Study on the Synergies and Analysis of Using (Agri)Photovoltaics in Recultivated Coal Mines

Imprint

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1 Executive Summary

The report, “Study on the synergies and analysis of using (agri)photovoltaics in recultivated coal mines”, explores the potential of implementing photovoltaic (PV) and agrivoltaic (APV) systems on reclaimed coal mining land, primarily focusing on German mining regions managed by RWE and LEAG.

The study identifies PV systems as a cost-effective and scalable option for renewable energy production in former opencast mining regions, given Germany's commitment to phasing out coal by 2038. It highlights the advantages of dual-use APV systems, which allow for both crop cultivation and energy generation, though these face challenges due to higher costs, regulatory complexities, potential soil quality issues in reclaimed mines, and lack of large capacity experiences/examples. The report provides case studies of RWE and LEAG’s approaches, including mostly conventional ground-mounted PV systems, but notes that only pilot-scale APV is currently being implemented and explored.

The report recommends continued research, financial incentives, and regulatory support for PV, especially APV systems, along with site-specific assessments and additional pilot projects. It emphasizes collaboration among energy companies, agricultural experts, and policymakers to address technical and regulatory barriers while also supporting sustainable job creation as part of a just transition in these coal regions.

2 Background

Photovoltaics (PV) harness solar energy by converting sunlight directly into electricity using semiconductor materials. This technology has been around for many decades, however, in recent years research and development in the field have been particularly robust, contributing to a dynamic and rapidly growing sector within the renewable energy landscape. This rapid advancement has led to PV offering a scalable and increasingly cost-effective solution for renewable energy generation, positioning PV to become a key pillar in the future energy system. PV systems can be deployed in various settings, from residential rooftops to large-scale solar farms, one of these settings is on agricultural land.

Agrivoltaics (APV) is the dual use of land for both agricultural activities and PV electricity generation. This innovative approach holds promise for expanding solar power generation while maintaining food security as it allows for the simultaneous production of food and energy. The dual-purpose nature of APV helps mitigate the growing problem of land scarcity. Furthermore, many other synergies arise from this partnership such as a reduced need for irrigation, reduced wind erosion, and a potential increase in crop yields in arid regions, just to name a few [1]. Although still in its relatively early stages, with evolving technologies, designs, and standards, APV is gaining momentum across certain parts of the world. An increasing body of research, scholarly literature, and pilot projects is contributing to its development and refinement.

Despite the many advantages of APV plants, there are also challenges as to how the symbiosis of agriculture and renewable energy production can be realised on a project-specific basis.

Nevertheless, the increasing number of APV projects worldwide, particularly in countries like China, Germany, France, the USA, and Japan, shows that this innovative solution has the potential to make an important contribution to sustainable development and the realization of the global energy transition.

At the same time as this rise in PV and APV, in many countries, large opencast coal mines are being phased out as part of a global shift towards cleaner energy sources and environmental sustainability. This transition is driven by growing concerns over climate change, air pollution, and the environmental impact of coal mining. As nations adopt stricter environmental regulations and invest in renewable energy technologies, the closure of these mines represents a step toward reducing carbon emissions and mitigating ecological damage. However, in order to enable a just transition, attention must be given to ensure local communities impacted by closures and lost jobs are properly consulted and supported. Creating new jobs through PV and APV projects, for example, can help revitalize these areas, providing local workers with sustainable employment opportunities that replace lost coal mining jobs, foster community resilience and contribute to the overall economic stability of the region.

2.1 Purpose of the Study

There are numerous opportunities to capitalize on the ongoing transition from coal to renewable energy sources, such as PV. One significant opportunity is to repurpose closed opencast mines for PV installations. This study will examine existing PV projects in coal mining regions to better understand their planning, objectives, and possibilities in other countries to explore and harness the potential.

2.2 Scope and Methodology

As a base for this study, PV plants in German coal regions will be explored. German coal regions are some of the first to begin transitioning from traditional coal mining to renewable energy solutions. This is part of the country's larger commitment to reduce carbon emissions, promote sustainable energy practices and completely phase out coal-fired power stations by 2038 [2].

Two German power companies, RWE AG (RWE) and Lausitz Energie Bergbau AG (LEAG), are currently a part of this transition and actively installing PV and/or APV within their transitioning opencast mines. Analysing and understanding the activities of these two companies will help to assess the potential of this approach. In particular, subsequent utilisation planning ("Folgenutzungsplanung"), the decision-making process for ground-mounted PV vs. APV, and the path forward will be explored.

For this study, information was collected from public online sources and reports from RWE and LEAG. For deeper insights, RWE provided input to the report through an interview held in August 2024 and follow-up exchanges with an expert directly working on the planning and management of the opencast mines. LEAG provided input through exchanges with a director responsible for managing their opencast mines. In addition, reports from scientific research institutes that study PV and APV, such as the Fraunhofer Institute for Solar Energy Systems (ISE), will be reviewed as a part of this study.

