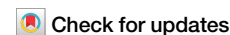




Future Mediterranean agrivoltaics: prospective life cycle assessment under climatic and socio-economic scenarios



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Agrivoltaic (AV) systems co-produce crops and solar electricity and are gaining attention as dual-purpose land solutions under climate change. This study conducts a prospective, spatially explicit consequential life cycle assessment of AV deployment for wheat production in Southern Europe focusing on climate change impacts, uniquely distinguishing between two economic logics: electricity-demand-driven and crop-demand-driven deployment. Under electricity-driven deployments, AV systems can reduce impacts compared to photovoltaics in high solar yield regions such as southern Spain but may increase impacts elsewhere due to material intensity and limited agronomic gains. By contrast, crop-driven AV deployment—motivated by rising food demand—can deliver strong climate benefits by substituting high-emission electricity, particularly in regions with low wheat yields but high solar output. These benefits, however, diminish as electricity mixes decarbonize. By integrating climate, agronomic, and economic uncertainties, this study offers critical insights for guiding sustainable AV development and policy in climate-vulnerable regions.

The Mediterranean basin is a “climate change hotspot”, experiencing ongoing warming at a rate exceeding global averages, and subsequent altered rainfall patterns^{1–3}. The main risk factor identified in the Mediterranean is drought, which is due to trends characterized by a widespread increase in evaporative demand and a decrease in precipitation^{4–6}. The drier conditions and increasing water scarcity pose significant threats to agriculture^{3,7}.

In the context of accelerating climate change and increasing pressures on land use, agrivoltaic (AV) systems are gaining attention as a pathway to support both agricultural adaptation to climate change and low-carbon energy production^{8,9}. AV systems combine crop growing and solar energy production, aiming to use land more efficiently and improve growing conditions—especially as heat and water stress increase. Converting a small share of EU farmland—around 1%—to agrivoltaic systems could not only meet the EU’s 2030 solar targets¹⁰ but could also potentially generate electricity far beyond current demand¹¹. Although partial shading from photovoltaic (PV) panels can reduce solar radiation and potentially limit crop yields, AV systems may be especially valuable in the Mediterranean basin^{7,12}. These climate stressors also risk amplifying agriculture’s environmental impact in a reinforcing cycle¹³. In this context, AV systems offer potential

benefits by moderating temperature extremes, reducing evapotranspiration, and shielding crops from more frequent extreme weather events^{9,14–16}. Ultimately, the effectiveness of AV systems in sustaining or improving yields will depend on the severity of future climate impacts and the ability of their designs to buffer them.

Assessing the true sustainability of future AV deployment—especially its impact on global warming—goes beyond considering energy and local agro-climatic benefits. A life cycle perspective¹⁷ is crucial for capturing broader effects, such as the consequences of changes in crop yields. Yield gains may reduce pressure elsewhere, while losses can drive more cultivation and higher impacts. Nevertheless, AV systems differ from conventional PV systems in infrastructure and materials, which also shape their environmental impact. Understanding these complex trade-offs requires a model that accounts for interacting factors, such as climate, yields, system design, and future socio-economic conditions.

Life cycle assessment (LCA) is a well-established method for quantifying the environmental impacts of a product across its entire life cycle^{17,18}. Although several studies have applied LCA to specific AV system configurations, no studies have accounted for future climatic, agronomic, and socio-economic changes^{19–25}. This study addresses this gap by providing a

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forward-looking, spatially explicit assessment of the global warming impact of large-scale AV deployment for non-irrigated wheat production in Southern Europe, compared to conventional PV systems and traditional crop production. To do so, we use a consequential LCA approach that focuses on the system-wide environmental consequences of changes in demand^{26,27}. This method captures causal chains, including yield changes from AV deployment driven by electricity demand, or additional electricity production resulting from crop-driven AV expansion and its associated market impacts. Unlike attributional LCA, which aims at retrospectively attributing impacts to products based on normative rules, thus artificially dividing the AV system into two subparts (electricity and crop production), the consequential framework acknowledges that impacts arise when the productive system installs new capacity and mobilizes new inputs as a response to demand signals. This causal modeling thus sets the focus on consequences of demand signals for different products, that translate into impacts according to the way the productive system reacts. The impacts are therefore not artificially inherent to the product or the system, but to the causal chain linking demand and response in specific conditions.

