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Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications

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HIGHLIGHTS

- Coverage of current agrophotovoltaic (APV) promotion policies in several countries.
- Comparative cost of electricity evaluation of APV and ground-mounted photovoltaics.
- Cost of APV implementation related to the economic benefit of obtaining cropland.
- Price-performance ratio calculation applied to measure economic quality of APV projects.
- Potato production under APV is economically beneficial, winter wheat production not.

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ABSTRACT

Rising demand for solar power generation will lead to increased land use competition, and thus to potential economic and social conflict. A solution to this challenge is to produce food and energy within an agrophotovoltaics (APV) system. Since 2017, governments in Japan, France, Massachusetts (USA), South Korea, and China have introduced policies supporting APV implementation. Governments considering APV implementation – e.g. in India and Germany – for evidence-based policy making are demanding information on how levelized cost of electricity (LCOE) of APV differs from that of conventional ground-mounted photovoltaics (PV), as well as on how additional costs associated with APV installation relate to the benefit of maintaining agricultural activity under APV. Data for a techno-economic price-performance ratio calculation has been retrieved from an inter- and transdisciplinary APV case study in Germany. We observed that the LCOE of APV with €0.0828 kWh^{-1} is 38% higher than that of ground-mounted PV, resulting in an annual cropland preservation price of €9,052 $ha^{-1}\,a^{-1}$. The annual revenue of potato and winter wheat production under APV resulted in a performance of €10,707 $ha^{-1}\,a^{-1}$ and €1,959 $ha^{-1}\,a^{-1}$ respectively, leading to a beneficial price-performance ratio of 0.85 for potato production and, with a ratio of 4.62, a disadvantageous result for winter wheat. Overall, APV is not necessarily recommended in crop rotating systems. However, in combination with permanent cultures – e.g. berries, fruits, or wine grapes – as the price for these types of applications is lower, while at the same time providing higher performance by optimizing techno-ecological synergies.

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Nomenclature

a	year
APV	agrophotovoltaics
BMBF	German Federal Ministry of Education and Research
BMEL	German Federal Ministry of Food and Agriculture
BMWi	German Federal Ministry for Economic Affairs and Energy
BnetzA	German Bundesnetzagentur
CAPEX	capital expenditures
ct	cents
€	euros
FM	Financial Mechanism of the UNFCCC
GM	ground-mounted
GWp	gigawatt-peak
ha	hectare
IFES	Integrated Food-Energy Systems
kWh	kilowatt hours
kWp	kilowatt-peak
LCOE	levelized cost of electricity
MWp	megawatt-peak
OPEX	operating expenses
p	price
pb	performance/performed benefit
ppr	price-performance ratio
PV	photovoltaics
RE	renewable energy
$	United States dollars

1. Introduction

Globally, ground-mounted photovoltaics (PV-GM) have become the most cost competitive source of power generation [1]. Accordingly, PV-GM represents a growing share in the PV marketplace [2]. Hardly discussed is the spatial aspect of PV-GM implementation, as well as the loss of cropland resulting from it. Land is the principal basis for human livelihood. It supplies food, fresh water and many other ecological resources. Yet due to socioeconomic development – e.g. infrastructure, industrial estate and housing development – as well as soil degradation and desertification, cropland is expected to decrease globally by between 50,000,000 ha (the size of Spain) and 650,000,000 ha (twice the size of India) by 2100 [3]. Consequently, cropland is becoming scarce. Accordingly, the availability of arable land per capita decreased by 48% between 1961 and 2016 due to the increase in global population [4]. Taking into account planetary boundaries [5] and the limited availability of cropland, it can be foreseen that the rising demand for PV-GM will lead to increased land use competition and thus result in potential economic, ecological, political, and social conflicts in the future. One approach to meeting the challenge in terms of sustainable land use is the Integrated Food-Energy System (IFES), which enables the simultaneous production of food and energy on the same plot of land. Moreover, it utilizes synergetic effects by optimally exploiting the potential offered by both production systems, as seen for instance in agroforestry systems or agrofuel production with cascade use [6]. One solution emerging from the PV sector for minimizing the impact of arable land grabbing is an agrophotovoltaic (APV)[3] dual use of agricultural land, which was proposed for the first time by Goetzberger and Zastrow [7]. Since 2017, APV has been recognized as a strategy for avoiding or minimizing land impacts from PV systems in the Global Land Outlook, focusing on energy and land use by IRENA and UNCCD [8]. In Germany, a total of eight APV power plants have been in operation since 2004, three of which were built for research purposes. General information on the APV power plants in Germany is presented in Table 1.

In parallel to the innovation process of APV in Germany, several APV pioneers have implemented demonstration projects, e.g. Japan, 2004 [9,10], Massachusetts (USA), 2008 [11], Italy, 2011[4] [12,13], Malaysia, 2015, Egypt, 2016,[5] and Chile, 2017 [14]. Some advanced governments have already implemented APV dissemination policies, e.g. Japan [15], South Korea [16–18], China [19], France [20], and Massachusetts (DOER [21],[6] while others are currently discussing the implementation of APV, e.g. India [22,23] and Germany [24]. We estimate that approximately 2200 APV systems have been installed worldwide since 2014, leading to a capacity of about 2.8 GWp as of January 2020.[7] Together with the increasing international APV market development, the scientific community has paid growing attention to APV, and a review of the applications, challenges, and opportunities presented by APV systems has recently been published [27]. Pearce (Michigan Technological University) presented a very comprehensive literature review on APV as part of his lecture entitled "Solar PV Science and Engineering."[8] The first international APV conference will be held in France in August 2020 to connect the scientific community and promote international exchange in a greater effort to advance APV system technology.[9] Techno-ecological aspects of APV have also been discussed [28–31], and geographical APV research gaps have been closed by Adeh et al. [32] and Majumdar and Pasqualetti [33]. Publications on plant ecology as well as assessments of the agricultural productivity of agave, wine grapes, lettuce, corn, and Java tea in combination with APV have also been written [33–42]. Evaporation, transpiration and irrigation in the context of APV has been covered as well [30,35,37,43,44]. Social, economic, and political considerations of APV have also recently been researched [45–48]. The present study is concerned with the APV research facility in Heggelbach, Germany, 2016. As a contribution to resource-efficient land use and the simultaneous reduction of land use competition, the "Agrophotovoltaics Innovation Group Resource Efficient Land Use (APV-RESOLA, Grant No.: 033L098AN)" was established in 2015.[10] An APV prototype was developed, installed, and tested under real-life conditions as part of an inter- and transdisciplinary project funded by the German Federal Ministry of Education and Research (BMBF). APV-RESOLA defines APV as a system technology that evidently increases land use efficiency by simultaneously enabling main agricultural crop production and secondary solar PV power generation on the same cropland area, while optimally utilizing the techno-ecological and techno-economic synergy effects of both production systems. The research project is divided into five key work focus groups: (1) Technology Development, (2) Environment and Biodiversity, (3) Society, (4) Agriculture, and (5)

[3] The name "agrophotovoltaics" is derived from FAO's IFES methodology as well as the terms "agroforestry" and "agrofuels" [6].

[4] Source: https://www.youtube.com/watch?v=03HraAXcb4g (01.10.2019).

[5] Source: https://www.gridparityag.com/ and claims by www.almaden-europe.com Dr. Erich Merkle as well as Maximilian Abouleish-Boes, http://www.sekem.com/en/index/ (31.08.2019).

[6] For more details on international APV market development and public policy on APV dissemination, please see information boxes in the attachment.

[7] By comparison, the total installed capacity of floating photovoltaics (FPV) worldwide is estimated at 1300 MWp SERIS [25] and the total installed capacity of concentrated photovoltaics (CPV) worldwide is estimated at 600 MWp and might reach 1.36 GWp by the end of 2020 IHS [26].

[8] Source: https://www.appropedia.org/Dual_use_of_land_for_PV_farms_and_agriculture_literature_review (07.01.2020).

[9] Source: http://www.agrivoltaics-conference.org/home/about.html (06.01.2020).

[10] For more information on the APV-RESOLA project, see following link: www.agrophotovoltaik.de.

Table 1
General information on APV power plants in Germany.

No.	Location (Federal State)	Capacity in kWp	Agricultural products grown at the APV plant site	Operator	Year of installation
1	Warmisried (Bavaria)	70	Potatoes, winter wheat, spring barley, beetroot, leeks, celery	Elektro Guggenmos	2004
2	Bürstadt (Hesse)	250	Flowers, e.g. peonies	Gärtnerei Haller	2010
3	Lampertheim Rosengarten (Hesse)	5000	Ginseng	Krug's Spargel	2013
4*	Freising (Bavaria)	28	Chinese cabbage, Pointed cabbage	Weihenstephan-Triesdorf University of Applied Sciences	2013
5	Bürstadt (Hesse)	5000	Ginseng	Krug's Spargel	2015
6*	Heggelbach (Baden-Württemberg)	194.4	Potato, winter wheat, celeriac, clover	Fraunhofer ISE and Farm community Heggelbach	2016
7	Freising (Bavaria)	14	Chinese cabbage, pointed cabbage	Weihenstephan-Triesdorf University of Applied Sciences and SolarTube GmbH	2017
8*	Dresden (Saxony)	12.9	Spinach, peas, bush beans, chard, radishes	Dresden University of Applied Sciences	2018

* Research facilities.

Political and Economic Analysis. Here, we are presenting the output of activities stemming the fifth work focus group. In contrast to previous APV studies, cost data on APV implementation is published here for the first time and assessed in relation to the economic benefit of obtaining cropland. We apply and introduce the method of price-performance ratio calculation as an indicator to measure the techno-economic quality of an intended APV project within an APV permitting process. We thereby provide a decision support tool for policy makers in order to design public policies for the promotion and dissemination of APV. Results from our case study on APV implementation support evidence-based policy making and close research gaps as follows:

(i) How does the levelized cost of electricity (LCOE) of APV differ from the cost of conventional ground-mounted PV installations in terms of capital expenditures (CAPEX) and operating expenses (OPEX)?
(ii) How does the potential additional cost of APV implementation (price) relate to the benefit of maintaining agricultural activity under APV (performance)?
(iii) What conclusions can be drawn from a techno-economic price-performance ratio analysis of APV implementation with regard to public policy design in terms of quality assurance, crop selection, land management, price, and level of quantity?

This is how we contribute to the current discussion on the social, economic, and policy aspects of APV.

