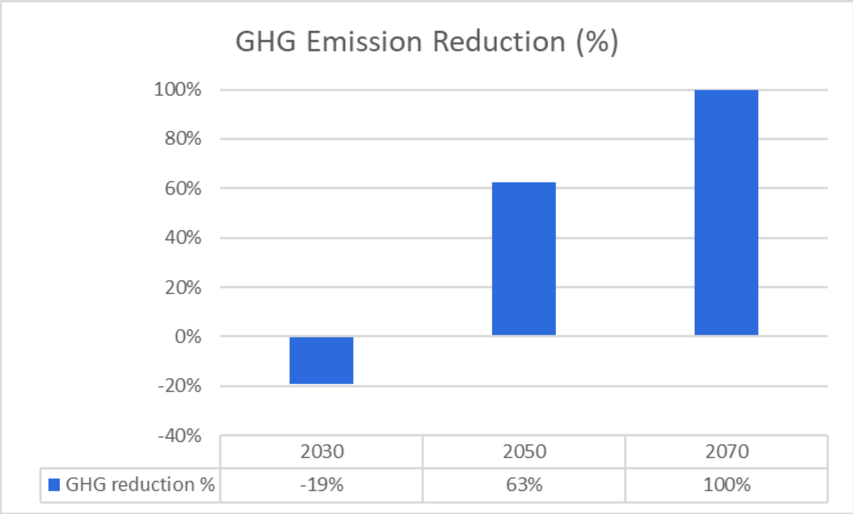


Figure 135: GHG emission reduction (Moderate – Tractors)

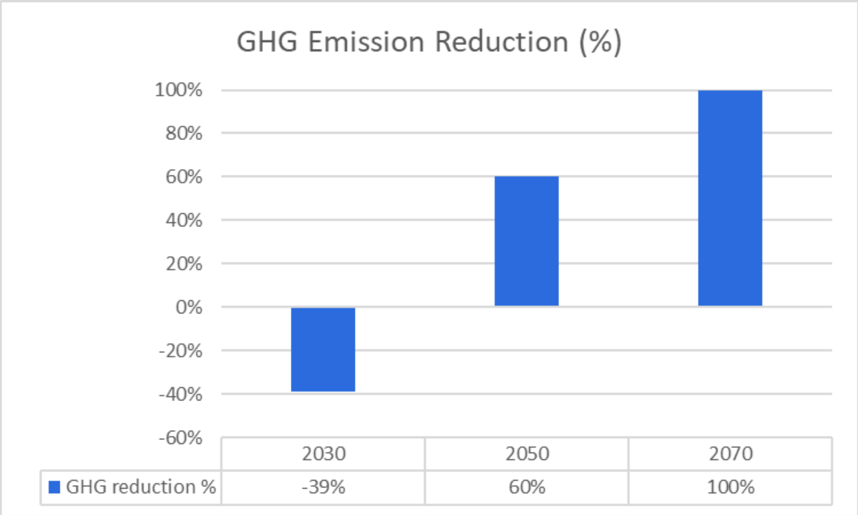


Figure 136: GHG emission reduction (Ambitious – Tractors)

GHG emission reduction is negative for all the scenario because of penetration with electrification technology in all the scenario. This leads to an increase in the electricity consumption of the sector. The grid emission factor of the electricity in 2030 is at the high end due to less contribution of RE technology in electricity generation mix of the country i.e., 780 gram of CO_2 per unit consumption of electricity when compared to future timelines.

HARVESTERS

SUMMARY OF EXISTING GOALS & POTENTIAL FOR NET ZERO THROUGH ELECTRIFICATION

In India, the level of mechanization in agriculture currently stands at 40-45%, wherein tractors have a majority share and other agriculture machinery like combine harvesters, among others, contribute very less. Hence, India is called "tractorised" and not "mechanized".

It is projected that the usage of combined harvesters will increase to 0.5 million by FY 2070. Currently, the harvesters which are in use are primarily powered by diesel. Hence, there is an urgent need to deploy low-carbon technologies in the combined harvester sector. It is projected that the level of electrification in combined harvester technology in use in FY 2070 will be 100% from the existing 0% level. Electric harvesters will be increasingly deployed until 2070, supported by H2 fuel cell-based harvesters whose share will increase up to 2050 and then drop to zero until 2070.

With the implementation of the above-mentioned technologies, 100% of the energy consumption of the sector can be electrified. This implementation would lead to a reduction in GHG emissions by 100% through 2070. Key findings of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

0.093 Mtoe of Energy Demand by 2070 from the sector

Reduction of **3.9 Mn tonne CO_{2e}** by 2070

Power demand of **0.27 GW** by 2070

Requirement of **1 GWh** of battery storage capacity by 2070

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Full Battery Electric

With respect to full battery-electric-powered agriculture machines, the main challenge lies with the energy density and weight of the batteries. This main challenge is followed by issues related to cost and life cycle. Smaller machines have the highest potential among the various electrification options for agricultural mobile machines with batteries as primary energy sources, as concluded by a study to assess the potential of different electrification options for various subsectors by 2030.[148] There is also an assumption that buyers in the future will pay an increased price for an electric-powered machine. The provision to do operations close to the farm and indoor applications will be the main drivers for small electric machines. Products such as electric vegetable harvesters are already there on the market. However, the main challenges observed are the reliable supply of electricity in farms, the charging infrastructure, and increased weight.[149]

Global Best Practice Examples[150]

De Pietri has launched Ecoline range harvesters, which can find application in harvesting and treating fourth-range fresh vegetables and medicinal and aromatic plants. The company claims that the harvesters and equipment are lightweight and manageable, and they are fully electric-powered machines designed with an aim to minimise environmental impact during harvesting. Moreover, these harvesters are quiet during their operations and have a complete absence of emissions. The company asserts that they are suitable for harvesting vegetables and herbs in glasshouses. They also state that the harvester is equipped with powerful, long-lasting and quickly rechargeable batteries, which require no special maintenance.

[148] VDMA doc 'Antrieb in Wandel' - https://elektromobilitaet.vdma.org/documents/266699/25083160/Antrieb+im+Wandel+-+Broschuere/1bdef884-8c1c-4681-8ac1-ef51bd12fff0

[149] https://www.cema-agri.org/publications/17-position-papers-publications/916-the-role-of-agricultural-machinery-in-decarbonising-agriculture

[150] https://dpdepietri.it/en/vegetables-medicinal-and-aromatic-plant-electric-harvesters/#gamma-prodotti

Figure 137: De Pietri's Electric Harvester

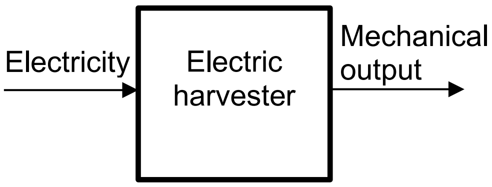
Technology Readiness Level

There are electric harvesters available on the market for a range of applications such as vegetables, medicinal and aromatic plants, and olive harvesting, forest application, among others. However, the harvester models available are still limited and hence, this technology is considered at a TRL of 8.

Energy Efficiency

There are multiple benefits of replacing diesel motors with electric ones. The highly efficient electric motors operate at over 90% energy efficiency. This results in cost savings with time compared to diesel motors operating at an efficiency between 30 – 40%.

Inputs – Outputs



Compatibility with currently used technologies

Considering the level of technology currently available in the market, retrofitting a diesel tractor with an electric motor is not a practical option. Hence, it is recommended to replace the existing diesel tractor with a new electric tractor. Deploying an electric tractor on a farm will demand a reliable electricity supply and adequate charging infrastructure.

ELECTRICITY REQUIRED FOR FULL DECARBONIZATION

Current and projected demand for harvesters

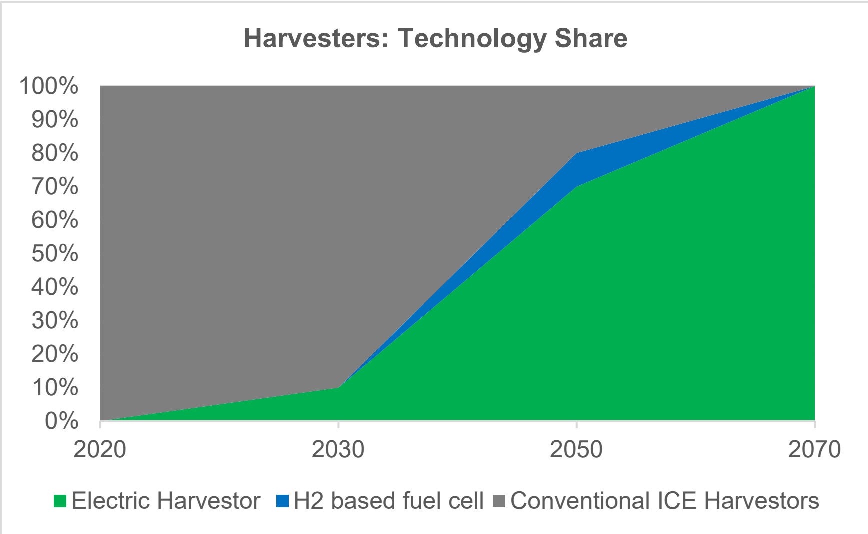
Detailed desk research and analysis have been conducted to project the demand for harvesters for the years 2030, 2050, and 2070. Taking into consideration the harvestable land in India and the level of mechanisation in developed countries, the harvester stock in FY 2070 was estimated. Based on this estimation for the number of harvesters in FY 2070, the year-on-year growth in the number of harvesters until FY 2070 was obtained. Considering the above year-on-year growth rate, the demand for harvesters in the country would be 0.08 Mn by 2030, and 0.2 Mn and 0.5 Mn by 2050 and 2070, respectively. A detailed list of assumptions, values and references is annexed in Annex 1.

Production Demand

Year	2020	2030	2050	2070
Harvester stock (Million)	0.05	0.08	0.2	0.5

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation and suitability of new technologies. The penetration level of the selected technologies is estimated considering the increased demand for harvesters due to growing mechanisation in farmland and India's target of net zero by 2070. Technology penetration levels are presented in the graph presented below.



The primary objective of the study was to focus on direct electrification and the technology associated with direct electrification, Electric Harvesters are the best alternative to conventional harvesters, as the GHG emission intensity of the electric harvester is low or nil if the source of electricity is RE when compared to conventional harvesters. The maturity level of the electric tractor is comparatively less than green hydrogen. That's why hydrogen-based fuel cell was estimated to penetrate the sector for 10% and by 2070 when electric tractors are commercialised and cost effective, it would completely replace all other technologies.

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on these scenarios, i.e., the effort of implementation resulting in the change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.196	0.2	0.093

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050 and 100% by 2070.

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.196	0.2	0.093

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050 and 100% by 2070. There is no change in energy consumption as we move from the conservative to the moderate scenario.

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	0.196	0.2	0.093

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070.

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070 average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based source of electricity. In the ambitious scenario, the power installation requirement for the sector would be **0.0025 GW** by 2030, and it is expected to increase by **0.17 GW, 0.27 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.6 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 32: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative / Moderate / Ambitious	0.0025	0.17	0.27

Table 33: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative / Moderate / Ambitious	0.003	0.29	0.6

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 0.62 million tonnes CO_{2e}, 1.55 million tonnes CO_{2e}, and 3.89 million tonnes CO_{2e} for years 2030, 2050, and 2070, respectively, in BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the pumps would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

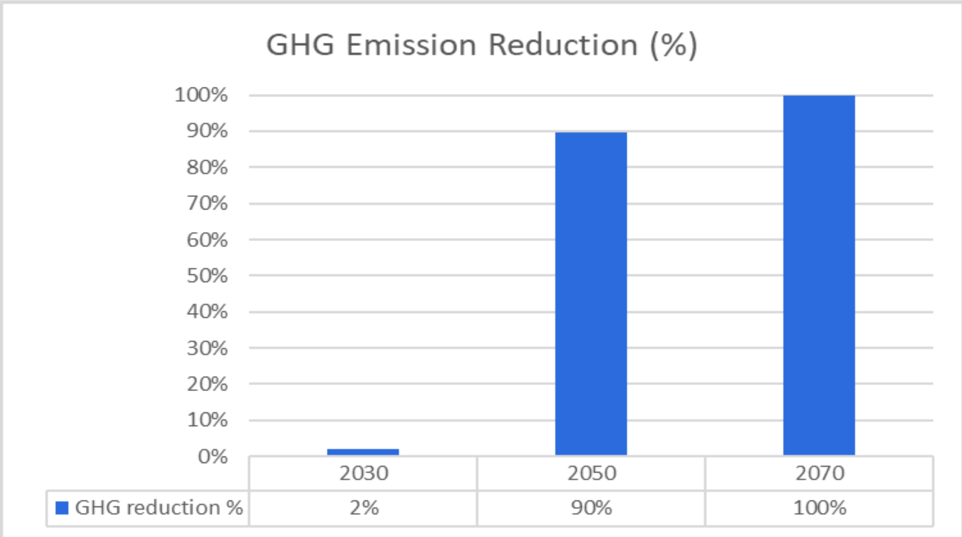


Figure 138: GHG emission reduction – Conservative

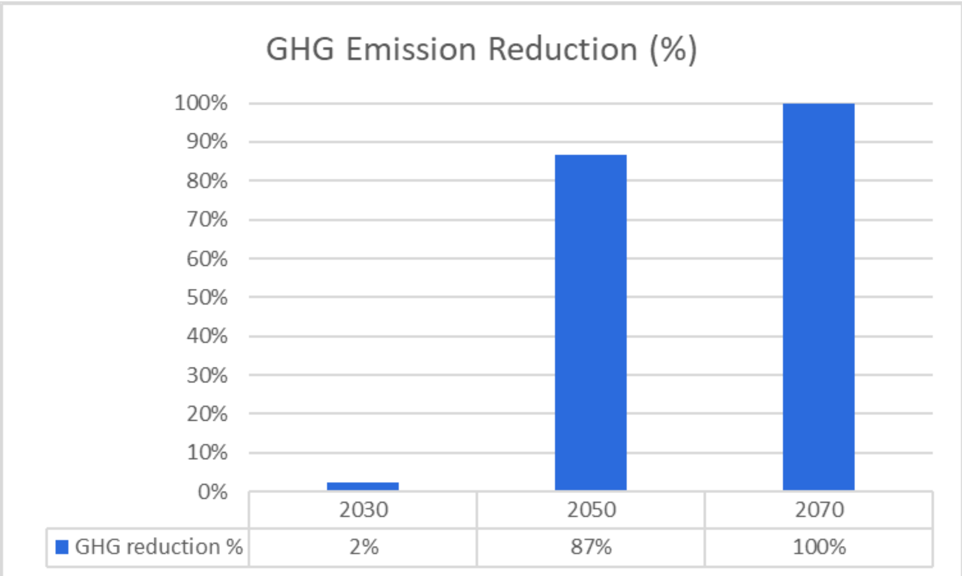


Figure 139: GHG emission reduction – Moderate

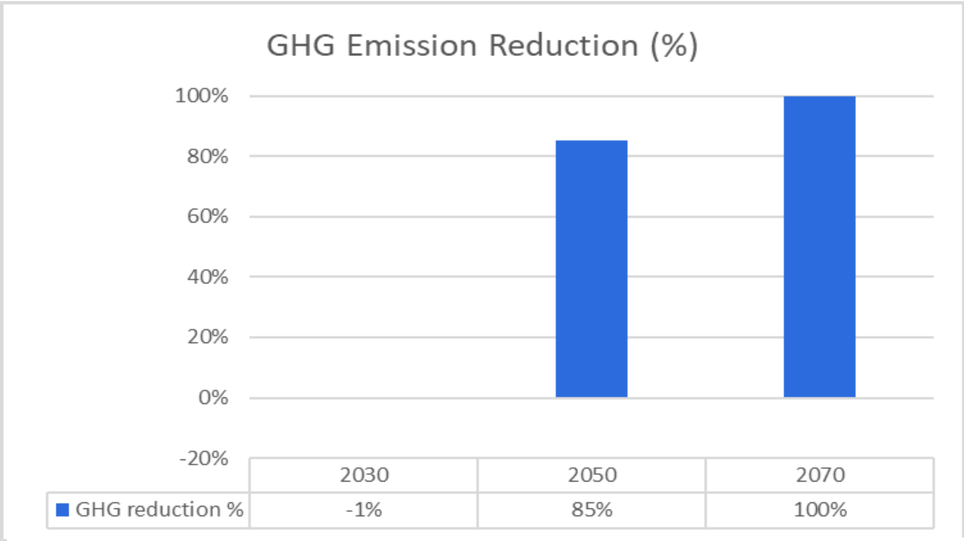


Figure 140: GHG emission reduction – Ambitious

4 Electrification of Transport

4.1 Electrification of Roadways

In India, it is estimated that passenger transport reached 6 trillion passenger kilometres (~725 km per person) in 2020[151]. India is one of the most important markets for motorcycles and scooters, at 20 million per year[152], whilst vehicle sales have doubled in the past decade, reaching 3 million per year. In addition, freight transport reached nearly 2 trillion tonne kms in 2020, with nearly half of goods being transported by rail and the other half transported by medium- to heavy-freight trucks[153]. Finally, by 2040, road-freight is expected to triple, leading to an additional 25 million trucks and a total of 300 million vehicles of all types, which is consequently projected to lead to the largest increase in oil demand of any country worldwide by 2040[154]. This implies that a significant shift in technology is required to bring down emissions from the transport sector and shift the entire sector from fossil fuels to sustainable technologies in the coming decades.

The Government of India has outlined measures to reduce emissions from the transport sector through The Mission on Sustainable Habitat published in the 2009 National Action Plan on Climate Change (NAPCC)[155], which includes better urban planning and a shift towards low-carbon transport systems. Moreover, the Government of India is committed to decreasing the emissions intensity of its GDP by up to 35% by 2030 compared to 2005, as well as reaching a share of 40% of renewable electricity capacity as outlined in India´s Nationally Determined Contribution (NDC)[156]. In order to meet the commitment, the Department of Heavy Industry published in 2012 the "National Electric Mobility Mission Plan" (NEMMP) 2020, which aims at promoting hybrid and electric vehicles. It sets out the target to achieve 6-7 million sales of hybrid and electric vehicles year on year from 2020 onwards by providing fiscal incentives. The main policy to achieve targets set out in the NEMMP is the "Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles" (FAME) scheme.

Overview

India has set for itself an e-mobility vision for 2030, which is 70 per cent of all commercial cars, 30 per cent of private cars, 40 per cent of buses, and 80 per cent of two-wheeler (2W) and three-wheeler (3W) sales to be electric by 2030. In addition, India has a goal to become net zero by 2070. Considering these targets, the roadways sector needs to be net zero by 2070, a target which will be achieved primarily by the electrification of vehicles.

With the deployment of electric vehicles, 100% of the energy consumption of the sector can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 55%, i.e., from 342 Mtoe in the base scenario to 154 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions: 55% by 2030,

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[151] ITF (2021), "Decarbonising India's Transport System: Charting the Way Forward", International Transport Forum Policy Papers, No. 88, OECD Publishing, Paris, https://doi.org/10.1787/4916dc15-en.

[152] Society of Indian Automobile Manufacturers (2021), Automobile domestic sales trends.

[153] IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

[154] International Energy Agency (IEA), World Energy Outlook Special Report: India Energy Outlook 2021

[155] National Action Plan on Climate Change (NAPCC) , Ministry of Environment, Forest and Climate Change https://moef.gov.in/wp-content/uploads/2018/04/Pg0152.pdf

[156] India Nationally determined contributions (NDCs), UNFCC, https://unfccc.int/documents/497567

100% by 2050, and 100% by 2070. Key findings of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

154 Mtoe of Energy Demand by 2070 from the sector

Reduction of **998 Mn tonne CO_{2e}** by 2070

Power demand of **446 GW** by 2070

Requirement of **277 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology and the level of efforts is as follows where the base scenario indicates the base projected scenario, which is a projection based on the correlation of GDP manufacturing of that particular sector and the production of the sector.

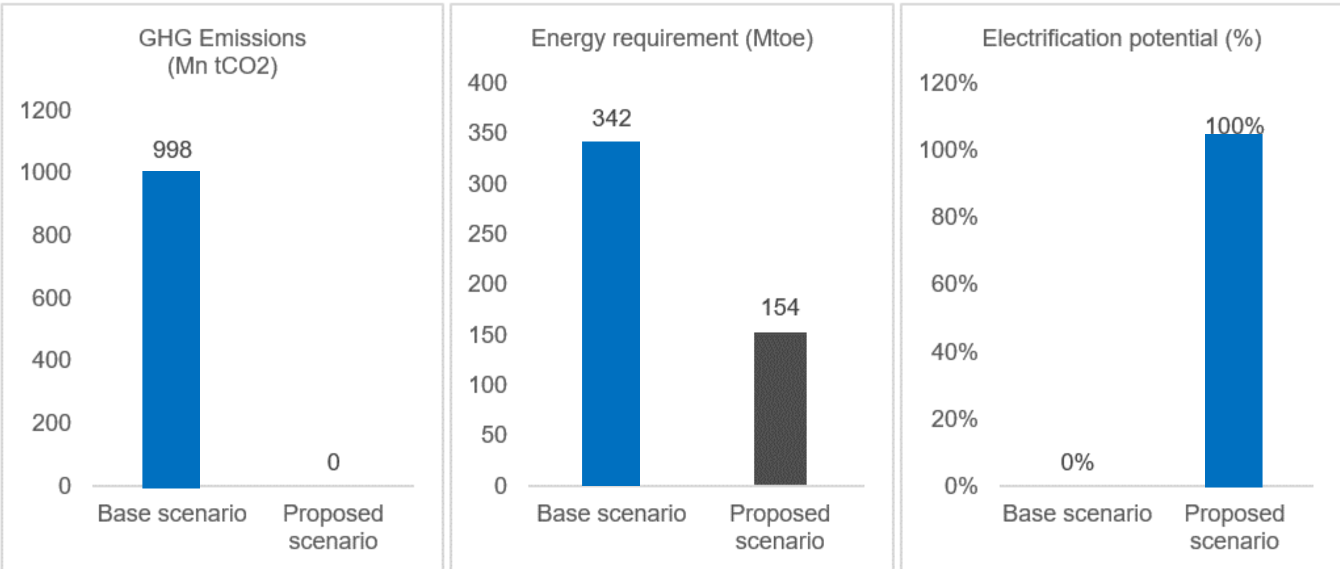


Figure 141: GHG emissions, energy requirement and electrification potential in proposed scenario

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Direct electrification of the transport sector, including trucks, vans, cars, motorcycles, and bicycles, is currently possible and is being implemented worldwide **(Table 34 and Table 35)**. Electrification of ships and aircraft is partially possible with current technologies.

Currently, state-of-the-art battery technologies are Li-ion batteries. Although Li-ion battery technologies are currently widely used in the e-mobility sector **(Table 34)** as well as for electrical storage, recent innovations in battery chemistry is leading to a new generation of batteries which are either using cheaper, more widely available components or batteries which have high energy density **(Figure 139),** faster charging rates and/or higher durability and which are expected to be brought onto the market by 2030. However, it is likely that a variety of battery chemistries will be used for different purposes and a single battery type is unlikely to fully replace Li-ion batteries in the immediate future.

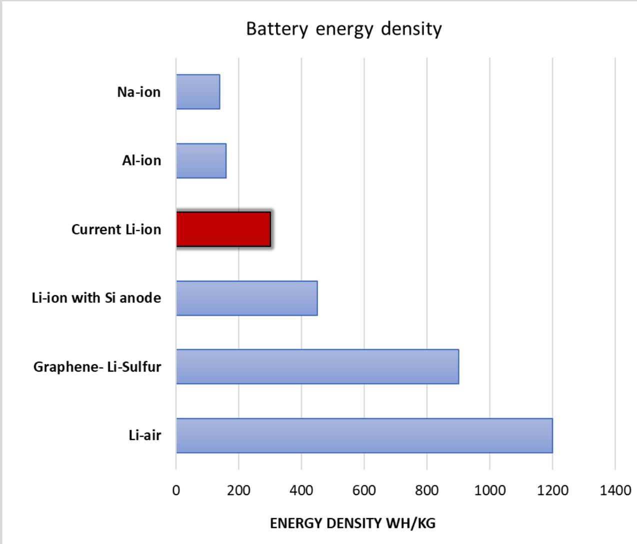


Figure 142: Illustration of battery energy density of different batteries. (Current Li-ion batteries are highlighted in red. Data are derived from CATL and Tesla for Li-ion batteries, Graphene Manufacturing Group for new Al-ion (Graphene) batteries, CATL and HINA B)

Table 34: Illustration of battery-powered vehicles, including efficiency, manufacturers and electrification (battery-powered)

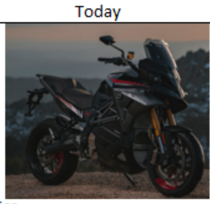
	Trucks	**Cars**	**Vans, Pick-up trucks**
Distances	200-800 km	95-685 km	240-330 km
Consumption	~ 0.8 kWh/km	~ 0.2 kWh/km	~ 0.3 kWh/km
Electrification	Li-ion Battery	Li-ion Battery	Li-ion Battery
Manufacturers	**BYD, Volvo Trucks, Daimler, Mercedes-Benz, Tesla Semi, Scania**	**Nio, VW Group, BMW, Tesla, Ford, Volvo, Polestar, Honda,Hyundai, Nissan, Kia, Jaguar, Lexus, BYD, Lucid, Mercedes-Benz**	**BYD, Ford, Maxus, Toyota, Fiat, Citroen, Renault, Maxus, Mercedes-Benz, Rivian**
Start of production	Today to 2024	Today	Today
Illustration	 Volvo Trucks	 Hyundai Ioniq	 BYD
	Buses	**Motocycles**	**Mining equipment**
Distances	120-550 km	95-400 km	-
Consumption	~ 1.4 kWh/km	~ 0..05 kWh/km	-
Electrification	Li-ion Battery	Li-ion Battery	Li-ion Battery
Manufacturers	**BYD, Protera, Volvo, Iveco, MAN, Daimler/Mercedes-Benz , Scania, VDL Groep, Yutong, Hess**	**Harley-Davidson, Zero, Lightning, Scorpio Electric, CSC, NIU, Sur-Ron, VOGE, EVOKE, Energica**	**Caterpillar:** battery electric 793 dump truck, Underground Mining R1700 XE; **Scania**
Start of production	Today to 2024	Today	Prototype/today
Illustration	 MAN	 Energica	 Caterpillar

Table 35: Illustration of electrification of transport with trolley-systems

	Mining equipment	Trucks	Buses	Trams
Consumption	-	-	1.5 kWh/km	1.5 kWh/km
Electrification	Li-ion, hybrid, trolley system	Li-ion, trolley system	Li-ion, supercapacitors, trolley system	Li-ion, supercapacitors, trolley system
Manufacturer	ABB E-Trolley	Siemens	Soaris, VanHole, Hess	Alston, Siemens
Start of production	Prototype	Prototype	Today	Today
Illustration	 ABB	 SIEMENS	 VanHool	 Alstom

Global Best Practice Examples

Timelines for the phasing-out of fossil-fuel cars are already being implemented in several countries as well as by several vehicle companies, with the most stringent targets set by Norway and Denmark (2025 and 2030 respectively) for countries as well as Jaguar and Volvo (2025 and 2030 respectively) for car manufacturers **(Figure 140)**. Even with such ambitious targets as Norway, the market is well on its way to phasing out fossil fuels before 2025, with the market share of electric vehicles reaching 65% in 2021 and 80% in 2022, with occasional monthly totals of electric vehicles reaching 90%[157]. As of 2022, over 20% of all vehicles in Norway were battery electric vehicles (BEV). This rapid transition to electric vehicles was a consequence of significant incentives such as free tolls, the exemption of purchase taxes, as well as the development of an extensive charging network throughout the entire country, which includes, as of 2022, a total of 18,000 charging stations, of which 5600 are rapid charging stations[158]. China has a requirement that 40% of all vehicles are to be electric by 2040 and has been leading the transition towards bus electrification, with several cities, such as Shenzhen, Tianjin, Zhengzhou, having already achieved 100% of bus fleet electrification as of 2022. By the end of 2020, there were already 378,700 Battery Electric Buses in China[159].

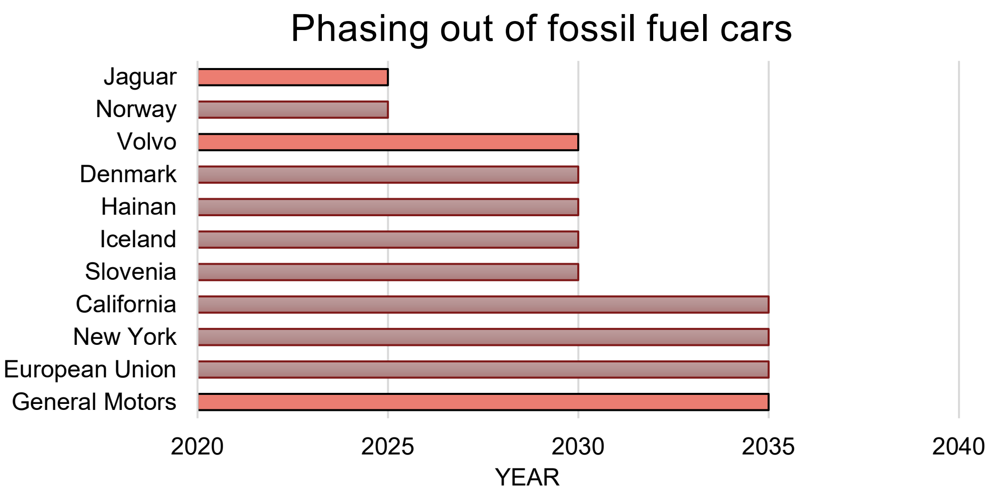
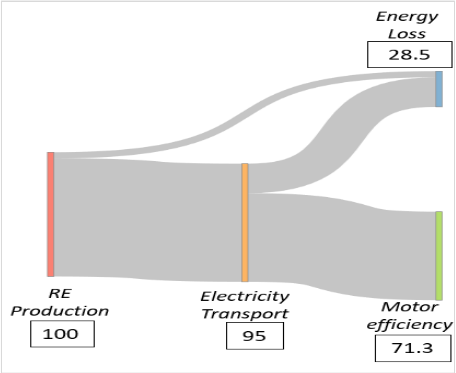


Figure 143: Timelines of phasing out fossil fuels for leading countries and vehicle manufacturers. (Note that fully electric manufacturers such as TESLA are not shown.)

Technology Readiness Levels (TRL)

[157] *The Norwegian Road Federation (www.of.no).*
[158] *Information accessible on www.ladestasjoner.no and www.elbil.no (March 2022)*
[159] *E-Bus Development in China: From Fleet Electrification to Refined Management - SUSTAINABLE TRANSITION CHINA (transition-china.org)*

Batteries: Li-ion batteries are a mature technology readily implemented throughout the transport sector and are, therefore, at a **TRL level 9**. Full penetration in different countries in the transport sector is currently underway. Na-ion technologies are currently produced by CATL and Hinai and are, therefore, at **TRL level 9**. Aluminium-Graphene batteries are currently being developed by The Graphene Manufacturing Group and The University of Queensland Research (Australia) and have higher energy- and power densities than Li-ion batteries. The first pilot manufacturing plant started producing batteries in 2021, indicating a **TRL level 6**. In 2021, a breakthrough in battery manufacturing is likely going to significantly decrease the cost of battery-powered vehicles and energy storage, as US-based Lyten will start manufacturing (Pilot plant by 2022, commercial plant by 2026) 3D Graphene Lithium-Sulfur batteries, which have 3 times the energy density of current batteries and lower weight, whilst being cobalt and nickel free (**TRL level 4 to 5**). Finally, in 2023, a breakthrough occurred in terms of solid-state Li-Air batteries, which have a theoretical energy density similar to the one of gasoline[160]. The lead researchers are now working with industrial partners to develop manufacturing of these batteries, indicating a **TRL 4-5**. Additional solid-state batteries with similar energy densities are currently being manufactured by Quantumscape[161] at a pilot facility and tested with several car manufacturers as of 2022. It is likely that solid-state batteries are still five years from being available at scale, but will significantly increase the electrification potential of trucks, cargo ships and planes in the 2030s.



Energy Efficiency

As illustrated in the adjacent figure, the total efficiency of battery-powered batteries is higher than 75%.

Compatibility with currently used technologies

The integrated electrical system of the electric vehicle has significantly fewer moving parts compared to a mechanical fossil-fuel-powered car (up to 90% less moving parts), implying that the car itself must be rebuilt around the battery pack. In addition, electric charging stations (standard and superfast chargers) will have to be installed throughout the road network in replacement of gas stations. However, the electrical grid is already in place and does not require as significant of an investment in comparison to other potential fuels (e.g., hydrogen).

[160] *Kondori, A., Esmaeilirad, M., Harzandi, A.M., Amine, R., Saray, M.T., Yu, L., Liu, T., Wen, J., Shan, N., Wang, H.H. and Ngo, A.T., 2023. A room temperature rechargeable Li2O-based lithium-air battery enabled by a solid electrolyte. Science, 379(6631), pp.499-505.*
[161] https://www.quantumscape.com/

Foreseen cost development

Li-Ion Batteries

Costs of Li-ion cells have dropped by 97% (as of 2020[162]) since their commercialisation in 1991 **(Figure 142)** and have reached a battery pack price of $132/kWh ($97/kWh for cells) according to a market analysis in 2021 by BloombergNEF. Costs have been decreasing in part due to the phasing-out of expensive materials such as cobalt from batteries. BNEF's 2021 Battery Price Survey predicts that the average price of a battery pack will be below $100/kWh by 2024 **(Figure 142 and Figure 141)**, although fluctuations in Li-prices might lead to yearly fluctuations in battery costs.

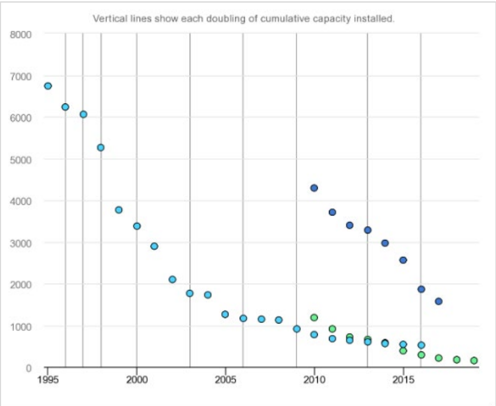


Figure 145: Evolution of Li-ion battery price (in USD/kWh), 1995-2019 (EIA, 2022) for consumer electronics (light blue), vehicles (green) and utility scale projects (dark blue)

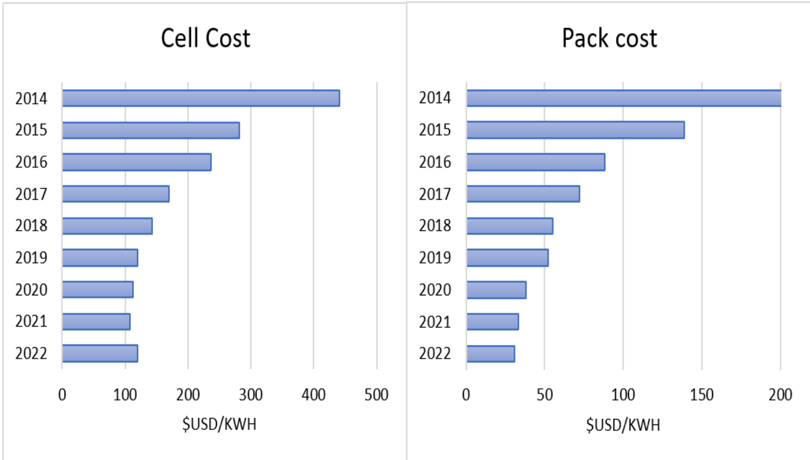


Figure 144: Evolution of average battery pack and cell price between 2014 and 2022 (Data from BloombergNEF, 2022).

Trolley-truck infrastructure

In terms of developing the infrastructure for trolley trucks on specific highway sections, a study in Sweden has estimated that a cost of € 2.5 million per kilometre of electric road in both directions in would be required[163]. Although the investment in such a system is significant, it must be weighed against the installation of superfast charging infrastructure specifically designed for large trucks. For instance, a report on bus electrification in Canada showed in 2022 that the cheapest option was indeed a trolleybus system as opposed to battery-powered buses when considering capital and operational expenditures[164].

[162] Ziegler, M.S. and Trancik, J.E., 2021. Re-examining rates of lithium-ion battery technology improvement and cost decline. Energy & Environmental Science, 14(4), pp.1635-1651.

[163] Börjesson, M., Johansson, M. and Kågeson, P., 2021. The economics of electric roads. Transportation Research Part C: Emerging Technologies, 125, p.102990.

[164] M. Wright, Bus Electrification: A comparison of capital costs, Urban Transport Magazine, https://www.urban-transport-magazine.com/en/bus-electrification-a-comparison-of-capital-costs/ (accessed 02 March 2023)

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Fuel Cell Electric Vehicles (FCEV)

Fuel cell electric vehicles (FCEVs) are powered by hydrogen. They are more efficient than conventional internal combustion engine vehicles and produce no harmful tailpipe emissions—they only emit water vapor and warm air.

FCEVs use a propulsion system similar to that of electric vehicles, where energy stored as hydrogen is converted to electricity by the fuel cell. Unlike conventional internal combustion engine vehicles, these vehicles produce no harmful tailpipe emissions. FCEVs are fuelled with pure hydrogen gas stored in a tank on the vehicle. Similar to conventional internal combustion engine vehicles, they can fuel in about 5 minutes and have a driving range of more than 300 miles. FCEVs are equipped with other advanced technologies to increase efficiency, such as regenerative braking systems that capture the energy lost during braking and store it in a battery.

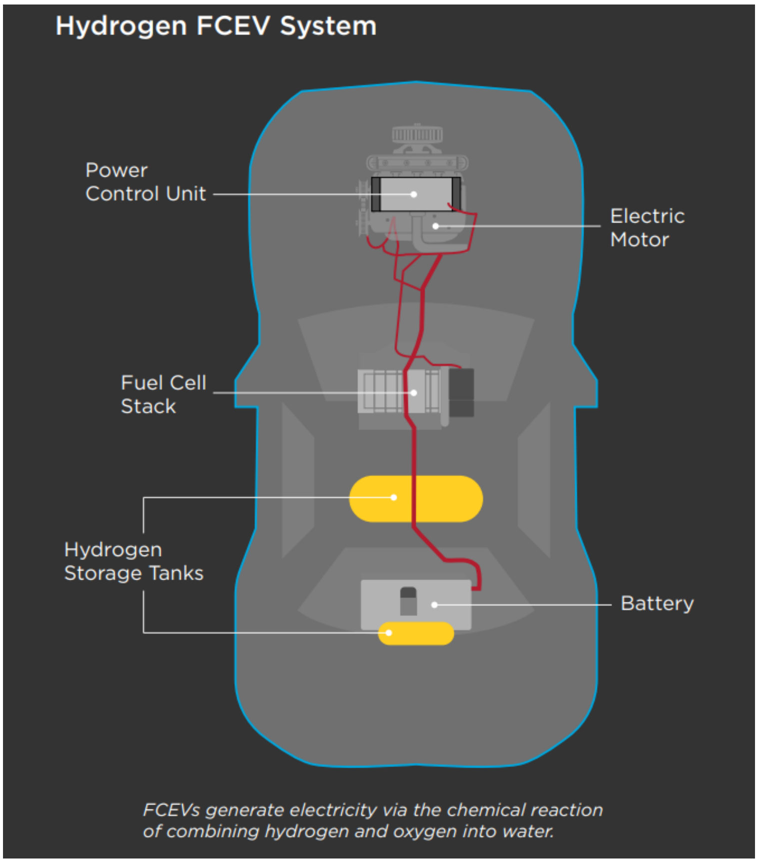


Figure 146: FCEV Infographic

The most common type of fuel cell for vehicle applications is the polymer electrolyte membrane (PEM) fuel cell. In a PEM fuel cell, an electrolyte membrane is sandwiched between a positive electrode (cathode) and a negative electrode (anode). Hydrogen is introduced to the anode, and oxygen (from air) is introduced to the cathode. The hydrogen molecules break apart into protons and electrons due to an electrochemical reaction in the fuel cell catalyst. Protons then travel through the membrane to the cathode. The electrons are forced to travel through an external circuit to perform work (providing power to the vehicles) and then recombine with the protons on the cathode side, where the protons, electrons, and oxygen molecules combine to form water.

ELECTRICITY REQUIRED FOR FULL DECARBONISATION

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation, and suitability. The penetration level of the selected technologies is estimated considering India's *2030 target for EV penetration* and target of *net zero by 2070*. Due to the current and future advancements in battery technology, electric vehicles are more favourable than other technologies like fuel cell electric vehicles. FCEVs are comparatively less energy efficient than electric vehicles because there is a double loss first from the generation of hydrogen through and its storage, and second loss is the transitioning of hydrogen from fuel cell to electricity. Currently, a Li-ion battery has an energy density of 350 Wh/kg, and the proposed Li-air battery would have having energy density as high as 1200 Wh/kg.

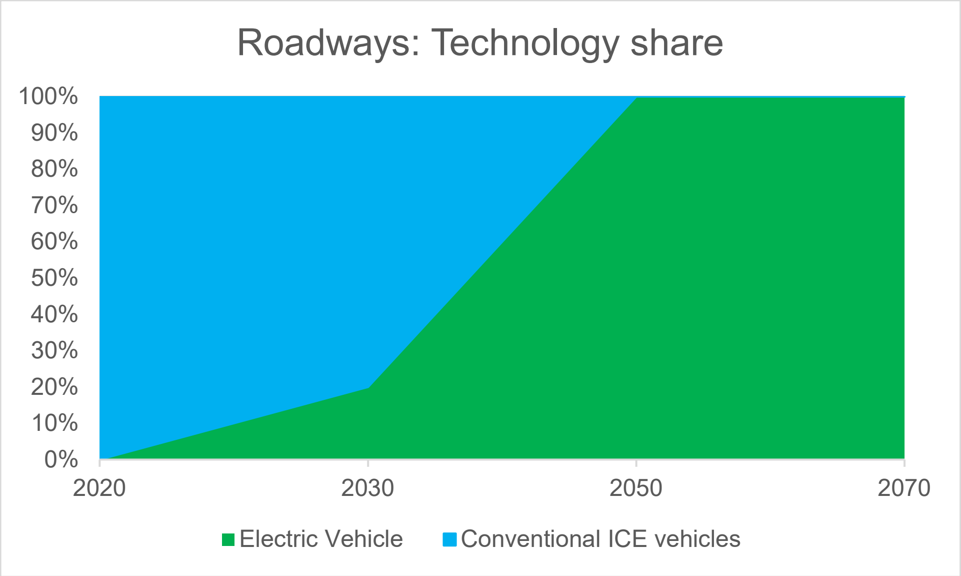


Figure 147: Penetration level of electrification technologies – Roadways

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenario, i.e., the effort of implementation results a change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	66	123	154

In the conservative scenario, efforts of penetration of the technology are considered at lower levels, i.e., 30% by 2030, 70% by 2050 and 100% by 2070.

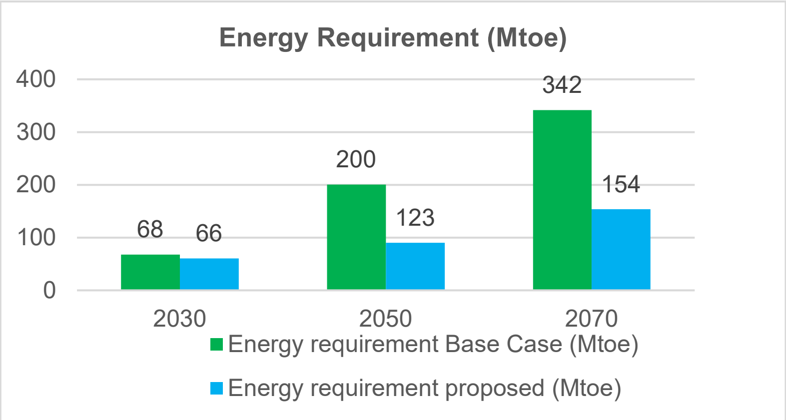


Figure 148: Energy requirement (Conservative - Roadways)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	64	101	154

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of the conservative scenario.

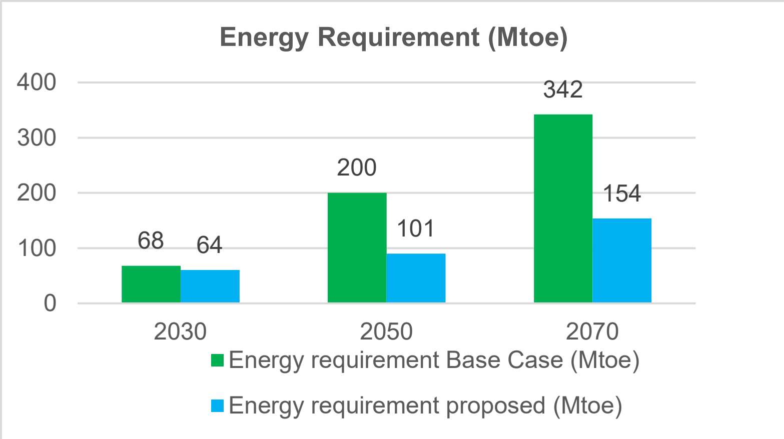


Figure 149: Energy requirement (Moderate - Roadways)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	61	90	154

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of conservative and moderate scenarios.

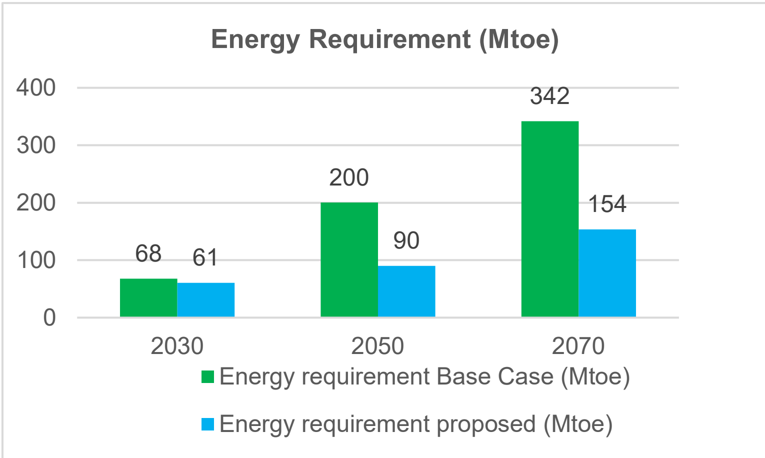


Figure 150: Energy requirement (Ambitious - Roadways)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070 average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based source of electricity. In the ambitious scenario, the power installation requirement for the sector would be **39 GW** by 2030, and it is expected to increase by **341 GW, 446 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **3.5 - 11 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 36: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	8	315	446
Moderate	14	336	446
Ambitious	27	334	446

Table 37: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	3.5	149	277
Moderate	6	157	277
Ambitious	11	156	277

Projected GHG emission reduction

The total GHG emissions for the sector is estimated to reach 198 million tonnes CO_{2e}, 585 million tonnes CO_{2e}, and 998 million tonnes CO_{2e} for the years 2030, 2050, and 2070 respectively, in BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the vehicles would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

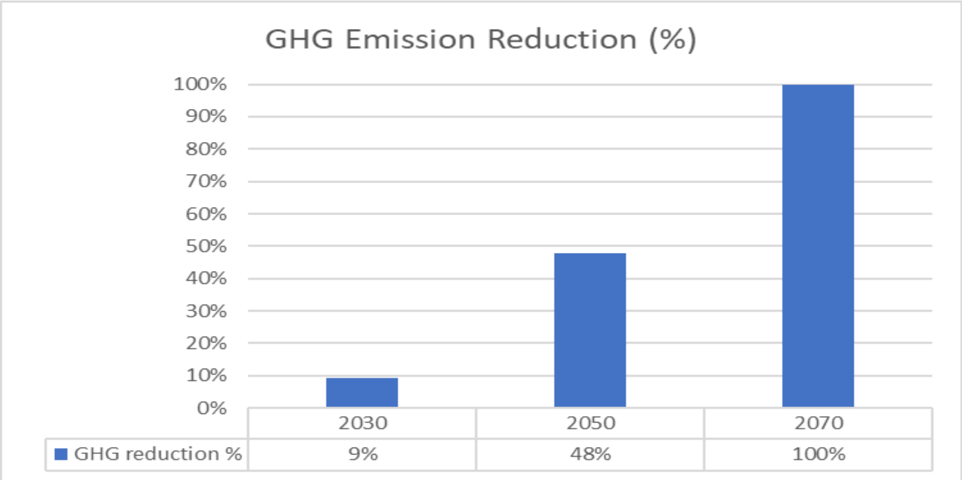


Figure 151: GHG emission reduction (Conservative – Roadways)

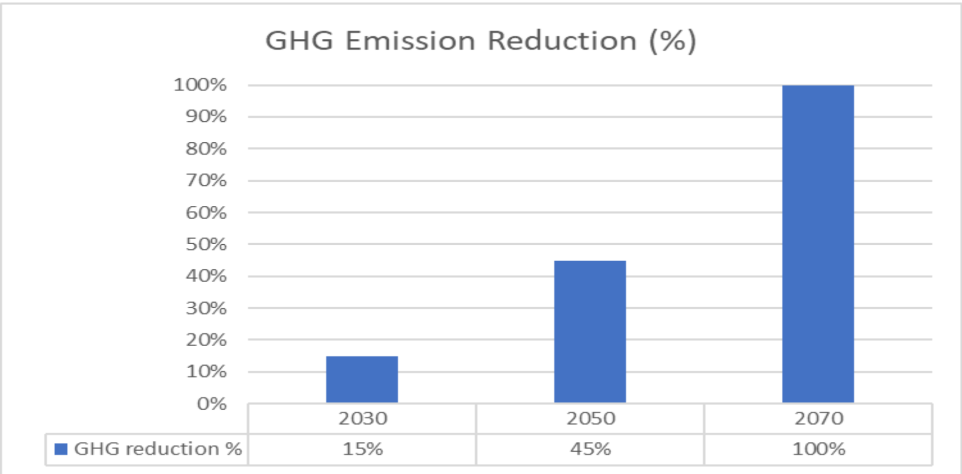


Figure 152: GHG emission reduction (Moderate – Roadways)

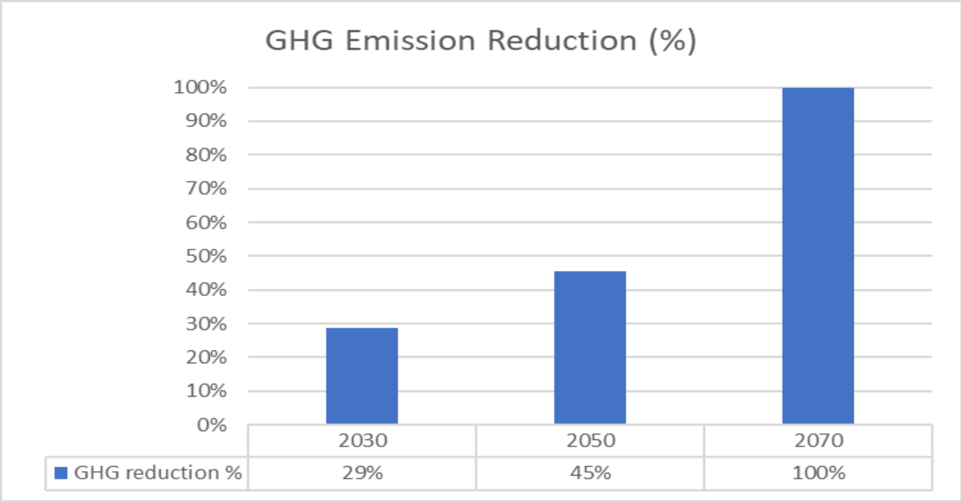


Figure 153: GHG emission reduction (Ambitious – Roadways)

4.2 Electrification of Shipping

SECTOR OVERVIEW AND EXISTING GOALS

According to the Indian Ministry of Ports, Shipping and Waterways, around 95% of India's merchandise trade is done through maritime transport. India has 12 major ports **(6 on the eastern coast and 6 on the western coast)** and 205 notified minor and intermediate ports. India is the sixteenth-largest maritime country in the world, with a coastline of about 7,517 km.

