

Agriphotovoltaics as a profitable land use approach for regions in transformation? - An economic analysis and technical validation of suitable concepts

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ABSTRACT

The study explores efficient land use models and their contribution to the energy transition for transformation regions from the perspective of Agriphotovoltaics (APV) and examines the economic viability of APV using the example of the model region in the Rhenish lignite mining area. The high population density of the region and the simultaneous phase-out of fossil fuels make APV a promising solution for sustainable energy generation and efficient land use. Based on a mixed quantitative and qualitative research approach, the economic feasibility of potential suitable systems in the regions' main agricultural activity of arable farming such as vertical and high-mounted APV systems are analyzed, considering valid feed-in tariffs and agricultural factors' impact on profitability. Results show that current remuneration structures, especially national tariffs, are deemed non-viable. Vertical systems achieve stable profitability when higher tariffs of 0.09€/kWh outside the national tariff are considered, and show better profitability compared to high-mounted systems due to lower investment costs. Electricity sales overshadow agricultural revenue and reduce agriculture's influence on feasibility in arable farming settings that are typical for regional agriculture. Experts view APV in arable farming critically, expecting limited synergy and compatibility challenges. However, a funding measure from the state government amounting to 25% of the acquisition costs significantly increases the profitability of even the more expensive, high-mounted APV systems and is a valuable example of how innovative regional development concepts can be successfully promoted. The methodology presented here is transferable to other regional research approaches and provides practical guidance for land-efficient regional development.

1. Introduction

Germany faces significant agricultural land loss, averaging 50 ha daily (Bundesministerium für Landwirtschaft und Ernährung, 2022), posing challenges for food production and ecosystem stability. The densely populated state of North Rhine-Westphalia (NRW) in Germany exacerbates land scarcity, with competing demands for settlement, agriculture, and renewable energy expansion (Dinesh and Pearce, 2016). The transition away from fossil fuels, especially with ambitious aims such as the strived lignite coal phase out in Germany by 2038 requires addressing potential land disputes (Die Bundesregierung, 2022; Nam et al., 2021). Agriphotovoltaics (APV) means the combination of agriculture and photovoltaic installations in the same area and gains

relevance amid global conflicts impacting energy and crop markets. Thus, APV systems can be used to avoid the rising land use conflict between food production and renewable energy supply (Edouard et al., 2023), therefore emerging as a solution to the defined “dilemma” of conflicting land use for food and energy production (Ketzer et al., 2020; Trommsdorff et al., 2021a; Weselek et al., 2019). With this, large amounts of cropland can be preserved achieving stable crop yield of >50 % compared to a no PV scenario (Xia et al., 2024).

The German government recognizes APV's importance in supporting renewable energy while preserving agricultural land.

The Rhenish Lignite Mining region, historically central to German energy production (Oei et al., 2020), faces structural changes following the government's decision to phase-out coal power, necessitating renewable energy adoption and a transformation of the landscape and

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Nomenclature

APV	Agriphotovoltaics
BMEL	Bundesministerium für Ernährung und Landwirtschaft (German Federal Ministry of Food and Agriculture)
Ct	Cent
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Act)
EU	European Union
GAP	Gemeinsame Agrarpolitik der EU (Common agricultural policy)
GAPDZV	GAP-Direktzahlungen-Verordnung (Common Agricultural Policy-Direct Payments Regulation)
ha	Hectare
IRR	Internal Rate of Return
ISE	Fraunhofer Institute for Solar Energy Systems
kWh	Kilowatt hours
kWp	Kilowatt-peak
LANUV	Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen (State Office for Nature, Environment and Consumer Protection North Rhine- Westphalia)
LCOE	Levelized Cost of Energy
LER	Land Equivalent Ratio
NPV	Net Present Value
NRW	North Rhine-Westphalia
PV	Photovoltaics

economic system. The region is located centrally between the settlement hotspots of the cities of Cologne, Aachen, Düsseldorf and Mönchengladbach. Thus, APV emerges as a potential contributor to the energy transition, offering a dual role in energy production and effective land use. In this way, a spatially efficient and sustainable form of energy production is promoted in the center of a settlement hotspot.

The region has become a model region for a sustainable bioeconomy, with some of the largest APV demonstration sites in Germany.

APV is planned as one of the priorities for photovoltaic expansion, as there is a large selection of suitable potential areas (Zukunftsagentur Rheinisches Revier, 2021). Various projects in the region that address landscape, society, economy, urban development, and infrastructure also include vertical and high-mounted APV approaches (Zweckverband LANDFOLGE Garzweiler, 2021), which were also considered in this study.

The region's vulnerability to climate change, with rising temperatures and extreme weather events (Landesamt für Natur Umwelt und Verbraucherschutz Nordrhein Westfalen (LANUV), 2021a, 2021b), further emphasizes the need for resilient agricultural practices like APV (Anter et al., 2018).

Although the potential for APV on German agricultural land is estimated to be substantial, its widespread adoption is hindered by uncertainties related to local conditions, legal frameworks, and acceptance.

Using the case of the Rhenish Lignite Mining region, our paper analyzes APV using economic methods to calculate feasibility scenarios and is supplemented by expert interviews to validate economic assumptions and assess overall APV feasibility.

Two compatible designs for the major agricultural farm setting of arable farming in the region were considered, studying vertical APV and high-mounted APV systems for a 2-hectare area.

Objectives include analyzing economic feasibility, exploring agriculture's contribution to APV economics, incorporating various valid feed-in tariffs, and identifying barriers and opportunities for APV implementation. The mixed-methods approach combines quantitative economic analyzes with qualitative expert insights.

Results include a quantitative assessment of PV and holistic APV systems, followed by a validation through expert interviews. The discussion addresses critical findings, limitations, and suggests future research directions.

In conclusion, the study analyzes to what extent APV are financially attractive in the Rhenish Lignite Mining region, exploring also conditions under which they become more appealing. The comprehensive exploration of APV's economic feasibility in the context of regional challenges contributes valuable insights for evidence-based policy and decision-making easily adaptable to other regional research contexts.

2. Literature review

APV systems are directly embedded in the agricultural system. The primary objective is not solely to maximize solar energy expansion but rather to ensure the sustainability of agricultural activities while optimizing land use in the context of the energy transition (DIN Deutsches Institut für Normung e.V., 2022).

Numerous studies have indicated that APV, as a dual land use approach, has the potential to significantly increase land use efficiency (Amaducci et al., 2018; Bhandari et al., 2021; Trommsdorff et al., 2021b). This underscores its capacity to address land use conflicts effectively.

APV systems are also highly relevant in the context of climate change. The IPCC reports that globally, an increase in climate hazards is projected (IPCC, 2023) also have the potential to increase the resilience of agricultural production and mitigate climate change, particularly under extreme climate conditions, such as in drought-prone regions, where they appear to be a promising solution (Schweiger and Pataczek, 2023).

Furthermore, Agri-PV provides advantages in terms of food-energy-water synergies, as precipitation can be collected and be used for pre-cised irrigation (Willockx et al., 2020).

Those synergies need to be analyzed to better understand the overall benefits of APV concepts.

Previous studies showed results of slightly reduced energy production compared to a commercial PV installation while the agricultural production even increased by 10 % (Edouard et al., 2023). As there is no overall consensus about the impact on crop production, it is crucial to identify and classify suitable areas for agricultural photovoltaic systems (Elkadeem et al., 2024). This is also crucial with regard to the selection of plants and their requirements, such as light and growth height, in order to create a suitable setting.

Kumpanalaisatit et al. identified two major groups of APV systems, those involving agricultural activities on land with pre-existing PV facilities and those intentionally designed for co-production. They provided guidance on implementing agricultural area under pre-existing PV power systems, providing a sustainable solution for efficient land use systems (Kumpanalaisatit et al., 2022). In this study we consider an opposite approach, first determining agricultural area and adding then a suitable APV system for the agricultural practices in the setting, consequently prioritizing the functionality of the agricultural activity and adding a fruitful concept for efficient land use.