2. Theory: Planning APV implementation based on the price-performance ratio

2.1. PV-GM land management in Germany: built-up area vs. arable land

Between 2004 and 2010, PV-GM dissemination was supported under Germany's Renewable Energy Act (EEG), having received a price-based feed-in tariff (FiT). To minimize ecological impacts, PV-GM implementation was governed in such a way that low-quality land, e.g. former military or landfill areas, was prioritized in PV-GM development. In 2005, the Nature and Biodiversity Conservation Union (NABU) published a planning guide for the environmentally sound implementation of PV-GM on arable land, including sheep and goat husbandry [49]. In 2010, however, conversion areas became scarce, and with the increasing share of PV-GM implementation on cropland, the German government decided to eliminate FiT support for PV-GM entirely. Between 2010 and 2014, no PV-GM projects were commissioned in Germany. In 2014, German policymakers decided to turn the former price-based FiT regulation for PV-GM dissemination into a quantity-based approval mechanism with an annual PV-GM capacity of 600 MWp, taking effect in 2015. This new support mechanism targeted institutional investors, financing utility-scale projects with capacities ranging from 750 kWp to 10 MWp and with a twenty-year FiT price set by a pay-as-bid, market-based auction rather than by the government itself.[11] Land availability was expanded to areas next to transportation infrastructure, e.g. 110-m strips along highways and railroads, as well as to less-favored areas – a subcategory of arable land characterized by low soil quality, for example. Furthermore, federal policymakers transferred decision-making power to the state level with regard to

[11] From a rational choice perspective and with all information available, for the policymaker, it would not matter if PV-GM dissemination is promoted via a price or quantity mechanism. Yet due to asymmetric information, lack of information, and non-rational behavior of policymakers and economic players, a restriction risk remains for policymakers when defining the 'right' price and quantity for the promotion of a certain good according to Weizmann [50]

utilizing less-favored areas[12] for PV-GM development, thereby justifying the principle of subsidiarity within a federal system [52,53]. From 2015 to 2018, the quantity-based PV-GM auctions were continuously oversubscribed, showing that there is sufficient cropland and demand for PV-GM development in Germany [54]. By the end of 2018, the total installed PV capacity had reached 45.4 GWp, of which 4.7 GWp were installed on 10,959 ha of arable land, leading to an average PV-GM land use efficiency of 2.33 ha/MWp between 2004 and 2018 [55]. Today, PV-GM covers 0.07% of Germany's arable land,[13] [56] which appears very little compared to the 15% of cropland utilized for the production of agrofuels, e.g. E5, E10, biodiesel, and biogas [57]. The re-inclusion of PV-GM into the EEG 2014 promoted economies of scale and increased the competitiveness of PV. In a cross-technological 200-MWp auction with onshore wind power plants in 2018, PV-GM received all the bids, thus becoming the lowest-cost renewable energy source in Germany [58]. The first subsidy-free PV-GM project on cropland in Germany was inaugurated in 2019 [59]. Subsequently, PV-GM advocates, industry representatives, and policymakers in favor of rapid PV-GM dissemination claim that PV-GM will occupy less than 1% of arable land by 2050. Following this argument, German policymakers passed a law enabling additional PV-GM auctions with a cumulative capacity of 4 GWp to be surcharged between 2019 and 2021 [60]. Thus, a total of 5.2 GWp of PV-GM is set to be installed by 2021, doubling PV-GM capacity on arable land. With a current average land use efficiency of 1.45 ha/MWp for PV-GM implementation, this policy will demand 7,540 ha of arable land, or 10.3 ha per day. At the same time, the German government intends to limit the expansion of built-up area from approximately 65 ha day^{-1} in 2018 to 30 ha minus × day^{-1} by 2030 [61],[14] and even to net zero by 2050 [62]. Since PV-GM is considered to be industrial estate area, as the main land functionality of PV-GM is not to produce biomass, but to generate solar PV power, the inclusion of PV-GM on arable land counteracts sustainable development policy targets. Evidently, the 10.3 ha day^{-1} of PV-GM built-up area expansion affiliated with the additional four GWp of PV-GM auction would require approximately 34.3% of Germany's targeted 30 ha minus × $days^{-1}$ of sustainable land, making limitations to the expansion of built-up area obvious. Since 2015, cropland under PV-GM has no longer been eligible for subsidies from the common agricultural policy of the European Union (EU) in Germany [63]), since PV-GM is considered an expansion of built-up area. Limitations to PV-GM dissemination do not correspond with the availability of cropland, but rather with its competition with socioeconomic development and the expansion of built-up areas for infrastructure, e.g. road construction, industrial estates, and housing developments. The first federal state that has taken political action to synchronize PV-GM land management with the expansion of built-up area is the Federal State of Bavaria. To push back "surface guzzling" and to protect the common good, arable land and landscape, Bavaria has initially set a quantity limit of 30 PV-GM projects each year in 2019, which will later rise to 70 [59,64]. Thus, it is important to compare PV-GM development with the expansion of built-up area rather than arable land availability within the context of the discussion surrounding land management for PV-GM dissemination. The unique selling point of APV in comparison to PV-GM is based on the simple fact that APV obtains cropland, and may even improve the agricultural yield production. Therefore, PV-GM and APV aim at different landscapes and qualities of cropland.

2.2. Governance of agrophotovoltaics: Theory of the price-performance ratio

In economic and innovation theories, it is believed that in an early stage of market penetration, products are often ineffective and expensive, targeting at wealthy innovators, first-movers, and early adaptors. Gradually, with continuous improvement and re-design of the product on the one hand and market entries, competition, higher R&D investments, and economics of scale on the other hand, products become more effective and cheaper [65,66]. When implementing innovations such as APV, governments try to minimize risks and adapt promotion of the innovation according to the technology readiness level (TRL) scale [67]. In early development stages, policymakers fund research and demonstration projects to gather information, focus on evidence-based policymaking, and search for the best practice. In late TRLs with promising scientific results, policymakers establish a pre-standard and thoroughly establish market penetration using the valley of death principle [68]. Furthermore, in democratic regimes, and in line with the rational choice approach to increasing welfare, governments may only justify their governing action by achieving a benefit higher than the paid price (or cost). For instance, with respect to the support of renewable energy and the related cost of quantity or price regulation, performance is measured by accounting for the economic savings from fewer energy imports, jobs created, patents registered, or avoided harm to ecosystem services. Ministerial reports regularly monitor and publish the results [69]. In applying the theory of the price-performance ratio to APV applications, we come into contact with the great diversity of the agricultural sector, requiring different APV technology designs. Policymakers working with the governance of APV implementation on a macro level seek to maximize the benefit and minimize the cost of APV dissemination policies. Accordingly, on a micro level, APV projects are most likely to be permitted in an APV dissemination policy, resulting in high performance at the lowest price possible. The price-performance ratio is an economical decision-making aid for policymakers, whose methodology in terms of APV is explained in the following chapter.

3. Methodology

3.1. Calculation method for the price-performance ratio

The quotient takes on positive values larger than zero and is calculated as follows:

$$ppr = \frac{p}{pb} \tag{1}$$

where

ppr	=	price-performance ratio	
p	=	price	[€/ha/a]
pb	=	performance benefit	[€/ha/a]

The **general assumption of the price-performance ratio (ppr)** is that a ratio larger than 1 is not reasonable to support APV dissemination of the analyzed systems since the techno-economic synergies are not great enough. However, a ratio of 1 assumes that APV implementation is economically reasonable since the resilience of the farmer in question has been improved by income diversification, adaptation to global warming, contribution to the energy transition, and achievements in land use efficiency. If the price of maintaining cropland is lower than the economic performance of the same cropland (ratio less than 1, a result policymakers seek), the project-specific benefits are higher than the affiliated costs. Thus, through policy learning and adaptation, policymakers strive to minimize this ratio in order to maximize techno-economic and techno-ecological synergies, thereby improving the cost-

(*footnote continued*)
Hepburn [51].

[12] Less-favored areas are areas covered by Council Directive 86/465/EEC of 14 July 1986 concerning the Community list of less-favored farming areas within the meaning of Directive 75/268/EEC (ABI, (EC) No. L 273, S1) as amended by EU Commission Decision 87/172 / EC of 10 February 1997 (OJ L (L) 72, p 0.1).

[13] Total agricultural land in Germany is 16,645,100 ha in 2018 [56].

[14] Originally this target should have been achieved in 2020 [61], but as it became evident that Germany will fail meeting this target, the political solution was to postpone the time horizon of the target by 10 years to 2030.

benefit relationship of the implemented policy.

Price of APV implementation (p): We have defined the price of APV implementation as the extra annual cost resulting from the adaptation of the PV-GM structure in order to maintain the cropland and enable techno-economic and techno-ecological synergies. The extra cost is deconstructed by the methodology of the levelized cost of electricity (LCOE) and separated into extra costs in capital expenditures (CAPEX) and operating expenses (OPEX). The annual price difference between a conventional PV-GM and an APV power plant installed on the same area of cropland under identical meteorological conditions is thus considered the price of arable land preservation and is expressed as follows:

$$p = LCOE_{APV} * M_{APV} - LCOE_{PVGM} * M_{PVGM} \tag{2}$$

where

p	=	price	[€/ha/a]
$LCOE_{APV}$	=	levelized cost of electricity for agrophotovoltaics	[€/kWh]
$LCOE_{PVGM}$	=	levelized cost of electricity for ground-mounted PV	[€/kWh]
M_{APV}	=	annual electrical yield per ha APV	[kWh/ha/a]
M_{PVGM}	=	annual electrical yield per ha PV-GM	[kWh/ha/a]

The price (p) of APV implementation per project is calculated by multiplying the LCOE by the respective annual electrical yields M per hectare occupied by the PV-system. The price (p) expressed in € ha^{-1} a^{-1} is predominantly affected by the type of farming process and the techno-economic performance, and thus by the LCOE of APV as well.

Performance of APV implementation (pb): The performed benefits (pb) from APV implementation are the preservation of cropland and the annual revenue from harvest under APV in € ha^{-1}. The resulting benefit depends on the value of the selected crops and on the impacts of the APV system, e.g. shading or land loss due to the construction. Here, the general economic assumption is that a greater expected annual farming revenue signifies a higher price for land preservation. Data for the calculation of the performance is derived from three sources: (a) revenue data for the organic potatoes and winter wheat at the Bavarian State Research Center for Agriculture (LfL)[15] on over area without APV, (b) sales data from the Demeter-certified farm community Heggelbach, and (c) project results on yields of potatoes as well as winter wheat which shares space with APV at the University of Hohenheim.[16] It is important to note that the price-performance ratio uses micro-economic data to pursue the principal course of thought. It is neither a profit assessment nor a macroeconomic cost-benefit analysis (CBA). The CBA is recommended in order to provide an estimated value of different methods of APV implementation comparing the total expected cost of each policy option. The CBA methodology is used for a holistic technology assessment including, e.g. impacts on the job market or environmental services [70]. Moreover, the CBA regulates public policies in several countries, e.g. in Canada where it is part of the National Guide for Regulatory Analysis [71], or in water resource development and healthcare regulations in the USA [72,73]. According to economic theory, the optimum result of a CBA of APV implementation can only be achieved if only APV projects are executed where the price-performance ratio is less than or equal to 1, or if the benefit of maintaining food production is higher than the cost of PV-GM adaptation. In the present APV case study, the farmer produced a relatively ineffective APV crop rotation culture including winter wheat as a crop which requires a high light intensity to grow. The background is that the construction had to be adapted to allow a harvester to operate under APV, and at the same time, it did not substitute any supplementary type of crop growing systems, e.g. hail protection nets used in fruit production. Consequently, the price for cropland conservation here is very high, whereas the microeconomic performance of grain production in a crop rotating system is relatively low compared to other APV applications that might be feasible for permanent and special high-yield crops. Therefore, we consider our case study economically conservative, leaving the need for future APV ppr optimization. In the following, details of the applied LCOE and ppr calculation methods are explained, the data basis is referenced, and the estimation strategy is outlined.