As of now, the Indian Shipping Industry is mostly reliant on fossil fuels, with LNG being introduced very recently in 2020.

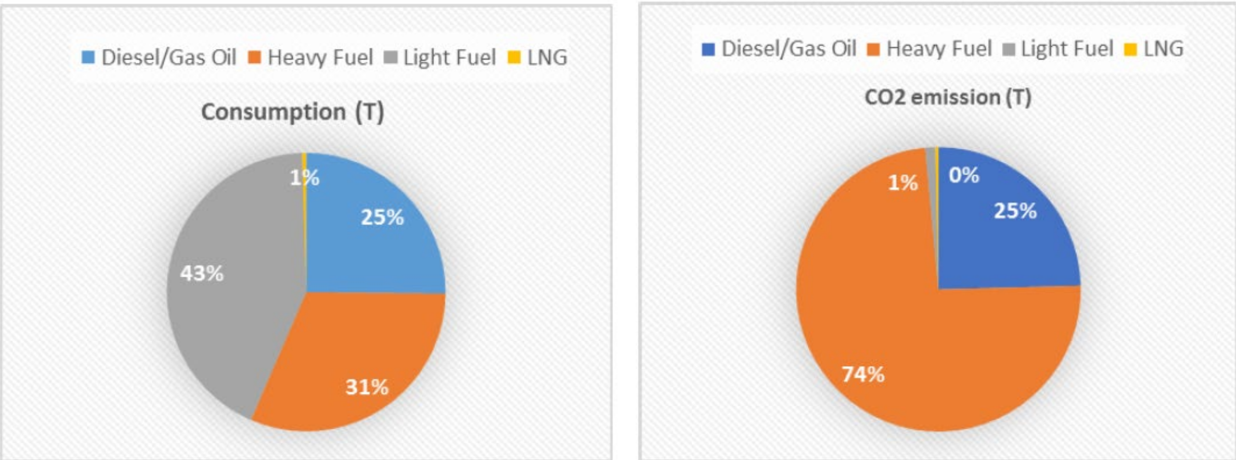


Figure 154 – Indian shipping fleet fuel consumption and CO2 emission summary[165]

For domestic shipping, there are five National Waterways (NWs) with a total length of 4,400 km. The waterways include Ganges, Brahmaputra, Krishna and Godavari, West Coast Canal, and the East Coast Canal.

As of 31st December 2021, India had a fleet strength of 1491 vessels with gross tonnage (GT) of 12.99 million. Out of the 1491 vessels, 1027 vessels (68.9%) with 1.56 million GT were engaged in coastal trade. Out of these 1027 vessels, the maximum number of vessels (372) were registered under the category "Tug". The remaining 464 vessels (31.1%) with 11.43 million GT were deployed for overseas trade. Thus, the tonnage deployed for overseas trade was 88% of Indian GT in contrast to 12% of the tonnage deployed for coastal trade.[166]

In November 2022, India's Ministry of Ports, Shipping, and Waterways launched the National Centre of Excellence for Green Port & Shipping (NCoEGPS), the country's first initiative towards providing greener solutions for the ports and shipping industries. The centre aims to develop a regulatory framework and alternative technology adoption roadmap for Green Shipping to foster carbon neutrality and a circular economy in the shipping sector in India, aligning with Prime Minister Narendra Modi's vision. The center's scope will focus on policy, regulatory and research, human resource development, network, exploration, and engagement. The Deendayal Port Authority Kandla, Paradip Port Authority, Paradip, V.O Chidambaranar Port Authority, Thoothukudi, and Cochin Shipyard Limited have extended their support to the ministry to establish this center.[167]

[165] https://www.dgshipping.gov.in/WriteReadData/userfiles/file/202207151041353645818AnnualFuelConsumptionReport2019-2020.pdf
[166] https://shipmin.gov.in/sites/default/files/ISS_2021_FINAL.pdf
[167] https://pib.gov.in/PressReleasePage.aspx?PRID=1877297

According to the Ministry of Ports, Shipping, and Waterways, India aims to increase the share of renewable energy to 60% of the total power demand of each of its major ports, up from a current share of less than 10%. The country also intends to reduce carbon emissions per ton of cargo handled by 30% by 2030. India's National Maritime Vision Document 2030 outlines a 10-year plan for a sustainable maritime sector and vibrant blue economy. The document includes goals such as increasing port capacity, improving logistics and infrastructure, and promoting coastal shipping as a cost-effective and environment-friendly mode of transport. India has also been selected as the first country under the IMO Green Voyage 2050 project to conduct a pilot project related to green shipping. This project aims to demonstrate the feasibility and practicality of using low-carbon and zero-carbon fuels and technologies in the shipping industry.[167]

In addition to the NCoEGPS, India is working actively with the Marine Environmental Protection Committee of the IMO to help devise acceptable regulatory requirements for GHG emission reduction in line with the IMO GHG initial strategy. The country is also implementing IMO energy efficiency requirements for existing ships and carbon intensity requirements on all its vessels, whether coastal or international, to help achieve IMO GHG reduction targets. Green shipping is expected to become more prevalent in the coming years as the shipping industry looks for ways to reduce its carbon footprint and achieve carbon neutrality. Countries and companies around the world are investing in green shipping technologies and exploring alternative fuels such as hydrogen, ammonia, and biofuels to meet their sustainability goals. [167]

The Directorate General of Shipping in India is also taking action to reduce GHG emissions from both Indian ships and foreign ships visiting Indian ports. Measures include supplying shore power to all ships at Indian ports by 2030 and enhancing port efficiencies to reduce ship stay in ports and turnaround time. The Directorate is also conducting a study with Norway to identify alternate fuels, technologies, and policy changes for the decarbonization of various ship types operating on the Indian coast. Pilot projects on bio-fuel blends have been conducted, and regulatory barriers are being addressed. [165]

India is also working on the Green Corridor with QUAD members and participating in the IMO Green Voyage 2050 project, which aims to start green shipping pilots in India that can be scaled up for adoption by other stakeholders. A Centre of Excellence related to Green Shipping, Regulatory Partnership, Digital Solutions, and Ship Recycling is being established at The Energy and Resource Institute in New Delhi. An MoU has been signed with Norway to establish a Maritime Knowledge Cluster - India, providing a platform for researchers and industry partners to interact and innovate in the mercantile marine sector [165]

While the transition to electric propulsion for ocean-going vessels will be less evident in the short to medium term, many large ocean-going vessels, such as offshore supply, large passenger ferries, and those serving the oil and gas industry, already use electrification in their propulsion systems. The electrification of propulsion systems within a vessel enables the optimization of power generation and energy efficiency, which can dramatically lower CO_2 emissions even if the overall power source comes from diesel. [168]

The electrification of marine transport has been widely recognized as one of the most effective solutions to reduce emissions in the industry, especially considering the International Maritime Organization's directive to cut emissions by 50% by 2050. However, the current energy crisis has

[168] https://www.danfoss.com/en/about-danfoss/articles/cf/electrification-is-the-future/#:~:text=Shipowners%20are%20now%20choosing%20to,effective%20and%20appealing%20to%20owners

brought an unprecedented focus on efficient solutions that reduce energy consumption from fossil fuel sources, making the electrification of marine transport more relevant than ever.[169]

The short-range marine transport sector, such as ferries, tugboats, and those transporting food, has the greatest potential for electrification. These vessels can operate using battery power and be charged while idle in ports using renewable energy sources. With technological advancements and battery improvements, larger vessels can now operate on longer routes using fully electric or hybrid-electric power.

The declining cost of batteries and the availability of renewable energy sources have made electrified vessels more cost-effective and appealing to owners, leading to an increasing number of shipowners choosing to implement electrical solutions on board. The industry is making progress in reducing emissions, with around 900 ferries operating on shorter routes in Europe alone, all with the potential to be electrified.[169]

Norway is a great example of how legal requirements can accelerate the transition to electrification in the marine industry. New Government regulations will make zero-emission mandatory in the World Heritage sites of Geirangerfjord and Naeroyfjord by 2026, which means that only electric vessels will be allowed to operate in these areas.[169]

Although there is still a long way to go to create the necessary infrastructure to support a fully electric marine industry, we can already see it being developed in major European cities where electric ferries are in use. The demand for electric vessels is expected to increase over the next few years, and many companies are already expanding their staff to keep up with demand. Overall, the electrification of the marine industry presents an exciting opportunity to reduce emissions and increase efficiency in the sector.

DECARBONISATION POTENTIAL

Electric ships, H_2 fuel-based ships and methanol fuel-based ships will be part of the shipping sector in 2070 in the electrification or decarbonisation scenario. With the deployment of these technologies, 30% of the energy consumption of the sector can be electrified from the existing 0% level. This implementation would result in a slight drop in the energy consumption of the sector by 33%, i.e., from 33.3 Mtoe in the base scenario to 22 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions of 100% by 2070. Key findings of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

22 Mtoe of Energy Demand by 2070 from the sector

Reduction of **99 Mn tonne CO_{2e}** by 2070

Power demand of **44 GW** by 2070

Requirement of **128 GWh** of battery storage capacity by 2070

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

[169] https://www.danfoss.com/en/about-danfoss/articles/cf/electrification-is-the-future/#:~:text=Shipowners%20are%20now%20choosing%20to,effective%20and%20appealing%20to%20owners

Battery electric ships

About

Battery-electric ships use batteries to store energy, which is then used to power electric motors that drive the propellers. These batteries can be charged using shore power, renewable energy sources, or onboard generators.

The greatest growth potential for marine transport electrification can be seen in vessels operating on short journeys close to shores and coastal areas, such as ferries, tugboats, and those transporting food. These vessels can fully operate on battery power and since they frequently enter harbors, it is easy for them to charge while standing idle in ports using renewable energy sources. These types of ships, on average, can potentially travel up to 80 km on a single charge. The distance and time the electric ship can travel varies depending on the size of the batteries and the duration of charge.

Electric ships offer several benefits over traditional diesel-powered ships, including reduced emissions, increased efficiency, and lower operating costs. By eliminating the need for fossil fuels, electric ships can significantly reduce greenhouse gas emissions and air pollution, making them a more sustainable option for the shipping industry. Electric ships are also quieter and require less maintenance than traditional diesel-powered ships since they have fewer moving parts.

Technology Readiness Levels (TRL)

Battery electric ships have reached a relatively high TRL level, around TRL 7 or 8, as they have been successfully demonstrated in several pilot projects and are currently being used in some commercial applications. Some inland vessels already sail using electricity, mainly ferries and pleasure boats. That’s because they sail shorter distances and can, therefore, use smaller batteries.

However, the widespread adoption of battery electric ships is still hindered by several challenges, including the high cost of batteries, limited range, and the need for extensive charging infrastructure.

To increase the TRL level of battery electric ships, further research and development are required to improve battery technology for large ships, increase range, and reduce costs. Infrastructure improvements, such as the installation of more charging stations and the use of renewable energy sources, will also be necessary to support the widespread adoption of battery electric ships.

Energy Efficiency

Battery electric ships are almost twice as efficient as ships with an internal combustion engine and the higher efficiency will offset the higher price of electric ships, given an average lifetime of 20-25 years.[170]

Compatibility with currently used technologies

The feasibility and cost-effectiveness of retrofitting existing fossil fuel-based ships can vary depending on the type and age of the ship, as well as the specific retrofit technology being used. Electric ships require electric motors and batteries or fuel cells to power the propulsion system, which is very different from conventional diesel engines used in traditional ships. In some cases, it may be necessary to replace the entire propulsion system, which can be expensive and time-consuming.

Electric ships are compatible with traditional oil-fuelled ships in terms of their ability to operate in the same waterways and ports. However, there are some challenges to integrating electric ships into existing shipping infrastructure and operations. Existing ports and shipping infrastructure are designed to support traditional oil-fuelled ships and may not have the necessary infrastructure to support electric ships. Ports will need to invest in charging infrastructure and other electrical equipment to support the charging of electric ships.

In addition, electric ships may require different maintenance and repair procedures compared to traditional oil-fuelled ships. This could require additional training for shipyard workers and other personnel.

Foreseen cost of development

Electric ships can potentially cost about three times a conventional ship price, but they may reduce operational expenses by 90%.[171]

Global adoption

Since 2015, the world's first electric vehicle ferry, the "Ampere," has been operating a regular scheduled service in Norway. It sails silently and without exhaust gases back and forth on the Sognefjord between Lavik and Oppedal 34 times a day, covering a distance of six kilometres each time. The ferry was developed by Siemens and Norwegian shipbuilder Fjellstrand and has lithium-ion battery packages installed in the ship and at both ports, each with a capacity of 1,600 automobile batteries. The ferry's batteries are briefly charged at each 10-minute stop and fully charged overnight using electricity from a hydroelectric power plant. Thanks to its lightweight aluminium design, the Ampere is only half the weight of a conventional vehicle ferry, despite its 11-ton battery. It saves a million litres of diesel each year, and its operating costs are about 80 percent lower. Additionally, its CO_2 emissions are only five percent of those of a conventional ferry.[172]

Figure 155 - World's first electric ferry, Ampere, constructed for Norled by the Norwegian Shipyard Fjellstrand[4]

[170] https://www.danfoss.com/en/about-danfoss/articles/cf/electrification-is-the-future/#:~:text=Shipowners%20are%20now%20choosing%20to,effective%20and%20appealing%20to%20owners
[171] https://www.sustainable-ships.org/stories/2021/worlds-first-electric-cargo#:~:text=She%20can%20carry%20a%20little,OPEX%20for%20Yara%20by%2090%25
[172] https://www.infineon.com/cms/en/discoveries/electrified-ships/

China has the first fully electric container ship – initially as a trial on Pearl River in Southern China. It is planned only for use on inland waterways, as the ship can travel a distance of just 80 kilometres. The 1,000 lithium-ion batteries on board weigh 26 tons and achieve 2,400 kilowatt hours. Norway is also working on an electric container ship: From the early 2020s, the "Birkeland" will transport chemicals and fertilizer from the plants of manufacturer Yara to the port in Brevik. The company uses trucks for this at present – around 40,000 trips per year. The ship will transport 120 containers.[173]

A fully electric ferry has also been sailing on the river Mosel in Germany since spring 2018. The "Sankta Maria II" transports 45 passengers and six cars. Some of the electricity is generated by 15 solar modules and is stored in two battery blocks. They have a capacity of 252 kilowatt hours. This enables the ferry to sail for 6.5 hours. Electric ferries also sail on other rivers: on the Ruhr in Witten, Germany, two electrically powered ships are in use and in Berlin, the four solar-powered ferries "FährBär 1 to 4" have been sailing on the Spree since 2014. Amsterdam wants to ban all diesel-powered passenger ships and ferries from the city canals by 2025.[173]

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Biofuels

About

Biofuels are fuels made from biomass materials, such as ethanol and can be used alone or blended with fossil fuels. They are considered the most "technologically ready" alternative zero-emission fuel option and are already being used, such as in the form of drop-in fuels like HVO or blend-in fuels like FAME (Fatty Acid Methyl Ester). However, the sustainability and scalability of biofuels are still being studied. The availability of biofuels for shipping depends on scalability, sustainability, and demand from other industries. Sustainability criteria and certifications are important to consider when exploring the use of biofuels in shipping's transition to decarbonization.

FAME is a popular biodiesel due to its shared properties similar to fossil fuel diesel. This form of biofuel is produced from fats, oils, and greases (FOGs) that are recycled from waste, which can come from a wide range of sources such as food production waste from factories, restaurants and households, or oil seeds such as rapeseed and palm seed.

To date, only trials have been completed using FAME blends, with a maximum of 30% being used by a vessel funded by the Mediterranean Shipping Company.

BTL, a type of synthetic fuel, is created through the thermo-chemical conversion of biomass. While the resulting fuels may differ chemically from traditional gasoline or diesel, they can still be used in diesel engines.

HVO, also known as hydrogenation-derived renewable diesel, is produced by refining fats or vegetable oils through a hydrotreating process called fatty acid-to-hydrocarbon hydrotreatment. This process can be used alone or in combination with petroleum. Unlike FAME biodiesel, HVO/HDRD is considered renewable diesel and can be directly used in existing diesel engines and fuelling facilities without any additional modifications. While the production process for HVO/HDRD is generally more expensive than for FAME biodiesel, the resulting fuel is a drop-in replacement that can be used immediately.

Technology Readiness Levels (TRL)

The overall use of biofuels in the marine industry can be assigned a TRL of 7-8. The Global Maritime Forum (GMF) states that biofuels are the most advanced among existing zero-emission fuel

[173] https://www.marineinsight.com/shipping-news/marine-biofuel-demonstration-on-lpg-carrier-completed/

alternatives in terms of technology readiness. They are already available in the form of drop-in fuels, such as hydrotreated vegetable oil (HVO), or blend-in fuels, like fatty acid methyl ester (FAME), which can be used in traditional engines without any modifications. Biofuels, such as biomethanol, are also used as alternative fuels in specialty engines.[174]

Energy Efficiency

Biofuels such as biodiesel provide 93% more usable energy than the fossil energy required for its production, which means that more energy can be extracted from it. Additionally, biodiesel reduces greenhouse gas emissions by 41% compared to diesel, making it an environmentally friendly alternative. It also helps to reduce major air pollutants, resulting in cleaner air. Moreover, biodiesel has minimal impact on human and environmental health through the release of nitrogen, phosphorus, and pesticides.[175]

Compatibility with currently used technologies

Currently, fuel blends of around 20-30% do not require any engine modification in a ship. Biofuels have an established infrastructure due to their use in multiple sectors. The infrastructure required for this alternative fuel can rely on existing HFO bunkering infrastructure, making transitioning to this fuel significantly cheaper. Existing commercial-scale second-generation biofuel market data is limited, which in turn severely limits estimations of scalability and supply/demand for FAME.

Foreseen cost of development

Currently, fuel blends of around 20-30% do not require any engine modification in a ship.

Global adoption

In March 2023, Astomos Energy Corporation and NYK Line successfully completed a pilot to test the use of FAME B24 marine biofuel in the LPG carrier Lycaste Peace, which was bunkered in Singapore. The demonstration is part of a project led by the Global Centre for Maritime Decarbonisation to establish an assurance framework for the supply chain of sustainable biofuels. The test showed that biofuels can be used without modifying existing ship engines and port infrastructure. Biofuels are expected to be one of the most promising next-generation fuels for decarbonisation, as they are considered carbon-neutral and made from biomass and feedstock such as waste cooking oil. The project aims to establish transparency in the supply chain of marine biofuels from upstream to downstream to ensure their wider adoption by the industry.[176]

Figure 156 - Chikura Maru, one of the tugs in the biofuel trial[12]

In March 2023, Norden and Spar Shipping bunkered 1100 tonnes of biofuel in Rotterdam for two voyages bound for Asia and Africa. This is a significant milestone in Norden's drive to provide greener transportation options, as biofuel can be used onboard vessels without any modification to the current engine design, minimizing risk for shipowners.[177]

NYK Line and Shin-Nippon Kaiyosha have launched a 100% biofuel supply trial for ships in Japan. The companies are using Neste Renewable Diesel, produced from waste cooking oil and animal oils, in Shin-Nippon Kaiyosha-run tugboats. Biofuel is expected to reduce greenhouse gas emissions by

[174] https://www.gasworld.com/story/new-shipping-deal-aims-to-decarbonise-maritime-industry-with-biofuels/
[175] https://www.pnas.org/doi/10.1073/pnas.0604600103#:~:text=Biodiesel%20provides%2093%25%20more%20usable,%2C%20P%2C%20and%20pesticide%20release
[176] https://www.marineinsight.com/shipping-news/marine-biofuel-demonstration-on-lpg-carrier-completed/
[177] https://glginsights.com/articles/low-carbon-fuel-alternatives-in-the-maritime-industry/

nearly 90% compared to petroleum-derived diesel. The trial is the first of its kind in Japan and is part of NYK's efforts to reduce emissions in the shipping industry.[178]

Hydrogen

Hydrogen (H_2) is one of the most viable fuels in the long term. Green H_2 produced from renewable energy through the process of electrolysis is the only viable option as an alternative shipping fuel, as it produces net zero life cycle emissions, unlike steam methane reforming, which produces high quantities of CO_2. Hydrogen can be utilized to fuel ships through various methods such as combustion engines, blending it with other fuels, or storing it in liquid organic solutions or ammonia. However, the most eco-friendly and widely used approach is to generate power from hydrogen through fuel cells.

Due to the early design phase for H_2 FCs, current applications can be considered for smaller vessels, such as ferries or passenger ships. H_2 FCs and engines have not yet been scaled up for merchant vessels and are still currently in the development stage, but they were successfully tested for maritime use in 2016. To power ships, hydrogen must be loaded into fuel cells, where it is converted into electricity and heat energy to drive the propulsion mechanism. This process, unlike electrolysis, can provide a continuous energy supply if fuel is provided to the cell, making it advantageous over batteries, which require recharging. Fuel cells have no moving parts, operate quietly, and can be easily scaled up for larger ships by stacking individual cells.[179]

Blue and green hydrogen are viable options for significantly reducing GHG emissions in the shipping industry, while fuel cells produce only water vapor and oxygen as by-products, reducing air pollution and limiting noise.

India aims to establish a hydrogen-based shipping industry by retrofitting at least two ships operated by its largest fleet operator, the state-run Shipping Corp of India (SCI), to run on green hydrogen-based fuels by 2027. Additionally, all state-run oil and gas firms that charter 40 vessels for fuel transport must annually hire at least one ship powered by green hydrogen from 2027 to 2030.[180]

Technology Readiness Levels (TRL)

Several pilot projects using hydrogen in shipping have been successfully completed already so a higher TRL 7-8 can be assigned. Although, there is still a lot of scope to improve the economies of scale of hydrogen production.

Energy Efficiency

Fuel cell efficiency of over 60% has been demonstrated, and over 80% efficiency is possible under certain conditions.[179]

Compatibility with currently used technologies

If H_2 is used as a fuel for the transport sector, a significant scaling-up of production levels is required. Some estimates predict a scale-up of three times the current production of H_2 is needed to supply the shipping sector alone with fuel.

H_2 is gradually picking up pace to be used commercially in the shipping industry and there are plans to start using compressed and liquid H_2 in vessels. Retrofits with fuel cells are feasible for most ships today.

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[178] https://www.ship-technology.com/news/nyk-shin-nippon-kaiyosha-biofuel/
[179] https://www.csis.org/analysis/hydrogen-key-decarbonizing-global-shipping-industry
[180] https://www.reuters.com/business/energy/india-sets-hydrogen-ammonia-consumption-targets-some-industries-govt-2023-01-13/

Foreseen cost of development

The main issues with using H_2 as a fuel for ships are the costs associated with engine retrofits, storage on ships and bunkering of H_2. Current green H_2 production costs are estimated at between USD 66/MWh and USD 85/MWh if electricity prices equate to USD 20/MWh. Electrolyser costs are between USD 650/kW and USD 1000/kW. Considering an electricity price of USD 65/MWh, the cost of green H_2 production was between USD 135/MWh and USD 154/MWh in 2020. This cost is relatively high in comparison to the market price of conventional fossil-based fuels.

Global adoption

Samsung Heavy Industries (SHI) has become the first shipbuilder to develop hydrogen fuel-cell technology for ships. The company acquired certification for system development and classification through a joint research project with South Korean hydrogen-related companies. Bumhan Fuel Cell and Jungwoo E&E worked with SHI on the development of the hydrogen fuel cell and liquid hydrogen storage tank, while S&Sys was responsible for the hybrid power management system. SHI has partnered with Pusan National University's Hydrogen Ship Technology Center to undertake research and development, production, and certification processes with DNV and South Korean firms. SHI is taking the lead in opening up the possibility of hydrogen power generation systems for ships using various fuel cells[181]

In March 2023, China Three Gorges Corporation launched China's first service ship powered by a 500-kilowatt hydrogen fuel cell, marking a significant breakthrough in new energy shipbuilding. The vessel, called Three Gorges Hydrogen Ship No.1, uses homegrown hydrogen fuel cells and a lithium battery system and will be used for transportation, patrol, and emergency in the Three Gorges reservoir area. The ship can reach a maximum speed of 28 kilometers per hour, has a maximum cruise range of 200 kilometres, and is more cost-efficient and quieter than traditional oil-fuelled ships. China has been focusing on developing the shipping industry fuelled by renewable energy, aligning with its green effort to achieve carbon neutrality by 2050.[182]

India's Ministry of Ports, Shipping and Waterways announced a green shipping initiative in April 2021, featuring the construction of the country's first hydrogen-powered fuel cell passenger ferry. Cochin Shipyard Limited, the largest shipbuilding and maintenance facility in India, has partnered with Pune-based KPIT Technologies Limited, hydrogen fuel cell developers, power train experts, and the Indian Register of Shipping to develop the vessel's regulations and rules. The project supports India's target of becoming carbon neutral by 2070 and aligns with the International Maritime Organization's standards of reducing international shipping's carbon intensity by 40% in 2030 and 70% in 2050. The initiative is expected to open up opportunities for India's coastal and inland vessel segments.[183]

Methanol

Methanol has one of the lowest carbon content and highest H_2 contents compared to other fuels. In comparison to HFO, methanol produced from NG is estimated to emit 25% less CO2. However, when considering the life cycle of both HFO and methanol from NG, methanol is estimated to have 10% higher GHG emissions than HFO. Therefore, it is imperative to introduce green methanol production to produce e-methanol and bio-methanol, which are fully renewable and the most sustainable options. As with most alternative shipping fuels, methanol can be used in two forms: in an ICE or as

[181] https://www.rivieramm.com/news-content-hub/news-content-hub/shi-to-develop-liquid-hydrogen-fuel-cell-system-for-ships-73744
[182] https://news.cgtn.com/news/2023-03-21/China-s-first-500kW-hydrogen-fuel-powered-ship-commences-operation--1imgAh2OSA0/index.html
[183] https://www.offshore-energy.biz/indias-first-indigenous-hydrogen-fuelled-electric-vessel-to-arrive-next-year/

a H_2 carrier for FCs. Methanol is currently used in a multitude of sectors and can be implemented within the shipping sector with relative ease.

In the production of methanol, there are multiple pathways. The current method of producing methanol uses coal, which is referred to as brown methanol, and NG referred to as grey methanol. These production methods are the most carbon-intensive and are not sustainable for the future of methanol production. The ideal production method for methanol is green methanol production, which is split between e-methanol and bio-methanol. E-methanol is produced by sourcing H_2 from electrolysis powered by renewables and utilising renewably sourced CO2 from BECCS and direct air capture (DAC). Bio-methanol is produced using biomass gasification and reformation. The feedstock for this method is usually forestry and agricultural waste and by-products, biogas from landfills, sewage, municipal solid waste, and black liquor from the pulp and paper industry. Bio-methanol produced from biomethane as feedstock can be certified under the International Sustainability and Carbon Certification (ISCC) scheme.

Technology Readiness Levels (TRL)

Methanol is being used today as a shipping fuel in an ICE. Currently, methanol can be used in two types of ICEs, in four-stroke and two-stroke engines, and this technology is quite well-developed. Many commercial ships have been retrofitted with methanol engines.

There are currently 25 methanol-fuelled vessels in service, almost entirely tankers. The orders, however are quickly building in the containership category, with it now up to 68 ships, according to DNV. They calculate that there are a total of 81 methanol-fuelled ships on order for delivery by 2028. The orders, however are quickly building in the containership category, with it now up to 68 ships, according to DNV. They calculate that there will be a total of 81 methanol-fuelled ships on order for delivery by 2028.[186] These engines have been installed in eleven new chemical tankers operated by Waterfront Shipping, Marinvest and MOL, with another eleven on order. These vessels are dual-fuel methanol engines with 10 megawatts (MW) of total power. Other commercial examples include Stena Lines' Stena Germanica, which was retrofitted with a dual methanol/diesel engine and has a total energy output of 24 MW. In total, there are 23 examples of commercial methanol-fuelled ships globally.

Hence, a higher TLR level of 9 can be assigned to the usage of methanol in the shipping industry.

Energy Efficiency

A direct methanol fuel cell (DMFC) converts methanol and oxygen into water and carbon dioxide, resulting in an efficiency of around 30-40%. However, it's possible to improve this efficiency up to 97%, and ongoing research is exploring ways to achieve this.[184]

Another type of methanol fuel cell is the reformed methanol fuel cell (RMFC), which uses a steam reformer to convert methanol into hydrogen. The hydrogen is then used in a fuel cell stack to produce electricity. RMFCs are smaller and more efficient than DMFCs, with efficiencies of up to 45%. They can also operate using lower-purity methanol, such as mixtures containing up to 40% water, although this can impact the volumetric energy density.[185]

An example of how an RMFC works is the steam reformer breaking methanol into two H_2 molecules and one CO. The CO then combines with a water molecule to produce another H_2 molecule and a CO_2 molecule, resulting in a total of three H_2 molecules that can be used in a standard PEM fuel cell stack. The amount of CO_2 produced is roughly the same as in the other two approaches mentioned earlier.[185]

Compatibility with currently used technologies

Compared to LNG, methanol has relatively simple design requirements on board ships. Methanol is liquid at ambient temperatures, non-cryogenic, and does not require refrigeration or expensive materials for tanks and pipes. Storage and handling technologies already exist, and bunkering can be easily implemented. However, methanol tanks require more space on board compared to LNG or HFO for the same trading distance. In addition, most current engines require a pilot fuel for efficient burning of methanol, which means diesel fuel must also be carried on board. This diesel fuel doubles as a fallback fuel in case of any issues with the methanol fuel system.

Despite these considerations, methanol is a promising alternative fuel for the shipping industry due to its compatibility with existing infrastructure and technology. The relatively simple design requirements make it easier to integrate into ships, and the fact that it does not require cryogenic temperatures or specific materials for storage and handling makes it a more cost-effective option compared to LNG.

Foreseen cost of development

The additional capital expenditure (CAPEX) for installing a methanol system on board a vessel is slightly higher than for a conventional low-sulphur HFO-burning ship and is roughly comparable to the additional costs associated with LNG. It is worth noting that the greenness of methanol fuel is irrelevant for the storage, processing equipment, and engines as only minor modifications or adjustments are needed when switching to green methanol. In a nutshell, methanol-ready ships are a low-risk investment for long-term compliance with the IMO's decarbonization goals. Of all the green alternative fuels available for green shipping, methanol requires the lowest CAPEX compared to the conventional HFO-powered vessel of the same size and vessel type.[186]

Global adoption

In March 2023, Maersk, a Danish shipping company, revealed the design for its first green methanol-powered container ship, a 2,100 TEU capacity feeder ship. This vessel is the first of 19 carbon-neutral ships that will be powered by green methanol fuel. The ship was ordered from Hyundai Mipo Dockyard in July 2021 and is set to be delivered later this year. It will be operated by Maersk's Sealand Europe brand on the Baltic shipping route between Northern Europe and the Bay of Bothnia. Maersk aims to

184 https://newatlas.com/energy/methanol-fuel-shipping/
185 https://newatlas.com/energy/methanol-fuel-shipping/
186 https://www.dnv.com/expert-story/maritime-impact/methanol-as-an-alternative-fuel-for-container-vessels.html

become carbon neutral by 2040 and has set targets to reduce greenhouse gas emissions intensity from its ocean fleet by 50% and absolute emissions from its fully controlled terminals by 70% by 2030. To power its methanol-fuelled fleet, Maersk is sourcing around 1 million metric tons of green methanol fuel per year, which will save approximately 2.3 million metric tons of CO2 emissions annually compared to conventionally fuelled ships.[187]

Samho Heavy Industries (HSHI) and HJ Shipbuilding and Construction (HJSC) have been awarded $1.12bn worth of newbuilding contracts from South Korean shipping company HMM for nine methanol-powered container ships. HSHI will construct seven vessels, while HJSC will construct two. The 9,000 twenty-foot equivalent unit (TEU) vessels will feature methanol dual-fuel engines and are expected to be delivered between 2025 and 2026. HMM plans to use the new vessels on the Asia-North/Latin America trade lanes and the Asia-India routes. HMM has also signed a memorandum of understanding with five fuel suppliers to deliver methanol to the new ships, and the company plans to achieve net zero carbon emissions across its fleet by 2050.[188]

Ammonia

Green ammonia is a promising alternative fuel for the shipping industry as it has the potential to become a zero-carbon fuel. However, the production of green ammonia is currently not commercially viable due to high costs, and there are several technical and regulatory challenges to overcome before it can be used as a mainstream fuel. For example, the slow flame propagation and high autoignition temperature of ammonia make it more difficult to combust efficiently than other fuels, and nitrous oxide emissions are a major concern.[189]

Despite these challenges, several companies are investing in the development of green ammonia as a fuel. For example, Yara International, a Norwegian chemical company, has announced plans to build a green ammonia plant in Norway, which will be powered by renewable energy sources. The plant will produce 500,000 tonnes of green ammonia per year, which could be used as a fuel for the shipping industry. Similarly, Nutrien, a Canadian fertilizer company, has announced plans to build a green ammonia plant in Western Australia, which will produce up to 1.5 million tonnes of green ammonia per year. [189]

India has targeted establishing bunkering of ammonia fuel and refuelling facilities at one port by 2025 and then in all major Indian ports by 2035.[190]

In addition to the production of green ammonia, there are also efforts underway to develop infrastructure for the handling and storage of the fuel. For example, the Port of Rotterdam is working on a pilot project to develop a green ammonia bunkering station, which will allow ships to refuel with green ammonia. The project is part of a larger initiative to develop a green hydrogen economy in the region. [191]

Ammonia tankers are considered ideal candidates for the first engines to be installed, as they already have the fuel as cargo and crews with experience in handling ammonia. Currently, there are around 200 gas tankers that can carry ammonia as cargo, and typically, 40 of them are deployed with ammonia cargo at any point in time. This makes it easier to establish a supply chain for green ammonia and to test and refine the technology in a controlled environment. [191]

Several companies are already working on developing ammonia-powered tankers. For example, the Japanese shipping company NYK Line has partnered with the Norwegian chemical company Yara to

[187] https://gcaptain.com/maersk-unveils-green-methanol-powered-feeder-ship-design/
[188] https://www.ship-technology.com/news/hmm-order-methanol-powered-boxships/
[189] https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html
[190] https://www.ammoniaenergy.org/articles/india-sets-renewable-milestones-for-shipping-fertiliser-sectors/
[191] https://www.dnv.com/expert-story/maritime-impact/Harnessing-ammonia-as-ship-fuel.html

develop an ammonia-fuelled tanker. The vessel, which is scheduled to be delivered in 2024, will be powered by a combination of ammonia and hydrogen fuel cells. [191]

In addition to ammonia tankers, other types of vessels may also be suitable for ammonia fuel. For example, the Dutch shipping company Spliethoff has ordered two new-built vessels that will be powered by ammonia fuel cells. The vessels, which are expected to be delivered in 2023, will be used to transport forest products in the Baltic and North Seas. [191]

Overall, green ammonia has the potential to become a major fuel source for the shipping industry in the future. However, significant investments in production, infrastructure, and technology will be required to make this a reality.

Technology Readiness Levels (TRL)

The development of engine technology for ammonia fuel is progressing fast, with the AEngine joint development project working on developing the first dual-fuel ammonia-powered combustion engines. The project is a collaboration between MAN Energy Solutions, Eltronic FuelTech, the Technical University of Denmark, and DNV and is funded by the Innovation Fund Denmark. MAN's two-stroke model is expected to go to market in 2024, with combustion testing scheduled for this spring.

Many other companies have expressed interest in using ammonia as fuel in the shipping industry as the technology is approaching commercial readiness. Until a successful launch of an ammonia-based ship, a lower TRL level of 4-5 can be assigned.

There are still several technical and regulatory challenges that need to be addressed before ammonia can be used as a mainstream fuel for shipping. These include the development of efficient combustion technology, the mitigation of harmful emissions, and the establishment of safety procedures for handling and storage.

Energy Efficiency

The Ammonia engine is expected to have an efficiency comparable to existing marine engines of around 50%.[192]

Compatibility with currently used technologies

Ammonia has existing infrastructure in terms of transport and handling, lending it an advantage over other alternative fuels such as H_2. Furthermore, there are established ammonia terminals across the world, with infrastructure in Japan, the United States, Europe and along the predominant maritime routes.

[192] https://en.nabu.de/imperia/md/content/nabude/verkehr/210622-nabu-study-ammonia-marine-fuel.pdf

Foreseen cost of development

According to DNV, the cost of building ammonia-ready ships is estimated to be $22 million higher than conventional ships. However, the current technology does not allow for the conversion of dual-fuel LNG engines to ammonia engines.[193]

Global adoption

In March 2023, The Nordic Green Ammonia Powered Ships (NoGAPS) consortium revealed the initial ship design for the ammonia-fuelled gas carrier M/S NoGAPS. The project aims to develop solutions for an ammonia-powered, zero-emission ship and is in its second phase, with the design contract awarded to Breeze Ship Design. The feasibility assessment for the ship design concept for the 22,000 cbm cargo capacity ammonia-fuelled gas carrier incorporated challenges, hazards, and opportunities of using ammonia as fuel, including the properties of ammonia and their effects on human health and the environment. The consortium opted for an ammonia-mechanical solution with a two-stroke main engine, driven by lower fuel consumption and reduced emissions. The project has now entered the initial design phase to increase the level of detail and analysis, including a hazard identification workshop, optimization of vessel efficiency, and submission of design drawings and documentation to target approval in principle from DNV. The project acknowledges that ammonia-fuelled engines and fuel supply systems are still in the early development stages.[194]

Mitsubishi Shipbuilding has completed a conceptual study for an ammonia bunkering vessel capable of supplying ammonia fuel to ships. The study, conducted in collaboration with INPEX Corporation, aimed to respond to increasing demand for ammonia-fuelled ships. Mitsubishi Shipbuilding utilized its knowledge of multi-purpose gas carriers capable of transporting ammonia to design a flexible ammonia bunkering vessel with enough tank capacity and bunkering equipment to ensure compatibility with various ammonia-fuelled vessels. The company plans to carry out further technical investigations and commercialize the vessel to contribute to a carbon-neutral society. As part of the MHI Group's Energy Transition strategy, Mitsubishi Shipbuilding will focus on developing and commercializing alternative fuel vessels and relevant equipment.[195]

Bureau Veritas has presented an assessment of ammonia as a fuel, highlighting its potential as a zero-carbon fuel for ships but also noting challenges such as toxicity, safety concerns, and the lack of commercially available ammonia-fuelled engines. While green ammonia has the potential to help shipowners meet the IMO's 2050 emissions reduction targets, it is unlikely to be ready for use by the time CII compliance is required. Short-term solutions such as improving energy efficiency or using low-carbon fuels may be more viable for now. However, in the long term, green ammonia may become a viable option if regulations evolve to take a well-to-wake approach to emissions. The cost of green ammonia is expected to depend on competition from other sectors, and shipowners must also factor in the costs of integrating technology onboard and training crew in safe ammonia handling.[196]

Liquefied Natural Gas (LNG)

According to DNV, LNG is currently the most widely used alternative fuel in the industry. As of 2022, there were 355 LNG-powered ships in operation and orders for an additional 521 LNG-fuelled vessels. LNG-powered container vessels and car carriers are the most popular types of ships to use LNG as fuel, accounting for 74% of the ship orders in 2022. LNG-powered crude oil tankers are also widely used, with 47 in operation. In addition to these vessels, there are also LNG-powered car and passenger ferries, oil/chemical tankers, and containerships in operation. Reportedly, there are 43 LNG bunkering

[193] https://lloydslist.maritimeintelligence.informa.com/LL1139640/Ammonia-ready-ships-add-$22m-to-newbuilding-costs
[194] https://www.offshore-energy.biz/ship-design-for-nogaps-ammonia-fueled-gas-carrier-comes-to-light/
[195] https://www.mhi.com/news/230202.html
[196] https://safety4sea.com/bureau-veritas-explores-ammonia-as-fuel-for-ships/

vessels currently in operation, with 18 on order. These vessels are used to supply LNG as fuel to other ships.[197]

The data suggests that the shipping industry is increasingly interested in using alternative fuels to reduce emissions and meet environmental regulations. While the high cost of LNG may be a challenge for some ship owners, the increasing availability of these fuels and the potential environmental benefits they offer make them an attractive option for many.

Technology Readiness Levels (TRL)

The use of LNG as fuel in ships has been in operation for several years, with hundreds of LNG-powered ships in operation and orders for hundreds more. As a result, the TRL level for the use of LNG as fuel in ships can be considered high at TRL 9.

Energy Efficiency

LNG-fuelled vessels can reduce their Energy Efficiency Design Index (EEDI) rating and Carbon Intensity Indicator by up to 20%, and competitive vessel design can ensure compliance for a longer period than conventional designs. The use of LNG as fuel can also reduce NOx emissions by up to 80%, almost eliminate SOx and particulate matter, and reduce GHG emissions by up to 23% with modern engine technology. Biogas and drop-in fuels offer additional options for reducing vessel carbon intensity.[198]

Compatibility with currently used technologies

Retrofitting a 2-stroke LNG engine on a VLCC includes modifications to the engine and necessary LNG delivery systems and incorporates a 4,600m3 LNG tank to provide a 14,000 nm range at 15% sea margin for market ballast/laden speeds. Retrofitting VLCCs with LNG as a marine fuel can contribute to significant energy savings and cleaner fuel-burning technology while also complying with Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations. Additionally, using LNG as fuel can extend a vessel's environmental compliance by several years while also restoring financial viability as per the analysis by SEA LNG, retrofitting LNG as a marine fuel potentially delivers strong investment returns over the remaining ten-year trading life of a VLCC.[199]

Foreseen cost of development

The CAPEX for a turnkey project to retrofit a 2-stroke LNG engine on a VLCC totals US$30.3 Million, which is a significant premium above the reference 2-stroke VLSFO conventional ship and assumes delivery one year after contract signing. The scope of work for the retrofit includes modifications to the 2-stroke engine for LNG fuel, necessary LNG delivery systems, and incorporating a 4,600m3 LNG tank to provide a 14,000 nm range at 15% sea margin for market ballast/laden speeds. The text notes that project optimization and market conditions are expected to significantly reduce the LNG retrofit CAPEX.[200]

Global adoption

The MV George III, the first of Pasha Group's two new 'Ohana Class' containerships, operates on LNG, making it the first LNG-powered vessel to fuel on the West Coast and the first to serve Hawaii. The 774-ft. Jones Act vessel surpasses the IMO 2030 emission standards for ocean vessels and achieves energy efficiencies with a state-of-the-art engine, an optimized hull form, and an underwater propulsion system with a high-efficiency rudder and propeller. The Ohana Class

[197] https://lngprime.com/europe/dnv-222-lng-powered-ships-ordered-in-2022/70166/
[198] https://www.dnv.com/maritime/insights/topics/lng-as-marine-fuel/index.html
[199] https://sea-lng.org/wp-content/uploads/2022/08/VLCC_Retrofit_Investment_Case_Study.pdf
[200] https://sea-lng.org/wp-content/uploads/2022/08/VLCC_Retrofit_Investment_Case_Study.pdf

containerships were designed from scratch to meet The Pasha Group's specific needs and offer several features aimed at operational efficiency and emission reduction. The Pasha Group plans to convert one of its 42-year-old steamships to an LNG power plant in April 2023, leaving one more reserve ship to decide whether to invest further and convert it to LNG. The Pasha Group's commitment to ESG matters extends beyond the LNG ships to include pioneering terminal projects and ties to the community and environmental concerns.[201]

In January 2023, Singapore's Sembcorp Marine unveiled JMS Sunshine, the country's first tug vessel running entirely on a LNG engine. The tug, designed by Norwegian subsidiary LMG Marin and classed by ABS, will avoid emitting approximately 251 tonnes of carbon dioxide per annum, which is equivalent to a conventional diesel tug. The vessel will be used in Sembmarine's yards for ship manoeuvring, mooring and unmooring operations and can be deployed by ship operators to escort vessels within Singapore port limits. JMS Sunshine runs on pure LNG with an energy storage system based on lithium-ion batteries to allow emission-free operation of the tug during idling and low-speed transit.[202]

TT-Line's second LNG-fuelled ferry, Peter Pan, is ready to start service, expanding the capacity of the company's fleet. The vessel features dual-fuel engines produced by MAN Energy Solutions that can be powered by LNG and other environmental features such as charging points for electric cars, improved hydrodynamics, and an optimized hull with a specially designed bulbous bow. The Green Ship concept is designed to carry 800 passengers and more than 200 articulated trucks, trailers, and containers. The Green Ship design was developed in collaboration with Copenhagen-based designer OSK-Shiptech, and by switching to LNG, TT-Line expects to significantly reduce particle, sulphur oxide, nitrogen, and CO_2 emissions compared to marine gas oil.[203]

ELECTRICITY REQUIRED FOR FULL DECARBONISATION

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated, considering India's target of *net zero by 2070*. In selecting the technology for the shipping sector, priority was given to the electrification technology. Since the complete electrification of shipping is not possible due to the low TRL of electric shipping, sustainable alternate fuels like methanol are being selected to fulfil the remaining demand of the shipping sector. The technology share of the shipping sector is depicted in the figure shown below.

[201] https://www.marinelink.com/news/great-ships-mv-george-iii-lng-501504
[202] https://www.upstreamonline.com/rigs-and-vessels/lng-powered-tug-vessel-to-cut-singapore-s-greenhouse-gas-emissions/2-1-1390204
[203] https://www.offshore-energy.biz/tt-lines-2nd-lng-fueled-ferry-ready-to-start-service/

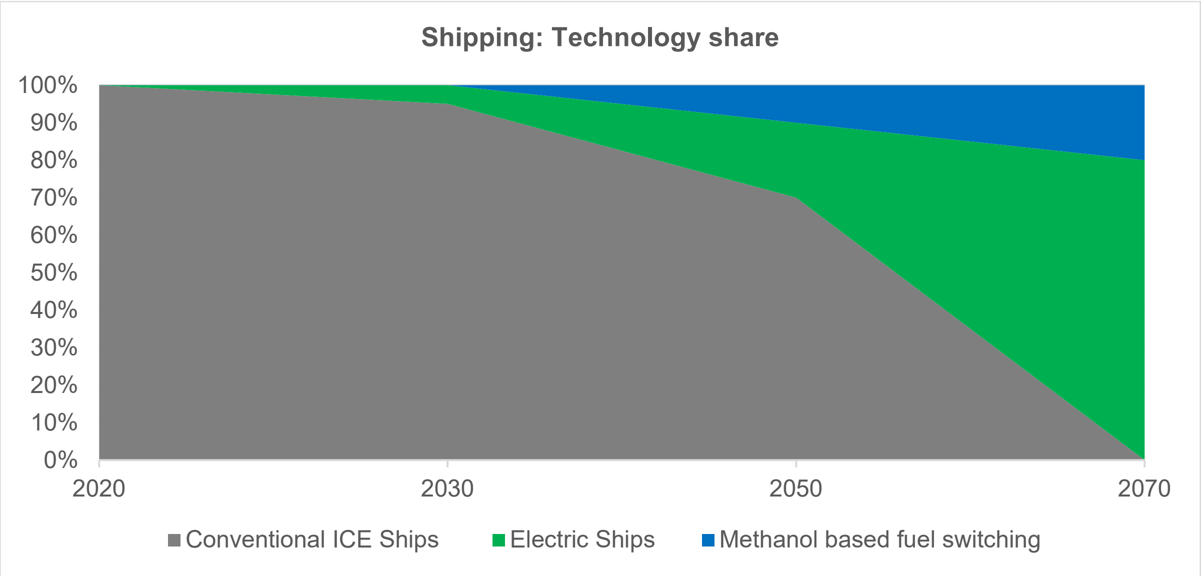

Figure 157: Penetration level of electrification technologies – Shipping

Projected Energy Consumption for Decarbonisation

The baseline energy consumption until 2070 was projected based on the correlation between GDP, energy consumption in the past few years and the GDP projections until 2070. Energy consumption is also projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenarios, i.e., the effort of implementation causing a change in energy consumption in each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	5	19	22

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050 and 100% by 2070.

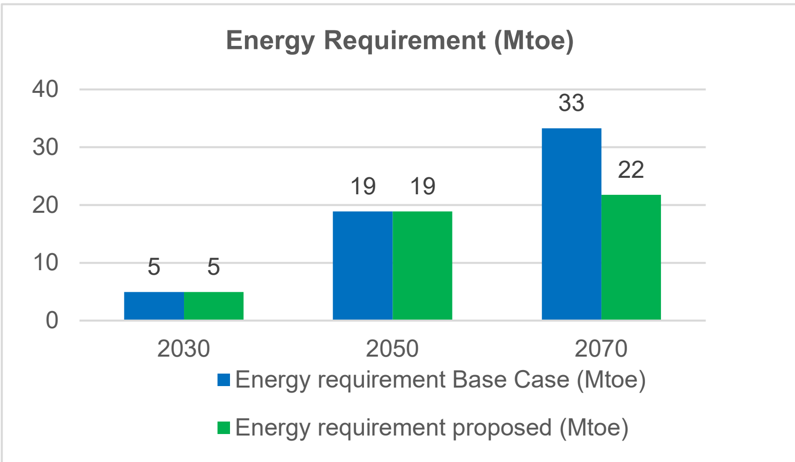

Figure 158: Energy requirement (Conservative - Shipping)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	5	19	22

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of the conservative scenario.