Regarding the selection of suitable crops within the APV system, there are significant variations in findings. Bhandari et al. categorized suitable crops for solar dual-use in positive, neutral and negative, indicating that for example potato, tomato, and lettuce are suitable crops, while wheat and fruits are not suiting the dual land use (Bhandari et al., 2021). Contrary to that, Laub et al. estimated that fruits show benefits up to 30 % shade (Laub et al., 2022) and Trommsdorff et al. reported a yield increase of 3 % of wheat in an APV setting compared to no Agri-PV and even an increase of 12 % of celery, (Trommsdorff et al., 2022) which Bhandari et al. categorized as a "neutral crop".

The differences in the reports of the effects on crop yields show an enormous range, indicating the importance of the environment in terms of climate, crop and APV design, making it difficult to identify an overall

appropriate design.

However, vertical and high-mounted systems are considered a suitable design especially in the context of extensive agricultural activities such as arable farming (Reker et al., 2022; Trommsdorff et al., 2022; Trommsdorff et al., 2021a), which is the predominant agricultural activity in the study region.

Studies showed that for both systems the Land Equivalent Ratio (LER) largely exceeds the mono-used area, indicating it as an overall economic investment (Amaducci et al., 2018; Arena et al., 2024).

Svitnik et al. analyzed that both vertical APV systems and high-mounted APV systems that do not restrict the harvesting process are still too expensive, suggesting that a subsidy is needed (Svitnič et al., 2024). The North Rhine-Westphalian state government offers such a subsidy, which is therefore analyzed in this study regarding its effect on successfully promoted measures on innovative technologies in regional development.

Besides that, APV can also serve as an income source, aligning with the trend of agricultural enterprises diversifying income through renewable energies (Statistisches Bundesamt (DeStatis), 2021; Weselek et al., 2019). Furthermore, in the context of climate change, APV's

potential impact has been highlighted, particularly in terms of its positive effects on the local microclimate and its protective functions.

The advantages mentioned include the fact that crops could be protected from excessive UV-B radiation (Coşgun, 2021), hail and precipitation (Willockx et al., 2020) and that the PV construction could serve as a windbreak, either as a roof or as a wall (Jain et al., 2021). This can have a positive effect on the quality of the harvest and reduce yield losses.

Furthermore, APV has the potential to reduce greenhouse gas emissions in the agricultural sector. 5 % on the area of the southern state of Baden-Württemberg in Germany has the potential to reduce up to 5.5 MT CO₂-eq which would be more than the total emissions of the agricultural sector in the region (Sponagel et al., 2024). Biodiversity measures are also very compatible with APV and easy to implement, also referred to as “ecovoltaics” (Sturchio and Knapp, 2023).

The prospect that APV can provide an additional source of income and at the same time offer further synergy effects for plants, farmers and land use underlines the need for a thorough feasibility study.

The concept of APV is integral to the transformation process in the Rhenish Lignite Mining region, located in the western part of Germany

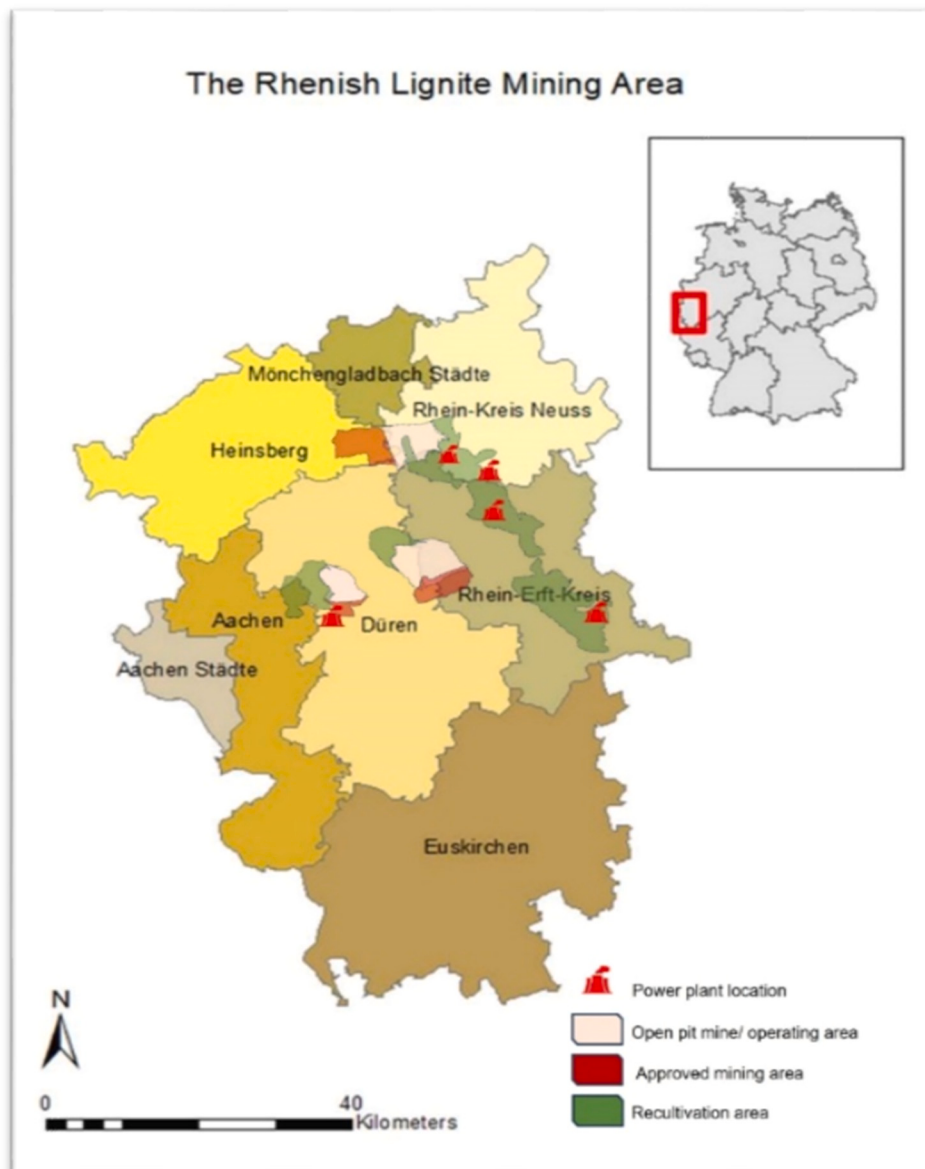


Fig. 1. The Rhenish Lignite Mining region.

(Fig. 1).

The region is undergoing a massive transformation as part of Germany's decision to transition away from fossil fuels, particularly lignite, with a mandated phase-out by 2030 (Die Bundesregierung, 2022). The region, once Germany's largest lignite region contributing significantly to electricity production, faces substantial challenges within the process of the energy transition. This phase-out not only impacts energy production but also the sectoral composition, regional employment distribution, and economic productivity (Heinisch et al., 2021). The landscape, heavily influenced by mining activities, is undergoing re-naturation and landscape development as part of the transition process. The region is recognized as a pioneer in energy and related industries, emphasizing energy management and renewable energies (Bornemann et al., 2018). There are leading initiatives to transform the region into a climate-neutral region, relying solely on renewable and secure energy within the next two decades.

The Forschungszentrum Jülich (Research Centre Juelich) and the energy enterprise RWE have built research facilities to study crop physiology in APV systems, including horticulture and agro-robotics applications (Forschungszentrum Jülich, 2021).