3.2. Levelized cost of electricity calculation method

The LCOE calculation method is used to calculate and compare the specific costs per unit of electricity produced (€ k^{-1} W h^{-1}). In practice, this method is the current cost comparison criterion of different electric power plant systems [74–76]. The calculations are made using Microsoft Excel software, and are based on the formula below:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} A_t * (1+i)^{-t} - R_n}{\sum_{t=1}^{n} M_{t,el} * (1+i)^{-t}} \tag{3}$$

The basic idea of the calculation method is to contrast the capital expenditures I_0 (CAPEX) and all operating expenses A_t (OPEX) minus the residual value R_n available at the end of the useful life n of the total generated electrical energy. Both the cost and the annual average amount of electrical energy produced are reduced to a common reference date, using the calculation interest rate i. This seems unrealistic, but since the energy produced implicitly stands for the revenue generated by the energy, this method makes sense financially [77]. The electrical energy produced in a year M is expressed by the following formula:

$$M_{t,el} = \sum_{t=1}^{n} S * \eta * (1-d)^t \tag{4}$$

The electrical energy produced in a year $M_{t,el}$ is calculated as the sum of the annual solar irradiation S multiplied by the system efficiency η and the annual efficiency losses d. It has been determined by the electricity yield certificates specific to the APV power plant in Heggelbach and a south-facing conventional PV-GM as a comparison value. It is assumed that the residual value R_n of the total APV system equals the dismantling costs, and can thus be neglected. Also, the costs for dismantling are not taken into account as a reserve against the annual operating costs [77].

3.3. The LCOE as a data basis

For the development, installation, and commissioning of the APV power plant Fraunhofer worked in close cooperation with project partners BayWa r.e. and the farm community Heggelbach to open a public call to tender procurements of the following products and services: ground surveys, building permission support, APV mounting structure including the associated logistics and installation, installation of the electrical system including the PV system, and electricity grid connection including a transformer station. As is common in German administration, the lowest bidder was awarded the contract. The offer for the APV mounting structure, including logistics and assembly, was obtained for the installation of an APV capacity of 0.2 MWp, 0.5 MWp, 1.0 MWp or 2.0 MWp in order to scrutinize scaling effects. To calculate the APV-LCOE, the data of an APV plant with a capacity of 1.04 MWp is used as a basis, corresponding to an area utilization of 2 ha. The costs incurred for the scientific support, including technical equipment such as sensors for agricultural and energy yield monitoring, microclimate stations, substructure development, and the creation of a time-lapse

[15] Data Source: https://www.stmelf.bayern.de/idb/oekospeisekartoffeln.html (24.09.2019).Data Source: https://www.stmelf.bayern.de/idb/oekowinterweizen.html (24.09.2019).

[16] The installation of the APV system did not impact the farm's typical crop rotation scheme. Data on the final harvest productivity and the agricultural research design are not presented in this manuscript since they will be published by the University of Hohenheim (manuscript in preparation).

video documenting the construction of the installation,[17] are not included in the APV-LCOE calculation. Income from agricultural production is not taken into consideration in the APV-LCOE calculation. An annual fee for the partial use of agricultural land (land lease payment[18]) paid by the APV owner to the farmer for the dual use of the land is included in the APV-LCOE calculation.[19] In the assumption that the lowest possible APV-LCOE increases the competitiveness of APV, thus increasing the likelihood of market introduction or the incorporation of APV into existing legislation, the purchase and installation of the APV system was always balanced by the lowest possible costs while maintaining compliance with the quality demanded and the agricultural requirements.

3.4. Time considerations

The APV prototype was installed in August and September 2016. The APV system is expected to be in operation for 25 years from its commissioning in September 2016. All cost data was updated to current market prices in June 2019.

3.5. LCOE comparison of APV to PV-GM

For the comparison of APV to PV-GM, the area was limited to 2 ha since it is assumed that APV power plants of this size can be realistically implemented in Southern Germany's small-scale agricultural structure. This area yielded an installed capacity of 689.66 kWp ha^{-1} with PV-GM and 519.18 kWp ha^{-1} with APV. The annual specific electricity yields of the PV-GM and the APV power plants were calculated in yield assessments conducted by Fraunhofer ISE. The yield assessment of the PV-GM was based on an energy system in close proximity to the APV trial area, so that the climatic and in particular the solar irradiation values are almost identical. In order to ensure comparability of the PV technologies, the annual specific electricity yield data was taken from the respective yield certification. More information on the accuracy of electricity yield certification and the underlying calculation method, e.g. the calculation of the performance ratio or degradation effects of the PV system and the bifacial PV modules, are discussed elsewhere [78–80].

3.6. Location and geography

The APV power plant was installed on a field of the Demeter-certified farm community Heggelbach in the municipality Herdwangen-Schönach, district of Sigmaringen, in the Lake Constance region of Upper Swabia. The APV complex is located about 400 m from the farming community. With a credit rating of 42, the field has an average soil quality, and is not located in a less-favored area. The field is slightly sloping, at elevations ranging from 655 to 670 m above sea level, and is exposed to relatively high wind and snow loads (snow zone 1). Extreme falling winds of up to 150 km h^{-1} and a snow load of 0.93 kN/m^{-2} at temperatures of $-25°$ to $+35$ °C were assumed in the development of the mounting structure. A permit was required for the turnkey construction of the APV power plant and was granted by regional authority in the context of construction planning carried out by the local municipality.

3.7. Technical parameters

The main technical parameters of the APV system technology are noted in Fig. 3 and can be summarized as follows: The PV modules are elevated with a clearance height of 5 m so that the work of the agricultural machinery, in particular of the combine harvester, is not hindered by the APV power plant. The overall height of the installation reaches 7.8 m. Each individual unit has a width of 19 m, having been chosen to be many times the width of the machine most frequently used for this particular cropland. This ensures that as little area as possible is lost and reduces the additional work for the farmer to a minimum. Overall, the APV system takes up seven units in width, adding up to a total width of 133 m. The length of each unit is 13 m and was also chosen by a multiple of the farm's most common machine, so that the farmer can process the field in both directions of the APV power plant in future. The power plant is two units long, resulting in a total length of 26 m. In order to ensure uniform crop growth, the APV installation must guarantee sufficient and homogeneous light distribution. The application of the Fraunhofer ISE patent EP2811819A1 "Method for simultaneously cultivating crop plants and utilizing the energy of sunlight" registered in 2012 ensures these conditions and controls exposure to sunlight during the plants' entire vegetative phase [81]. The results of a light simulation fundamentally influence the development and design of the APV substructure, e.g. the inclination of the PV modules, PV module row spacing, and the location-specific alignment to the sky.[20] To gather robust data of agricultural yields, a minimum size needed to be established for the APV system, taking boundary effects from light entering from the sides of the power plant into consideration. To reduce boundary effects in our case study, we applied Fraunhofer ISE patent application DE102014218458A1 "Solar module arrangement with reduced edge effects and use of the solar module arrangement for simultaneous cultivation of crops and energetic utilization of sunlight" [82]. Commercially available silicon-based PERC PV module technology was considered for both APV and PV-GM, but for the area of cereal and vegetable production where APV was employed, bifacial PV modules were selected, as this type of PV technology processes both direct and indirect light not only on the front, but also on the back sheet of the PV module. The back sheet is made of glass, thus ensuring that the light also reaches the solar cell from below. This means that this type of PV module achieves greater efficiency and partially compensates for the larger PV module row distances necessary for providing sufficient light to the agricultural production system. Further advantages of the bifacial modules include the fulfillment of the guidelines for overhead glazing of the state building regulations in Baden-Württemberg and the fact that no further construction measures, e.g. safety nets, were necessary for ensuring work safety in conjunction with the APV system. Moreover, crops grown under the APV benefit from diffused light instead of direct shading near the ground (see Figs. 1 and 2).

For the APV prototype, a total of 720 SolarWorld SW 270 duo bifacial PV modules were installed, resulting in a module area of 1206 m^2 and a total output of 194.4 kWp. The additional electrical yield depends predominantly on the installation height and the background reflectance (albedo factor) and was calculated for the APV plant at 8%, having been confirmed in the first year of operation.[21] In total, the APV system has 30 PV module rows, consisting of two modules per row attached to one module rack. The module row spacing is 27% greater

[17] Source: Fraunhofer ISE/AMA Films, https://www.youtube.com/watch?v=NJnXSzvy-8 (01.10.2019).

[18] A land lease in the true sense is not present, as the landowner and farmer can continue farming his area. It is legally controversial whether this initially constitutes a lease or rent. The contract as such is a sui generis contract, which is based on the land use contract, for example by having a notary public register the rights-of-way in the land register.

[19] With regard to the additional costs for the farmer to manage the arable land in the APV power plant, it can be anticipated that the land lease payment will compensate for the cost of the additional effort. Details will be discussed in a separate study.

[20] Detailed information and further data on the technical development, installation, and operation of the APV system, including land equivalent ratio calculations and measurements of boundary effects in light management, will be published by Fraunhofer ISE (manuscript in preparation).

[21] APV power yield data is online available: http://www.ise.solar-monitoring.de/system.php?system=apvh&untersystem=0&date=2017–05-03&lang=de (24.09.2019).

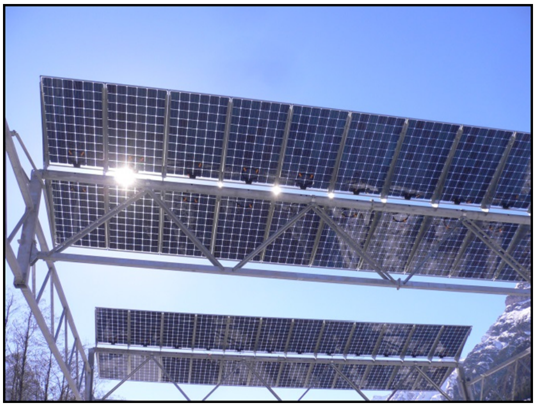

Fig. 1. Left: Bifacial glass-glass PV Modules from below (Source: [41]).

Fig. 2. Right: Diffuse shadows from bifacial PV modules near the ground (Source: [41]).

than that of a conventional PV-GM[22]. As a result, the annual average photosynthetically active radiation (PAR) available for crop production below the APV system is about 60%, rising to about 63% of the original available sunlight in the summer months. Yet depending on the light saturation point of the crops grown in APV, the impact of shading on PAR varies significantly, with the potential of having a positive or negative influence, or none at all [83,84].