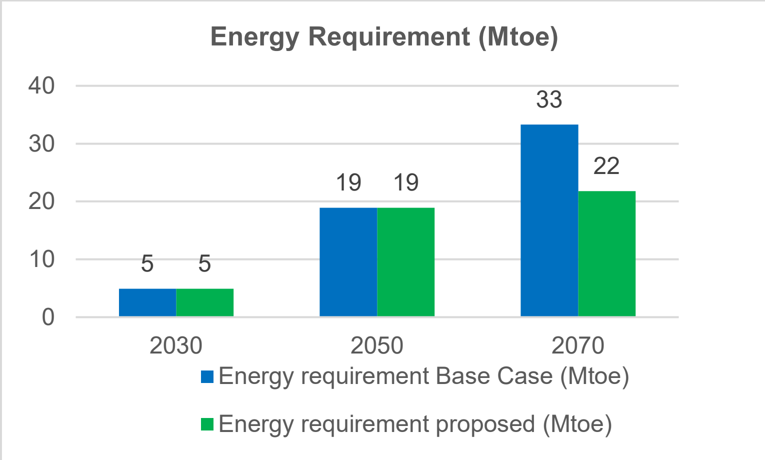

Figure 159: Energy requirement (Moderate - Shipping)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	5	19	22

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of the conservative and moderate scenarios.

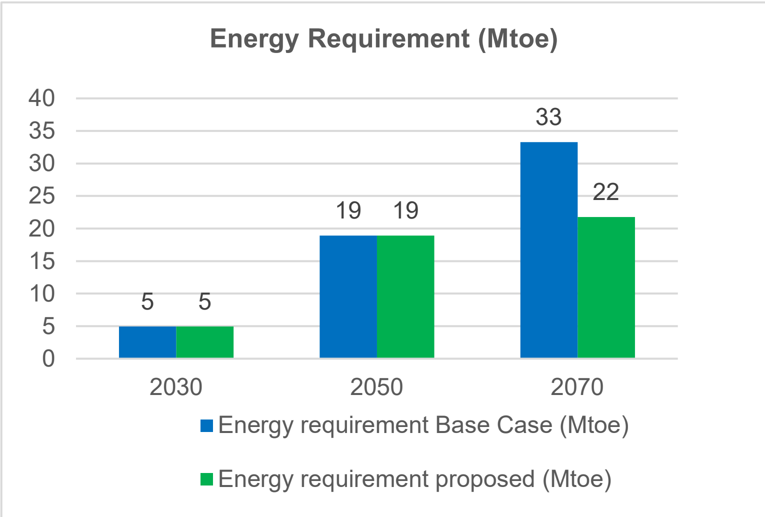

Figure 160: Energy requirement (Ambitious - Shipping)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **1 GW** by 2030, and it is expected to increase by **14 GW, 44 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would be **1.8 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios are presented in the table shown below.

Table 38: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	1	14	44
Moderate	1	14	44
Ambitious	1	14	44

Table 39: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative	1.8	29.6	128
Moderate	1.8	29.6	128
Ambitious	1.8	29.6	128

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 15 million tonnes CO_{2e}, 56 million tonnes CO_{2e}, and 99 million tonnes CO_{2e} for the years 2030, 2050, and 2070, respectively, in the BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the transport would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

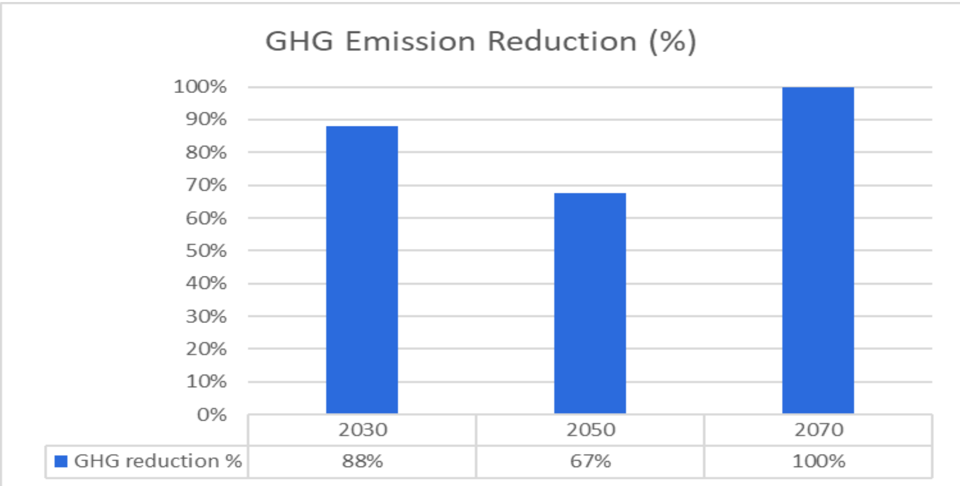

Figure 161: GHG emission reduction (Shipping)

4.3 Electrification of Aviation Sector

SECTOR OVERVIEW

The aviation industry is a major contributor to the global economy and plays a crucial role in connecting people and businesses around the world. It includes airlines, aircraft manufacturers, airports, air traffic control, etc. The industry is a significant contributor to greenhouse gas emissions and climate change. According to the International Civil Aviation Organization (ICAO), the aviation sector is responsible for approximately 3% of global carbon dioxide emissions. As air travel continues to grow, it is projected that emissions from the sector will increase unless steps are taken to reduce them.

In terms of growth, the aviation industry has been impacted by the COVID-19 pandemic, which has resulted in a significant decline in demand for air travel. According to the International Air Transport Association (IATA), the global aviation market is expected to return to pre-pandemic levels by 2024.

The aviation industry in India has been growing rapidly in recent years, with a growing middle class and an increase in disposable incomes leading to rising demand for air travel. There are around 100 domestic airports, around 30 international airports, and ten customs airports in India. The aircraft fleet in India consists of a mix of narrow-body and wide-body aircraft operated by both domestic and international airlines. The fleet of aircraft in India is comprised of over 700 commercial aircraft, with the majority of them being narrow-body aircraft such as the Airbus A320 and the Boeing 737.

In India, the aviation industry primarily uses two types of fuel: aviation turbine fuel (ATF) and aviation gasoline (AVGAS).

- ATF, also known as jet fuel, is a kerosene-based fuel that is used in most commercial and military aircraft. Jet A-1 fuel is the most common ATF in the Indian aviation industry. It is used for powering engines of jet-powered aircraft.
- AVGAS is a high-octane gasoline that is used in smaller aircraft such as general aviation and recreational aircraft. It is used for powering the engines of piston-powered aircraft.

In recent years, there has been a growing interest in alternative fuels for the aviation industry in India, such as biofuels and synthetic fuels. These fuels have the potential to reduce the carbon footprint of the industry and are being explored to make air travel more sustainable.

DECARBONISATION POTENTIAL

Electric aircraft, H_2 fuel-based aircraft and methanol fuel-based aircraft will be part of the aviation sector in 2070 in the electrification or decarbonisation scenario. With the deployment of these technologies, 50% of the energy consumption of the sector can be electrified from the existing 0% level. This implementation would result in a slight drop in the energy consumption of the sector by ~1%, i.e., from 89 Mtoe in the base scenario to 88 Mtoe in the ambitious effort scenario. Key findings of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

88 Mtoe of Energy Demand by 2070 from the sector

Reduction of **264 Mn tonne CO_{2e}** by 2070

Power demand of **38 GW** by 2070

Requirement of **23.7 GWh** of battery storage capacity by 2070

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

For short- to medium-haul flights of up to 1100 km, an energy density of at least 800 Wh/kg would be needed to electrify a substantial part of the aviation sector, a technological leap currently being addressed by the development of solid-state batteries and likely to be arriving on the market in the upcoming decade (2030). Electrification of such short- to medium-haul flights could electrify half of global flight departures, substitute 15% of fuel burnt per revenue passenger kilometre, displace 15% of fossil fuel usage and remove 40% of global landing- and take-off NOx emissions[204]. However, higher densities of 1600 Wh/kg will be needed for long-haul (>2200 km) inter-continent flights[205] and seem, therefore, unlikely considering current battery technologies.

Technology Readiness Levels (TRL)

Li-ion batteries are a mature technology readily implemented throughout the transport sector and are, therefore, at a **TRL level 9**. Full penetration in different countries in the transport sector is currently underway. Na-ion technologies are currently produced by CATL and Hinai and are, therefore at **TRL level 9**. Aluminium-Graphene batteries are currently being developed by The Graphene Manufacturing Group and The University of Queensland Research (Australia) and have higher energy- and power densities than Li-ion batteries. The first pilot manufacturing plant started producing batteries in 2021, indicating a **TRL level 6**. In 2021, a breakthrough in battery manufacturing is likely going to significantly decrease the cost of battery-powered vehicles and energy storage, as US-based Lyten will start manufacturing (Pilot plant by 2022, commercial plant by 2026) 3D Graphene Lithium-Sulphur batteries, which have three times the energy density of current batteries and lower weight, whilst being cobalt and nickel free (**TRL level 4 to 5**). Finally, in 2023, a breakthrough occurred in terms of solid-state Li-Air batteries, which have a theoretical energy density similar to Gasoline[206]. The lead researchers are now working with industrial partners to develop manufacturing of these batteries, indicating a **TRL 4-5**. Additional solid-state batteries with similar energy densities are currently being manufactured by Quantumscape[207] at a pilot facility and tested with several car manufacturers as of 2022. It is likely that solid-state batteries are still five years from being available at scale, but will significantly increase the electrification potential of trucks, cargo ships and planes in the 2030s.

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[204] *Schäfer, A.W., Barrett, S.R., Doyme, K., Dray, L.M., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P. and Torija, A.J., 2019. Technological, economic and environmental prospects of all-electric aircraft. Nature Energy, 4(2), pp.160-166.*

[205] *IEA (2022), Aviation, IEA, Paris https://www.iea.org/reports/aviation, License: CC BY 4.0*

[206] *Kondori, A., Esmaeilirad, M., Harzandi, A.M., Amine, R., Saray, M.T., Yu, L., Liu, T., Wen, J., Shan, N., Wang, H.H. and Ngo, A.T., 2023. A room temperature rechargeable Li2O-based lithium-air battery enabled by a solid electrolyte. Science, 379(6631), pp.499-505.*

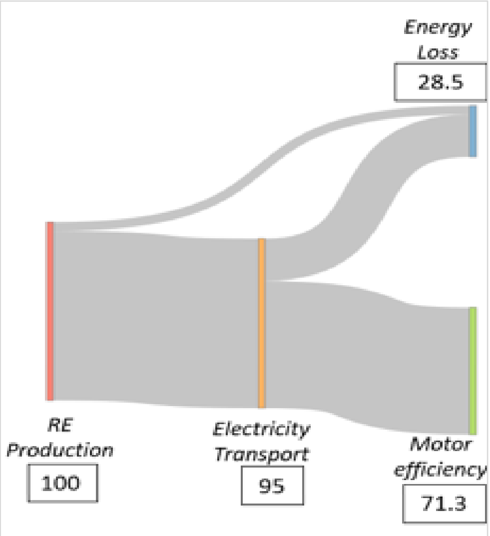
[207] *https://www.quantumscape.com/*

Overview of the battery technology

Conventional Li-ion	Next Generation 1: Gr-Si Anode/Hi-Ni Anode	Next Generation 2: Solid State Battery	Next Generation 3: Li-air
Most favorable technologies for today's EV and stationary energy storage applications	Most likely to be adopted on light vehicle EVs that require longer ranges and fast charging.	Key technology to eliminate battery fire concerns and deliver moderate performance improvements.	Revolutionary technologies that diverge from all previous chemistry systems.
• Cathode material: NMC 532, NMC 622, NCA, or LFP • Anode material: artificial graphite or natural graphite • Electrolyte: carbonate-based liquid organic solvents • Separator: Polymer thin films • Current collector: Cu and Al foils	• Cathode material: NMC 811 or NCA 90 • Anode material: natural/artificial graphite with SiOx or pure Si • Electrolyte: carbonate-based liquid organic solvents • Separator: Polymer thin films • Current collector: Cu and Al foils	• Cathode material: NMC 811, NCA 90, LNMO (high-voltage) • Anode material: graphite with a large amount of pure Si or Li-metal • Electrolyte: ceramic, polymer or sulphur-based solid electrolyte • Separator: as part of solid-state electrolyte • Current collector: Cu and Al foils	• Cathode material: Li-metal • Anode material: Sulphur or Oxygen/Air • Electrolyte: solid-state • Separator: as part of solid-state electrolyte • Current collector: Porous carbonaceous material, noble metal catalysts, and Cu foil

Energy Efficiency

The total efficiency of battery-powered batteries is higher than 75%.



Foreseen cost development

Batteries

Although upfront costs for current electrical ships are higher than current fossil fuel alternatives, the operational costs are significantly lower. The development of large-scale charging infrastructure is not limited to trucks and cars. Ports will require sustained investments to develop charging infrastructure. Two features offer significant opportunities to electrify ports, namely the close access to offshore wind energy and the fact that the average queuing/berthing time ranges from 31 to 97 hours for cargo ships, meaning significant opportunities for charging. Thus, a combination of onshore and offshore charging ports could be developed to charge incoming ships. The total operational and capital costs of a 300 MW charging station are estimated at USD0.03/kWh. Smaller aeroplanes are already electrifying. However, for passenger flights, a significant development in battery density is required, which is likely to be addressed in the upcoming decades for short- to medium-haul flights transporting 100-200 passengers.

INDIRECT ELECTRIFICATION AND OTHER DECARBONISATION TECHNOLOGIES

Alternative sources of energy other than battery-powered flights and fossil fuels will be required for medium- to long-haul flights. It is likely that by 2050, aviation will be subdivided between battery-electrified, regional flights and inter-continental, SAF-powered aviation[208].

These alternative sustainable fuels act as drop-ins for current fossil fuels and are derived from a variety of processes, both from biomass and other feedstock (SAF fuels) and from the production of hydrogen through electrolysis powered by renewable energy combined with the addition of CO_2 (e-fuels). Particularly promising leaders include Lanzatech, based in the US, which has five industrial demonstration sites producing ethanol and other higher-value fuels from waste gas and syngas streams. The use of bacteria leads to the fermentation of components and the production of ethanol, which can then be transformed into fossil fuels. The subsidiary Lanzajet has partnered with British Airways to provide SAFs derived from ethanol for flights by 2022. Carbon Recycling International utilises captured CO_2 and combines it with green or recovered hydrogen to produce methanol. The first pilot plant for converting carbon dioxide to methanol started operation in 2006. The first industrial scale plant started operating in 2012 and a commercial scale plant was operational as of 2022. Current usage of such methanol includes usage as a fuel for ships **(Figure 159)**.

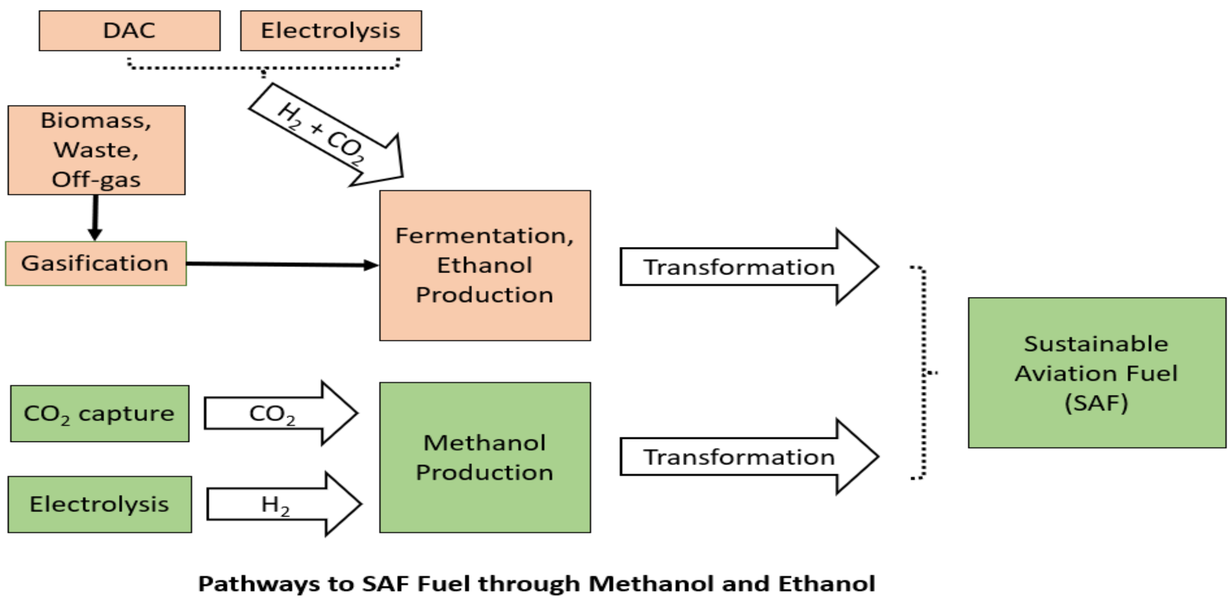


Figure 162: Simplified illustration showing two main pathways leading to the production of green jet fuels (SAF), through the production of Ethanol (e.g., LanzaTech) or through the production of methanol from biomass (e.g., ExxonMobil) or through methanol produce

[208] *Schäfer, A.W., Barrett, S.R., Doyme, K., Dray, L.M., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P. and Torija, A.J., 2019. Technological, economic and environmental prospects of all-electric aircraft. Nature Energy, 4(2), pp.160-166.*

Global Best Practice Examples

Through the European Climate Law and the "Fit for 55" package, the use of SAF fuels is mandated, gradually increasing from 2% by 2025 to 63% by 2050[209] **(Figure 160)**. However, clear long-term mandates or pathways for the full decarbonisation of aviation are still lacking.

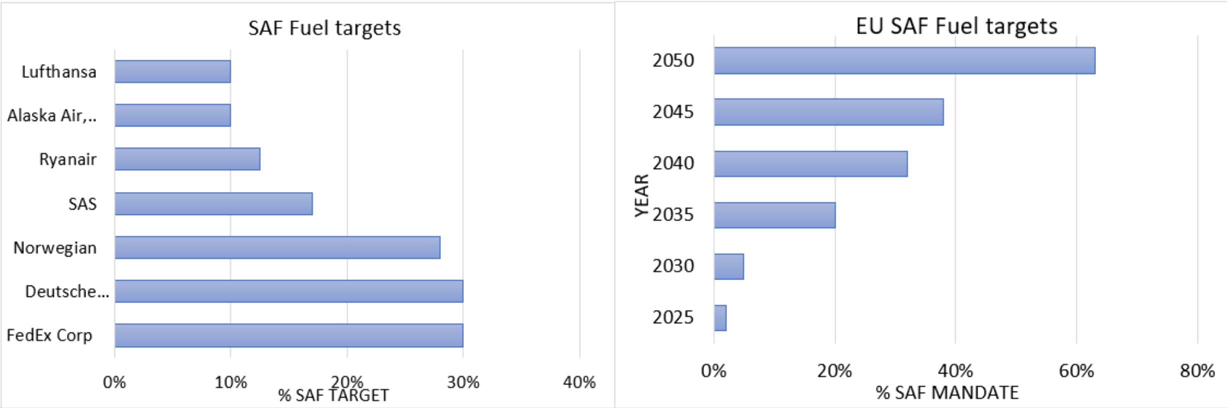


Figure 163: Illustration of fuel targets for individual companies (left) and mandated targets for SAF fuels for flights departing from the European Union (European Climate Law and the Fit for 55 packages).

Technology Readiness Levels (TRL)

Sustainable Jet Fuel: There are an array of pathways to producing sustainable jet fuels which depend on the specific feedstock (vegetable fat, waste, crops), thereby ranging from TRL 5 (Microalgae) to TRL 9 for gasification. Commercial test flights with Virgin Atlantic and All Nippon Airways are already underway. LanazTech is developing a large-scale production plant in Georgia, USA in 2023 and is expected to produce >100 million gallons by 2025 worldwide and 1 billion gallons in the USA alone by 2030. Note that the EU already has mandated blending requirements of SAF-fuels in aviation[210].

Methanol: The production of methanol in a single step and its distillation are a mature technologyies **(TRL 9)**. Production of methanol is not limited by technology, as it is a proven, commercially available technology when applied to fossil fuel-based syngas. However, the key issue in terms of TRL resides in the scaling up of green hydrogen production and CO_2 capture (either from industrial flue gas, syngas, biomass, or Direct Air Capture). The main barrier to green methanol is the cost (i.e., electrical consumption) of producing green hydrogen as well as CO_2 if derived from Direct Air Capture technologies.

Energy Efficiency

As illustrated in **Figure 161**, methanol, ammonia and SAF-fuels burn more efficiently and with fewer contaminants than traditional fossil fuels.

[209] European Fit for 55 Package, https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3541
[210] European Aviation Environmental Report 2022, European Environment Agency and EuroControl, doi: 10.2822/04357

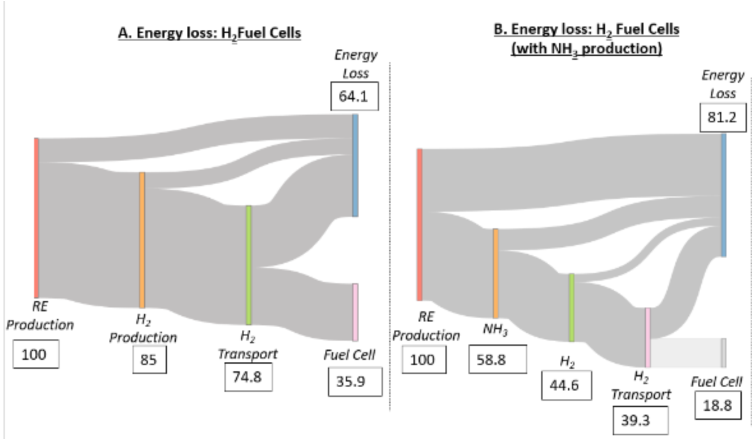


Figure 164: Sanky Diagram illustrating energy losses for hydrogen-based (with and without ammonia transformation) and electric-based transport systems.

Compatibility with currently used technologies

SAF-fuels for aviation can be used within the global aviation fleet and use the current fuel supply infrastructure. Ammonia already has a well-established global transport infrastructure.

Foreseen cost development

Methanol

Methanol costs depend on the manufacturing process. For e-methanol, the cost is strongly dependent on the cost of hydrogen electrolysis and the cost of capturing CO_2 (direct air capture or industrial point-source capture). A main factor in bringing the cost down will, therefore, be the cost of electricity from renewable energy in order to produce green hydrogen. Current estimates of e-methanol indicate a cost of $800 to $1500 per ton, with prices projected to drop to $250-600 per ton by 2050, within the range of current costs of fossil methanol[211]. Total operational and capital costs of bio-methanol, derived from biomass or massive solid waste, range between 450 and 100 USD per ton currently and are expected to reach a price of $300 to $550 per ton in 2050, depending on the availability and price of the feedstock.

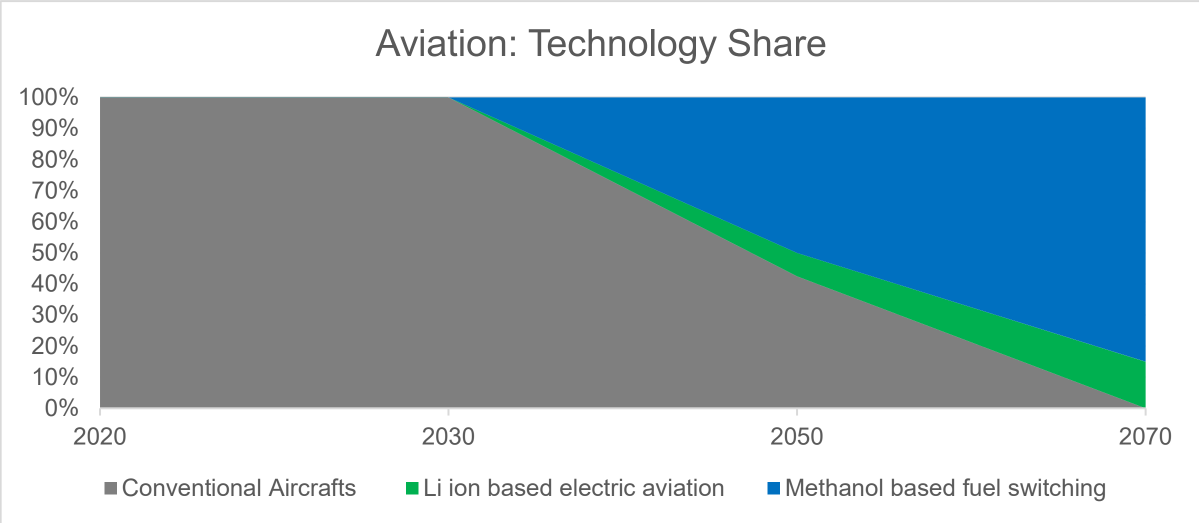
Sustainable Aviation Fuel

SAF-fuels derived from methanol and ethanol have the advantage of being considered a "drop-in" fuel, meaning that minimal engine modifications are required. However, the current costs of SAF fuels are higher than those of fossil fuels. The price of fossil jet fuel is $600 per tonne, while current SAF prices are between 1.5 to 6 times higher. SAF industry is currently still at a very early stage of development, and estimating costs depends significantly on scaling up the technology as well as bringing the costs down for **1)** renewable energy, **2)** electrolysis of hydrogen, and **3)** carbon capture. Additional issues concern the evolving costs and accessibility of different types of biomass to produce SAF fuels, as well as the cost of carbon emissions from the aviation industry.

ELECTRICITY REQUIRED FOR FULL DECARBONISATION

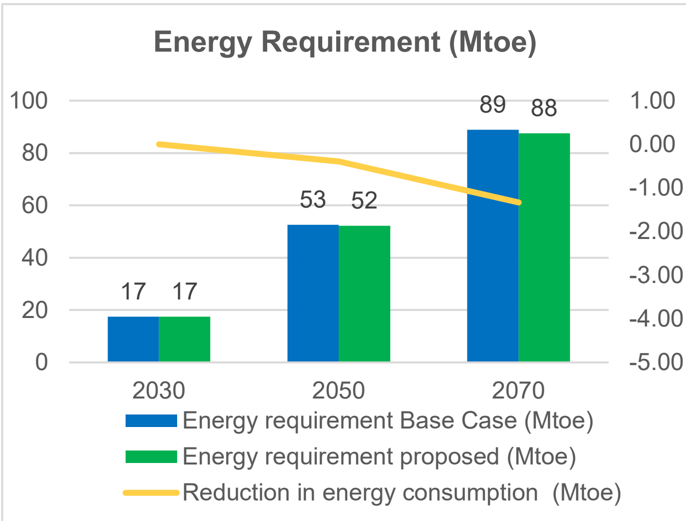
Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential of decarbonisation and suitability of the technologies. Penetration level of the selected technologies is estimated considering India's target of *net zero by 2070*. Aviation sector is one of the challenging sector which requires immense development of the electrification technology because with current maturity level of the technology, only 15% penetration of the electric aviation is possible by 2070. Remaining demand of the aviation sector would be met be the switching to the cleaner fuels lie sustainable alternate fuel e.g., methanol as a fuel.



Projected Energy Consumption for Decarbonisation

The baseline energy consumption until 2070 was projected based on the correlation between GDP and energy consumption in the past few years and the GDP projections until 2070. Energy consumption is also projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenarios, i.e., the effort of implementation leading to change in energy consumption in each scenario.



Conservative Scenario

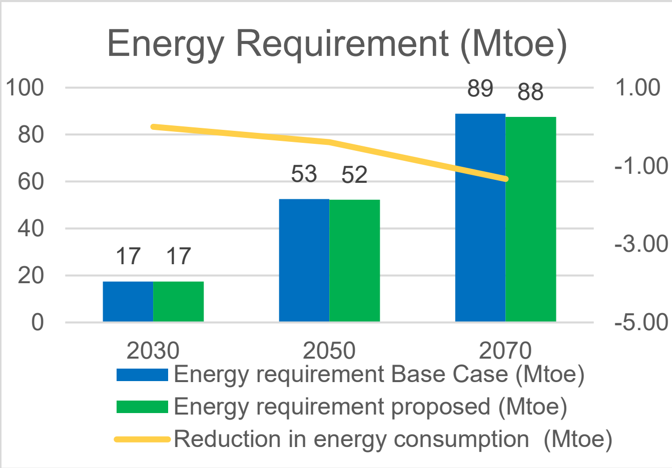
Year	2030	2050	2070
Energy Demand (Mtoe)	17	52	88

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050 and 100% by 2070.

[211] *Irena and Methanol Institute (2021), Innovation Outlook: Renewable Methanol, International Renewable Energy Agency, Abu Dhabi.*

Moderate Scenario

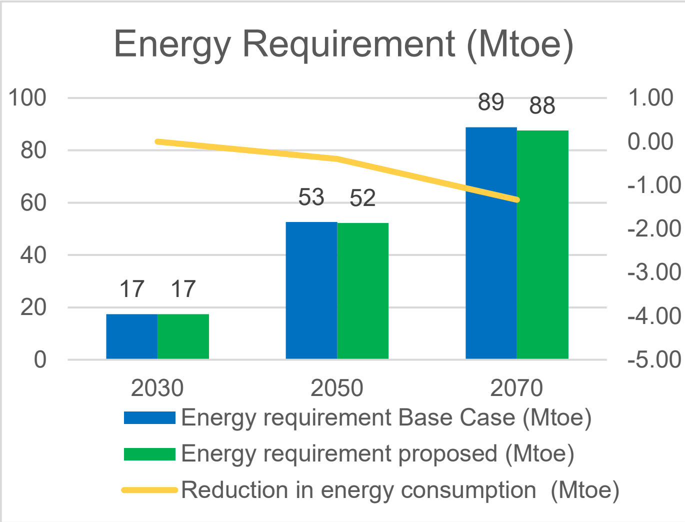
Year	2030	2050	2070
Energy Demand (Mtoe)	17	52	88



In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of the conservative scenario.

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	17	52	88



In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is same as that of the conservative and moderate scenarios.

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based source of electricity. In the ambitious scenario, the power installation requirement for the sector would be **0.5 GW** by 2030, and it is expected to increase by **15 GW, 38 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **1 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios is presented in the table shown below.

Table 40: Projected RE hybrid (GW) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070

Conservative	0	15	38
Moderate	0	15	38
Ambitious	0	15	38

Table 41: Projected Battery Storage (GWh) requirements till 2070

Scenarios ↓ / Year →	2030	2050	2070
Conservative		6.8	23.7
Moderate		6.8	23.7
Ambitious		6.8	23.7

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 52 million tonnes CO_{2e}, 156 million tonnes CO_{2e}, and 264 million tonnes CO_{2e} for years 2030, 2050, and 2070 in the BAU scenario, respectively. Under the ambitious scenarios it is estimated to be net zero in 2070 as the majority of the entities would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

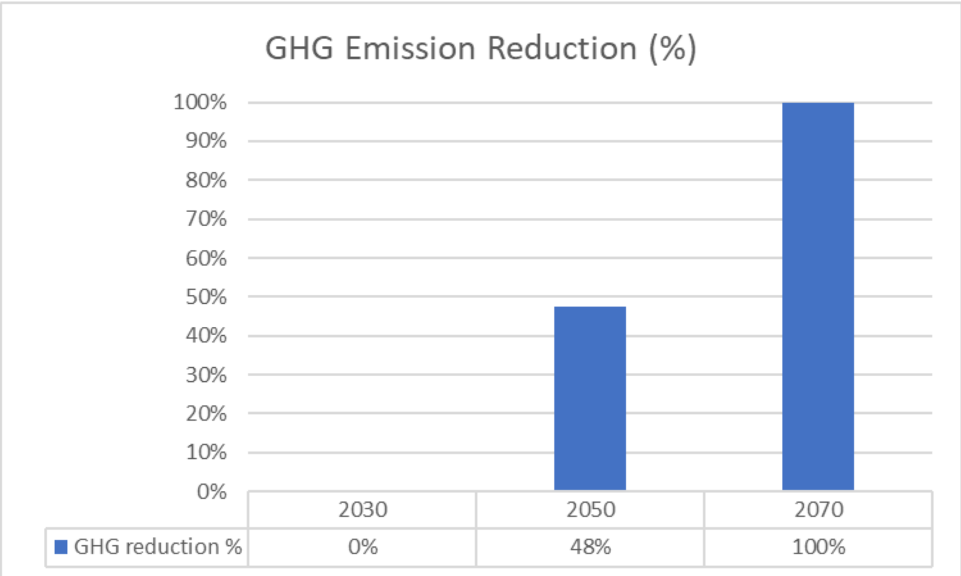


Figure 165: GHG emission reduction (Aviation)

4.4 Electrification of Railways

Railway Electrification in India had been slow prior to 2014, but in the last six years, significant positive changes have occurred. The worldwide energy sector has also progressed, with more countries taking the net zero emissions pledge to tackle climate change. In India, two notable developments for full electrification of railways are the mission of 100% electrification of the entire Broad-Gauge network to provide an environmentally friendly mode of transport and the potential to use renewable energy, particularly solar, by utilizing the vast land available along the railway track.

India's *Mission 100% electrification* by 2030 for railways is a game changer in the country's energy sector, providing an opportunity to meet the demands of citizens for both freight and passenger transportation without following a high-carbon pathway. India is the world's third-largest energy-consuming country, with 80% of demand met by coal, oil, and solid biomass, and solar accounting for less than 4% of electricity generation. However, India has set a target to reach 450 GW of renewable capacity by 2030, in which the Indian Railways has a significant role to play. Railway electrification is necessary to reduce India's dependence on imported petroleum-based energy and enhance energy security while providing an eco-friendly, faster, and energy-efficient mode of transportation. Electrification also eliminates pollution and India's dependence on imported fuel, leading to significant foreign exchange savings. Additionally, electrification increases the average speed of trains and promotes the development of industries, agro-based businesses, and the progress of villages and farmers along electrified routes. [212]

Status of electrification of railway lines in India

India's railway network has grown to around 68,000 km, making it the fourth largest railway network globally. For a long time, the network was primarily fueled by coal and diesel, but with increased emphasis on electrification, the share of electrified tracks has surged from 24% in 2000 to over 65% by the end of 2020. Additionally, the share of electricity in total energy use by the Indian Railways has seen a corresponding increase, with a renewed focus on transforming railways for long-distance transport and urban public mobility. [212]

The total Broad-Gauge network for electrification is 64,689 RKM, with more than 66% already being electrified. With the increasing electrified network, there has been a complete turnaround in the share of GTKMs hauled by electric traction. This has resulted in a reduction in diesel fuel consumption by about 76% and a saving of foreign exchange on imports, besides reduced carbon footprints. The highest-ever allocation of INR 7,542 Cr has been made for railway electrification projects during 2021-22, with highly remunerative projects being given importance over zone-wise allocation of funds. [212]

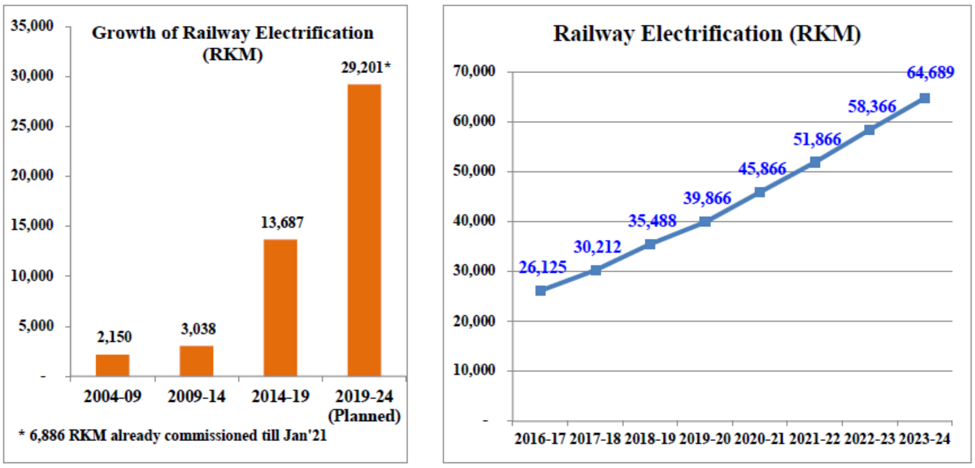


Figure 166 - Growth of electrified railway network in India[212]

Indian Railways has recorded a 371% increase in electrification work during the period of 2014-2020 compared to 2009-2014, with around 18,065 km of railway routes being electrified during these six

[212] https://indianrailways.gov.in/railwayboard/uploads/directorate/secretary_branches/IR_Reforms/Mission%20100%25%20Railway%20Electrification%20-%20Moving%20towards%20Net%20Zero%20Carbon%20Emission.pdf

years. While India has impressively added to its railway network post-independence, the extent of electrification has trailed, with only close to 66% of the entire Broad Gauge network length being electrified so far. However, the advantage of a 66% electrified network is that it accounts for 60% of passenger traffic and 67% of freight traffic for Indian Railways at only 38% of the total fuel bill incurrence. Full electrification is regarded as a game-changer in pushing railways further to handle greater freight-hauling requirements and passenger traffic with enhanced speed and lower operating costs. [212]

To ramp up progress, innovative ways have been adapted, such as using cylindrical mechanized foundations that take less time and state-of-the-art Automatic Wiring Train for expeditious completion of RE work, which strings both Catenary and Contact wire together to achieve desired tension in overhead conductors, helping in wiring at a faster pace. [212]

With the deployment of electric trains, 100% of the energy consumption of the sector can be electrified. This implementation would result in a significant drop in the energy consumption of the sector by 51.9%, i.e., from 5.6 Mtoe in the base scenario to 3 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions: 36.8% by 2030, 68.4% by 2050, and 100% by 2070. Key findings of the ambitious scenario of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

3 Mtoe of Energy Demand by 2070 from the sector

Reduction of **30 Mn tonne CO_{2e}** by 2070

Power demand of **8 GW** by 2070

Requirement of **7 GWh** of battery storage capacity by 2070

The improvement in key parameters is based on the proposed penetration level of the technology and the level of efforts is as follows where the base scenario indicates the base projected scenario, which is a projection based on the correlation of GDP manufacturing of that particular sector and the production of the sector.

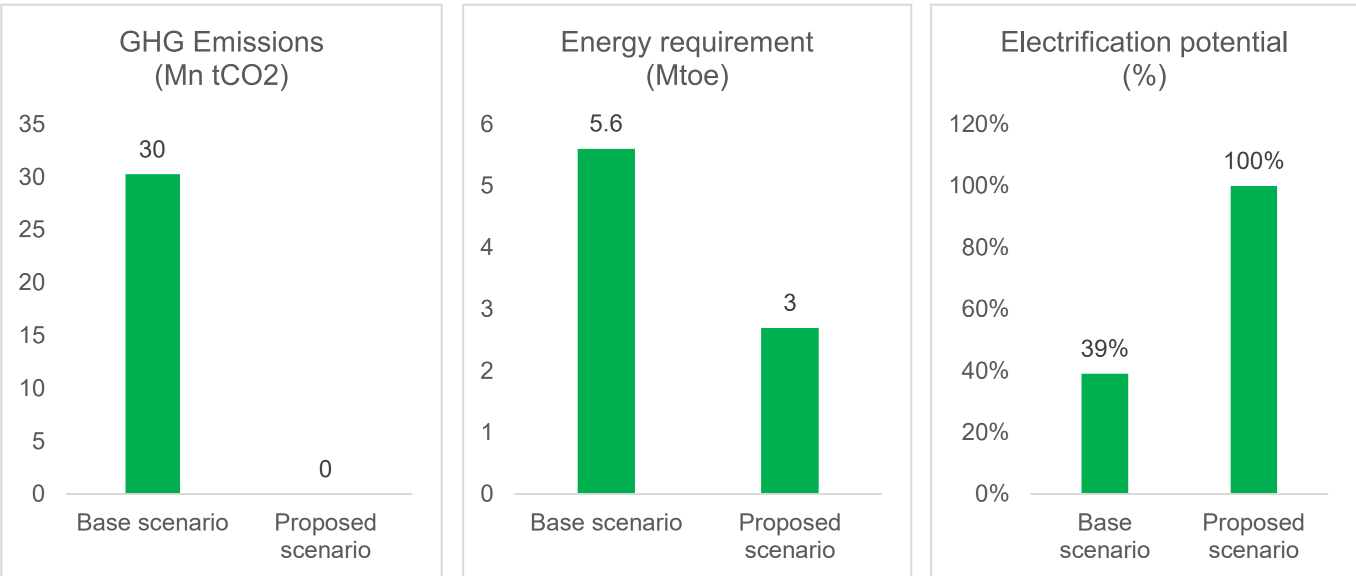


Figure 167: GHG emissions, energy requirement and electrification potential in proposed scenario

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION

Electric trains

Electric trains are powered by electricity collected from overhead lines. The power flows through the wheels and into the grounding cable of the track. In the simplest design, a single sliding wire collects the power and feeds it to a single-phase induction motor, which is connected to the wheels. The motor's other terminal is grounded through the axle brush, and the current flows through the wheels, the motor, and the grounding connection.[213]

To make the train more functional, a step-down transformer is added to reduce the voltage from the overhead line to the desired level. Three-phase induction motors are used to achieve high, uniform torque requirements. The single-phase supply is converted to three-phase through a rectifier and inverter. A transmission system with some gear ratio between the motor shaft and the wheel axle can increase torque output.

A complete electric locomotive engine has several motor-wheel pairs to make it more powerful. Pantographs are used to adjust the height of the current-collector to ensure proper power collection, and the overhead line is arranged in a zig-zag manner to minimize wear and tear on the collector head. Electric trains use regenerative braking systems to slow down the train without metal-to-metal contact. By lowering the supply frequency, the direction of induced current in the rotor bars reverses, creating a perfect brake. However, this method cannot stop the train completely, so a pneumatic braking system is applied to bring the train to a dead stop.[213]

Power is supplied to each coach through self-generation, where an alternator is mounted under the coach frame and driven by a cardan shaft, or head-on-generation, where an extra winding is added to the locomotive transformer to supply power to all the coaches.[213]

Technology Readiness Levels (TRL)

The electrification of railways in India is a high TRL (9). The technology has been extensively tested and is proven to be safe, reliable, and efficient.

Energy Efficiency

Electric traction is the most energy-efficient mode of rail transport. Studies show that every 100 km of electrified rail section can save over four million litres of diesel oil annually, resulting in a savings of Rs. 2500 Crores worth of foreign exchange per year. This highlights the significant energy savings that can be achieved through electrification of railways.[214]

In addition to energy savings, electrification of railways also offers other benefits, such as reduced emissions and improved operational efficiency. Electric trains have lower operating costs and require less maintenance than diesel-powered trains, making them a more cost-effective and sustainable option in the long run.[214]

Compatibility with currently used technologies

Electrification of railways can be compatible with the existing setup if the infrastructure is in good condition and can support the installation of overhead lines, substations, and other necessary equipment. In some cases, retrofitting of existing infrastructure may be required to accommodate the electrification system.

The availability of power supply is also an important consideration when it comes to the compatibility of electrification of railways with existing setups. The power supply infrastructure must be able to

[213] https://www.lesics.com/how-does-an-electric-train-work.html
[214] https://core.indianrailways.gov.in/view_section.jsp?lang=0&id=0,294,302,538

support the additional demand created by electric trains. This may require upgrading the power supply infrastructure, such as adding new power plants or expanding the existing grid.

Foreseen cost development

The full electrification plan for Indian railways is estimated to cost more than Rs 1 lakh crore, which includes approximately Rs 50,000 crore for converting the 29,880 kilometres of un-electrified tracks, Rs 50,000 crore for electric locomotives, and another Rs 5,000 crore for constructing sheds to house these locomotives. The cost of training loco pilots is also an additional expense. The average cost of each electric locomotive is estimated to be Rs 12 crore, which means that the purchase of 4,000 electric locomotives to replace the current diesel engines will cost Rs 48,000 crore. Additionally, there may be a loss incurred on the diesel locomotives, which could add up to about half the total cost of the electric locomotives. [215]

The high cost of electrification is a significant challenge for the Indian railways, given the precarious state of rail finances. The operating ratio of Indian railways touched an alarming figure of 98.4% during 2017-18, meaning that it spent 98.4 paise to earn every rupee. [215]

Despite the large-scale electrification and scrapping of diesel locomotives, the railways' overall fuel consumption has either remained the same or even risen in the last few years. The reasons for this are not clear, but it may be due to the fact that old diesel engines have not been fully scrapped or that more routes have been electrified but are not fully usable. [215]

Furthermore, the change in procurement practice for locomotives may have contributed to the surplus of both diesel and electric engines, which are idling away. The high cost of electrification and the challenges associated with implementation highlight the need for careful planning and investment in the electrification of Indian railways. [215]

Global adoption

Switzerland has one of the most extensive railway networks in Europe, with around 5,300 kilometres of railway lines, which is the densest transport network in the world. The first rail line built exclusively on Swiss territory, the Swiss Northern Railway between Zurich and Baden, was opened in 1847. In 1912, the Swiss Study Commission for Electric Railway Operation recommended the single-phase alternating current that is still used today. By 1936, over 70% of the SBB network was electrified. Currently, 100% of Switzerland's rail network is electrified. [216]

In September 2022, Caltrain unveiled its new electric train cars, which were a key component of its electrification project on the corridor from the San Francisco Station to the Tamien Station in San Jose. The new high-performance trains were quieter and faster than the previous diesel locomotive-hauled passenger cars, and each train set had seven cars, allowing Caltrain to expand its service levels beyond the previous 104 trains every weekday. The new trains featured digital onboard displays, power outlets, energy-efficient lighting, security cameras, and expanded storage. The electrification project was expected to cost $462 million, and the new electric trains were set to go into service in 2024 after testing was completed. This was the first project in North America to switch from diesel to an electrified system in a generation. [217]

Superconducting magnetic train

Maglev, short for magnetic levitation, is a technology that uses magnetic forces to levitate and propel trains. Maglev trains operate on a guideway, which is a track-like structure that contains powerful magnets. The train itself has magnets mounted on its undercarriage, which are attracted to the magnets on the guideway, allowing the train to levitate above the track.

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[215] https://theprint.in/india/modi-govt-wants-100-rail-electrification-but-doesnt-know-what-to-do-with-diesel-engines/349339/
[216] https://www.houseofswitzerland.org/swissstories/history/nation-railway-enthusiasts-history-swiss-railways
[217] https://railway-news.com/us-caltrain-unveils-new-electric-trains/

The three essential parts of maglev functionality are levitation, propulsion, and guidance. Levitation is achieved through either electromagnetic suspension (EMS) or electrodynamic suspension (EDS). EMS uses the attractive force of electromagnets, while EDS uses the repulsive force of superconducting magnets. Propulsion is achieved through an electric linear motor, which produces motion in a straight line by sending a magnetic field down the guideway that pulls the train along. The primary is in the guideway, and the secondary is attached to the bottom of the train cars. Guidance is what keeps the train centered over the guideway and is achieved through repulsive magnetic forces. Maglev trains have the potential to be faster, safer, and more energy-efficient than conventional transportation systems, but their development and implementation require expensive infrastructure and specialized technology.[218]

Because maglev trains do not rely on friction between wheels and rails, they can travel at much higher speeds than traditional trains. The Shanghai Maglev, for example, has a top speed of 430 km/h (267 mph), making it the fastest commercial train in operation. Maglev trains are also quieter and smoother than traditional trains, as there is no contact between the train and the track.[218]

In terms of safety, maglev trains are designed to be highly resilient to derailments, as the levitation technology helps keep the train on the track. Additionally, maglev trains can be built to run on elevated guideways, reducing the risk of collisions with other vehicles or obstacles.[218]

Maglev trains offer many benefits over traditional rail trains, including faster speeds, increased safety, longer lifespan, energy efficiency, reduced environmental impact, and lower noise pollution. However, maglev guideways are not compatible with existing rail infrastructure, and the initial investment required to build a new set of tracks is high. In addition, maglev trains may not be significantly faster than high-speed rails in countries where they are already in place. Electrical engineers have played a crucial role in the development of maglev technology and continue to work on improving its speed, energy efficiency, and safety. The future of maglev technology is promising, with potential applications in intercity public transportation and even underground tubes. While it may take time to become prevalent, maglev trains have the potential to revolutionize transportation.[218]

Technology Readiness Levels (TRL)

Maglev trains have been successfully demonstrated in commercial systems hence, they can be assigned a TRL level of 9.[218]

Energy Efficiency

Maglev trains are generally considered to be more energy-efficient than traditional trains, as they do not lose energy to friction between the wheels and the track. Instead, maglev trains use magnetic forces to levitate and propel the train along the guideway, which requires much less energy. However, as compared to conventional trains, they are more efficient at higher speeds (>330km/hour).[219]

Compatibility with currently used technologies

Maglev guideways are not compatible with existing rail infrastructure. A new maglev system can cost up to USD 1 billion.[220]

Foreseen cost development

The initial investment required to build a new set of tracks is high.[218]

Global adoption

The Shanghai Maglev Train, which started operating in 2004, is the world's first commercial maglev line. It runs between Longyang Road Station on the Shanghai Subway Line 2 and Pudong International

[218] https://sites.tufts.edu/eeseniordesignhandbook/2015/maglev-magnetic-levitating-trains/
[219] http://large.stanford.edu/courses/2010/ph240/ilonidis2/
[220] https://www.science.gov/topicpages/m/maglev+system+costs

Airport, covering a distance of 30 km (19 miles) in just 8 minutes, with a maximum speed of 431 km/hr (268 mph). The trains use magnetic levitation technology, making them environmentally friendly, energy-efficient, and quieter than traditional trains. The facilities on board are modern and comfortable, with air-conditioning, LCD screens showing the train's speed, and trained attendants. The Shanghai Maglev Train has gained global recognition for its speed and efficiency, and it remains a popular mode of transport for locals and tourists alike.[221]

In January 2023, China successfully tested a new transportation system that involved an ultra-high-speed maglev train running in a low-vacuum pipeline. The project aimed to combine railway and aerospace technology to build an ultra-high-speed mega transport system that would operate in low vacuum pipelines, potentially allowing maglev trains to travel at speeds that rival planes. The technology of maglev eliminated friction while operating the train in a low-vacuum pipeline reduced resistance and noise. The experiment, conducted at the beginning of 2023, verified a series of key technologies for the system's high-speed vehicle and related coordination work. The development and promotion of high-speed rail was a major priority in China, with several new maglev networks reportedly under construction.[222]

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Hydrogen fuelled train

Hydrogen trains, also known as "hydrail," use hydrogen as a fuel either in a hydrogen internal combustion engine or through a reaction with oxygen within a hydrogen fuel cell. Hydrail vehicles are currently hybrids, using renewable energy storage like batteries or supercapacitors to supplement the hydrogen fuel, improving efficiency and reducing the amount of hydrogen storage space required.