The agricultural sector in the Rhenish lignite mining region is monostructured, dominated by arable farming (75 %) and permanent grassland (25 %) (Bornemann et al., 2018; Landwirtschaftskammer Nordrhein-Westfalen, 2020). Given the fertile soil in the Lower Rhine Bay, crop cultivation, especially arable farming, is a significant operational orientation for agricultural farms (Geologischer Dienst NRW - Landesbetrieb Krefeld, 2016). The predominant crop rotation includes wheat, sugar beet, barley, crops for fodder production, and potatoes (Landwirtschaftskammer Nordrhein-Westfalen, 2020). The region's agriculture faces further challenges like a decrease in the number of farms, farm succession issues, and varying farm sizes (Landwirtschaftskammer Nordrhein-Westfalen, 2020). Climate conditions in the Rhenish lignite mining region are crucial, with current data showing an annual mean temperature ranging from 9.3°Celsius to 10.9°Celsius. Over the past 110 years, there has been a significant temperature increase, with even more notable increases especially in the springs and winters since 1994 (Landesamt für Natur Umwelt und Verbraucherschutz Nordrhein Westfalen (LANUV), 2021a, 2021b). The region has also experienced a 3.8–6.8 % increase in total precipitation, with intensified winter precipitation and a slight decrease in summer precipitation (Anter et al., 2018). Climate change is expected to impact agriculture, leading to more frequent yield losses and increased production risks due to rising agricultural prices (Anter et al., 2018).

Future climate predictions indicate a need for adaptation strategies, with irrigation becoming essential. The Thünen-Institute predicts a significant decrease in groundwater regeneration, leading to increased demand for irrigation in parts of the study region (Anter et al., 2018). Evapotranspiration, a critical factor in the water balance, is identified as a challenge. In the face of climate change, APV emerges as a potential resilience-enhancing measure, particularly with its capacity to prevent evapotranspiration. A recent study in France demonstrated a reduction of irrigation inputs by up to 47 % in an APV system with maize, showcasing its potential benefits (Ramos-Fuentes et al., 2023). APV is a promising solution when it comes to increasing resilience to combat climate change and overcoming the challenges of water availability, especially given the projected impact that climate change will have on agriculture in the region.

3. Methods

This study uses a multi-method approach combining quantitative and qualitative methods to assess the potential of APV as an efficient land use model and renewable energy source for transformation regions. The model region of the Rhenish Lignite Mining area was used as an example, as the phase-out of fossil fuels, which have significantly characterized the region, opened the way for innovation concepts such

as APV through appropriate support measures for sustainable energy production with efficient land use.

In the quantitative approach, the economic feasibility of vertical and high-mounted APV systems is assessed through key financial metrics like Levelized Cost of Energy (LCOE), Net Present Value (NPV), and Internal Rate of Return (IRR). Sensitivity analyses, incorporating discount rates, and additional calculations with specific feasibility targets enhance result interpretation. A second scenario considers the economic feasibility of an “integrated APV system,” incorporating agricultural returns and various scenarios accounting for respective regional yield expectations, long-term impacts, and climate change within an APV context.

The qualitative approach involves expert interviews to validate and critically appraise quantitative calculations. The guidelines with the individual interview questions for the experts are provided in the Supplementary Information. Explorative, field-developing, and guided expert interviews gather perspectives on APV in the region and provide comprehensive insights into opportunities and barriers.

Detailed explanations of the data used are provided, starting with photovoltaic data and values assigned to annual electricity production. The analysis method for the quantitative and qualitative parts is presented, introducing economic aspects of agricultural photovoltaics, feasibility methods, and calculation methods like LCOE, NPV, and IRR. The concept of time preferences and economic assumptions used in the calculations are highlighted in the quantitative application.

The research follows an inductive approach due to the absence of existing commercial agricultural photovoltaic plants in Germany or the study region. Relying on literature-based assumptions, this study acknowledges potential variations from current market conditions. Despite data limitations, the study aims to offer an overall perspective on the economic situation to better comprehend current challenges, serving as a general reference with inherent variability in economic assumptions. The research framework is illustrated in Fig. 2.

3.1. Data collection

3.1.1. Photovoltaics data collection

The capacity and annual electricity production of APV systems is contingent upon project-specific conditions. The system's design, incorporating factors like PV module size, arrangement, and site conditions, influences its capacity. High-mounted APV systems are suggested to range from 520 kW_p/ha (Feuerbacher et al., 2022; Feuerbacher et al., 2021) to potentially reaching 900 kW_p/ha (Müller, 2023). Vertical APV systems range from 300 kW_p/ha (Trommsdorff et al., 2022) to 400 kW_p/ha (Müller, 2023; next2sun, 2022). Adopting a capacity of 600 kW_p for high-mounted and 350 kW_p for vertical systems, calculations are based on a 2-hectare area, aligned with common arable farming field sizes in the study region.

To calculate the specific electricity production, technical parameters such as capacity, orientation, azimuth, angle, losses, and bifaciality impact must be considered. High-mounted systems commonly have a south-west orientation with an azimuth of 20° and a slope of 52.5° (Beck et al., 2012; Feuerbacher et al., 2021). As the modules are mounted on high locations, it makes sense to use bifacial modules to benefit from the reflected irradiation on the rear side. An average additional electricity yield of 6 % is assumed for the bifaciality (Feuerbacher et al., 2022). Vertical systems favor an east-west orientation with a slope of 90° and azimuth of 90°/−90° for higher irradiation during morning and afternoon hours. The bifaciality approach assumes the front and back sides contribute 95 % of the system power. System losses of 13 % are assumed for both vertical and high-mounted designs (Reker et al., 2022).

Using the PVGIS tool by the European Commission the annual electricity production for three representative locations within the Rhenish lignite mining region is calculated. The locations were selected based on representative conditions for solar irradiation and temperature within the region. After adjusting for bifaciality, the mean value was calculated, providing representative yearly yields in kWh/kW_p for the selected

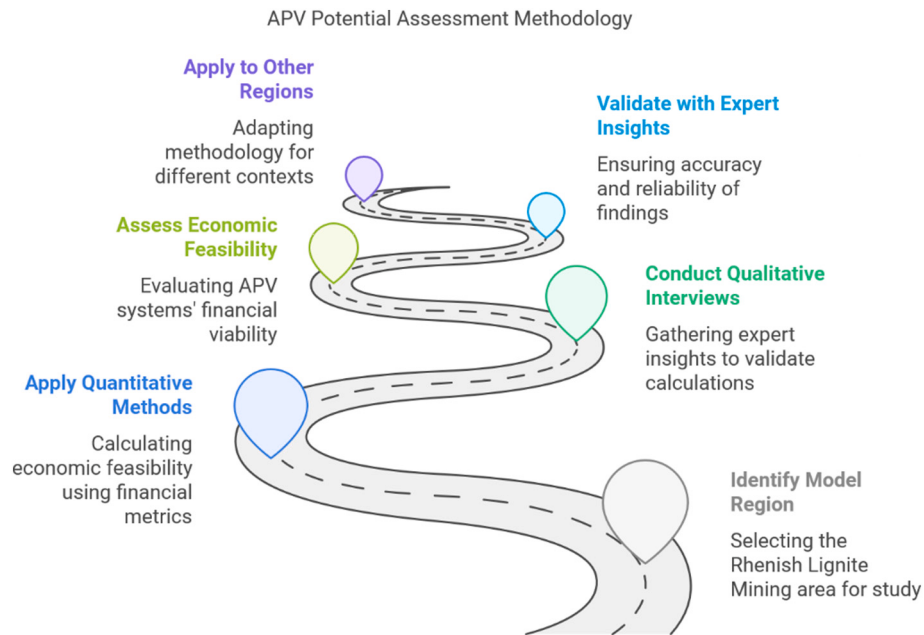


Fig. 2. Research framework of the applied methodology

locations.

Table 1 indicates the selected locations and the calculated yearly yield in kWh/kW_p. The methodology employs literature-based assumptions due to the absence of practical data specific to the region, offering a general reference with inherent variability in economic assumptions.

