Draft Report (Task 1 & 2)

Study on the commercial potential and synergies for Agrivoltaics + Green Hydrogen production in India

Version 3.0

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1 Introduction

India's quest for sustainable development has placed Green Hydrogen and Agrivoltaics systems at the forefront of its energy transition strategy. Green Hydrogen, produced through renewable energy-powered electrolysis, offers a zero-emission alternative to conventional fuels, while Agrivoltaics systems enable dual land use by combining solar energy generation with agriculture. Together, these technologies hold transformative potential for addressing climate challenges while enhancing energy security and boosting rural livelihoods.

1.1 Overview of Indian Agrivoltaics Sector

India's unique geographic and socio-economic characteristics position it as a promising leader in Agrivoltaics. As a country situated within the equatorial sunbelt, India receives an estimated solar energy potential of 5,000 trillion kWh annually, ranking it among the highest globally. Simultaneously, agriculture is the backbone of the Indian economy, occupying nearly 60% of its land area.

The Indian government has embraced Agrivoltaics as a potential solution to mitigate the growing challenge of land scarcity, which intensifies the food-energy nexus. Agrivoltaics systems allow for simultaneous farming and solar energy generation on the same land, addressing land-use conflicts. By reducing water evaporation and creating cooler microclimates for crops, these systems also improve agricultural productivity and solar panel efficiency, making them particularly suited for a resource-constrained yet sun-rich country like India.

Potential of Agrivoltaics Systems:

With abundant solar radiation and significant agricultural land, India is well-positioned to leverage Agrivoltaics systems to generate electricity for hydrogen production while supporting dual land use for farming.

India aims to achieve 450 GW of non-hydro renewable energy capacity by 2030[1], driven by a strong regulatory framework, financial de-risking, increased natural gas use, battery adoption for EVs, biofuels like ethanol and biodiesel, and industrial decarbonization through technologies like carbon capture and hydrogen production.

By 2040, under the IEA's IVC scenario, India targets 783 GW of solar PV capacity. In a moderate scenario, New Innovative Solar Applications (NISA) like Agrivoltaics, Floating PV, and others contribute 10% (78 GW), with the rest divided between ground-mounted and rooftop solar. In an optimistic scenario, NISA's share grows to 30% (235 GW), with Agrivoltaics playing a key role due to its dual-use approach, supporting both energy and agriculture.

Agrivoltaics capacity is projected to grow from 0.97 GW by 2030 to 14.11 GW by 2040 in the optimistic scenario, making up 27.5% of the NISA mix (52.2 GW). This highlights its potential as a sustainable energy solution that enhances land use and agricultural productivity. Annual capacity estimates for Agrivoltaics are shown in the following figure[2].

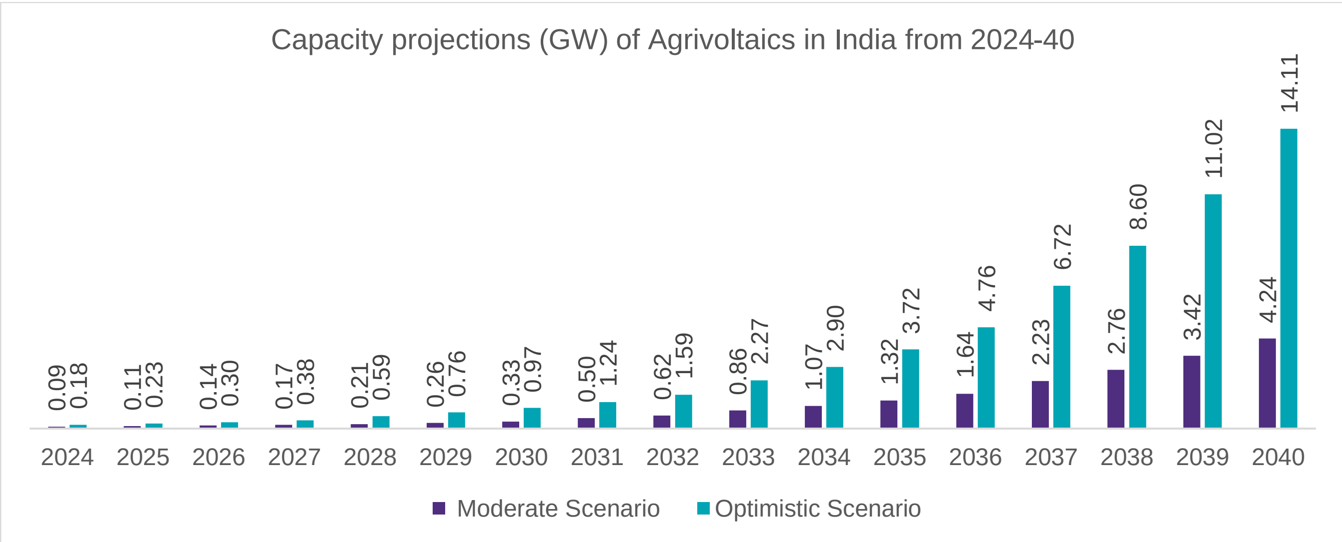

Figure 1: Capacity Projections of Agrivoltaics in India (GW)[3]

[1] https://pib.gov.in/Pressreleaseshare.aspx?PRID=1762960
[2] https://beta.cstep.in/staaidev/assets/manual/APV.pdf
[3] https://beta.cstep.in/staaidev/assets/manual/APV.pdf

The State-wise Technical Potential of Agrivoltaics Systems in India highlights the immense scope for integrating solar PV with agriculture across diverse regions. States like Rajasthan, Gujarat, and Madhya Pradesh lead in potential due to the abundant solar irradiance and vast agricultural land available. The chart below provides a comparative analysis of technical capacities, emphasizing regional adaptability for various crop patterns and solar installations. This data is crucial for strategizing Agrivoltaics adoption and scaling renewable energy adoption in India.

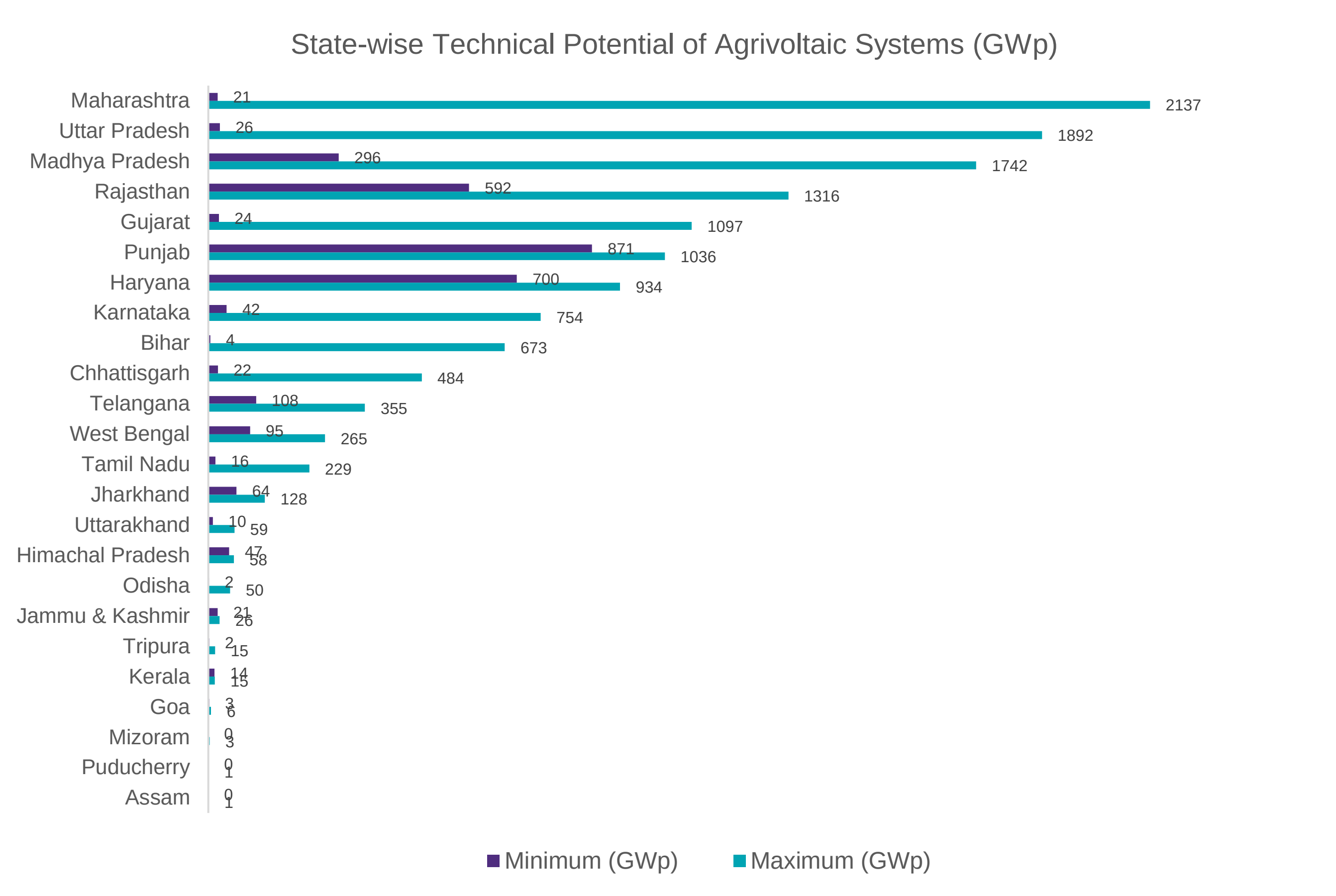

Figure 2: State-wise potential of Agrivoltaics[4]

As per the report from National Institute of Solar Energy (NSEFI) published on July 2023, agrivoltaics they have identified cumulative capacity of 14.3 MW of agrivoltaics project installed in India in various regions having both Agricultural and Solar PV generation benefiting dual use of land. There are upcoming projects which were in execution stage having total capacity of 4 MW of agrivoltaics capacity in India.[5]

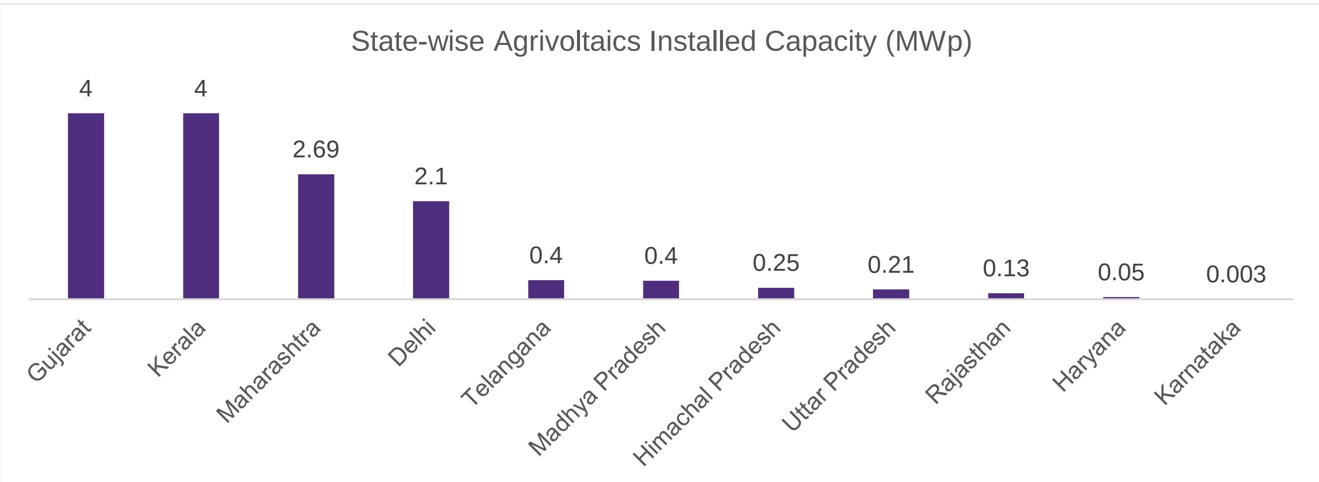

Figure 3: State-wise Agrivoltaics Installed Capacity (MWp)

[4] https://beta.cstep.in/staaidev/assets/manual/APV.pdf
[5] Agrivoltaics in India – NSEFI report 2023 https://www.nsefi.in/reports/#myReport

State wise summary of the installed agrivoltaics projects in the report are depicted in the figure above in which Gujarat, Kerala, Maharashtra, and Delhi having the highest installed agrivoltaics projects operational currently.

1.2 Overview of India's Green Hydrogen (GH2) Sector

Global hydrogen demand continued to grow in 2023 to reach a new high of more than ~97 MTPA[6], India constituted ~9% of the total global demand in 2023 consuming in the range of 8 to 9 MTPA of Hydrogen, constituting an indirect consumption of 2.1 MTPA through imported fertilisers, ammonia, and methanol, due to larger demand in refining and the steel sector. More than 90% of this volume is consumed by two sectors in India- Fertilizers (48%) and Refining (46%). A substantial portion of it being used in ammonia production for fertilizers and crude oil refining. However, this hydrogen is predominantly produced through fossil fuel-based methods, specifically grey hydrogen, which contributes to significant carbon emissions. As India looks to decarbonize, green hydrogen presents a crucial opportunity for reducing the carbon footprint of these sectors.

[7]

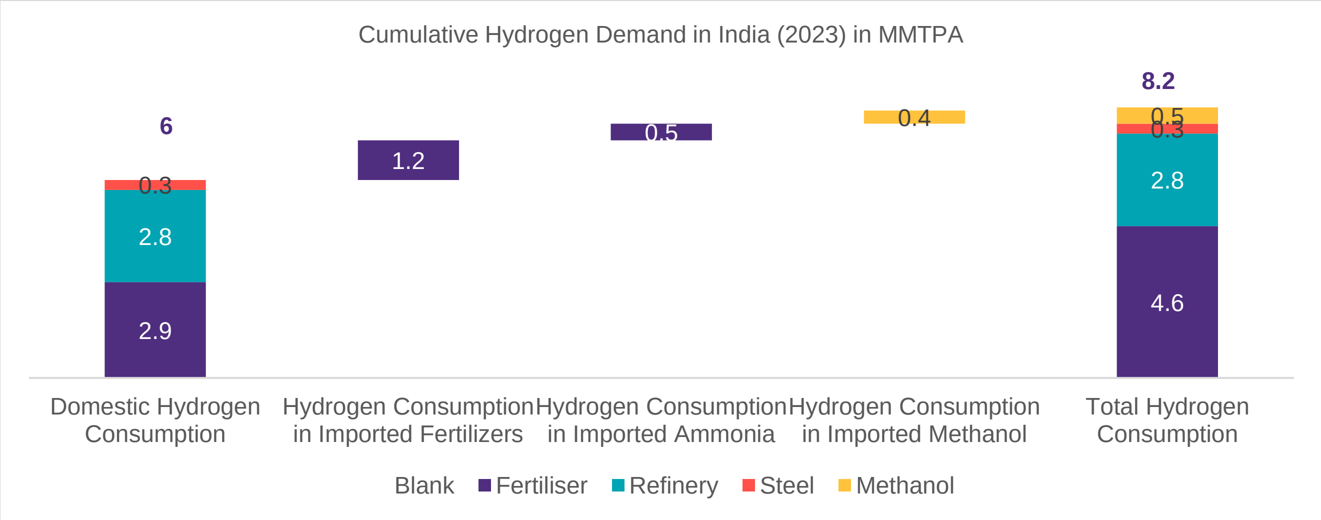

Figure 4: Cumulative Hydrogen Demand in India (2023) in MMTPA

India's green hydrogen industry is still in its early stages, with only a few pilot projects operational. However, to meet its ambitious targets, India would need 65 GW of electrolyser capacity by 2030 to produce around 5 MMT of green hydrogen annually as per National Green Hydrogen Mission (NGHM)[8].

Industries that are already significant consumers of hydrogen are most likely to lead the adoption of green hydrogen. This includes sectors like refining, fertilizers, steel production, and chemicals, where hydrogen is already integral to operations. The refining sector, in particular, uses hydrogen for desulfurization processes and converting crude oil into higher-value products. Similarly, the fertilizer industry relies on hydrogen for ammonia production, which is vital for urea and other fertilizer outputs. These industries are expected to be early adopters of green hydrogen, driven by both regulatory pressures and the desire to reduce operational emissions.