A fuel cell-based hydrogen train typically consists of a fuel cell, a hydrogen tank, and an electric motor. The fuel cell generates electricity through an electrochemical reaction between hydrogen and oxygen from the air, producing water as a by-product. The electricity generated by the fuel cell powers the electric motor, which provides the necessary propulsion for the train. The hydrogen tank stores compressed hydrogen, which is supplied to the fuel cell as needed. The tank can be refilled quickly, making it possible to operate the train for long distances without the need for frequent refuelling. Hydrogen trains are environmentally friendly, as they emit only water and steam as by-products. They are also quieter than traditional diesel trains, as the electric motor produces less noise and vibration.

Hydrail has potential applications for various types of rail transportation, including industrial, passenger, freight, mine railways, light and rapid rail transit, and trams. Transport operators around the world are investigating fuel cells and hydrogen-generating equipment, similar to that being developed by the automotive and aerospace industries.

In February 2023, Indian Railways announced plans to run 35 hydrogen trains under the "Hydrogen for Heritage" initiative on various heritage/hill routes. Each train was estimated to cost Rs. 80 crores, with ground infrastructure per route costing Rs. 70 crores. A pilot project to retrofit hydrogen fuel cells on existing Diesel Electric Multiple Unit (DEMU) trains was also awarded at a cost of Rs. 111.83 crores. Field trials for this project were expected to begin in 2023-2024. While the running cost of hydrogen fuel-based trains in the Indian Railways scenario was unknown, the use of hydrogen fuel supported zero-emission goals as a clean energy source. The initiative aimed to promote green transportation technology in the country.[223]

Technology Readiness Levels (TRL)

[221] https://www.chinahighlights.com/shanghai/transportation/maglev-train.htm
[222] https://www.ecns.cn/news/sci-tech/2023-01-16/detail-ihcivkeu5241864.shtml
[223] https://pib.gov.in/PressReleasePage.aspx?PRID=1896102

Hydrogen trains have been successfully demonstrated at a commercial level in countries such as Germany and China. Hence they can be assigned a TRL level of 9.

Energy Efficiency

Hydrogen trains can be more energy-efficient than diesel trains, as they can recover energy through regenerative braking. When the train brakes, the electric motor functions as a generator, converting the kinetic energy of the train into electrical energy, which can be stored in a battery or capacitor for later use.

Compatibility with currently used technologies

Hydrogen trains can be designed to be compatible with existing railway infrastructure, including tracks, signalling systems, and stations. This is because hydrogen trains are electric trains, and the basic components of the propulsion system, such as the electric motor and the power supply, are similar to those used in traditional electric trains.

However, there are some differences between hydrogen trains and traditional electric trains that may require modifications to existing infrastructure. For example, hydrogen trains may require additional infrastructure for the storage, transport, and distribution of hydrogen fuel. Additionally, the safety requirements for hydrogen fuel are different from those for traditional fuels, which may require modifications to existing safety systems.

Foreseen cost development

Indian Railways estimated the cost of a hydrogen train under the "Hydrogen for Heritage" initiative to be Rs. 80 crores per train. The cost of ground infrastructure per route was estimated to be Rs. 70 crores.[223]

Global adoption of electric anode baking furnaces

On August 24, 2022, Germany inaugurated the world's first hydrogen-powered train fleet in Lower Saxony state. A fleet of 14 trains provided by French company Alstom replaced diesel locomotives on a 100km track connecting four cities near Hamburg. Hydrogen trains mix hydrogen with oxygen present in the air to produce electricity through a fuel cell installed on the roof. The fleet cost €93 million and is expected to prevent 4,400 tonnes of CO2 emissions annually. Hydrogen trains are considered a promising way to decarbonize the rail sector and replace diesel, which still powers 20% of journeys in Germany. Alstom's competitors, such as Siemens, are also developing hydrogen train prototypes. However, the sector faces supply challenges, and Europe's infrastructure for hydrogen production and distribution is still lacking.[224]

In January 2023, China's CRRC Corporation Ltd. launched Asia's first hydrogen urban train, becoming the second country in the world to do so after Germany. The hydrogen train has a top speed of 160 km/h and an operational range of 600 km without refuelling. The train was developed on a high-speed platform and included four cars. CRRC had previously introduced a hydrogen shunting locomotive in 2021 and hydrogen trams in the mid-2010s. The train is also equipped with digital solutions, including GoA2 automation, component monitoring sensors, and 5G data transmission equipment. Operation of the train is expected to reduce CO2 emissions by 10 tons per year compared to diesel traction. India is also set to introduce its first indigenous hydrogen trains by December 2023 as part of its plans to promote environmentally friendly transport.[225]

Vacuum-train

[224] https://www.aljazeera.com/news/2022/8/24/germany-inaugurates-worlds-first-hydrogen-powered-train-fleet
[225] https://currentaffairs.adda247.com/china-becomes-first-country-in-asia-to-launch-hydrogen-powered-train/

A vacuum train, also known as a vactrain or vacuum tube train, is a proposed mode of transportation that operates on the principle of a vacuum-sealed tube. The concept involves transporting passengers or cargo through a tube from one location to another at high speeds with minimal air resistance.

The vacuum tube is typically made of steel or other materials and is sealed at both ends to create a near-vacuum environment inside the tube. The train is propelled by electromagnetic forces, which levitate it slightly above the track and propel it forward. The lack of air resistance inside the tube allows the train to achieve high speeds with minimal energy consumption.

One of the main advantages of a vacuum train is its high-speed potential. With minimal air resistance, a vacuum train could theoretically reach speeds of up to 6,400 km/h (4,000 mph). This would make it one of the fastest modes of transportation available, capable of transporting passengers or cargo over long distances in a matter of minutes.

Another advantage of a vacuum train is its potential environmental benefits. By operating on renewable energy sources, such as wind or solar power, a vacuum train could be a highly sustainable mode of transportation with minimal greenhouse gas emissions. However, there are also several challenges associated with vacuum trains. One of the main challenges is the high cost of construction. The vacuum tube and the necessary infrastructure would be expensive to build, and the project would require a significant amount of funding.

Additionally, the technology is still largely untested, and there are concerns about safety and reliability. The high speeds involved in vacuum train travel could also pose safety risks, and there are concerns about how the system would cope with changes in air pressure and other environmental factors. Despite these challenges, vacuum trains remain an exciting possibility for high-speed transportation in the future. Several companies and organizations are currently exploring the technology, and it is possible that vacuum trains could become a viable mode of transportation in the coming decades.

Technology Readiness Levels (TRL)

The technology is at a lower TTRL of 3-4 as it has not been tested at scale. It may take several years to test and demonstrate before the technology becomes commercially available.

Energy Efficiency

Vactrains have the potential to be significantly more energy efficient than conventional trains. This is because they operate in a near-vacuum environment, which reduces air resistance and allows them to achieve high speeds with minimal energy consumption. However, there are significant technical and cost challenges associated with building and operating vacuum train systems, and it is not yet clear how feasible they will be in the long term.

Compatibility with currently used technologies

Vactrains are not compatible with existing train infrastructure. They require a completely new type of infrastructure, including a vacuum-sealed tube system and specialized track and propulsion systems.

Foreseen cost development

The proposed vacuum train would travel through a near-vacuum environment, propelled by magnetic pulses, at speeds of up to 4,000 mph (6,437 kph), allowing it to cover long distances in just one hour. However, the construction of the necessary infrastructure is estimated to cost between $25 million and $40 million per mile, making the entire project's estimated cost around $100 billion. [226]

Global adoption of electric anode baking furnaces

[226] *https://www.industrytap.com/transatlantic-meglev-train-would-be-largest-project-in-human-history/16108#:~:text=The%20train%20would%20travel%20through,was%20estimated%20at%20%24100%20billion.*

China has claimed to be the first country in the world to successfully test a magnetically levitated train, or "vactrain," inside a vacuum tube, according to the state-run newspaper China Daily. The test, which took place on a 1.25-mile track in northern China, saw the train reach speeds of up to 80 mph in a "low vacuum tube." The researchers behind the test plan to construct a full-scale, 37-mile test track and eventually have trains reach speeds of up to 621 mph. The concept of a vactrain is similar to Elon Musk's "Hyperloop," which has yet to be realized despite early testing.[227]

[227] *https://futurism.com/the-byte/china-maglev-vactrain-hyperloop*

Autonomous underground cargo train

Underground autonomous trains for cargo are a type of transportation system that uses driverless trains to transport goods through underground tunnels. Unlike traditional cargo transportation systems that rely on trucks or ships, these trains operate in a dedicated underground system, which can offer several advantages, including increased safety and speed.

The trains are typically designed to operate on a fixed route and are guided by an automated control system. They can be powered by a variety of energy sources, including electricity or hydrogen fuel cells, and can be designed to carry a wide range of cargo, from packages and parcels to large containers.

One of the main advantages of underground autonomous trains for cargo is their ability to operate with minimal human intervention. This can make the system more efficient and cost-effective, as it reduces labour costs and streamlines the transportation process.

Another advantage of underground autonomous trains for cargo is their ability to operate in a dedicated underground tunnel system. This can reduce congestion on roads and highways and can also reduce the risk of accidents and other safety issues associated with traditional cargo transportation methods.

Switzerland is building an underground autonomous freight transport system called Cargo Sous Terrain (CST), which will reduce the country's dependence on building more roads and rails. The system uses an automatic conveyor in tunnels to move freight to hubs in urban areas. The hubs have vertical lifts that can load or unload goods in an automated system that is completely underground. The system uses zero-emission electric vehicles that move at 18 mph (30 kph) through tunnels that have diameters of 20 feet (6 meters) and are divided into three lanes. The first section under construction will run from Harkingen-Niederbipp to Zurich and will have ten hubs. It is expected to reduce freight load on cities by up to 30% and noise and emissions by 50%. The construction of the tunnels is designed to have minimal effect on city residents, and the project could be replicated in other urban areas across the globe. [228]

Technology Readiness Levels (TRL)

The technology is at a lower TRL of 3-4 as it has not been tested at scale. It may take several years to test and demonstrate before the technology becomes commercially available.

Energy Efficiency

Autonomous underground cargo trains have the potential to be highly energy efficient, but much will depend on the specific technology used and the availability of renewable energy sources to power them.

Compatibility with currently used technologies

Autonomous underground cargo trains are not directly compatible with currently used transportation technologies, as they require a dedicated underground tunnel system and specialized track and propulsion systems.

[228] https://www.goodnet.org/articles/underground-autonomous-freight-system-will-make-roads-less-crowded-1

Foreseen cost development

Switzerland has approved the development of an underground autonomous cargo delivery system called Cargo Sous Terrain (CST) that is expected to cost between USD 30 and USD35 billion and will run on renewable energy.[229]

Global adoption

Figure 168: Switzerland Underground Autonomous Cargo Delivery Cargo Sous Terrain

Cargo Sous Terrain (CST) is a collaboration between Swiss firms involved in transportation, logistics, retail, telecom, and energy. The project aims to provide an autonomous, eco-friendly freight transport system that will help reduce Switzerland's dependence on building more roads and railways, which are already congested with freight and passenger traffic. The system will operate in a dedicated underground tunnel network, which will be divided into three lanes and will use electric-powered vehicles with induction rails. The vehicles will travel at a constant speed of around 30 kilometres per hour and will transport goods on pallets or in modified containers. The system will also include refrigeration-compatible transport vehicles for the transportation of chilled and fresh goods, as well as a rapid overhead track for smaller goods packages.[229]

The construction of the CST system will be funded entirely by the private sector and is expected to cost between USD 30 and USD 35 billion for the full 500-kilometer network. The first phase of the project, which will involve a 70-km section with 10 hubs that connects Zurich with a logistics center in Harkingen-Niederbipp to the west, is estimated to cost around USD3 billion. The entire project will run on renewable energy, and CST expects the number of heavy trucks on roads to be reduced by up to 40% as its underground vehicles take over transport. The Swiss Government has also indicated that the system could help reduce noise and emissions associated with traditional freight transport methods.[229]

The CST system is expected to be completed in several stages, with the first section scheduled to be operational by 2031. The project has already received significant interest from other Swiss cantons, with some suggesting that an underground CST connection is “technically and economically realistic” and they have begun determining possible hub locations.[229]

Hyperloop

Hyperloop technology involves transporting passengers or cargo through low-pressure tubes at extremely high speeds using a combination of vacuum technology and magnetic levitation. The tubes are designed to reduce air resistance, which allows the pods to travel at speeds of up to 1000 km/h or more.

The pods are propelled by electric motors that are either mounted on the pods themselves or located along the tube. The pods levitate using magnetic levitation technology, which involves using magnets to create opposing fields that lift the pods off the ground and propel them forward. The tube is maintained at a low pressure of around 1% of atmospheric pressure, which reduces air resistance and

[229] https://spectrum.ieee.org/cargo-sous-terrain

allows the pods to travel faster with less energy. The pods themselves are designed to be aerodynamic and lightweight, with a streamlined shape that reduces drag.

The hyperloop system is designed to be energy-efficient and environmentally friendly, as it uses renewable energy sources such as solar power to generate the electricity needed to power the system. It also has the potential to reduce congestion on roads and railways, as well as reduce travel times between cities.

The first person to imagine a prototype of the hyperloop was British inventor George Medhurst, who filed a patent for a system that could move goods through a system of iron pipes in 1799. In the 20th century, levitating pods and air cushion technology were explored, before the first hyperloop designs were published in 2013 by Elon Musk.[230]

Musk's original Hyperloop Alpha design involves enclosed capsules or pods that travel through a system of tubes on skis that levitate on a cushion of air. Since then, several companies have worked on developing hyperloop technology, including Virgin Hyperloop and Zeleros. These systems use a combination of vacuum technology and magnetic levitation to transport passengers or cargo through low-pressure tubes at extremely high speeds. Virgin Hyperloop, for example, started actively working on the hyperloop in May 2016 and successfully carried out its first open-air test in North Las Vegas later that year. In 2020, the company conducted the first successful passenger test of its hyperloop system. Zeleros has also been working on developing its hyperloop prototype, which uses aerodynamic propulsion inside the vehicle, similar to an airplane, while being 100% electric.[230]

The Indian Government has explored various futuristic transportation systems, including the Hyperloop. The Indian Government signed bilateral agreements with Virgin Hyperloop in 2018 and 2020 to connect various cities within the country, and test rides with human passengers began in November 2020. However, in March 2022, Virgin Hyperloop announced that it would no longer work on a human transportation system, citing global supply chain issues and Covid, and would instead focus on cargo transport. This led to speculation that India's plans for Hyperloop passenger transport were in doubt. However, some academic initiatives in India, such as Avishkar Hyperloop at IIT Madras and Team VegaPod Hyperloop at MIT World Peace University in Pune, are still exploring the development of an indigenous Hyperloop system.[231]

Technology Readiness Levels (TRL)

The technology is at a lower TTRL of 3-4 as it has not been tested at scale. It may take several years to test and demonstrate before the technology becomes commercially available.

Energy Efficiency

They have the potential to be highly energy efficient, but much will depend on the specific technology used and the availability of renewable energy sources to power them.

Compatibility with currently used technologies

They are not directly compatible with currently used transportation technologies, as they require a dedicated tunnel system and specialized track and propulsion systems.

Foreseen cost development

The cost of building an Hyperloop line could go as high as USD121 million per mile or as low as USD11.5 million per mile that Elon Musk pledged in 2013. The cost of building a Hyperloop system remains a significant barrier to its widespread adoption, and it is uncertain whether engineers will be able to significantly reduce the cost of building such a system in the future.[232]

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[230] https://www.railway-technology.com/features/timeline-tracing-evolution-hyperloop-rail-technology/

[231] https://swarajyamag.com/tech/indias-ultra-high-speed-hyperloop-passenger-transport-ambitions-appear-crushed-but-some-desi-alternatives-emerge

[232] https://leonard.vinci.com/en/hyperloops-speed-but-at-what-cost/

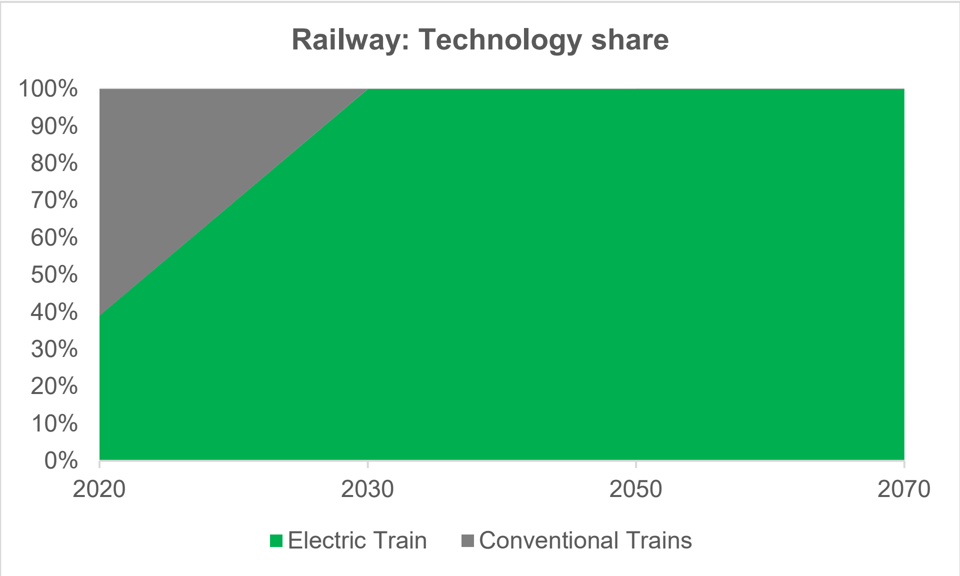
Global adoption

In October 2022, it was reported that researchers at North University of China had successfully tested a Hyperloop-like train system that utilized magnetic levitation technology in a low-vacuum environment inside a tube, according to China Daily.

In the reported test, the maglev train ran at speeds of up to 80 miles (130 km) per hour on the 1.25-mile (2 km) Datong Test line constructed in Shanxi province. Following the success of the preliminary test, the laboratory began constructing a full-scale 37-mile (60 km) test track to be completed in three phases. The full-scale track will allow the testing of trains at speeds up to 621 miles (1,000 km) an hour. The North University of China and the Third Research Institute of China Aerospace Science and Industry Corp. jointly set up a laboratory for high-speed maglev vehicles operating in low-vacuum environments. The groundbreaking ceremony for the Datong test line was carried out in May the previous year.[233]

ELECTRICITY REQUIRED FOR FULL DECARBONISATION

Suitable technology mix



Technologies are evaluated primarily based on their TRL level, potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering the targets under the Government of India's *Mission of 100% Electrification*. Technology penetration and TRL levels are presented in the graph presented below. The Ministry of Railways has committed to electrify the entire sector by 2030 and this sector can achieve net zero emissions when electricity supplied to the railways would be carbon-free.

[233] https://interestingengineering.com/innovation/china-tests-hyperloop-like-system

Projected Energy Consumption for Decarbonisation

Energy consumption is projected, considering the ambitious scenario of decarbonisation, i.e., 100% electrification by 2030. The ambitious scenario is considered as the Government of India succeeding in its *Mission 100% Electrification* with the target to electrify 100% of the railway track by 2030.

Ambitious scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	2	2	3

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070. The energy demand of the railway sector would reduce by 51.9% in 2030, 2050, and 2070 over the base scenario.

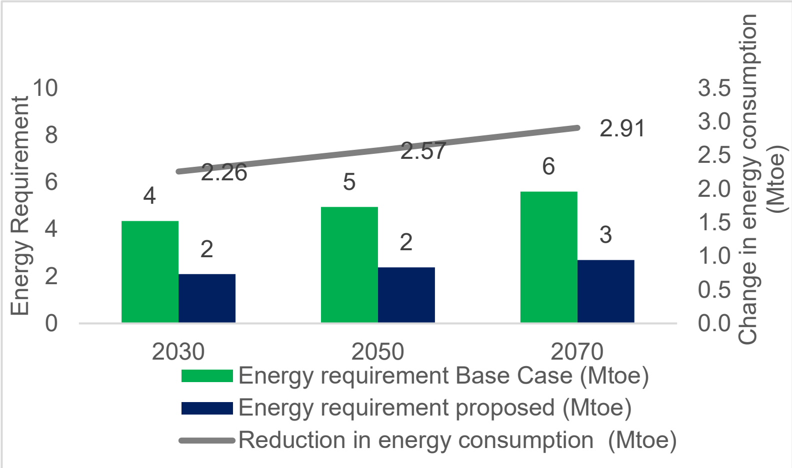


Figure 169: Energy requirement (Railways)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the different timelines 2030, 2050 and 2070. The average capacity utilisation factor is calculated for the different timelines based on the mix of different sources of energy, i.e., fossil and non-fossil fuel-based sources of electricity. In the ambitious scenario, the power installation requirement for the sector would be **0.4 GW** by 2030, and it is expected to increase by **1 GW, 0.9 GW** by 2050 and 2070, respectively. Additional battery storage capacity is also estimated to meet the demand on one-day autonomy period in case of any seasonal disruption for RE power. Battery storage capacity for the sector would vary in the range of **0.1 GWh** for 2030 in all different scenarios. Power requirement and battery storage capacity in each timeline and different scenarios is presented in the table shown below.

Year	2030	2050	2070
RE hybrid installed capacity (GW)[234]	7	9	8
Battery Storage (GWh)	1.8	4.1	4.9

[234] Minitry of Railway has already committed to be net zero by 2070. Therefore, numbers would be same for all the sceanrio

Projected GHG emission reduction

The total GHG emissions for the sector is estimated to reach 23 million tonnes CO_{2e}, 27 million tonnes CO_{2e},, and 30 million tonnes CO_{2e} for years 2030, 2050, and 2070 in the BAU scenario, respectively. Under the ambitious scenario, it is estimated to be net zero in 2070 as the locomotives would be electrified and powered by green energy sources. GHG emissions reduction, in this case, is calculated and presented in the graph shown below.

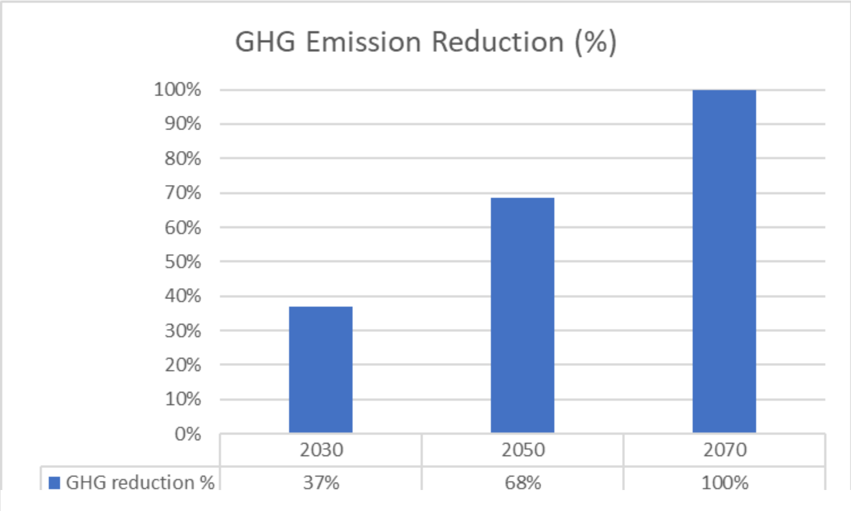


Figure 170: GHG emissions reduction (Railways)

5 Electrification of Building & Appliances

5.1 Electrification of Building & Appliances Sector

India's urban population is expected to increase rapidly, expected to hit 525 million by 2025 and 600 million by 2030.[235] In this environment, with the vast housing infrastructure that will need to be made, it is important for the Government to decouple GHG emissions with economic growth in the buildings and construction sector. The Indian Government does have comprehensive climate action plans and targets, which are clearly stated in India's Paris Climate Agreement NDC. What it doesn't have is a comprehensive sub-sectoral policy target within the buildings and construction sector, which is responsible for 40% of the generated carbon footprint.[236]

75% of the consumption of energy in India's buildings sector is from commercial buildings, and the number is only set to rise in coming years. This energy consumption is largely changing in pattern, with increasing intensity of energy usage due to air conditioning contributing significantly.[237] The commercial building sector is growing at 9% per year, 50% of the buildings projected till 2030 have not been built yet and operational cooling is only 3-10% of the country's energy use[238] as of 2021. Hence, it is really important to focus on renewable technologies so that India's NDC goals are met parallelly with the urban transition expected.

India has been on a path towards providing clean cooking fuels (i.e. LPG cylinders) to most of its rural population ever since the PM Ujwala Yojana (PMUY) was launched. From about 83% of the rural population using wood and biomass-based cooking in 2011-12, 40% of the rural population had adopted LPG cylinders by 2019. The cooking sector saw a decrease in energy consumption from 4439PJ in 2007 to 4162PJ in 2017, thanks to the PMUY scheme. However, LPG being a carbon-intensive fuel, the GHG emissions from India's cooking sector have also increased, and the sector accounted for an overall 6% of India's emissions in 2014.[239]

While India did make a lot of progress in improving its situation of indoor air pollution through the PMUY scheme, there have been certain counter-effects in other areas. For starters, the imports of LPG to India doubled over the 2010s to reach INR 49939 crore in 2018-19. This poses a risk to India's energy security and causes a heavy dependence on imports for something essential to people's daily lives. Apart from this, India's climate goals and Paris Agreement NDC mandates a reduction in GHG emissions over the coming decades. With rising incomes, the demand for energy is bound to increase for activities such as cooking, and as a result, the Government has recognized a need for a policy shift towards more energy-efficient cooking technology such as electric cookers.[239]

The draft energy policy by NITI Aayog aimed to achieve clean cooking energy access to all by 2022 and had a special emphasis on electricity-based cooking. It aimed to cut oil imports by 10% of 2014-15 levels by 2022. At the same time, it aimed to have non-fossil fuel-based generation at 40% of the

[235] https://economictimes.indiatimes.com/industry/services/property-/-cstruction/new-construction-industry-coalition-aims-to-rapidly-accelerate-decarbonisation-of-the-built-environment-in-india/articleshow/94019857.cms?from=mdr
[236] https://www.outlookindia.com/business-spotlight/the-carbon-footprint-of-the-construction-industry-in-india-news-247342
[237] https://www.conserveconsultants.com/ecbc-residential-building-energy-code#:~:text=ECO%20Niwas%20Samhita%202018%2C%20is,of%20homes%2C%20apartments%20and%20townships.
[238] UNEP – 2022 Global Status Report for Buildings and Construction
[239] https://www.cda.eu/hobs/how-does-induction-cooking-work/

electricity mix by 2030. Through suitable interventions, it has been found that India's energy demands could be brought down by 17% by 2040 over the baseline scenario. It aimed to provide electricity to 304 million more people and clean cooking fuel to 500 million more people by 2022. It also had a good emphasis on energy security.

While there hasn't yet been a strategy towards the electrification of the cooking sector by the Government yet, there is an emphasis on the same by government bodies and think tanks. However, in order to facilitate equitable mass adoption, certain other parameters need to be fulfilled. For starters, complete electrification of all homes in India is needed.

Existing Policy Interventions

The Energy Conservation Building Code (ECBC) was launched by the Ministry of Power in 2007. It was aimed at improving the energy efficiency and standards of new commercial buildings and set minimum energy standards for new buildings with an over 100kW connected load or over 120kVA contract load. The code focuses on effective comfort for building occupants, which includes adequate lighting, cooling, passive design and daylight integration. There is a particular emphasis in these codes on being technologically carbon-neutral, with the promotion of renewable energy strategies and enhanced life cycle cost of the building as important pillars. These codes were redesigned in 2017, making them futuristic, pragmatic and easier to implement. The prime focus of this new design was to encourage public and private sector players to not just meet the criteria mentioned but to exceed them as well.[240]

Phase-1 of the ECBC-R (residential) code was formulated in 2018, and they were designed to be simple and easy to implement, requiring only simple calculations from architectural drawings. The two main aspects of this code are fresh air compliance and daylight compliance. While technological improvements are not covered in the first phase of the ECBC-R, the code is still effective through various standards on technical ratios and parameters.

To improve thermal comfort and reduce cooling energy, the code recommends the openable window-to-floor area ratio (WFR op) to be equal to the carpet area of the dwelling units. It also caps on thermal transmittance to improve cooling by reducing the heat transmitted via rooftops. To reduce lighting energy utilized, the code recommends minimum Visible Light Transmittance (VLT) standards for buildings.

Another area being focused upon in India is embodied carbon, mainly by private sector players. Embodied carbon is different from operational carbon in that it has spikes during the construction phase of the building and is projected to be responsible for half of the new construction emissions until 2050. Many major and influential private sector players (mostly in the cement and paint industries) have come up with net zero carbon roadmaps and environmental product declarations.[241]

The Indian Government has also come up with a rating system known as Green Rating for Integrated Habitat Assessment (GRIHA), which is used to classify a building as a "green building". The rating system is a comprehensive 100+5 point system that considers parameters relevant to a building's entire life cycle and offers a holistic analysis of how "green" or environmentally friendly the building is from the time it is built. Through benchmarks and limits, GRIHA provides incentives for buildings and constructions to reduce their resource consumption and waste generation. Multiple state and local administrations, such as the Pimpri Chinchwad Municipal Corporation, NOIDA Authority, Ghaziabad

[240] https://beeindia.gov.in/en/energy-conservation-building-code-ecbc
[241] https://rmi-india.org/reducing-embodied-carbon-is-key-to-meeting-indias-climate-targets/

Municipal Authority, Kerala PWD and many others, have adopted GRIHA through incentive schemes and rebates.[242]

GRIHA v.2019			
Section	Criterion No.	Criterion Name	Maximum Points
1. Sustainable Site Planning	1	Green Infrastructure	5
	2	Low Impact Design	5
	3	Design to Mitigate UHIE	2
2. Construction Management	4	Air and Soil Pollution Control	1
	5	Top Soil Preservation	1
	6	Construction Management Practices	2
3. Energy Efficiency	7	Energy Optimization	12
	8	Renewable Energy Utilization	5
	9	Low ODP and GWP Materials	1
4. Occupant Comfort	10	Visual Comfort	4
	11	Thermal and Acoustic Comfort	2
	12	Maintaining Good IAQ	6
5. Water Management	13	Water Demand Reduction	3
	14	Wastewater Treatment	3
	15	Rainwater Management	5
	16	Water Quality and Self-Sufficiency	5
6. Solid Waste Management	17	Waste Management-Post Occupancy	4
	18	Organic Waste Treatment On-Site	2
7. Sustainable Building Materials	19	Utilization of Alternative Materials in Building	5
	20	Reduction in GWP through Life Cycle Assessment	5
	21	Alternative Materials for External Site Development	2
8. Life Cycle Costing	22	Life Cycle Cost Analysis	5
9. Socio-Economic Strategies	23	Safety and Sanitation for Construction Workers	1
	24	Universal Accessibility	2
	25	Dedicated Facilities for Service Staff	2
	26	Positive Social Impact	3
10. Performance Metering and Monitoring	27	Commissioning for Final Rating	7
	28	Smart Metering and Monitoring	0
	29	Operation and Maintenance Protocol	0
Total Points			100
11. Innovation	30	Innovation	5
Grand Total Points			100 + 5

Table 19: Parameters used for GRIHA[243]

Not only is cooling an integral part of the Montreal Protocol and the Paris Agreement, but it is also extremely paramount for India for the amount of cooling required in the country owing to the tropical climate. In order to drive the projected future demand for cooling in a sustainable manner, the India Cooling Action Plan (ICAP) was designed as a 20-year recommendation plan to address energy efficiency in cooling across sectors. It has broadly sliced cooling into building space cooling, cold chain refrigeration and transport cooling.[244] The prime focus of this report is on building cooling technology.

Existing Technology: Cooling

[242] https://www.re-thinkingthefuture.com/2022/05/17/a6917-what-is-griha-certification-and-why-it-is-beneficial/
[243] https://www.grihaindia.org/griha-rating
[244] http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

ICAP has identified the broad cooling techniques used for building cooling in India, and these are given in Figure 2. It must be noted that while the vast majority of India still relies on non-refrigerant-based and natural cooling techniques for building space cooling, there have been vast technological improvements in cooling even within fans and air coolers.[244]

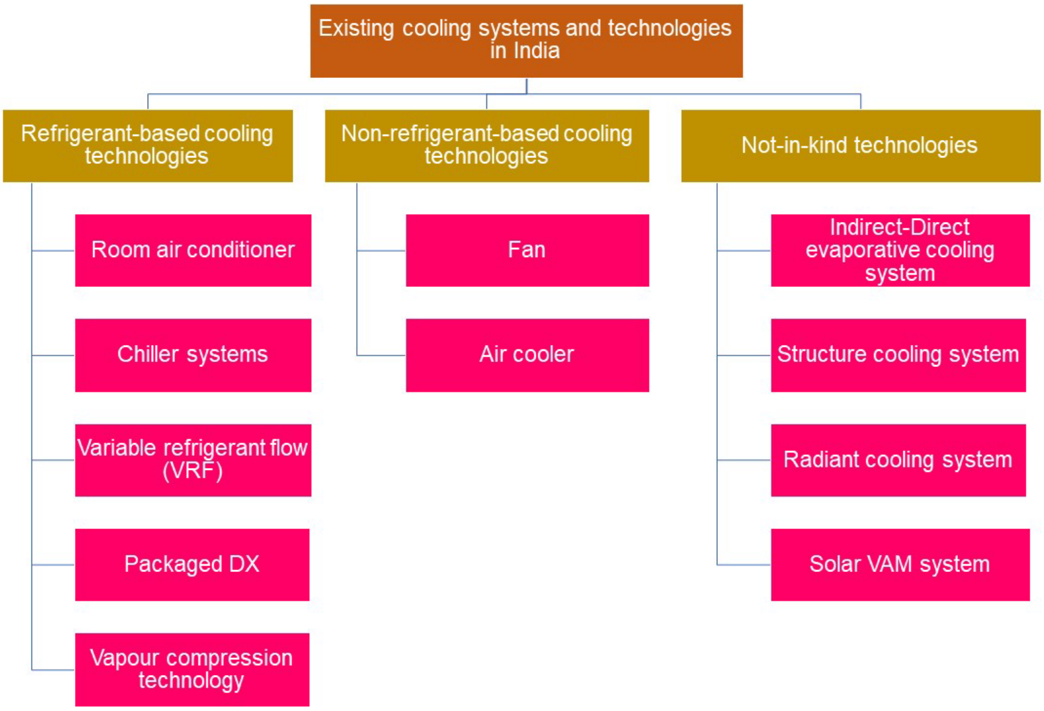


Figure 171: Classification of existing building space cooling systems in India

Non-Refrigerant Based

Non-refrigerant-based technologies for cooling mainly comprise fans and air cooler systems. Fans are almost a given in every electrified Indian household, and many times, these fans are run side-by-side with air conditioners. Air coolers, on the other hand, are used in residential and small-to-medium commercial establishments. These devices have certain constraints in their operation, including but not limited to humidity, ambient temperature, and ventilation.[244]

Bladeless DC ceiling fans offer 220-230 m^3/min air delivery at 30W, compared to similar air delivery by conventional single-phase induction motor fans at 80W. Similarly, some of the limitations that air coolers experience due to humidity can be mitigated with cooling pads made of materials such as aspen and honeycomb. In a scenario where the majority of the population is not expected to move towards air conditioning over the next 20 years, focusing on energy efficiency in non-refrigerant-based technology could play an important role in cutting down cooling-led GHG emissions.[244]

Refrigerant Based

Refrigerant-based cooling techniques are not limited to the conventional room air conditioners. While air conditioners are the natural choice of adoption for households in India, commercial establishments such as hotels, hospitals and malls use air-cooled or water-cooled chiller systems.[244]

A lot of progress has already been made in making ACs energy-efficient through star ratings issued by the BEE. These ratings have been based on how much particles, such as CFCs, are emitted by air conditioning products. There are good technological advancement adoptions in chiller systems as well, which include Variable Refrigerant Flow (VRF) systems. Although VRFs have high initial costs, they are quick to install, easy to operate and highly energy-efficient as demonstrated by their 2.5-20TR rating compared to 50-500TR ratings of comparable chiller systems.[244]

Not-In-Kind Technologies

Many low-energy cooling techniques have already been deployed and tried out in India. Such technologies offer reduced cost, reduced energy usage for cooling, peak demand reduction and GHG emission savings. These have already been applied at large scales across Indian commercial buildings and have even been seen to provide IoT-related benefits.[244]

One such technology is the Indirect-Direct Evaporative Cooling System (IDEC), which functions by cooling the process air within a building room without adding humidity to the supply air stream. This is a very important added benefit as supply air humidity rises, resulting in GHG emissions and global warming. Between 2008 and 2017, 43 million ft^3/min of airflow through IDEC was installed in India, equivalent to a 0.1 million TR rating.[244]

Another innovative case of technology adoption would be structure cooling systems. Approximately 4600 TR has been replaced by structure cooling through 0.6 million ft^2 of the built-up area using this technology in 28 large commercial buildings in India between 2005 and 2017.[244]

DECARBONISATION POTENTIAL

A major share of the buildings sector is already electrified, including cooling, heating, lighting and appliances, making it the top sector with regard to the level of electrification. Fossil fuels such as LPG, fuelwood and other biomass are used only for cooking applications. The electrification scenario of the buildings sector will thus include the penetration of electric cookstoves. With the deployment of this technology, 100% of the energy consumption of the sector can be electrified from the existing 74% level. This implementation would result in a drop in the energy consumption of the sector by 38%, i.e., from 699 Mtoe in the base scenario to 431 Mtoe in the ambitious effort scenario. Reduction in energy consumption would also lead to a reduction in GHG emissions by 100% by 2070. Key findings of the tool are presented in the illustration shown below. Detailed analysis of each parameter is further explained in the next sections.

431 Mtoe of Energy Demand by 2070 from the sector

Reduction of **1673 Mn tonne CO_{2e}** by 2070

Power demand of **1272 GW** by 2070

Requirement of **1061 GWh** of battery storage capacity by 2070

The improvement in key parameters based on the proposed penetration level of the technology and the level of effort is as follows.

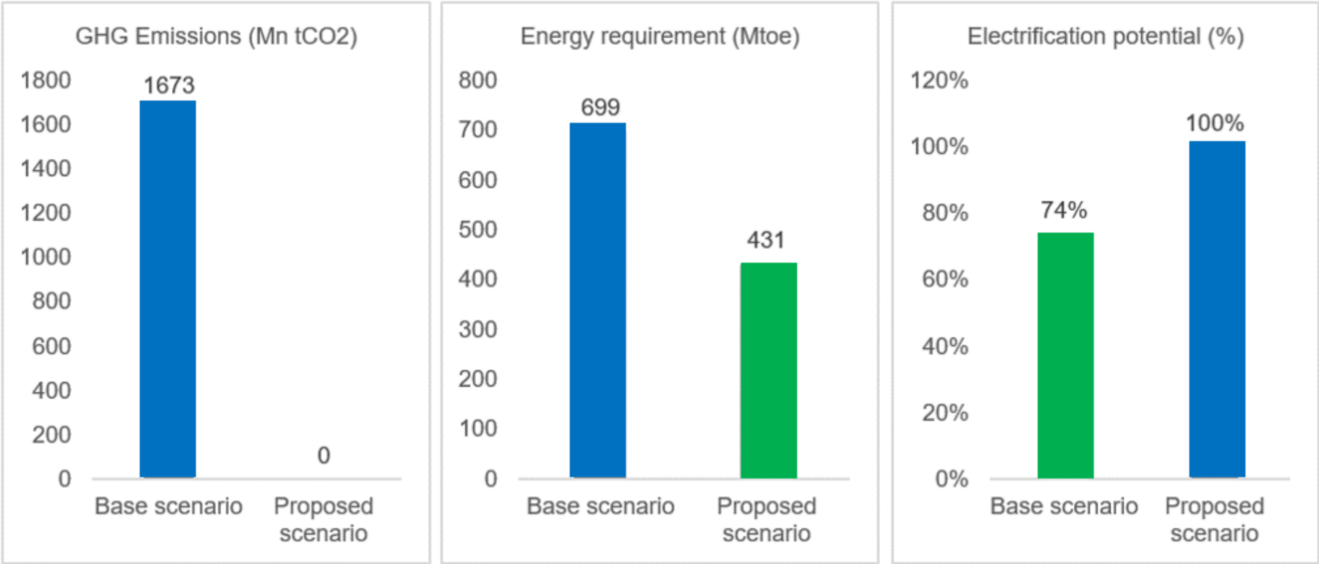


Figure 172: GHG emissions, energy requirement and electrification potential in proposed scenario

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION: Cooling/Heating

District Heating and Cooling – 5th Generation (5GDHC)

The interchange of thermal energy between buildings with various needs forms the foundation of a fifth-generation district heat and cold (5GDHC) grid. The main grid transports a flow of low-temperature energy to distributed and active substations, which raise the temperature to the necessary level. The variation in the supply and demand of heat and cold is reduced by distributed thermal storage. The proportion of low-grade renewable and waste energy sources is maximised by this architecture.[245]

5GDHC networks are district heating networks with operating temperatures at room temperature (about 5-35 °C). With this technology, heat pumps are installed in buildings in 5GDHC networks, raising the temperature of the heat coming from the network to the supply temperature in the building's heating system. It is mainly seen in Europe, where it is believed that more than 100 districts using this technology exist.[246]

These networks are unique in that they can provide both heating and cooling with one single thermal network (i.e. with two pipes). It can also exploit ambient heat from many unexpected sources, such as waste heat from sewage water or geothermal energy. There is a good degree of sector coupling here, with the electricity and heat sectors being closely coupled together through mutual independence. Despite any heat storage systems, there is a good degree of balancing between heating and cooling demands within a district using this technology.[246]

Although many 5GDHC networks have already been realised, one drawback is that there is still a lack of technical expertise, as well as appropriate calculation techniques and tools, for the design of 5GDHC

[245] https://5gdhc.eu/5gdhc-in-short/#:~:text=A%205th%20generation%20district%20heat,temperature%20to%20the%20required%20level.
[246] https://www.npro.energy/main/en/5gdhc-networks/price-cost-data

networks. In addition, 5GDHC networks have bigger volume flows compared to typical district heating networks with a substantial temperature difference between supply and return, necessitating wider pipe diameters. The use of plastic pipes, which are frequently less expensive, partially offsets this drawback. The system control is more complicated than for ordinary district heating networks, which is another drawback. The system can be monitored carefully to assist guarantee effective performance.[247]

One important pre-requisite for 5GDHC is the ability to effectively identify whether the need is for heat or cold. This could be termed as the ability to assess two different kinds of loads. Additionally, energy sources should have low-temperature differences with the ambient temperature. A 100% renewable energy target is also important in this technology, considering decarbonization goals and potential. During the design of the 5GDHC system, this needs to be kept in mind.[247]

Whether 5GDHC technology is more cost-effective than others depends largely upon individual country conditions and existing pricing policies and incentives. Dependent factors include size and type of available heat sources, existing methods for cooling and pricing efficiencies that already exist with other technologies. Hence, in order to make 5GDHC appealing, there needs to be a focus on existing heating technology and making the technology 100% renewable in a cost-effective manner.[246]

Technology Readiness Level (TRL)

5GDHC has a high technology readiness level of 9. This is because it is highly reliant on existing technologies being integrated with each other and does not require much further R&D for effective deployment. If local context is taken care of, the technology can effectively be used in India, just like it has proliferated so well in countries in Europe, such as Germany, Switzerland and the Baltics.

Energy Efficiency

Because 5GDHC uses lower-grade and low-temperature energy sources than traditional energy sources for its operation, it naturally offers better energy efficiency and management. Another contributing factor is the fact that a single pipeline system is used for both heating and cooling, leading to closed energy loops and energy reuse, complemented by good energy storage. Finally, the decentralized nature of the system allows better contribution by individual household units and individual district units ineffective close-attention management of the entire system.[247] It has been noticed that effective temperature control using 5GDHC systems can cut operating costs by 10-60%.[248]

Compatibility with currently used technologies

Industries in India are plenty, and therefore, there are plenty of assets (such as manufacturing installations, data centres, etc.) whose heat waste can be used for 5GDHC implementation. However, despite such assets, there is a lack of technical experience around the world in effective design, tools and calculation methods for such systems. Moreover, this technology is more suited to countries that require high levels of both heating and cooling, whereas the same may not be true for India as it is for Europe.[249]

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[247] https://www.araner.com/blog/5th-generation-district-heating-and-cooling-systems
[248] https://www.sciencedirect.com/science/article/pii/S2352484722014275#:~:text=The%20annual%20consumption%20of%20thermal,only%201.7%20TWh%20of%20electricity.
[249] https://www.npro.energy/main/en/5gdhc-networks

Global adoption

Mijnwater Project, Heerlen (Netherlands)

The project began as a 4th generation district heating and cooling network, with the lower end temperature being 16°C and the upper end temperature being 28°C. However, with the geothermal source getting depleted, an upgrade was sought after, and storage heat of buildings themselves was integrated into the network, thereby making it a scalable 5GDHC system that runs well to this day. In 2020, over 400 buildings and 250000 m^2 of built-up area were under the Mijnwater Project. The aim of the project is to connect over 30000 dwellings in Parkstad by the year 2030.[250] In order to aid this transition, Mijnwater BV has plans to invest 300 million euros until 2030.[251]

Amsterdam

Real estate developer group Caransa, in 2020, started to develop a data center that could reportedly "power people's homes". The 1 million ft^2 data center is envisioned as part of a 5GDHC system that could potentially heat the buildings of Amsterdam using the residual heat from the data center operations.[252]

Heat Pumps

Heat pumps are heating and cooling devices that rely on heat transfer to regulate the temperature in closed areas. They can heat indoor areas by transferring heat from a cooler area into your home and also cool indoor areas by transferring heat from your home to the outside.[253] During winters, they need to absorb hot air from the outside and transfer it indoors in a situation where such hot air is in short supply. On the other hand, in hotter climates such as those in India, hot air is available in abundance indoors, and this is transferred outside by the heat pump to cool the room. Hence, it can be said that heat pumps are more energy-efficient at cooling than at heating[254]. Details of the technology are explained in section *8.1 Cross-cutting technologies*

Two-speed and variable-speed compressors

These are compressors that offer more than a single speed or stage of air conditioning. Taking two-speed compressors for simplicity, we can see that high-speed modes can be used for extreme weather events and low-speed modes can be used for normal weather conditions. Such compressors provide the versatility required to handle any type of weather, and they do so in an energy-efficient manner. The reason here is that in such conditions, these compressors will have to turn on and off less often. Additionally, they remove humidity from the air, which makes it suitable for most of India's climatic conditions. While they are expensive to set up and repair (the average cost to replace two-stage compressors in the US is $1900[255]), the energy efficiency benefits this technology offers make it worth it.[256]

Variable-speed motors

In most households with air conditioning systems in India, ACs and fans are used simultaneously owing to the need for better cooling and reduction in humidity. In such situations, having fan motors that go beyond the usual stepper motor functions and instead operate as variable frequency drives

[250] https://www.euroheat.org/resource/mijnwater-project-in-heerlen-the-netherlands.html
[251] https://guidetodistrictheating.eu/heerlen/#:~:text=Mijnwater%20BV%20plans%20to%20invest,2050%20requires%201.5%20billion%20euros.
[252] https://datacentremagazine.com/data-centres/new-dutch-data-centre-will-heat-peoples-homes
[253] https://www.energy.gov/energysaver/heat-pump-systems
[254] https://www.raleighheatingandair.com/blog/is-a-heat-pump-more-effective-at-cooling-or-heating/#:~:text=Heat%20pumps%20use%20less%20energy,heat%20for%20it%20to%20absorb.
[255] https://www.forbes.com/home-improvement/hvac/ac-compressor-cost/#:~:text=Replacing%20an%20AC%20compressor%20costs,cost%20as%20little%20as%20%24100.
[256] https://www.parkershvac.com/blog/variable-speed-vs-two-stage-compressor/

(VFDs) can greatly improve energy efficiency in household cooling. VFDs do so by adjusting the frequency and, thereby, fan speeds according to requirements. Any kind of inverter-rated motor is compatible with a VFD, and while this is the only condition that needs to be met, multiple factors such as motor winding insulation, speed ratings and lead length need to be taken into account while designing VFDs for cooling systems.

Desuperheater

In the process of cooling during heat pump operation, hot air from inside is transferred outside, making the air outside even warmer. This waste heat can be problematic and needs to be mitigated efficiently, and a desuperheater is designed to do exactly that. It lowers the temperature of any "super-heat" released as a cooling by-product through water release, and this is done through an effective control loop that regulates when to release water and how much water to release downstream based on temperature sensing and control. Through this operation, downstream heat conditions and equipment are controlled and protected better. The design of individual desuperheaters depends on the underlying cooling applications being optimized, and pipeline size, velocity, water temperature and quantity need to be taken into account during the desuperheater design. These parameters also have limit bounds. For instance, velocities of piped water in desuperheaters can range between 30 feet/sec and 250 feet/sec.[257]

Combinations

Generally, heat pumps use electric heaters for backup in cold weather. However, they can be equipped in combination with a gas furnace as a dual fuel-electric hybrid system. Such combinations have been seen to improve energy efficiency quite well through their ability to operate more efficiently at lower temperatures and thereby use less electricity. Although there are few manufacturers today who design pumps equipped with such hybrid systems, it is an option worth exploring due to the economic and energy savings offered.[253]

While heat pumps are broadly used in both residential and industrial markets, India has mostly seen heat pumps used in commercial and industrial applications. The growth seen in the Indian industrial heat pump market has largely been due to industry efforts to cut down on carbon footprint, and this market size is expected to grow at 13.6% CAGR between 2021 and 2027. The market can be segmented broadly into air-to-air, air-to-water and water-to-water heat pumps, with water-to-water pumps seeing the most popularity in India due to high levels of efficiency and less electricity required to function.[258]

These pumps are mostly used in the Southern part of India, where multiple industries such as pharmaceuticals, textiles, chemicals, manufacturing and automobiles are situated. With the most amount of pump efficiency being seen in the 20°C - 90°C segment of the market, this is the most preferred segment within the Indian industry. Some of the prime players in the Indian industrial heat pump market are Brio Energy Pvt. Ltd, Flamingo Heat Pumps, Johnson Controls International PLC and Midea Group Co. Ltd.[258]

[257] https://instrumentationtools.com/desuperheater/
[258] https://www.6wresearch.com/industry-report/india-industrial-heat-pump-market-2021-2027

Technology Readiness Level (TRL)

Heat pumps have a TRL of 9, with widespread adoption already seen across different countries, including India. They are comparatively easier to set up than 5GDHC and other heating/cooling technology and do not require too much expertise and high-level design for effective setup.