Assessing the future environmental performance of AV systems under changing climate and economic conditions involves large uncertainties across multiple dimensions. To address this, we explore a broad range of possible outcomes by applying the Shared Socio-Economic Pathways (SSP) framework, incorporating diverse global socio-economic scenarios, climate models, and LCA parameters. Our approach integrates spatially explicit simulations of crop and electricity production under climate change—performed with the ORCHIDEE land surface model²⁸ adapted for AV systems¹⁶—with forward-looking LCA databases that reflect the evolution of the global economy, as modeled by various Integrated Assessment Models (IAMs)²⁹.

This study provides a comprehensive assessment of future scenarios and associated uncertainties, offering spatial maps of global warming impacts from AV deployment in southern France, Spain, and Italy. Integrating prospective and consequential LCA with climate modeling, land surface simulations, and IAMs highlights where, when, and conditions under which AV systems can outperform conventional alternatives. The analysis critically evaluates the promises of AV technology and pinpoints the key drivers behind its potential climate benefits.

Results

The results section presents the large scope of possible futures assessed in this study. The analysis follows the RCP 4.5 scenario, a moderate emissions trajectory that stabilizes radiative forcing at 4.5 W/m² by 2100 without requiring overshoot, implying considerable but achievable mitigation efforts³⁰. This global pathway is downscaled to local conditions using nine climate models from the EURO-CORDEX ensemble³¹. Global socio-economic trajectories affecting the production system are represented through six archetypal futures derived from three SSPs and modeled with varying policy constraints using two IAMs. From these projections, future marginal suppliers are identified through two algorithms that capture both short- and long-lasting changes in demand. Overall, a total of $9 \times 6 \times 2$ archetypal socio-economic and climatic futures are explored. Additional uncertainties—stemming from crop yield responses in the ORCHIDEE-AV system model and LCA parameters—are incorporated through stochastic sampling. The first subsection analyzes AV systems' impacts under electricity-driven deployment, starting with an overview and then scenario-specific observations. The final part examines impacts linked to crop demand-driven AV deployment. The reader is referred to the Methods section for a detailed explanation of these two different deployment logics.

Electricity-demand-driven AV deployment

From the perspective of electricity demand driving AV deployment (cf. Methods), Fig. 1 shows the relative global warming impact over a 100-year time horizon (GW100, in CO₂-eq.) of AV kWh compared to conventional PV kWh across the full range of future scenarios and associated uncertainty. Identical electric yields are assumed for both AV and PV due to sun-tracking

systems with back-tracking strategies, while AV-induced changes in wheat yields are modeled to substitute local production within the same agro-climatic zone. Three distinct geographical patterns emerge across the years. In France, AV systems tend to have higher GW100 impacts per kWh than conventional PV systems, with third-quartile differences reaching up to +19% by 2090 (Fig. 1a, Supplementary Data I.1). This disadvantage arises from yield losses due to panel shading and limited agronomic benefits, which fail to compensate for the higher material intensity and lower panel density of AV systems. By contrast, southern Spain and Italy consistently exhibit climate benefits from AV deployment. In these regions, all model runs show lower GW100 impacts for AV systems (Fig. 1b), with third-quartile reductions reaching −55% (Fig. 1a, Supplementary Data I.1). Here, AV systems improve yields through microclimatic effects, inducing substitution—that is, the avoided production—of local, low-yield, high-impact wheat. This results in substantial avoided emissions per unit of electricity generated. A third zone, spanning parts of central France and northern Spain, shows mixed outcomes with impact differences centered around zero—reflecting strong sensitivity to local context and scenario variables.