3 Photovoltaics in German Coal Regions

3.1 RWE Case Study

Founded in 1898, RWE is a German multinational energy company with a global workforce of approximately 20,000 employees. As of 2024, the company operates three major opencast lignite (brown coal) mines, all in the Rhenish mining region of Germany: Garzweiler, Hambach, and Inden (see Table 1). Around 90 percent of the lignite extracted from these mines is used for electricity generation [3]. However, in response to the German government's plan to phase out coal in energy production, all three mines are scheduled for closure within the next decade.

Once lignite mining in the opencast mines has ended, they will be recultivated and the land will be made usable again. In addition to large agricultural and forestry areas, the three opencast mines will be developed into lakes and filled with water as part of the environmental restoration process. Depending on the opencast mine, filling the lakes will take between 25 and around 40 years (see Table 1).

In coordination with the region (municipalities, cities) and other stakeholders, framework plans were drawn up that describe and specify the future use of the lake and surrounding landscape. Until the opencast mine lakes are completely filled with water, the open areas within the open-cast mine basin should be used as optimally as possible. Therefore, it makes sense to "temporarily" employ other forms of energy production, namely PV and in some special cases wind power. In addition, RWE plans to install a temporary hydropower station, utilizing the Rhenish Water Pipe, during the lake filling process. This will supplement other installations around the edges of the mine and surrounding land.

Table 1 RWE opencast mines

Garzweiler	
Area:	40 km^2
Closure:	early 2030 (possible extension to 2033 per Federal State request)
Flooding Time:	35 years to fill the opencast mine
https://www.rwe.com/en/the-group/countries-and-locations/garzweiler-mine-site/	
Hambach	
Area:	46 km^2
Closure:	end of 2029
Flooding Time:	40 years to fill the opencast mine
https://www.rwe.com/en/the-group/countries-and-locations/hambach-mine-site/	
Inden	
Area:	17 km^2
Closure:	end of 2029

FloodingTime:	25 years to fill the opencast mine
https://www.rwe.com/en/the-group/countries-and-locations/inden-mine-site/	

3.1.1 Utilisation Planning (Folgenutzungsplanung)

There are many stakeholders with different interests when it comes to the soon-to-be-closed opencast mine sites. Scientists would like to conduct various research activities on the land, ecological groups would like to maximize the renaturation areas, and the public wants to have space for recreation. However, generating renewable energy in the temporary areas of the opencast mine is overall viewed as a useful measure. Through years of planning and stakeholder interaction, RWE attempted to balance the interests of the various stakeholder groups as best as possible.

Thus, a so-called framework plan “Rahmenplan” was drawn up together with the neighbouring municipalities, which reflects all interests. It describes important guidelines for the early reuse of the post-mining landscape which should be as diverse as possible. In the framework planning, topics that are perceived as contradictory today are brought together to form a cohesive whole. Recreation and tourism, biotope networks, agriculture and forestry, commerce and knowledge production, new forms of housing, multimodal mobility and renewable energy production are all considered together here. The end goal is to develop a landscape that brings ecological, social and economic demands into a sustainable interaction.

RWE has based its mining planning on this framework plan. The final mining activities for surface design and recultivation for the opencast mines are described in the final operating plan. To get an idea of the post-flooding “land use plan” for the town of Inden, which encompasses part of the Inden opencast mine see Appendix 1a and 1b.

For the period until the lake is filled, RWE has carried out so-called “potential analyses” that show the possible PV installations in the open-cast mine basin. It shows at which levels of the open-cast mine PV systems can be installed and how long they can be operated until the water level of the lake reaches the respective system. For safety reasons, the system must be removed again with sufficient advance notice so that it is not submerged by the lake water and the components do not remain in the lake. Based on this analysis and in accordance with the concepts and ideas of the framework plan, which also describes the use of the open-cast mine basin during the filling of the lake, the PV projects in the open-cast mines will be pushed forward in the coming years.

As part of the energy portion of this framework plan, RWE is constructing and already operating wind and solar farms as well as biomass plants in and next to the mining district, ensuring that the region remains an important energy location.

3.1.2 Existing Installations

Across the three sites, there is already around 300 MW of installed renewable energy capacity. With roughly 200 MW from wind, 100 MW from PV and a small amount from biomass plants. The PV portion of this is spread across 7 individual conventional ground-mounted systems. In addition, there is one more plant that is currently in the phases of planning and construction. These systems are built as a part of RWE’s “potential analyses” and many will only be in operation until a certain point in the flooding and recultivation process. For example, the "Neuland Solar Farm", shown in Figure 1, is a 12 MWp plant with a 4.1 MW battery storage system. This system was fully commissioned in 2024 and is situated along the shore of the future Hambach opencast mine lake, and therefore can be in operation until nearly 2070 [4].

Figure 1 RWE Neuland Solar Farm at Hambach [4]

"Jackerath" is another hybrid photovoltaic and storage plant, as seen in Figure 2, and is located on the western edge of the Garzweiler opencast mine. Construction of this 12.1 MWp plant with a 4.1 MW battery storage system began in 2021 and was commissioned in 2023. Although this area is not affected by the actual flooding, it will also be decommissioned and dismantled in the future as part of the recultivation process [5].