Energy Efficiency

To measure heat pump efficiency, a parameter called Coefficient of Performance (CoP) needs to be considered. This parameter effectively measures the amount of heat given for each unit of electricity consumed. The average heat pump was seen to have high values of CoP, basically implying that they produce more energy as heat than they consume as electricity.[259]

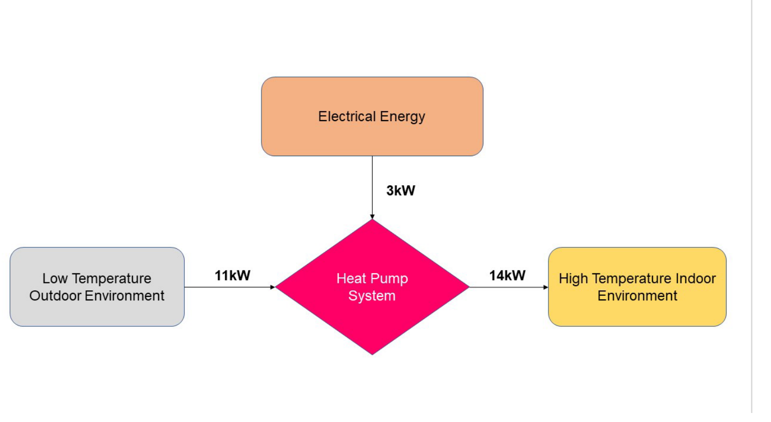

Figure 173: Heating Operation of Heat Pumps – Only 3kW energy is used externally

Compatibility with currently used technologies

We have seen in the above sections the innovations that are available in our arsenal to enhance the energy efficiency and decarbonization potential of heat pumps. Variable-speed compressors, variable-speed motors, desuperheaters ,gas furnaces and other fuel hybrids are some of the few technologies that are compatible with heat pumps.

Global adoption

As of 2021, around 10% of global space heating needs were met by heat pumps globally. Global sales of heat pumps grew by nearly 15% in 2021. Governments across the world are rapidly investing in this technology as a means to achieve their decarbonization and net zero goals. The share of heat pumps in global heating demand is expected to grow from 9% in 2021 to 19% in 2030.[260]

- In the European Union, natural gas is still the preferred means of heating homes during winter. In the backdrop of the Ukraine war, gas prices have increased the most in the EU. A projected rise of heat pump sales to 7 million units in 2030, from 2 million in 2021, can help reduce natural gas consumption by 7 bcm by 2021 and 21 bcm by 2030. Heat pump sales across the European Union grew at around 35% in 2021, led by Poland (66%), Italy (63%), France (36%) and Germany (26%). 60% of all buildings in Norway are equipped with heat pumps, while the same number is over 40% for both Sweden and Finland. Overall, Europe's installed capacity of heat pumps is projected to go up from 197GW in 2021 to 449GW in 2030.[260]
- While 2021 saw the maximum adoption of heat pumps in Europe, China saw the largest increase in new adoptions. 45% of all heat pump manufacturing was in China, and much of the building stock, particularly in the South, relies on heat pumps for both cooling and heating in summers and winters. This has come as an effort to reduce its high reliance on coal for heating and energy production.[261]

[259] https://energysavingtrust.org.uk/advice/in-depth-guide-to-heat-pumps/
[260] https://www.iea.org/reports/the-future-of-heat-pumps/executive-summary
[261] https://www.iea.org/reports/the-future-of-heat-pumps/executive-summary

Domestic Air Conditioning

A single split domestic air conditioner consists of an outlet unit that delivers cool air inside and an outside compressor. These are referred to as ductless mini-split air conditioners since they do not require ductwork on walls or ceilings but instead rely on pipes to connect the outdoor unit to the indoor unit. Such technology is best suited for small indoor areas, which include home and domestic installations.[262] However, when considering commercial establishments, chillers can be considered as the analogy for split ACs on a larger scale.

When it comes to air conditioning, the biggest determinant of global warming potential (GWP) is hydrofluorocarbons (HFCs). HFCs have a GWP hundreds to thousands of times more serious than CO_2. Around 80% of all HFCs globally are emitted in cooling, which includes domestic, cold-chain and transport cooling. With projected increases in cooling demand in emerging markets susceptible to hot climates, there is a need to transition towards low-GWP materials in cooling.[263]

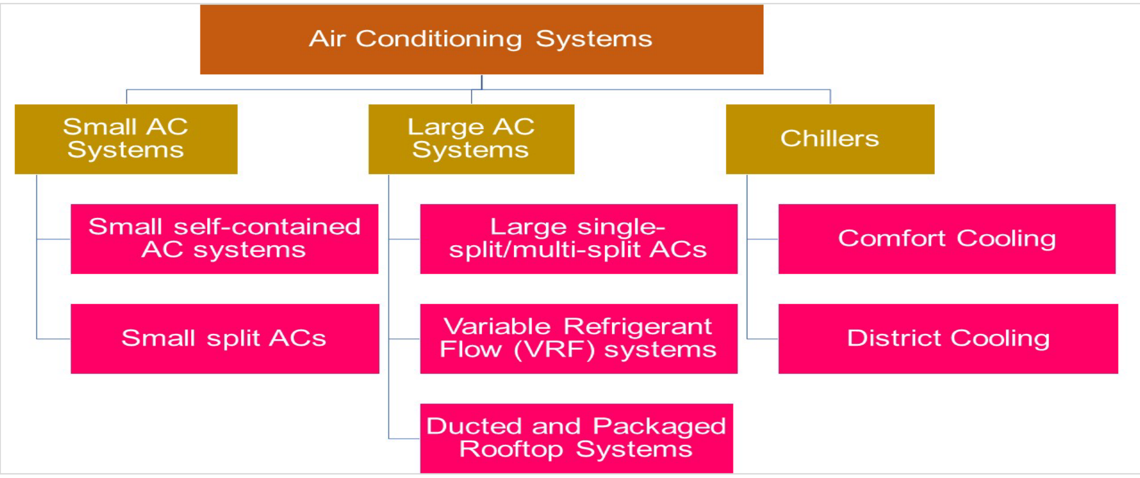

Figure 174: Different kinds of air conditioning systems

Under the Montreal Protocol, many ozone-depleting refrigerants such as CFC-11, CFC-12 and HCFC-22 are being phased out. However, these are still under use in commercial and residential setups, and although we have many HFC blends available, such as R-410A and R-407C, under use today, we need HFCs with lower GWP values. Let's analyse some of these low-GWP HFCs.[263]

Refrigerants

R-290 (Propane)

R-290, also known as Propane (C_3H_8), is a low-to-medium temperature refrigerant often used these days for small self-contained AC and small split AC applications. It has also found its use in certain outdoor appliances in countries such as Indonesia, Malaysia and the Philippines. Propane has a GWP value of 3 and an Ozone depletion potential of 0, with efficiency and performance better than R-410A in most places. It also offers refrigeration efficiency similar to popular refrigerants such as R-22 and R-404A at much lower costs due to the low refrigerant mass flow and lower wattage requirements. However, this is offset by the fact that R-290 is a highly flammable substance and can, therefore, require expertise to set up cooling infrastructure to avoid leaks and fires.[263]

[262] https://modernize.com/hvac/central-air-conditioner-installation/split
[263] https://www.epa.gov/sites/default/files/2016-12/documents/international_transitioning_to_low-gwp_alternatives_in_res_and_com_ac_chillers.pdf

R-717 (Ammonia)

While Propane is more suited towards smaller-scale applications, R-717 or Ammonia (NH_3) is more suited towards medium and large chillers and absorption systems. Ammonia's wide range of applications include thermal storage systems, HVAC chillers, food processing and supermarkets.

R-717 has a GWP of 0 and is used largely in the Middle East, China and the US. Similar to Propane, although it is one of the most efficient refrigerants in the market (due to which it is the first choice for larger-scale chiller applications), Ammonia also has safety concerns that push up the cost of installation due to a demand for expertise and requirement of safety hazard prevention.[263]

HFC-32

HFC-32 actually makes up half of the blend R-410A, and it was not used in isolation initially due to flammability concerns. The number of units of HFC-32 has been estimated to be over 100 million, and it has versatile applications covering both residential and commercial air conditioning. It can even be used in portable AC units and window units.[263] [264]

While HFC-32 does have a GWP higher than Propane or Ammonia, the GWP value is one-third of that of R-410A, the refrigerant that replaced it due to flammability concerns. Moreover, systems running on HFC-32 require 40% less refrigerant in general than R-410A. However, the major drawback of HFC-32 as a refrigerant, despite its high versatility, is its flammable nature.

Many companies have also adopted low-GWP refrigerants into their product mix. For instance, Godrej has come up with a product line for low-GWP air conditioners that use R-290 as the primary refrigerant.[265]

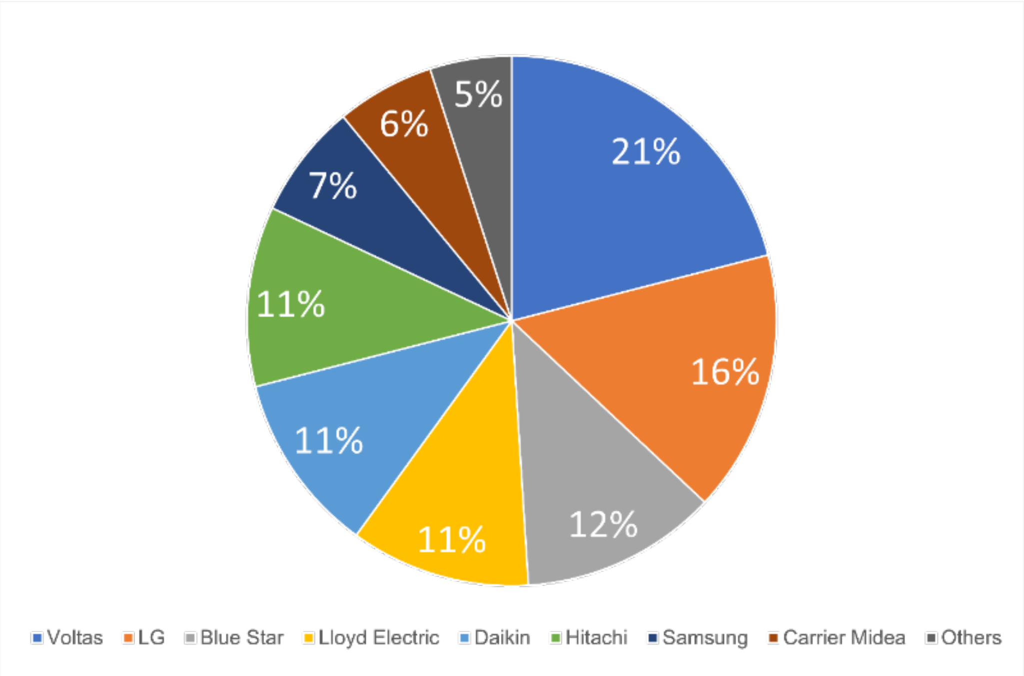

Figure 175: Air conditioning market share in India[266]

[264] https://www.superradiatorcoils.com/blog/refrigerant-focus-r-32-difluoromethane#:~:text=R%2D32%2C%20also%20known%20as,which%20is%20insoluble%20in%20water.
[265] https://www.godrej.com/appliances/r290-eco-friendly-air-conditioners
[266] https://www.statista.com/statistics/1018500/india-leading-ac-providers-market-share/

Technology Readiness Level (TRL)

Air conditioners have been used for decades now, and many of the refrigerants being discussed today for GHG reduction were developed as early as the 1930s. Hence, these can be easily integrated into existing systems and standards can be effectively set without many problems. Due to these factors, air conditioning as a technology has a TRL of 9.

Energy Efficiency

The new refrigerants used for GWP improvement have all shown efficiencies either equivalent to or better than the HFCs that they would be replacing. This is true for all the refrigerants discussed in earlier sections – R-290, R-717 and HFC-32. Hence, it can easily be said that the path towards better energy efficiency and, hence, decarbonization in air conditioning goes through changes in refrigerant material.

Compatibility with currently used technologies

For each refrigerant that was discussed, there was a uniform drawback – the problem of in flammability. In this scenario, we can say that while non-polluting refrigerants are desirable for their low-GWP and low ozone-depleting potential, they all require technical expertise to prepare and set up systems such that leaks and fires are avoided.

Global adoption

There has been a tremendous spurt in the adoption of R290 in Europe. This started off as a phenomenon observed mainly in Denmark and other Nordic countries. However, within a span of 12 years, cooling systems company Euroklimat witnessed growing interest from the UK, Germany, Austria and France for the adoption of R-290. As of 2021, 60% of the company's production was in R-290, which the company hopes to increase to 90% over the next five years.[267]

In 2021, Midea launched the first R-290 based air conditioning model on the German-European market. The company claimed to have three industrial refrigeration units with cooling capacities of 240 kW each, along with 160 commercial refrigeration units that use propane as a refrigerant. Additionally, it claimed to use R290 in 7–11 kW small, air-cooled chillers. It also had heat pumps that operated at R290.[268]

Centralized Cooling Systems

Central air conditioner systems can be seen as an extension of normal air conditioners in that it uses supply and return ducts to circulate air and thereby cool rooms and indoor spaces. One of the primary advantages of central air conditioners over normal air conditioners is effective dehumidification. With normal operating conditions of centralized air conditioners being that of air circulation, users can customize cooling to their requirements as well within individual rooms.[269]

There are two types of centralized cooling systems – split system units and packaged units. In a split system unit, an outdoor cabinet contains the outdoor heat exchanger, fan and compressor. At the

[267] https://hydrocarbons21.com/steep-growth-seen-in-r290-adoption-in-europe/
[268] https://www.green-cooling-initiative.org/news-media/news/news-detail/2021/11/15/midea-sets-benchmark-for-more-climate-protection-with-first-r290-model-on-the-german-european-market
[269] https://www.energy.gov/energysaver/central-air-conditioning#:~:text=Central%20air%20conditioners%20circulate%20cool,air%20conditioner%20to%20the%20home.

same time, an indoor cabinet contains the indoor heat exchanger and blower. Here, an indoor heat exchanger/furnace/heat pump is required for indoor heat exchange regulation.[269]

In a packaged unit, all heat exchangers, fans and compressors are situated in one outdoor compartment on a platform. This system cannot take advantage of existing heat pumps or furnaces, as the entire heat transfer mechanism comes packaged in one unit. Supply and return ducts all end within the packaged unit situated outside.[269]

The global central air conditioning market is set to go from $32.94 billion in 2019 to $46.62 billion in 2027. This would mean a CAGR of 4.5% during the forecast period. This is largely led by increasing needs for air conditioning, as well as a push for energy star ratings and cooling energy efficiency in emerging economies, leading to investment opportunities.[270] Looking at the Indian scenario, centralized air conditioning is at less than a 25% market share with a CAGR lesser than room air conditioners but more than ductless and ducted air conditioners.

Technology Readiness Level (TRL)

Similar to other air conditioning systems discussed earlier, the TRL for centralized air conditioning is also fairly high at 9, and the fairly large-scale adoption of the technology seen in India is proof.

Energy Efficiency

Central air conditioning systems have been found to be more efficient than window and portable air conditioners on average but less efficient than ductless air conditioners. In this scenario, it would be up to consumer judgement as to which option will be the most energy efficient among available options.[271]

[270] https://www.fortunebusinessinsights.com/central-air-conditioning-market-102842
[271] https://itlandes.com/how-many-watts-does-an-air-conditioner-use/#:~:text=Central%20air%20conditioners%20use%201%2C000,about%203%2C500%20watts%20per%20hour.

Water-cooled Air Conditioner Units

As seen in earlier sections, the way to reduce GHG emissions and achieve decarbonization through standalone air conditioning units is to use refrigerants that have low GWP values and ozone depletion potential. These refrigerants have already been discussed, and while using low-GWP HFCs can go a long way in balancing future cooling demand in India with decarbonization goals, there is another way this can happen: by using different materials for cooling through efficiency increases. A relatively new approach to retail and commercial cooling is the use of a water-cooled air conditioner or a water condenser. The main principle by which it operates is the rejection of heat absorbed in the evaporator by the refrigerant. Here, the hot air refrigerant is cooled using water, which can come from any prominent source – including wastewater. Water has higher efficiency than air in cooling refrigerants since it can operate at lower condensing temperatures. This new type of air conditioner, however, is relatively more expensive than standard split air conditioner systems and requires more technical expertise to set up. Therefore, it is not used much in residential setups and is instead a viable option for commercial air conditioner systems.[272]

Water-cooled air conditioners can be classified broadly into three types.

Tube within a tube

In this design, there are two tubes – the inner tube containing water and the outer tube containing the refrigerant. A grooved design for the inner tube can increase the heat transfer between the water and the refrigerant. In order to keep the temperature of the refrigerant constant throughout the operation, a counter-flow arrangement is constituted in which water and the refrigerant flow in opposite directions. One drawback of this method would be mineral deposits in water, and the only way to mitigate this is to use suitable chemical breakdowns to flush out the deposited minerals.[272]

Shell and Coil

In this design, the condenser is in the form of a steel shell that contains the refrigerant in ample amounts, and coils of copper tube are situated within this shell. Water flows through this coil to cool the hot gas refrigerant inside the shell. For the problem of mineral deposits, these copper tubes can be removed and cleaned to flush out these deposits. These are costlier to set up than tube-within-a-tube designs.[272]

Cooling Towers

The water used for cooling the refrigerant needs to be recirculated and not wasted or sent to ponds or the drainage system after use. For this, one of the best ways forward is the use of a cooling tower that can transfer the heat from water to air. This cooling can either happen through natural air or by forcing air through the wind. Since the cooling tower is exposed to both water and air, it should be made of material that is corrosion-resistant.[272]

Technology Readiness Levels (TRL)

Since most of the technology required to adopt water condensers is already available, we can say that the TRL level of this technological design is 9.

Energy Efficiency

[272] https://www.airconditioning-systems.com/water-cooled-air-conditioner.html

Since water is better able to cool refrigerants than air implies better performance of refrigerants and fewer refrigerants used, we can say that energy efficiency is improved by water-cooled condensers in air conditioning units.

Solar Thermal Heating and Cooling

Solar thermal technologies function by absorbing the heat of the sun and then using that energy to either heat a building or cool a building, depending upon the functionality required. The two broad kinds of technology that can accomplish this are solar collectors that capture passive solar heat and photovoltaic cells that produce electricity out of solar power.[273] However, before we come to the different kinds of broad technology that use solar power for heating and cooling applications, let's touch upon absorption cooling technology.[273]

Absorption Refrigeration Cooling

The same theory that enables the human body to be cooled via perspiration underlies absorption refrigeration. When you perspire, heat from your body is absorbed by the water molecules in your sweat to loosen the bonds, keeping them in a liquid state. Your body loses heat as a result of the water evaporating.[274]

Modern air conditioners repurpose the refrigerant they once used to replace water instead of discharging it into the atmosphere. There are four main processes in the absorption refrigeration method.[274]

Evaporation
As the refrigerant evaporates, it absorbs heat from the indoor air and leaves behind cooled air or water.

Absorption
The vapour is absorbed into the absorber, a different liquid. By preventing the refrigerant from condensing, which would reverse the cooling that has just occurred and release heat back into the system, this step increases the speed and efficiency of evaporation.

Separation
The absorber and refrigerant mixture is heated until the refrigerant separates from the fluid in the absorber. This technique, which uses the most energy overall, is how air conditioners can turn hot water into chilly air. Renewable resources can be used to provide the hot water needed for Step 3.

Condensation
A condenser is used to pump the refrigerant, returning it to liquid form. This is a process that releases heat, and this heat is vented outside, returning the entire process to step 1.

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[273] https://www.epa.gov/rhc/solar-heating-and-cooling-technologies#:~:text=How%20It%20Works,applications%20such%20as%20pool%20heating.
[274] https://www.epa.gov/rhc/renewable-space-cooling

Unglazed Solar Collectors

Unglazed solar collectors are one of the simplest types of solar thermal technology. Sunlight is absorbed by a heat-conducting substance, which is typically a dark metal or plastic, and the energy is then transferred to a fluid that is moving through or behind the heat-conducting surface. It works in a manner akin to how a garden hose left out in the open will absorb solar radiation and warm the water within.[273]

These collectors are referred to as "unglazed" because the collector box does not have a glass covering or "glazing" to keep heat in. There is a trade-off because there is no glazing. Unglazed solar collectors are easy to use and cheap, but because they cannot store heat, they lose heat to the outside air and must function at low temperatures. Because they can pre-heat water or air, unglazed collectors typically perform best in small to moderate heating applications or as a supplement to conventional heating systems. In this way, they can help reduce fuel consumption.[273]

This is one technology that is largely used for residential building heating and cooling. It operates in a three-step process:[273]

Sunlight collection
Sunlight hits the dark material of the collector, which causes it to heat up.

Circulation
Cold fluid, i.e. either water or air, absorbs this heat by circulating through the collector.

Heating
This hot water is used to then heat water bodies or other articles within households that need to be heated, such as pools. This hot water can also be used as a space-cooling agent by combining it with absorption refrigeration processes.

Evacuated Tube Solar Collectors

In the case of evacuated tube solar collectors, thin copper tubes with a fluid such as water are housed inside larger vacuum-sealed plastic or glass tubes. This allows the sun's heat to be used more effectively and produce temperatures higher than comparable technology, such as unglazed solar collectors or flat-plate collectors. This is the result of an increase in effective surface area available for the sun, as well as a good reduction in heat loss to the environment through the vacuum with clear glass enclosure.[273]

The following four-step process is followed for evacuated tube solar collector operation:[273]

Sunlight collection
As the first step, sunlight is absorbed by the glass material through the angles available and heated well.

Heat reflection
With the help of a clear glass or plastic casing, a greenhouse-like effect is seen that traps heat that would otherwise leak out.

Convection
The stored heat in the cylinder is absorbed by a copper tube running through each cylinder, causing fluid inside the tube to rise to the top of the cylinder.

Circulation
We have cold water at the top of the cylinder, which circulates through and absorbs heat.

Evacuated tube solar collectors are highly expensive and can produce extremely high temperatures, enough for effective cooling through absorption refrigeration. Energy efficiency is comparatively higher here due to the compounding obtained through greenhouse effects.[273]

Concentrating Solar Systems

The basic principle of a concentrating solar system is to project sunlight from a large area onto a small one. This is done through reflective bowl-shaped arrays that heat the water flowing through them through sunlight and effective solar panel area management. Through this process, high-pressure steam and superheated fluids are produced for effective heating, absorption, refrigeration, cooling and power generation.[273]

The operation of concentrating solar systems follows the following steps:

Sunlight collection
Sunlight hits a trough or dish-shaped reflective mirror surface and heats it effectively.

Solar reflection
This process of reflection concentrates the sunlight onto smaller areas and provides the adequate amount of heat required to heat the fluid material that circulates.

Circulation
A fluid material (most likely water) circulates through a pipe and absorbs the heat, further preparing the system for absorption refrigeration cooling.

While this process produces highly heated fluids that can be used for a variety of cooling processes, the system is much more complex than the other heating and cooling systems mentioned above. In such a scenario, this would be one of the most costly solar cooling technologies available, albeit highly rewarding due to the efficiencies offered.[273]

Installed solar power capacity in India was 61.97GW as of November 2022, over 60% of the 100GW target set by the Ministry of Renewable Energy.[275] Considering also the fact that India has the 5th largest installed solar capacity in the world[276], the country is well-poised to take advantage of these technologies for renewable cooling and heating.

Globally, the solar thermal industry is set to see a CAGR of 5.1% between 2022 and 2031. The market was valued at $21.5 billion in 2021 and is projected to reach $35.3 billion in 2031. However, most of this growth is projected in Europe and North America, where this technology is focused more on heating.[277]

Technology Readiness Level (TRL)

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[275] https://mnre.gov.in/solar/current-status/
[276] https://ornatesolar.com/blog/the-top-5-solar-countries-in-the-world
[277] https://www.alliedmarketresearch.com/solar-thermal-market-A06891

With the Indian Government being highly bullish on solar power and technology, the country has become the world's 5th largest solar capacity country.[276] It has launched multiple schemes to continue this trajectory and reach its target of 100GW installed capacity, including production-linked incentive schemes for photovoltaic cells and materials. Hence, due to such large-scale investments, we can say that this technology has a TRL of 9. However, the challenge of global standardization and harmonization across all regions needs to be met before a global adoption of this technology can be achieved.[278]

Energy Efficiency

It is needless to say that, solar power is one of the cleanest forms of energy in the industry today. As a result of this, solar-powered cooling can offer GHG emissions reduction for cooling that, if adopted, can solve the problem of high future residential GHG projections in India due to higher demands for cooling.

Compatibility with currently used technologies

While the technologies used for effective solar thermal heating and cooling are easily available, these technologies require high levels of technical expertise for proper installation and maintenance. This is a significant cost driver, and hence, policymakers must make sure that sufficient technical expertise in the area is created before venturing into investment in these technologies.

Global adoption

In Italy, by making good use of a 110% super bonus given by the Government for building energy efficiency, solar thermal installations hit a record in 2021. 158 MW of capacity was installed in 2021, showing an 83% growth from 2020 numbers. One of the schemes that helped in achieving this was Conto Termico, which provided grants for solar heat plants of sizes up to 2500m^2, a maximum amount of 65% of investment cost. It was seen that the amount of grants has increased from EUR 36 million in 2016 to EUR 327 million in 2021. It has been noticed that over 90% of the newly installed collector area was used for hot water provision.[279]

AVAILABLE TECHNOLOGIES FOR DIRECT ELECTRIFICATION: Cooking

Solar Photovoltaic Thermal Systems

A solar photovoltaic system is different from a solar thermal system in working principle. Photovoltaic (PV) systems work on the basis of the photovoltaic effect, in which electrons are generated from semiconductor surfaces when exposed to sunlight to create electricity and power. This is different from solar thermal systems, which use solar energy and sunlight for heating purposes.[280] However, when these two systems are combined, we get a hybrid solar panel or a photovoltaic thermal (PVT) panel that, although less efficient than individual thermal and photovoltaic panels, can produce more energy per unit area than both.[281]

Photovoltaic cells generally have an efficiency of 15-20%, and out of the rest, the largest share of the solar spectrum (i.e. 65-70% of it) is turned into heat. This heat is absorbed by the solar thermal system and used in cooling, while the PV cells are used for electricity and power generation. Hence, both PV cells and solar thermal systems complement each other to produce more energy per unit area than they would produce individually. It has been noticed that air-based PVT collectors have an

[278] https://www.iea.org/reports/solar-thermal-technologies-deployed-in-around-400-million-dwellings-by-2030
[279] https://solarthermalworld.org/news/superbonus-has-pushed-solar-heat-in-italy/
[280] https://www.greenmatch.co.uk/blog/2016/04/differences-between-solar-photovoltaics-and-solar-thermal
[281] https://hydrosolar.ca/collections/hybrid-pvt-photovoltaic-and-thermal-solar-panels

efficiency of 30-60% over and above the PV component. The most common classification of PVT systems is based on the collector material used (i.e. liquid, air, etc.)[281] [282]

During a market research survey conducted by the IEA, where 26 manufacturers of PVT collectors from 11 countries were identified, it was noted that the market for PVT collectors worldwide as of 2023 is still fairly small. 80% of the manufacturers focused on liquid-based PVT collectors, 12% on air-based PVT collectors and 8% on concentrated PVT collectors. The market for PVT collector systems in India is not considerable, and this technology hasn't been adopted as much as it should have been. 273 $kgCO_2/(m^2$ year) savings are projected through the installations of air-based PVT systems in all available solar installations in India.[282]

Technology Readiness Level (TRL)

India has a fairly good number of solar plant installations and schemes to promote important components for photovoltaic generation, such as the PLI schemes.[275] It can take advantage of these by adopting solar thermal heating and cooling technologies and can directly transition into the more efficient PVT space. Hence, this technology has a TRL of 9 in India.

Energy Efficiency

As seen in the above sections, the PVT technology was seen to improve the efficiencies of normal photovoltaic cells from 15-20% to 30-60%. This is done by utilizing the heat released in PV cell power generation in the solar thermal systems, thereby enhancing the energy efficiency of the solar thermal system and the PV cell simultaneously.[282] Due to these characteristics, more R&D needs to be done for this technology to ensure proper implementation ability.

Compatibility with currently used technologies

PVT technology is seen as an extension of solar thermal heating and cooling systems. The only additional component here would be photovoltaic cells, and while it is still not adequately scalable, the benefits that it promises make it a worthwhile investment for adequate technological investment and R&D.

Global adoption

Globally, a total of 1160000m^2 area of PVT collectors was installed in 2019. This had a total thermal capacity of 530MW and peak PV power of about 180MW. The lion's share of this deployment was seen in Europe, with 484000m^2 area installed in France and 112000m^2 in Germany. South Korea, on the other hand, had an installed area of 280000m^2, and China had an area of 133000m^2 installed.

Induction Cooktops

Cooking stoves usually work through the thermal conduction of heat into a vessel. This can happen through a flame or an electrical heating element. However, an induction cooktop uses electrical induction as the way to pass heat onto the vessel, which is required to be made of a ferromagnetic material such as cast iron or stainless steel. In this case, the heat required for the cooking process is coming from within the pan and not from an external source of heat through the pan, making the cooking process more energy efficient by avoiding heat losses through conduction.[283]
The factors that determine the working of an induction cooker are the switching frequency of the oscillating current produced by the cooker, the planarity of the coil embedded on the cooking surface

[282] https://www.sciencedirect.com/science/article/pii/S0360128523000023#sec2
[283] https://www.cda.eu/hobs/how-does-induction-cooking-work/

and the magnetic permeability and resistivity of the cookware. The switching frequency of a typical induction cooker ranges between 25 kHz and 50 kHz. It needs to be noted that this property works only with materials with ferromagnetic abilities, such as cast iron and some varieties of stainless steel. In other words, copper vessels do not work on induction cooktops.[284]

In India, the induction cooker market stood at $916 million in 2022 and is expected to grow to $1.31 billion by 2028. This comes down to a CAGR of 6.23%, with a 48% market share currently in the South of the country. The key players in this field in India currently are TTK Prestige LTD., Crompton Greaves Consumer Electricals Limited, Stove Kraft Limited, Bajaj Electricals Limited, Sunflame Enterprises Pvt. Ltd., Kaff Appliances (India) Private Limited, Glen Appliances Private Limited, Franke Faber India Private Limited, Usha International Limited and Havells India Limited.[285]

Technology Readiness Levels (TRL)

Induction cooking technology is already fairly widespread across the world and is known to be energy efficient. Even in India, the affluent middle class has seen good degrees of adoption of this technology already. Hence, it has a TRL of 9.

Energy Efficiency

Induction cooktops are generally considered more energy efficient and easier to use than other cooktops, not only because of the amount of energy consumed, but also because they don't heat up the air around it. This provides better cooking comfort. Through an analysis of the energy efficiency of conventional electric, natural gas and induction cooker methods, the following results were obtained.

Table 22: Annual energy consumption of cooktop technologies using only small cookware (energy costs based on USA standard prices)[237]

Technology	Efficiency	Annual Energy Consumption	Cooking Energy	Energy Cost
Conventional Electric	42%	128 kWh	54 kWh	$15.36
Induction	76%	71 kWh	54 kWh	$8.49
Natural Gas	30%	720 kBtu	216 kBtu	$7.05

It can be clearly seen that the most energy-efficient technology of the three prominent cooking technologies is induction cooking. However, when compared with conventional electric cookers, induction cooking was, on average, found to be $300 more expensive on initial investment. This yielded a total payback period of 44 years, thereby making conventional electric cookers more cost-effective. This is the biggest barrier to the widespread adoption of induction cookers.[284]

Compatibility with currently used technologies

The only major constraint towards adopting induction cooking, apart from the initial investment, is the shift of utensils towards metals with ferromagnetic ability. Most new users of induction cookers will have to buy these ferromagnetic vessels, which is an added investment cost. Hence, while

[284] https://www.aceee.org/files/proceedings/2014/data/papers/9-702.pdf
[285] https://www.grandviewresearch.com/industry-analysis/induction-cooktops-market#:~:text=The%20global%20induction%20cooktops%20market,8.5%25%20from%202021%20to%202028.

induction cooking is a good option for the electrification of cooking, its mass adoption needs support in terms of initial investment costs.

Global adoption

The global market for induction cookers was $18.6 billion in 2020 and is expected to grow at a CAGR of 8.5% per annum between 2021 and 2028. The CAGR between 2021 and 2028 for North America is predicted to be 8.1%. This is due not only to more residential demand and shifts to clean cooking methods but also to commercial initiatives such as modular kitchens, restaurants and eateries. At the same time, rising fuel prices are also a factor that is driving up demand for induction cookers.[285]

Electric Cookers

In an electric cooker, no flame is produced. Instead, an electric current is what causes the stove to heat and start the cooking process. For stoves with coils, heat is transferred from these coils directly to the cookware, whereas for stoves with a glass or ceramic top, the heat emanates to this top and transfers to the vessel. Hence, for a glass or ceramic top stove, radiant heat is used for heating vessels. It has been seen that while conventional coils tend to heat up the surroundings, glass tops and ceramic stoves tend to heat only the vessel and therefore are more comfortable to use.[286]
In India, while the Government kicked off the "Go Electric" campaign aimed at electrifying India's cooking landscape in Feb 2021, a study of CEEW found that only 10.3% of urban households and 2.7% of rural households had access to electric cooker technology. Overall, just 5% of households in India had switched to e-Cooking. Moreover, it was also seen that 93% of e-cooking adopters used the technology only as a backup, with LPG being their primary go-to technology. The biggest impediment to e-Cooking adoption was found to be cost constraints, with e-Cooking having high investments and high operating costs.[287]

Technology Readiness Levels (TRL)

Technology advancements in e-cooking and electric stoves are fairly advanced already, and hence, the TRL for electric stoves stands at 9.

Energy Efficiency

Based on a further analysis of Figure 1, it can be seen that, in general, electric stoves consume more energy than gas stoves. This implies better energy efficiency for LPG gas stoves. However, depending on how the electricity being used here is generated, it is to debate whether electric cooking or natural gas/LPG cooking is more energy efficient. Hence, the energy efficiency of stoves is largely dependent upon the source of power generation.

Compatibility with other technologies

Electric cookers are cheaper to set up than induction cookers or gas stoves. They can also be easily powered by clean and renewable sources of energy. Hence, electric stoves are fairly compatible with existing technologies and can be easily integrated into electrified homes and dwellings.

Global adoption

The electric cooker market is expected to grow at a CAGR of nearly 10% between 2019 and 2028, with the fastest-growing segment and the largest market being Asia-Pacific. Some of the major global

[286] https://www.hunker.com/13409456/how-does-an-electric-stove-work
[287] https://economictimes.indiatimes.com/news/india/delhi-tamil-nadu-lead-indias-transition-to-electric-cooking-with-17-adoption-ceew-study/articleshow/87107173.cms?from=mdr

players in the industry are Electrolux, Newell Brands, Koninklijke Philips and Spectrum Brands. Some of reasons behind the preference for electric cookers are digitization, display technology, and smart features such as voice control. [288]

AVAILABLE TECHNOLOGIES FOR INDIRECT ELECTRIFICATION

Thermal Energy Storage (TES)

One of the biggest challenges of using renewable energy sources is the seasonality of technology, which may bring out the requirement for energy storage systems. However, it is not easy to store energy, and there are few technological options available for proper energy storage. [289] One such option for energy storage would be thermal energy storage.

When excess heat is released from heat-based renewable systems, thermal energy storage technology (or thermal stores in short) can be used to store the excess heat generated. These thermal stores are mostly constituted of large, well-insulated cylindrical water tanks where hot water is stored. These tanks are also called accumulator tanks. By connecting these thermal stores to heat exchangers, they can be easily designed to fulfil many applications involving space heating, water heating and even power generation. They can also be purpose-built and designed to fulfil specific tasks based on requirements, whether the heat is taken from a biomass boiler, solar water heating system or a heat pump. [290]

TES technologies can be classified into four different groups.

Sensible Heat Storage

In a sensible heat storage system, heat is stored as a solid or a liquid without any change in the phase of matter. In such a scenario, the amount of heat stored is denoted by the rise or fall in temperature seen on charging within the operational temperature range and material thermal capacity. These systems offer storage capacities between 10kWh and 50kWh per tonne and storage efficiencies ranging between 50% and 98%. Working temperatures for these systems range between -160°C and 1000°C. [291]

Of all the heat storage technologies available in the market today, sensible heat storage offers the cheapest and simplest storage systems. For instance, the material used in the storage system is often water. Hence, these appear in the form of water tank thermal energy storage, solid state energy storage, molten salt energy storage and underground thermal energy storage. [291]

Latent Heat Storage

Phase Change Materials (PCMs) have latent heat as their prime material for use. Latent heat is the amount of heat change required at a phase-change temperature to successfully manage the change in phase aimed at. In contrast to sensible heat storage, PCMs do not have a change in temperature as the measuring parameter for the amount of heat stored. In other words, the heat stored within these systems does not cause a temperature change in the material itself, and due to this property, it can be used to provide specific output temperatures according to engineering needs. [291]

PCM-based latent heat storage systems can be classified based on their temperature of operation. The categories are

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[288] https://www.mordorintelligence.com/industry-reports/electric-cookers-market
[289] https://www.weforum.org/agenda/2021/04/renewable-energy-storage-pumped-batteries-thermal-mechanical/
[290] https://energysavingtrust.org.uk/advice/thermal-energy-stores/#:~:text=renewable%20heating%20system.-,What%20is%20a%20thermal%20store%3F,a%20buffer%20or%20accumulator%20tank.
[291] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf

Sub-zero PCMs

The phase-change temperature here is below 0°C. Examples of such PCMs are salt-water mixtures.

Ice PCMs

Here, the phase change temperature is exactly 0°C. The only example of this is actual ice.

Low-temperature PCMs

Here, phase change temperatures range between 0 and 120°C. Examples of this are paraffin waxes and salt hydrates.

High-temperature PCMs

The phase change temperatures for these PCMs are over 120°C. Examples of this include inorganic salts and eutectic mixtures.

The biggest advantage of PCMs, apart from temperature targets and controls, is the smaller physical footprint they use. Since it can charge and discharge at an almost constant temperature, the control that it offers is useful in industrial applications such as cold chain cooling, where narrow temperature ranges are necessary.[291]

Thermochemical Heat Storage

In thermochemical heat storage systems, the heat released from thermochemical reactions is used as a means of enhancing heat storage capacity in an area with little density. It can be classified into reversible reaction-based and sorption-based storage systems. In reversible reaction-based systems, a high amount of energy is released through an exothermic synthesis reaction in a reversible chemical reaction between two separate chemical substances. In a sorption process, on the other hand, heat is stored by breaking the binding force between the sorbent and sorbate.[291]

While sorption processes have a limit of 350°C of operation, reversible reactions can operate at temperatures much higher than that. However, sorption systems have an advantage in that they can store heat within their systems with very minimal losses. Moreover, thermochemical heat storage systems are highly energy-dense.[291]

Mechanical TES Systems

In this method, traditional TES systems are coupled with mechanical energy storage technologies so that both can complement each other.[291]

Globally, 234 GWh of TES was estimated to have been installed in 2019, with a total of 400 TES projects identified. Out of these, 160 projects were meant for space cooling in buildings and districts, amounting to over 13.9 GWh. 199GWh capacity of TES installation was for buildings and district heating, with large upticks in the UK, France and China. The global TES installation by 2030 is projected to grow to over 850GWh by 2030, with the most increase seen in power-based projects largely led by solar and wind power installations.[291]

The global TES market in terms of revenue was estimated to be $188 million in 2020 and is expected to reach $369 million in 2025 with a CAGR of 14.4%. The largest market for TES is Europe, with the large-scale proliferation of concentrated solar power (CSP) and district heating and cooling systems in the continent driving demand for TES systems. The most widely used type of TES system in Europe is molten salts-based sensible heat storage, with Spain driving up most of the demand.[292]

TES has not seen much adoption in India yet. However, there have been roadmaps and simulations from government bodies to study the viability of TES systems in the country, and while they seemed unprofitable with negative values of IRR pre-2021, they were projected to be profitable by 2025. With profitability due to electricity savings in India, with TES systems projected to be the highest, penalty payment savings are said to go down due to power factor increases with increased energy storage.[293]

Technology Readiness Levels (TRL)

Currently used TERs in European countries can be retrofitted with existing technologies involving renewables and heat pumps. Hence, since very little new R&D is required for the efficient adoption of TES systems, the TRL levels in India can be said at around 9.

Energy Efficiency

The prime advantage of using TES systems is the better proliferation of renewable energy technology. As explained at the start of this section, one of the biggest challenges of using renewable energy sources is the seasonality of technology, which may bring out the requirement for energy storage systems. Thus, energy efficiency is a parameter that scores highly when considering TES systems.

Global adoption

In order to improve the seasonal storage efficiency of district heating in Canada, a technical demonstration known as Darkes Landing was constituted. A borehole thermal energy storage system was used to store 1.5MW of solar thermal capacity in multiple households so that heat could be extracted from these energy stores in winter months when large-scale heating would be demanded. The project resulted in a reduction in GHG emissions of each household by around 80%.[291]
In the UK, where 90% of homes rely on gas heating, 25% of the domestic carbon footprint is generated by heating operations. Thermal batteries with a phase change material of sodium acetate (with a phase change temperature of 58°C) could rectify this situation. The battery could deliver heat at about $0.05/kWh, considerably less expensive than heat stored in an electrochemical battery. The UK Government has announced a $2 million fund trial for the development of this battery, and if

[292] https://www.marketsandmarkets.com/Market-Reports/thermal-energy-storage-market-61500371.html
[293] https://www.niti.gov.in/sites/default/files/2019-10/ISGF-Report-on-Energy-Storage-System-%28ESS%29-Roadmap-for-India-2019-2032.pdf

successfully adopted, it could go well with the government's targets to ban gas heating in new homes from 2025 in an attempt to reduce the carbon footprint produced through heating operations.[291]

OTHER TECHNOLOGIES

Passive Cooling

While active methods of heating and cooling can be optimized for energy efficiency, passive methods of cooling and heating can go a long way in ensuring indoor thermal comfort. These can be done using the inherent physical and thermal properties of the construction and design, building envelope and the surroundings. This step ideally comes before thinking of active, energy-efficient modes of heating and cooling. There are a few key envelope-level strategies for effective heating and cooling without having to resort to active consumption of energy.[294]

Microclimate

Appropriate vegetation, water bodies, shade, soil and pollution exposure around buildings and construction can go a long way in facilitating good cooling or heating of the building itself. Builders can manage this appropriately by taking into account the climate conditions of the location itself, and there are different things to be taken care of for both warm and cool climates. Warm climates can plant vegetation along directions such that unwanted sunlight can be prevented in peak times such as the afternoon. For cold climates, on the other hand, solar incidence can be encouraged instead.[294]

Microclimate measures also come with a lot of maintenance requirements and spatial limitations. For instance, large urban agglomerations might find it hard to perform appropriate landscaping due to cost hikes and land problems. Similarly, vegetation patterns may vary according to climatic conditions, and therefore, there cannot be a uniform standard for landscaping and microclimate measures in a broad sense.[294]

Orientation

The parameter to optimize for adequate heating and cooling with orientation would be the building's leading axis. The orientation of this axis can be optimized according to climatic conditions to facilitate the ingress of sunlight, wind and moisture for temperature and ventilation. For this purpose, seasonal and annual sunlight and wind charts need to be adequately analysed. The aim must be to minimize summer sunlight and maximize winter sunlight, and vice versa, for airflow and ventilation. By managing this simple parameter, a lot of passive cooling can be achieved.[294]

Roofing

Roofs are the primary point of contact between sunlight and your building. Hence, by appropriately designing roofs according to climate and temperature, passive cooling can be achieved well. For instance, the goal of roofing in warm climates could be to prevent the inward movement of heat through radiation reflection, reduction of inward heat flow and roof shading through vegetation and high emissivity materials. At the same time, roofs in cold climates should focus on restricting the outward flow of heat, which can be done through good insulation. This insulation is typically placed on the indoor portion of the roof.[294]

Facades

Just like roofs, facades are also natural barriers to sunlight and heat. Adequate design of facades will go a long way in achieving passive cooling, and here, too, an understanding of solar angles and

[294] https://www.archdaily.com/994391/the-decarbonization-challenge-4-passive-strategies-for-energy-efficient-building-systems

microclimate is necessary. Some effective measures for this could be installing horizontal/vertical shading devices such as louvres, overhangs, movable shades and even the right plants, which include potted plants such as Wisteria and Ivy.[294]

Shading

Based on certain studies, solar shading can decrease indoor temperatures by 2.5°C to 4.5°C. To put it simply, it is a method to block out sunlight before it can enter the room, and this can go a long way in facilitating passive cooling. Shading using the right materials is important, as is deciding how much time in the year shading would be required based on the local climatic conditions [294]

Evaporative Cooling

While today's methods for evaporative cooling involve the use of low-energy technology to speed up the process of cooling through evaporation, the basic principle behind evaporative cooling does not depend upon intense use of energy but on the principle of evaporation instead. In an evaporative cooling system, hot air is sent outside using wet cooling pads, and this process is sped up by the use of a fan that blows all the hot air outside. Once this hot air is cooled down by the cooling pads, it is blown back into the room, either naturally or using a fan. While this process does require an external source of energy to make it efficient, its basic principle is based on evaporative media. This simple technique has the potential to reduce room temperatures by up to 10°C but has an added drawback that the cool air obtained through this method is extremely humid in nature.[295]

An example of good passive cooling implementation in India in recent times is the Krushi Bhavan campus in Bhubaneshwar. The campus has many innovative measures to ensure good cooling through design, including a distinctive brick façade made of three different clays that act as a solar shading device and a courtyard that allows optimal air ventilation and deeply recessed windows and balconies restricting heat penetration from sides.[296] In an environment where the proliferation of air conditioners in the country will be still less than 50% by 2040, cooling through passive measures can be a very good technique to reduce the need for higher carbon emissions through air conditioning.[238]

Technology Readiness Levels (TRL)

Passive cooling does not require any particular technological intervention as such and instead depends upon good architecture. Hence, any TRL value given here would be 9.

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[295] https://www.oxy-com.com/what-is-evaporative-cooling#:~:text=In%20an%20evaporative%20cooling%20system,then%20blown%20into%20the%20building.

[296] https://www.thebetterindia.com/235351/delhi-ecofriendly-sustainable-building-how-to-build-architects-architecture-passive-cooling-india-gop94/

Global Adoption

The African continent is a good case study to observe how traditional building methods can adopt passive cooling techniques to reduce GHG emissions. Such cases are highly relevant to India since over 50% of the population still won't have access to air conditioning technology by 2040.

- Thermal insulation boards are used for building construction in Gambia, which is CO_2 neutral from growth to transport. These boards are created using Napier grass, which does not need to be burnt for disposal. German company ISOCALM is also involved in the production of this grass.[238]
- In a similar manner, the Rwandan company Strawtec manufactures compressed boards for partitioning using straw and recycled paper. This process has very low embodied carbon emissions. [238]
- In Uganda, carbon-negative construction materials are being supported through sustainably sourced timber from Arua. This is being led by the company Easy Housing. [238]
- Again in Rwanda, a healthier indoor environment is being promoted by the company Earth Enable. This is being done by waterproof compressed earth floors made from laterite and fine earth mix that is locally sourced sealed by a layer of oil. This technique can replace traditional dirt floors, thereby helping improve living standards and achieve decarbonization progress. [238]

Liquified Petroleum Gas (LPG)

Liquified Petroleum Gas, in its raw form, is not considered a greenhouse gas since it has non-toxic vapors. It is attractive in comparison to most other fuels, including ethanol and natural gas. It also has a higher octane rating compared to conventional gasoline, thereby offering performance and emissions benefits.[297]

The cooking footprints of each type of burner majorly used in Europe are shown below.

Table 23: Cooking footprints in Europe[298]

Fuel	Burner type	Efficiency	Cooking footprint (g CO_{2e})
Natural gas, European mix	High-efficiency	42.00%	53.7
Electric	Induction	84.00%	56.1
Natural gas, European mix	Standard	39.90%	56.6
LPG	High-efficiency	42.00%	59
LPG	Standard	39.90%	62.2
Electric	Smooth	74.20%	63.5
Electric	Coil	73.70%	63.9

It can be seen that LPG has a carbon footprint and efficiency levels comparable to natural gas. While this does not provide an incentive to switch to either from the other, it does provide a good incentive to shift from traditional coal-based cooking to LPG. This is further proved by the fact that LPG's carbon footprint is one-third that of charcoal.[297]

[297] https://auto-gas.net/wp-content/uploads/2017/11/WLPGA-Literature-Review-FINAL.pdf
[298] https://www.nefco.nl/app/uploads/2014/04/atlantic-consulting-scientific-review-carbon-footprint-ed.-2009.pdf

Technology Readiness Levels (TRL)

LPG is a fairly old and well-proliferated technology, and today, we have ways to provide LPG connections to homes en masse without the use of gas cylinders. As such, its TRL level is at 9.

Energy Efficiency

By switching from wood and coal-based cooking to LPG, the CO_2 emissions from cooking can be cut by 60%. 800 million to 2 billion people making this switch will lead to a net CO_2 emission reduction of 170-415 million tonnes and annual savings per person of 211 kgCO_2.[299] Due to these reasons, LPG is highly energy-efficient compared to the currently used options in India.

ELECTRICITY REQUIRED FOR FULL DECARBONISATION

Suitable technology mix

Technologies are evaluated primarily based on their TRL level, potential for decarbonisation and suitability of the technologies. The penetration level of the selected technologies is estimated considering India's target of *net zero by 2070*. In India, other than cooking, all other areas like cooling, heating, and appliances are electrified. Cooking also contributes to major energy consumption of the sector, so efforts have been made to electrify the cooking sector of the Indian economy to completely electrify the building and appliance sector.