These patterns shift under alternative systems and market assumptions. Using larger AV structures—entailing greater use of steel, cement, and aluminum (cf. Methods, Supplementary Information I.2.1)—reduces the spatial extent of AV's climate impact advantage, restricting it mostly to southern Spain (cf. Supplementary Information I.5). However, when these structures are compared to fixed-tilt PV systems instead of sun-tracking ones, AV regains its relative benefit across much of the domain, with only limited northern areas showing higher impacts (cf. Supplementary Information I.5). Similarly, comparing smaller reference AV systems to fixed PV systems results in AV outperforming PV across the entire study area (Fig. 2a). These results emphasize the importance of mounting structure design and electric yield assumptions, in line with prior analyses³² and the global sensitivity analysis (cf. Supplementary Information I.6). An alternative scenario assumes that changes in AV crop yields affect the global wheat market rather than local production. In this case, increased yields reduce wheat imports rather than substituting regional supply. Since the global wheat market is modeled as unaffected by climate change, the avoided emissions are relatively small and do not offset the higher material burdens of AV systems. Therefore, AV electricity shows higher GW100 impacts across the entire domain, including southern Spain (Fig. 2b).

It is important to note that the distributions in Fig. 1 are not probabilistic; no likelihoods are assigned to the various projected futures or modeling choices. Each scenario combination must be interpreted independently to fully assess its influence on the conclusions (Fig. 2).

Figure 2 presents the mean relative GW100 differences between the AV and PV systems across the selected scenarios; however, it does not capture the uncertainty underlying those estimates. Figure 3b, along with supplementary results in Supplementary Information I.5.2, reveals that across most years and scenarios, uncertainties in climate projections, crop and electricity yield simulations, and life cycle modeling lead to substantial ambiguity in the comparative climate performance of AV systems. In much of Italy, France, and northern Spain, the interquartile range indicates an equal impact of AV and PV systems under many plausible futures (i.e., the relative impact difference is zero). Nonetheless, most regions in Spain remain a robust area of advantage for AV systems, with consistently lower GW100 values.

This uncertainty is primarily driven by the variability in the crop yield ratio between AV and conventional local wheat systems. As shown by the Borgonovo global sensitivity analysis (cf. Methods, Supplementary Information I.6), this parameter ranks as the third most influential factor affecting impact differences—following the relative amounts of steel and aluminum used in AV versus PV mounting structures. By contrast, the choice of algorithm used to construct background LCA databases from IAM simulations exerts minimal influence on the results (cf. Methods, Supplementary Information I.4).

Interestingly, the relative impact difference between AV and PV kWh generally grows in absolute value over time, with various timings and