The structural pillars were outfitted with a form of protection to prevent direct collisions between the agricultural machinery and the pillars of the APV mounting structure**.** The APV system is designed such that the system can stand freely without bracing. The supports are only secured by a sort of corkscrew bolt (spider anchor) in the ground, so that the entire system can forgo concrete foundations and be dismantled without leaving behind any residue. Mobile soil protection panels were laid for the heavy construction machinery and cranes were employed to protect the fertile soil from soil compaction during APV system installation (see Fig. 3).

3.8. Three land users, one business case

Cooperation between the three land users – the APV operator, the farmer, and the landowner – plays an important role in calculating the LCOE of the APV. Overall, five cooperative configurations (A–E) were identified, which all led to different cost structures (Table 2) (See Figs. 4–7).

To successfully implement an APV project, all three key land users must cooperate, where one type of land user can assume more than one land use role. The subject of the present study is represented by scenario “A”, in which the APV investor cooperates with a farmer who is also owns the land on which the APV is installed. Accordingly, we suggest that APV power plants be designed to be smaller in size than the large conventional PV-GM, but greater in size than large private PV rooftop systems. In Germany, a realistic nominal capacity of an APV system is estimated at between 1 and 10 MWp. As the size of an APV system increases, it is assumed that APV cooperation scenarios C, D and E will become less practicable on account of the high investment costs, while scenarios A and B establish themselves as more common models, appealing to institutional financial organizations such as banks and insurance companies. Assuming that the APV operator is neither the farmer nor the landowner, the revenue and cost of food production in an APV system – including the additional costs and contribution margin from the fieldwork in conjunction with APV – are disregarded in the calculation of the LCOE of APV. From a purely microeconomic and rational-choice perspective, both the APV investor and the farmer-landowner strive for profit maximization in implementing APV on cropland. The price of the annual land lease which the APV operator pays to the landowner is included in the LCOE calculations, representing the business case for the farmer-landowner. Firstly, the annual land cost payment compensates for the diminished food production revenue due to land loss and an estimated decrease in average crop yield on account of increased shade. Secondly, it reimburses the farmer for the higher costs associated with land machinery operation in an APV system, which is more labor- and fuel-intensive compared to the reference area without APV. Finally, as the farmer continues to produce food on the land area under APV, the income received from the European Union (EU) Common Agricultural Policy (CAP) subsidy is maintained for the same area. This also means that the farmer-landowner benefits from additional income on top of the average estimated contribution margin for each hectare of APV. This land rent represents income diversification for the farmer, decreasing the operational risk, as the APV investor pays this annual land cost even if the farmer has a bad harvest, for instance due to drought or another extreme event. Generally, it is assumed that the expected annual average contribution margin including the EU CAP subsidy for each hectare under APV and the land rent from the APV investor is higher than the land rent paid by conventional PV-GM for the same area.[23] The business case for the APV investor is selling APV power at a higher price per kWh than the LCOE of APV.[24]

4. Empirical application and data

4.1. Price of APV implementation

In the following, the investment, operating, and maintenance costs of the APV system technology for the case study in Heggelbach are compared with those of conventional PV-GM. LCOEs are calculated and the LCOE difference between APV and PV-GM is illustrated. Finally, the price of cropland preservation in conjunction with APV is defined based on a calculation of the annual LCOE difference between conventional PV-GM and APV built on identical land areas.

[22] With a PV module height factor of 2.8 instead of 2.2.

[23] In our case, the farmer additionally benefits from the self-consumption of APV power, allowing for a reduction of the electricity cost and thus decreasing the full cost calculation of the entire farm. However, we believe that the self-consumption of APV power will remain an exception in APV business case development and the cost and benefit will remain neglected in the calculation of the LCOE of APV.

[24] As there is no governmental support mechanism for APV implementation in Germany, for instance a feed-in tariff or tax credit, there is no business case for the APV investor. Since power prices on the electricity stock market are lower than the price of PV production, there is hardly any subsidy-free business case, and if there were, it would only be for conventional PV-GM due to a very low LCOE. This is why we see an intensifying land use conflict between PV-GM and food production on arable land.

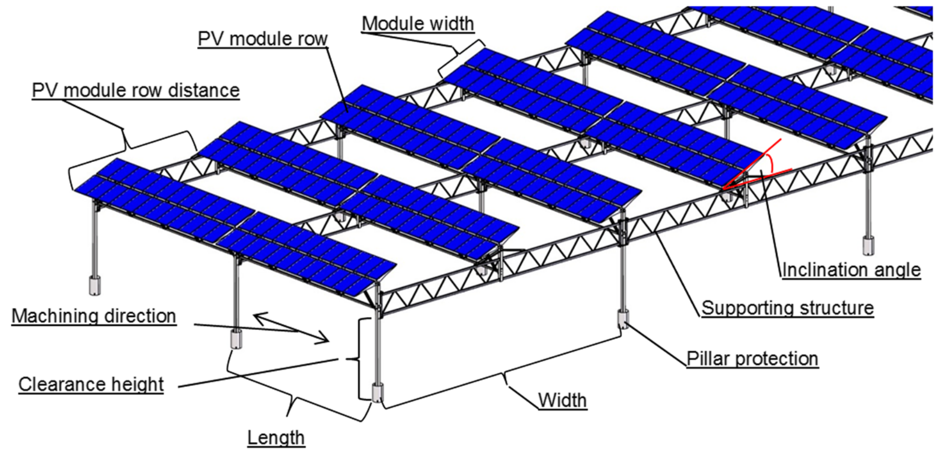

Fig. 3. Fundamental technical parameters of APV system technology (Source: Hilber Solar, [41]).

Table 2
Land user and APV cooperation scenario.

	Land User		
APV cooperation scenario	APV operator	Farmer	Land owner
A	***APV investor***	***Farmer***	
B	APV investor	Farmer	Land owner
C	Farmer		
D	Farmer		Land owner
E	Land owner	Farmer	Land owner

Fig. 4. (Left, source: BayWa r.e.): Installation of APV power plant with mobile soil protection panels in August 2016.

Fig. 5. (Right, source: farm community Heggelbach): Installation of APV power plant with mobile soil protection panels in August 2016.

Fig. 6. (Left, source: BayWa r.e.): Scientific APV power plant from above with reference area next to it and in operation in 2018, producing Demeter-certified organic potatoes, winter wheat, clover, and celery.

4.2. Capital expenditures (CAPEX) of APV and PV-GM

Fig. 8 compares the additional or reduced CAPEX of APV and PV-GM and illustrates the different cost factors. Both systems examined reference an area of land of 2 ha, corresponding to an APV capacity of 1038.36 kWp and an installed PV-GM capacity of 1379.32 kWp. The total CAPEX for the installation and the commissioning of APV amounts to €1294.20 kWp^{-1} (total cost of €1343849.53), and for PV-GM €747.50 kWp^{-1} (total cost of €1031034.48). A table comparing specific investment costs for each cost factor for both APV and PV-GM is provided in Appendix A: Cost Data (see Fig. 8).

Of note are the higher specific investment costs of APV for the cost factors (1) PV modules, (3) mounting structure, (6) site preparation and installation, and (13) soil protection. As fencing is not necessary for the APV power plant, APV CAPEX is reduced slightly as regards cost factor (7) fence.

Fig. 7. (Right, source: farm community Heggelbach): Scientific APV power plant from above with reference area next to it and in operation in 2018, producing Demeter-certified organic potatoes, winter wheat, clover, and celery.

4.3. Operating expenses (OPEX) of APV and PV-GM

Fig. 9 presents the additional or reduced OPEX of APV and PV-GM, as the case may be, and illustrates the different cost factors. The total OPEX of the 1038.36 kWp APV system are €16.25 kWp^{-1} (total annual costs €16,873), equaling 1.1% of the CAPEX. For the 1379.32 kWp generated by PV-GM, the OPEX are €18.65 kWp^{-1} (total annual costs €25,724), which corresponds to 2.2% of the CAPEX for PV-GM. A table comparing specific operational and maintenance costs for each cost factor for both APV and PV-GM is provided in Appendix A: Cost Data.

In terms of operating costs, it can be seen that cost factor (15) land cost per year is lower for APV than for PV-GM. Furthermore, the costs of (16) maintenance and mowing are significantly lower and (17) surveillance costs are somewhat lower. The higher (22) repair services costs have a cost-increasing effect for APV (Tables 3 and 4).

4.4. Input parameters for the electricity yield assumptions and the discount factors for calculating the LCOE of APV and PV-GM

Table 5 illustrates the input parameters for the electricity yield assumptions and the discount factor calculation. For the discount factors, it is assumed that these input parameters are equally valid for both APV and PV-GM. An indication that the project-specific risks for APV are no larger than those for PV-GM are the identical costs of insurance, which also cover the risk of earning losses. If the risk of default on APV were higher, the banks would provide less leverage or offset them with higher insurance costs. Since the APV power plant was insured under the same terms as a PV-GM, it can be assumed that capital costs for debt are also at the same level. The inflation rate is assumed to be 2%. However, it is not deducted from the nominal WACC, but rather from the life cycle-adjusted annual OPEX (see Table 3).

4.5. LCOE results for PV-GM and APV

With a LCOE of €0.0829 kWh^{-1} of APV and a LCOE of €0.0603 kWh^{-1} of PV-GM, the LCOE of APV is €0.0226 kWh^{-1} (38%) higher than that of PV-GM. In total, €0.0673 kWh^{-1} (81%) of the LCOE of APV can be traced back to CAPEX and €0.0156 kWh^{-1} (19%) to OPEX. The LCOE of PV-GM comprises €0.0413 kWh^{-1} (68%) in CAPEX and €0.0190 kWh^{-1} (32%) in OPEX Fig. 10.

4.6. Price (p) results of APV implementation

The total annual price (p) of obtaining cropland for food production is the difference between the land use price of APV and that of PV-GM: €59329.81 € $ha^{-1}a^{-1}$ minus €50278.08 € $ha^{-1}a^{-1}$, equaling €9051.73 $ha^{-1}a^{-1}$.