Figure 2 PV & Storage Jackerath at Garzweiler [5]

Directly between "Jackerath" and the A44 Autobahn, RWE launched a large APV research/demonstration plant on land already recultivated with known and suitable soil quality. The project involved close cooperation with many partners including the local municipalities, the Jülich Research Center (Forschungszentrum Jülich), Fraunhofer ISE, and the Federal State of NRW. The plant went online in January 2024 after a quick construction phase with a peak capacity of 3.2 MWp spanning 7 hectares of land. On this land, crops such as alfalfa, broad beans and raspberries were planted in the spring of 2024 [6]. In order to maximize research impact, not only were various species of crops planted, but three different APV concepts are being tested, that are described in more detail in Table 2

Table 2 RWE research project design [7]

Concept 1: Vertical modules with cultivation between the module rows

Solar modules are mounted vertically on a supporting structure, with ample space between the rows to accommodate harvesting machinery. This arrangement allows for testing the dual use of land for both solar energy generation and agricultural activities.

Pros:

- Easier Access: The vertical orientation and spacing allow easy access for harvesting machinery and farm operations.
- Minimal Shading: The vertical panel arrangement reduces shading on crops, which can enhance agricultural yield.

Cons:

- Lower Energy Yield: Vertical modules may produce less energy compared to optimally tilted or tracked systems.
- Complex Design: Requires a carefully designed support structure to maintain stability, for example, due to wind load issues.

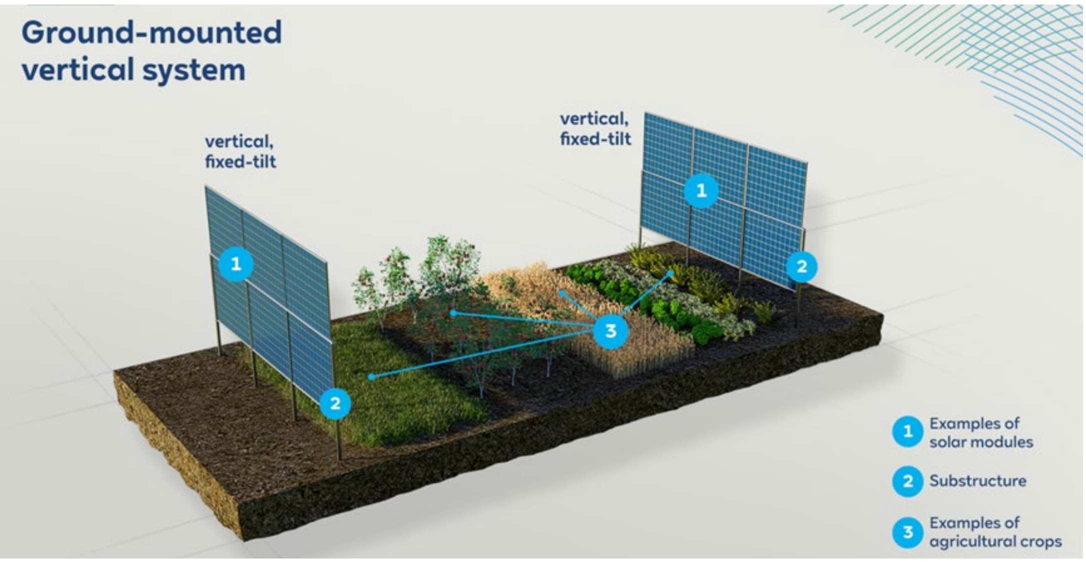

Figure 3 Ground-mounted vertical system [7]

Concept 2: Tracked modules with cultivation between the module rows

Solar modules are mounted on a movable axis that tracks the sun's path from east to west, maximizing energy production. The rows are spaced to enable continued agricultural use of the land beneath and between the modules.

Pros:

- Maximized Energy Production: Tracking the sun increases the energy yield of the solar panels.
- Increased Crop Yield: Adjustable shading can help protect crops from extreme sunlight or allow more sun to pass when needed.

Cons:

- Higher Initial Costs: The tracking mechanism adds to the initial installation and maintenance costs.
- Maintenance Complexity: Moving parts increases the complexity and frequency of maintenance.