3.1.2. Capital expenditures and operational expenditures

This study examines capital expenditures (CAPEX) for APV systems, encompassing material, labor, and initial costs. According to estimations in other studies, high-mounted system CAPEX ranges from 1234€/kW_p (Scharf et al., 2021) to 1294€/kW_p (Feuerbacher et al., 2022; Feuerbacher et al., 2021). Substructure, surface preparation, and bifacial PV-panels are identified as key cost factors (Trommsdorff et al., 2022). For vertical systems, CAPEX are lower, with reported values of 700€/kW_p (next2sun, 2022) and 688€/kW_p (Scharf et al., 2021). Two CAPEX scenarios are considered: CAPEX I (without subsidy) and CAPEX II (with a 25 % subsidy by the State of NRW). Operational expenditures (OPEX) cover maintenance, cleaning, insurance, marketing, dismantling, and monitoring (Böhm, 2022). APV OPEX are expected to be lower than conventional PV systems due to reduced maintenance costs from agricultural activities underneath (Willockx et al., 2022). Assumed OPEX values include 16€/kW_p (Feuerbacher et al., 2022), 1.26ct/kWh (Trommsdorff et al., 2022) and 1.1 % of the initial CAPEX (Willockx et al., 2022). For this study, 1.1 % of the initial CAPEX are assumed because it represents an intermediate assumption in accordance with other studies. In Table 2, the applied economic data is presented.

Table 1

Calculated energy yield per kW_p in three locations within the Rhenish lignite mining region generated by the PVGIS software and adjusted according to the bifaciality assumptions.

Location	50.907, 6.430	51.151, 6.525	50.437, 6.651	Mean value
Slope 90°	1008.63	1006.72	984.05	999.8 kWh/kW_p
Azimuth 90/ −90°	kWh/kW _p	kWh/kW _p	kWh/kW _p	
Slope 52,5°	1034.76	1036.27	987.44	1019.49
Azimuth 20°	kWh/kW _p	kWh/kW _p	kWh/kW _p	kWh/kW_p

Table 2

Overview of applied economic data in the photovoltaic section in accordance to applied technical factors.

Parameter PV	Vertical systems	High-mounted systems	Unit
Capacity	700	1200	kW _p /2 ha
Annual electricity production	699.860	1.223.388	kWh
Investment costs	700€	1250€	€/kW _p
Investment costs (CAPEX I)	490.000€	1.500.000€	€/2 ha
Investment costs with subsidy of 25 % (CAPEX II)	367.500	1.125.000	€/2 ha
Annual operational costs (OPEX)	5390	16,500	€/2 ha

3.1.3. Agricultural data

Agricultural data for the study are sourced from the Agricultural Chamber of North Rhine-Westphalia, chosen based on typical arable farming crop rotation—winter wheat, winter barley, sugar beets, and potatoes (Landwirtschaftskammer Nordrhein-Westfalen - Arbeitskreis für Betriebsführung Köln-Aachener Bucht, 2022; Landwirtschaftskammer Nordrhein-Westfalen Geschäftsbereich 5 Fachbereich 51, 2023). Economic factors for wheat and barley utilize mean values from 2012 to 2022, while sugar beets use data from 2013 to 2022. Potato values incorporate punctual data from 2021. Adjustments for agricultural contribution margin involve EU subsidies, factoring in the complexity of the Common Agricultural Policy. A uniform subsidy of 226€/ha is assumed for the study. An overview is provided in Table 3.

3.1.4. Selection of experts

A total of seven expert interviews were additionally conducted to validate the overall research framework, economic calculations and assumptions. The experts were chosen based on Meuser and Nagel's principles (Meuser and Nagel, 1991), aligning with the researchers' interests and the research question. The selection involved scientists with relevant research background such as economic, agricultural, and APV knowledge, alongside farmers with expertise in regional agriculture and experts in the field of renewable energy potential and solar energy. The experts were interviewed applying a semi structured method. The chosen experts collectively contribute valuable insights at the interface of economics and agriculture, ensuring knowledge alignment with the

Table 3

Overview of applied data in the agricultural section.

	Winter wheat (mean value 2012–2022)	Winter barley (mean value 2012–2022)	Sugar beet ^a (mean value 2013–2022)	Potatoes ^c
Average reference yield (t/ha)	9.29	9.26	82.02	42.81
Average Market price (€/t)	176.59	162.62	33.75 ^b	181.18
Market output (€/ha)	1640.52	1505.86	2768.18	7756
Average variable costs (€/ha)	754.36	743.36	1380.8	3.833.50
contribution margin (€/ha)	886.16	762.5	1387.38	3922.5
EU Subsidies (€/ha)	226			
Contribution margin + subsidy (€/ha)	1112.16	988.5	1613.38	4148.5

^a Yield “Pure beets”.^b Including shreds.^c Reference yield is the mean value 2010–2021 obtained from BMEL Test-statistik for the whole of Germany; market price and variable costs are point data from 2021 received from the Chamber of Agriculture, NRW.

research focus.

3.2. Method of analysis

3.2.1. Quantitative analysis: economic consideration of agriphotovoltaics

Static investment calculations offer simplicity but may lead to distorted long-term results, treating money equally regardless of the time of payment (Poggensee and Poggensee, 2021). While static methods like the amortization period assess cost recovery within a set timeframe, dynamic investment methods like Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Costs of Energy (LCOE) account for the time value of money, providing more reliable evaluations for long-term investments in the energy industry (Berk, 2013; Konstantin, 2017). These dynamic indicators, along with the static amortization period, are crucial for assessing economic viability, influencing decisions on APV plant investments. The contribution margin in agriculture further complements holistic economic efficiency assessments (Unterguggenberger, 1974).

The Net Present Value is a crucial economic metric indicating the present value of expected project cash flows (Burksaitiene, 2009). A positive NPV signifies increased company value, while a negative NPV implies a detrimental investment. NPV is calculated by discounting future cash flows based on risk-associated opportunity costs, providing insight into project profitability (Žizlavský, 2014).

The Internal Rate of Return complements NPV, representing the interest rate where an investment's net present value equals zero (Laws, 2018). The IRR compares with minimum expected interest rates, and profitability hinges on IRR exceeding the assumed NPV calculation interest rate (Heesen, 2012; Konstantin, 2017).

The Levelized Costs of Electricity assesses economic sustainability by comparing total investment and operational costs with the lifetime energy production of a power plant (San Miguel and Cerrato, 2020). It aids in comparing costs and benefits over an investment's planning period, accounting for time preference (Kost et al., 2021). A range of the discount rate is assumed as the discount factor reflects positive, negative, or indifferent time preferences, influencing decision-makers' considerations (Faber et al., 1989). In functioning capital markets, market interest rates guide discounting future payments, while imperfect markets may see varying discount rates based on individual risk aversions (Laux,

2005). Balancing short-term considerations with long-term consequences is crucial, especially with higher discount rates potentially overlooking significant long-term drawbacks (Faber et al., 1989).

3.2.2. Quantitative application

The economic feasibility of vertical and high-mounted PV systems is assessed through calculations of LCOE, NPV, and IRR. LCOE considers only the PV system, while NPV and IRR evaluate both the PV and agricultural contribution margins. Specific feasibility targets, including the amortization period, are set for the PV system alone. Different payment options, such as EEG tariff, exchange price, and subsidies, are compared.

The German financing landscape for solar energy encompasses diverse methods, including the governmental tariff under the Renewable Energy Act (EEG) and options beyond the EEG, aligning with free-market principles and guided by solar power exchange prices. Incentives vary based on capacity and APV system category, with distinct payment structures within the EEG. For capacities up to 100 kW_p, a feed-in tariff applies; beyond that, third-party commercialization or tender processes are mandated. The 2023 EEG feed-in tariff is 0.07€/kWh. Additionally, the EEG introduces a technology bonus supporting APV systems, decreasing from 1.2 to 0.5 cents/kWh by 2028. Alternative financing outside the EEG involves direct marketing, utilizing exchange prices or Power Purchase Agreements (PPAs), influenced by market fluctuations. The state government of North Rhine-Westphalia offers a 25 % subsidy on APV installation costs, contingent on opting for alternative remuneration structures without simultaneous EEG payments, thus reducing acquisition costs (status 2023). Three selected remuneration structures are set to provide an overview of the different influences a certain feed-in tariff might have on the feasibility and in accordance with the technical setting and capacity of the relative APV system. The selected payment options are presented in Table 4.