4.7. Performance (pb) results of APV implementation

In our case study, the performance of APV implementation is measured by the preservation of Demter-certified organic potatoes and winter wheat growing under APV. The performance is expressed in € ha^{-1} a^{-1} and is derived from organic potato-growing data without APV from the Bavarian State Research Center for Agriculture (LfL). According to the farmers from the farm community Heggelbach, however, the producer price for organic potatoes and winter wheat can be increased by 15% due to Demeter-certification. At the same time, the average yield of the organic potato and winter wheat harvests

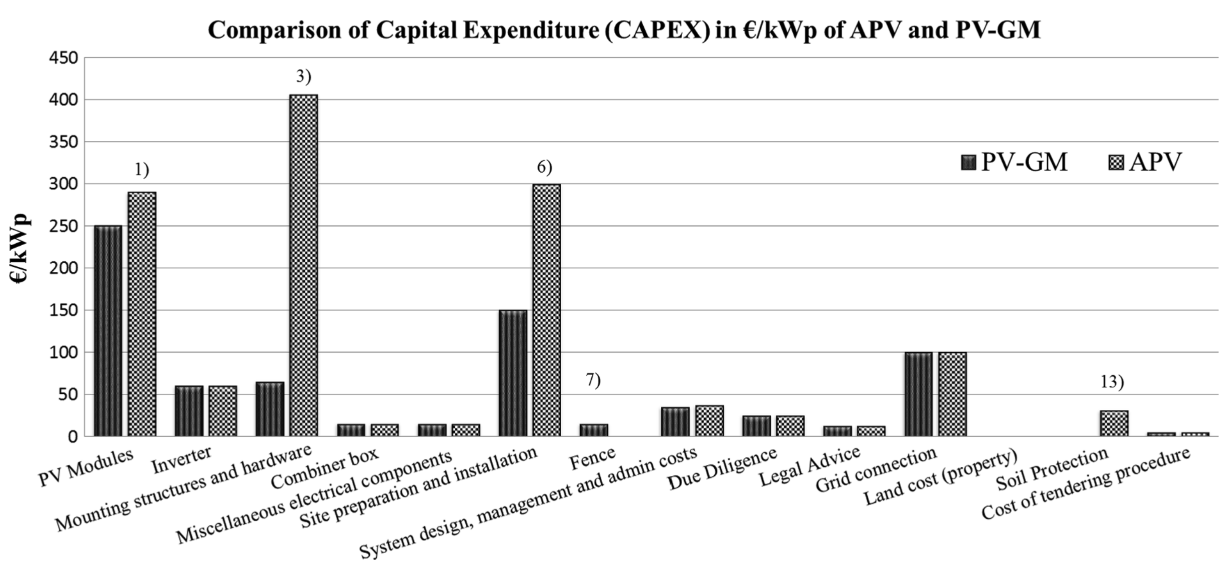

Fig. 8. Comparison of capital expenditure (CAPEX) associated with APV and PV-GM in € kWp^{-1} (Source: Fraunhofer ISE).

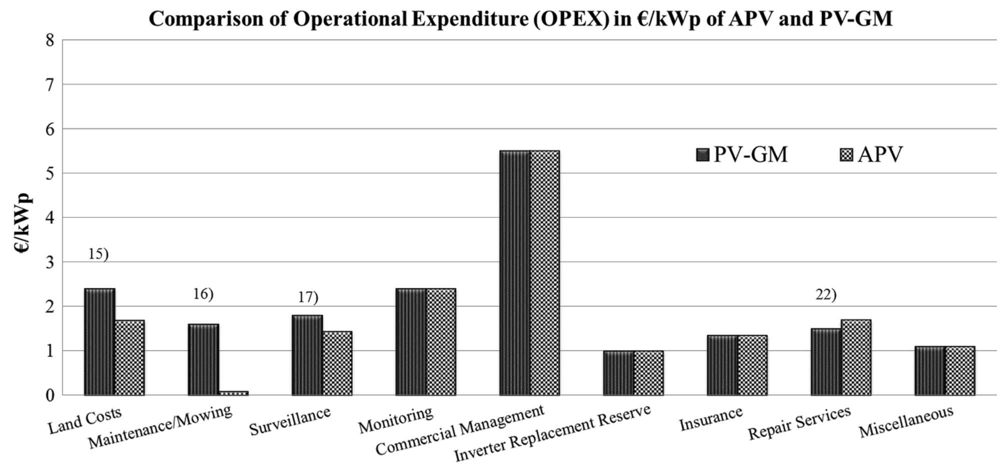

Fig. 9. Comparison of the OPEX of APV and PV-GM in € kWp^{-1} (Source: Fraunhofer ISE).

Table 3
Input parameters and electricity yield assumptions.

No.	Input parameter	Value	Unit
1	Lifetime	25	a
2	Electricity yield PV-GM (standard PV modules)	1209	kWh/kWp/a
3	Electricity yield APV (bifacial PV modules)	1284	kWh/kWp/a
4	Annual regression of electricity yield	0.25	%
5	Area demanded PV-GM	14.5	m^2/kWp
6	Area demanded APV	19.3	m^2/kWp
7	Total land use (in each case)	2	ha
8	Installed capacity PV-GM	1379.31	kWp
9	Installed capacity APV	1038.36	kWp
10	Equity share	20	%
11	Debt capital share	80	%
12	Cost of equity capital	9.5	%
13	Cost of debt	4.0	%
14	Nominal weighted average cost of capital (WACC)	4.1	%
15	Inflation rate	2	%

Table 4
Annual land use price in € ha^{-1} of APV and PV-GM implementation.

Type	LCOE in euro cents kWh^{-1}	Installed capacity in kWp ha^{-1}	Electricity yield in kWh kWp^{-1} a^{-1}	Land use price in € ha^{-1} a^{-1}
APV	8.29	519.18	1284	59329.81
PV-GM	6.03	689.66	1209	50278.08
Annual price (p) of obtaining cropland for food production				9051.73

decreased between 2017 and 2018 by 11.5%[25] and 16.15%[26] respectively due to APV effects such as shading and land loss. The data is summarized in Table 5.

In the cases of Demeter-certified organic potato and winter wheat production, the total annual pb of land use with APV was €10707.07 ha^{-1} a^{-1} and €1959.38 ha^{-1} a^{-1} respectively. Picture 11 depicts potato harvesting in 2017 Fig. 11.

4.8. *Price-performance ratio (ppr) results of APV implementation*

The total annual price of implementing APV to maintain arable land for the farmer's crop rotation of Demeter-certified organic potatoes and winter wheat is €9051.73 ha^{-1} a^{-1}. The total annual pb of the land used for producing potato in conjunction with APV was €10707.07 ha^{-1} a^{-1} and €1959.38 ha^{-1} a^{-1} for winter wheat. Thus, in the case of the potato crops, pb of APV implementation was higher than p, whereas for winter wheat, p was higher than the achieved pb. Accordingly, the ppr equates to 0.85 for the potatoes grown under the APV installation and 4.62 for the Demeter-certified organic winter wheat.

5. Discussion

We have gained four key insights from the calculation of the ppr associated with this case study's APV implementation.

[25] Organic potato harvest 2017: −18%; harvest 2018: +11%. Land loss in each year due to non-utilized land area between protection pillars: −8%. Average yield = 100% reference area −8% + (−18% + 11%/2a) = 88.5%, or an average yield decrease of 11.5% over a period of two years.

[26] Winter wheat harvest 2017: −19%; harvest 2018: +2.7%. Land loss in each year due to non-utilized land area between protection pillars: −8%. Average yield = 100% reference area −8% + (−19% + 2.7%/2a) = 83.9%, or an average yield decrease of 16.2% over a period of two years.

Table 5
Total annual performance of organic and Demeter-certified organic potato and winter wheat production as affected by APV in € $ha^{-1} a^{-1}$.

Crop type	Producer price in €dt^{-1}	Yield in dt ha^{-1}	Total annual performance of land use in € $ha^{-1} a^{-1}$
Organic potato *without* APV	45.02	233.70	10521.17
Organic winter wheat *without* APV incl. €150 $ha^{-1} a^{-1}$ of straw	45.96	39.70	1974.61
Demeter-certified organic potato *with* APV	51.77	206.82	10707.07
Demeter-certified organic winter wheat *with* APV incl. €200 $ha^{-1} a^{-1}$ of straw	52.85	33.29	1959.38

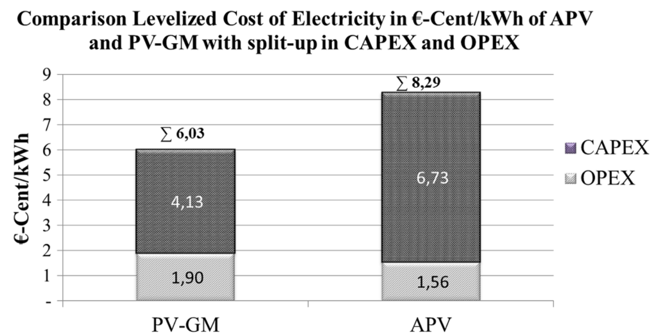

Fig. 10. Comparison of the LCOE in euro cents per kWh of APV and PV-GM split into CAPEX and OPEX (Source: [40]).

Fig. 11. Potato harvesting under APV panels in 2017 (Source: farm community Heggelbach).

5.1. Non-consideration of cost reduction potential from technological and policy learning

It is not surprising that, with €0.0829 kWh^{-1}, the LCOE of our APV prototype is higher than that of conventional PV-GM with €0.0603 kWh^{-1}. After all, the higher CAPEX, which are mainly due to the high elevation, outweighed the economic advantages offered by the synergies of dual land use which have a cost-reducing effect on OPEX. To improve the price-performance ratio of APV projects, the price of their implementation should be as low as possible. The largest cost-reducing potential for the CAPEX is when possible techno-ecological synergies and double functions are considered, for instance when the APV structure substitutes an existing supplementary growing structure such as hail protection nets used in fruit growing. But for strategic reasons, we optimized a crop rotation scheme with vegetables and cereals under APV, assuming the highest possible elevation cost with a harvester operating under the APV system. In the future, it will be easier to downscale the necessity of public and private funding for further research and APV implementation rather than to upscale both at a later date. However, our results confirm our expectations in terms of ppr and also provide information about cost-driving and cost-reducing factors that can be considered in future APV developments. It should also be taken into account that the comparison of the LCOE of an established PV-GM application and that of a relatively new APV system technology with a relatively steep learning curve is not entirely fair, as neither technological nor political insights are considered in the APV results presented here. In addition to the endogenous parameters, namely that the drivers of new technology must learn to keep pace with political developments, exogenous parameters also affect ppr and the development of the LCOE of APV, for instance the impacts of EU CAP subsidy legislation on the calculation of the annual land cost per area that the APV investor pays to the farmer-landowner. We assumed that farmers do not receive EU CAP subsidies for grassland operation under PV-GM, but that they do receive agricultural subsidies for food production on cropland shared with APV. We made this assumption due to the fact that farmers and landowners will only provide access to cropland for APV investors if and only if the APV investor compensates the farmer for potential income loss resulting from lower agricultural yield per area and higher operational costs under APV. This principle favors the argument of the EU CAP that compensation for damage or cost incurred in restoring the previous condition of arable land as well as compensation for other expenses is equal to free use of land. Free use of arable land for non-agricultural purposes is an indication that the main purpose of land use is agricultural activity [85]. Accordingly, in APV cooperation scenario A, where the APV investor associates with a farmer who is also the landowner, the arable land under APV remains EU CAP-eligible area. Nonetheless, current legislation in Germany does not foresee any EU CAP subsidy on areas where PV or APV is installed [63]. Farmers continuing agricultural production under PV have taken legal action against this legislation and obtained justice in the first instance [86]. It is very likely that the legislative and executive authorities in Germany will be forced by the judiciary to adapt their laws in favor of APV in the near future. Further exogenous parameters affecting the ppr and LCOE of APV are political decisions that do not follow rational choice, but rather public choice. Nevertheless, the work at hand follows a line of thought originating from economic theory rather than the actual political economy. From a policymaker's point of view, optimal APV implementation might include much more steel for elevating the PV modules in order to support the steel industry. In 2018, Germany's first "steel summit" took place [87]. Many German and European steel manufactures are suffering from reduced steel prices. Thus, even though the economic theory of the ppr model would not recommend doing so, German policymakers might support APV systems with a ppr greater than 1, as was true in our case study with cereal farming, in conjunction with a harvester operating under APV in order to protect labor forces in the steel market. Another exogenous parameter could be a decreasing social acceptance of PV-GM and APV implementation in rural areas. Technological solutions, for example the use of colored PV modules in brown or green, could counteract this acceptability risk by camouflaging PV to match the landscape. However, this would lead to a higher price of implementing APV while performance would remain steady, thus resulting in a ppr greater than 1 – a clear indicator that it is not a good idea to implement such an APV project. For political reasons, and to increase the total sustainability level in Germany, the project could still potentially receive public support. In general, exogenous parameters affect the ppr's threshold limit value of 1, and yet the ppr model for APV implementation shows that, economically, it makes sense to strive for an APV implementation scenario in which the ppr outcome is as low as possible, aiming for APV solutions offering high performance at the lowest price possible. Macroeconomic impacts of