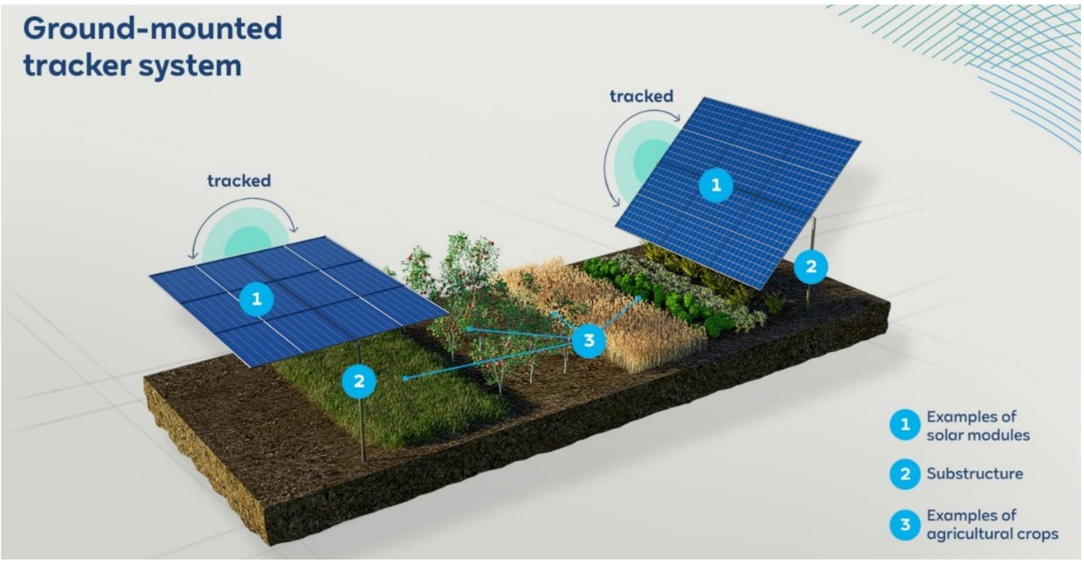

Figure 4 Ground-mounted tracker system [7]

Concept 3: Fixed-tilt modules with cultivation below them

Solar modules elevated on a pergola-like structure, fixed at a tilt. The height of the structure allows crops, such as raspberries, to be grown underneath, facilitating both solar energy generation and agricultural production on the same land.

Pros:

- Simple and Stable Structure: Fixed-tilt systems are simpler to install and maintain.
- Protective Shading: Provides shade that can protect sensitive crops from extreme weather conditions.

Cons:

- Reduced Light for Crops: Fixed shading may reduce the amount of light available for the crops below, potentially affecting their growth.

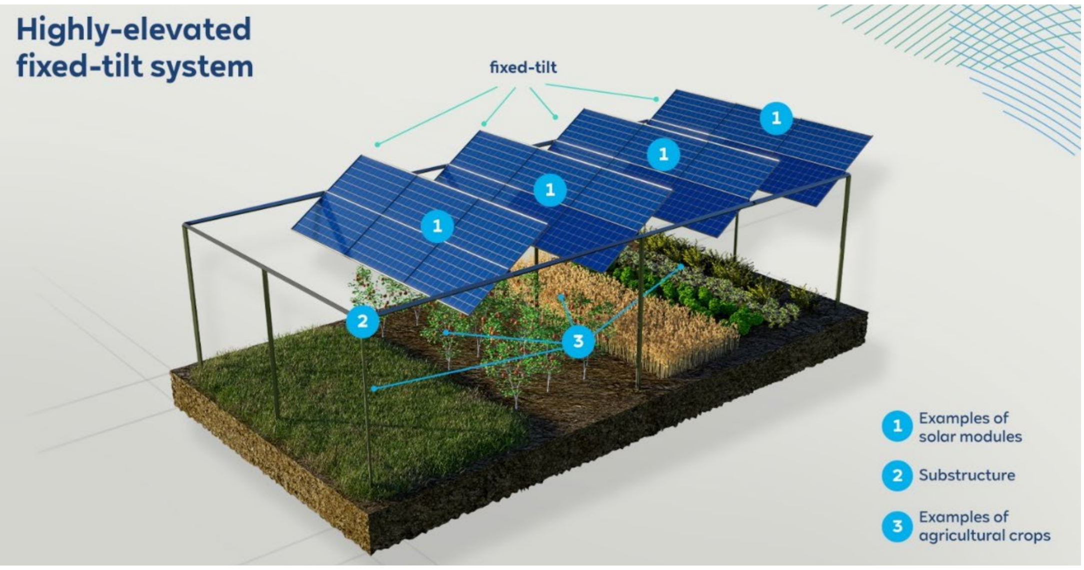

Figure 5 Highly-elevated fixed-tilt system [7]

The following figures show the RWE agrivoltaics research and demonstration plant.

Figure 6 RWE agrivoltaics research and demonstration plant [8]

Figure 7 RWE agrivoltaics research and demonstration plant [8]

Figure 8 RWE agrivoltaics research and demonstration plant [8]

Figure 9 RWE agrivoltaics research and demonstration plant [8]

Figure 10 RWE agrivoltaics research and demonstration plant [8]

Figure 11 RWE agrivoltaics research and demonstration plant [8]

Figure 12 RWE agrivoltaics research and demonstration plant [8]

Figure 13 RWE agrivoltaics research and demonstration plant [8]

3.1.3 Permitting and Grid Integration

The approval of PV systems in the opencast mining landscape is granted via a building permit, which is submitted to the responsible building authority. In this building application, all technical aspects are described and aspects such as environmental protection, fire protection, etc. are dealt with. Because opencast mining is regulated in terms of area planning in the so-called lignite plan ("Braunkohlenplan"), the responsible supervisory authority for RWE's mines, the

Arnsberg district government, is involved in the approval process and asked to provide an opinion. In addition to ensuring that all aspects relating to the mining operation are met, this also ensures that the later form of re-use in the recultivation plan is mentioned in the approval.