Excel is used for calculations, and assumptions about system lifetime, discount rates, inverter replacement, degradation rate, and inflation are outlined according to the literature. A 25-year lifetime (Feuerbacher et al., 2022; Feuerbacher et al., 2021; Schindele et al., 2020), inverter replacement in the 11th year (Böhm, 2022), 0.25 % annual degradation of the solar panels (Schindele et al., 2020), and 2 % of yearly increase in inflation for the OPEX are assumed in accordance with the inflation target by the European Central Bank. As the impact of the assumed discount rate was outlined, higher discount rate assumes a higher risk with respect to agricultural yields and climate change impacts. The higher the risk, the more unstable and unpredictable the crop yields. Consequently, this analysis adopts a range of discount rates, spanning from 1 % to 10 %, to encompass distinct assumptions regarding the potential risk of the investment in an APV plant.

3.2.3. Qualitative analysis: expert interviews

The expert interviews aim to validate business cases and identify factors influencing calculations, adopting an explorative approach with

Table 4

Considered payment structures inside and outside the Renewable Energy Act (EEG).

APV system	Payment structure according to the EEG	Considered payment structure outside the “EEG” alternative direct marketing according to the exchange price for solar electricity
High-mounted system (>1 MW capacity)	Average volume-weighted award value tender round 03/2023: 0.0703€/kWh + technology bonus 2023: 0.012€/kWh = 0.0823€/kWh	Average exchange price for solar electricity 2023 (Status June 2023): 0.09€/kWh
Vertical system (<1 MW)	Remuneration according to the EEG feed-in tariff 2023: 0.07€/kWh	

an external perspective. Guided by an open discussion, experts contribute to evaluating quantitative research findings and provide insights into APV potential. Following a simplified adaptation of Meuser and Nagel's methodology, interviews involve transcription, thematic comparison, and summarization (Meuser and Nagel, 1991). The focus on individual perspectives, reflecting diverse backgrounds, aligns with a situational design, prioritizing valuable insights over direct comparisons (Ullrich, 2006). While some steps deviate from the recommended pattern, this approach is deemed appropriate for a comprehensive analysis of varied expert perspectives.

4. Results and discussion

4.1. Agriphotovoltaic systems without agriculture input

4.1.1. Levelized costs of electricity

This study compares LCOE scenarios for vertical and high-mounted designs, considering both subsidized and non-subsidized cases. The discount rate significantly impacts LCOE, with higher rates leading to increased costs, reflecting capital-related expenses. Lower interest rates favor more favorable LCOE values, enhancing renewable project competitiveness. Subsidies play a pivotal role in cost reduction, emphasizing government incentives' importance in project attractiveness. For vertical systems, LCOE without subsidies ranges from 0.045€/kWh to 0.090€/kWh per unit, while subsidized values range from 0.037€/kWh to 0.070€/kWh. High-mounted systems incur higher LCOEs, ranging from 0.08€/kWh to 0.157€/kWh without subsidies and 0.065€/kWh to 0.123€/kWh with subsidies. The consistent lower LCOEs with subsidies underscore their positive impact on economic viability and cost-effectiveness in energy management. Overall, vertical systems prove more economically viable, exhibiting lower LCOEs compared to high-mounted ones. The wide LCOE range emphasizes the need for project-specific assumptions in assessing APV system costs. The obtained results are presented in Fig. 3.

4.1.2. Net present value and internal rate of return

The overall profitability of vertical APV systems is positive, with positive Net Present Values even at medium to higher discount rates (Fig. 4). For the EEG payment option, NPVs are positive up to 6 %, turning negative at higher rates, indicating potential losses. The alternative payment option outside the EEG yields positive NPVs up to 10 %, showcasing high profitability. When a 25 % subsidy is applied to the alternative payment option, NPVs remain positive for all assumed discount rates, indicating profitability within the calculated risk range.

Compared to that, the profitability for the high-mounted systems

appears to be significantly lower (Fig. 5). Considering the EEG as payment option, the NPV is only positive at around 1 % interest rate, as the interest rate increases, the NPV turns negative, suggesting potential financial losses. The NPV with the alternative payment option outside the EEG is only profitable at an interest rate up to 2 %, showing negative NPVs assuming higher interest rates. The NPV with subsidy and payment option outside the EEG indicates that even with a 25 % subsidy, the project remains profitable only at an interest rate of around 5 % but becomes unprofitable at higher interest rates. The profitability of is therefore significantly increased compared to the other two payment options, however all-over on a lower level compared to the vertical systems.

The Internal Rate of Return for vertical systems varies based on payment options. With a 25 % subsidy and alternative payment, the IRR reaches 14.3 %, significantly boosting project profitability. In contrast, high-mounted systems display lower profitability, with positive NPVs only at lower interest rates. The IRR for high-mounted systems is lower than for vertical systems (Figure 6; and 7:).

Varying interest rates and compensation structures impact APV investment feasibility, with lower rates enhancing attractiveness and subsidies potentially offsetting losses. Overall, vertical systems demonstrate better feasibility compared to high-mounted systems.

4.1.3. Interpretation

The results show that vertical systems are more feasible compared to high-mounted systems. The payment structure is crucial to obtain better profitability. Since profitability is highly dependent on the discount rate, specific results regarding profitability are difficult to obtain and highly dependent on the respective risk. In the following, the results are considered in the context of specific feasibility targets. This approach aims to compare current payments with feasibility structures and to determine if the governmental tariffs are sufficient. Therefore, the prior included subsidy is disregarded.

4.1.3.1. Determining levelized cost of electricity. Regarding the LCOE, a standard value for the assumed discount rate for large-scale solar plants is 3.5 % (Bódis et al., 2019). Assuming that and leaving out the subsidy, for the vertical systems, LCOE of 0.056ct/kWh are obtained and for high-mounted systems, 0.098ct/kWh are obtained (Table 5). These findings, influenced by assumed cost structures, align with Fraunhofer ISE estimates. LCOEs for APV systems, while participating in the same EEG tender system as ground-mounted PV systems, are considerably higher, emphasizing the challenges in achieving cost competitiveness.

4.1.3.2. Minimum compensation threshold for investment neutrality.

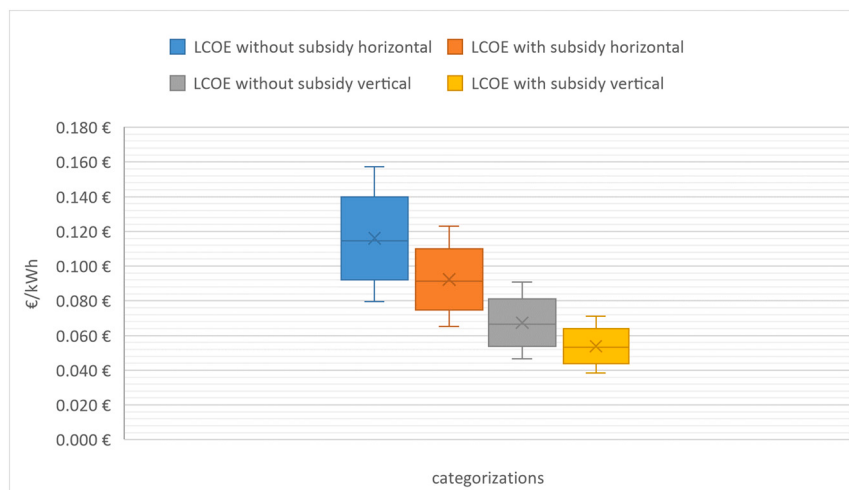


Fig. 3. Overview of Levelized Costs of Electricity (LCOE) of considered Agriphotovoltaic systems representing discount rates from 1 to 10 %.