NITI Aayog envisages that the 5 MTPA by 2030[9] ambition is expected to be met in six sectors through three main strategies – Mandates, Clusters, and Corridors which is ad depicted below:

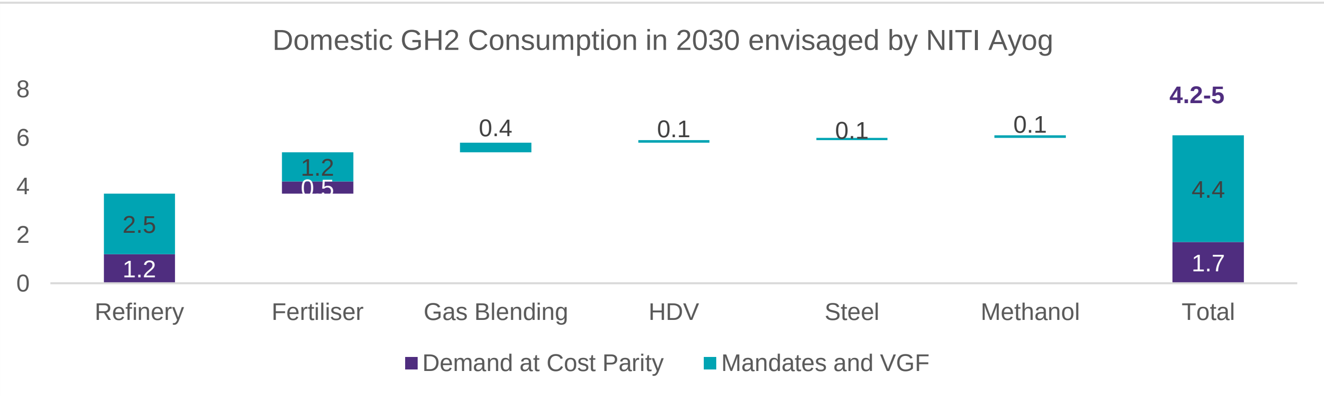

Figure 5: Domestic GH2 Consumption in 2030

Source: NITI Aayog & RMI Report, GT Analysis

[6] https://iea.blob.core.windows.net/assets/89c1e382-dc59-46ca-aa47-9f7d41531ab5/GlobalHydrogenReview2024.pdf
[7] Source: IEA Global Hydrogen Review, MNRE, PIB, TERI, EXIM Data Bank (GoI), GT Analysis (2024).
[8] https://mnre.gov.in/en/national-green-hydrogen-mission/
[9] https://www.niti.gov.in/sites/default/files/2022-06/Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf

1.3 Green Hydrogen Production and its's Application

Green Hydrogen refers to hydrogen produced using renewable energy sources through processes such as water electrolysis. In this method, an electrolyzer splits water molecules into hydrogen and oxygen using electricity generated from renewable sources like solar, wind, or hydropower. This production process reduces Greenhouse gas (GHG) emissions as compared to other conventional processes like Steam Methane Reforming (SMR), making Green Hydrogen a clean and sustainable energy carrier.

Production of Green Hydrogen

The production of Green Hydrogen involves several key steps that integrate renewable energy sources, water electrolysis, storage, and distribution to cater to various end-use applications:

- **Renewable Energy Generation:**

  Renewable energy sources such as solar, wind, or hydropower are harnessed to produce clean electricity. This renewable electricity serves as the energy input for the hydrogen production process, ensuring a zero-emission lifecycle.

- **Electrolysis Process:**

  Using the renewable electricity, an electrolyzer splits water (H_2O) into hydrogen (H_2) and oxygen (O_2). This process, known as electrolysis, is central to Green Hydrogen production. It is free from carbon emissions, as no fossil fuels are involved.

- **Hydrogen Storage:**

  Once produced, hydrogen can be stored in multiple forms, such as:

  - Gas Storage: Hydrogen is compressed and stored in high-pressure tanks for easy transportation and on-demand usage.
  - Liquid Hydrogen: By cooling hydrogen to cryogenic temperatures, it is converted into a liquid form, which offers higher energy density and facilitates efficient storage for large-scale applications.

- **Distribution:**

  Hydrogen is transported to end-use sectors through pipelines, trucks, or shipping. The flexibility of hydrogen as a transportable fuel allows its use across diverse regions and industries.

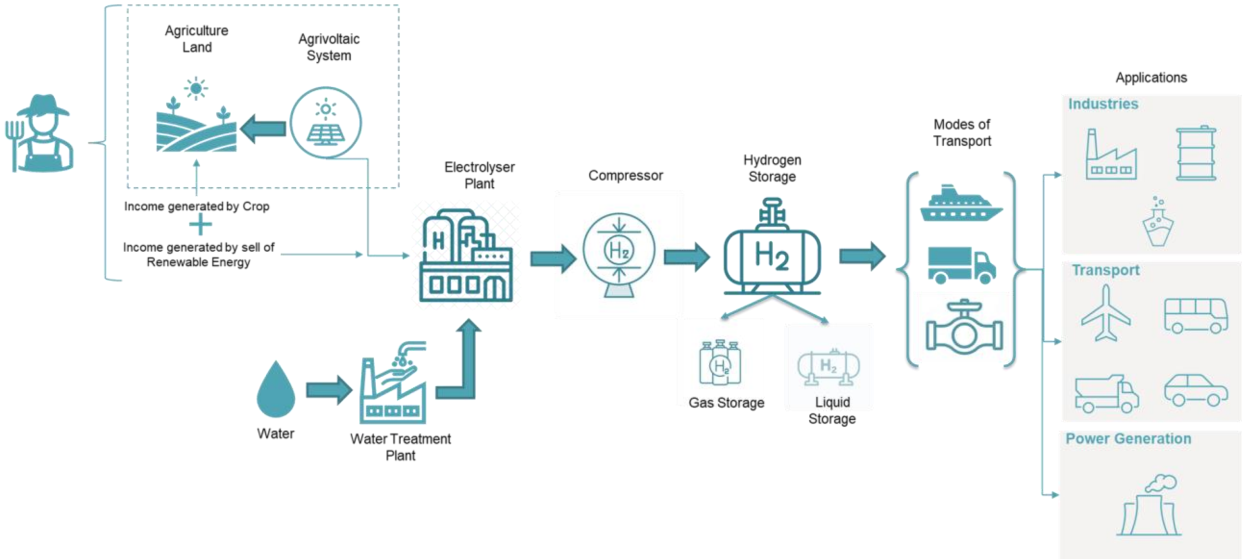

Image courtesy: GT Asset

Figure 6: Agrivoltaic powered Green Hydrogen Production and End Use

Applications of Green Hydrogen

Hydrogen stands as a versatile energy carrier with the potential to revolutionize multiple sectors, driving the transition to a sustainable, low-carbon economy. The graphic below encapsulates its diverse applications across key areas such as industrial processes, transportation, energy storage, power generation, and domestic heating. These applications underscore hydrogen's critical role in decarbonizing hard-to-abate sectors while bolstering energy system resilience and flexibility. By integrating hydrogen into these domains, we can unlock new pathways for achieving global sustainability goals.

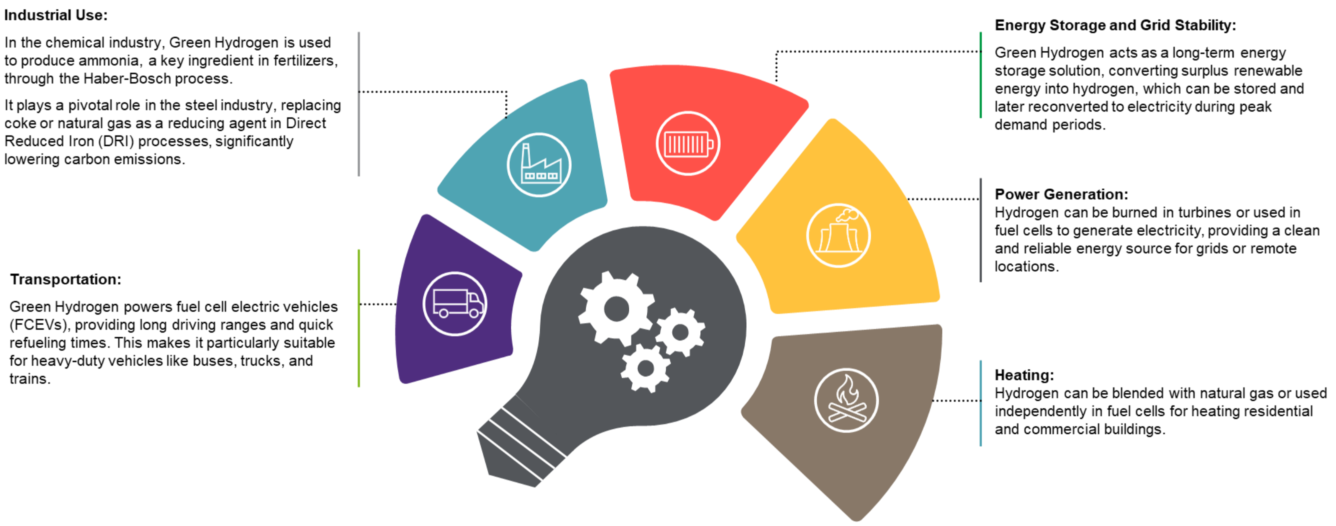

Figure 7: Green Hydrogen Applications

Image courtesy: GT Asset

2 Current Developments and Initiatives

2.1 Current Developments in Agrivoltaics Sector in India

2.1.1 Agrivoltaics Definition

Many nations have been working on Agrivoltaics, recognizing its potential to address global challenges such as food security, water scarcity, and climate change. Below are the definitions provided by some of these leading countries. Definition of Agrivoltaics in India is in discussion phase with Ministry of New and Renewable Energy (MNRE) and Ministry of Agriculture and Farmers Welfare (MoA & FW) based on several national and international workshops, however, some definitions formulated by few countries leading in the Agrivoltaics sector do exist. Germany, after several rounds of deliberation among stakeholders, arrived at a definition of Agrivoltaics that restricts yield reduction to a maximum of 33%[10]. In Japan, this number is 20%. In USA[11], Agrivoltaics is defined as agriculture, such as crop production, livestock grazing, and pollinator habitat, located underneath solar panels and/or between rows of solar panels. Certain regulatory requirements – Agrivoltaics policies of few countries is as captured below:

Table 1: Regulatory requirements – Agrivoltaics policies of few countries

Sr. No.	Country	Maximum lost areas*	Minimum Relative crop yield
1	France[12]	Not considered	90%
2	Germany[13]	• Category 1 – Overhead APV: 10% • Category 2 – Interspace APV: 15%	66%
3	Italy[14]	30%	Not defined
4	Japan[15]	Not considered	80%

**Lost areas are zones that cannot be occupied by crops due to the PV installation*

2.1.2 Recent Agrivoltaics Projects in India

India as an agrarian country has recognized the potential of Agrivoltaics, which allows the integration of renewable energy with farming and in on the verge of revolutionizing the renewable energy and agricultural sectors. Various pilot and commercial projects have been launched across the country to assess their technical feasibility, economic viability, and impact on agricultural productivity. These initiatives aim to create a sustainable model for dual land use, integrating energy generation with agricultural activities to support rural livelihoods while contributing to India's renewable energy targets. India has implemented over 22 operational Agrivoltaics projects, with an additional 3 upcoming installations.[16] Some of the projects - 1 MW GIPCL plant in Amrol, Gujarat, 1 MW GSECL Harsha Abakus plant in Sikka, Junagadh Agriculture University plant in Junagadh, Gujarat, with a capacity of 7 MW, In Maharashtra, the 1.4 MW Agrivoltaics plant in Parbhani and the 2 MW SunMaster Agri-PV System in Najafgarh, Delhi.

[10] https://elib.dlr.de/204251/1/Agrivoltaic_webinar_UniRome_final.pdf
[11] https://www.energy.gov/eere/solar/farmers-guide-going solar#:~:text=Agrivoltaics%20is%20defined%20as%20agriculture,between%20rows%20of%20solar%20panels.
[12] https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000049386027
[13] DIN SPEC 91434 (2021)
[14] https://www.mase.gov.it/notizie/impianti-agri-voltaici-pubblicate-le-linee-guida
[15] https://doi.org/10.1063/5.0054674
[16] https://energyforum.in/fileadmin/india/media_elements/Photos_And_Gallery/20201210_SmarterE_AgroPV/20201212_NSEFI_on_Agrivoltaic_in_India_1__01.pdf

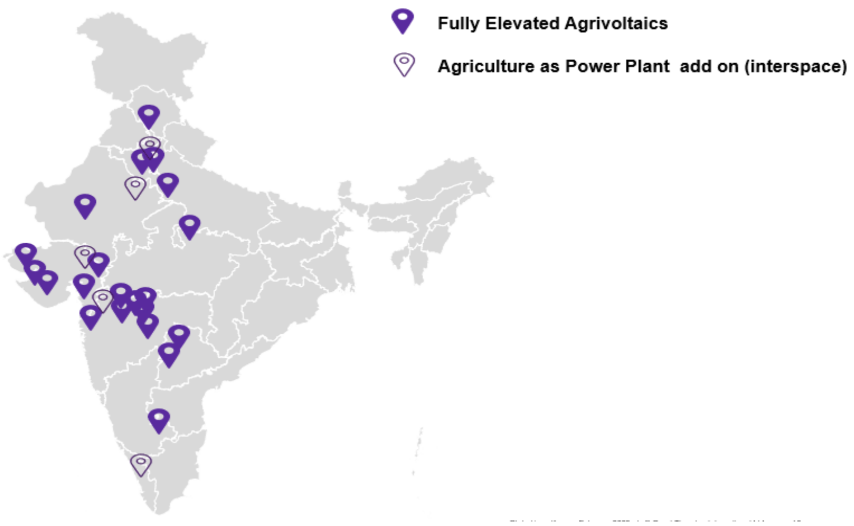

Figure 8: Agrivoltaics Project in India Site Map[17]

The cumulative capacity of these installations is relatively modest, reflecting the nascent stage of Agrivoltaics adoption in the country. However, the successful implementation of these projects (≈23 MWp cumulatively) has generated valuable insights into optimizing land use, enhancing farmer incomes, and contributing to renewable energy generation.

2.1.3 Policy Measures

The Government of India has taken significant strides in promoting and adopting Agrivoltaics systems, recognizing their potential to revolutionize the renewable energy and agricultural sectors. To support this initiative, the government has launched multiple schemes and programs. Among these, the most prominent is the **Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) Yojana**, which comprises of three components

Component A: Small decentralized solar power plants comprise of up to 2 MW are installed on barren, fallow, pasture, marshy, or cultivable land. Farmers can set up these Renewable Energy Power Plants (REPPs) either independently or through partnerships with cooperatives, panchayats, or Farmer Producer Organizations (FPOs). The generated solar power is purchased by DISCOMs at pre-fixed levelized tariffs, ensuring a steady income stream for farmers leasing their land. Additionally, DISCOMs receive a Performance-Based Incentive (PBI) of ₹0.40/kWh or ₹6.6 lakh per MW annually, whichever is lower, for five years from the plant's commissioning. AIF Support: The Agriculture Infrastructure Fund (AIF) provides financial support, including 3% interest subvention and credit guarantee for loans up to ₹2 crore.

Component B: This component focuses on deploying standalone solar agricultural pumps to replace existing diesel pumps or provide irrigation where there is no grid connectivity. Farmers can install solar pumps with capacities up to 7.5 HP on their agricultural lands. These pumps operate independently from the grid, harnessing solar energy to draw water for irrigation. Financial assistance is provided in the form of Central Financial Assistance (CFA) covering 30% of the benchmark cost, with higher support of 50% in special category states like the Northeastern States and Himalayan regions.

Component C: This component aims at solarizing existing grid-connected agricultural pumps through two approaches: Individual Pump Solarisation (IPS) and Feeder Level Solarisation (FLS). Under the IPS mode, farmers can install solar panels to power their existing grid-connected pumps, enabling them to use solar energy for irrigation and reduce their electricity consumption. Any excess solar power generated can be fed back into the grid, providing an additional revenue stream. Feeder Level Solarisation (FLS) involves solarizing entire agricultural feeders to ensure reliable daytime power supply for irrigation. Central Financial Assistance (CFA) of 30%, or 50% in special category states, is provided to support these initiatives.