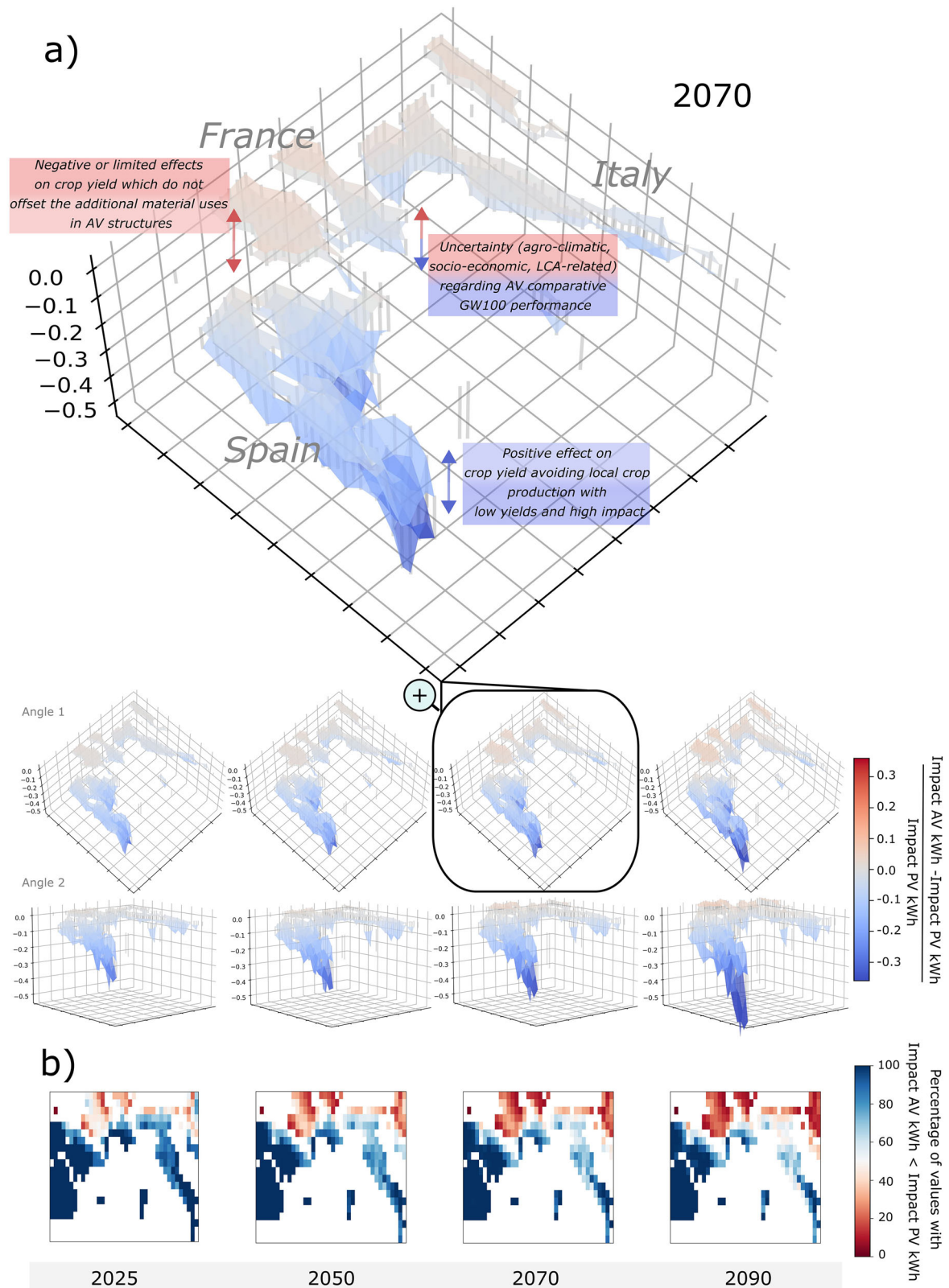


Fig. 1 | Comparative global warming impact of agrivoltaic (AV) electricity across modeled scenarios: Relative GW100 impact (kg CO₂-eq per kWh over 100 years) of AV systems compared to conventional photovoltaic (PV) systems across a wide range of modeled futures. Scenarios combine different Shared Socio-economic Pathways, Integrated Assessment Models, policy constraints, marginal mix identification methods, and stochastic uncertainties. All results assume local substitution

of AV-induced wheat yield changes, reference AV mounting structures, and sun-tracking PV systems with equal electricity output. **a** Three-dimensional overlay of two surfaces representing the interquartile range (from first to third quartile) of relative GW100 differences between AV and PV kWh with a zoom on the 2070 subpanel. **b** Percentage of model runs where AV outperforms PV.