APV implementation such as the support of the labor market or effects from increases in land use efficiency as well as the preservation of environmental services are not taken into consideration in the ppr model and should be integrated in general equilibrium trade models or holistic CBAs of APV policy design.

5.2. Stable price and increasing performance to improve the effectiveness of APV implementation over time

Over a 25-year period, the price of APV implementation is predicted to remain relatively stable due to high CAPEX, whereas the agricultural performance is likely to increase due to increasing labor costs. With an increasing performance benefit value (pb) in relation to a relatively constant price value (p), today's critical APV projects might become economically favorable in the future. Furthermore, the shade provided by solar cells on the crops grown under APV installations has a positive impact on the harvestable crop yield as this also reduces evapotranspiration [44], resulting in less water evaporation and greater soil moisture compared to the reference area [37,43]. Due to climate change, extreme weather events are likely to become more frequent in the future, adding value to the secondary function of APV of protecting agricultural crops and improving agricultural performance and thus the price-performance ratio. In the present study, this beneficial effect on APV performance has been proven by agricultural results in the hot and dry summer of 2018 in Germany. Harvestable yields of winter wheat, potato, and celeriac grown under APV were greater than those of the reference field. Thus, APV may act as a climate change adaptation technology by combining new functions with already existing extreme event protection systems.

5.3. Effects of crop rotation vs. permanent crop planting on the price-performance ratio and missing long-term data

In our APV case study, the farm is Demeter-certified with agricultural processes conducted in an eight-year crop rotation, typical of the Demeter standard. Within the present research project, we were able to analyze the harvestable yield of four crops from this rotation: winter wheat, potato, clover grass, and celeriac. From each year's crop cultivation, it could be deduced that the pb of APV – and thus the price-performance ratio – varies annually. For a more robust ppr result, the average performance of the crop rotation for a particular farm should serve as a baseline order to justify its economic viability. In general, the baseline of crop yield under APV is rather small. Globally, no long-term study of APV impacts on crop physiology, soil, and agricultural production exists. The lifetime of an APV installation is estimated at about 25 years. The typical crop rotation of a conventional farm is based on a 3-year cycle [88], such that each crop is cultivated at least eight times when grown under an APV system. This offers the farmer opportunities to adapt the crop variety, thereby enhancing performance. In contrast, the ppr of APV in combination with permanent crops – e.g. apple, cherry, pear, wine grape, almond, peach, berry, tomato, hops – cannot be calculated with as much certainty, but ppr results are estimated to be much more promising. Here, special growing systems such as hail protection nets, hops gardens, or indoor farming systems with steel and foil can be substituted by APV mounting structures, decreasing the farm's operating costs since less foil (or no foil at all) would need to be repurchased. This also would also reduce annual foil waste. Figs. 12–14 present existing growing systems for special crops.

Furthermore, the special crops sector uses different and smaller types of land machinery, thereby decreasing the required height of APV systems and leading to lower costs in terms of materials, construction work, and logistics, allowing for reduced CAPEX. Many special crops have relatively high producer prices, increasing the value of APV performance. In France, wine producers offer up their land for APV use for free, with the benefit of not having to invest in hail protection and shade-growing systems, thus optimizing the techno-ecological synergies

Fig. 12. (Left, source: Pixabay): Indoor farming with foil tunnels.

and benefiting both land users. Accordingly, these farms become more resilient and annual land payments made to an APV investor are minimized or eliminated altogether.

5.4. Organic vs. conventional farming crop yields and their impact on the APV price-performance ratio

Agricultural crop yields from our case study have been criticized in the context of performance calculation for two main reasons. Firstly, conventional farming processes involving the use of chemical herbicides, insecticides, fungicides, and fertilizer are used on approximately 91% of Germany's agricultural land [89]. However, our case study was conducted on an agricultural land area where organic farming processes are employed, representing the remaining 9.1% of Germany's agricultural land. Secondly, since organic farming processes do not involve the use of chemical pesticides and fertilizer, agricultural crop yields may decrease by up to 50% per area [90,91]. This yield gap leads to doubt with regard to the transferability of our results to APV farms when comparing organic farming with conventional farming. We therefore decided to evaluate the data from our conventionally grown, Demeter-certified potato production, relying on the same controls (2 ha, from 2015 to 2017) and data source (Bavarian State Research Center for Agriculture (LfL)).[27] Table 6 presents the total annual performance of conventional APV and non-APV potato production expressed in € $ha^{-1}a^{-1}$.

Compared with the data on the performance of APV implementation (see Section 4.3), we observed a gap of 44.1% between the 418.40 dt ha^{-1} yield of conventionally grown potato tubers and the 233.70 dt ha^{-1} yield of organic potato tubers. However, as the process in organic farming is more labor-intensive, e.g. with regard to weed control, and as consumer demand for organic food remains higher than supply in Germany [92], the producer price of organically grown potatoes (€45.02 dt^{-1}) is more than two times (222.7%) higher than that of conventionally grown potatoes (€13.95 dt^{-1}). To this end, the higher price of organic potatoes compensates for the yield gap between these and conventionally grown potatoes, resulting in a total annual performance of land use for conventional potato production of €5836.68 ha^{-1} a^{-1}. This is 44.5% less than the performance of organically produced potatoes at €10521.17 ha^{-1} a^{-1}. If we transfer these differences to the Demeter-certified APV potato production in our case study and pessimistically assume a drop in crop yield by an average of 20% for conventionally produced potatoes,[28] we find that the producer price of Demeter-certified potatoes (€51.77 dt^{-1}) is more than 2.5 times higher (271.1%) than that of conventional potatoes (€13.95 dt^{-1}). By contrast, the Demeter-certified potato tuber yield (206.82 dt

[27] Data Source: https://www.stmelf.bayern.de/idb/speisekartoffeln.html (24.09.2019).

[28] Compared to the recorded 11.5% average yield reduction for Demeter-certified potatoes.

Fig. 13. (Middle, source: BayWa AG): Fruit-growing systems in Southern Germany.

Fig. 14. (Right, source: Magnetic Magazine): Hops harvest in Oregon, USA.

ha^{-1}) was dropped by 38.2% in crops grown under APV compared to the assumed conventional potato tuber yield of 334.72 dt ha^{-1}. This results in an assumed total annual performance of €4,669.34 ha^{-1} a^{-1} for potatoes grown under an APV installation following otherwise conventional practices, which is 56.4% lower than Demeter-certified potato production under an APV installation (€10,707.07 ha^{-1} a^{-1}). At 1.94, the ppr of conventionally produced potatoes is non-beneficial compared to the positive price-performance ratio result of 0.85 seen in Demeter-certified potatoes under APV. Consequently, the performance of organically produced potatoes in terms of revenue per area seems to be higher than that of conventionally produced potatoes, leading to the assumption that APV implementation seems economically justifiable, especially in organic farming systems.

6. Policy implications: How to implement APV

Here, we present the policy implications of APV implementation which we have derived from our empirical results. According to the theory of price-performance calculation, policymakers seek to minimize the ratios calculated, looking for cases with the highest techno-economic and techno-ecological APV synergies. We explore the policy parameters (i) quality assurance, (ii) crop selection and land management, (iii) price level and (iv) quantity level. In Appendix B (see information boxes on international APV implementation), we present recommendations for an APV policy design in Germany and provide additional information on APV markets and policies in Japan, South Korea, France, China, and Massachusetts (USA).

6.1. APV definition, funding guidelines, and quality assurance

6.1.1. APV definition

APV is an integrated food-energy system, utilizing its dual functionality by maintaining or even improving agricultural production. This allows policymakers to categorize land area under APV as agricultural land, whereas land area below PV-GM is considered built-up area since common agricultural practices are significantly hindered or disabled and techno-ecological synergies are not sufficiently utilized. To govern policy parameters of APV implementation, it appears necessary to establish a domestic legal definition for APV that includes or excludes certain agricultural practices and with them certain land areas. In our case study, we focused on cropland areas for vegetable and cereal production. Consequently, our definition of APV is limited to land areas for agricultural production processes involving agricultural crops. To differentiate between PV-GM and APV governance, we purposely excluded APV implementation on grassland which enable "rangevoltaic" applications [29] for animal husbandry under PV systems, such as sheep, goat, cattle, or chicken farming. These types of synergies are regularly found in conventional PV-GM implementation, as seen in Germany since 2005 [49], the UK [93], and France. A strict definition of clear land area boundaries is also recommended to establish an efficient command and control mechanism.

6.1.2. Funding guidelines

In nations where governments support their agricultural sector with subsidies, the subsidy regulation may act as a control mechanism to the functionality of an APV installation over its lifetime, as the farmer only receives subsidies if agricultural production is well-documented and maintained. In terms of funding guidelines, skepticism was expressed as regards the feasibility of receiving two public support schemes for one area, for example a price-regulating feed-in tariff for solar power and a subsidy for the agricultural operations on the land below. This critique seems unjustifiable for three reasons. Firstly, the business case of solar power and farming involves two operations with separate accounts and thus separate bookkeeping systems. Secondly, APV serves as a climate change mitigation tool *and* adaptation technology for the agricultural sector, offering mutual benefits for both businesses to cooperate thanks to techno-economic and ecological synergies, e.g. lower OPEX of APV and the increasing agricultural yields in 2018. APV can act as an adaptive technology, reducing the demand for governmental intervention in the case of total crop yield failure due to climate change impacts, e.g. extreme events such as droughts or hail storms, which were already subsidized in Germany in 2018 [94]. On an intergovernmental level, the Green Climate Fund (GCF) launched by the United Nations Framework Convention of Climate Change (UNFCCC) has been asked to develop an APV methodology which would allow APV projects to tap into funding from both the mitigation and adaptation budgets. In agreement, Goetzberger suggested that the Common Agricultural Policy of the European Union finance the implementation of APV systems [46]. Thirdly, the debate on funding guidelines is a politically motivated argument and a matter of political will. There are positions asking

Table 6
Total annual performance of conventional APV and non-APV potato farming in € $ha^{-1}a^{-1}$.