Status of the PM-KUSUM Yojana

The following status table illustrates the progress under PM-KUSUM as of December 31, 2024:

Table 2: Present status of PM KUSUM Yojana[18]

Current Status	Sanctioned	Installed	Limitation
Component A	9962 MW	396.98 MW	Limited availability of suitable barren or fallow land, high initial setup costs, challenges in obtaining clearances and approvals from local authorities.
Component B	1232327 nos.	616210 nos.	High upfront costs for farmers, even with financial assistance, and the need for consistent maintenance and technical support.

[17] https://www.agrivoltaics.in/Agrivoltaic-map-of-india
[18] National Portal for PM-KUSUM

Current Status	Sanctioned	Installed	Limitation
Component C (IPS)	131640 nos.	5272 nos.	Issues with the integration of solar systems with existing grid infra and reluctance of farmers to switch from traditional energy sources due to familiarity and reliability concerns.
Component C (FPS)	3435874 nos.	107184 nos.	

The figures below illustrate the progress under PM-KUSUM Components A and B as of December 31, 2024, showing the sanctioned and installed capacities across various Indian states.

In addition to PM-KUSUM, few national level schemes include:

- **National Mission for Sustainable Agriculture (NMSA):** Focuses on enhancing agricultural productivity through sustainable practices, including integrated farming systems and efficient water management.
- **Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)**: Aims to expand irrigated areas, improve water use efficiency, and promote micro-irrigation techniques like drip and sprinkler systems

Moreover, several state-specific policies and schemes have been introduced to promote the adoption of Agrivoltaics systems across India. These initiatives include:

- **Delhi - Mukhyamantri Kisan Aay Badhotri Solar Yojana:** Provides additional earnings to farmers by placing solar modules on raised structures, ensuring uninterrupted farming underneath and a fixed monthly income.
- **Gujarat - SKY Scheme:** Guarantees a stable income for farmers by facilitating the sale of solar-generated electricity at a fixed rate for 25 years.
- **Karnataka - Surya Raitha Scheme**: Focuses on replacing inefficient pumps with energy-efficient solar pumps, allowing farmers to use two-thirds of the generated electricity and sell the surplus to DISCOMs.
- **Maharashtra - Mukhyamantri Saur Krushi Vahini Yojana (Mission 2025)**: Aims to achieve 30% feeder solarization by 2025 through decentralized solar projects near agriculture load-dominated substations.
- **Odisha - KUSUM Implementation (Annual Lease Model):** Involves developing solar projects by SECI and OREDA, with farmers receiving an annual lease payment for the use of their land.

Major gaps in regulatory policy in implementation of Agrivoltaics in India

- High Initial Costs: In August 2024, the government allowed convergence between PM-KUSUM Component-A and the Agriculture Infrastructure Fund (AIF). However, no predefined funding is exclusively reserved for PM-KUSUM Component-A under AIF, creating financial uncertainty for AgriPV projects. [19].
- Policy gaps: Ambiguities in guidelines, especially around tariff rates and surplus power purchase, hinder implementation. For example, the Domestic Content Requirement (DCR) raises costs without adding significant value to solar pump efficiency.
- Infrastructure constraints: In rural and remote areas, poor maintenance support, unavailability of spare parts, and weak grid infrastructure complicates the adoption of Agrivoltaics.
- Awareness and capacity building: Farmers often lack awareness about solar technologies and their long-term benefits.
- Over-extraction of water: Without effective groundwater management policies, the availability of subsidised solar pumps could lead to overextraction of water resources in vulnerable regions.

[19] https://pib.gov.in/PressNoteDetails.aspx?ModuleId=3&NoteId=152061&utm=&reg=3&lang=1

2.2 Current Developments in Green Hydrogen Sector in India

2.2.1 Green Hydrogen Definition:

The Ministry of New and Renewable Energy (MNRE), after extensive consultations with stakeholders, defined Green Hydrogen as hydrogen with well-to-gate emissions—including processes like water treatment, electrolysis, gas purification, drying, and compression—capped at a maximum of 2 kilograms of CO2 equivalent per kilogram of hydrogen (kg CO2 eq/kg H2).

Table 3: Definitions of Green Hydrogen Across Selective Countries[20]

Parameters	India[21]	Japan[22]	Europe[23]	Global Target by 2050[24]
Standard (12 months avg.)	2 kg CO2e per kg H2	3.4 kg CO2 per kg H2 0.84 kg CO2/kg NH3	3.38 kg CO2 per kg H2	<1 kg CO2 per kg H2 < 0.3 kg CO2/kg NH3
Scope	Well to Gate	H2: Well to Gate NH3: Gate to Gate	Full life cycle[25] (excluding embodied emissions)	H2: Well to Gate NH3: Gate to Gate (excl. upstream and downstream emission)

2.2.2 Policy and Regulatory Landscape of Green Hydrogen Sector in India

India is taking bold strides toward establishing itself as a global leader in green hydrogen and green ammonia production, driven by the ambitious targets outlined in the National Green Hydrogen Mission. The government is fostering domestic capacity through policy incentives, financial support, and strategic programs like the Strategic Interventions for Green Hydrogen Transition (SIGHT).

National Green Hydrogen Mission:

The National Green Hydrogen Mission, launched by the GoI[26], represents a strategic initiative aimed at fostering a Green Hydrogen ecosystem in the country. The Mission was approved by the Union Cabinet on January 4, 2023, with a total financial outlay of ₹19,744 crore27. Of this, ₹17,490 crore has been allocated for the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme, ₹1,466 crore for pilot projects, ₹400 crore for research and development (R&D), and ₹388 crore for other mission components.

The NGHM's primary objectives are to:

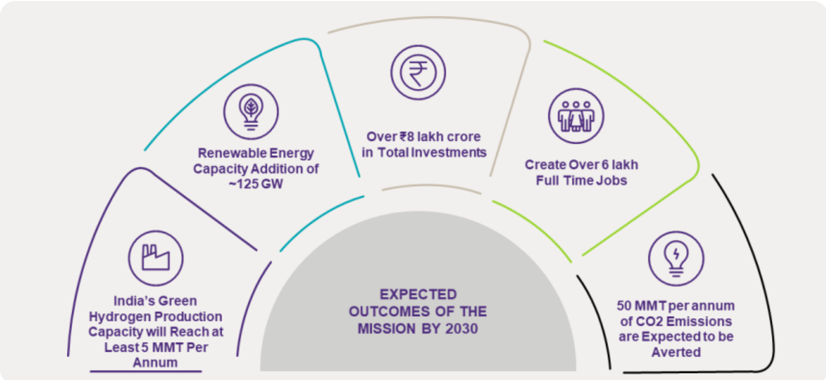

Figure 10: Objectives of NGHM

[20] Source: Government Document
[21] https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1950421
[22] https://www.meti.go.jp/shingikai/enecho/shoene_shinene/suiso_seisaku/pdf/20230606_5.pdf
[23] https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747085/EPRS_BRI(2023)747085_EN.pdf
[24] https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf
[25] https://gh2.org/sites/default/files/2024-01/GH2%20briefing%20three%20pillars%20CAN-EU-US.pdf
[26] https://mnre.gov.in/national-green-hydrogen-mission/
[27] https://mnre.gov.in/national-green-hydrogen-mission/

Alongside the National Green Hydrogen Mission, the Government of India has introduced a range of supportive policy initiatives aimed at boosting green hydrogen production, driving demand, and encouraging its adoption across the country (Refer Annexure 1 for detailed Scheme Guidelines).

Supplementary National Level Policy Initiatives for Green Hydrogen (GH2) and Green Ammonia (GA):

To promote the Green Hydrogen ecosystem, the Government of India has introduced several regulatory reforms and incentives under the Green Hydrogen Policy, aligned with the NGHM's goals. These initiatives focus on reducing costs, encouraging investment, and providing policy clarity. Key initiatives include:

- **Priority Connectivity to the Inter-State Transmission System (ISTS)**

  Green hydrogen projects are granted priority access to the ISTS, in accordance with the Electricity (Transmission System Planning, Development and Recovery of Inter-State Transmission Charges) Rules, 2021. In addition, projects commissioned before December 31, 2030[28], are exempt from paying ISTS charges for a period of 25 years, significantly reducing the cost of Green Hydrogen production.

- **Open Access for Renewable Energy Sourcing**

  Green hydrogen plants are provided open access to renewable energy sources within 15 days of application submission[29]. This regulatory provision ensures a streamlined process for obtaining renewable energy, crucial for the cost-effective production of Green Hydrogen.

- **Power Banking and Regulated Charges**

  The policy allows Green Hydrogen producers to bank renewable energy for up to 30 days[30]. Banking charges are capped to the cost difference between the average renewable energy tariff and the Day Ahead Market (DAM) price, thus ensuring a fair and transparent pricing mechanism for energy storage.

- **Land Allotment and Manufacturing Zones**

  To further facilitate the development of Green Hydrogen projects, land within renewable energy parks will be allotted for setting up manufacturing facilities. The policy also supports the establishment of dedicated Green Hydrogen manufacturing zones to drive large-scale production.

- **RPO Compliance for Renewable Energy Consumption**

  The energy used to produce Green Hydrogen will be counted towards the Renewable Purchase Obligation (RPO) compliance of manufacturers[31]. This measure incentivizes the adoption of renewable energy in Green Hydrogen production while providing regulatory flexibility.

- **Single Window Clearance for Approvals**

  To streamline the regulatory process, the Ministry of New and Renewable Energy (MNRE) has established a single portal for all necessary clearances related to Green Hydrogen production, transportation, storage, and distribution[32]. This simplifies the administrative burden on developers and accelerates project timelines.

These progressive policy measures unlock transformative opportunities for the convergence of Agrivoltaics and Green Hydrogen production, paving the way for a greener agricultural ecosystem. Agrivoltaics can be seamlessly integrated with Green Hydrogen production through priority access to renewable energy sources and open ISTS connectivity.

Moreover, the establishment of dedicated manufacturing zones and streamlined land allotments within renewable energy parks could inspire the co-location of Agrivoltaics and hydrogen facilities. The ability to bank renewable energy for up to 30 days at regulated charges ensures that even fluctuations in solar output can be efficiently managed, enabling year-round productivity for hydrogen plants and agricultural operations alike.

2.2.3 Driving Initiatives for Green Hydrogen and Ammonia Adoption in India

The Solar Energy Corporation of India (SECI), a Central Public Sector Undertaking (CPSU) dedicated to the development and expansion of Renewable Energy (RE) capacity in India, has been instrumental in advancing this vision by floating tenders and auctions aimed at scaling up electrolyser manufacturing, green hydrogen production, and green ammonia supply. These initiatives not only incentivize private sector participation but also strengthen India's supply chain capabilities, ensuring self-

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[28] https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1928128#:~:text=Applicable%20ISTS%20Charges&text=The%20government%20has%20also%20granted,2025%20to%2031%20Dec%202030
[29] https://powermin.gov.in/sites/default/files/Green_Hydrogen_Policy.pdf#:~:text=Green%20Hydrogen/Green%20Ammonia%20plants%20will%20be%20granted,within%2015%20days%20of%20receipt%20of%20application
[30] https://powermin.gov.in/sites/default/files/Green_Hydrogen_Policy.pdf
[31] https://powermin.gov.in/sites/default/files/Green_Hydrogen_Policy.pdf
[32] https://powermin.gov.in/sites/default/files/Green_Hydrogen_Policy.pdf

reliance and competitiveness in the emerging global green hydrogen market. By aligning these efforts with sustainability goals, India aims to decarbonize hard-to-abate sectors, enhance energy security, and reduce its reliance on fossil fuels.

Recent tender by SECI invited bids for green ammonia production under the Strategic Interventions for Green Hydrogen Transition (SIGHT) program. The tender, launched in mid-2024, initially aimed at 550,000 MT/year but was later expanded to 750,000 MT/year by the Ministry of New and Renewable Energy[33] (MNRE) in response to the increase in demand of Green Ammonia from the fertilizer sector. This capacity enhancement underscores the government's commitment to meeting domestic demand and strengthening the role of green ammonia in fertilizer production and other industrial applications. This is a significant boost for both the Agrivoltaics and Green Hydrogen sectors. The growing demand for green ammonia presents an excellent opportunity for co-located small-scale Agrivoltaics systems and green hydrogen plants. By utilizing on-site RE to power electrolyzers, these integrated setups can produce green hydrogen for local consumption, such as ammonia production (Refer Annexure 2 for details on various tenders floated by SECI).

[33] https://solarquarter.com/2024/06/24/mnre-increases-green-ammonia-production-capacity-to-750000-mt-per-annum-under-sight-programme-to-boost-green-hydrogen-mission/

3 Combination of Agrivoltaics and Green Hydrogen System

The integration of Agrivoltaic systems with Green Hydrogen production represents a transformative approach to addressing energy demands while supporting agricultural development. This synergistic model can enhance resource efficiency, promote sustainable agriculture, and contribute to India's energy transition.

1. **Optimizing Resource Use**

   Agrivoltaic systems combine solar photovoltaic (PV) panels with agricultural land use, enabling dual land productivity. By layering Green Hydrogen production within these systems, multiple resource optimization opportunities emerge:

   A. **Land Utilization:**

   - Agrivoltaic systems utilize agricultural land to generate solar energy adding Green Hydrogen production facilities allows for vertical integration, utilizing the same land for energy generation and hydrogen production.
   - This dual-purpose land use reduces the need for additional land acquisition, mitigating deforestation or loss of arable land.
   - A comparative analysis of conventional Ground mounted systems and Agrivoltaic systems highlights the difference in land requirements for around 1 MWp installation. With a conventional ground mounted system requiring 2.9 acres (Solar PV area) and Agrivoltaic system considering tractor movement require 3.2 acres. While a single axis tracking Agrivoltaic system requiring 5.52 acres, which is approximately 90.34% more than conventional system. This increase is due to the spacing adjustments in Agrivoltaic systems to facilitate tractor movement and maintain agricultural productivity alongside solar energy generation having east to west rotational movement. Assessment's representation in detail has been discussed in the annexure 3 attached to the document.

   B. **Water Management:**

   - Treated wastewater from nearby agricultural or community setups can also be repurposed, minimizing the strain on freshwater resources.
   - Agrivoltaic structures can collect rainwater, which can be used for both irrigation and electrolysis in green hydrogen production.

   C. **Energy Synergy:**

   - Solar energy generated from Agrivoltaic systems is connected to the electrolyser through a Maximum Power Point Tracker (MPPT) and/or a DC-DC buck converter. These converters ensure maximum solar energy is available to the electrolyser[34].
   - Excess solar energy during peak hours is predominantly stored in Lithium-ion batteries, or the excess energy can be used to produce Green Hydrogen, ensuring round-the-clock energy availability.

2. **Enhancing Energy Efficiency**

   Integrating Agrivoltaic systems with Green Hydrogen production can vary according to the application and the efficiency required, which changes for each case. In this regards we see that alkaline electrolysers have an efficiency in the range of 50-78kWh/kgH2, PEM electrolysers have an efficiency in the range of 50-83kWh/kgH2, AEM electrolysers are in the range of 57-69kWh/kgh2 and SOEC electrolysers are in the range of 45-55kWh/kgh2. Through these numbers we see that SOEC electrolysers consume the least energy to produce 1kg of GH2, but it's also important to look at the readiness of the technology the overall costs and how and where the electrolyser is being used to make the right selection. Following are ways in which the electrolyser and hydrogen can be used[35]:

   A. **On-site Energy Utilization:**

   - Co-locating Green Hydrogen production with Agrivoltaic systems eliminates energy transportation costs and losses.

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[34]https://www.sciencedirect.com/science/article/abs/pii/S0360319909001244#:~:text=In%20order%20to%20interface%20the,allow%20for%20different%20current%E2%80%93voltage
[35]https://www.irena.org//media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

- Electrolyzers can be dynamically operated based on solar energy availability to maximize efficiency. However, not all types of electrolyzers are suited for dynamic operation. Proton Exchange Membrane (PEM) electrolyzers are better equipped to handle fluctuating energy inputs, making them more compatible with variable renewable energy sources like solar. In contrast, Alkaline electrolyzers typically operate more efficiently in a steady, round-the-clock (RTC) mode and may not perform as effectively under dynamic conditions.

B. **Grid Integration:**

- By combining solar energy with Green Hydrogen, the system can act as a flexible load balancer for the grid. Excess solar power is used for hydrogen production, reducing curtailment issues associated with high renewable energy penetration.

C. **Energy Storage:**

- Green Hydrogen serves as an energy storage medium. During periods of low solar output or high energy demand, stored hydrogen can be converted back to electricity using fuel cells or turbines, ensuring consistent energy supply.