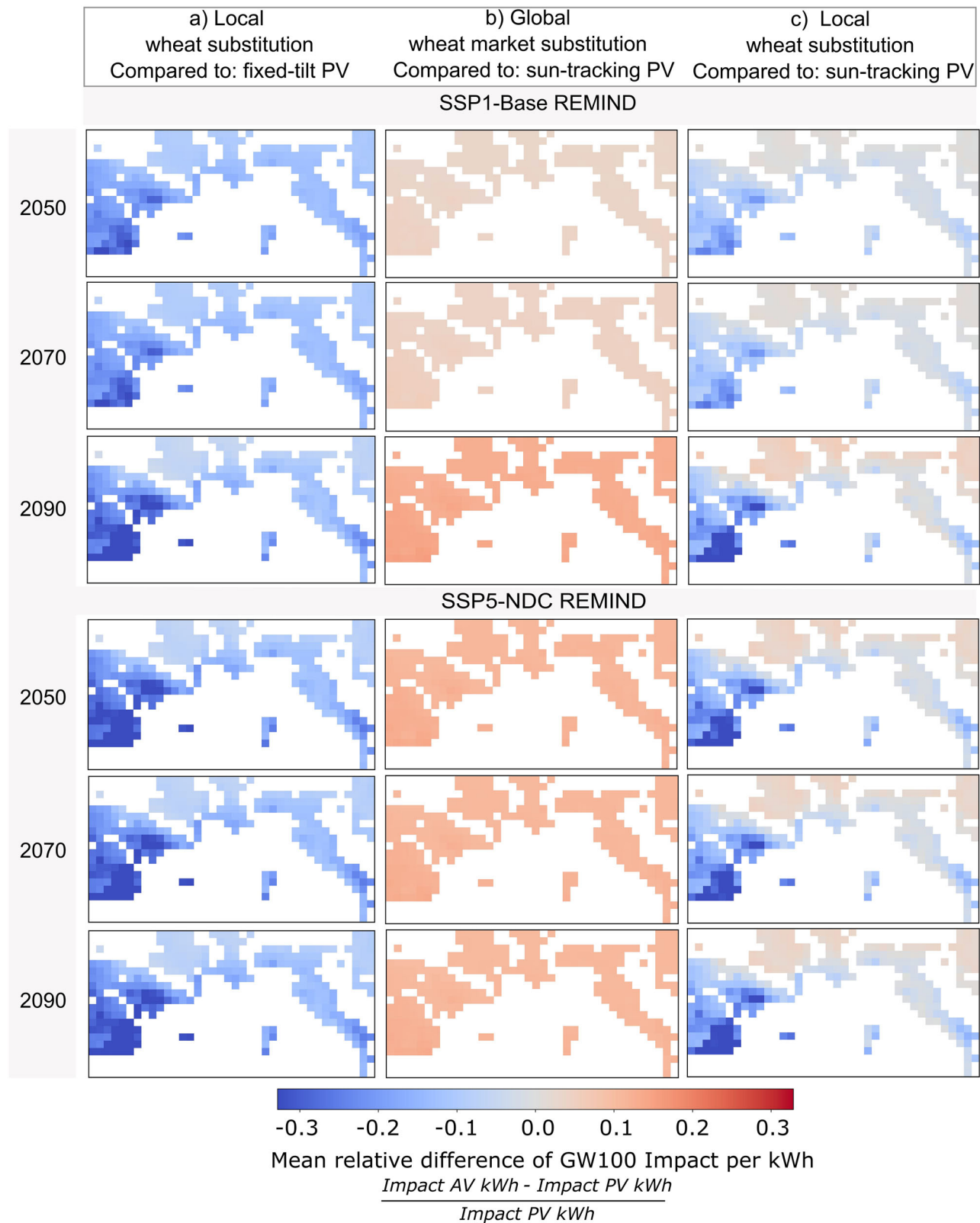
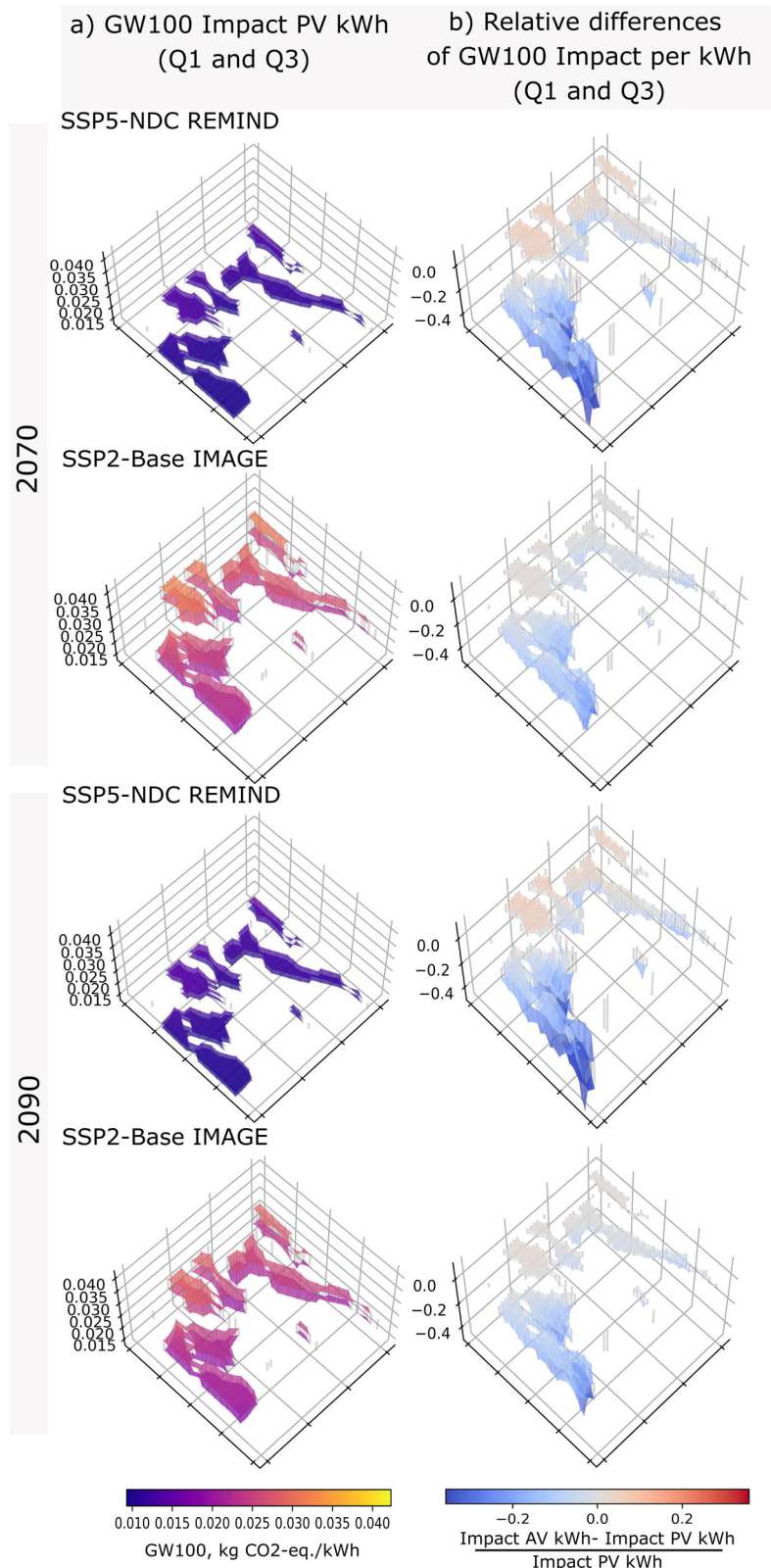