Type	Producer price in € dt^{-1}	Yield in dt ha^{-1}	Total annual performance of land use in € ha^{-1} a^{-1}
Conventionally grown potatoes without APV	13.95	418.40	5836.68
Conventionally grown potatoes under APV	13.95	334.72	4669.34

to entirely eliminate the funding guidelines for climate change mitigation and adaptation investments, suggesting that more investments in these sectors will lower the risk of falling behind in the urgency to act against global warming.

6.1.3. Quality assurance

A strict APV definition and a political debate on the funding guidelines lead to the necessity to establish APV quality assurance measures in the form of a permitting process. Certain aspects of APV quality assurance are not only important for the farmer and the APV investor for minimizing the technological risk in the installation and operational processes, but also for improving the bankability and the social acceptance of APV [47]. Here, we established a definition that APV should enable main agricultural crop production while optimally utilizing the synergetic effects of both production systems. In addition to a binary method of measurement (is crop growing feasible, yes or no?), this means assessing the expectations of crop yield needs that are to be fulfilled. In measuring the degree of expected crop growth under APV, APV systems must be clearly defined and a line must be drawn separating them from pseudo-APV systems, which potentially aim to gain windfall profits from the increased financial support for APV systems in comparison to regular PV-GM regulations. For APV market integration, we recommend that governments ask an independent APV expert to justify the theoretical feasibility of a given APV design in an early stage of the permitting process as a sort of support mechanism. This could involve the evaluation of key performance indicators (KPI), e.g. the relationship between the light saturation point of a certain crop within a crop rotation and the sufficient and homogenous light conditions according to the proposed APV design. The ppr calculation for an envisaged APV project as suggested in this article may also act as a KPI measurement in permitting processes. Countries with a longer history of APV implementation might ask their agricultural and PV sectors to jointly create and introduce an APV standard to guarantee a high level of APV quality assurance. An example of quality assurance in APV policy design is the "Guideline Regarding the Definition of Agricultural Solar Tariff Generation Units" introduced by the Solar Massachusetts Renewable Target Program. Here, the APV system design enforces a maximum reduction of direct sunlight of 50% during the entire crop growth period. Since this policy's measurements do not take into account the crops' light saturation point, we consider this restriction to be too extreme. The innovation potential of the APV market is restricted by the exclusion of certain plants such as fruit trees (e.g. kiwi, apple, pear, cherry), berries (e.g. raspberries, blackberries), tomatoes, sweet peppers, coffee, and ginseng, which are all able to cope with reductions of > 50% in solar radiation [27].

6.2. Crop selection and land area management

6.2.1. APV use with permanent special crops recommended

Thanks to the highly effective techno-economic synergies which emerge when APV installations replace existing separate agricultural climate change protection systems for permanent cultures such as fruits, berries, almonds, or hops, the extra price per area for the APV structure is reduced, thus improving the ppr. At the same time, these permanent cultures demonstrate a relatively high producer price, thereby improving the economic performance per area and also contributing to an increased ppr. Accordingly, APV projects with permanent cultures seem more economically suitable than applications with crop rotation schemes, including cereals. It is therefore recommended that policymakers consider these types of cultures in particular within the land area management of APV policy design.

6.2.2. APV use on organic farmland recommended

In particular with organically produced vegetables, e.g. potatoes, a higher producer price compensates for the crop yield gap experienced and therefore improves the revenue performance per area. As regards the ppr of APV implementation scenarios, organic farming thus appears to be more suitable than conventional farming methods.

6.3. Price level

Our results show that the LCOE of APV is higher than that of PV-GM. Therefore, even if a price- or market-based regulation were to support PV-GM projects on arable land, APV would not be on a level playing field in terms of cost competitiveness, as it can hardly compete with PV-GM. Ergo, implementation thereof does not appear economically feasible. Correspondingly, policymakers have at least two options. One option would be to support APV implementation through a special support scheme and permitting process in parallel to the already existing PV-GM regulation, e.g. in France. Or, they could introduce additional special provisions for solar dual-use applications in agriculture, thereby offering additional financial support of the adaptation costs in PV-GM, e.g. in Massachusetts (USA).

6.3.1. Price floor

On the national level, if a new APV FiT or auction regulation is introduced, PV-GM project pipelines that have already received grants for implementation may be transformed into APV projects by accepting bids or paying an add-on price, for instance an additional €0.0300 kWh^{-1}. So, introducing a price floor within an APV support scheme in order to offer an APV add-on price within an existing FiT regulation is not recommended.

6.3.2. Price ceiling

In our case study, the LCOE of APV was €0.0829 kWh^{-1}, which is considered to be relatively high, and yet the LCOE of APV is less than the FiT support for rooftop PV installations (< 10 kWp), which amounts to €0.1033 kWh^{-1} in Germany [95]. It is very likely that APV projects would be economically feasible if they received the FiT price that is already paid out for small rooftop PV installations. Bids for APV projects asking for a higher price than the FiT price for small rooftop PV would be refused at the national level in an APV auction.

6.4. Quantity

6.4.1. Market size

The quantity of APV implementations will increase in accordance with typical innovation processes and the development of technology readiness levels.

6.4.2. Research and showcase facilities

Only small quantities are required for showcasing and research purposes to promote public and institutional learning, raise awareness, and adapt APV implementation to regional demands first.

6.4.3. Small series

After these initial demands are met, small APV series can be defined. This will attract private R&D investments, promoting technological learning and supporting economies of scale in further enhancing the ppr of APV. In turn, this will also expand implementation opportunities, allowing the farming and PV sectors to find appropriate partners for cooperation and initiate the first minor APV rollout. In keeping with land management policy parameters, it could become an option to initiate an APV innovation cluster and fund a certain amount of APV installations for a region where APV implementation could be of particular interest. For policy learning and for research purposes, it is recommended that small APV series be accompanied by scientific evaluation in order to measure, analyze, report on, verify, and document the results and alter the policy parameters for the next innovation step accordingly.

6.4.4. Diffusion

Finally, once the prior steps have been successfully completed, APV diffusion with or without clearly defined quantity parameters – for example in combination with an APV land use ceiling of about 2% of cropland – could be introduced.

Furthermore, it is important to note the polity aspects of the APV innovation process. In different stages of APV implementation, different government officials and institutions are in charge of controlling the APV quantity. This is evidenced by the prototype being sponsored by the ministry of education and science, or small series by the ministry of agriculture and/or environment, and the diffusion by the ministry of climate change and energy. As APV is a cross-sector system technology, APV implementation is politically challenging to order and execute on account of changing governmental structures and the transfer of responsibilities. Therefore, it is recommended that governments develop a transparent rollout strategy that includes stakeholders from the relevant sectors and defines the PV market segments, and that they adopt policies in line with this strategy. A positive example comes from Korea, where the 30.8-GWp PV market is set to be developed in four segments by 2030 and the 10-GWp farmland APV sector will represent 33% of the overall market [17].

6.4.5. Project size

Similar to the market size, the project size will also differ in response to the innovation process. There is no need to sponsor public R&D budgets for a large-scale APV system. However, in order to gather robust data on agricultural yields, the APV plant would need to be a certain size to consider boundary effects on the light management design. Within the small series, a focus on medium- to large-scale (> 750 kWp–10 MWp) APV implementation is recommended. This would create economies of scale from which potential smaller APV projects (< 750 kWp) would also benefit. For the market rollout, a range of APV projects from small- and medium-scale to large-scale ones is recommended. APV projects smaller than 750 kWp shall be supported with a FiT price proportional to a small-scale rooftop PV installation. Projects with capacities from 750 kWp to 10 MWp shall be regulated within a market-based, pay-as-bid auction. APV capacities greater than 10 MWp are said to be subsidy-free and do not require any financial support from the government for their implementation. International experience has shown that the project size relates to secondary political purposes. In Japan and Korea, for example, policymakers intended to ensure that as many farmers and technicians benefit from APV as possible. In Japan, the original purpose of APV implementation was to counteract the exodus from rural areas and farmers' surrendering of their businesses because of income deficits due to contaminated agricultural crop yields following the Fukushima catastrophe. In Korea, policymakers aim to establish an APV pension scheme by considering the demographic change in an aging farming sector, with many farmers retiring in coming years, thereby suffering from reduced income and buying power as their agricultural land lies fallow. Solar dual-use will at least enable retired farmers to benefit from the additional income generated by selling solar electricity, while the cropland beneath APV installations remains preserved for potential agricultural use in the future. Furthermore, policymakers in Korea have designed their APV implementation regulation in such a way that projects are executed by farmers in cooperation with local technicians such as mechanics and electricians, thereby ensuring a decentralized, equal distribution of APV. With a market size goal of 10 GWp and an intended APV project size of 100 kWp, 100,000 APV projects are set to be implemented in Korea by 2030. By contrast, the project size of APV projects in France is relatively large, with a nominal capacity of up to 3 MWp, and in China, there is no limit. The main political impetus for APV implementation was to increase land use efficiency and to preserve agricultural land area. With respect to the ppr calculation, it is best to focus on medium- to large-scale projects, as economies of scale will lower the price of APV implementation, thus decreasing the ratios in keeping with policymakers' intentions.