While conventional ground-mounted PV installations in Germany generally operate within a well-established regulatory framework, APV projects must navigate a more complex landscape due to their dual-use nature [1]. For example, elevated PV systems, which are often used for APV, are classified as structural facilities. Their PV modules must meet electrical requirements through certification, as well as comply with construction product standards, particularly regarding the use of glass in the construction industry. Furthermore, APV systems, unlike conventional ground-mounted PV systems, must accommodate the movement of farm equipment and machinery. To ensure safety while working under the glass PV modules, the modules must adhere to specific planning, measurement, and design requirements set out in the building codes of each German state [1].

One positive aspect of both conventional ground-mounted PV and APV at opencast mines is that grid integration is typically able to combine with the existing opencast mine installations. For the RWE case study, their current plants fully utilize the existing infrastructure from the mining operations to connect to the grid, requiring only minor modifications and additions.

3.1.4 Social and Economic Aspects

Germany's transition away from coal is an essential part of its broader strategy to combat climate change and promote sustainable energy. This shift promises significant benefits, including reduced greenhouse gas emissions, and the growth of renewable energy that can drive innovation and job creation in this sector. However, this transition also brings localized challenges, particularly in regions like the Rhenish mining area, where the lignite industry was an important economic factor for a long time and where the three RWE opencast mines are located.

In these regions, the coal phase-out has the potential to threaten jobs and is a challenge for local economies. To address these challenges, the German government has introduced measures such as financial support, retraining programs, and investments in alternative industries to help these communities transition [8]. Balancing the national environmental goals with the needs of affected regions is a delicate and ongoing process, aiming to ensure that the benefits of the energy transition are equitably shared across society.

One highly impacted group are the workers currently employed in lignite-related fields. In RWE’s case, they employ roughly 7,500 employees whose work is directly linked to the opencast lignite mines [3]. In the very near future, only a reduced number of these jobs will be necessary to accompany the lake-filling process. On the one hand, RWE is already using its know-how and employees to support the new PV projects. Planning services, site preparation, construction management and subsequent maintenance are key areas of activity. On the other hand, they are removing barriers between their different sister companies to allow former lignite workers to switch to new roles more easily.

Not only RWE is impacted by the phase-out process, but the municipalities around the opencast mines are also impacted. These municipalities must also plan for a future after the mining activities and have already held numerous workshops in the communities surrounding their opencast mines over the last few years. These workshops act as a platform to both inform citizens as well as to hear their inputs and perspectives [10].

Such changes are not necessarily negative, especially if properly addressed. For example, the town of Inden has seen decreased or slow growth in population in the last 20 years, but with the flooding of the mine, it is projected that many more residents will move there in the coming decades [10].

3.1.5 Conclusion and Decision-Making: PV vs. Agrivoltaics

All the factors discussed above, from impacts on society to the permitting process must be taken into consideration when designing a PV plant and deciding whether to employ APV practices. However, as with any other project, it often comes down to the costs and return on investment. On average, an APV plant tends to be more expensive than a conventional ground-mounted PV system, with capital expenditure (CAPEX) costs being roughly 25% higher [1]. The increased CAPEX often pose a barrier to the adoption of APV systems and can lead to their exclusion from discussions at an early stage. One other important consideration when dealing with opencast mines is the soil quality. The unique aspect of APV is the agriculture component which requires fertile or farmable soils. This must be considered on a site-by-site basis.

In the RWE example, they are in cooperation with the local municipalities developing the successor landscape and ensuring an optimal balance between agricultural development and the simultaneous use of the areas within the opencast mine for the installation of renewable energies. As part of its growth strategy in renewable energy, RWE has plans to install another 500 MW of renewables across its three sites by the year 2030. The vast majority of these 500 MW will be conventional PV installations inside the area of the opencast mines. Regarding APV, at the moment, RWE's pilot plant has yet to prove that it can compensate or overcompensate for the disadvantages of higher investment costs with operational advantages. However, depending on the experience gained from this pilot plant, further projects will be examined on agricultural land outside of the opencast mines.

3.2 LEAG Snapshot

LEAG was founded in 2016 after the Swedish energy group Vattenfall AB sold off its lignite interests in Germany and currently employs around 7,000 people [10]. LEAG's opencast mines are located in the mining region of Lusatia in the German States of Brandenburg and Saxony. Despite LEAG being a new company, mining has played a major role in this region since the turn of the 20th century. The Lusatia region is on the opposite side of Germany as the Rhenish mining area where RWE is active, but many similarities can be drawn between these regions because of their strong history of mining [11].