3. Supporting Sustainable Agriculture

Agrivoltaic + Green Hydrogen systems can significantly benefit India's agricultural sector by providing sustainable energy and improving overall farm productivity:

A. **Improved Crop Yield and Microclimate:**

- Solar panels in Agrivoltaic systems provide shade to crops, reducing heat stress and water evaporation. This controlled microclimate can enhance yields of shade favourable crops, especially in regions prone to high temperatures.

B. **Renewable Energy Access:**

- Green Hydrogen-powered fuel cells can provide reliable electricity to remote farms, enabling the operation of advanced irrigation systems, cold storage, and other machinery.

C. **Green Fertilizers:**

- Hydrogen produced on-site can be used to manufacture ammonia-based fertilizers, reducing dependence on conventional fossil fuel-derived fertilizers and lowering agricultural emissions.

D. **Income Diversification:**

- Farmers can earn additional income by leasing land for Agrivoltaic systems or selling excess solar energy to beneficiaries (e.g. Discom, Private entity) and Green Hydrogen (e.g. ammonia fertilizer manufacturers, hydrogen refueling stations).

E. **Farming Equipment Powered by GH2:**

- Hydrogen fuel cells can replace diesel in tractors and harvesters, reducing carbon emissions in farming.
- GH2 can serve as an off-grid energy source for remote agricultural areas, providing consistent power for equipment during peak farming seasons.

4. Environmental and Economic Impact

A. **Reduced Carbon Footprint:**

- Solar energy and Green Hydrogen production minimize reliance on fossil fuels, reducing greenhouse gas emissions.
- Efficient resource utilization reduces waste and promotes circular economy principles in rural areas.

B. **Cost Savings:**

- Integrated systems reduce operational and maintenance costs by sharing infrastructure and resources.

- Farmers save on energy costs through self-sustaining renewable systems, improving overall profitability.

4 Potential Synergies, Benefits, and Challenges

Integrating Agrivoltaics systems with green hydrogen production offers a transformative approach to sustainable agriculture and renewable energy. This synergy has the potential to address critical issues such as energy access, environmental degradation, and economic disparities. While the integration presents significant opportunities, it also comes with its share of challenges. This section explores the social, economic, technological, and ecological dimensions of combining Agrivoltaics and green hydrogen systems, highlighting the potential benefits, analyzing the challenges, and identifying solutions to maximize impact.

Workforce Estimate:

According to a recent study by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, the Full-Time Equivalent (FTE) job potential for Agrivoltaics is **5.5 jobs per MW**[36]. This includes roles spanning the application, project approval, engineering, and O&M stages. FTE measures the ratio of an employee's annual work hours on a specific task or project to the standard total working hours in a year.

In comparison, the FTE for utility-scale solar PV projects **is 3.45 jobs per MW**[37], encompassing EPC and Operation and Maintenance. Furthermore, under the National Green Hydrogen Mission (NGHM), the green hydrogen sector is expected to generate 6 lakh new jobs[38]. It is clear that, Agrivoltaics demonstrates a higher Full-Time Equivalent (FTE) job creation potential, generating 5.5 jobs per MW compared to 3.45 jobs per MW for large-scale utility solar systems.

This workforce estimate assumes that **5%** of the total 125 GW renewable energy capacity is derived from Agrivoltaics systems, alongside the development of 5 MMTPA green hydrogen projects.

Social-Economic Dimensions

1. **Job Potential**:
    - The integration of Agrivoltaics and green hydrogen sectors presents significant employment opportunities spanning installation, operation, maintenance, and manufacturing.
    - **Agrivoltaics Sector**:
        - Installation and O&M activities in a 6.25 GW Agrivoltaics project (5% of 125 GW) could generate over 34,375 jobs, primarily in rural areas, fostering rural employment.
        - Opportunities will span across semi-skilled and skilled labor, offering significant potential for local communities to upgrade their skills.
    - **Green Hydrogen Sector**:
        - A 5 MMTPA green hydrogen project, leveraging its FTE job potential (averaging 120 jobs per 1,000 tonnes of production), could generate approximately 600,000 jobs.
        - The sector includes high-tech roles in electrolyzer manufacturing, process optimization, and foundational positions such as equipment assembly and site operations.
    - The combined workforce estimate of **634,375** jobs highlights the transformative role of these sectors in reducing rural unemployment and fostering skill development.
2. **Benefit Sharing**:
    - **Farmers**: Agrivoltaics projects enable dual land use, allowing farmers to maintain agricultural productivity while leasing their land for solar installations, ensuring a stable secondary income.
    - **Local Communities**: Projects catalyze local economic growth through infrastructure development, improved energy access, and additional job creation in ancillary industries.
    - **Investors**: Revenue-sharing agreements or co-ownership models can equitably distribute benefits, encouraging private sector participation while supporting community welfare.

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[36] agrivoltaic-in-india-report.pdf
[37] IRENA(2024), CEEW(2022), CSEIndia.
[38] https://mnre.gov.in/en/national-green-hydrogen-mission/

Techno-Economic Dimensions

1. **Cost-Benefit Analysis**:
   - **Capital and Operational Costs**:
     - Combined Agrivoltaics and green hydrogen projects are capital-intensive. For example, Agrivoltaics installation costs range between **INR 6-8 Cr. per MW**, while green hydrogen systems cost **$1,000-$1,500 per kW** for electrolyzer setups.
   - **Return on Investment**:
     - Green hydrogen production can enable monetization through exports and domestic applications in industry, transport, and power generation.
     - Agrivoltaics offers long-term returns through reduced energy costs for farmers and stable land lease revenues.
   - **Scalability**:
     - Modular designs for Agrivoltaics systems and electrolyzers can enhance scalability, enabling phased implementation to manage costs and risks.
     - Integrated projects reduce duplication of infrastructure (e.g., shared transmission lines), further improving economic feasibility.

Ecological Dimensions

1. **Environmental Impact**:
   - **Reduced Carbon Emissions**:
     - Green hydrogen eliminates CO_2 emissions associated with conventional grey hydrogen. A 5 MMTPA green hydrogen project could avoid **50 million tonnes of CO_2 annually**.
     - Agrivoltaics CO2 abatement: A 1MW agrivoltaics plant generates approximately 17,20,000kWh units annually leading to CO2 emission savings of approximately 1500t annually. [39]
     - Fertilizer CO2 abatement: A 1MW Agrivoltaic plant where turmeric is cultivated in 0.9 acers of land. It requires a combination of fertilizer types amounting to 332kg, of which 89kg is nitrogen-based fertilizers. Where 231.4kg of CO2 emission savings takes place by using green ammonia based fertilizers[40] [41]
     - Agrivoltaics systems reduce fossil fuel dependency by producing clean solar energy, contributing to decarbonization goals.
   - **Enhanced Biodiversity and Soil Health**:
     - Agrivoltaics setups provide shade for crops, reducing water evaporation and heat stress, improving soil moisture retention, and promoting biodiversity.
   - **Potential Risks**:
     - Large-scale Agrivoltaics installations could disrupt land-use patterns and affect local ecosystems.
     - Green hydrogen production, if not carefully managed, may strain water resources required for electrolysis in water-scarce regions.
   - **Mitigation Strategies**:
     - Use of water-efficient technologies such as desalination and wastewater treatment for hydrogen production.
     - Community-driven land management and adaptive designs for Agrivoltaics installations to balance ecological and agricultural needs.

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[39] https://www.researchgate.net/publication/367534491_The_Relationship_between_the_Low_Carbon_Industrial_Model_and_Human_Well-Being_A_Case_Study_of_the_Electric_Power_Industry
[40] https://kisanvedika.bighaat.com/field-preparation-for-turmeric/
[41] https://www.carbonchain.com/blog/understand-your-synthetic-fertilizer-emissions

5 Potential Use Cases and Technical Options

Green hydrogen holds the potential to redefine agriculture by enabling sustainable and efficient energy solutions across the sector. From powering heavy-duty machinery like tractors and smaller agricultural equipment to decentralized fertilizer and ammonia production, its applications are vast and transformative. This section explores how green hydrogen can also be used for decentralized energy storage, blended into gas grids or fuelling stations, and integrated into everyday agricultural operations. These innovations promise to reduce emissions, enhance resource efficiency, and pave the way for a more sustainable and self-reliant agricultural future.

5.1 Heavy-Duty Agricultural Machinery (Tractors) Powered by Green Hydrogen

Heavy-duty agricultural machinery, such as tractors and harvesters can be powered by green hydrogen to provide a clean alternative to diesel engines. Hydrogen fuel cells offer high energy density and rapid refuelling, making them ideal for continuous, high-demand operations in the field. This not only reduces greenhouse gas emissions but also improves air quality in rural areas while ensuring reliable performance for heavy-duty tasks. Major manufacturers like Fendt, Xcient, Tafe, and others have recently introduced hydrogen fuel cell-powered tractors, signalling a significant shift toward decarbonizing farm machinery.

- **Feasibility**: Hydrogen fuel cells offer high energy density and longer operational durations, making them suitable for intensive farming activities.
- **Benefits**:
    - Reduction in greenhouse gas emissions, contributing to sustainable farming practices.
    - Decreased reliance on fossil fuels, enhancing energy security.
    - Potential for quieter operation, improving the working environment for farmers.
- **Examples**:
    - **Fendt Helios[42]:** Fendt's Helios hydrogen tractor is a key player in the DLG award-winning project, with two prototypes already operational. These tractors are equipped with five hydrogen tanks, each capable of storing 4.2 kg of compressed hydrogen at up to 700 bars. The hydrogen powers a 100-kW fuel cell, which, along with a 25-kWh battery, supplies continuous power to the electric traction motor and auxiliary systems. With up to 21 kg of hydrogen stored, the tractors can refuel using a special protocol at dedicated hydrogen filling stations, highlighting the need for supportive infrastructure. The Fendt Helios hydrogen tractor is still in the prototype stage and undergoing field tests, so it is not commercially available yet.

Figure 11: Fendt Helios Hydrogen tractor

Image courtesy: Fendt Helios

    - **Xcient Fuel Cell Tractor[43]:** The XCIENT Fuel Cell tractor boasts a twin array of 90 kW fuel cell stacks, delivering 180 kW of clean power. With a driving range of more than 450 miles on a full load and reduced refueling times.
    - **Tafe Hydrogen Tractor[44]:** Tafe's hydrogen-powered tractor features a 55 hp Simpson combustion engine that runs on hydrogen. While the tractor is functional, Tafe acknowledges that widespread adoption hinges on the development of reliable hydrogen refuelling infrastructure, which is still in its early stages. This hydrogen tractor is still a concept and not for sale. According to Tafe, the tractor works but has no plans to market it yet due to insufficient hydrogen refuelling infrastructure.

Image courtesy: Future Farming

Figure 12: Tafe Hydrogen Tractor

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[42] https://www.fendt.com/int/h2-fendt-helios-tractor-on-display-as-part-of-german-hydrogen-week-2024
[43] https://ecv.hyundai.com/global/en/products/xcient-fuel-cell-tractor-fcev
[44] https://www.futurefarming.com/tech-in-focus/indian-tafe-presents-tractors-powered-by-hydrogen-and-electricity/#:~:text=Due%20to%20the%20electric%20motor,like%20a%20continuously%20variable%20transmission.&text=This%20is%20Tafe's%20electric%20tractor,12%20hours%20of%20light%20tasks.

5.2 Hydrogen-Powered Agricultural Utility Vehicles

Hydrogen-powered utility vehicles are transforming the agricultural landscape by providing clean and efficient transportation for supporting farm operations. These vehicles, such as pickup trucks and multi-purpose utility vehicles, play a critical role in moving equipment, supplies, and personnel across farms. With the ability to combine long ranges, quick refueling times, and rugged performance, hydrogen-powered utility vehicles are an excellent alternative to diesel counterparts. The following examples highlight how hydrogen is being integrated into agricultural utility vehicles:

1. **Toyota Hilux[45]:** Toyota has introduced a hydrogen-powered version of its iconic Hilux pickup truck. The vehicle features three 2.6 kg high-pressure hydrogen tanks, providing a total capacity of 7.8 kg. With an impressive driving range of up to 600 km, the fuel cell Hilux offers a robust and practical solution for agricultural applications. So far ten prototypes have been built at Toyota's UK facility, five of them are undergoing intense field testing to evaluate safety, performance, and durability, gathering real-world test drive data, showcasing the potential for hydrogen to power utility vehicles with ranges beyond what battery-electric systems can achieve.

   Image Courtesy: [Toyota]

Figure 13: Toyota Hilux

2. **Glickenhaus Hydrogen Pickup[46]:** Glickenhaus is developing a hydrogen-powered pickup truck that promises a range of up to 800 miles (1287 km). It features a swappable hydrogen tank system designed for quick replacements making it as convenient as diesel for refueling. The truck is designed to deliver diesel-like performance, capacity, and costs but with zero emissions.

   Image Courtesy: [Motorauthority]

Figure 14: Glickenhaus hydrogen pickup

5.3 Decentralized Mini Fertilizer/Ammonia Production

Decentralized mini fertilizer and ammonia production is redefining how farmers access essential nutrients for their crops, enabling on-site, sustainable, and cost-effective production. By utilizing renewable energy, air, and water, these systems eliminate the need for traditional centralized production and long supply chains, reducing costs and emissions while enhancing supply chain resilience. The following examples highlight cutting-edge technologies making this transformation possible:

1. **Debye[47]:** Debye has developed a modular and containerized system that empowers farmers to produce zero-carbon nitrogen fertilizers locally using only air, water, and electricity. The innovative process involves nitrogen fixation, where air molecules are broken down into nitrogen oxides, followed by nitrate formation and the creation of compound fertilizers such as calcium nitrate. The Debye 100kW unit allows for a flexible range of production capacities, from as little as 1 kg N/day to up to 1000 tonnes N/day, without the need for ammonia. This fully decarbonized process enhances supply chain resiliency and offers efficiency, adaptability, and low maintenance, making it an attractive solution for farms of all sizes. It is commercially available.

   Image Courtesy: [Debye]

Figure 15: Debye 100 kW unit

   The UK Agri-Tech Centres[48] in collaboration with innovative start-up Debye Ltd. are trialing a Debye's lightning-based fertilizer the details are captured as below:
   - **Location of company:** Debye Ltd. (United kingdom (UK) based company) Agri tech Centres (UK)
   - **Location of (pilot) projects:** CHAP's vertical farming facility at Stockbridge, UK
   - **Size of plant:** 1 kW proof-of-concept prototype
   - **Type of fertilizer:** Nitrate-based fertilizer
   - **Requirements:**
     - Renewable Energy (RE): Electricity (renewably powered)
     - Nitrogen: Captured from the atmosphere via lightning simulation

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[45] https://www.topgear.com/car-news/first-look/toyotas-hydrogen-powered-hilux-pick-claims-373-miles-range
[46] https://fuelcellsworks.com/2024/12/02/clean-hydrogen/american-hydrogen-pickup-truck-teased-with-similar-cost-capacity-performance-as-diesel-pickups-carbuzz
[47] https://debye.co.uk/
[48] https://fareasternagriculture.com/technology/machinery-a-equipment/trials-to-be-run-on-debyes-groundbreaking-lightning-based-fertiliser-technology

  - Carbon: Not explicitly mentioned, but aims for near-zero emissions
  - Water: Required for nitrogen capture and conversion into nitrates
- **Output:** Nitrate-based fertilizer for crops
- **Suitability for AgriPV as RE source:** Since the process requires electricity and aims to be renewably powered, Agrivoltaics could also be a suitable energy source.

2. **Stamicarbon[49]:** Stamicarbon, part of the MAIRE Group, has developed a modular solution for decentralized green ammonia production, ideal for small- and medium-scale plants with capacities ranging from 50 to 500 metric tons per day (MTPD). Using renewable energy as a feedstock, the technology features a high-pressure synthesis loop operating at over 300 bar and a compact footprint of 50 x 50 meters for a 500 MTPD plant. This setup reduces capital expenditure by 25-30% through the integration of a single multi-service reciprocating compressor. In May 2023, Stamicarbon was awarded a project to develop a 450 MTPD green ammonia plant in the USA, which will use its state-of-the-art Stami Green Ammonia technology. Expected to launch in 2026, this facility will produce green ammonia for nitrogen-based fertilizers, demonstrating the viability of sustainable, decentralized production.