7. Conclusions

Rising demand for solar power generation will lead to increased land use competition and thus to potential economic, ecological, political, and social conflicts in the future. Agrophotovoltaic (APV) system technology provides a solution to the challenges of sustainable land use in terms of food and energy production. We have determined that APV increases land use efficiency primarily by enabling agricultural crop production and secondarily generating solar PV power simultaneously within the same agricultural area while optimally utilizing the synergetic techno-ecological and techno-economic effects of both production systems. Since 2017, governments in Japan, France, Massachusetts (USA), South Korea, and China have introduced policies supporting APV market implementation and diffusion. Nowadays, more than 2200 APV systems are installed worldwide, totaling an estimated APV capacity of 2.8 GWp. And some other governments are currently considering implementing APV, including those of India and Germany. But they are first demanding information on how the levelized cost of electricity (LCOE) of APV differs from that of conventional ground-mounted PV and how additional costs associated with APV implementation relate to the benefit of maintaining agricultural production activity under APV. Data for a techno-economic price-performance ratio calculation has been retrieved from an inter- and transdisciplinary APV case study in Germany, where a prototype has been installed and operational since 2016. We find that, at €0.0828 kWh^{-1}, the LCOE of APV is 38% higher than that of conventional ground-mounted PV systems, resulting in €0.0226 kWh^{-1} extra LCOE, or an annual cropland preservation price of €9052 $ha^{-1} a^{-1}$. The higher LCOE of APV in comparison to that of PV-GM is the result of CAPEX, predominantly due to extensive mounting structure costs and soil protection measures during the installation of the PV power plant. OPEX of APV are lower than those of PV-GM due to the synergetic effects of both production systems leading to cost reduction, for example due to a decreased demand for surface care and lower land costs. The annual revenue generated from the Demeter-certified production of organic potatoes and winter wheat under an APV installation results in a performance of €10,707 $ha^{-1}a^{-1}$ and €1959 $ha^{-1} a^{-1}$ respectively, leading to a beneficial price-performance ratio of 0.85 for potato production and a non-beneficial price-performance ratio of 4.62 for winter wheat. Overall, APV implementation is not necessarily recommended in crop rotating systems, but rather in combination with permanent organically grown cash crops, e.g. berries, fruits, herbs, nuts, pharmaceutical plants, hops, or wine grapes. Depending on the stage of APV market development, different government officials may be put in charge of setting certain quantity targets, from prototype installations to diffusion. Either an APV price regulation scheme could award an add-on to already commissioned PV-GM projects, making up for the price of technology adaptation as is the case in in Massachusetts, or a separate APV funding program could be introduced like in Japan and France. To avoid windfall profits and to increase social acceptance and bankability, governments will be asked to legally define APV, introducing a national APV standard which will ensure high-quality APV implementation. Compared to PV-GM, the APV technology is relatively young, showing a steep learning curve, but offering the potential for many more techno-ecological synergies. APV's dual function of agricultural yield protection while simultaneously generating solar power increases the economic output per area and enhances farmers' resilience against the impacts of global warming by securing and diversifying their sources of income. From our international investigations we observed a variance in the political reasons to support APV implementation. In France, China, and Massachusetts (USA), financial support schemes for APV were introduced to preserve cropland. In South Korea and Japan, diversifying farmers' income sources and counteracting the exodus from rural areas were the motivating political objectives behind the introduction of APV diffusion regulations.

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CRediT authorship contribution statement

Stephan Schindele: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Maximilian Trommsdorff:** Software, Validation, Formal analysis, Investigation, Writing - review & editing, Project administration. **Albert Schlaak:** Software, Formal analysis, Investigation, Writing - review & editing, Visualization. **Tabea Obergfell:** Validation, Investigation, Data curation, Writing - review & editing, Project administration. **Georg Bopp:** Data curation, Writing - review & editing, Project administration, Funding acquisition. **Christian Reise:** Data curation. **Christian Braun:** Validation, Data curation, Writing - review & editing. **Axel Weselek:** Investigation, Data curation. **Andrea Bauerle:** Investigation, Data curation. **Petra Högy:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Adolf Goetzberger:** Validation, Formal analysis, Supervision, Funding acquisition. **Eicke Weber:** Conceptualization, Investigation, Writing - review & editing, Supervision, Funding acquisition.

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Appendix A. Cost data

See Tables 7 and 8.

Table 7
Specific investment cost of each cost factor in € kWp^{-1} for APV and PV-GM respectively.

CAPEX		€ kWp^{-1}		Δ in € kWp^{-1}	Δ in %
No.	Type of Cost	APV	PV-GM	–	–
1	PV modules	290	250	+40	+16
2	Inverter	60	60	0	0
3	Mounting structures and hardware	405.1	65	+340.1	+523.2
4	Combiner box	15	15	0	0
5	Miscellaneous electrical components	15	15	0	0
6	Site preparation and installation	299	150	+149	+99.3
7	Fencing	0	15	−15	−100
8	System design, management, administration costs	36.8	35	+1.8	+5
9	Due diligence incl. yield certificate	25	25	0	0
10	Legal advice	12.5	12.5	0	0
11	Grid connection	100	100	0	0
12	Land cost (property)	0	0	0	0
13	Soil protection	30.9	0	+30.9	+100
14	Cost of tendering procedure	5	5	0	0
	Σ CAPEX	1294.20	747.50	+546.7	+73.1

Table 8
Operating expenses (OPEX) in € $kWp^{-1} a^{-1}$ of APV and PV-GM respectively.

OPEX		€ $kWp^{-1} a^{-1}$		Δ in € $kWp^{-1} a^{-1}$	Δ in %
No.	Type of Cost	APV	PV-GM	–	–
15	Land costs	1.68	2.40	−0.72	−30
16	Maintenance/Mowing	0.08	1.60	−1.52	−95
17	Surveillance	1.44	1.80	−0.36	−20
18	Monitoring	2.40	2.40	0	0
19	Commercial management	5.50	5.50	0	0
20	Inverter replacement reserve	1.00	1.00	0	0
21	Insurance	1.35	1.35	0	0
22	Repair services	1.70	1.50	+0.20	+13
23	Miscellaneous	1.10	1.10	0	0
	Σ OPEX	16.25	18.65	−2.40	−12.9

Appendix B. Information boxes on international APV implementation

Japan

In 2013, the Japanese Ministry of Agriculture, Forestry and Fisheries adopted a law that allows PV systems to be installed on agricultural land if and only if at least 80% of agricultural yields of crops grown below PV modules continue to be generated. The law was introduced in response to the nuclear disaster in Fukushima and enables farmers to diversify their income through solar sharing, thereby counteracting the decline in Japanese agricultural exports due to the disruption of farming outputs as a consequence of the disaster and the related rural exodus of farmers who had given up their businesses and moved into cities. In total, 1654 APV projects were implemented between 2013 and 2018, each occupying a maximum area of 0.2 ha (ha), corresponding to an estimated total APV capacity of approximately 150 MWp, or 90.7 kWp per APV project [15].

South Korea

Faced with even less availability of arable land per capita than Japan, the government of South Korea has supported APV implementation since autumn 2018. The current policy goal is to increase the share of renewable energy (RE) from 7% in 2016 to 20% by 2030. The PV capacity is set to increase from 7.9 GWp in 2018 to 30.8 GWp by 2030, with the PV market being developed in four separate sectors: 2.4 GWp (8%) from private households via self-consumption regulation, 7.5 GWp (24%) from small-scale PV installations in the private and business sector, 10.9 GWp (35%) from large-scale ground-mounted and floating PV installations in the industrial sector, and 10 GWp (33%) of farmland APV from farmers and technicians [17]. Similar to Japan, the South Korean government supports rather small-scale APV projects with approximately 100 kWp on average, leading to 100,000 APV plants by 2030. In April 2019, a total of 18 APV systems were installed, leading to an estimated 2 MWp of APV. The average CAPEX of APV equal €1,520 kWp^{-1} for a system size of 100 kWp. APV land use efficiency amounts to 435 kWp ha^{-1} [18]. Besides the scarce availability of arable land in South Korea, further political reasons for APV promotion are the aging farmers and the issue of farm abandonment, since no descendants or newcomers are willing to take them over. Accordingly, it can be assumed that many agricultural areas will lie fallow, and the farmers' monthly pension will remain low since the land cannot be leased. Thus, APV will increase land use efficiency, providing farmers with an additional monthly income and preserving the potential of future crop cultivation on the arable land. With respect to crop selection, the Korean government considers the current account for agricultural goods as part of the balance of payments. The implementation of APV is subsidized for crops for which Korea records a current account surplus, with exports higher than imports. Therefore, reductions in agricultural crop yield due to APV do not have a negative effect on food security. The Korean Agrivoltaic Association (KAVA) receives governmental support, allowing farmers and technicians to be trained to use and become familiar with the APV technology [16].

China

By far the largest APV projects and the highest APV capacity installed can be seen in China. According to Jinlin Xue, an estimated 4.0 GWp of agricultural PV capacity was installed in China between 2015 and 2018 [19]. It is assumed that 2.3 GWp of this APV capacity was implemented as solar greenhouses, whereas APV as it is considered in the present study accounted for 1.7 GWp. The largest APV plant known to be successfully implemented is in Ningxia and was constructed by Huawei Fusion Solar in 2016. It boasts a capacity of over 700 MWp.[29] Other Chinese PV companies such as Talesun[30] and Jinko[31] have also installed large-scale APV plants.

France

In the European Union (EU), France was the first country to implement an APV financial support scheme in September 2017. The French Energy Regulatory Commission (CRE) published the specifications for tendering a total APV capacity of 45 MWp (subfamily 4) under the French Energy Code (Code de l'Énergie). Divided into three auctions, 15 MWp of APV capacity was tendered between 2017 and 2019 [20]. The political context that has contributed to APV policy implementation was the loss of agricultural land and the farming sectors need to adapt to global warming and the effects resulting from climate change, in particular the impacts to food security and the water scarcity due to drought. The average bid price of the contracted APV projects in the initial 15 MWp auction in 2018 was €0.0865 kWh^{-1}, compared to €0.0596 kWh^{-1} for PV-GM and €0.0808 kWh^{-1} for large-scale rooftop PV installations [96].

Massachusetts, United States of America (USA)

In the USA, the first state to support dual land use with APV was Massachusetts in 2018. The Solar Massachusetts Renewable Target (SMART) program regulates incentives associated with new solar PV developments. Here, it is expected that, in most cases, individual crop yield (lbs/acre) or electricity output (kWh/acre) will be lower in dual-use systems than it would be if either activity was carried out alone, but that the combined value of crops and electricity produced will be equal to or higher than that of a singular use of the land for the production of crops or electricity alone.[32] To qualify for compensation as an Agricultural Solar Tariff Generation Unit, an APV system must be installed on a property officially defined as land for agricultural use or prime agricultural farmland. The system parameters required are limited to 2 MWp and the lowest edge of a PV panel must be at least 8 feet above the ground for fixed tilt panel systems, or 10 feet in a horizontal position for tracking systems. During the growing season, the maximum sunlight reduction due to shading from the PV panels on any square foot of land under the dual-use system may be no more than 50%. The

[29] Source: https://www.youtube.com/watch?v=abOabHj0K4A (Min. 1:02; 24.09.2019).

[30] Source: https://www.youtube.com/watch?v=rJw_2zGTRdk (25.09.2019).

[31] Source: https://www.youtube.com/watch?v=lf2tN0oaX8A (25.09.2019).

[32] The methodology to measure this is called the land equivalent ratio (LER) and has been adopted from agroforestry. Fraunhofer ISE has published LER measurements of its APV harvest in 2017 and 2018: https://www.ise.fraunhofer.de/en/press-media/press-releases/2019/agrophotovoltaics-hight-harvesting-yield-in-hot-summer-of-2018.html (24.09.2019).

shading analysis must be completed using the Shading Analysis Tool, provided be the state.[33] Dual-use systems qualifying as Agricultural Solar Tariff Generation Units receive an additional \$0.0600 kWh^{-1} on top of their base compensation rate of \$0.1400 kWh^{-1} to \$0.2600 kWh^{-1}, depending on the size of the system and the local utility supplier.[34]

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