Table 3 LEAG opencast mines [12] [13]

Active Mines	Area

Nochten	48 km^2	
Welzow-Süd	90 km^2	
Reichwalde	11 km^2	
Transitioning Mines	**Area**	**Note**
Jänschwalde	60 km^2	The transition from operations to post-mining recultivation began in 2023
Cottbuser Nord	20 km^2	Mining operations & production ended in 2015 Flooding from 2019 to approx. 2025

Unlike the RWE opencast mines, the timeline for the LEAG mines is slightly longer. Germany has set the target to phase out coal by 2038 in the Coal Phase-out Act ("Kohleausstiegsgesetz"), therefore, it is expected that all mines are to close by 2038 [2]. There is the possibility for extension of individual opencast mines based on various factors and negotiations, including regulatory approvals, regional planning decisions, and economic considerations, however, extensions beyond 2038 are currently not expected.

Regardless of the exact closure dates, LEAG has already begun restoration and repurposing efforts on their opencast mines, whether completely decommissioned or not. They plan to first renaturize all the areas, and then apply other uses such as energy production or recreation. Similar to the RWE case, many stakeholders have competing interests when it comes to the future use of these opencast mine sites. As indicated earlier in Table 3, LEAG has already flooded another one of their opencast mines that ceased operation in 2015, creating the "Cottbuser Ostsee" lake, which is nearly completed [14].

As part of the energy portion of LEAG's utilisation planning ("Folgenutzungsplanung"), the largest areas of the opencast mines are earmarked for renewable energy projects. LEAG has numerous ongoing and planned activities including PV, wind, H_2, storage and beyond. These activities can be seen in Figure 14, which lays out LEAG's projects across the region.

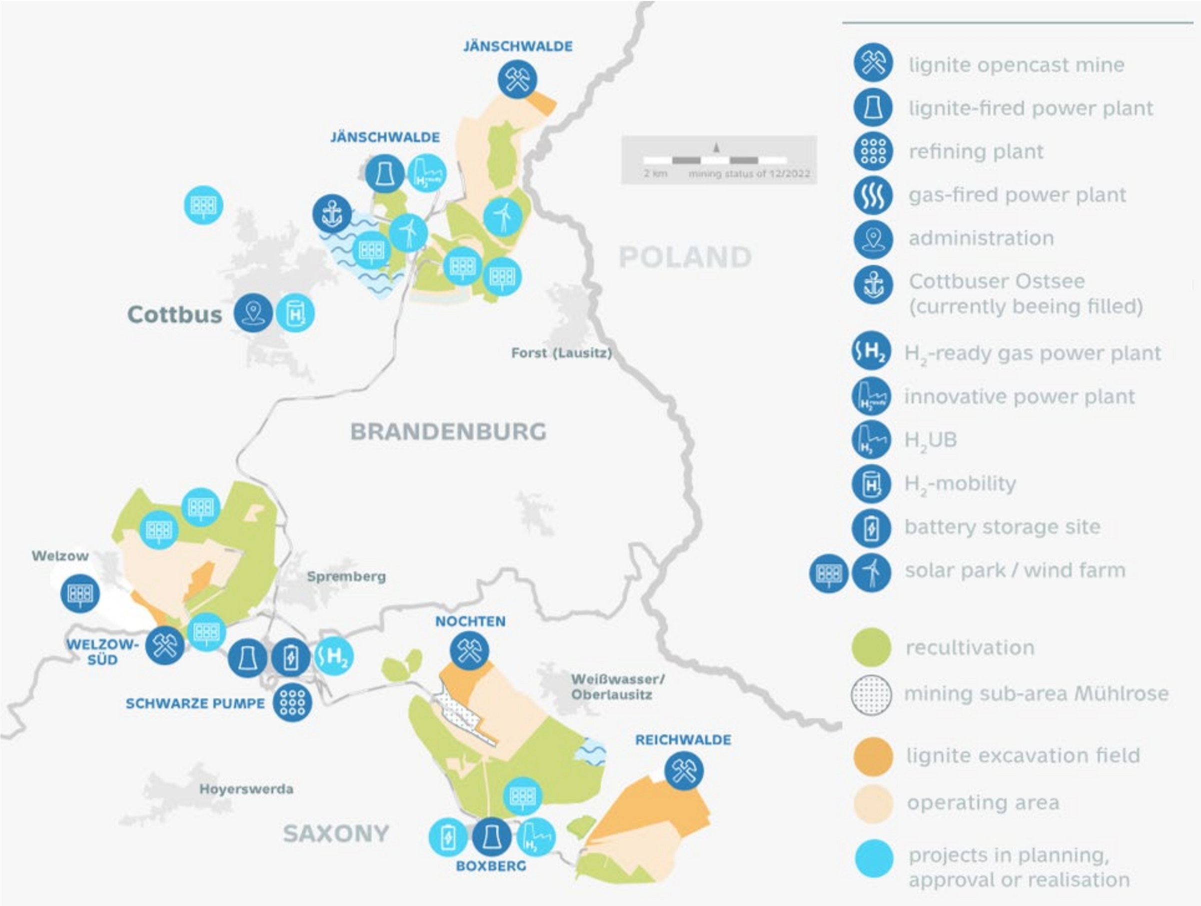

Figure 14 Lustian Mining District [15]

LEAG has already built, and has further plans to build, numerous conventional ground-mounted PV plants, as seen in Figure 14. For example, in 2021, LEAG received initial permissions for the planning of a 400 MWp solar park “Energiepark Bohrau”. This park is being built on recultivated land of the Jänschwalde opencast mine that is currently being used for agriculture. To do this, LEAG needed to prepare a development plan per the German Building Code with input from the local city council, change the land use permits, and finally receive a building permit per the Brandenburg Building Code [16].