Figure 16: Stamicarbon Green Ammonia Plant

Image Courtesy: Stamicarbon

Stamicarbon is leading a renewable power-to-fertilizer project in Kenya, producing green ammonia for sustainable agriculture. The facility will reduce carbon emission with approximately 100,000 tons of CO2 per annum, compared to a gas-based fertilizer plant. Further details are captured as below[50]:

- **Location of company:**
  - Maire Tecnimont S.p.A. (Headquartered in Milan, Italy)
  - Oserian Development Company (Kenya)
  - Stamicarbon (Netherlands)
- **Location of (pilot) projects:** Oserian Two Lakes Industrial Park, Nakuru County, Kenya (100 km north of Nairobi)
- **Size of plant:**
  - Target production capacity: 550 metric tons per day (mtpd) of Calcium Ammonium Nitrate (CAN) and/or NPK fertilizers
  - Requires approximately 70 MW of renewable power
- **Type of fertilizer:**
  - Calcium Ammonium Nitrate (CAN)
  - NPK fertilizers (Nitrogen, Phosphorus, and Potassium-based)
- **Requirements:**
  - Renewable Energy (RE): Solar and geothermal energy
  - Nitrogen: Captured from the air
  - Carbon: Eliminates fossil fuel use, reducing CO_2 emissions by approximately 100,000 tons per year
  - Water: Used for electrolysis to produce hydrogen for ammonia synthesis
- **Output:**
  - Green ammonia as the primary feedstock
  - Calcium Ammonium Nitrate (CAN) and/or NPK fertilizers
- **Suitability for AgriPV as RE source:** The plant will be partly powered by on-site solar energy, making AgriPV (Agricultural Photovoltaics) a suitable renewable energy source.

5.4 Decentralized Energy Storage

Decentralized energy storage is becoming an essential solution for farms seeking reliable, off-grid energy sources. By storing excess energy generated from renewable resources like solar or wind, these systems provide farmers with the flexibility to use energy when needed, ensuring operational continuity even during periods of low renewable generation. Coupled with hydrogen technology, decentralized energy storage offers an innovative way to enhance energy security and reduce dependency on the grid.

- **Process**: Excess solar energy is converted into hydrogen via electrolysis, stored, and later reconverted to electricity or used directly as fuel.

- **Benefits**:
  - Provides a sustainable solution for energy storage, complementing intermittent renewable sources.

[49] https://www.stamicarbon.com/our-business/stami-green-ammonia
[50] https://www.stamicarbon.com/press-release/maire-group-starts-preliminary-work-renewable-power-fertilizer-plant-kenya

- ○ Enhances energy independence for agricultural operations.
- ○ Potentially offers longer storage durations compared to traditional batteries.

- **Examples:**
  - ○ **Oncore Energy – Agriculture Hydrogen Fuel Cell Generator**[51]: Oncore Energy provides modular hydrogen fuel cell generators designed for residential and light commercial applications, ranging from 4 kW to 32 kW. These systems are flexible, catering to the specific energy needs of the user, whether for a small farm or a larger agricultural operation. By harnessing hydrogen as a storage medium, Oncore Energy offers a scalable solution that can store excess energy from renewable sources and release it when demand spikes or when other energy supplies are unavailable. This decentralized approach not only increases energy independence for farmers but also supports the broader push toward a clean energy future.

Figure 17: Oncore Energy Mobile Unit[51]

  - ○ **Stargate Hydrogen's Solutions**: The GREENFLOW project[52], a collaboration between Stargate Hydrogen and BPT d.o.o., exemplifies the synergy between agrivoltaics and green hydrogen. By utilizing hydroenergy from the Mošenik stream, the project aims to generate green hydrogen while also supporting agricultural irrigation. A hydrogen filling station will be installed for local farming use, showcasing a sustainable model where renewable energy, hydrogen production, and agriculture coexist.
  - ○ This initiative highlights how hydropower-driven electrolysis can reduce carbon emissions while enhancing resource efficiency in agriculture. With a focus on technology integration, field testing, and resource planning, GREENFLOW aligns with European IPCEI goals, offering a scalable blueprint for future agrivoltaic-hydrogen projects across Europe..

5.5 Blending into Gas Grid or Fueling Stations

Integrating green hydrogen into existing energy infrastructures can support agricultural operations.

1. **Gas Grid Integration**:
   - ○ Blending hydrogen with natural gas can decarbonize energy supplies for heating and other applications in agriculture.
   - ○ The United States has launched several blending projects, but the most successful and longest-running to date is Hawaii Gas's integration of a 12% to 15%[53] blend into its network.
2. **Fueling Stations**:
   - ○ Establishing hydrogen fueling stations near agricultural hubs can facilitate the adoption of hydrogen-powered machinery and vehicles.

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[51] https://oncoreenergy.com/applications/ag/
[52] https://stargatehydrogen.com/news/hydrogen-production-in-slovenia/
[53] https://asmedigitalcollection.asme.org/IPC/proceedings-abstract/IPC2020/84447/V001T03A057/1095967

5.6 Hydrogen Powered Drones and Robots

Hydrogen is emerging as a transformative force in agriculture, powering innovative technologies that enhance efficiency, sustainability, and productivity. By leveraging hydrogen as a clean and efficient energy source, farmers can adopt cutting-edge solutions like drones and robots for various agricultural applications. Here are two examples showcasing the potential of hydrogen in farming:

1. **Hydrogen-Powered Drones – HevenDrones H2D55[54]:**

   HevenDrones has unveiled the H2D55, a hydrogen-powered drone designed for commercial use. With five times the energy efficiency of traditional lithium battery-powered drones, the H2D55 can fly for 100 minutes while carrying a payload of up to 7 kg. In agriculture, this capability makes hydrogen drones highly effective for crop monitoring, precision spraying, and transporting lightweight materials across large fields. Their extended flight time and zero-emission operation position them as a game-changing tool for farmers striving for greener and more efficient practices.

Figure 18: Heaven Drones

Image Courtesy: [Heaven Drones]

2. **Hydrogen-Powered Robots – TRAXX Concept H2 by EXXACT Robotics[55]:**

   The TRAXX Concept H2 robot from EXXACT Robotics exemplifies how hydrogen can revolutionize agricultural machinery. Equipped with a full-power fuel cell and high-capacity batteries delivering up to 35 kW, this autonomous machine can operate continuously for up to 12 hours. With two hydrogen tanks holding just over 9 kg of fuel, it offers a quiet, lightweight, and zero-emission alternative to conventional gasoline or diesel-powered machines. This makes it particularly valuable for sustainable farming applications such as vineyard management, field inspections, and precision agriculture tasks. Moreover, its quick refueling capability ensures minimal downtime and maximum productivity.

Image Courtesy: [Hydrogen Central]

Figure 19: TRAXX Concept H2 from EXXACT Robotics

[54] https://hevendrones.com/hydrogen-drones/
[55] https://hydrogen-central.com/gofar-x-fira-worlds-first-hydrogen-powered-vineyard-tractor-arrived-traxx-concept-h2/

6 International Developments and Technologies

Integrated PV technologies such as Agrivoltaics presents itself as a strong solution to unlock additional avenues for energy generation when used by itself but more so when coupled with other energy solution such as green hydrogen. The synergies of Agrivoltaics and green hydrogen will not complement the traditional sources already but also aid in use of green hydrogen in various application around the farms and also in other general applications. The following section explores the innovative technologies and case studies for the synergies between agrivoltaics and green hydrogen.

6.1 New Technologies

There are several new technological innovations that have enabled the production of green hydrogen and its other use cases such as ammonia. These innovations have been possible through years of R&D to improve efficiency and product design.

This section will cover two major technological developments, one of which is the process of absorbing water vapour to make hydrogen through electrolysis and extraction of nitrogen form the air, and both are combined to make ammonia which has several use cases such as in fertilizers and in other industrial processes. The other technology is a solar hydrogen panel that uses solar energy coupled with the device's ability to absorb water vapour and convert it into hydrogen through electrolysis, this hydrogen can be further stored or used in hydrogen vehicles in the farm or elsewhere.

These innovative technologies have indicated the progress made to produce hydrogen and ammonia through strong R&D and efficiency improvements, which are now indicating market forces to adopt across different applications.

6.1.1 TalusAg Project[56]:

The TalusAg project advances sustainable farming by providing low-cost, carbon-free nitrogen fertilizers through modular, on-site green ammonia systems. Powered by renewable energy, these autonomous systems produce anhydrous ammonia from air, water, and electricity, reducing reliance on carbon-intensive fertilizers and promoting environmental and economic resilience in agriculture. TalusAg aims to reduce dependency on traditional, carbon-intensive fertilizer production methods, thereby promoting environmental sustainability and economic resilience in the agricultural sector.

- **Key Objectives:**
    - **Sustainability:** Reduce the carbon footprint of nitrogen fertilizer production.
    - **Cost Reduction:** Lower the cost of fertilizers by 50% for farmers.
    - **Accessibility:** Avoid supply chain issues and provide an on-site solution that can be deployed in diverse geographical regions.

Figure 20: TalusAg installation in Kenya[56]

- **Technological Innovations:** The TalusAg project incorporates several technological advancements to achieve its objectives:
    - **Modular Design:** The green ammonia systems are modular and containerized, allowing for easy transportation and installation. This design ensures scalability and flexibility, enabling the systems to be deployed at various scales to meet the specific needs of different farms or industrial sites.
    - **Autonomous Operation:** The systems are fully autonomous, equipped with advanced sensors and control systems for remote monitoring and operation. This autonomy reduces the need for manual intervention and ensures continuous, efficient production.
    - **Renewable Energy Integration:** The green ammonia systems are designed to integrate seamlessly with renewable energy sources. By using solar or wind power, the systems produce green ammonia without generating carbon emissions, aligning with global sustainability goals.

[56] https://www.talusag.com/?_sm_nck=1#Uses

- **Key Specifications**

1 Production Capacity

Each modular unit can produce **up to 3 tons of carbon-free ammonia per day** depending on system size

2 Cost Efficiency

Lowers nitrogen fertilizer costs by over 50%, making them an economically viable option for farmers

3 Scalability

Its customizable design allows **scalability, enabling the expansion of production capacity** as needed

- **Deployment and Pilot Projects:** The TalusAg project has been piloted in several locations to demonstrate its feasibility and effectiveness. In Belgium, projects near Leuven refined the technology under real-world conditions, while the Green Energy Park in Zellik tested hydrogen distribution networks and integrated green ammonia with existing infrastructure. At the VDL Industrial Site in North Brabant, a local microgrid project reduces reliance on the electricity grid by pairing green ammonia production with renewable energy. In Angola, the Capanda Green Ammonia Project, in partnership with Minbos Resources, uses low-cost hydropower to produce green ammonia, supporting agriculture and mining industries. TalusAg also has a green ammonia project in Kenya Nut Company's Morendat farm, the project produces approximately 1 tonne of green ammonia daily and is power by a 2.1MW solar farm, the project demonstrates how decentralized green ammonia production in rural and supply vulnerable communities.
- **Lessons Learned and Challenges:** The development and deployment of the TalusAg project have provided valuable insights and highlighted several challenges:
  - **Technical Feasibility**: The initial pilot projects have demonstrated the technical feasibility of producing green ammonia using modular, autonomous systems.
  - **Economic Viability**
    - **Cost Competitiveness:** The economic analysis has shown that green ammonia produced by TalusAg systems is cost-competitive when compared with traditional nitrogen fertilizers.
    - **Initial Investment:** While the systems offer significant cost savings over time, the initial capital investment remains a barrier for some farmers. Financial incentives and support from governments and organizations are essential to overcome this challenge.
  - **Scalability and Adaptability**
    - **Geographic Adaptability:** The containerized system developed by TalusAg allows for a more decentralized approach to fertilizer manufacturing at the same time having the technology to deploy larger fertilizer manufacturing plants in any geography underscoring their potential for widespread adoption.
    - **Renewable Integration:** The integration with renewable energy sources is crucial for the project's success. Ensuring a reliable and consistent supply of renewable energy is a key consideration for future deployments. Access to reliable RE supply allows for large scale deployment of these fertilizer manufacturing systems.
  - **Regulatory Support**
    - **Policy Incentives:** Supportive regulatory frameworks are essential for the successful deployment of green ammonia systems. Policies that incentivize renewable energy adoption and support research and development are crucial for the growth of the TalusAg project.

Conclusion:

The TalusAg project represents a significant advancement in sustainable agricultural practices and renewable energy technology. By providing low-cost, carbon-free nitrogen fertilizers through on-site green ammonia systems, the project addresses critical challenges in the agricultural sector and contributes to global efforts to combat climate change.

The project's success lies in its innovative approach to integrating modular, autonomous green ammonia systems with renewable energy sources. The economic and environmental benefits of this technology are substantial, offering a viable solution for sustainable farming and industrial applications.

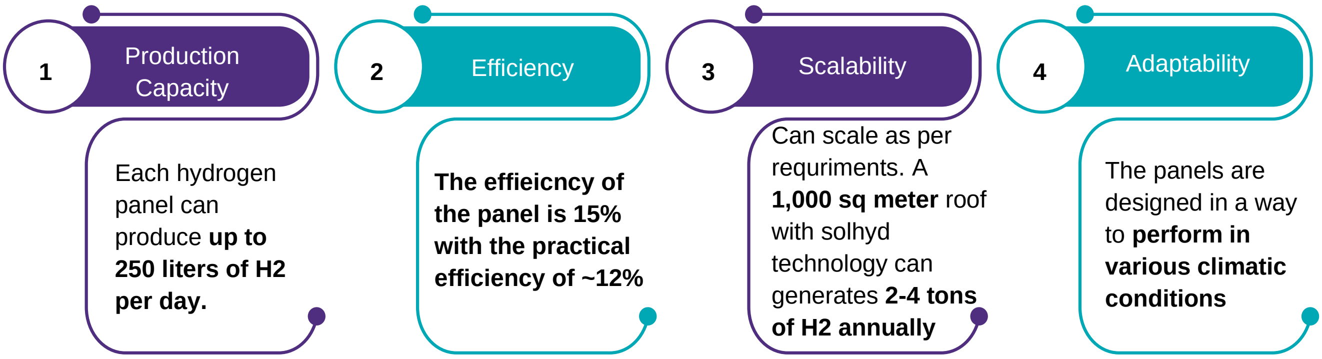
As the TalusAg project continues to grow and evolve, it will play a pivotal role in the global transition to sustainable agricultural practices and renewable energy. By making green ammonia accessible to farmers and industrial users worldwide, the project is paving the way for a more sustainable and resilient future.

6.1.2 Solhyd Project[57]

The Solhyd project aims to make green hydrogen accessible by using innovative hydrogen panels that harness water vapour and solar energy to produce hydrogen gas. These panels combine photovoltaic (PV) technology with a hydrogen production layer, capturing water from the air and splitting it into hydrogen and oxygen using sunlight. Solhyd offers a sustainable solution to the global energy challenge, contributing to a greener future.

Figure 21: Solhyd device[57]

- **Key Objectives**
    - **Sustainability:** Provide a clean and renewable source of hydrogen.
    - **Accessibility:** Make green hydrogen available to anyone, anywhere.
    - **Innovation:** Utilize advanced technology to efficiently produce hydrogen.
- **Technological Innovations:** The Solhyd project incorporates several technological innovations that set it apart from conventional renewable energy solutions:
    - **Membrane Technology:** The panels use advanced membrane technology to channel water vapor from the air to the hydrogen production layer. This process is both efficient and environmentally friendly, as it eliminates the need for external water sources.
    - **Bifacial Solar Modules:** The hydrogen panels utilize bifacial monocrystalline solar modules, which are capable of capturing sunlight from both sides. This design increases the overall energy capture and enhances the efficiency of the hydrogen production process.
    - **Integration:** The hydrogen panels are designed for easy integration into existing solar systems. This compatibility allows for seamless adoption and minimizes the need for extensive infrastructure modifications.
- **Key Specifications**



- **Pilot Projects and Deployment:** The Solhyd project has been piloted and deployed in various locations to demonstrate its feasibility and effectiveness:
    - **Leuven, Belgium:** The first pilot production line for hydrogen panels was established near Leuven. This pilot project served as a proof of concept and helped refine the technology for broader deployment.
    - **Zellik, Flemish Brabant:** The Green Energy Park serves as a comprehensive living lab for testing hydrogen distribution networks. This facility provides valuable insights into the integration of hydrogen panels with existing energy infrastructure.

[57] https://solhyd.eu/en/

- North Brabant: A local microgrid project aims to reduce dependence on the electricity grid by integrating hydrogen panels with other renewable energy sources. This pilot project highlights the potential of hydrogen panels to support localized energy solutions.