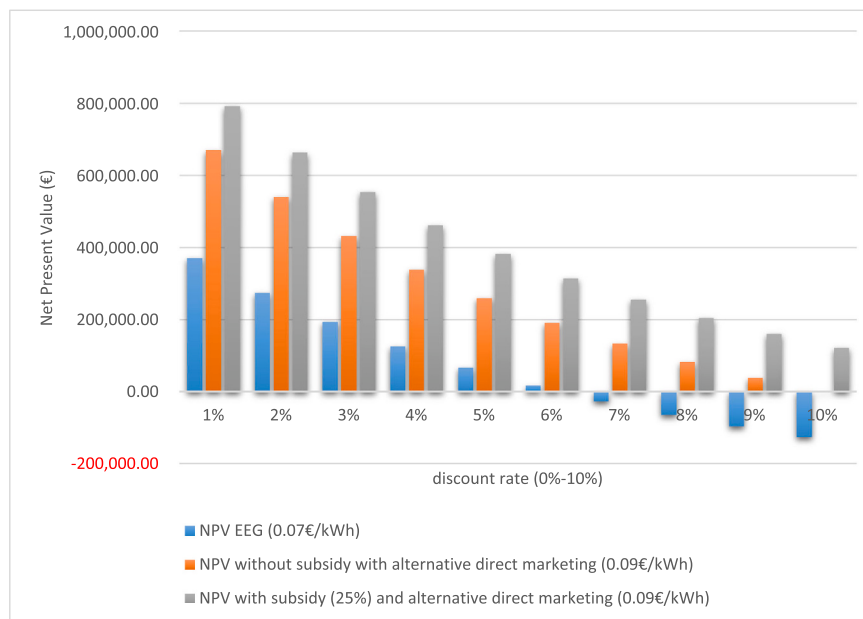


Fig. 4. Net Present Value (NPV) of vertical systems according to payment structure and discount rate.

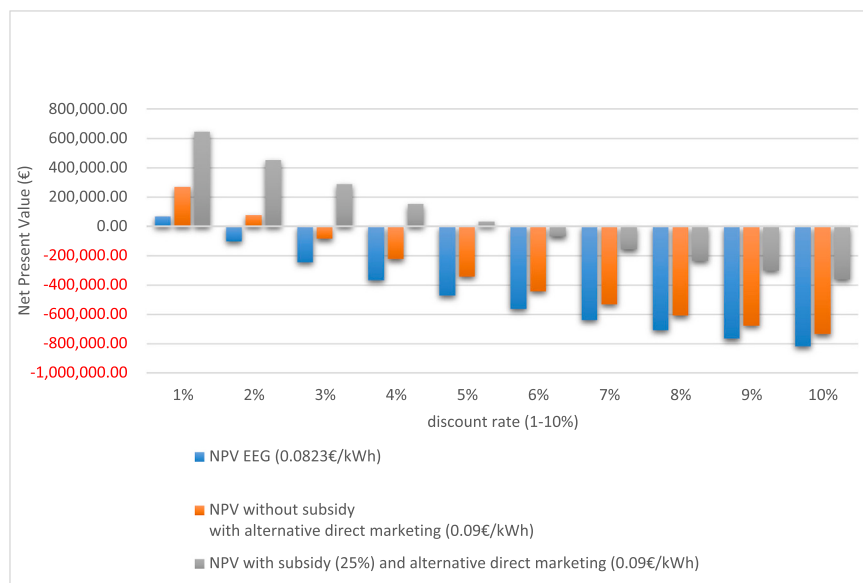


Fig. 5. Net Present Value (NPV) of high-mounted systems according to discount rate and payment structure.

Assuming profitability should be achieved at discount rates of 3 % and 5 %, the vertical systems are positive under all compensation structures. Vertical systems remain profitable at 3 % and 5 % discount rates under various compensation structures, including the lowest assumed compensation per EEG 2023. In contrast, high-mounted systems are not profitable without subsidies. Calculating the minimum compensation for investment neutrality, it is determined that at 3 % and 5 % discount rates, the high-mounted systems require at least 9.4 and 11.028 cents per kWh, respectively (Table 6). Given the common 3–5 % investment achievement benchmark in Germany, the existing governmental fixed tariff is deemed insufficient, emphasizing the need for higher compensation.

4.1.3.3. Amortization at half of the lifespan. Aiming for project amortization after 12 years, neither design is feasible under current payment structures for vertical systems. To achieve amortization, a payment of

12.47 Ct/kWh is needed, significantly deviating from both EEG Tariff and non-EEG remuneration. For vertical systems, a payment of 7.29 Ct/kWh aligns better with EEG tariff intentions and is covered by non-EEG tariff (Table 7). The current governmental payment favors neither system for a moderate amortization period, especially rendering high-mounted systems unfeasible. Elevated cost parameters could further jeopardize vertical system feasibility.

4.2. Holistic agriphotovoltaic systems with agriculture

The economic feasibility considers the holistic impact of APV systems on agricultural contribution margins. Mutual influences, such as shading affecting crop yield and protection benefits, are recognized. Various harvest scenarios, based on crop rotation data for a two-hectare area, are evaluated. The EU agricultural payment assumption aligns with the legal framework of the GAPDV. Three scenarios—baseline,

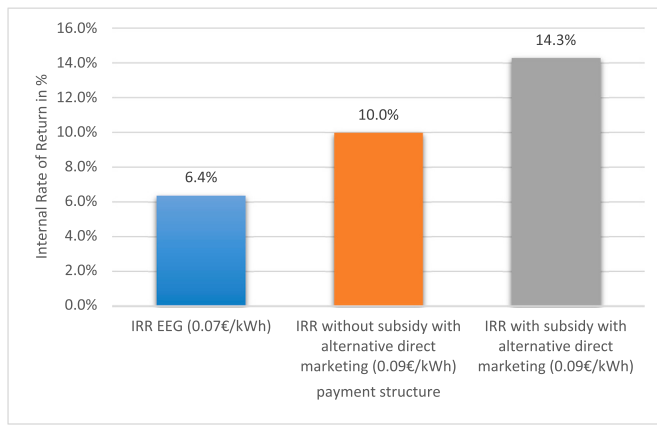


Fig. 6. Internal Rate of Return (IRR) of vertical systems according to the payment structure.

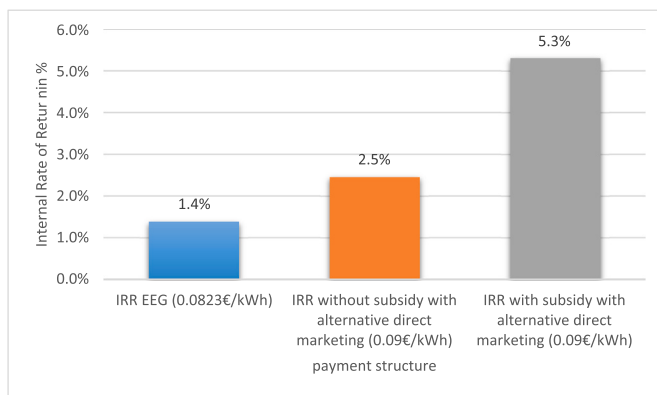


Fig. 7. Internal Rate of Return (IRR) of high-mounted systems according to the payment structure.

Table 5

Levelized Costs of Electricity (LCOE) considering a standard discount rate of 3.5 %.

	LCOE without subsidy high-mounted	LCOE without subsidy vertical
Discount rate of 3.5 %	0.098ct/kWh	0.056ct/kWh

Table 6

Minimum compensation threshold about realistic discount rates.