Another interesting project currently going through the approval process is the “Solarpark Hühnerwasser und Wolkenberg,” with a planned capacity of 300 MWp. This plant aims to generate energy while at the same time improving the ecological value of 35 hectares of recultivated mine area by including flower strips, open areas for specific species, wildlife corridors and other measures to foster biodiversity [16]. Similarly, the “Dissen-Striesow” PV Park will also include such ecological measures, leaving 5-meter spacing between panel rows to allow for managed ecological strips [17].

So far LEAG has only built conventional ground-mounted PV plants as these systems were always feasible and more straightforward. However, they are currently in the planning stages of an APV pilot project with single-axis tracking and row spacing that allows for cultivation. Although the soil at the opencast mine sites is well known to LEAG, part of the planning will include soil tests specifically considering concrete for APV structures. This particular site was

chosen because licensing for APV was more feasible because of conditions in the lignite plan ("Braunkohlenplan").
In addition to their planned APV pilot project, LEAG is already working in close cooperation with local farmers and organizations at some of their conventional ground-mounted PV plants [16] [17]. Some examples of this cooperation are:

- Developing agreements on the use of partial agriculture areas for the ground-mounted PV system
- LEAG awarding contracts in connection with the management and maintenance of the areas
- Working with farmers on the ecological measures implemented at certain PV parks
- Using PV to help farmers diversify when their land is not profitable for agricultural purposes

Such cooperations take into account the needs of stakeholder groups and attempt to balance the demand for land used for food production, energy production and ecological improvement.

In addition to ground-mounted PV, LEAG also decided to utilize their newly created "Cottbuser Ostsee". LEAG has just finished installing more than 51,000 PV modules, see Figure 15, in what is to be Germany's largest FPV installation [18]. The area of this FPV plant is roughly 0.16 km^2, covering less than 1% of the lake area, and will have an installed capacity of 29 MWp [16].

Figure 15 LEAG Floating-PV Cottbuser Ostsee [16]

4 Conclusions and Recommendations

4.1 Conclusions

PV has boomed in the last decades, cementing its place in the future energy system. Within that, APV has been a hot topic in recent years across the globe, particularly in countries like Germany which have invested significantly in research. Overall, APV plants can serve as a promising example of combining agriculture and renewable energy production to address the pressing challenges of the 21st century: climate change, energy supply, food security and sustainable land use.

Despite its numerous benefits, APV in Germany is likely not to play a major role in the specific niche of opencast mines in the near future. The challenges are twofold: direct challenges, such as the fact that some opencast mine sites do not contain the necessary soil quality to support agriculture, necessitating different renaturation approaches, and the higher costs of APV plants compared to conventional ground-mounted plants. Additionally, there are softer challenges, such as the relative novelty of APV. Although Germany is a leader in APV research, it is still a relatively new practice especially when considering large-scale projects, which means there may not be enough time for knowledge, best practices, and regulations to catch up with the rapid changes occurring in the German energy system.

FPV should also be mentioned when discussing opencast mines as it is an alternative that utilizes the large water surfaces left by often flooded mines. This method bypasses issues like specific soil requirements and also does not compete with other land uses like food agriculture or public recreation. However, despite being already planned and implemented by energy-generating companies, like APV, FPV can face higher costs, regulatory challenges, and knowledge gaps, that limit rapid adoption in Germany's energy landscape.

Conventional ground-mounted systems also face unique challenges when being constructed in opencast mines. However, as they are cheaper, less complex, more standardized, and better understood, these complications can usually be more easily overcome.

Despite large companies like RWE and LEAG not including APV as a major building block of their "Abschlussbetriebsplan" for their opencast mines in 2030 and beyond and sticking with standard PV installations, ongoing research by institutes like Fraunhofer ISE and pilot projects like RWE’s new site and LEAG’s planned site will provide additional insights into APV and further develop expertise within the companies, making future projects more achievable. Furthermore, supportive legislation such as recent the German Solar Package 1 (“Solarpaket 1”) should encourage broader adoption of PV overall by providing incentives and streamlining regulatory processes [19].