- **Economic and Environmental Impact:** The Solhyd project has significant economic and environmental implications:
  - **Economic Impact**
    - **Cost Reduction:** The hydrogen panels lower the cost producing green hydrogen. By producing hydrogen on-site, the panels eliminate the need for transportation and reduce supply chain costs.
    - **Market Stability:** This technology helps produce hydrogen on site and thus has the potential to scales in applications such as fertilizer manufacturing as it could help stabilize fertilizer prices by providing a consistent and local supply of hydrogen protecting manufacturers from market volatility.
  - **Environmental Impact**
    - **Carbon Reduction:** The use of renewable energy sources in hydrogen production eliminates carbon emissions, and on site production enable reducing emission caused through transportation.
    - **Land Utilization:** The panels can enhance land use efficiency by combining crop production with onsite hydrogen generation. This dual-use approach maximizes the value of available land and supports sustainable agricultural practices.
- **Lessons Learned and Challenges:** The deployment of projects, provided valuable lessons and highlighted several challenges:
  - **Technical Feasibility:** The initial pilot projects have demonstrated the technical feasibility of producing hydrogen using solar energy. The integration of hydrogen panels with existing energy infrastructure has shown promising results. Improving efficiency of the system can give way for large scale installations and broaden the horizon for different applications such as at crop fields promoting agrivoltaics with hydrogen production.
  - **Economic Viability**: The overall yield of 2-4 tons of green hydrogen annually is not at par with the scale of traditional electrolysers and hence economic viability is not achieved. Increasing the efficiency of the panels would be a step towards higher yield and economic viability.

Conclusion

The Solhyd project represents a significant advancement in renewable energy technology, offering a viable solution for sustainable hydrogen production. Its innovative approach to capturing and utilizing solar energy to produce hydrogen gas has the potential to transform the energy landscape and support a greener future. Increasing system efficiency and improving the hydrogen yield will see large scale adoption and give way for innovative end use cases where hydrogen is produced on site using solar.

The success of the technology lies in its ability to integrate cutting-edge technology with practical applications, demonstrating the feasibility and benefits of hydrogen panels. As this technology continues to grow and evolve, it will play a pivotal role in the global transition to renewable energy.

6.2 Case Studies

The dual use of land for agricultural activities and solar PV installation is fast gathering pace. The opportunities it presents to both industries is undeniable. The ability of the farmer to use their land to draw extra value by installing solar PV presents multiple revenue generating opportunities, such as leasing the land to a project developer for electricity generation, but more so in using the solar energy to produce green hydrogen and ammonia that can further be used by him for fuelling his vehicles and as fertilizers. The potential unlocked by using their farmland wisely makes them less reliant for fuel and fertilizers and adds to the sustainability and carbon neutral cause.

In this section some case studies are be identified and analysed on how the synergies of agrivoltaics and green hydrogen are developed around the world and if there are any models that can be adopted in India.

6.2.1 The Good Earth Green Hydrogen and Ammonia Project (GEGHA)[58]

The GEGHA project is developed in Moree, in northern New South Wales, Australia. The project is a part of a cotton farm owned by sundown pastotal which is a privately owned agricultural enterprise in Australia. The project is being developed by Hiringa Energy.

[58] https://www.gegha.com.au/

- **Goal:** To help farmers reduce emission associated with their production and enable them to meet consumer demand for low-carbon and sustainable produce in an increasingly carbon conscious market.

- **Key Objective:** To make farmers more resilient, provide locally produced and low emission supply of key inputs to farm production and transport market such as fuel (GH2) and Fertilizers (NH3).

- **Project Details:** The GEGHA project is an integrated solar energy to hydrogen and ammonia operation developed on Sundown's Keytha agricultural property. The key projects components are.

    - **Solar Capacity:** 27MW
    - **Electrolyser Capacity:** 15MW
    - Project connected to battery storage system and low capacity grid connection
    - **Ammonia Plant:** Can produce upto 16 tonne per day
    - **Storage:** 3 tonne of hydrogen storage and 600 tonnes of ammonia storage capacity
    - **Offtake:** Ammonia will be directly used as fertilizer locally, where as hydrogen can may be used for on farm vehicles or supply to on road transport vehicles.

- **Economic, Environmental and Social Impact:** The production of ammonia as fertilizer and hydrogen as fuel provides a low carbon alternative for farm use and transportation. This project acts as a linchpin in the region transition towards a sustainable living and green energy economy.
    - **Economic:** The construction of the project will provide significant direct and indirect employment, apart from that prove base to develop a sustainable economy in the region through the use and trade of sustainable fertilizers and hydrogen produced.
    - **Social:** The project will improv the overall social fabric of the region by providing sustainable resources for end use, train and provide jobs to individuals in operation and maintenance of the plant.
    - **Environmental:** The GEGHA project will deliver a direct abatement of over 17,000t CO2 equivalent per annum and with the further expansion of the project in the region the abatement could grow to 164,000t CO2 equivalent per annum. The project will act as a direct substitute for fossil fuel generated fertilizers and LPG/fossil fuels used for transportation.

The stage one of the project is being supported by the New South Wales (NSW) government's hydrogen hub initiative and will prove to be a source of decentralized low carbon fertilizers and hydrogen for the local community. Further regional expansion in the area is planned for other sundown pastoral farms and may be adopted by other farm owners as well.

6.2.2 H2 Agrar – Developing GH2 mobility foe the agricultural state of lower Saxony[59]

The H2 Agrar joint project focuses on reducing the greenhouse gas emission form the fuel used in agricultural machinery and transport vehicles. It is an innovative project in Germany that aims to develop a sustainable way for farmers to integrate with renewable energy alternatives.

- **Goal:** Help farmers in reducing greenhouse gas emissions through their agricultural vehicle fleet.
- **Key Objective:** Develop a local source for sustainable fuel for farmers in the lower saxony region.

Figure 22: H2 Agrar Project in Lower Saxton[44]

[59] https://h2agrar-niedersachsen.de/

- **Project Details:** The H2 Agrar project is based in the model region of Haren (Ems) which is a strong agricultural area in the lower saxony region in Germany. The project includes a solar PV and wind installation coupled with battery energy storage and electrolyser for GH2 production[60]. The projects key components are:
    - **Solar Capacity:** ~1MW split between two farms
    - **Wind Capacity:** 67.2MW of Nominal power (16 E138 EP3 wind turbines)
    - **Battery Storage:** 7.4MWh of battery capacity
    - **Electrolyser:** 2MW
    - **Offtake:** Hydrogen Fuelling stations
- **Economic and Environmental Impact:** The development of the hydrogen infrastructure for agricultural vehicles and other forms of transport based on the use of renewable energy sources such as solar, wind and battery storage will act as a model to synergies agricultural land with renewable energy making it beneficial for all stakeholders.
    - **Economic**: The use of renewable energy to produce green hydrogen provides an additional source of income to the farmers and reduce their own fuel consumption for on farm vehicle creating a win-win situation for all.
    - **Environmental**: The use of green hydrogen for on farm vehicles and other transportation vehicles through the hydrogen fueling hubs contributes to the abatement of CO2 emissions.

The H2 Agrar project was financed predominantly by the state of Lower Saxony and further funding and grants are in progress to increase the number of pilots and improve the efficiency of the projects and create a more sustainable environment for the farmers in the region.

6.2.3 HydroGlen Project[61]

The Hydroglen hydrogen powered farming community built at the James Hutton Institute's Glensaugh research farm in northeast Scotland. The project will integrate renewable energy sources such as agrivoltaics, wind and energy storage to produce green hydrogen. The use of renewable energy and green hydrogen will contribute to the decarbonizing efforts of Scotland and aid in developing a green economy through energy transition.

- **Goal**: Create an in-house facility to manufacture green hydrogen for decarbonizing efforts
- **Key objective**: Encourage the use green hydrogen by farmers for on farm vehicles and fertilizers for the fields.
- **Project Details**: The project aims to be an integrated source of energy and fuel for framers which meets their on-farm needs and a business opportunity to use the surplus energy for hydrogen fueling station and electric charging stations proving additional source of revenue to the farmers. Funding form the Scottish Government is secured and the project is expected to be completed by 2025. The key project components for the base case of the study are[62]:
    - **Solar**: 50kW
    - **Wind**: 800kW
    - **Electrolyser**: ~150kW
    - **Hydrogen Storage**: 950kg
    - **Annual Hydrogen Production**: 2,740kg
    - **Battery Storage**: 100kW
    - **Hydrogen Fueled vehicles**: 2
    - **Hydrogen Fueling stations**: 1
    - **Battery Electric Vehicles**: 10
    - **Electric Vehicle Charing Station**: 5 x 7.2kW

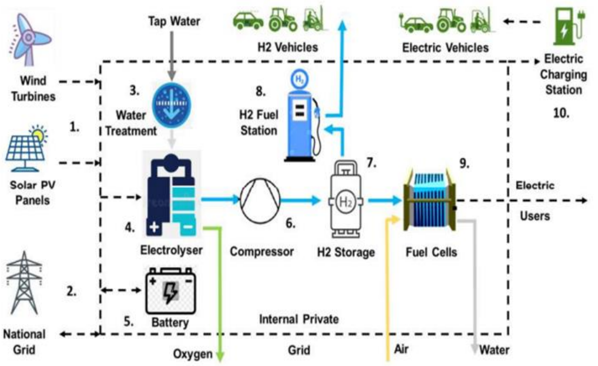


Figure 23: Layout of HydroGlen project[47]

[60] https://cec-haren.de/
[61] https://glensaugh.hutton.ac.uk/climate-positive-farming/renewable-energy
[62] https://www.hutton.ac.uk/sites/default/files/files/publications/Glensaugh_HydroGlen_NonTech_Feasibility_March2021.pdf

- **Economic and Environmental Impact:** The HydroGlen demonstrates the feasibility of enabling farming and other rural communities to become self-reliant, low carbon energy producers, exporters and are capable for meeting all their energy requirements for heating, fuel and electricity through sustainable means.
    - **Economic**: The use of renewable energy on the farm allows the farmers to become self-reliant through consumption of energy by solar/wind sources and fuel from hydrogen sources which reduces their expenses, additionally the sale of additional power and fuel provides an additional source of income as well.
    - **Environmental**: The installation of renewable energy source to generate electricity and green hydrogen helps in aiding the decarbonizing efforts and encourage other rural areas and farms to take the sustainable route and become self-reliant.

The HydroGlen initiative in an effort by the Scottish government and the Jame Hutton Institute to make the farming community more sustainable and self-reliant and developing a model that can be replicated in the near future in other region of the country.

6.2.4 Project Burgundy[63]

This Project is a joint development partnership between Q Enenrgy a renewable energy developer and Inthy French company that aids in financing renewable energy projects. The project aims to develop an agrivoltaics project and use it for the production of green hydrogen. The project is expected to be complete by 2028. The project will aid in the decarbonizing the local fleets, farm equipment and other local industrial processes.

- **Goal:** To increase the productivity of farmland by integrating renewable energy source and green hydrogen production
- **Key Objective:** The use of renewable energy to produce green hydrogen will aid in the decarbonizing efforts and provide an alternative fuel source to vehicles and industrial processes.
- **Project Details:** The project aims to produce green hydrogen through renewable energy sources which will provide a secure supply of fuel for local consumption for the long term at reasonable price.
    - **Solar:** 7MW
    - **Electrolyser:** 5MW
    - **Hydrogen Production:** 2 tonnes per day
    - **Farming land:** 11 hectares
    - **Offtake:** recharge up to 65 buses a day or other farming vehicles

This project is expected to be developed in a farm in Burgundy, near Dijon in France and is being developed by Q Energy and Inthy. Where the project aims to develop an agrivoltaics project and produce green hydrogen using electrolysers. The project is expected to be completed by 2028 and will aid in producing reliable and sustainable fuels to transport vehicles and farm vehicles. This project will aid in increasing decarbonizing efforts in the nearby farming areas and increase the productivity of farms by producing electricity through agrivoltaics and green hydrogen.

6.3 SWOT Analysis & Best Practices / Standard Operating Procedures (SOP) for synergising Agrivoltaics and Green hydrogen projects.

The concept of agrivoltaics which is a novel and a developing technology, it serves as dual use of land for agricultural activities and solar PV installation mitigating the conflicts between solar installations and agricultural activities serving as an opportunity for all stakeholders to benefit from such innovative technologies. Whereas green hydrogen technology has been more established and accepted in the market and continues to have technological advancements to improve its efficiency and safety standards to provide better reliable decarbonising solution.

The integration of two relatively developing technologies of Agrivoltaics and green hydrogen provide a deeper value to the farm owner substantially increasing the revenue for the plant owner through sale of excess electricity, sale of green hydrogen and produce ammonia for fertilizer at a relatively low cost or the farm owner may also consume the manufactured hydrogen and ammonia and save on fuel and fertilizer costs. The entire operation of integrating is a win - win situation for everyone involved.

[63] https://fuelcellsworks.com/2024/10/15/clean-energy/france-q-energy-and-inthy-join-forces-to-develop-a-renewable-project-combining-green-hydrogen-and-agrivoltaics

6.3.1 SWOT Analysis[64] [65]

A SWAT analysis integrating two independently growing technologies will provide an overview of different aspects in each technology that will allow them to scale together and understand aspects where there can be challenges in bringing the technologies together. The Analysis will also look at the overall benefits and disadvantages of using the technologies together as a complete system.

Strengths	Weakness	Opportunities	Threats
• **Dual use of land:** Optimise land use for energy and agriculture. • **RE Synergy:** SolarPV supports GH2 production, shaded crop growth and sale of excess energy. • **Decarbonization:** Aids in reducing carbon footprint across agriculture and energy sector.	• **High Initial Cost:** Expensive to setup an electrolyser plant and run it using agrivoltaics plant. • **Technical Challenges:** Requires expertise in agrivoltaics and GH2 production. • **Intermittent power supply:** Availability of solar energy affects consistent GH2 production. • **Policy & Regulations:** No clear policies or regulations around synergising GH2 and Agrivoltaics.	• **Job Creation:** New Employment opportunities across the value chain of both technologies. • **Rural Development:** Exposure to clean energy and training individuals for jobs especially in rural areas encourages technology adoption. • **Government Incentives:** Forward looking policies in solar and GH2 in countries and specific states make technology adoption more lucrative. • **Collaboration with Private Sector:** Private sector investing and collaborating with farmers to develop Agrivoltaics and GH2 projects for captive consumption and additional sale.	• **Market Volatility:** Both Agrivoltaics and GH2 are developing technologies and hence market acceptance despite opportunities is volatile. • **Offtake Issue:** managing hydrogen production and developing avenues for sale across different applications. • **Competition with other fuel options:** Competition form biofuel and electric vehicle provide better return compared to GH2 vehicles. • **High Maintenance Cost:** Regular maintenance of agrivoltaics plant, electrolyser, storage units will be expensive.

The above-mentioned SWOT analysis broadly covers the all the considerations for both technologies separately and together as well, providing and overarching view on the benefits of using the technologies together and the complications that can arise.

[64] https://www.ceew.in/sites/default/files/renewable-energy-green-hydrogen-land-water-nexus-in-india.pdf
[65] https://beta.cstep.in/staaidev/assets/manual/APV.pdf

6.3.2 Best Practices / Standard Operating Procedures to synergise Agrivoltaics and Green Hydrogen[66] [67] [68] [69]

To scale these synergies between agrivoltaics and green hydrogen certain best practices or SOPs need to be developed to provide guidelines in implementing such projects which involve different kinds of technologies and require additional care while developing projects.

The best practices can be categorised into four primary themes “The 4 Cs Method”.

1. **Climate:** Consideration should be given to understanding the soil, environmental conditions in terms of irradiance, availability of water for green hydrogen production and most importantly crop cycles to design the height and overall design of the agrivoltaics installation.
2. **Configuration:** This involves meticulously designing the agrivoltaics site considering aspects such as the tilt angle of the panels, the height of the installation, the type of solar panel used, sizing the electrolyser as per the requirements of the project and positioning all the key components in appropriate locations to avoid any reconstruction.
3. **Compatibility:** Designing the entire project to meet the exact needs of the end user which could vary from on-farm consumption in tractors, to manufacturing and selling fertilizers, storing and sale of green hydrogen to recharge facilities or selling the excess electricity to the grid. The project must be compatible to the requirements of the user and have room for any future modifications when required.
4. **Collaboration:** The project must be able to add value to the entire community providing access to decarbonizing solutions for all stakeholders involved and engage in community building and increasing awareness about the synergies of agrivoltaics and green hydrogen.