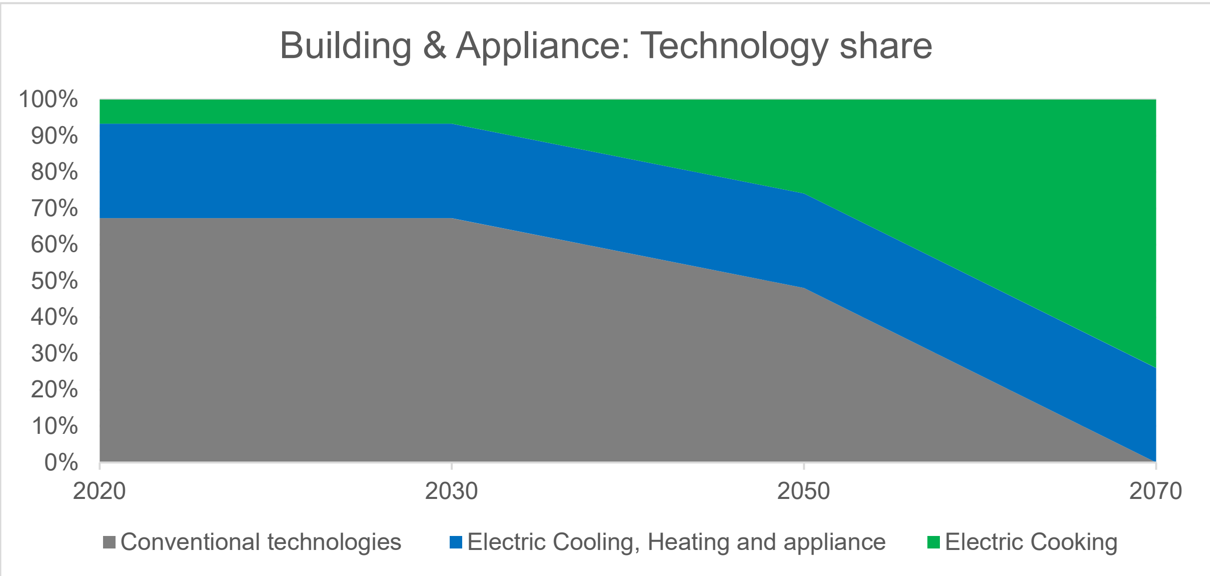


Figure 176: Penetration level of electrification technologies – Buildings

Projected Energy Consumption for Decarbonisation

Building and appliances are further subdivided into five categories - **residential heating and cooling**, **residential lighting and appliances**, **commercial heating and cooling**, **commercial appliances and lighting**, and **cooking**. Projections of energy demand of all the sub-sectors except cooking are based on the direct correlation between GDP and energy consumption scenarios. For cooking, the correlation between GDP and the number of households is established, and the projection is based on that correlation.

[299] https://www.wlpga.org/wp-content/uploads/2018/10/Substituing-LPG-for-Wood-Carbon-and-Deforestation-Impacts-Updated.pdf

Energy consumption is also projected, considering the scenario of decarbonisation (conservative, moderate and ambitious). Technology penetration varies depending on the scenarios, i.e., the effort of implementation resulting in a change in energy consumption for each scenario.

Conservative Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	159	272	431

In the conservative scenario, efforts of penetration of the technology are being considered at lower levels, i.e., 30% by 2030, 70% by 2050 and 100% by 2070. The reduction in energy consumption is 18% in 2030, 39% in 2050 and 38% in 2070, over the base scenario.

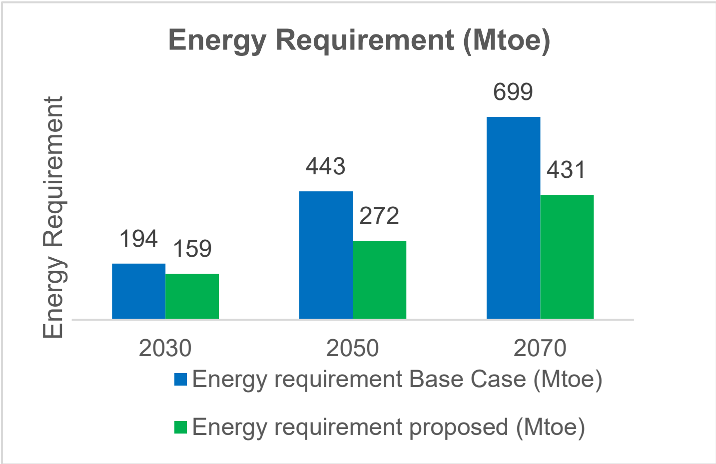


Figure 177: Energy requirement (Conservative - Buildings)

Moderate Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	164	295	431

In the moderate scenario, efforts of penetration of the technology are being considered at medium levels, i.e., 50% by 2030, 90% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of the conservative scenario.

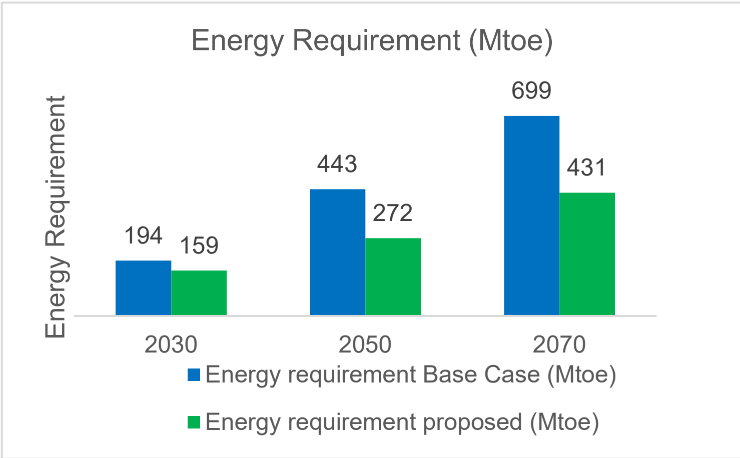


Figure 178: Energy requirement (Moderate - Buildings)

Ambitious Scenario

Year	2030	2050	2070
Energy Demand (Mtoe)	177	330	431

In the ambitious scenario, efforts of penetration of the technology are being considered at high levels, i.e., 100% by 2030, 100% by 2050 and 100% by 2070. The reduction in energy consumption in 2070 is the same as that of conservative and moderate scenarios.

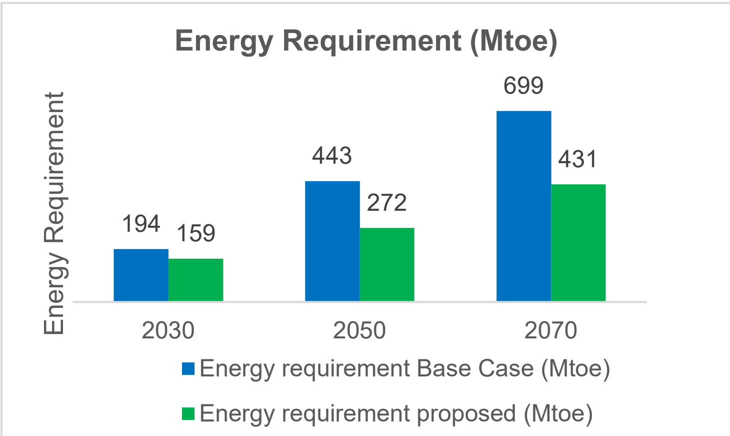


Figure 179: Energy requirement (Ambitious - Buildings)

Projected RE installed capacity for Decarbonisation

Based on the different scenarios, RE hybrid installed capacity and battery storage capacity have been estimated for the years 2030, 2050 and 2070 at the plant load factor of 45%. Considering future updates in RE technology, there is a high chance of improvement of the load factor. Detailed sensitivity analysis has been done to calculate the RE installed capacities at different improved load factors. In the ambitious scenario, the RE installation requirement is 1272 GW at a 45% load factor, and this RE requirement would reduce to 1041 GW if the load factor is improved to 60%.

Projected GHG emission reduction

The total GHG emissions for the sector are estimated to reach 464 million tonnes CO_{2e}, 1059 million tonnes CO_{2e}, and 1673 million tonnes CO_{2e} for the years 2030, 2050, and 2070, respectively, in the BAU scenario. Under the ambitious scenario, it is estimated to be net zero in 2070 as the majority of the buildings would be electrified and electricity would come from green energy sources. GHG emissions reduction for all the scenarios are calculated and presented in the graph shown below.

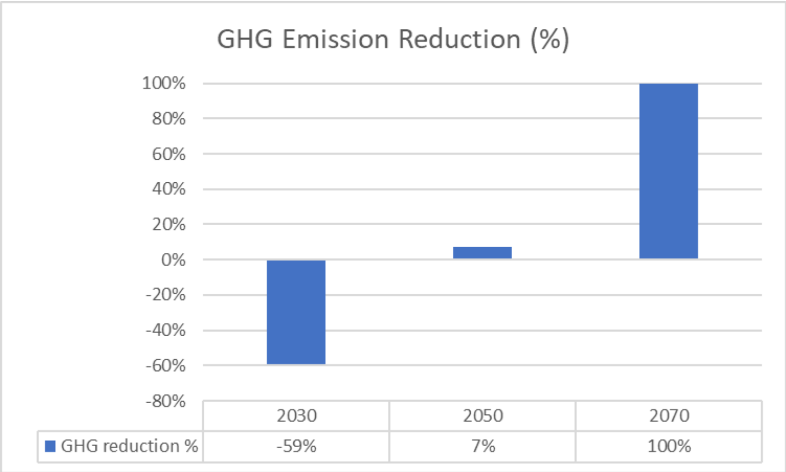


Figure 180: GHG emission reduction (Moderate – Building)

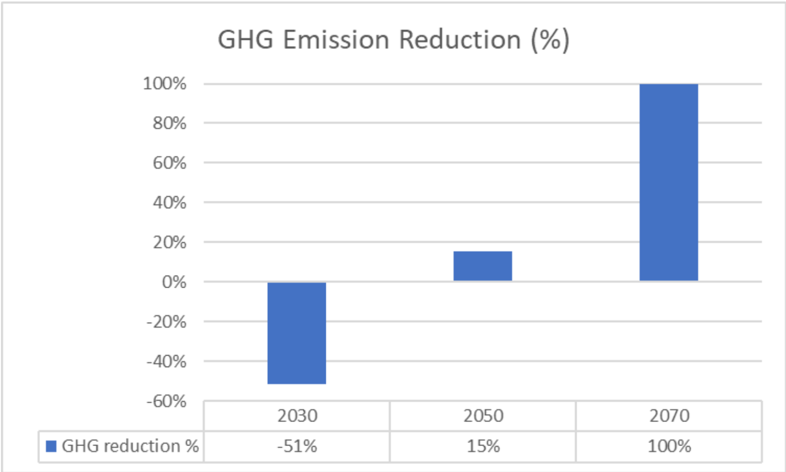


Figure 181: GHG emission reduction (Conservative – Buildings)

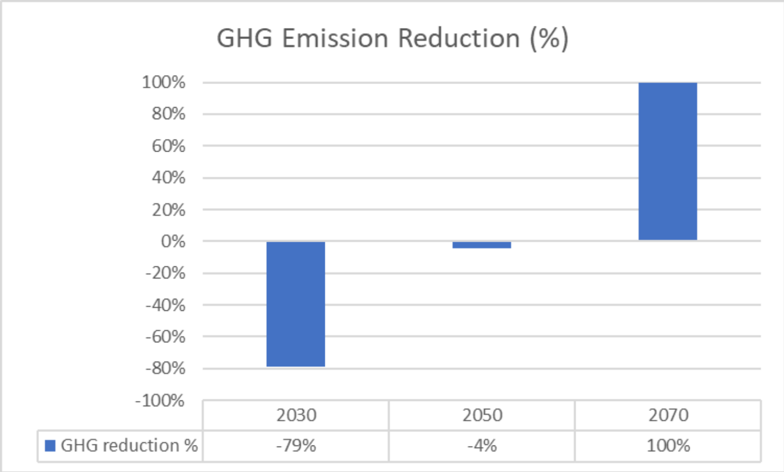


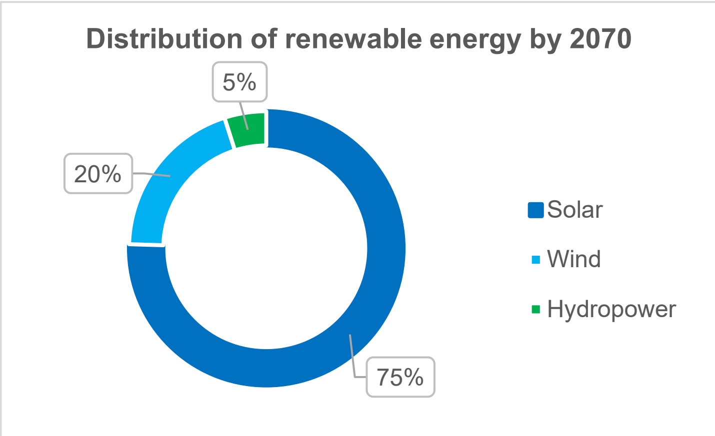
Figure 182: GHG emission reduction (Ambitious – Buildings)

6 Electricity Generation Vs Demand

6.1 Electricity Generation and Demand

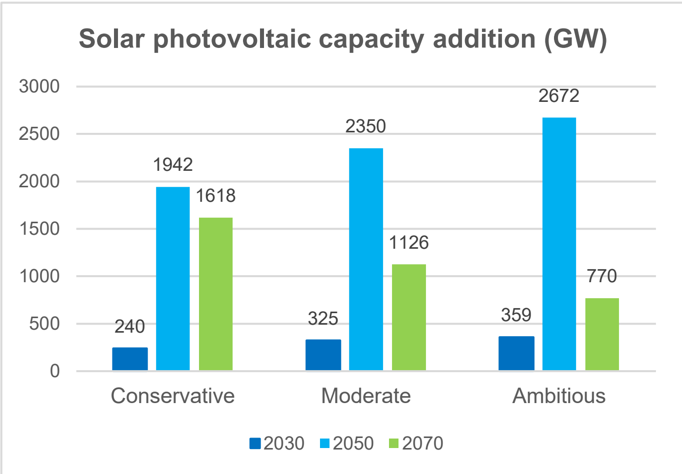
Renewable energy technologies are the key to reducing emissions from electricity supply and it would be only possible with the expansion of wind and solar energy. Wind and solar that quadruple renewables generation by 2030 and, as per the analysis, would increase to almost 20 times by 2070 in the net zero emission scenario. Presently, the share of renewables in total electricity generation is 43% and it would be nearly 100% in 2070. To achieve this, annual capacity additions of wind and solar between the present time and 2070 are four times higher than the average over the last three years.

Renewable energy would be the key source of electricity, and it would act as critical to maintaining energy security in India, together with other low-carbon generation, energy storage, and robust electricity transmission and distribution networks. In the 2070, i.e., net zero scenario, the main renewable energy would be solar photovoltaic (75% of generation), wind energy (20%), and hydropower (5%).



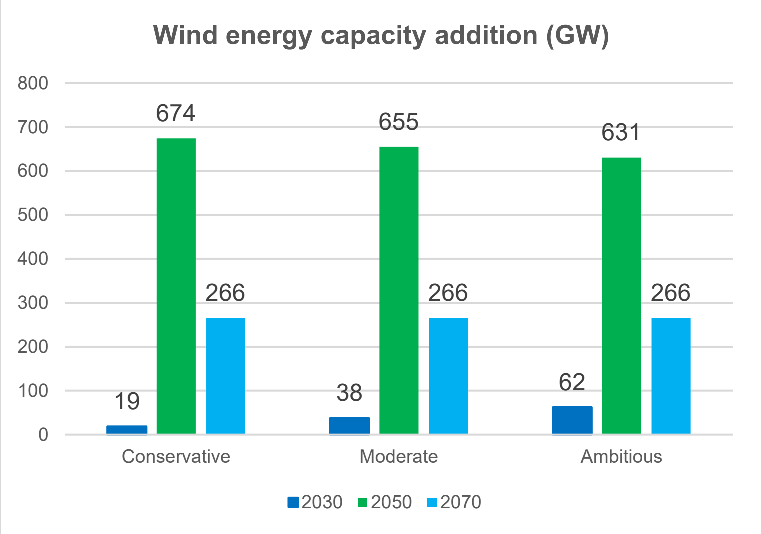
Additional renewable energy capacity installation

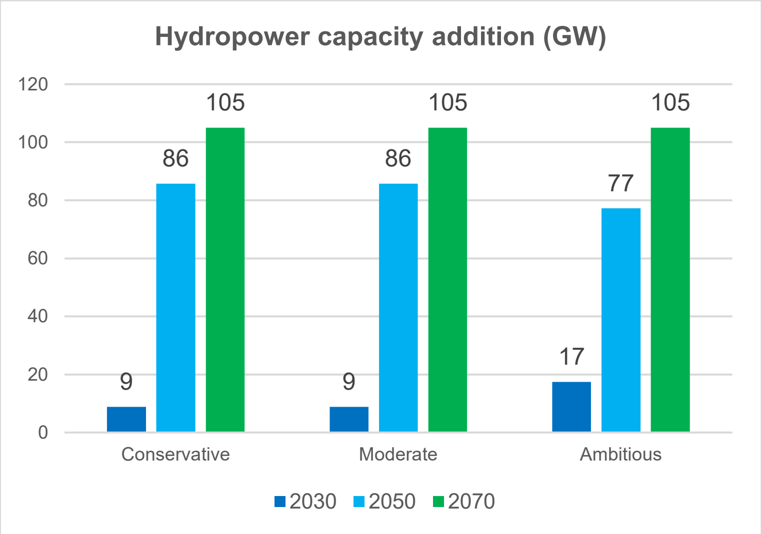
As part of the study, this report covers the installation capacity of all the different sources of renewable energy mentioned above. Due to the recent development in solar photovoltaic technology, it is clear that to install one kWp solar plant, there is a requirement of 9-10 sq. meters of land. To estimate the solar potential for India, we have considered that 4% of the total wasteland area of India, i.e., ~ 3.6 million hectares[300] of land, can be utilized to install solar photovoltaics to cater to the major electricity requirement of India. The illustration presented next details the additional capacity required for solar photovoltaic energy by different periods in the timeline to 2070.



[300] https://pib.gov.in/PressReleseDetailm.aspx?PRID=1590395

As per the study conducted by the National Institute of Wind Energy (NIWE), India has a total installed capacity for wind energy at a 120-meter height of ~700 GW. As per PwC estimation, total wind energy capacity would be increased to ~925 GW at 150-meter height. This study also considers the off-shore wind energy potential as per Ministry of New and Renewable Energy (MNRE). The total potential of offshore wind is 71 GW, which includes 36 GW in Gujarat and 35 GW in Tamil Nadu. Wind energy would make a significant contribution to meeting the country's total electricity requirement. The installation capacity of wind energy in each scenario is presented in the illustration. In this study, we have also considered bioenergy, though the contribution of bioenergy to the country's total electricity requirement is less, i.e., 1% of the total electricity requirement. As per the study, on average, India has an annual availability of 570 million tonnes of biomass and with that capacity, a total of 28 GW of biomass-based power plants can be installed.





The total potential of other sources of renewable energy is also considered in this study. Hydropower energy including all categories of hydropower projects - micro, small and large, is considered in the present analysis. As per MNRE, there is a total potential of 145 GW of hydropower, excluding small hydro. As per NHPC, 250 GW is the total potential of hydropower in India. The image shown next depicts the potential installation capacity of hydro projects for all different scenarios and different timelines.

Monthly Electricity Generation

This report also covers the monthly electricity generation from all the different sources of renewable technology, i.e., solar, wind, and biomass. For solar, we have considered Delhi as the sample location because the monthly solar irradiation in the Delhi region is similar to the average monthly solar irradiation of different regions of the country. For wind, we considered the coastal area, i.e., the Kutch region to represent the average wind flow in comparison with other coastal belts of India.

Capacity utilization factor (CUF) is estimated based on the current CUF of all three renewable energy technologies and the past trend of growth of CUF due to the advancement of renewable energy technology. Technology-wise, CUF is presented in the table below.

CUF	Solar	Wind	Biomass

2030	20%	30%	83%
2050	32%	40%	83%
2070	45%	50%	83%

Monthly variation in the electricity generation from all the sources of energy, i.e., fossil and non-fossil-based generation, is presented in the table below for all the scenarios and for each timeline, i.e., 2030, 2050, and 2070.

Conservative Scenario

2030						
Capacity (GW)	274.30	56.55	14.50	236.70	59.25	12.10
Total Capacity (GW)	**653**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	34566	5958	8770	104193	17301	7066
February	37587	5362	8770	104193	17301	7066
March	46648	10062	8770	104193	17301	7066
April	47319	20058	8770	104193	17301	7066
May	45641	24030	8770	104193	17301	7066
June	39600	19330	8770	104193	17301	7066
July	35909	19131	8770	104193	17301	7066
August	39936	16417	8770	104193	17301	7066
September	41278	6620	8770	104193	17301	7066
October	41950	6024	8770	104193	17301	7066
November	35573	7149	8770	104193	17301	7066
December	34566	8473	8770	104193	17301	7066
Total	480575	148613	105235	1250316	207612	84797
Gross Total (MU)	**2277148**					
Total Demand (MU)	2170673					
CUF	**20%**	**30%**	**83%**	**60%**	**40%**	**80%**
Average CUF	**39.78%**					

2050						
Capacity (GW)	2,217	731	28.00	65	145	16
Capacity (GW)	**3200**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	446958	102615	16934	28439	42340	9040
February	486013	92353	16934	28439	42340	7066
March	603176	173305	16934	28439	42340	7066
April	611855	345470	16934	28439	42340	7066

May	590158	413880	16934	28439	42340	7066
June	512049	332928	16934	28439	42340	7066
July	464316	329508	16934	28439	42340	7066
August	516388	282761	16934	28439	42340	7066
September	533746	114017	16934	28439	42340	7066
October	542425	103755	16934	28439	42340	7066
November	459976	123138	16934	28439	42340	7066
December	446958	145941	16934	28439	42340	7066
Total	6214018	2559672	203213	341272	508080	86771
Gross Total (MU)	**9913026**					
Total Demand (MU)	8363148					
CUF	**32%**	**40%**	**86%**	**60%**	**40%**	**80%**
Average CUF	**35.36%**					

2070						
Capacity (GW)	3,835	996			250	
Total Capacity (GW)	5081					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	1087381	174896	0	0	73000	0
February	1182395	157406	0	0	73000	0
March	1467437	295379	0	0	73000	0
April	1488551	588816	0	0	73000	0
May	1435765	705413	0	0	73000	0
June	1245737	567440	0	0	73000	0
July	1129609	561610	0	0	73000	0
August	1256295	481935	0	0	73000	0
September	1298523	194329	0	0	73000	0
October	1319637	176839	0	0	73000	0
November	1119052	209875	0	0	73000	0
December	1087381	248741	0	0	73000	0
Total	15117764	4362677	0	0	876000	0
Gross Total (MU)	**20356441**					
Total Demand (MU)	17136900					
CUF	45%	50%	0%	60%	40%	80%
Average CUF	45.73%					

Moderate Scenario

2030						
Capacity (GW)	359	75	15	237	59	12
Total Capacity (GW)	**757**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	45238	7944	8770	104193	17301	7066
February	49190	7149	8770	104193	17301	7066
March	61049	13416	8770	104193	17301	7066
April	61927	26744	8770	104193	17301	7066
May	59731	32040	8770	104193	17301	7066
June	51826	25773	8770	104193	17301	7066
July	46994	25508	8770	104193	17301	7066
August	52265	21889	8770	104193	17301	7066
September	54022	8826	8770	104193	17301	7066
October	54900	8032	8770	104193	17301	7066
November	46555	9532	8770	104193	17301	7066
December	45238	11298	8770	104193	17301	7066
Total	628935	198151	105235	1250316	207612	84797
Gross Total (MU)	**2475046**					
Total Demand (MU)	2345868					
CUF	**20%**	**30%**	**83%**	**60%**	**40%**	**80%**

Average CUF	**37.33%**

2050						
Capacity (GW)	2,709	731	28	65	145	15
Total Capacity (GW)	**3692**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	546174	102615	16934	28439	42340	9040
February	593898	92353	16934	28439	42340	7066
March	737070	173305	16934	28439	42340	7066
April	747675	345470	16934	28439	42340	7066
May	721162	413880	16934	28439	42340	7066
June	625714	332928	16934	28439	42340	7066
July	567384	329508	16934	28439	42340	7066
August	631016	282761	16934	28439	42340	7066
September	652227	114017	16934	28439	42340	7066
October	662832	103755	16934	28439	42340	7066
November	562082	123138	16934	28439	42340	7066
December	546174	145941	16934	28439	42340	7066
Total	7593407	2559672	203213	341272	508080	86771
Gross Total (MU)	**11292415**					
Requirement (MU)	9569752					
CUF	32%	40%	86%	60%	40%	80%
Average CUF	34.91%					

2070						
Capacity (GW)	3,835	996			250	
Total Capacity (GW)	**5081**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	1087381	174896	0	0	73000	0
February	1182395	157406	0	0	73000	0
March	1467437	295379	0	0	73000	0
April	1488551	588816	0	0	73000	0
May	1435765	705413	0	0	73000	0
June	1245737	567440	0	0	73000	0
July	1129609	561610	0	0	73000	0
August	1256295	481935	0	0	73000	0
September	1298523	194329	0	0	73000	0
October	1319637	176839	0	0	73000	0
November	1119052	209875	0	0	73000	0
December	1087381	248741	0	0	73000	0
Total	15117764	4362677	0	0	876000	0
Gross Total (MU)	**20356441**					
Total Demand (MU)	17136900					

CUF	**45%**	**50%**	**0%**	**60%**	**40%**	**80%**
Average CUF	**45.73%**					

Ambitious Scenario

2030						
Capacity (GW)	393	100	15	277	68	16
Total Capacity (GW)	**868**					
Month	Solar (MU)	Wind (MU)	Biomass (MU)	TPP (MU)	Hydro (MU)	Nuclear (MU)
January	49578	10524	8770	121716	19793	9040
February	53910	9472	8770	121716	19793	9040
March	66906	17774	8770	121716	19793	9040
April	67868	35432	8770	121716	19793	9040
May	65462	42448	8770	121716	19793	9040
June	56798	34146	8770	121716	19793	9040
July	51503	33795	8770	121716	19793	9040
August	57279	29000	8770	121716	19793	9040
September	59204	11694	8770	121716	19793	9040
October	60167	10641	8770	121716	19793	9040
November	51022	12629	8770	121716	19793	9040
December	49578	14968	8770	121716	19793	9040
Total	689274	262524	105235	1460587	237515	108484
Gross Total (MU)	**2863619**					
Total Demand (MU)	2697888					
CUF	**20%**	**30%**	**83%**	**60%**	**40%**	**80%**
Average CUF	**37.68%**					

2050						
Capacity (GW)	3,065	731	28	65	145	15
Total Capacity (GW)	**4049**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	618054	102615	16934	28439	42340	9040
February	672058	92353	16934	28439	42340	9040
March	834072	173305	16934	28439	42340	9040
April	846073	345470	16934	28439	42340	9040
May	816071	413880	16934	28439	42340	9040
June	708061	332928	16934	28439	42340	9040
July	642056	329508	16934	28439	42340	9040
August	714062	282761	16934	28439	42340	9040
September	738064	114017	16934	28439	42340	9040
October	750065	103755	16934	28439	42340	9040

November	636055	123138	16934	28439	42340	9040
December	618054	145941	16934	28439	42340	9040
Total	8592744	2559672	203213	341272	508080	108484
Gross Total (MU)	**12313465**					
Requirement (MU)	10467916					
CUF	**32%**	**40%**	**86%**	**60%**	**40%**	**80%**
Average CUF	**34.72%**					

2070						
Capacity (GW)	3,835	996			250	
Total Capacity (GW)	**5081**					
Month	**Solar (MU)**	**Wind (MU)**	**Biomass (MU)**	**TPP (MU)**	**Hydro (MU)**	**Nuclear (MU)**
January	1087381	174896	0	0	73000	0
February	1182395	157406	0	0	73000	0
March	1467437	295379	0	0	73000	0
April	1488551	588816	0	0	73000	0
May	1435765	705413	0	0	73000	0
June	1245737	567440	0	0	73000	0
July	1129609	561610	0	0	73000	0
August	1256295	481935	0	0	73000	0
September	1298523	194329	0	0	73000	0
October	1319637	176839	0	0	73000	0
November	1119052	209875	0	0	73000	0
December	1087381	248741	0	0	73000	0
Total	15117764	4362677	0	0	876000	0
Gross Total (MU)	**20356441**					
Requirement (MU)	17136900					
CUF	**45%**	**50%**	**0%**	**60%**	**40%**	**80%**
Average CUF	**45.73%**					

Battery Storage

During the evaluation of the electrification under the different scenarios across the three distinct timelines, i.e. 2030, 2050 and 2070. The annual electrical energy required to meet the operations in each sub-sector is calculated in millions of tonnes of oil equivalent.

Electrical Energy requirement in the sector is generated from different sources based upon the energy mix in a particular scenario (i.e. the share of the solar, wind, hydro, biomass, nuclear and TPP). Energy generation from solar energy has a daily variation; energy is generated only during a few hours a day. However, the other sources don't have such a high level of variation for 24 hours time span. To have the reliable energy required during the day, energy generated from solar needs to be stored to meet the sectoral requirements.

Energy from the solar needs to be stored in the battery to serve the requirement of the sectoral energy demand during the non-sunny hours. To build the battery capacity size, losses in different energy generation/conversion/storage etc., need to be factored in. Details of the losses and day of autonomy considering the cloud and non-cloud day are considered to derive the factor of battery size vis-à-vis requirement. The table below presents the detailed assumptions. All assumptions and details are cross-verified from multiple sources, including PwC internal teams extensively supporting NITI aayog in energy storage and other well-accepted international sources like IRENA, IEA etc.

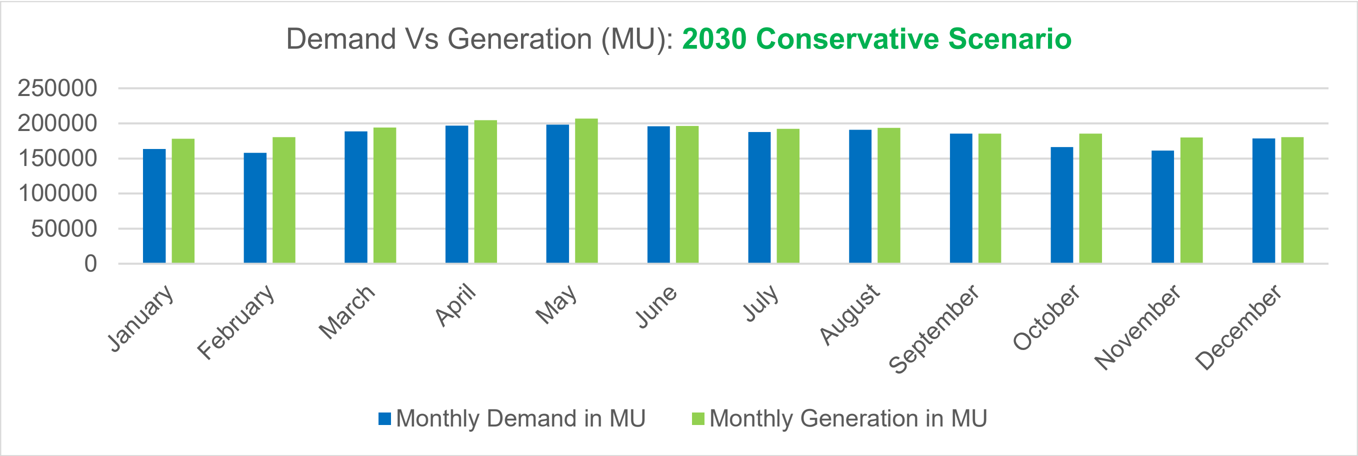
Parameters	Unit	Value
Daily energy requirement	kWh/ day	100
Total RE system losses		23%
DC Energy	kWh/day	123
Battery efficiency	%	95%
Battery drainout	%	85%
DC energy after battery loss	kWh/day	152.3
Day of autonomy		1.216
Battery Bank Size	kWh	185.32
Energy Requirement to Battery Size	ratio	**1.8532**

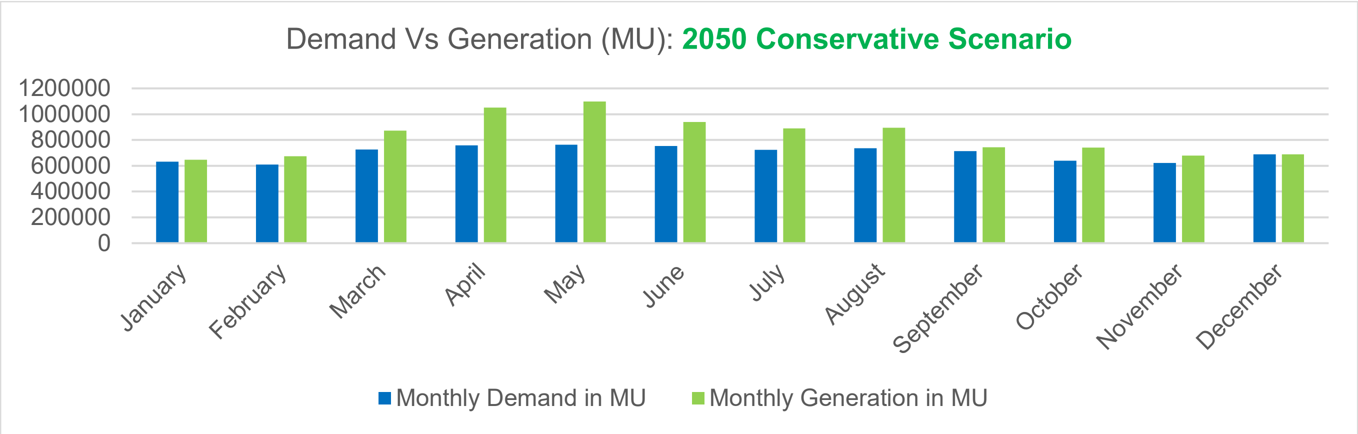
The energy requirement is divided by the PLF of the unit, and the energy calculated after the PLF deduction is then converted into kWh requirement from Mtoe. The share of the solar energy is then multiplied by the derived value to calculate the energy requirement for Solar. Energy (kWh/day) derived is then multiplied by the factor derived in the above table and converted into GWh.

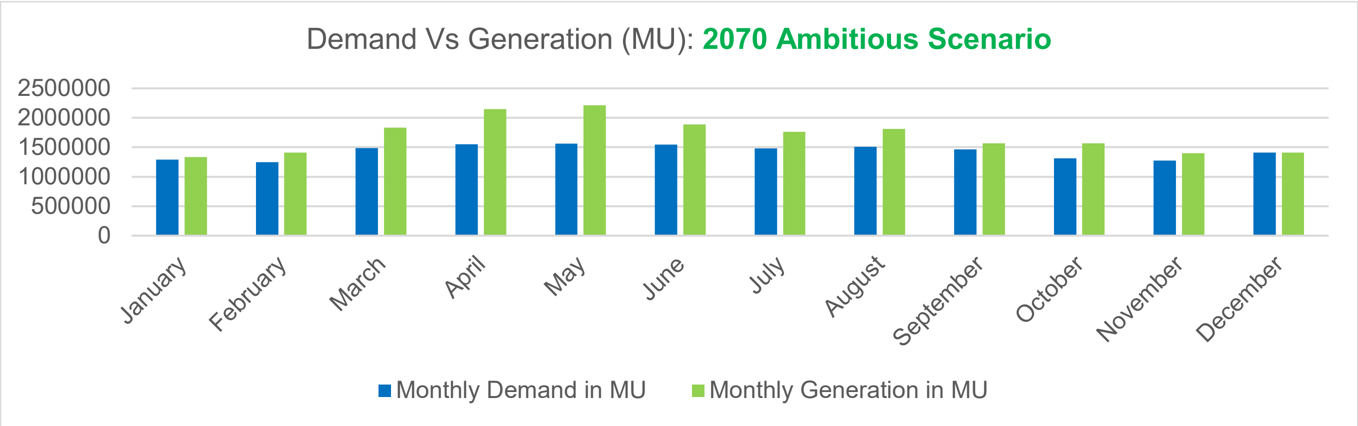
Monthly Electricity Demand

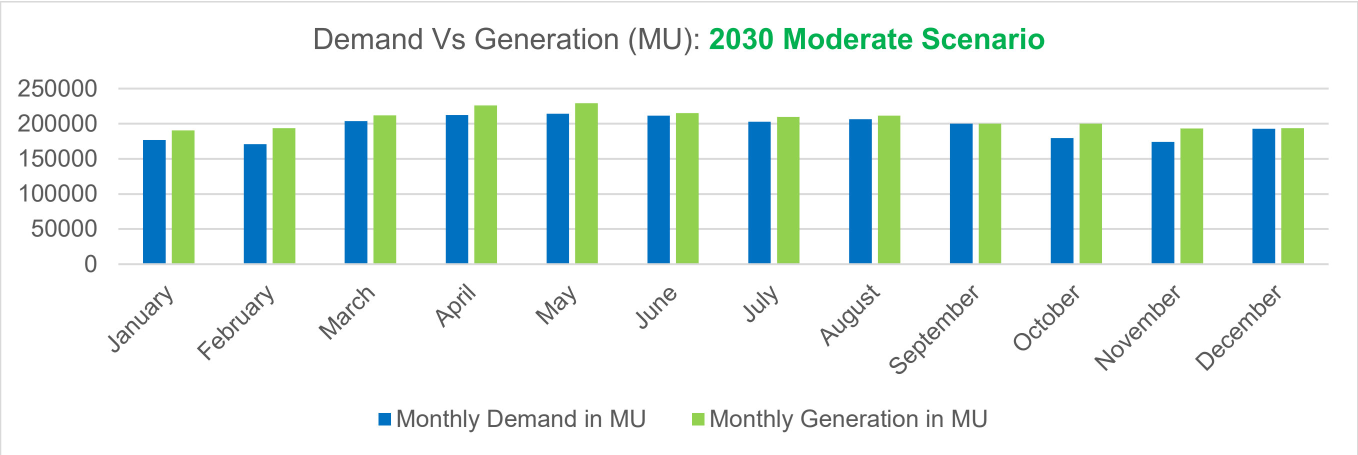
India's power sector is one of the most diversified in the world. Sources of power generation range from conventional sources such as coal, lignite, natural gas, oil, hydro and nuclear power to viable non-conventional sources such as wind, solar, agricultural and domestic waste. Electricity demand in the country has increased rapidly and is expected to rise further in the years to come. In order to meet the increasing demand for electricity in the country, a massive addition to the installed generating capacity is required. The monthly electricity demand of the country is estimated based on the secondary desk research. We have considered the power supply position[301] of the country to estimate the monthly electricity consumption percent. Based on the percent, we have distributed our annual requirement of electricity in all the scenarios and timelines to monthly patterns. Images shown below depict the monthly variation of the demand versus estimated generation capacity.

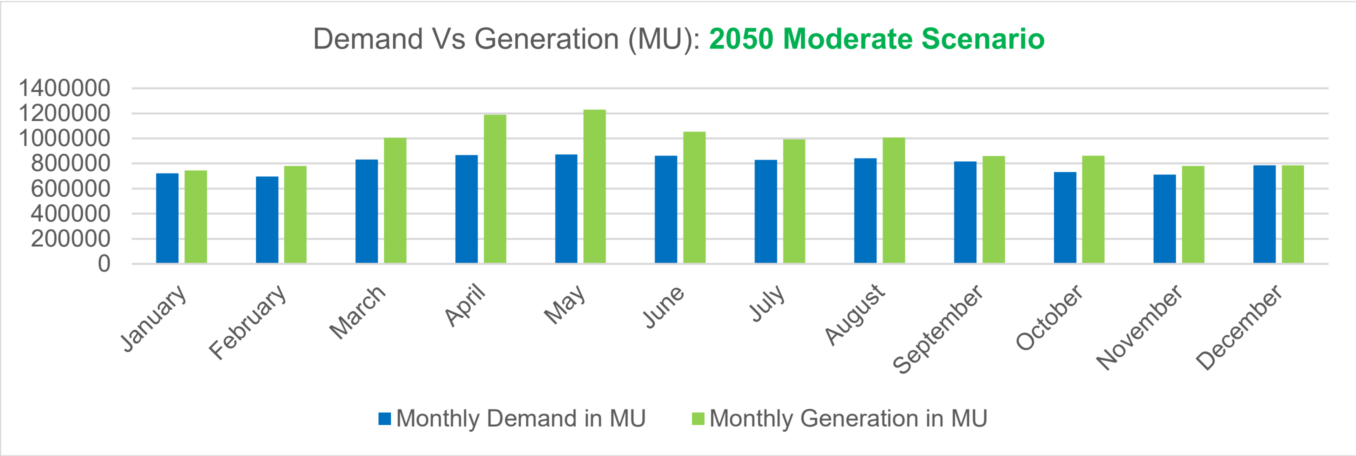
[301] https://cea.nic.in/dashboard/?lang=en

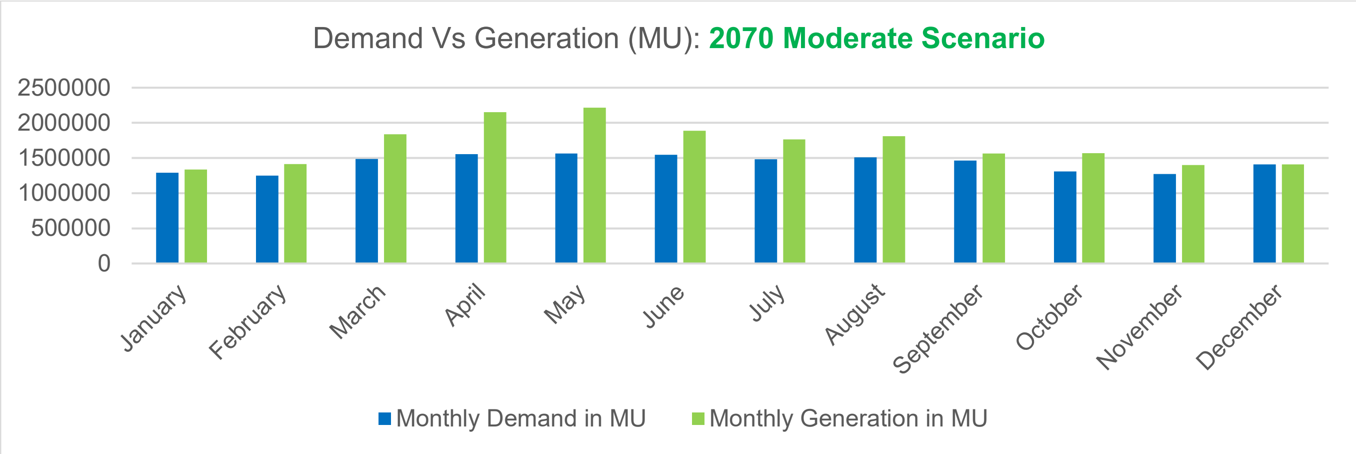

Demand Vs Generation (MU): 2030 Conservative Scenario
250000
200000
150000
100000
50000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU

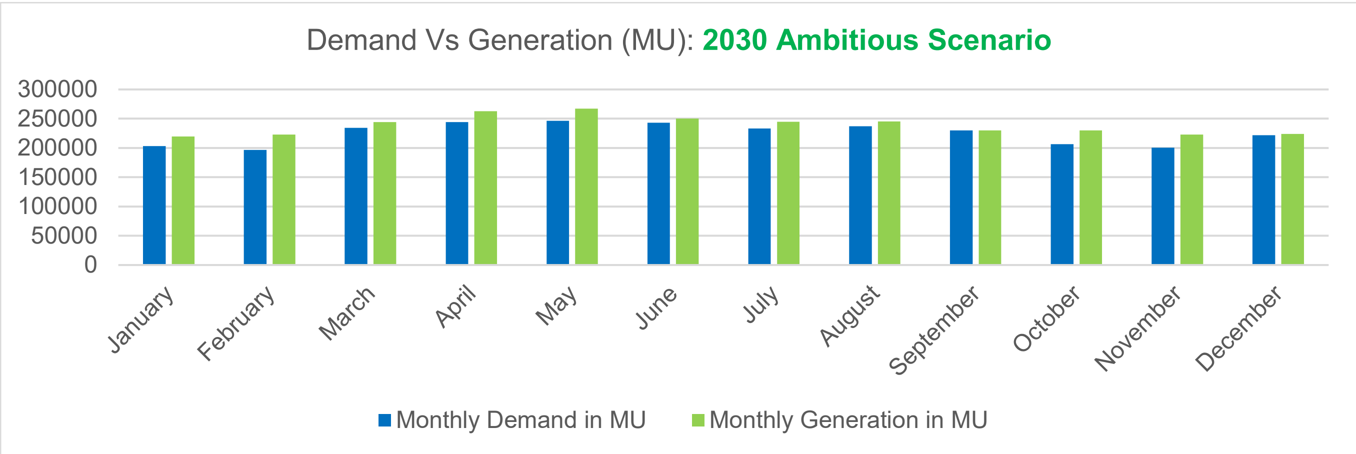

Demand Vs Generation (MU): 2050 Conservative Scenario
1200000
1000000
800000
600000
400000
200000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU

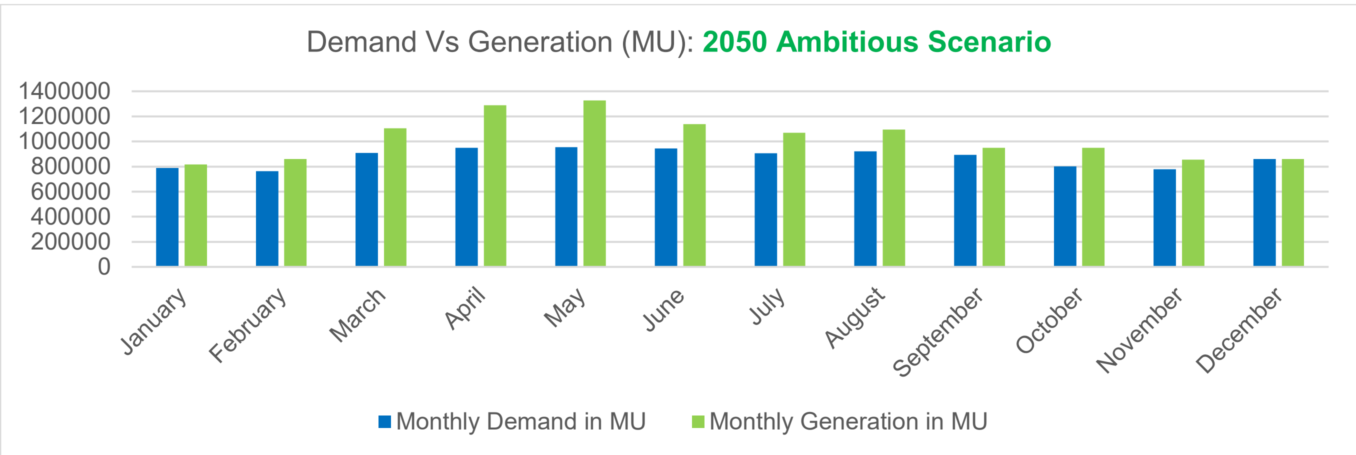

Demand Vs Generation (MU): 2070 Ambitious Scenario
2500000
2000000
1500000
1000000
500000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU


Demand Vs Generation (MU): 2030 Moderate Scenario
250000
200000
150000
100000
50000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU


Demand Vs Generation (MU): 2050 Moderate Scenario
1400000
1200000
1000000
800000
600000
400000
200000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU


Demand Vs Generation (MU): 2070 Moderate Scenario
2500000
2000000
1500000
1000000
500000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU


Demand Vs Generation (MU): 2030 Ambitious Scenario
300000
250000
200000
150000
100000
50000
0
January
February
March
April
May
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU


Demand Vs Generation (MU): 2050 Ambitious Scenario
1400000
1200000
1000000
800000
600000
400000
200000
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January
February
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April
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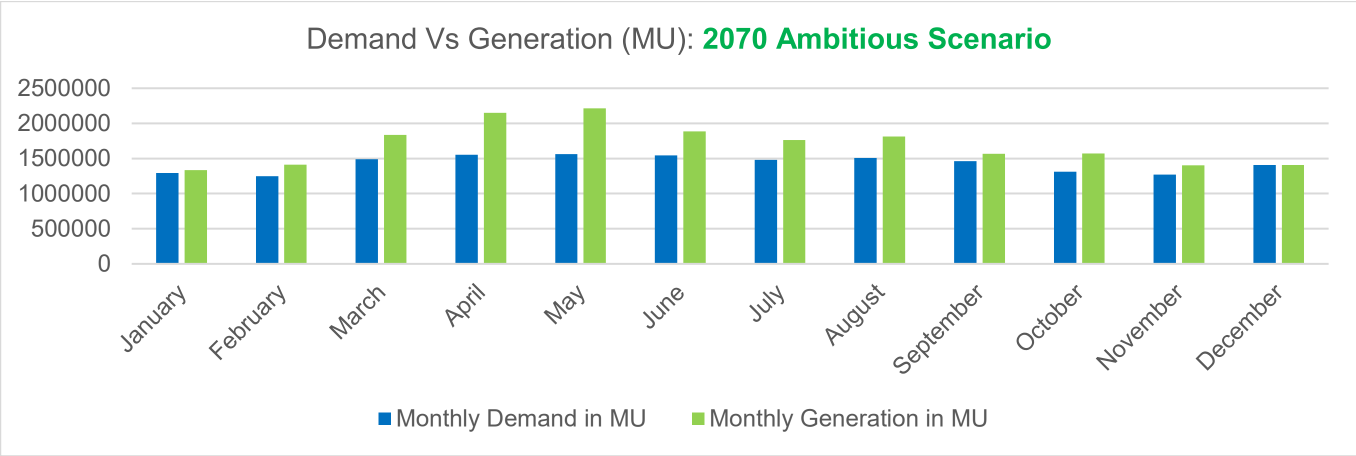
June
July
August
September
October
November
December
Monthly Demand in MU
Monthly Generation in MU



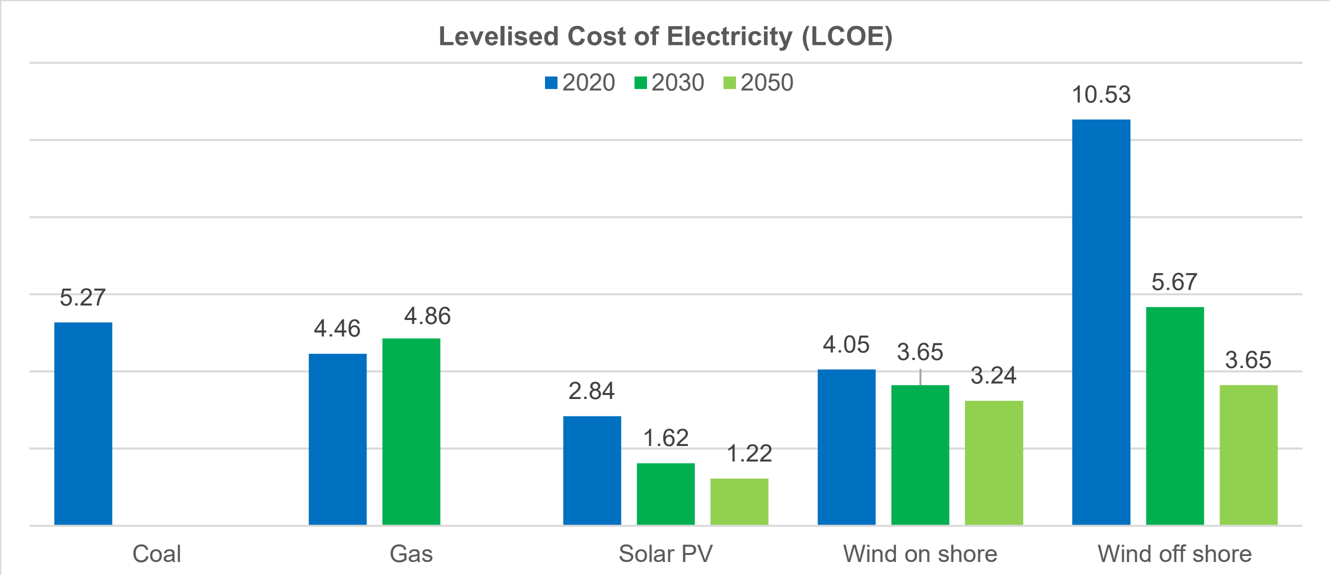
Levelised cost of electricity (LCOE)

The levelized cost of electricity is a measure of the average net present cost of electricity generation for a generator over its lifetime. Major contributors to the LCOE include overnight capital costs, capacity factor that describes the average output over the year relative to the maximum rated capacity (typical values provided), the cost of fuel inputs, plus operation and maintenance. Economic lifetime assumptions are 25 years for solar PV, onshore and offshore wind.