High-mounted systems	3 % discount rate	5 % discount rate
Payment per kWh for Net Present Value of + −0,00€ w/o subsidy for investment costs	9.4ct/kWh	11.028ct/kWh

Table 7

Compensation threshold regarding amortization after 12 years.

	High-mounted systems	Vertical systems
Payment per kWh for amortization after 12 years w/o subsidy for investment costs	12.47ct/kWh	7.29ct/kWh

reduced yield, and increased yield—are analyzed. The non-consideration of potential acreage loss due to plant design is acknowledged. The resulting NPVs, along with the agricultural component, are presented in Table 8 for comparison.

To better compare the combined yield from PV and agriculture, the three types of remuneration considered were considered separately and the agricultural yield scenarios were included in each of the remuneration types.

For the vertical systems, the NPV results are categorized into three groups based on remuneration structures (EEG, non-EEG, and non-EEG with subsidy). Within each group, graphs cluster closely. Regardless of interest rates, adding agricultural yield presents marginal differences in profitability. For EEG tariffs, NPVs are positive from a 1–6 % discount rate, turning negative at 7 %, emphasizing the significance of agricultural income for overall project profitability. Non-EEG scenarios, except “w/o agriculture,” remain profitable, like subsidized scenarios, which consistently exhibit profitability across discount rates and agricultural yields (Fig. 8).

The high-mounted system exhibits similar groupings but with greater profitability deviation than vertical systems. For EEG tariffs, only up to a 2 % discount rate results in positive NPVs. Non-EEG scenarios are profitable with up to a 3 % discount rate. Subsidized non-EEG scenarios maintain profitability across all discount rates up to 6 % (Fig. 9).

The IRR analysis in Fig. 10 reveals minimal agricultural influence on returns, particularly in high-mounted systems, with a maximum 0.6 % increase. Vertical APV plants show a 1.4 % difference at most, suggesting an insignificant agricultural impact.

4.2.1. Interpretation

In assessing APV systems holistically, the PV component predominantly influences economic feasibility, overshadowing potential effects on agricultural yields. Varying interest rates, compensation structures, and subsidies impact APV project viability. Comparing vertical and high-mounted systems, vertical ones demonstrate superior economic feasibility with lower LCOEs, higher NPVs, and IRRs. The range of results emphasizes the uncertainty in APV system feasibility. Payment options significantly affect outcomes, with subsidies enhancing profitability, especially for vertical systems. APV proves more expensive than ground-mounted PV systems, and achieving profitability aligning with EEG tariffs poses challenges, particularly for high-mounted systems. The operator model and financing type crucially determine the feasibility balance between advantages and disadvantages.

4.3. Expert interviews

Expert interviews have significantly contributed to validating the approach and calculations for APV systems. While there is consensus on the uncertainty of specific cost assumptions, experts criticize the lack of representative data, particularly from research facilities. Skepticism surrounds the viability of APV in arable farming due to perceived limited synergies and operational constraints. There is no unanimous agreement on the prevailing APV system, with high-mounted systems facing

Table 8

Overview of applied agricultural return assumptions.

Crop	Average farm contribution margin with 85 % EU subsidy (2 ha)	Agricultural contribution margin − 25 % with 85 % EU subsidy (2 ha)	Agricultural contribution margin + 25 % with 85 % EU subsidy (2 ha)
Winter wheat	2156.52€	1713.44€	2599.6€
Winter barley	1909.2€	1527.95€	2290.45€
Sugar beet	3158.96€	2465.27€	3852.65€
Potatoes	8229.2€	6267.95€	10,190.45€

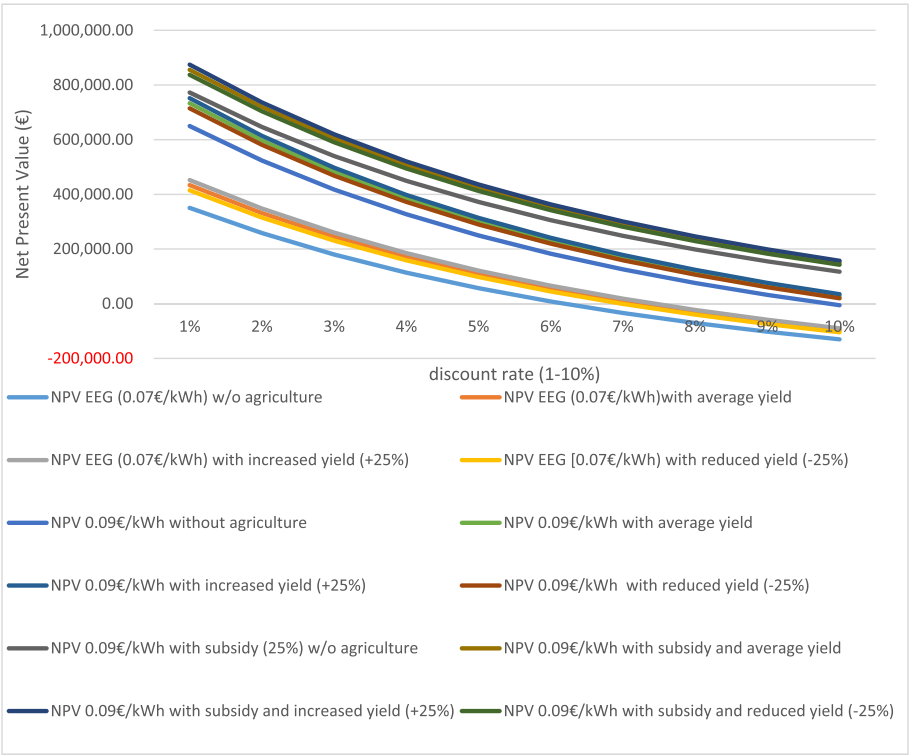


Fig. 8. Overview of Net Present Values (NPVs) of vertical systems according to payment structure and agricultural scenarios.



Fig. 9. Overview of Net Present Values (NPVs) of high-mounted systems according to payment structure and agricultural scenarios.

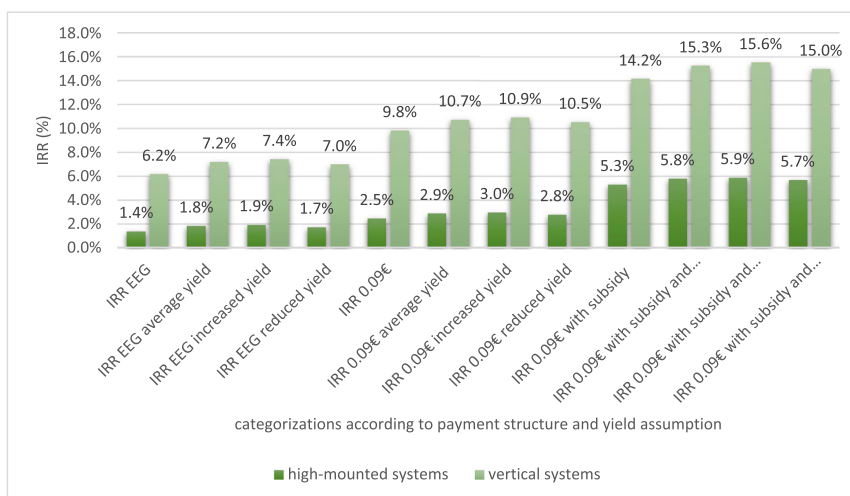


Fig. 10. Overview of the Internal Rate of Return (IRR) of Agriphotovoltaic systems according to payment structure and agricultural scenario.

unanimous criticism and attitudes toward vertical systems varying between critical and promising. Differing assessments of cost structures, technical details, and ownership structures highlight the complexity of APV implementation. Experts emphasize the need for larger system examinations to reveal scale effects realistically.