These best practices/SOPs will act as guardrails for scaling and designing agrivoltaics and green hydrogen projects together. The 4 Cs method provides a comprehensive and inclusive approach to any project which synergises agrivoltaics and green hydrogen acting as a strong framework to develop large scale integrated projects keeping in mind the key consideration to understanding offtake strategies and involvement of community to create awareness about agrivoltaics and green hydrogen.

[66] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Jul/IRENA_Green_hydrogen_strategy_design_2024.pdf
[67] https://www.nrel.gov/docs/fy22osti/83566.pdf
[68] https://gh2.org/sites/default/files/2023-12/GH2_Standard_2.0_Dec%202023.pdf
[69] https://isa.int/uploads/publiction_pdf/1738651828Factsheet_4_Agri-PV.pdf

Annexures

Annexure 1: Different Scheme Guidelines for Green Hydrogen in India

Scheme Guidelines for Green Hydrogen Pilot Projects in the Shipping Sector[70]

The Ministry of New and Renewable Energy (MNRE) issued guidelines on February 1, 2024, for pilot projects aimed at utilizing green hydrogen in the shipping sector under the National Green Hydrogen Mission. The scheme seeks to decarbonize the economy, reduce dependency on fossil fuel imports, and position India as a global hub for green hydrogen production, use, and export.

The scheme includes two components:

- Component A: Retrofitting existing ships to operate on green hydrogen or its derivatives.
- Component B: Developing bunkering and refueling facilities at ports for green hydrogen-based fuels.

The Shipping Corporation of India will act as the Scheme Implementation Agency (SIA) for Component A, while a separate SIA, nominated by the Ministry of Ports, Shipping and Waterways (MoPSW), will oversee Component B.

Funding and Disbursement:

- Total budgetary allocation: ₹115 crore until the financial year 2025-26.
- ₹80 crore allocated for Component A.
- ₹35 crore for Component B.

The funds are interchangeable and transferable between components.

The scheme will evaluate the economic viability, performance, and safety of green hydrogen propulsion and refueling systems in the shipping sector.

Scheme Guidelines for Green Hydrogen Pilot Projects in the Steel Sector[71]

The Ministry of New and Renewable Energy (MNRE) issued guidelines on February 2, 2024, for the implementation of pilot projects using green hydrogen in the steel sector under the National Green Hydrogen Mission. These projects aim to integrate green hydrogen technologies into steel manufacturing to reduce carbon emissions, improve energy efficiency, and promote sustainable practices in the industry.

Funding and Disbursement:

- Funding covers up to 50% of total project costs, with potential for 70% funding for consortiums of Independent Steel Producers or Direct Reduced Iron (DRI) industry associations.

Disbursement is structured as:

- 20% upon issuance of the letter of award.
- 70% based on milestones outlined in proposals.
- 10% upon project completion.

The scheme has a total budget allocation of ₹455 crore until the financial year 2029-30.

Scheme guidelines for setting up hydrogen hubs[72]

The Ministry of New and Renewable Energy (MNRE), under the National Green Hydrogen Mission, has outlined a plan to establish Green Hydrogen Hubs to promote large-scale hydrogen production. The guidelines focus on developing essential infrastructure such as storage, transportation, refueling stations, and advanced technologies like hydrogen compression and liquefaction. The initiative, overseen by designated Scheme Implementing Agencies (SIAs), aims to enhance the cost competitiveness of green hydrogen and stimulate domestic use and exports.

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[70] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2024/02/20240205992946502.pdf
[71] https://mnre.gov.in/notice/scheme-guidelines-for-implementation-of-pilot-projects-for-use-of-green-hydrogen-in-steel-sector-under-the-national-green-hydrogen-mission-nghm/
[72] https://mnre.gov.in/notice/scheme-guidelines-for-setting-up-hydrogen-hubs-in-india-under-the-national-green-hydrogen-mission-nghm/

The mission seeks to develop at least two hubs by FY 2026, with a budget of ₹2 billion allocated until FY 2025-26. Key features of these hubs include:

- Strategic Locations: Hubs will be networks of producers and end-users, located either inland or near ports to facilitate exports. Regions with clusters of refineries or end-use industries will be prioritized.
- Capacity and Infrastructure: Each hub must have a minimum production capacity of 100,000 metric tonnes per annum, with preference given to higher capacity hubs. The scheme encourages the use of existing infrastructure to reduce costs and expedite development.
- Resource Integration: Infrastructure, projects, and resources will be systematically mapped under the PM Gati Shakti initiative for better coordination and resource utilization.
- Additional Designations: MNRE may designate other regions as hydrogen hubs, which may not receive financial support but will qualify for benefits.

This initiative aims to create a robust hydrogen ecosystem, contributing to India's decarbonization and energy independence goals.

Scheme Guidelines for Funding of Testing Facilities, Infrastructure, and Institutional Support[73]

On July 4, 2024, the Ministry of New & Renewable Energy (MNRE) issued guidelines for funding testing facilities, infrastructure, and institutional support as part of the National Green Hydrogen Mission. The scheme aims to develop standards and regulatory frameworks for green hydrogen and its derivatives.

The primary focus is on:

- Identifying gaps in existing testing facilities for components, technologies, and processes related to green hydrogen.
- Upgrading existing testing infrastructure and creating new facilities to ensure safe and secure operations across the hydrogen value chain.

Funding and Disbursement: Total budget: ₹200 crore until the financial year 2025-26.

The National Institute of Solar Energy (NISE) will serve as the Scheme Implementation Agency (SIA).

This initiative will enhance the reliability and safety of green hydrogen production, distribution, and utilization by supporting the development of a robust testing ecosystem.

Scheme Guidelines to Support Pilot Projects on New and Innovative production techniques and applications of Green Hydrogen in Residential, Commercial, Localised Community, Decentralised/Non-Conventional areas[74]:

On November 08th, 2024, the Ministry of New and Renewable Energy (MNRE) has issued guidelines to promote innovation in green hydrogen production and utilization. The initiative, part of the National Green Hydrogen Mission, aims to support pilot projects exploring new methods for green hydrogen production, such as using floating solar, wastewater, and biomass. These methods aim to enhance the efficiency and sustainability of hydrogen production. Additionally, the focus on decentralized applications seeks to demonstrate the practical benefits and versatility of green hydrogen in residential and community settings. The pilot projects will rigorously test the safety, reliability, and technical feasibility of green hydrogen in new sectors, helping to establish it as a viable and secure energy source.

The policy emphasizes several key areas:

- **Innovative Production Methods**: The projects will explore various cutting-edge techniques for green hydrogen production, including the use of floating solar panels, wastewater, and biomass. These methods aim to enhance the efficiency and sustainability of hydrogen production.
- **Decentralized Applications**: A significant focus is placed on the use of green hydrogen in decentralized settings. This includes residential and community applications such as cooking, heating, and off-grid power generation. By targeting these areas, the policy aims to demonstrate the practical benefits and versatility of green hydrogen.
- **Safety and Feasibility**: The pilot projects will rigorously test the safety, reliability, and technical feasibility of green hydrogen in new sectors. This will help establish green hydrogen as a viable and secure energy source for diverse applications.

Funding and Disbursement: Total budget of ₹2 billion until 2025-26.

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[73] https://mnre.gov.in/notice/nghm-testing-scheme/
[74] https://cdnbbsr.s3waas.gov.in/s3716e1b8c6cd17b771da77391355749f3/uploads/2024/11/20241108456000928.pdf

Annexure 2: Results of Different Tenders Floated by SECI

SECI's Electrolyser Manufacturing Auction and Results

The Solar Energy Corporation of India (SECI) has been instrumental in implementing India's ambitious green hydrogen roadmap under the National Green Hydrogen Mission. In a bid to develop domestic manufacturing capacity for electrolysers, SECI launched two tranches of its Electrolyser Manufacturing Auction, each with a capacity of 1.5 GW. These auctions are a critical step toward reducing dependency on imports and achieving self-reliance in green hydrogen production infrastructure.

Tranche-I: Electrolyser Manufacturing Auction

SECI floated the tender for Tranche-I in mid-2023, targeting a capacity of 1.5 GW. The auction witnessed significant interest from Indian conglomerates, signaling growing confidence in the country's renewable energy sector. The competitive bidding process focused on encouraging domestic manufacturing aligned with India's 'Make in India' initiative.

In January 2024, SECI declared the results, awarding capacities to prominent players:

Table 4: Award for Manufacturing of electrolyser under SIGHT scheme –Bucket 1

Sr. No.	Name of the Bidder	Awarded Capacity	Type of Electrolyser
1	Reliance Electrolyser Manufacturing Limited	300	Alkaline
2	Ohmium Operations Private Limited	137	PEM
3	John Cockerill Greenko Hydrogen Solutions Private Limited	300	Alkaline
4	Advait Infratech Limited (consortium with Rajesh Power Service Private Limited)	100	Alkaline
5	Jindal India	300	Alkaline
6	L&T Electrolyser Limited	63	Alkaline
	Total	**1200**	

Table 5: Award for Manufacturing of electrolyser under SIGHT scheme –Bucket 2

Sr. No.	Name of the Bidder	Awarded Capacity	Type of Electrolyser
1	Homi hydrogen Private Limited	101.5	AMSE/Solid oxide
2	Adani New Industries Limited	198.5	Alkaline
	Total	**300**	

The projects under Tranche-I are expected to commence operations within 24 months. These facilities will manufacture high-efficiency electrolysers for green hydrogen production, catering to both domestic demand and potential exports.

Tranche-II: Electrolyser Manufacturing Auction

Following the success of Tranche-I, SECI launched Tranche-II in early 2024, offering an additional 1.5 GW capacity. The tender aimed to further boost domestic manufacturing and accommodate the rising demand for green hydrogen production infrastructure.

The tender, floated in March 2024, was divided into three distinct buckets:

- Bucket 1: Allocated 1,100 MW of electrolyzer manufacturing capacity, open to any stack technology.
- Bucket 2A: Designated 300 MW to be developed using indigenously developed stack technology.
- Bucket 2B: Focused on smaller units, with 100 MW mandated to use domestically developed stack technology.

By September 2024, SECI announced the winners:

Table 6: Winner under Bucket 1

Sr. No.	Company Name	Capacity (MW)
1	Waaree Energies	300

Sr. No.	Company Name	Capacity (MW)
2	Matrix Gas and Renewables	237
3	Advait Infratech	200
4	Ohmium Operations	137
5	GH2 Solar	105
6	Newage Green Electro	71.5
7	Avaada Electrolyser	49.5
	Total	1100

Table 7: Winner under Bucket 2A

Sr. No.	Company Name	Capacity (MW)
1	Adani Enterprises	71.5
2	Newage Green Electro	228
	Total	300

Table 8: Winner under Bucket 2B

Sr. No.	Company Name	Capacity (MW)
1	Adani Enterprises	30
2	Eastern Electrolyser	30
3	Newtrace	30
4	Suryaashish KA1 Solar Park (InSolare)	10
	Total	100

The second tranche is designed to expedite manufacturing capabilities, with completion timelines set at 18 months. Both tranches align with India's vision of producing 5 million tonnes of green hydrogen annually by 2030.

SECI's Green Hydrogen Manufacturing Production

SECI also floated a tender in July 2023 for green hydrogen manufacturing, targeting the production of 450,000 metric tonnes (MT) annually. This auction aimed to incentivize companies to establish large-scale green hydrogen production facilities while offering competitive production-based subsidies.

The tender results were announced in January 2024, with the capacities divided into two categories:

Bucket I (410,000 MT/year):

Table 9: Bucket-1 (Technology Agnostic Pathways)

Sr. No.	Company	Production Target (MT/year)	Incentive per kg (₹)
1	Reliance Industries	90,000	18.9
2	Greenko	90,000	30
3	ACME	90,000	30
4	Welspun New Energy	20,000	20
5	JSW Energy	6,500	34.66
6	Hygenco	75,000	25.04
7	Torrent Power	18,000	28.89

Sr. No.	Company	Production Target (MT/year)	Incentive per kg (₹)
8	Calcutta Electric Supply Corporation (CESC)	10,500	0
9	UPL	10,000	0
	Total	**4,10,000**	

Bucket II (40,000 MT/year):

Table 10: Bucket-2 (Biomass Based Pathways)

Sr. No.	Company	Production Target (MT/year)	Incentive per kg (₹)
1	Bharat Petroleum Corporation Limited (BPCL)	2,000	30

While most of the capacities in Bucket I were allocated, 38,000 MT in Bucket II remained unawarded due to insufficient bids. Successful bidders are required to commission their projects within 30 months.

SECI's Tender for Green Ammonia Production

To complement its efforts in green hydrogen, SECI invited bids for green ammonia production under the Strategic Interventions for Green Hydrogen Transition (SIGHT) program. The tender, launched in mid-2024, initially aimed at 550,000 MT/year but was later expanded to 750,000 MT/year by the Ministry of New and Renewable Energy (MNRE) in response to the increase in demand of Green Ammonia from the fertilizer sector.

Sr. No.	Name of Procurer	Annual GA Requirement (MT)
1	Indian Farmers Fertiliser Cooperative Limited (IFFCO), Gujarat	1,00,000
2	Indian Farmers Fertiliser Cooperative Limited (IFFCO), Odisha	1,00,000
3	Madras Fertilizers Limited (MFL)	4,000
4	Gujarat Narmada Valley Fertilizers & Chemicals Limited (GNFC)	50,000
5	Paradeep Phosphates Limited (PPL), Odisha	75,000
6	Paradeep Phosphates Limited (PPL), Goa	25,000
7	Indorama India Private Limited (IIPL)	20,000
8	Mangalore Chemicals & Fertilizers Ltd. (MCFL)	15,000
9	Coromandel International Limited (CIL) Vishakhapatnam	50,000
10	Coromandel International Limited (CIL) (Kakinada)	85,000
11	Coromandel International Limited (CIL) (Ennore)	15,000
	Total	**5,39,000**

This capacity enhancement underscores the government's commitment to meeting domestic demand and strengthening the role of green ammonia in fertilizer production and other industrial applications. The SIGHT program includes procurement agreements to ensure market viability and attract private sector investment.

India’s green ammonia initiative is expected to boost the adoption of green hydrogen derivatives in the fertilizer sector, with MNRE facilitating an additional purchase of 200,000 MT/year on behalf of fertilizer manufacturers.

Annexure 3: Assessment of Agrivoltaics system with fixed conventional Solar PV system

Defining the land usage comparison between fixed conventional solar systems and Agrivoltaic systems is crucial, particularly when exploring the synergy between Agrivoltaic and green hydrogen production. A conventional system prioritizes energy generation, utilizing land solely for solar installations, whereas Agrivoltaic systems enable dual land use by integrating solar energy generation with agricultural activities. When combined with green hydrogen production, Agrivoltaic systems offer a transformative approach to sustainable development by maximizing land efficiency.