4.2 Recommendations

To support the global development and adoption of both APV and standard PV systems at opencast mines, it is essential to encourage further research to address knowledge gaps and develop best practices for their implementation. Policymakers should create and adapt regulatory frameworks to support the integration of these systems, particularly in challenging sites like opencast mines, and consider financial incentives or subsidies to offset the higher initial costs. Industry stakeholders should invest in pilot projects to gather practical insights and demonstrate the feasibility of PV and APV systems in diverse settings. Collaboration between energy companies, agricultural experts, and research institutions is crucial to share knowledge and drive innovation.

Additionally, increasing public awareness and acceptance of PV and APV through educational campaigns and transparent communication about their benefits and challenges is important. Future studies should focus on conducting longitudinal research to assess the long-term impacts of these systems on agriculture and energy production and performing detailed site-specific studies to identify the best locations for implementation and optimize system designs accordingly. Studies should also follow the social impacts of transitioning coal mining regions in order to establish best practices for a just transition to renewables. Incorporating these conclusions and recommendations provides a comprehensive overview of the current state and future potential of PV and APV at opencast mines, while also offering actionable steps to enhance their viability and adoption.

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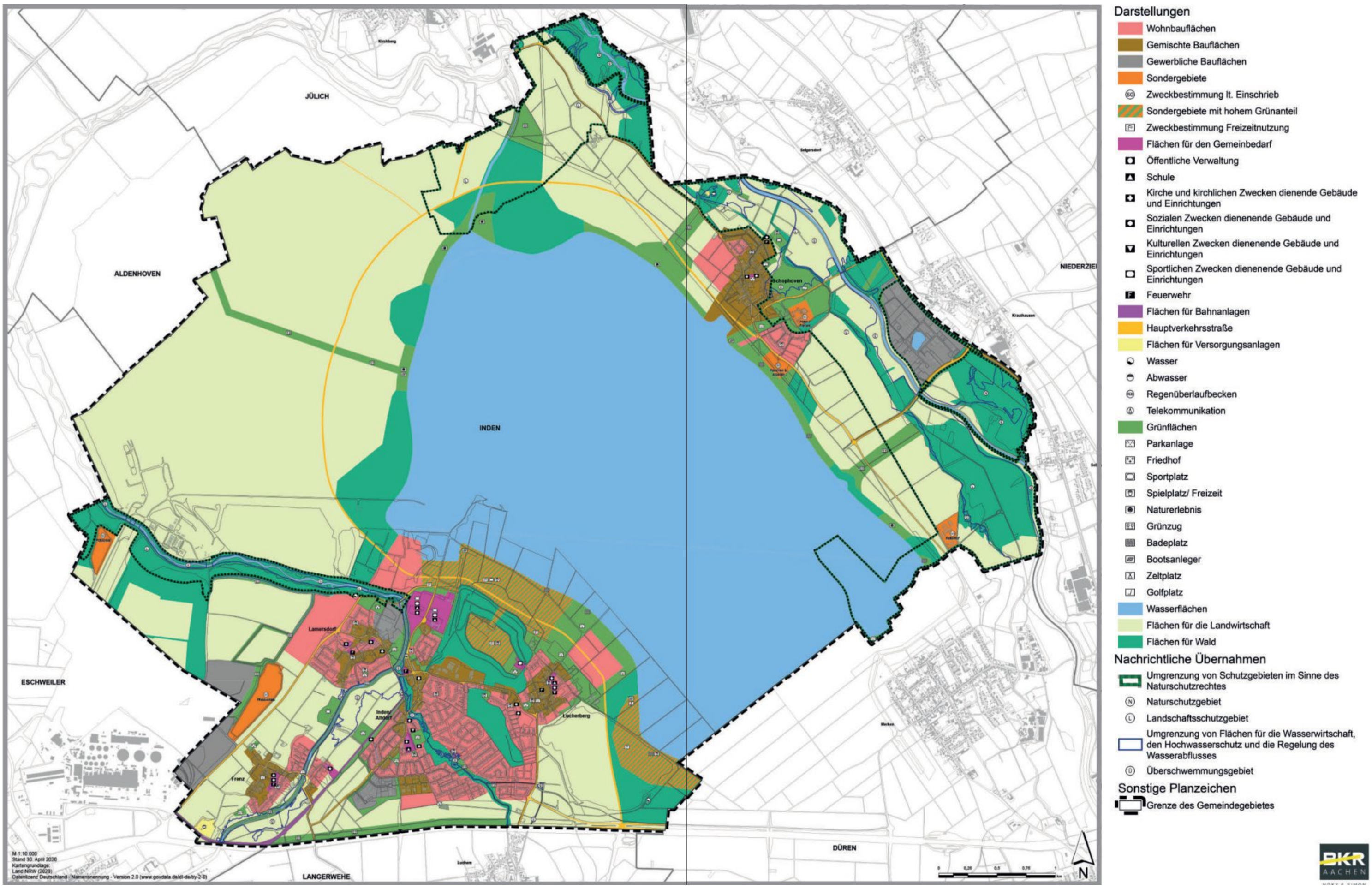
Appendix:

Appendix 1a. Draft land use plan for the municipality of Inden [19]



Appendix 1b. Draft land use plan for the municipality of Inden [19]