Table 42: Electricity generation renewable energy cost (LCOE)[302]

	Financing Rate (%)	Capital Costs (INR/kW)			Capacity Factor (%)			Fuel, CO2, and O&M (INR/MWh)			LCOE (INR/kWh)		
	All	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**	**2020**	**2030**	**2050**
Coal	7%	97200	97200	97200	50			2835	4050	6075	5.27		
Gas	7%	56700	56700	56700	55	50		3645	3645	4050	4.46	**4.86**	
Solar PV	5.8%	46980	25110	17820	20	21	21	405	405	405	2.84	**1.62**	**1.22**
Wind on shore	5.8%	84240	79380	76140	26	28	29	810	810	810	4.05	**3.65**	**3.24**
Wind off shore	6%	241380	136080	95580	32	37	38	2025	1215	810	10.53	**5.67**	**3.65**

[302] https://www.iea.org/reports/net-zero-by-2050



Summary

Detailed analysis of the monthly generation and peak demand has been covered in this section. The generation capacity of the different sources of electricity is estimated in a way to meet the monthly demand of the country. In addition to this, additional battery storage capacity has been estimated to meet the contingency requirement of the electricity. The table presented below depicts the energy mix, additional RE requirement for green hydrogen, and battery storage capacity for all the different scenarios and for each timeline.

CEA projection for India's electricity installation capacity requirement is 777 GW, which is in line with our moderate scenario, i.e., 757 GW. We have estimated the requirement of green hydrogen as well as the additional source of electricity. Due to the surplus generation of electricity annually from the proposed installed capacity, surplus electricity can be used to produce green hydrogen, and it can be stored and used as and where required. Other than surplus electricity generation, an additional RE requirement is also considered in this study.

Thermal power plants (TPP) have also been considered for the near-term scenario, as it would be difficult to meet the electricity requirement in 2030 without TPPs. But in the long-term scenario phasing out of all the TPPs in a phased manner has been considered and by 2070, the country's requirement would be completely met by RE.

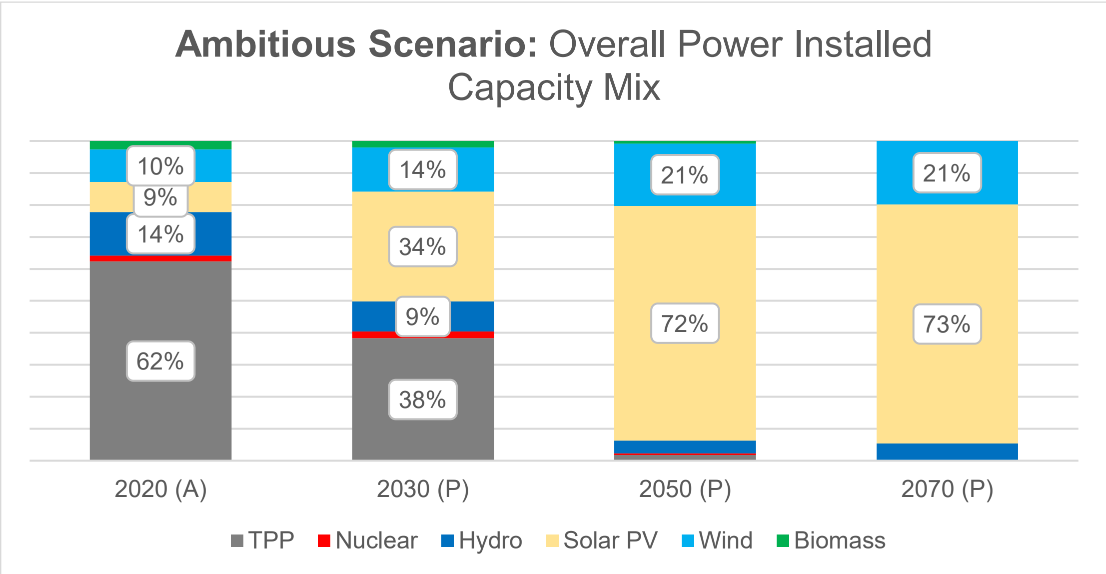
Ambitious				
Installed Capacity (GW)	***2020 (A)[303]***	***2030 (P)[304]***	***2050 (P)***	***2070 (P)***
TPP	230	277	65	
Nuclear	7	16	16	
Hydro	50	68	145	250
Solar PV	34	393	3,065	3,835
Wind	38	100	730	996
Biomass	10	15	28.0	
Total	**369**	**868**	**4,049**	**5,081**
Additional Solar PV for GH2		271	278	
Grand Total	**369**	**1,138**	**4,327**	**5,081**
Battery Storage Capacity (GWh)		382	2796	4298

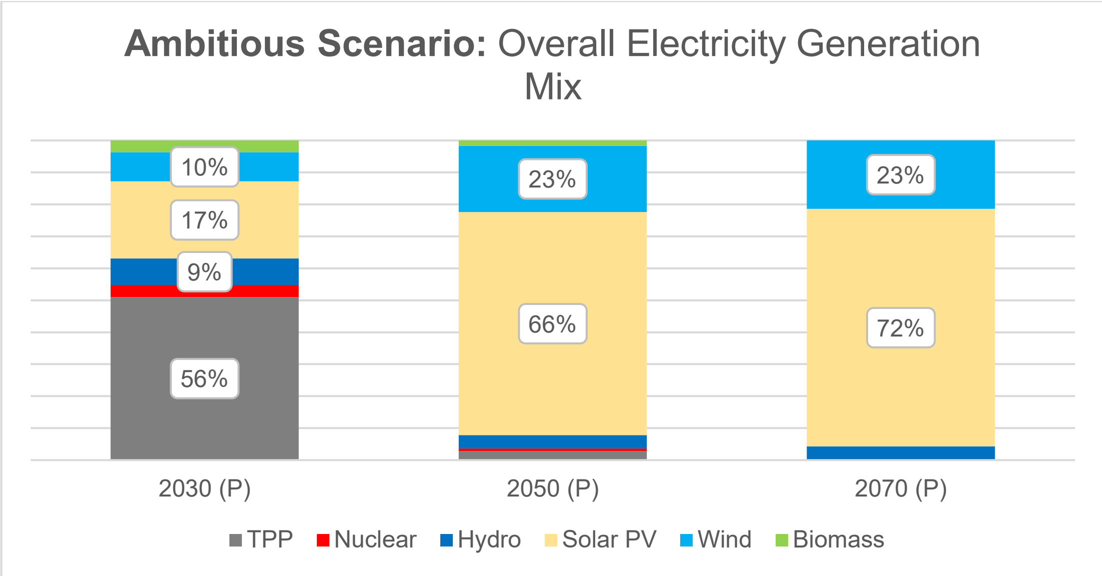
[303] *A stands for Actual*
[304] *P stands for Projected*

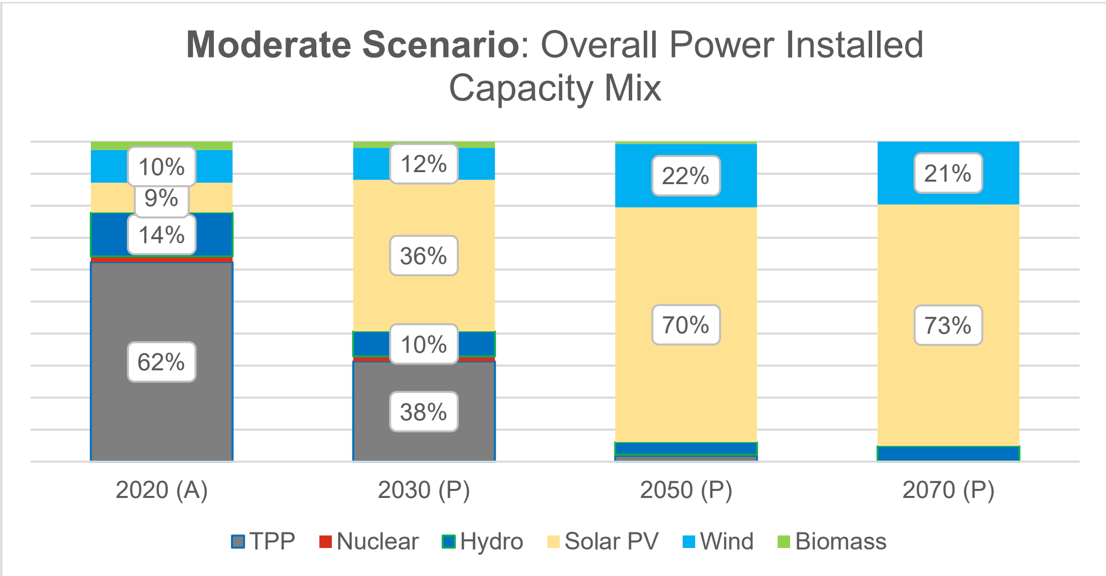
GH2 Generation (MMT)		**12**	**51**	**62**

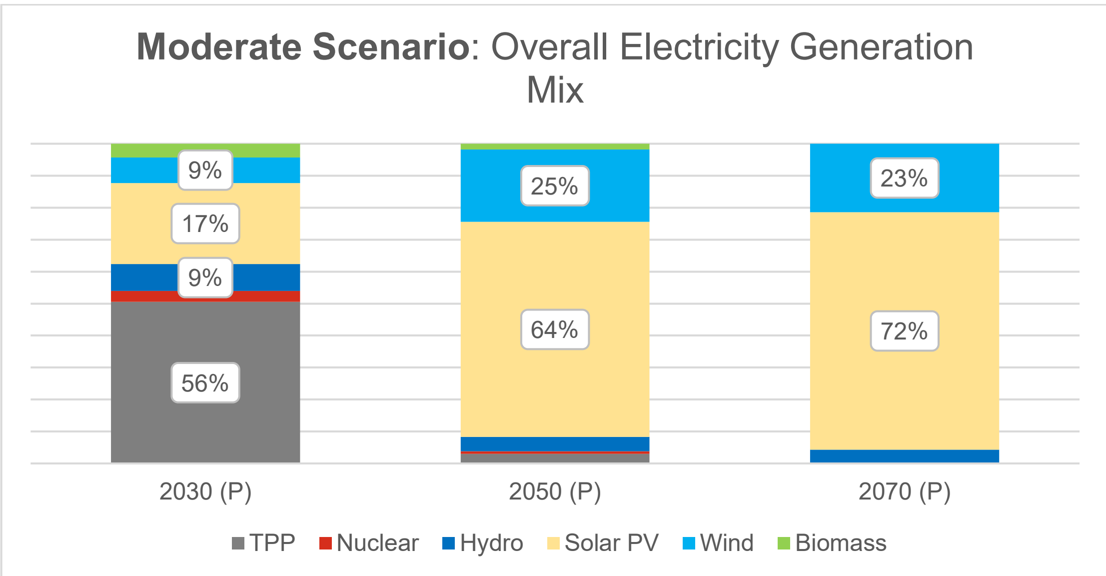
Moderate				
Installed Capacity (GW)	***2020 (A)***	***2030 (P)***	***2050 (P)***	***2070 (P)***
TPP	230	237	65	-
Nuclear	7	12	15	-
Hydro	50	59	145	250
Solar PV	34	359	2,709	3,835
Wind	38	75	731	996
Biomass	10	15	28	-
Total	**369**	**757**	**3,692**	**5,081**
Additional Solar PV for GH2	-	184	293	-
Grand Total	**369**	**941**	**3,985**	**5,081**
Battery Storage Capacity (GWh)		354	2524	4298
GH2 Generation (MMT)	**-**	**9**	**49**	**62**

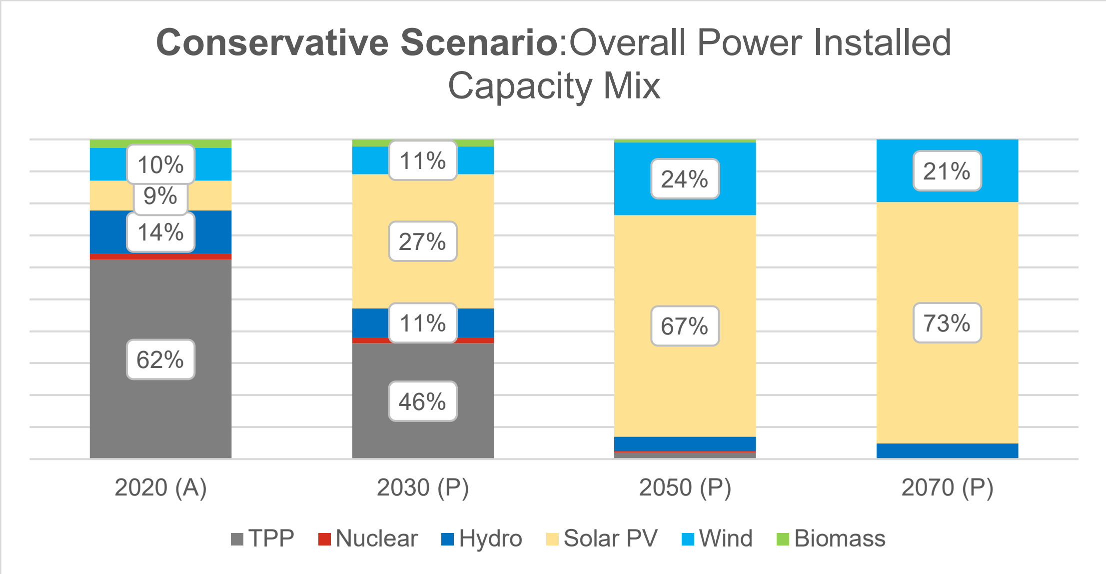
Conservative				
Installed Capacity (GW)	***2020 (A)***	***2030 (P)***	***2050 (P)***	***2070 (P)***
TPP	230	236.7	64.6	-
Nuclear	6.8	12.1	15.5	-
Hydro	50.4	59.3	145.0	250.0
Solar PV	34.4	274.3	2,216.8	3,835.0
Wind	37.7	56.6	730.5	996.0
Biomass	9.8	14.5	28.0	-
Total	**369**	**653**	**3,200**	**5,081**
Additional Solar PV for GH2	-	152.9	252.2	-
Grand Total	**369**	**806**	**3,453**	**5,081**
Battery Storage Capacity (GWh)		229	2154	4298
GH2 Generation (MMT)	**-**	**7.2**	**43.4**	**61.9**

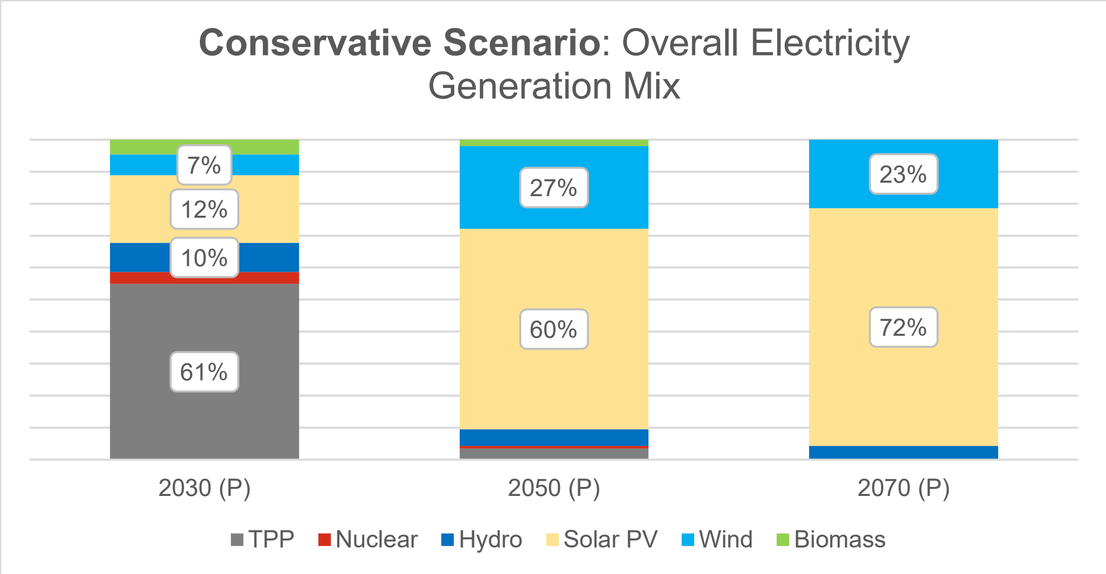



Ambitious Scenario: Overall Electricity Generation Mix
10%
17%
9%
56%
23%
66%
23%
72%
2030 (P)
2050 (P)
2070 (P)
TPP
Nuclear
Hydro
Solar PV
Wind
Biomass


Moderate Scenario: Overall Power Installed Capacity Mix
10%
9%
14%
62%
12%
36%
10%
38%
22%
70%
21%
73%
2020 (A)
2030 (P)
2050 (P)
2070 (P)
TPP
Nuclear
Hydro
Solar PV
Wind
Biomass


Moderate Scenario: Overall Electricity Generation Mix
9%
17%
9%
56%
25%
64%
23%
72%
2030 (P)
2050 (P)
2070 (P)
TPP
Nuclear
Hydro
Solar PV
Wind
Biomass


Conservative Scenario:Overall Power Installed Capacity Mix
10%
9%
14%
62%
11%
27%
11%
46%
24%
67%
21%
73%
2020 (A)
2030 (P)
2050 (P)
2070 (P)
TPP
Nuclear
Hydro
Solar PV
Wind
Biomass


Conservative Scenario: Overall Electricity Generation Mix
7%
12%
10%
61%
27%
60%
23%
72%
2030 (P)
2050 (P)
2070 (P)
TPP
Nuclear
Hydro
Solar PV
Wind
Biomass

7 Green Hydrogen

7.1 Green Hydrogen

Introduction of Green Hydrogen

India's pathway to net zero emission economy by 2070 is incomplete without transitioning the thermal energy and feedstock needs of industries and other sectors like transport to green hydrogen. Hydrogen plays an important role as an energy carrier. This is why industries like iron & steel, fertilizers, cement, and others need hydrogen to meet high temperature requirements. Currently, this heat is produced by burning fossil fuels. For hard-to-abate sectors, it would be difficult to reach net zero without transitioning to green hydrogen.

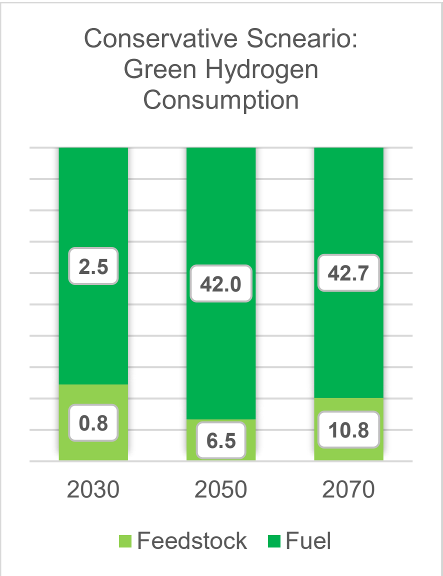
Hydrogen from fossil fuel sources is often referred to as "grey" hydrogen unless the facilities are equipped with Carbon Capture and Storage (CCS), in which case the hydrogen is called "blue" hydrogen. Today, in the country, the majority of the hydrogen is produced from fossil fuels, and none of the facilities are equipped with CCS. Hydrogen produced with electrolysis is generally called "green" hydrogen under the assumption that the supplied electricity is generated with renewable resources. Producing one kilogram of hydrogen with electrolysis requires 50-55 kWh[305] of electricity. This power consumption leads to indirect CO_2 emissions, and the level of intensity will vary from the different sources of electricity. Meanwhile, hydrogen production from fossil fuels leads to the direct consumption of fossil fuels and their associated high emissions.

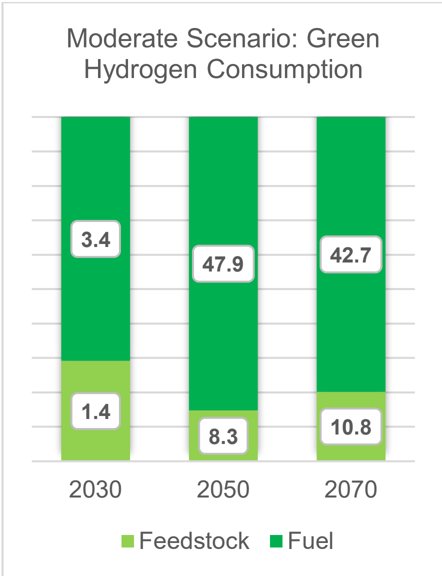
The Government of India has launched the National Green Hydrogen Mission through a comprehensive and integrated approach. The Ministry of New and Renewable Energy is responsible for the overall coordination for implementation of the Mission. The overarching objective of the mission is to make India a global hub of green hydrogen production and promote the use of green hydrogen to significantly decarbonize the Indian economy. To achieve this objective, the focus is to promote the production of green hydrogen by at least 5 MMT with an additional potential to cater 5 MMT of exports to the global market. Green hydrogen can be used as feedstock also as a fuel in many industries like ammonia production and petroleum refining, blending Green Hydrogen in City Gas Distribution systems, production of steel with Green Hydrogen, and use of Green Hydrogen-derived synthetic fuels (including Green Ammonia, etc.) to replace fossil fuels in various sectors including mobility, shipping, and aviation.

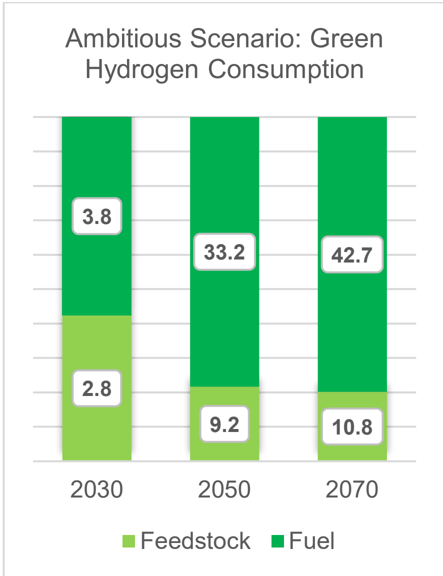
As per this analysis, consumption of green hydrogen in India by 2030 would vary in different scenarios in the range of **3.3 MMT to 6.6 MMT**. Which is further subdivided in two categories i.e., feedstock (0.8-2.8 MMT) and as a fuel (2.5-3.8 MMT). However, the Government of India's target and PwC's moderate scenario are in line with each other, but for aggressively achieving the net zero emission by 2070, then there should be an increase in domestic consumption by **~45%** from the current target by 2030. Variation in consumption in different scenarios and in different timelines is depicted in the below-presented table and image.

[305] *Hydrogen's Decarbonization Impact for Industry, Rocky Mountain Institute (RMI)*

Total Consumption (MMT)	2030		2050		2070	
	Feedstock	Fuel	Feedstock	Fuel	Feedstock	Fuel
Ambitious	2.8	3.8	9.2	33.2	10.8	42.7
Moderate	1.4	2.6	8.3	36.9	10.8	42.7
Conservative	0.8	2.5	6.5	42.0	10.8	42.7







Sectoral Consumption

Iron & Steel: Using hydrogen for steel production is a technology currently in the late research and development stage. In this study, the focus was to replace conventional DRI with H_2 DRI or blend with natural gas process. With quite a broad margin, using hydrogen for steelmaking has the highest decarbonization impact of the analyzed use cases. This is because hydrogen is not only used for heat but also as a catalyst in the process where prevailing technology uses fossil fuels.

The sector's green hydrogen consumption in 2030 is estimated to be in the range of 0.5 – 0.9 MMT in different scenarios of the study, where its usage in feedstock is estimated to be in the range of 0.1-0.3 MMT by 2030 in different scenarios. Green hydrogen consumption for all scenarios and each timeline is presented in the table below.

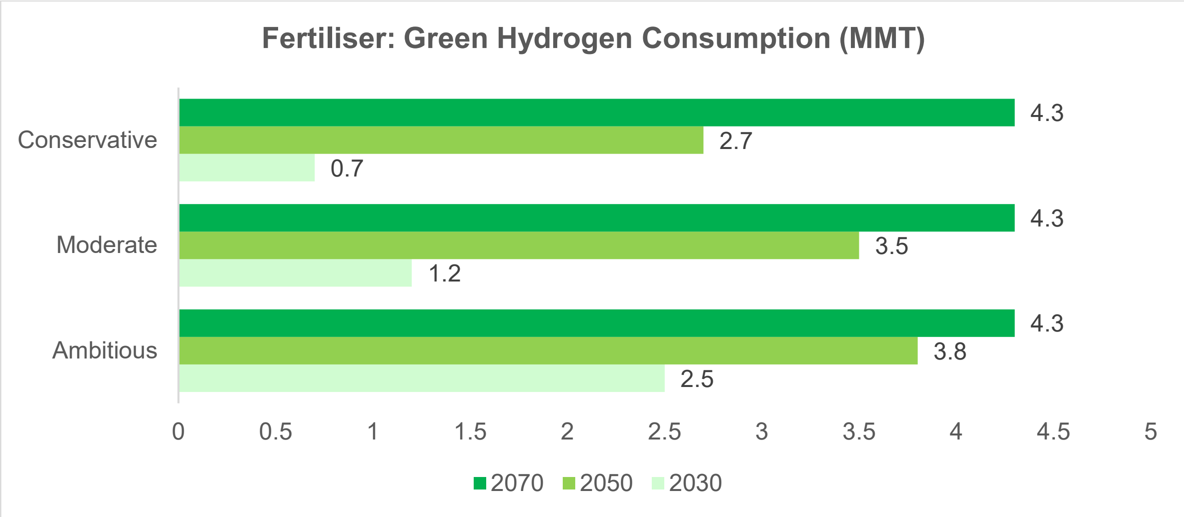
Iron & Steel (MMT)	2030		2050		2070	
	Feedstock	Fuel	Feedstock	Fuel	Feedstock	Fuel
Ambitious	0.3	0.6	5.4	12.6	6.5	10.6
Moderate	0.2	0.3	4.8	14.7	6.5	10.6
Conservative	0.1	0.2	3.8	16.8	6.5	10.6

Fertiliser: The fertilizer industry consumes hydrogen in the form of ammonia, primarily to produce urea, diammonium phosphate (DAP) and other complex fertilizers. Each ton of ammonia production requires roughly 178 kgs[306] of hydrogen. To produce hydrogen, feedstocks such as natural gas, naphtha, or coal are employed in today's scenario. The Ministry of Chemicals and Fertilizers has to encourage the adoption of indigenous green ammonia-based fertilizers to progressively replace

[306] https://wri-india.org/blog/emission-reduction-potential-green-hydrogen-ammonia-synthesis-fertilizer-industry#:~:text=Each%20ton%20of%20ammonia%20production,naphtha%2C%20or%20coal%20are%20employed

imports of fertilizers and fossil fuel-based feedstocks (natural gas and ammonia) used to produce fertilizers. This will enable decarbonization of the sector and reduce dependence on imports.

The fertilizer sector would primarily consume green hydrogen as a feedstock only, and its consumption is estimated to be 2.5 MMT in 2030 and 3.8 MMT, 4.3 MMT in 2050 and 2070 respectively, in the ambitious scenario. Consumption in various scenarios and different timelines is presented in the image shown below.



Others (industrial heating): Hydrogen can also be burned to generate heat; it is considered to be the low-carbon option to achieve really high-temperature process environments. In these applications, a direct comparison of the thermal content of the different fuels applies. Combustion of one Metric Million British Thermal Unit (mmbtu) of coal leads to the emission of 95 kg of CO2. In order to displace one mmbtu of coal, you need 8.07 kg of hydrogen, which in turn will require 440 kWh of electricity. The equivalent carbon emissions from the combustion of natural gas are 53 kg of CO2 per mmbtu. It would be consumed in sectors like cement, MSME, food processing, and other non-specified industries like petroleum refining and others.

The Ministry of Petroleum and Natural Gas (MoPNG) has to facilitate the uptake of Green Hydrogen in refineries and city gas distribution. New refineries and city gas projects have to be planned and designed to be compatible with the maximum possible green hydrogen deployment, with a goal to progressively replace imported fossil fuels. Consumption of green hydrogen in various sectors in different scenarios and in different timelines is shown in the table below.

Green Hydrogen Consumption (MMT)	2030	2050	2070
Others (Non-specified Industry)			
Ambitious	2.2	9.06	18.48
Moderate	1.1	8.15	18.48
Conservative	0.66	6.34	18.48
Cement			
Ambitious	0.7	8	0
Moderate	1	10.8	0
Conservative	1.5	16.4	0
MSME			
Ambitious	0.3	3.1	12.7
Moderate	0.3	3.1	12.7
Conservative	0.3	3.1	12.7

Food Processing			
Ambitious	0	0.411	0.96
Moderate	0	0.411	0.96
Conservative	0	0.411	0.96
Harvesters			
Ambitious	0	0.006	0
Moderate	0	0.006	0
Conservative	0	0.01	0

8 Cross-cutting technologies

8.1 Cross-cutting technologies

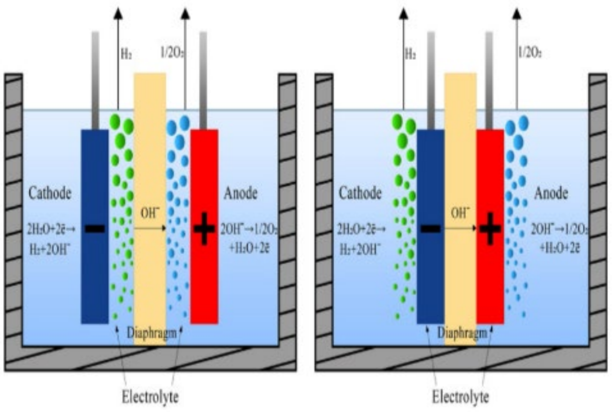
This chapter consists of the details of all the technologies that are repetitive in more than one of the sub-sectors, like electric boilers, heat pumps, green hydrogen, etc. Each of the technologies mentioned below has a detailed description covering the working principle, TRL, cost development, compatibility with other technology, and efficiency level.

Green Hydrogen Electrolysis

There are three principal types of electrolysers.

Alkaline Electrolysers

The cheapest and currently most suitable for large-scale electrolysis (> 50 MW). Their effectiveness has been proven over a century of use – Nangal Fertiliser Plant[307] uses an alkaline electrolyser commissioned by De Nora, Norway, which built an enormous 135MW alkaline electrolyser in the 1920s. The best alkaline electrolysers can operate with an efficiency of 74-87% (45 to 53 kWh/ per kilogram of hydrogen). They offer a large degree of flexibility as they can operate between 20 and 100% of design capacity, allowing them to handle a fluctuating power supply. An alkaline electrolyser can operate for 30 years or longer, though its central component (cell stacks) must be replaced every 8 to 10 years.



Two types of ALK electrolysers: (a) the gap cells with a gap between the electrodes and the cell separator (b) the zero-gap cell with porous electrodes pressed against the cell separator.

Working Principle

In this type of electrolyser, two metallic electrodes are placed in an electrolyte, which is basically an aqueous solution of NaOH or KOH with a concentration of about 20-40 wt%. KOH has higher conductivity than NaOH and hence is preferred. At the cathode, the reduction of water occurs.

$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$

At the anode, the hydroxyl ions oxidise as follows:

$2OH^- \longrightarrow 1/2\ O_2 + H_2O + 2e^-$

And the overall reaction is,

$H_2O_{liq} \longrightarrow H_{2\ gas} + 1/2\ O_{2\ gas}$

Global Best Practice Examples[308]

Asahi Kasei has installed a 10 MW electrolysis system at the Fukushima Hydrogen Energy Research Field (FH2R) as part of a NEDO project. Trials are being performed since 2020 and based on the positive results achieved Asahi Kasei plans to commercialise large scale alkaline water electrolysis system with

[307] https://documents1.worldbank.org/curated/en/579061468915012649/pdf/multi0page.pdf
[308] https://www.asahi-kasei.com/news/2022/e221107.html

multiple 10 MW modules by 2025. Additional suppliers of ALK electrolyser include Nel Hydrogen (Norway), Asahi Kasei (Japan), Thyssenkrupp (Germany), Teledyne Energy Systems, Inc. (United States), McPhy (France), Suzhou Jingli (China), TianJin Mainland Hydrogen Equipment Co., Ltd. (China), Hydrogenics (Canada), MVS Engineering Pvt. Ltd. (India), Green Hydrogen.dk (Denmark), among others.

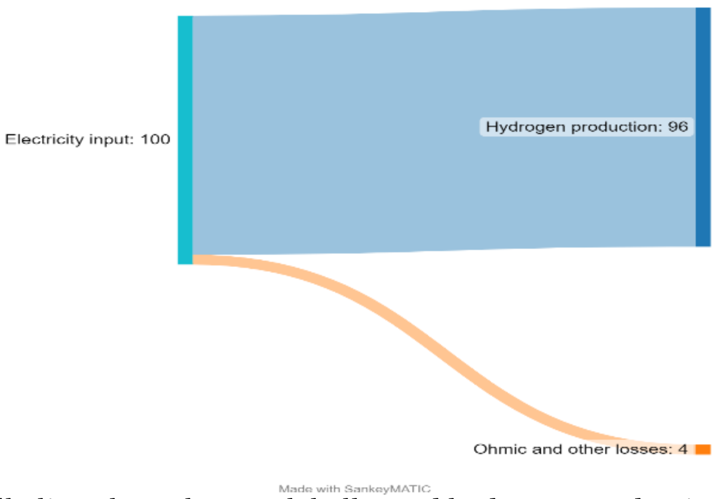
Figure 183: 10 MW alkaline water electrolysis system installed at Fukushima Hydrogen Energy Research Field (FH2R) (Source: FuelCellsWorks)

Technology Readiness Levels (TRL)

Alkaline electrolysers are a mature technology with a long history of use in the chlor-alkali industry. Thus, the TRL for an alkaline electrolyser is 9. Hence, this technology has the potential for full penetration till 2035.

Efficiencies

In the case of the iron and steel industry, hydrogen is used as a raw material and also as energy source. Hence, it makes more sense to evaluate the technology based on Faraday's efficiency rather than energy efficiency as Faraday's efficiency is a ratio of actual hydrogen production to the maximum possible theoretical hydrogen production. Faraday's alkaline electrolyser efficiency is more than 96%[309].



Compatibility with currently used technologies

There is a proven history of the application of alkaline electrolysers globally, and hydrogen production can also be done using this technology. Conventional method where methane, steam and air mixture are reacted in a converter, there is a requirement of new infrastructure with electrolysers powered by renewable electricity.

Foreseen cost development

[309] https://iarjset.com/wp-content/uploads/2021/09/IARJSET.2021.88118.pdf

The CAPEX requirement for ALK electrolysers ranges between USD 500 and 1400[310]/kW$_e$. The figure next showcases the approximation in cost reduction over a period of 30 years.

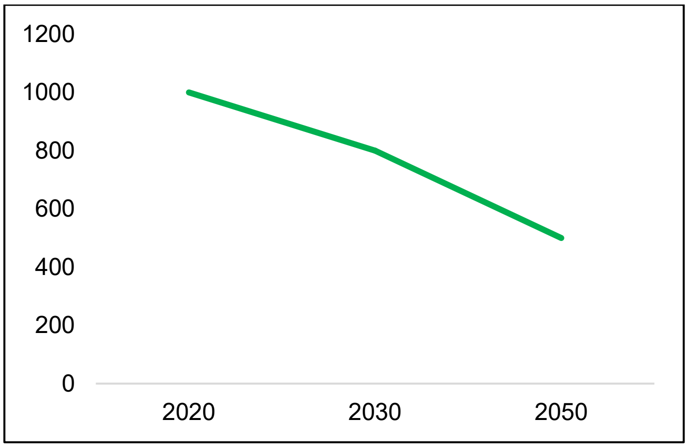


Figure 184: Approximation in CAPEX reduction for ALK electrolyser (Source: DNV 2022)

The cost of H_2 production is estimated to vary from $2.41/kg at present to $1.79/kg in future[311].

Polymer Electrolyte Membrane (PEM) electrolysers

The efficiency of PEM electrolysers is similar to alkaline electrolysers but with the advantage of starting up and powering down very rapidly (in seconds). This enables them to be coupled closely with intermittent renewable energy and respond to fast-changing electricity prices. Their drawbacks include shorter life expectancy and higher costs compared to alkaline electrolysers. This makes them less suitable for large systems, although PEM electrolysers on the 5-10MW scale are now being built. It is anticipated that in 10 years' time, PEM will be the cheapest and most efficient electrolyser technology.

Working Principle

Electrolysers are basically an anode and a cathode, which are separated by an electrolyte. In PEM electrolysers, a solid speciality plastic material is used as an electrolyte. At the anode, the water reacts to form oxygen, positively charged hydrogen ions and electrons. The hydrogen ions flow through the electrolyte towards the cathode, whereas the electrons flow through the external circuit as in PEM electrolysers, the electrodes are electrically insulated. At the cathode, the hydrogen ions and electrons from the external circuit combine to form hydrogen gas.

At anode: $2H_2O \longrightarrow O_2 + 4H^+ + 4e^-$

At cathode: $4H^+ + 4e^- \longrightarrow 2H_2$

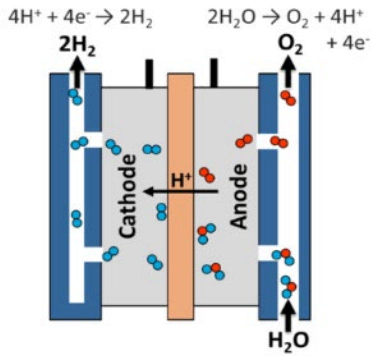


Figure 185: PEM Electrolyser

The several advantages offered by this almost gas-tight solid electrolyte include a physical divider between the anode and cathode, thereby preventing the mixing of generated gases, which helps it operate with a differential pressure. In addition, a high gas product purity is ensured in case of dynamic operation or more extended part-load operation.

[310] https://www.iea.org/reports/electrolysers
[311] https://www.hydrogen.energy.gov/pdfs/review22/p204_james_2022_p.pdf

Global Best Practice Examples

In 2021, Air Liquide inaugurated a PEM electrolyser in Quebec, Canada. This unit is 99% powered by renewable electricity from Hydro-Québec and can produce over 8.2 metric tonnes of low-carbon hydrogen per day. This low-carbon, high-purity hydrogen is supplied to the group's North American industrial and transport customers. This new hydrogen production unit at Air Liquide's Canada factory is estimated to reduce 27,000 metric tons of CO_2 emissions annually. Additionally, PEM electrolysers are manufactured by Siemens, NEL, GREEN Hydrogen, Hydrogenics, and Ohmium, which has recently announced the establishment ofa factory for electrolysers in India.

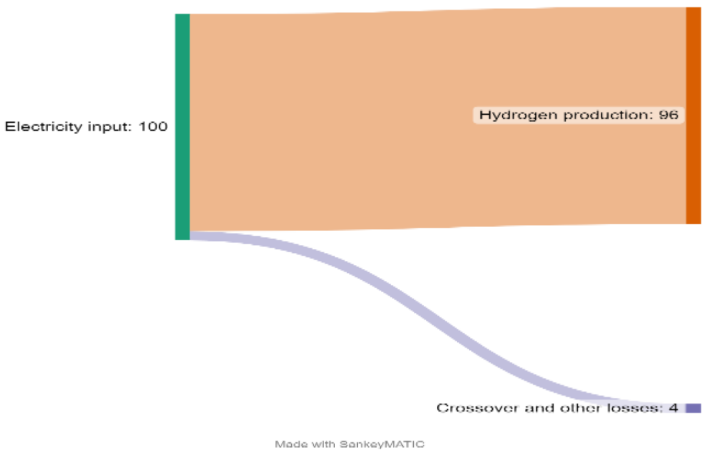
Figure 186: Air Liquide's PEM Electrolyser in Bécancour, Canada

Technology Readiness Levels (TRL)

The TRL for this technology is at 9 as there are commercial installations using Polymer Electrolyte Membrane technology for hydrogen production. Hence, this technology has the potential for complete penetration by 2035.

Efficiencies

The Faraday's Efficiency of PEM electrolyser is greater than 96%[312]. The figure next showcases the losses in the PEM electrolyser. The crossover losses occur when the hydrogen and oxygen gases produced at the cathode and anode, respectively permeate across the membrane, resulting in a mixture of both gases at electrodes.



[312] https://res.mdpi.com/d_attachment/energies/energies-13-04792/article_deploy/energies-13-04792-v2.pdf

Compatibility with currently used technologies

There is a proven history of application of PEM electrolyser globally and hydrogen production with this technology is more favourable than the previous electrolysis method. Conventional method where methane, steam and air mixture are reacted in a converter, there is a requirement for new infrastructure with electrolysers powered by renewable electricity.

Foreseen cost development

The CAPEX requirement for PEM electrolysers ranges between USD 1100 and 1800[313]/kW$_e$. The figure next showcases the approximated reduction in CAPEX cost of PEM electrolysers over a period of 30 years. These values are for a 1 MW reference system.

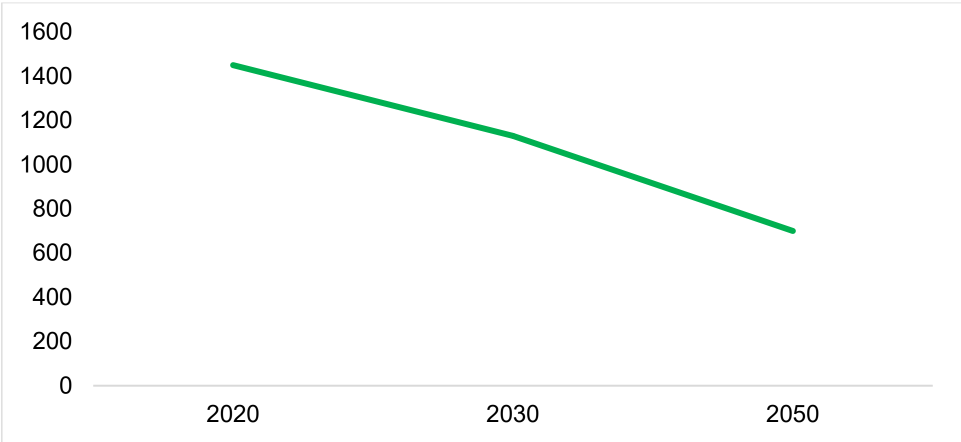


Figure 187: Approximation of cost reduction till 2050 (Source: DNV 2022)

The estimated cost of H_2 production through PEM electrolyser is ~$5 to $6/kg-$H_2$[314].

Solid Oxide Electrolysers

Electrolyze water (steam) at high temperatures (500°C to 800°C), which, in theory, enables an improvement in efficiency, although this technology is still in the development stage. If some challenges can be overcome, solid oxide electrolysers have the potential to become the dominant electrolyser technology in 10 years or more.

Working Principle

Solid oxide electrolysers use a solid ceramic material as an electrolyte. At the cathode, the steam reacts with electrons from the external circuit, forming hydrogen gas and negatively charged oxygen ions. The electrolyte at elevated temperature conducts negatively charged oxygen ions (O^{2-}) through it. At the anode, the oxygen ions react to form oxygen gas and electrons for the external circuit.

Cathode: $H_2O + 2\ e^- \rightarrow H_2 + O^{2-}$

Anode: $2\ O^{2-} \rightarrow O_2 + 4\ e^-$

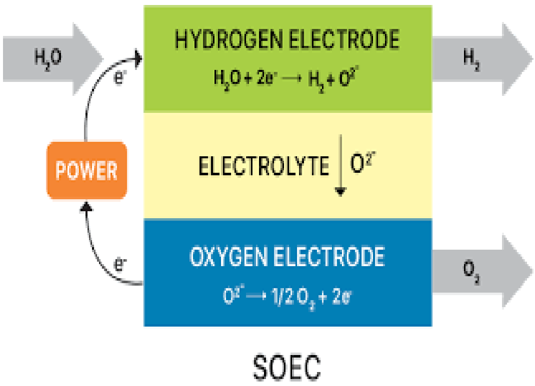


Figure 188: Solid Oxide Electrolyser Cell (Source: h2e Power)

[313] https://www.iea.org/reports/electrolysers
[314] https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf

Net Reaction: $2\ H_2O \rightarrow 2\ H_2 + O_2$

Global Best Practice Examples

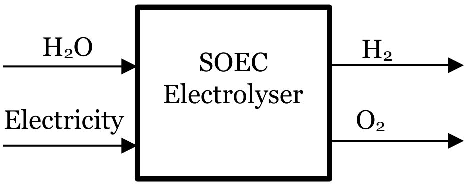
Sunfire has begun the installation of 12 electrolysis modules at Neste's renewable products refinery site in Rotterdam. The capacity of the electrolysis system is 2.6 MW, making it the world's first high-temperature electrolyser to produce green hydrogen. It operates at 850 °C and uses industrial waste heat, thereby reducing the demand for electricity. The electrolyser is expected to be commissioned in 2023 and will produce more than 60 kg of green hydrogen per hour.

Figure 189: Sunfire's SOEC Module "Generation 2" (225 kW) (Source: Sunfire GmbH)

Technology Readiness Level (TRL)[315]

SOEC electrolysis technology is under demonstration and is currently at TRL 7. This technology has the potential for full penetration by 2040.

Inputs – Outputs



[315] https://www.iea.org/reports/electrolysers

Compatibility with currently used technologies

As this is a new technique of hydrogen production the conventional method where methane, steam and air mixture are reacted in a converter, there is a requirement for new infrastructure with electrolysers powered by renewable electricity.

Foreseen cost development

The figure below showcases the variation of CAPEX per kW until 2030.

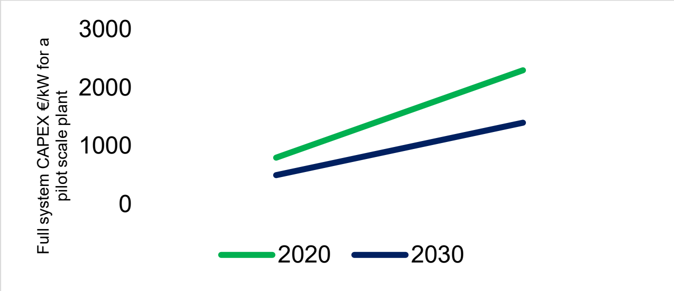


Figure 190: SOEC electrolyser CAPEX (Source[316]: Monitor Deloitte)

The projected hydrogen production costs in the near to longer term by using SOEC technology ranges from ~$2.80 to ~$5.80/kg H2 at high volume.[317]

Anion Exchange Membrane (AEM) Electrolysers

Working Principle

This type of electrolysis uses a semipermeable membrane that conducts hydroxide ions (OH^-) and is hence called an anion exchange membrane. A high-cost noble metal catalyst is not required in AEM electrolysis. Rather a low-cost transition metal catalyst can be used. Water travels through the membrane from the anode towards the cathode. At the cathode, a hydrogen evolution reaction takes place as water combines with electrons from the external circuit to produce hydrogen gas and negatively charged hydroxide ions. The hydrogen gas produced at the cathode is released via the gas diffusion layer. The OH^- ions move back through the membrane towards the anode. At the anode, an oxygen evolution reaction takes place as oxygen gas is produced from the OH^- ions and is released via the gas and liquid diffusion layer.

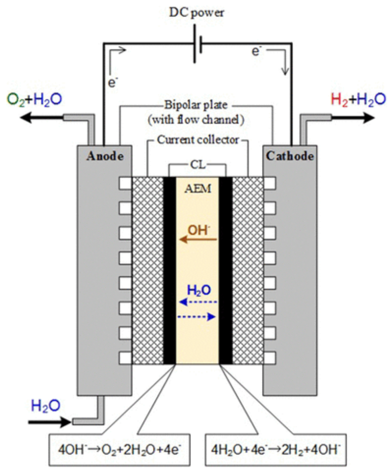


Figure 191: Anion Exchange Membrane Electrolyser

At cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
At anode: $2OH^- \rightarrow H_2O + 1/2\ O_2 + 2e^-$

Figure 188[318] showcases the details of the Anion Exchange Membrane electrolyser.

Global Best Practice Examples[319]

Oil India Limited (OIL) has commissioned India's first 99.999% pure green hydrogen pilot plant at its Jorhat Pump Station in Assam. The plant has an installed capacity of 100 kW and produces 10 kg of green hydrogen per day. It is powered by electricity generated through an existing 500 kW Solar

[316] https://www2.deloitte.com/content/dam/Deloitte/jp/Documents/global-business-support/jp-gbs-fueling-the-future-of-mobility-hydrogen-electrolyzers.pdf
[317] https://www.hydrogen.energy.gov/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf
[318] Ito, Hiroshi & Miyazaki, Naoki & Sugiyama, Shota & Ishida, Masayoshi & Nakamura, Yuka & Iwasaki, Shinya & Hasegawa, Yasuo & Nakano, A.. (2018). Investigations on electrode configurations for anion exchange membrane electrolysis. Journal of Applied Electrochemistry. 48. 10.1007/s10800-018-1159-5.
[319] https://economictimes.indiatimes.com/industry/renewables/oil-india-limited-commissions-indias-first-99-999-pure-green-hydrogen-pilot-plant/articleshow/90963593.cms

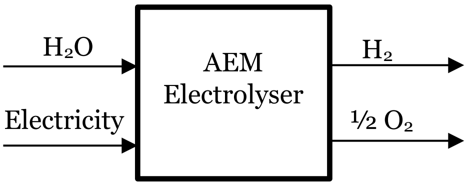
plant. The green hydrogen production capacity is expected to increase from the existing 10 kg per day to 30 kg per day in future.