The potential impacts of PV systems on crop yields are deemed uncertain, with experts calling for more research, especially regarding climatic effects on crop-PV compatibility. While some experts in fruit cultivation see benefits, overall, the increase in resilience amidst climate change is considered irrelevant. Farmers acknowledge climate change effects in agriculture, such as increased irrigation needs for specific crops. The assumption of focusing on feed-in scenarios aligns with experts' views, as on-farm consumption in agriculture is deemed insignificant. Although discussions on on-farm consumption increase exist, opinions are critical, and it is not a current focus in agriculture.

Despite critical opinions on details, experts unanimously acknowledge the potential of APV, deeming it future proof given land area potential, energy transition goals, and the need to preserve agricultural land. However, more comprehensive research across various aspects is essential for more informed conclusions about APV systems.

4.4. Discussion

The study began by addressing the practical significance of APV in the Rhenish Lignite Mining region, aiming to reconcile land use conflicts, preserve agricultural areas, and advance the energy transition. Focused on economic aspects, the research aimed to evaluate the financial feasibility of APV, crucial in a region grappling with climate change impacts. The study's objectives included analyzing small-scale APV viability, exploring agriculture's role in economic feasibility, and identifying barriers and opportunities. The chosen methodology, with an explanatory design, aimed to provide a realistic assessment of APV potential by not only calculating quantitative models but also eliciting and critically evaluating them. This approach aligns with previous studies that successfully combined quantitative and qualitative results for solar-related potentials (López et al., 2020). Our methodology presented here can also be applied to other regions and countries by taking into account corresponding parameters such as respective national tariffs, agricultural production, local climate conditions and impacts of climate change or regional development frameworks.

Key findings highlighted the growing interest in APV, especially in the context of structural changes and the urgency of climate action. As mentioned before, it has been proven that APV systems have the potential to reduce greenhouse gas emissions as well as to potentially cover yield losses by electricity selling due to severe climate events. Experts

have raised the uncertainty of the effect on crops and the overall suitability of crops. How a plant develops in an APV system depends on many interacting factors such as shading, water availability, soil structure and microclimate and the results vary considerably. The range of yield results shows that there are no generally valid rules yet for how plants behave in an APV environment, since situational influences such as location in combination with irradiation and climate, shading and other factors influence the results.

These factors need to be further investigated in case studies to enable conclusions to be drawn for different regions and types of cultivation.

The analysis revealed that vertical APV systems exhibited greater economic feasibility than high-mounted systems. However, achieving specific feasibility targets remained challenging, emphasizing uncertainties in profitability. Qualitative findings indicated no consensus on various APV assumptions, underscoring uncertainties in cost structures, suitability in arable farming, and the benefits related to crop increase and climate resilience. Despite uncertainties, there was agreement on APV's potential contribution to the energy transition and efficient land use, essential considerations given the variability in discount rates.

4.4.1. Critical findings

The study identifies several critical points. Firstly, the economic importance of agricultural yield in APV schemes is challenged because it appears irrelevant to feasibility from an investor's perspective and potentially compromises agricultural guarantees. The choice of focusing on arable land, while the most extensive, may not be the best practice in APV design. Orchards, with similar lifespans to PV systems, may offer more promise, especially given the higher market value of fruits (Eurostat, 16. Juni). The uncertain trajectory of arable farming in the region over the next 25 years adds complexity to this approach. The lack of consensus on the benefits of APV emphasizes the need for further research to provide efficient recommendations and secure agricultural activities. The dynamic legal basis underscores the necessity for ongoing research to maintain up-to-date assumptions. The study reveals the crucial role of cost assumptions in influencing results. However, these assumptions, based on studies of research plants, lack commercial parameters, and vary among experts. This limitation hinders the overall interpretation of the study, emphasizing the need for caution in accepting cost assumptions.

4.4.2. Limitations

The research acknowledges limitations, notably in data and analysis. Data, primarily derived from APV plant studies, may not represent a true market scenario, impacting the reliability of cost assumptions. Future

cost estimations pose challenges, and while subsidies represent potential reduced costs, exploring higher cost scenarios was constrained. Legal assumptions, particularly payment options, are subject to quarterly and monthly updates, respectively. Solar irradiation variations and shading effects were simplified, neglecting peak-time shutdowns. Agricultural data assumes a consistent crop rotation for 25 years, raising realism concerns in the context of climate change. However, given the minor significance of the agricultural component compared to the PV component, this assumption was deemed acceptable. Operator models and financing structures were not considered, limiting specific investor insights. The study used general assumptions for selected crops in APV settings due to a lack of crop-specific physiological results. The chosen payment option outside the EEG may face uncertainties in tariff duration and pricing changes over the 25-year lifespan, affecting feasibility predictions. Despite these limitations, the research aimed to provide an overall feasibility overview and highlights the need for further investigations into specific feasibility targets, crop physiology, and payment option dynamics.

Furthermore, the effects of public acceptance were not considered in the economic analysis, since a quantitative inclusion appeared complex. However, the effects of social acceptance on economic efficiency will be analyzed in more detail in future studies, since awareness campaigns are being conducted in the model region for the demonstration plants, which will provide insights.

4.4.3. Research outlook

The research indicates that open-space PV installations on leased land may offer more profitability than agricultural cultivation (Böhm, 2022), emphasizing the societal debate on whether the differential costs justify avoiding land competition. To enhance APV's competitiveness, alternative strategies are proposed, such as creating a separate payment structure for APV systems, encouraging farmer involvement through incentives, and exploring economies of scale (Feuerbacher et al., 2022). Collaboration among farmers to build solar installations, forming energy cooperatives, is suggested to bolster regional energy security and foster societal acceptance (Bündnis Bürgerenergie e.V., 2023). Larger installations, potential synergies with emerging technologies like electric vehicles (Schneider et al., 2023), and the integration of water considerations and smart irrigation and fertilization systems (Bazaluk et al., 2022; Canaj et al., 2021) are seen as avenues for further research to unlock the full potential and economic viability of APV systems (Sharifnasab et al., 2023). Additionally, exploring the nexus of water, energy, and food in APV settings, evaluating biodiversity measures, and investigating "Ecovoltaics" (Sturchio and Knapp, 2023) are identified as potential research directions for sustainable and multifunctional APV systems.

The research concludes by highlighting the need for broader economic evaluations that consider evolving technologies and contextual factors, paving the way for comprehensive assessments of APV system potential.

5. Conclusions

This study aimed to analyze the economic feasibility of APV systems in the Rhenish Lignite Mining area as a model transformation region to identify potential barriers and opportunities. The feasibility was assessed by considering different payment structures and agricultural scenarios.

In summary, APV faces economic challenges within current government compensation frameworks, with discrepancies between vertical and high-mounted systems, indicating a barrier for APV implementation. Feasibility appears more promising outside the EEG, yet uncertainties in long-term compensation prices pose reliability issues. Proposed funding by the state government improves feasibility and thus demonstrates targeted government measures in the lignite mining region that can serve as a model for transformation regions and is

therefore identified as an opportunity.

Expert interviews highlight ongoing ambiguity in evolving cost structures. The agricultural return is dominated by PV component yields, making agriculture less decisive in the investment decision. APV's comparative economic analysis with alternative solar energy systems, such as ground-mounted PV or on-site consumption-focused systems, reveals uncertainties and limited financial attractiveness, particularly in arable farming. The research acknowledges APV's promise in addressing land use conflicts and contributing to the energy transition but emphasizes the need for enhanced government support, suggesting subsidies as a hopeful starting point. The study concludes that while APV presents advantages worth further exploration, political backing and alternative compensation structures are crucial for achieving financial attractiveness.

CRedit authorship contribution statement

Chantal Kierdorf: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Sabine Schlüter:** Writing – review & editing, Supervision. **Matthias Meier-Grüll:** Writing – review & editing. **Sandra Venghaus:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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Declaration of competing interest

The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *Sustainable Production and Consumption* and was not involved in the editorial review or the decision to publish this article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.spc.2025.01.001>.

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