Assessment Results

Table 11: Assessment of fixed solar pv system and Agrivoltaics - Single axis tracking system

Parameters	Fixed Solar PV System	Fixed Solar PV System considering Tractor Movement	Agrivoltaics - Single axis tracking system	Units
Solar PV system capacity:	≈ 1 MWp			MWp
Number of solar modules:	1512			Nos.
Solar module maximum power:	660			Wp
Tilt Angle:	22	22	+/- 60	Degree
Facing of PV module:	Towards south	Towards south	Towards East - West	Degree
Pitch:	8.90	10.00	10.00	Meters
Minimum Height from the ground:	1.20	1.20	4.07	Meters
Table to table distance:	4.50	5.57	7.62	Meters
Area requirement for Solar PV modules placement (Excluding other equipment BOS and arrangements)	2.9	3.2	5.52	Acres

A comparative analysis of conventional solar systems and Agrivoltaic systems highlights the difference in land requirements for around 1 MWp installation. With a conventional system needing 2.9 acres and a single axis tracking Agrivoltaic system requiring 5.52 acres, the additional land requirement is approximately 90.34% more. This increase is due to the spacing adjustments in Agrivoltaic systems to facilitate tractor movement and maintain agricultural productivity alongside solar energy generation. Assessment's representation in the drawing has been shown below for the reference for both systems:

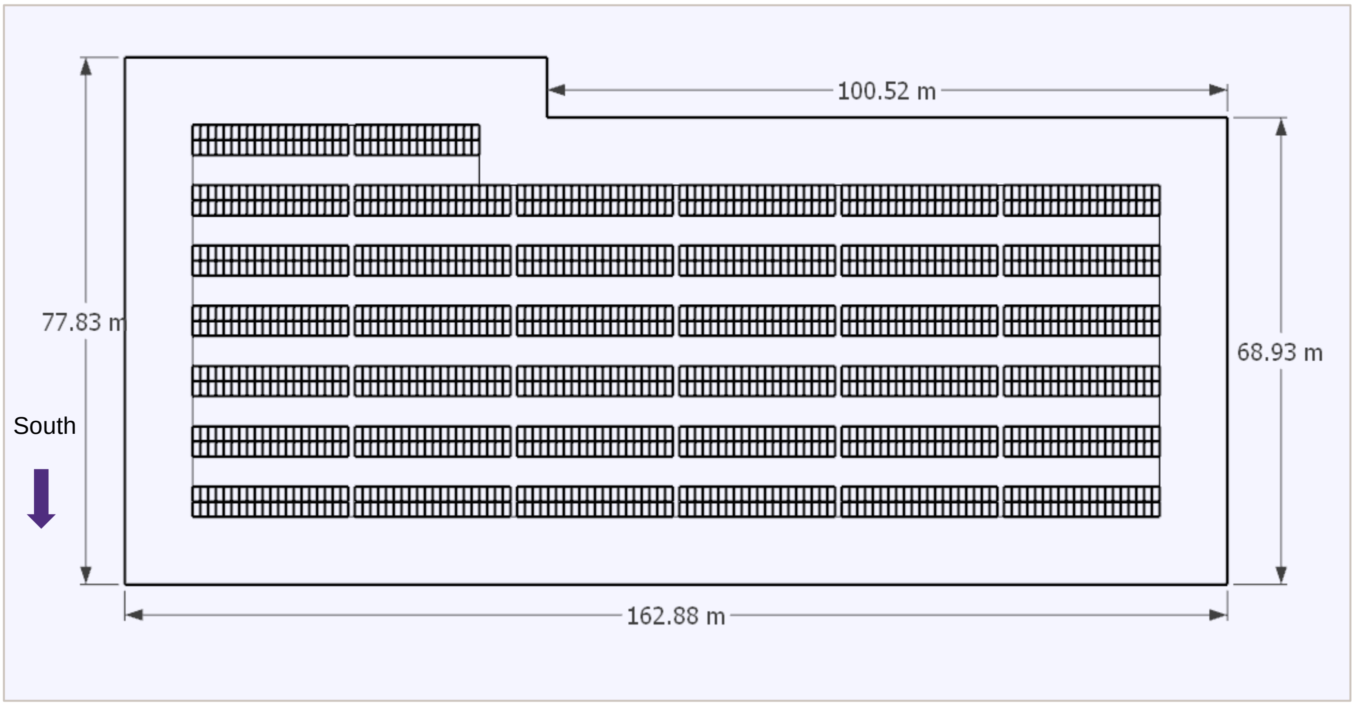

Figure 24: MW Fixed tilt conventional Solar PV System

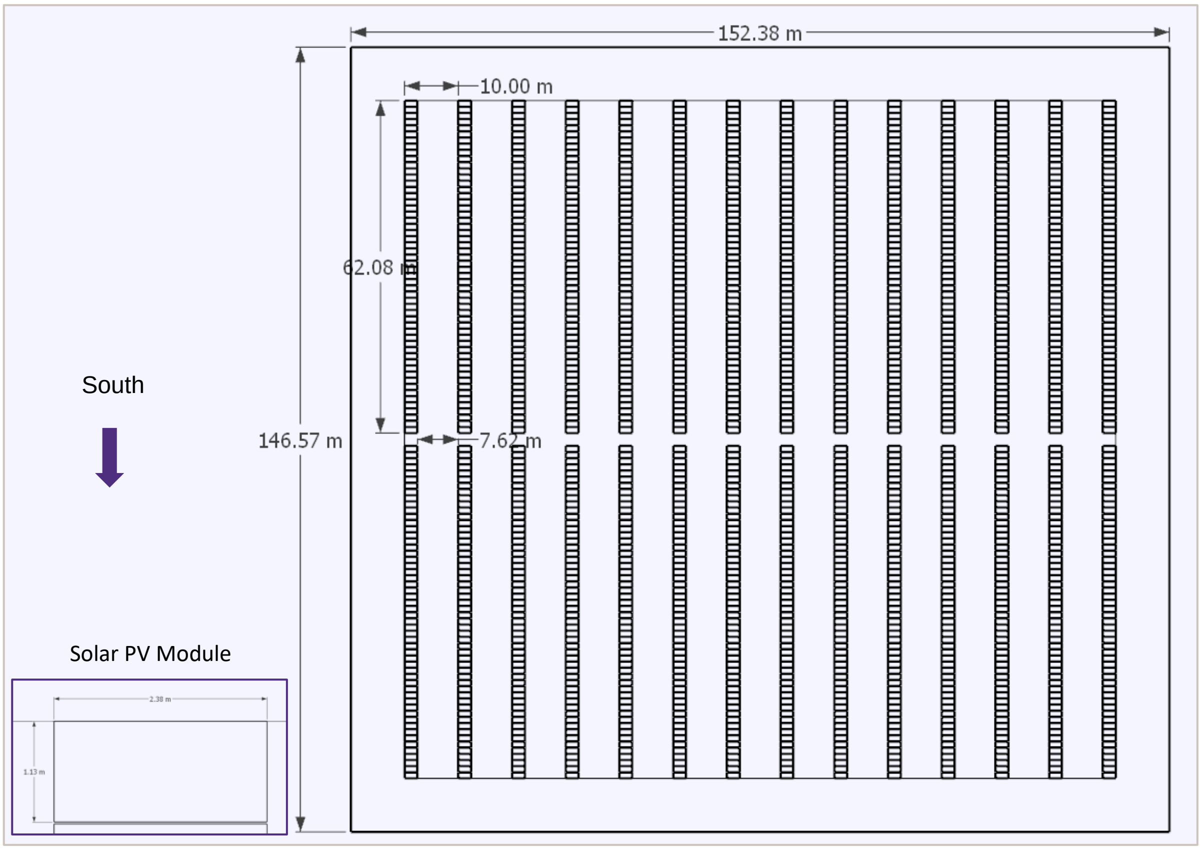

Figure 25: 1 MW Agrivoltaics system arrangement (Single Axis Tracking NS)

Annexure 4: PM Kusum Yojana Progress

Component Wise Progress as on 31 December 2024.

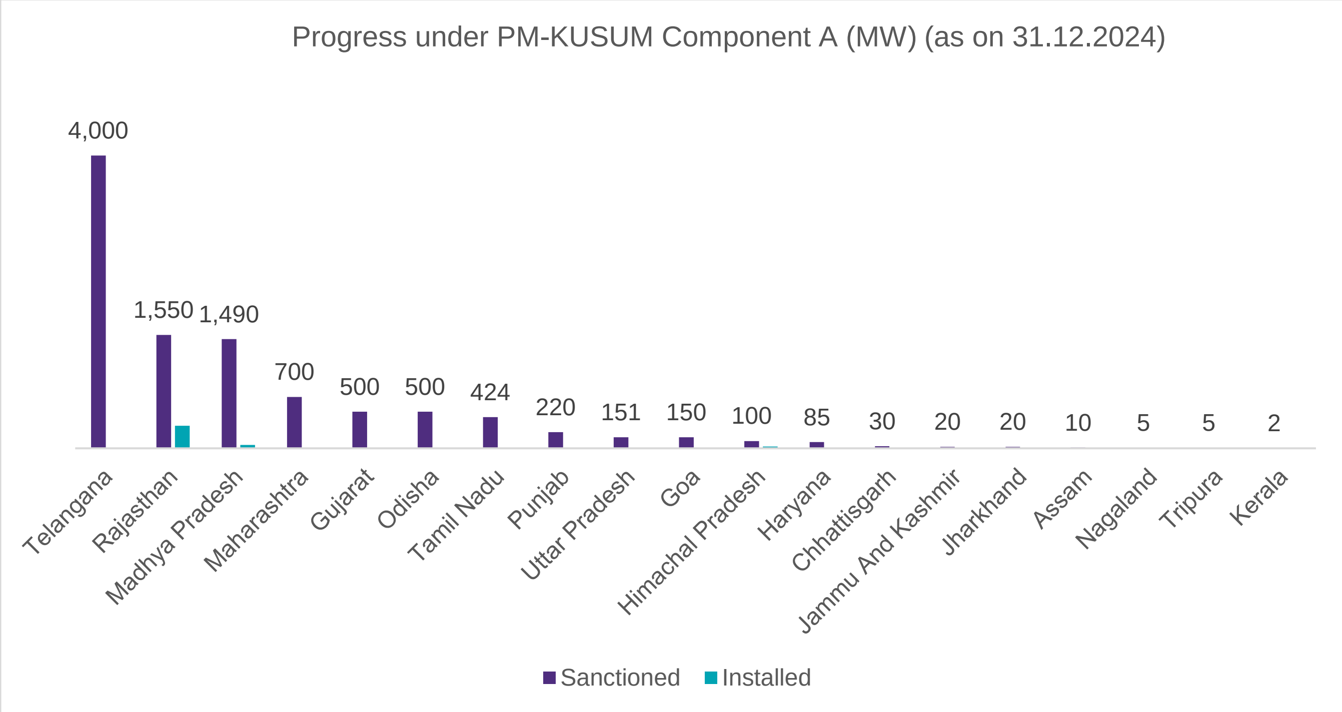

Figure 26: PM-KUSUM Component A state wise progress

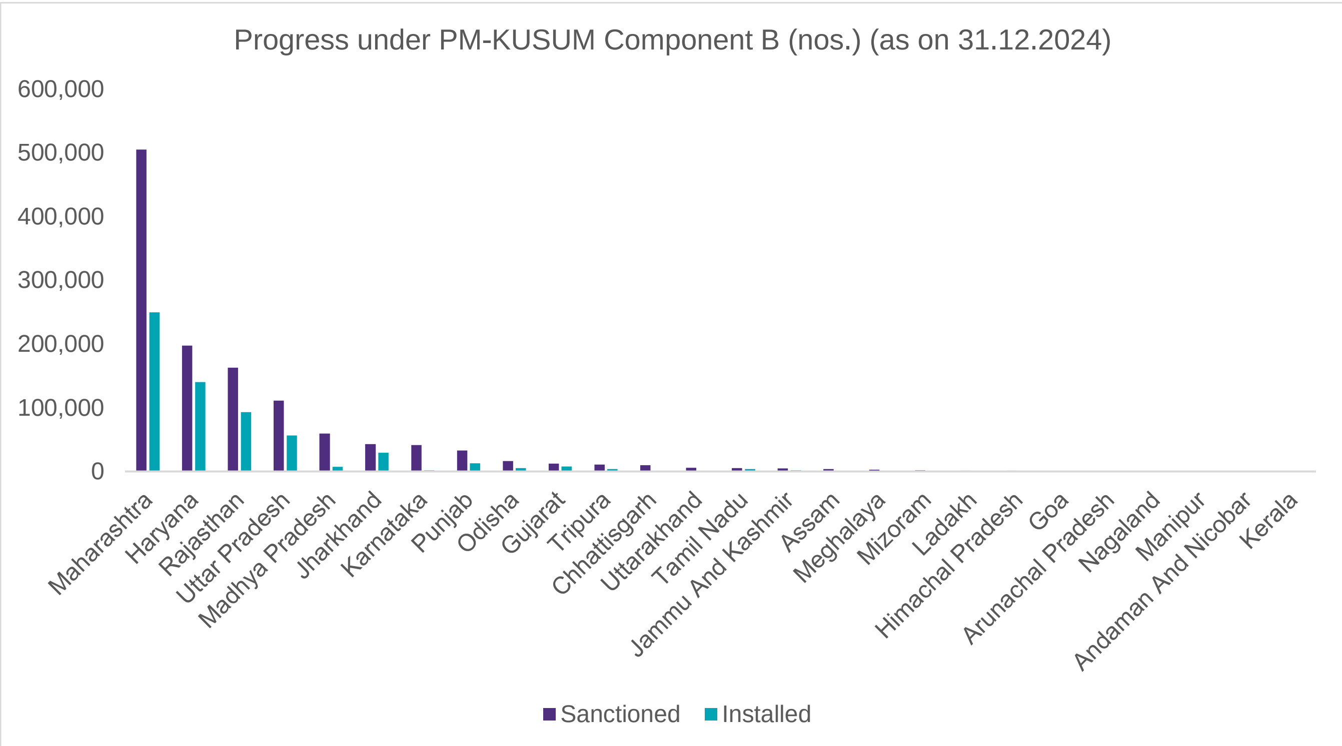

Figure 27: PM-KUSUM Component B state wise progress

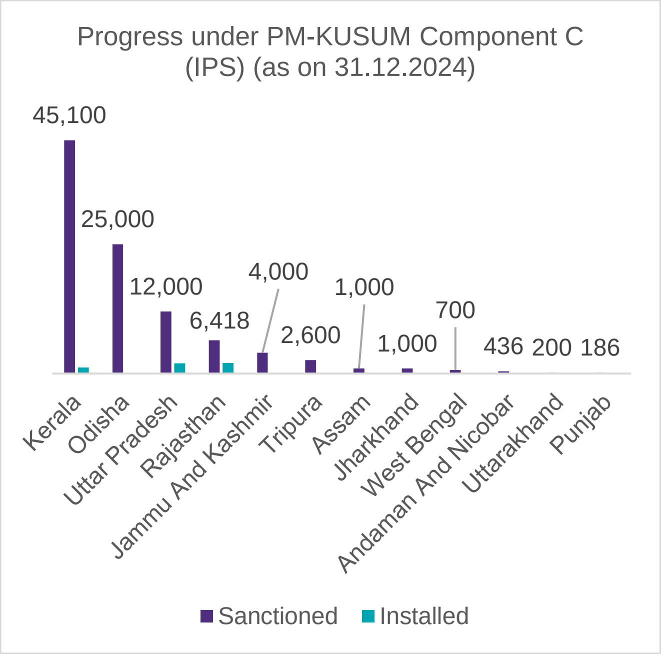

Figure 2828: PM-KUSUM Component C (IPS) state wise progress[75]

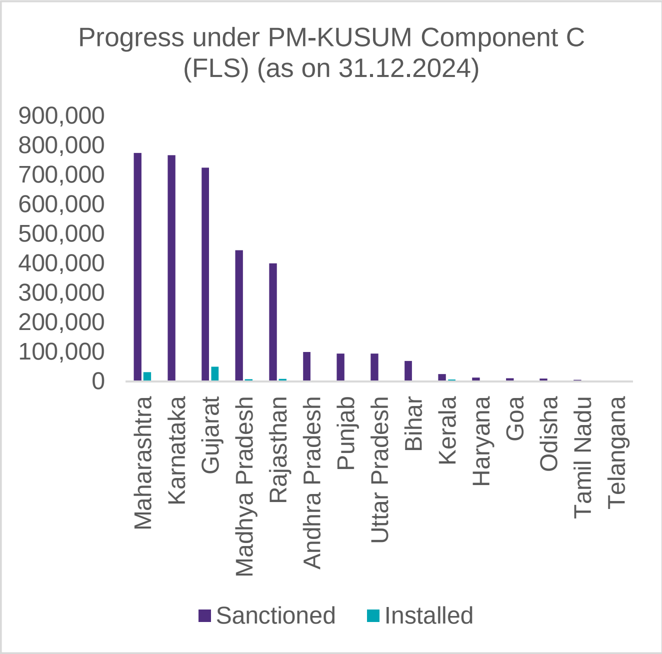

Figure 2929: PM-KUSUM Component C (FLS) state wise progress [76]

India is promoting Agrivoltaics systems under the PM-KUSUM scheme, with an increasing focus on decentralized solar installations. Rajasthan is at the forefront, emerging as a leader in the deployment of Agrivoltaics systems. The state has sanctioned substantial capacities owing to its favourable solar radiation levels and vast tracts of land. Other states like Maharashtra, Madhya Pradesh, and Gujarat are following closely, contributing to the growing momentum of Agrivoltaics adoption. These states leverage their agricultural potential and solar resources, aligning with the government's vision to integrate renewable energy with farming practices.

[75] National Portal for PM-KUSUM
[76] National Portal for PM-KUSUM

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