Figure 192: Green Hydrogen Pilot Plant at Oil India Limited's Jorhat Station (Source: T&D India)

Technology Readiness Level (TRL)

The prototypes of AEM electrolysers are available at scale, and hence, the TRL for this technology is considered at 6 by IEA. Considering the TRL, this technology is projected to have a potential for full penetration by 2050.

Inputs – Outputs



Compatibility with currently used technologies

As this is a new technique of hydrogen production the conventional method where methane, steam and air mixture are reacted in a converter, there is a requirement for new infrastructure with electrolysers powered by renewable electricity.

Foreseen cost development

Figure 190[320] showcases the estimated cost reduction trend for hydrogen production through AEM electrolysis technology until 2035.

[320] https://www.hydrogen.energy.gov/pdfs/review22/p204_james_2022_p.pdf

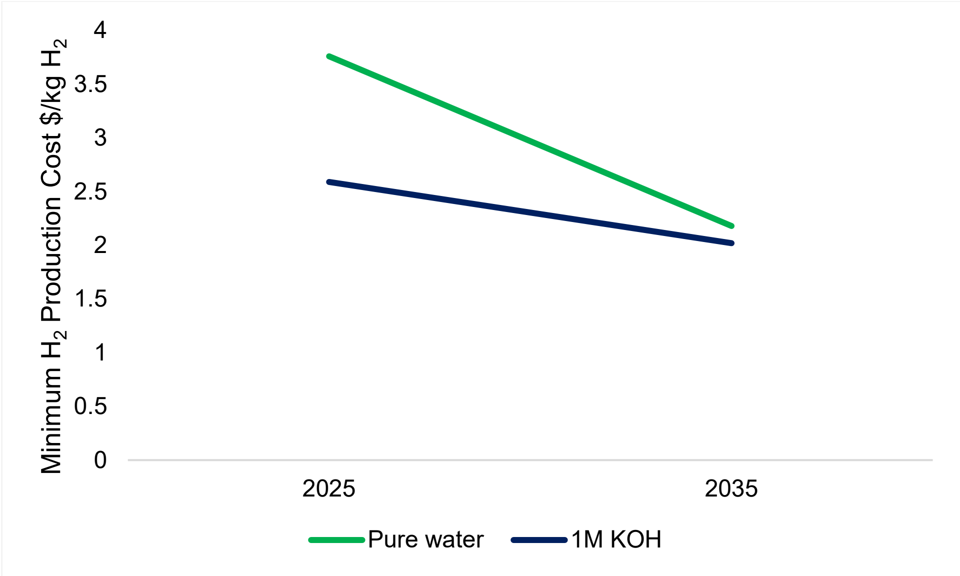
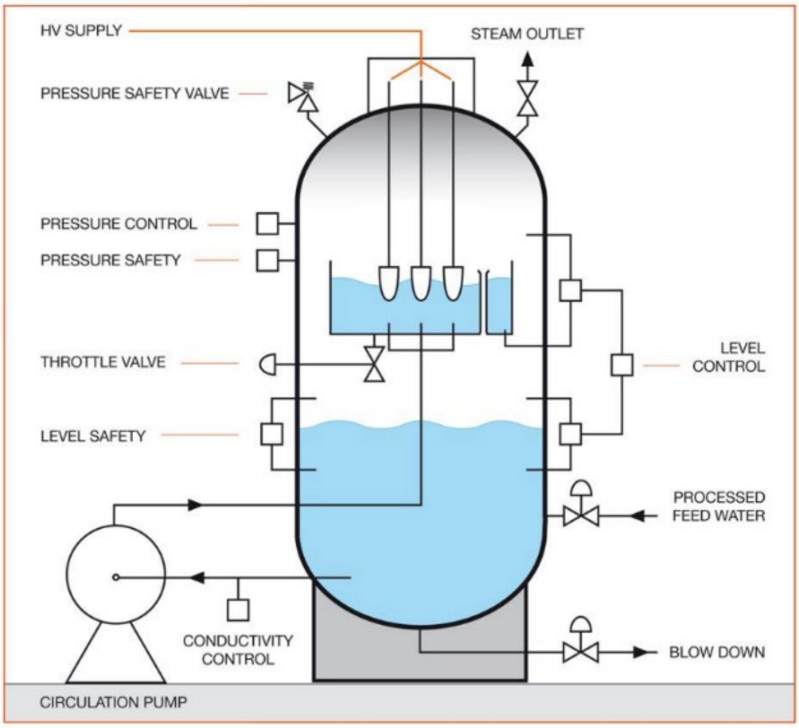


Figure 193: Hydrogen production cost in 2025 and 2030 (Source: DOE Hydrogen Program)

Electric Boiler (Electrode Type)

The most common types of electric boilers are electric resistance boilers and electrode boilers. In electric resistance boilers, an electric-powered resistive element transfers heat to the water, raising its temperature to the process level. In electrode boilers, the electric current passes directly through the water to boil the water. Electric resistance boilers possess lower thermal capacities, typically up to 5 MWe). On the other hand, electrode boilers have capacities ranging between 3 MWe and 70 MWe.



Steam is generated by circulating the boiler water through the upper chamber where the electrodes are suspended. Steam is produced in the upper chamber and released at the upper side of the boiler. The boiler regulates on constant pressure up to its maximum power setting. The output is controlled by a throttle valve that regulates the level in the upper boiler chamber. An important parameter related to the optimal function of the electrode boiler is the water conductivity. The conductivity is continuously monitored to ensure that the boiler gives the correct output. When the conductivity exceeds the programmed set point, automatic blow-down is initiated. When the boiler is in operation mode, the boiler can regulate from 4-100% in 1 minute.

Global Examples

In 2016, the first electrode boiler for grid regulation Volkswagen was delivered to their plant in the Czech Republic.

Technology Readiness Levels (TRL)

The technology readiness level (TRL) of industrial electric boilers is relatively high, with commercial products already available on the market. However, ongoing research and development are focused on improving their efficiency and reducing their environmental impact. Electrode boilers are commercially available, and technology providers like PARAT, Norway and Synlait, New Zealand, have successfully installed the boilers at different sites. The TRL forelectrode-type electric boilers is 9.

Efficiencies

Compared to highly efficient condensing boilers that typically fall within the range of 75% to 85% efficiency, electric boilers have an efficiency rate of around 99%. As a result, electric boilers waste minimal energy, ensuring that their performance is as fully optimized as possible[321]. Efficiencies of electrode-type boilers is in the range of 97-99%[322]

Compatibility with currently used technologies

One of the primary considerations when installing an electric boiler is the electrical infrastructure. Electric boilers require a significant amount of electrical power to operate, so the electrical infrastructure must be capable of supplying the necessary power. In some cases, upgrades or modifications may be required to the electrical infrastructure, such as the installation of a new transformer or the upgrading of power supply cables.

[321] https://www.greenmatch.co.uk/blog/electric-vs-gas-boiler
[322] https://www.parat.no/en/products/industry/parat-ieh-high-voltage-electrode-boiler/

Another consideration is the available space. Electric boilers tend to be larger than traditional boilers, so the installation site must have sufficient space to accommodate the boiler and any associated equipment, such as pumps or heat exchangers.

The specific requirements of the industrial processes must also be considered when considering the compatibility of electric boilers with existing setups. For example, some processes may require steam at high pressure or temperature, which may require a customized electric boiler design.

Despite these considerations, electric boilers are generally compatible with existing setups in the chemical industry. In many cases, they can be installed as a replacement for traditional boilers with minimal modifications to the existing infrastructure. Additionally, their compact size and flexible installation options make them suitable for a wide range of industrial applications, including those in the chemical industry.

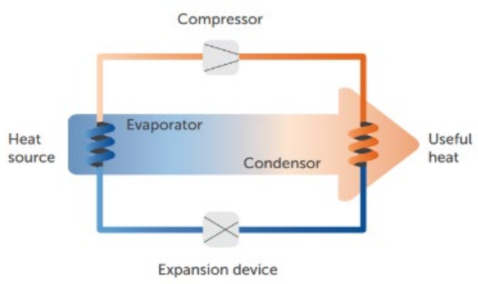
Cost Development

The CAPEX requirement of a 30 MW electrode boiler system at 34 barg system design is 875,000 USD., with the specific cost determined primarily by the boiler's size and the amount of steam needed per hour[323]. While electric boilers have a higher upfront cost than traditional boilers but require less maintenance, which can result in cost savings over time. The amount of fuel needed to produce 1 kg of steam depends on several factors, including the type of fuel being used, the efficiency of the boiler or generator, and the temperature and pressure of the steam. However, a rough estimate is that it takes about 100 grams of coal to produce 1 kg of steam, which is equal to INR 2 per kg of steam. Whereas in the case of an electric boiler, 0.722 kWh[324] of electricity is required to generate 1 kg of steam, which is equal to ~ INR 5 per kg of steam. In today's scenario, the operating cost of an electric boiler is higher than that of a conventional boiler, but in the longer run, as the non-fossil fuel cost will increase and there would be an advancement in the technology, electrode boiler would be more economical than a conventional boiler.

Heat Pump

An electric heat pump is a technology for producing hot air, hot water, or steam. It does this very efficiently by extracting thermal energy from a convenient source of heat. It is particularly useful for reusing heat wasted by many industrial processes.

Heat pumps take a low-temperature heat source and transfer its thermal energy to a higher-temperature heat output. Potential heat sources include the outside air or the ground or waste heat from industrial processes. Heat pumps create heat by compressing and expanding a refrigerant fluid. They exploit the property of the refrigerant to heat up when compressed (like in a bicycle pump) and cool when expanded (like an aerosol can). A heat pump moves a refrigerant between four key parts: compressor, condenser, expansion device and evaporator.



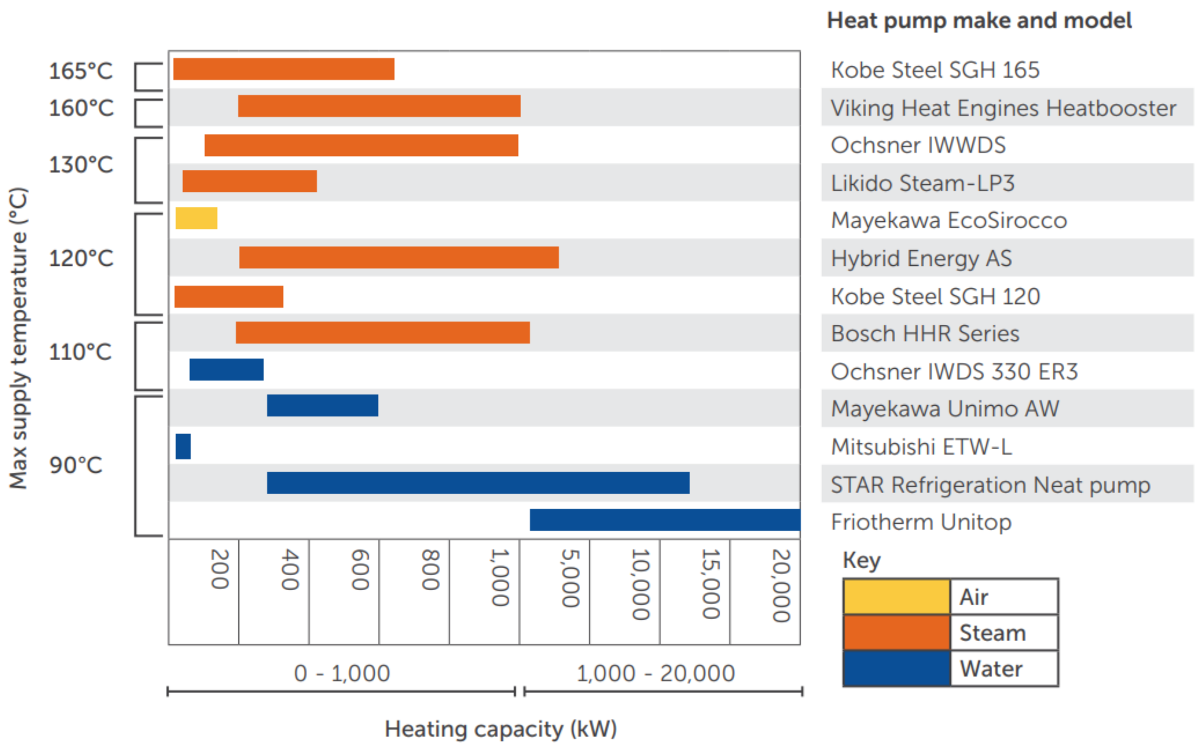
Compressor: compresses working fluid, causing temperature to increase (electrically powered).

Condenser: gas condensed to liquid - releasing heat

323 https://boilerexprot.com/industrial-electric-steam-boiler-cost.html
324 https://www.ebe-eng.com/pages/environment#:~:text=According%20to%20the%20ASME%20Steam,per%20tonne%20of%20steam%20generated.

Expansion device: reduces pressure of gas

Evaporator: low pressure refrigerant evaporated, absorbing heat from external source



Heat source: waste heat or external air, water, or ground

Mechanical vapour recompression (MVR) is a special type of heat pump that compresses the vapour form of the fluid being processed (usually water) rather than a refrigerant. Compressing the vapour makes it hotter. MVR systems usually compress water vapour at 70-80°C and deliver steam between 110°C and 150°C, in some cases up to 200°C. Their performance is particularly impressive, with a coefficient of performance (COPs) of 10 to 30.

Global Example

Smurfit Kappa, Netherlands, a company in the packaging paper industry, installed the Bronswerk Heat Transfer pump for a temperature requirement of 65 - 115°C. The heat pump recovers heat from moist air released from paper drying to produce steam at 115°C, which is used at different steps in the production process.

In 2022, BASF and MAN Energy Solutions joined forces to build an industrial-scale heat pump at the BASF site in Ludwigshafen, aimed at reducing greenhouse gas emissions while also reducing the site's natural gas consumption. The project aimed to use waste heat from the cooling water system at the BASF site as a source of thermal energy, and the residual heat will be processed using compression to produce steam. The project could reduce CO_2 emissions at the site by up to 390,000 metric tons per year and produce up to 150 metric tons of steam per hour. Once the heat pump is developed, the technology could be standardized and deployed at other sites.[325]

Technology Readiness Levels (TRL)

[325] https://www.chemeurope.com/en/news/1176746/basf-and-man-energy-solutions-enter-into-partnership-for-construction-of-one-of-the-worlds-largest-heat-pumps.html

Heat Pumps are commercially available, there are several technology providers across the globe. TRL is 9.

Industrial heat pump technology readiness by temperature range		
Temperature range	**TRL level**	**Application in Industrial process**
<80°C	TRL 9: Proof of market stability	Bio-reactions
80°C to 100°C	TRL 9: Commercial and competitive, but largescale deployment not yet achieved	Boiling
100°C to 140°C	TRL 8-9: First-of-a-kind commercial applications in a relevant environment	Concentration
140°C to 160°C	TRL 7-8: Pre-commercial demonstration	Distillation, Steam production
160°C to 200°C	TRL 6-7: Early to large prototype	High-temperature steam production
>200°C	TRL 6: Early prototype	High-temperature processes

Efficiencies

The coefficient of performance (COP) of a heat pump varies in the range of 4-5. Industrial heat pumps can exhibit high levels of efficiency, with a coefficient of performance (COP) exceeding three, when there is a temperature lift of around 30-50°C between the input and output temperatures. If the temperature lift is higher, the COP typically decreases, but it is possible to design a heat pump in a manner that mitigates this loss of efficiency by incorporating intermediate heat exchangers or cascaded cycles. In a cascaded cycle, the heat pump operates as two single-stage cycles interconnected via a cascade heat exchanger. However, these advanced heat pump systems usually entail higher costs.[326]

Heat pumps are 3 to 5 times more efficient than gas boilers. However, at temperatures above 200°C, direct electrification of industrial processes is generally preferable to overheating pumps at present.

Compatibility with currently used technologies

Installing a heat pump in an industrial process requires specialized planning, design, and installation, which can vary depending on the facility and industry. Industrial heat pumps are typically designed for specific processes and temperature configurations, which makes mass production difficult and increases design and manufacturing costs. Retrofitting existing processes with heat pumps can also be more complex and costly than installing them in new processes.

Cost Development

CAPEX of a heat pump having a heating capacity of 1.6 MW is USD 832,000[327] , whereas operating cost would be low because of its high COP, which has a payback of almost two years.

[326] https://iea.blob.core.windows.net/assets/4713780d-c0ae-4686-8c9b-29e782452695/TheFutureofHeatPumps.pdf

[327] *Zero Carbon Industry Plan: Electrifying Industry should be attributed to Beyond Zero Emissions.,* http://bze.org.au

The capital cost for installation of a heat pump is often quite less as compared to the operating costs.

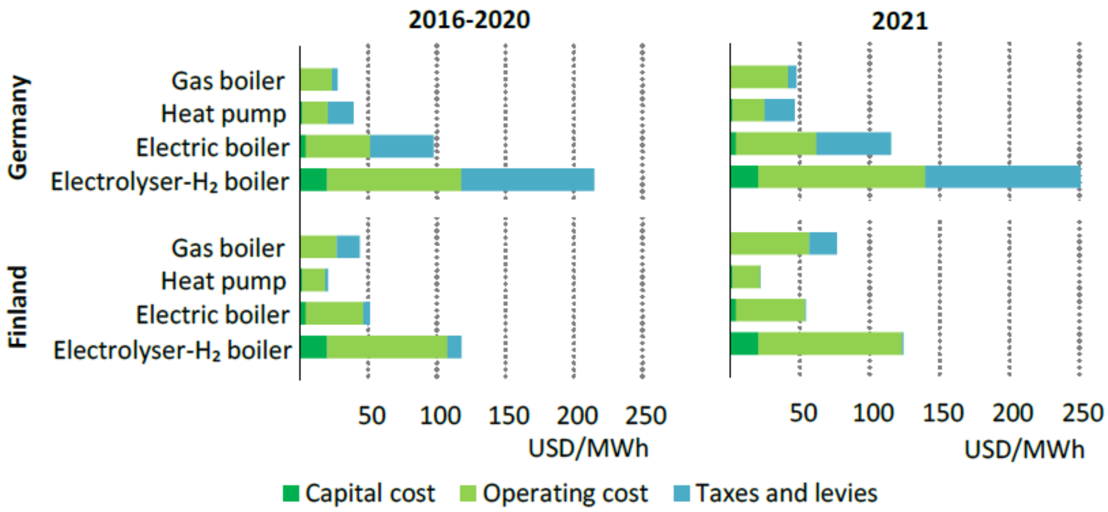


Figure 194 - Average levelized cost of production of industrial heat in Finland and Germany[328]

Cooperation with heat pump manufacturers can be beneficial in reducing costs and improving efficiency in the installation of industrial heat pumps. By establishing standard temperature settings for industrial heat pumps in specific processes and subsectors, such as inlet temperatures and temperature lift ranges, equipment manufacturing and installation can be streamlined.

CCUS

Carbon Capture, Usage and Storage (CCUS) is a technology that can capture and make effective use of the high concentrations of CO_2 emitted by industrial activities. Consequently, it has a key role to play in decarbonization and addressing the challenge of global climate change.

Technology Readiness Levels (TRL)

CCUS technologies for the aluminium industry are still in the early stages of development and deployment. While some pilot projects and demonstrations of CCUS in the aluminium industry have been carried out, the technology is not yet widely deployed on a commercial scale and can be assigned a low TL level of 3 to 4.

Energy Efficiency

Energy efficiency will depend on the type of technology used to capture carbon. For example, the all-electric carbon capture technology being developed by Verdox and Hydro is fully electric and highly energy-efficient, unlike many other carbon capture technologies that rely on thermal, pressure, or heating and cooling of liquid substances.

Compatibility with currently used technologies

CCUS technologies are generally compatible with existing infrastructure. However, some of these technologies would depend on the composition of the smelter off-gas.

[328] https://www.chemeurope.com/en/news/1176746/basf-and-man-energy-solutions-enter-into-partnership-for-construction-of-one-of-the-worlds-largest-heat-pumps.html

Foreseen cost development

It is difficult to predict the exact cost of the development of CCUS technologies for smelters as it is still under development. However, it can be estimated to be in the range of USD5-20 Mn. CCUS project cost is anticipated to range between USD75 and USD100[329] per tonne of CO2 captured by 2030.

Global adoption

In 2022, Norwegian aluminium company Hydro invested $20m in US company Verdox, which is commercializing an all-electric carbon capture technology that can capture CO_2 emissions both from industrial off-gas and directly from air. Verdox is a Massachusetts Institute of Technology spin-off. Hydro and Verdox have been collaborating since early 2021, and the technologies have been tested to assess their applicability to capturing the CO_2 in the off-gas of Hydro's primary aluminium smelter technology. Hydro's studies have shown that capturing CO_2 directly from the off-gas can eliminate most of the direct emissions from the aluminium smelting process[330].

Different methods of carbon capture are explained in the table presented below.

[329] https://www.rystadenergy.com/news/carbon-capture-capacity-poised-to-surge-more-than-10-times-by-2030-but-aggressive
[330] https://www.hydro.com/en/media/news/2022/hydro-invests-in-carbon-capture-company-verdox-to-eliminate-emissions-from-aluminium-production/

Technology	TRL	Year available (importance for net zero emissions)	Deployment status	Energy/Emission Reduction	Costs	Country
Carbon capture, utilisation and storage						
Chemical absorption (partial capture rates, <20%)	8	Today (Medium)	The commercial facility opened in 2014 at Capitol Aggregates plant in Texas, capturing 15% of emissions (75 ktCO_2/yr) for use in materials like baking soda, bleach and hydrochloric acid (Capitol Aggregates, 2020; Global Cement, 2014).	<20% of CO_2		USA
Chemical absorption (full capture rates)	7	2024 (Very high)	• Successful industrial-scale feasibility study in 2016 at the Norcem plant in Norway; operations of full-scale plant (0.4 MtCO_2/yr) expected in 2023/24 (Norcem, 2020). • An industrial-scale feasibility study is being conducted at the Lehigh Cement plant in Canada (0.6 MtCO_2/yr) (Lehigh Hanson, 2019; Voorhis, 2019). • Dalmia Cement will undertake a large-scale demonstration (0.5 MtCO_2/yr) at a plant in India (Perilli, 2019). • Anhui Conch pilot plant (50 ktCO_2/yr) began operation in 2018 in China (Global CCS Institute, 2018b).	The current cost of CCS for the cement industry worldwide: 100$/t$CO_2$		

Technology	TRL	Year available (importance for net zero emissions)	Deployment status	Energy/Emission Reduction	Costs	Country
Calcium looping	7	2025 (Very high)	• Testing at Heping Plant by Taiwan Cement since 2017, pilot-scale trials successfully completed; aiming for commercial scale (0.45 $MtCO_2/yr$) by 2025 (Taiwan Cement, 2020; Cemnet, 2019). • Pilot-scale demonstration completed by CEMCAP in Germany; pre-commercial retrofit demonstration (1.3 Mt cement/yr) in Italy by CLEANKER project expected to begin in 2020 (Buzzi Unicem, 2019; Hornberger, Sporal and Scheffknecht, 2017; Jordal, 2018).			Taiwan, Germany
Oxy-fuel	6	2030 (High)	• Successful pilot in kiln precalciner in Denmark (Davison, 2014). • The European Cement Research Association aims to develop oxy-fueling; however, its two proposed pilot plants appear to be on hold due to funding challenges (ECRA, 2020a). • A joint research initiative by four European cement producers, formed in late 2019, is planning to build a semi-industrial oxy-fuel test facility in Germany (Beumelburg, 2019).	<55-99% of CO_2 emissions (from calcination, not heating fuel)	The integration of this equipment more than doubles the amount of electricity required per tonne of clinker, raising the final cost of the production by 40%-50%.	Germany

Annexures

Methodology, assumptions and references for baseline projections

GDP Projection

GDP has been projected as per the table shown below. All assumptions and details are cross-verified from multiple sources like IMF World Economic Outlook 2021, NITI Aayog's IESS projection and other well-accepted international sources like data from the world bank, etc.

GDP		
Projection from 2022-2027		IMF World Economic Outlook 2021
Projection from 2027-2030	7.28%	NITI Aayog's IESS projection (High Growth)
Projection from 2030-2040	6.11%	NITI Aayog's IESS projection (Medium Growth)
Projection from 2040-2050	4.70%	NITI Aayog's IESS projection (Low Growth)
Projection from 2050-2070	2.60%	Average of developed nation's GDP trend
Contribution of Manufacturing industry in country's GDP	India's CAGR – (-) 0.60%; China's CAGR – (-) 0.80%; USA's CAGR – (-) 1.60%	https://data.worldbank.org/indicator/NV.IND.MANF.ZS?end=2021&locations=IN&start=2000
Share of agriculture sector GDP in total GDP for India, China and US	Growth in share of agriculture sector in total GDP for FY 2010 to FY 2021: India: (-)0.1% China: (-)2.06% US: (-)0.58%	World Bank https://data.worldbank.org/indicator/NV.IND.MANF.ZS?end=2021&locations=IN&start=2000

Methodology for Baseline Projections of the Transport Sector

Energy Consumption and Energy Mix

The sub-sector-wise methodology used for projecting the energy consumption of the transport sector under the baseline scenario is briefed below:

For the transport sector, we assessed and collated the data of different fuels used across **roadways, railways, shipping and aviation** subsector in India over the course of years. We sourced the data for the fuel used from the Ministry of Statistics and Programme Implementation (MOSPI) website, Government of India. The data sourced from this portal is used to establish a baseline and project the future energy requirements up till 2070.

In the case of roadways, the prominent fuels used by the roadways subsector are LPG, petrol, diesel and natural gas. For railways, the locomotives run primarily on electricity and diesel. The domestic shipping sector and the domestic aviation sector have their respective fuel, which have been mapped by the Ministry of Statistics and Programme Implementation on their data sheet.

Baseline Scenario Projections up to 2070

Firstly, a correlation factor between GDP and fuel consumption was obtained based on the respective values for the past few years. Based on this correlation factor, the fuel consumption for the different subsectors was projected up to FY 2070.

The baseline data garnered from the Indian Energy Statistics by MOSPI was used to project the fuel consumption up till 2070.

Data	Value		Source
Roadways			
Diesel	2662 Mn Tonne	35,138.81 ktoe	Indian Energy Statistics (2021), Ministry of Statistics and Programme Implementation, https://www.mospi.gov.in/ http://www.indiaenvironmentportal.org.in/ For establishing the baseline we referred to the Indian Energy Statistics published by MOSPI for the years (2014,2015,2016,2017,2018,2019,2020,2021)
Fuel Oil	121 Mn Tonne		
Petrol	29975 Mn Tonne		
LPG	173 Mn Tonne	10,010.88 ktoe	
Natural Gas	10833 Mn Tonne		
Railways			
Diesel	2539 Mn Tonne	2,625.84 ktoe	Indian Energy Statistics (2021), Ministry of Statistics and Programme Implementation, https://www.mospi.gov.in/ http://www.indiaenvironmentportal.org.in/ For establishing the baseline we referred to the Indian Energy Statistics published by MOSPI for the years (2014,2015,2016,2017,2018,2019,2020,2021)
Electricity	19577 Mn Tonne	1,683.62 ktoe	
Domestic Aviation			
HSD + LDO	3 Mn Tonne	8,524.06 ktoe	Indian Energy Statistics (2021), Ministry of Statistics and Programme Implementation, https://www.mospi.gov.in/ http://www.indiaenvironmentportal.org.in/ For establishing the baseline we referred to the Indian Energy Statistics published by MOSPI for the years (2014,2015,2016,2017,2018,2019,2020,2021)
Domestic Shipping			
Diesel	811 Mn Tonne	1,538.70 ktoe	Indian Energy Statistics (2021), Ministry of Statistics and Programme Implementation, https://www.mospi.gov.in/ http://www.indiaenvironmentportal.org.in/ For establishing the baseline we referred to the Indian Energy Statistics published by MOSPI for the years (2014,2015,2016,2017,2018,2019,2020,2021)
Fuel Oil	729 Mn Tonne		
Other Petroleum Products	7999 Mn Tonne		

Methodology for Baseline Projections of Industry Sector

The sub-sector baseline projections were predominantly based on the below-mentioned parameters,

Production Demand: historical production data was sourced from sectoral reports, publications, and statistics and from previous studies by BEE.

Specific Energy Consumption: For the purpose of this study, the SEC values for each sector were sourced from reports available in the public domain and from the previous study by BEE.

Fuel Mix Ratio: the fuel mix ratio for each sector was sourced from BEE's 'Impact of Energy Efficiency Measures' published in March 2021 and a previous study of BEE.

Parameters	**Value**	**Reference**
Iron & Steel		
Production (Mn tonne)	102.62	Page No. – 2 of PDF https://steel.gov.in/sites/default/files/An%20OVERVIEW%20OF%20STEEL%20SECTOR.pdf (Ministry of Steel, Annual Report)
Division of Production	BOF – 45% DRI – 25% EAF – 30%	Page No. – 69 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
SEC (toe/tonne)	BOF – 0.61 DRI – 0.65 Scrap - 0.13	Page No. – 209 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Energy Mix	**BF**: Coal – 94%; Oil – 1%; Electricity – 5% **DRI**: Coal – 84%; Gas – 14%; Electricity – 2%	Page No. – 71-72 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Cement		
Production (Mn tonne)	334.37	Page No. : 2 of https://ibm.gov.in/writereaddata/files/12102021174214Cement_2020.pdf Page No. : 93 of Annual Report (2021-22) by Ministry of Commerce and Industry https://dpiit.gov.in/sites/default/files/IPP_ANNUAL_REPORT_ENGLISH.pdf
SEC (toe/tonne)	0.083	Page No. – 205 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Energy Mix	Coal – 94.4%; Oil – 0.2%; Electricity – 3%; Biomass – 2.4%	Page No. – 45 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Aluminium		
Production (Mn tonne)	3.62	Page No. : 104 of Annual Report (2021-22) by Ministry of Mines https://mines.gov.in/writereaddata/UploadFile/Mines_AR_2021-22_English.pdf

Division of Production	Integrated – 70%; Refinery – 30%	Page No. – 36 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
SEC (toe/tonne)	Integrated – 5.12; Refinery – 0.49	Page No. – 204 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Energy Mix	**Integrated**: Coal – 96%; Oil – 4%; Electricity – 0.03% **Refinery**: Coal – 83%; Oil – 14%; Gas – 3%; Electricity – 0.1%	Page No. – 37 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Pulp & Paper		
Production (Mn tonne)	Wood: 3.9; Agro: 1.16; RCF: 16.29	Page No. : 4 of Annual Report (2021-22) by CPPRI https://cppri.res.in/sites/default/files/annual%20report%20%2820-21%29%20english.pdf https://cppri.res.in/sites/default/files/Annual%20Report_English.pdf
SEC (toe/tonne)	Wood: 0.87; Agro: 0.69; RCF: 0.48	Page No. – 210 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Energy Mix	Coal: 73%; Electricity: 14%; Biomass: 13%	Page No. – 83 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Textile		
Production (Mn tonne)	6.1	Page No. – 210 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
SEC (toe/tonne)	0.74	Page No. – 5 https://www.keralaenergy.gov.in/files/Resources/TEXTILE_Sector_Report_2018.pdf
Energy Mix	Coal – 56.72%; Oil – 0.9%; Gas – 2.6%; Electricity – 24.7%; Biomass – 15.08%	Page No. – 94 BEE Study - Assessment of Various Industrial Sectors of Economy to meet NDC Targets
Chemicals		
Production (Mn tonne)	11.94	Page No. : 4 of Annual Report (2021-22) by Ministry of Chemicals and Fertilisers https://chemicals.nic.in/sites/default/files/Annual%20Report%202022%20Date%2017-2-2022%20final%20LOW.pdf
Energy Intensity and Energy Mix	13.79	Page No. 78 of Energy Statistics 2021 http://www.indiaenvironmentportal.org.in/files/file/Energy%20Statistics%20India%202021.pdf

Bricks		
No. of Kiln	210,000	Page No. – 16 of https://beeindia.gov.in/sites/default/files/Brick%20Sector%20Market%20Transformation%20Blueprint_BEE%281%29.pdf
Coal Consumption	35 million tonne	Page No. – 16 of https://shaktifoundation.in/wp-content/uploads/2018/04/Roadmap-for-promoting-Resource-Efficient-Bricks-in-India-Summary-report.pdf
Glass		
Production (Mn tonne)	2.67	Page No. 32 of https://www.mospi.gov.in/documents/213904//2103804//1662467927520_Summary%20Results%20for%20Factory%20Sector%202019-20.pdf//6d5745c6-91c0-7635-94bb-8f94df422ec2
SEC	0.21	Page No. – 14 of https://www.teriin.org/sites/default/files/2018-02/Glass%20Report.pdf
MSME		
Energy Consumption	53.7	https://beeindia.gov.in/sites/default/files/BEE_Final%20Report_Website%20version.pdf Energy consumption in the above report for MSME is 70 Mtoe including bricks and glass. So, we have subtracted the energy consumption of bricks and glass sector from 70 Mtoe.
Food processing		
Milk production	198.44 Mn tonne	https://rbidocs.rbi.org.in/rdocs/Publications/PDFs/84T_2411215E8C65E7989F4D0195139AF1976518B1.PDF
Milk processing	35%	Slide no 8 - https://www.basu.org.in/wp-content/uploads/2020/06/CHARACTERISTICS-OF-INDIAN-DAIRY-PROCESSING-AND-EXPORT-INDUSTRY.pptx
Dairy SEC and energy mix	SEC - 15.7 kWh/ton + 0.12 GJ/ton; 66% oil, 21% electricity, 13% biomass	SEC - Page 17, Energy mix - Page 16 http://www.sameeeksha.org/pdf/dpr/Gujarat_Dairy.pdf
F&V Production	290.85 Mn tonne	Fruits - https://rbidocs.rbi.org.in/rdocs/Publications/PDFs/67T_24112112F8F6D9AA9C44FEA2D5C84D2B5D97FA.PDF Vegetables -

		https://rbidocs.rbi.org.in/rdocs/Publications/PDFs/74T_191120220F65B038F47041C5A4B4E4CD52F08F7A.PDF
F&V Processing	2%	Page 3 https://www.mofpi.gov.in/sites/default/files/OpportunitiesinFruits%26VegetablesSectorinIndia.pdf
F&V SEC	0.011 toe/tonne	Assumption
Fish production	14.16 million tons	Landing page https://www.indiabudget.gov.in/economicsurvey/ebook_es2021/files/basic-html/page616.html#:~:text=The%20fish%20production%20in%20India,46%2C662%20crores%20during%202019%2D20.
Fish processing	26%	Page 16 https://www.grantthornton.in/globalassets/1.-member-firms/india/assets/pdfs/grant_thornton-cii-food_and_beverage_sector-the_new_wave.pdf
Fish SEC and energy mix	SEC - 1,100 kWh/tonne Energy mix - 3% coal, 97% electricity	Energy mix - Page 8, SEC - Page 7 http://www.sameeeksha.org/pdf/clusterprofile/Veraval-Seafood-Processing-Gujarat.pdf
Meat production	8.599 Mn tonnes	https://rbidocs.rbi.org.in/rdocs/Publications/PDFs/83T_241121A898C708E097425EBEEDB5CFC63B04C7.PDF
Meat processing	21%	Page 2 https://face-cii.in/wp-content/uploads/2021/09/Food-Processing-Report-2019.pdf
Meat SEC	0.1 toe/tonne	Landing page https://www.maximpact.com/energy-efficiency-meat/
Meat energy mix	66% coal, 34% electricity	https://www.researchgate.net/figure/1-Example-breakdown-of-energy-use-at-a-typical-meat-plant-continued_tbl15_37621627
Biscuit production	0.632 Mn tonne	https://www.statista.com/statistics/762057/india-biscuits-and-cookies-production-volume/
Biscuit SEC	0.523 toe/tonne	Page 4 https://www.academia.edu/57675540/Energy_Consumption_Pattern_of_Value_Added_Products_of_Pearl_Millet
Biscuit energy mix	Gas - 50%, electricity - 50%	Assumption
Poultry processing	6%	Page 16 https://www.grantthornton.in/globalassets/1.-member-firms/india/assets/pdfs/grant_thornton-cii-

		food_and_beverage_sector-the_new_wave.pdf
Egg SEC	0.0081 kWh/kg	Below Figure 7 https://www.mdpi.com/2076-3417/10/4/1352
Egg fuel mix	71% oil, 29% electricity	Page 111 https://www.researchgate.net/publication/259008695_Relation_between_energy_inputs_and_yield_of_broiler_production_in_Guilan_province_of_Iran/link/00b4952bb215b05688000000/download
Rice production	117.9 Mn tonne	https://pib.gov.in/PressReleseDetailm.aspx?PRID=1624044#:~:text=Total%20production%20of%20Rice%20during,at%20record%20107.18%20million%20tonnes.
Rice processing	90%	Assumption
Rice SEC and energy mix	SEC - 0.062 toe/tonne Energy mix - 10% electricity, 90% biomass	Energy mix - Page 7; SEC - Page 6 http://www.sameeeksha.org/pdf/clusterprofile/Karnal-Rice-Mill.pdf
Cattle feed production	7.5 million tonnes	https://indiadairy.com/expert-article/cattle-feed-industry-on-fast-track/
Cattle feed SEC	0.005 toe/tonne	https://sidhiee.beeindia.gov.in/pdf/audit-report/Gujarat/2.pdf
Cattle feed energy mix	60% coal, 40% electricity	https://sidhiee.beeindia.gov.in/pdf/audit-report/Gujarat/2.pdf
Pulses production	33.88 Mn tonnes	https://pib.gov.in/PressReleasePage.aspx?PRID=1798835
Dal SEC	0.004 toe/tonne	Estimated from production details on page 1 and energy consumption details on page 5 http://www.sameeeksha.org/pdf/clusterprofile/Indore-Dal-Mill-Cluster.pdf
Dal energy mix	45% electricity, 55% biomass	Page 6 http://www.sameeeksha.org/pdf/clusterprofile/Indore-Dal-Mill-Cluster.pdf
Sugar production	27.41 Mn tonnes	https://www.chinimandi.com/statistics/statewise-sugar-production-in-india/
Sugar SEC and energy mix	SEC - 0.038 toe/tonne Energy mix - 98.8% biomass, 1% electricity, 0.2% oil	Energy mix - Page 6 http://www.sameeeksha.org/pdf/clusterprofile/Gokak-jaggery-cluster.pdf
Spices production	10.14 Million Tonne	https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1810624
Spices SEC and energy mix	48% electricity, 52% biomass	SEC - Page 11, Energy mix - Page 6 https://www.researchgate.net/publication/353769813_Analysis_of_Energy_Use_and_Energy_Savings_A_Case_Study_of_a_Condiment_Industry_in_India/link/61114ece1ca20f6f860bc87a/download
Oilseeds production	33.22 Mn tonnes	https://pib.gov.in/PressReleasePage.aspx?PRID=1798835

Oilseed processing	90%	Assumption
Oilseed SEC and energy mix	Fuel mix - 100% electricity; SEC - 0.011 toe/tonne	SEC - Page 20, Fuel mix - Page 19 http://www.sameeeksha.org/pdf/dpr/Alwar_Oil%20Mill.pdf
Beverage production	26 Bn litres	Slide 8 https://icrier.org/pdf/ICRIER-IBA_Report_Release_May_27_2022.pdf
Beverage SEC	0.00002 toe/litre	Based on past projects
Beverage energy mix	47% oil, 53% electricity	Page 19 https://shaktifoundation.in/wp-content/uploads/2017/06/widening-of-pat-sectors-beverage.pdf
Cold Storage		
Capacity	37.42 Mn Metric tonnes	https://pib.gov.in/PressReleasePage.aspx?PRID=1658114
Conversion factor	3.4 m3/t	https://www.coolingindia.in/powering-cold-storage-plants/
SEC	35 kWh/m3/year	Page 41, Fig 4.4 http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf
Energy mix	87% electricity, 13% diesel	Page 39 http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf

Energy Consumption and Energy Mix

The sub-sector-wise methodology used for projecting the energy consumption of the industrial sector under the baseline scenario is briefed below:

Industry: Industry comprises various sectors, including iron & steel, cement, fertilizer, chemicals, textiles, and food processing, etc. For the above-mentioned sectors, the annual energy consumption and energy mix are arrived from the annual production, SEC and energy mix numbers mentioned in the table below.

Cold Storage: In the case of cold storage, the total capacity and average SEC value were used for estimating the total energy consumption.

Baseline Scenario Projections up to 2070

Industries

The industrial sectors are further sub-categorized into iron & steel, cement, aluminium, fertilizer, textile, paper & pulp, bricks, glass, MSMEs, and food processing. Other than MSMEs, energy demand projections for all the sectors are derived based on the correlation between the GDP manufacturing growth rate projection and the past trend of annual production of each sector. Historical trends of the share of the manufacturing sector in the country's total GDP were considered for projecting the manufacturing sector's GDP values till FY 2070. For FY 2020 to FY 2030, India's historic trend was considered. For FY 2030 to FY 2050, China's historic trend was considered and for FY 2050 to FY 2070, considering India as a developed economy by then, the US's trend was considered. Further, the SEC and energy mix values as of today were used for arriving at the energy consumption and energy mix, respectively, up to 2070.

In the MSME sector, due to the limited availability of the data, we have projected the energy demand growth based on the compounded annual growth rate of the manufacturing GDP directly linked with the energy consumption of MSME.

Methodology for Baseline Projections of Building & Appliances Sector

Energy Consumption and Energy Mix

The sub-sector-wise methodology used for projecting the energy consumption of the agriculture sector under the baseline scenario is briefed below:

Building and appliances energy projection is based on the correlation of past energy consumption and the growth in the sector. References for the data point are mentioned in the table presented below. Whereas, for cooking, correlation is based on the assumption that by 2070, all types of cookstoves will be converted to induction-based cookstoves.

Parameters	Value	Reference
Energy consumption /share	**Residential** **27 Mtoe/y** **Commercial** **9 Mtoe/y** **Cooking** **95 Mtoe/y** **Usage/Year** — **% Share** Residential Heating & Cooling — 31% Commercial Heating & Cooling — 20% Commercial Lighting & Appliances — 6% Residential Lighting & Appliances — 44%	https://mospi.gov.in/documents/213904/1606151/Energy%20Statistics%20India%20202216 44825594802.pdf/aed59aac-4d5a-995b-1232-bb68397cd873 http://www.indiaenvironmentportal.org.in/files/file/Energy%20Statistics%20India%202021.pdf (Page no.78) https://beeindia.gov.in/sites/default/files/Elements%20of%20Electrification%20Strategy%20for%20India.pdf (Page no. 19) https://www.ceew.in/sites/default/files/CEEW-Roadmap-for-Access-to-Clean-Cooking-Energy-in-India-Report-31Oct19-min.pdf (Page no. 26) http://iess2047.gov.in (Explore: sector-wise drilldown)

<table>
<tr>
<td>Number of households (million)</td>
<td>
<table>
<tr><td>Rural</td><td>180 Mn</td></tr>
<tr><td>Urban</td><td>96 Mn</td></tr>
<tr><td>Total</td><td>276 Mn</td></tr>
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<td>https://shaktifoundation.in/wp-content/uploads/2020/10/Residential-EDM-White-Paper.pdf (Page no. 13), Estimated using CAGR for 2019</td>
</tr>
<tr>
<td>Cooking fuel by source</td>
<td>
<table>
<tr><th>Source</th><th>Urban</th><th>Rural</th><th>Total</th></tr>
<tr><td>Electricity</td><td>0.9%</td><td>0.5%</td><td>0.6%</td></tr>
<tr><td>LPG/Natural Gas</td><td>88.6%</td><td>42.3%</td><td>57.7%</td></tr>
<tr><td>Biogas</td><td>0.2%</td><td>0.4%</td><td>0.3%</td></tr>
<tr><td>Kerosene</td><td>0.5%</td><td>0.4%</td><td>0.4%</td></tr>
<tr><td>Coal/Lignite</td><td>0.7%</td><td>0.8%</td><td>0.8%</td></tr>
<tr><td>Charcoal</td><td>0.3%</td><td>1.0%</td><td>0.8%</td></tr>
<tr><td>Wood</td><td>7.5%</td><td>43.7%</td><td>31.7%</td></tr>
<tr><td>Straw/Shrubs/Grass</td><td>0.2%</td><td>2.0%</td><td>1.4%</td></tr>
<tr><td>Agri Crop Waste</td><td>0.2%</td><td>2.9%</td><td>2.0%</td></tr>
<tr><td>Dung Cakes</td><td>0.6%</td><td>5.7%</td><td>4.0%</td></tr>
<tr><td>Other</td><td>0.4%</td><td>0.3%</td><td>0.4%</td></tr>
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<td>https://dhsprogram.com/pubs/pdf/FR375/FR375.pdf (Page no. 40)</td>
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<tr>
<td>Household appliances</td>
<td>
<table>
<tr><th>Appliance(s)</th><th>Urban</th><th>Rural</th><th>Total</th></tr>
<tr><td>Fan</td><td>96.4%</td><td>84.3%</td><td>88.3%</td></tr>
<tr><td>TV</td><td>86.8%</td><td>58.4%</td><td>67.8%</td></tr>
<tr><td>Refrigerator</td><td>63.4%</td><td>25.2%</td><td>37.9%</td></tr>
<tr><td>Washing Machine</td><td>36.1%</td><td>9.0%</td><td>18.0%</td></tr>
<tr><td>Water Pump</td><td>22.3%</td><td>17.3%</td><td>19.0%</td></tr>
<tr><td>Lighting</td><td>99.0%</td><td>95.3%</td><td>96.5%</td></tr>
<tr><td>Water Heater</td><td>3.0%</td><td>12.0%</td><td>3.0%</td></tr>
<tr><td>Cooler</td><td></td><td></td><td>12.0%</td></tr>
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<td>https://dhsprogram.com/pubs/pdf/FR375/FR375.pdf (Page no. 47)

https://www.ceew.in/sites/default/files/CEEW-IRES-Awareness-and-adoption-of-EE-in-Indian-homes-07Oct20.pdf (Page no. 4)</td>
</tr>
<tr>
<td>Space cooling</td>
<td>
<table>
<tr><td>Installed capacity (million TR)</td><td>90</td></tr>
<tr><td>Room AC</td><td>83%</td></tr>
<tr><td>Chiller System</td><td>8%</td></tr>
<tr><td>VRF System</td><td>4%</td></tr>
<tr><td>Packaged Units</td><td>6%</td></tr>
</table>
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<td>http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf (Section 3, Page no. 28). Estimated using CAGR for 2019</td>
</tr>
</table>

Methodology for Baseline Projections of the Agriculture Sector

Energy Consumption and Energy Mix

The sub-sector-wise methodology used for projecting the energy consumption of the agriculture sector under the baseline scenario is briefed below:

Agriculture Machinery:

In the case of pumps, the total number of pumps was first segregated based on capacity and fuel used (grid electricity, solar electricity, diesel). Further considering parameters such as capacity-wise and fuel-wise number of pumps, average annual running hours, capacity-wise SEC and capacity utilisation factor (0.75 considered), the total energy consumption was estimated.

In the case of tractors, the historical trend for fuel consumption was considered for projecting the fuel consumption till FY 2070.

In the case of harvesters, the number of machines, annual average running hours and SEC value were used for estimating the energy consumption.

Baseline Scenario Projections up to 2070

Firstly, a correlation factor between GDP and production was obtained based on the respective values for the past few years. Based on this correlation factor, the number of agriculture machinery was projected up to FY 2070. Further, the SEC and energy mix values as of today were used for arriving at the energy consumption and energy mix, respectively, up to 2070.

In the case of tractors, the historical trend of the share of the agriculture sector in the country's total GDP was considered for projecting the agriculture sector's GDP values till FY 2070. For FY 2020 to FY 2030, India's historic trend was considered. For FY 2030 to FY 2050, China's historic trend was considered and for FY 2050 to FY 2070, considering India as a developed economy by then, the US's trend was considered. A correlation between the agriculture sector GDP and fuel consumption by tractors was determined for projecting the fuel consumption by tractors till FY 2070 in the baseline scenario.

Data	*Value*	*Source link*
Pumps		
No of grid-connected and diesel-powered pumps	Grid-connected - 20.3 Mn Diesel powered - 8.8 Mn	https://www.iea.org/data-and-statistics/charts/estimated-stock-of-agricultural-irrigation-pumps-in-india-2010-2022
No of solar powered pumps	0.8 Mn	http://164.100.24.220/loksabhaquestions/annex/179/AS275.pdf
Energy use by grid-connected pumps	187 billion kWh/year	http://agdsm.in/
Pump capacity	1HP - 3%, 3HP - 19%, 5HP - 36%, 7.5HP - 24%, 10HP - 11%, 15HP - 6%	https://loksabhaph.nic.in/Questions/QResult15.aspx?qref=41907&lsno=17#:~:text=2022%2C%20a%20total%20solar%20capacity,of%20the%20PM%2DKUSUM%20Scheme.
No of days of pump operation	140 days/year	Page 11 https://www.ceew.in/sites/default/files/CEEW-

Data	*Value*	*Source link*
		Solar-for-Irrigation-Deployment-Report-17Jan18_0.pdf
No of hours of pump operation	6 hours/day	Page 24 https://pmkusum.mnre.gov.in/pdf/Solar%20Irrigation%20Pump%20(SIP)%20Sizing%20Tool%20User%20Manual%20-%20Beta%20Version.pdf
Diesel usage	1HP - 0.2lit/hr, 3HP - 0.7 lit/hr, 5HP - 1.1 lit/hr, 7.5HP - 1.6 lit/hr, 10HP - 2.2 lit/hr, 15HP - 3.3 lit/hr	Based on consultation with a vendor
Tractors		
Fuel consumption		https://www.statista.com/statistics/1051869/india-consumption-volume-of-diesel-in-agriculture/
Share of agriculture sector GDP in total GDP for India, China and US	Growth in the share of agriculture sector in total GDP for FY 2010 to FY 2021: India: (-)0.1% China: (-)2.06% US: (-)0.58%	World Bank
Harvesters		
Number of harvesters	50000 no's	Page 2 https://agritech.tnau.ac.in/banking/nabard_pdf/Farm%20mechanization/2.Model_scheme_on_combine_harvester.pdf
Fuel consumption	6 litre/hour	Page 3 https://agritech.tnau.ac.in/banking/nabard_pdf/Farm%20mechanization/2.Model_scheme_on_combine_harvester.pdf
Annual usage hours	500 hours	https://indianexpress.com/article/india/india-news-india/farm-mechanisation-migrant-machines-2981908/