Fig. 2 | Mean relative differences of GW100 impact between agrivoltaic (AV) kWh and photovoltaic (PV) kWh for two distinct combinations of shared socio-economic pathways, integrated assessment models and policy constraints. Reference AV mounting structures with sun-tracking are considered. Only short-lasting demand changes are used to identify marginal mixes in the background

database. The AV crop yield modification either induces avoided or required wheat production from the local region (a,c) or from a global market (b). Impact differences are computed considering conventional PV systems with sun-tracking (b,c) or with fixed-tilt (1). The results for the remaining socio-economic scenarios are available in Supplementary Information I.5.1.

Fig. 3 | Three-dimensional overlay of two surfaces representing the interquartile range (from first to third quartile) of GW100 impact values for conventional photovoltaic (PV) kWh (a) and relative differences of GW100 impact between agrivoltaic (AV) kWh and PV kWh (b). Local wheat substitution, reference AV mounting structures, and conventional PV systems with sun tracking are considered. Only short-lasting demand changes are used to identify marginal mixes in the background databases for the two combinations of Shared Socio-economic Pathways, Integrated Assessment Models and policy constraints displayed. The results for the remaining socio-economic scenarios and years are available in Supplementary Information I.5.2.



magnitudes depending on the scenario. Regions where AV systems outperform PV tend to see this advantage strengthen, while regions where they underperform see the gap widen (as shown by intensifying red and blue areas in Figs. 2 and 3). This effect is due to the declining impact share of the PV component, which results in a larger relative penalty or gain for AV wheat yield modifications. As an illustration of this phenomenon, the rapid

fossil-driven technological progress associated with scenario SSP5-NDC-REMIND induces low impacts for PV panels and structures (Fig. 3a), which exacerbates the relative advantage or disadvantage of AV systems over PV systems (Figs. 2a, 3b). Overall, this pattern shows that the comparative impact trajectory is shaped more by global socio-economic developments

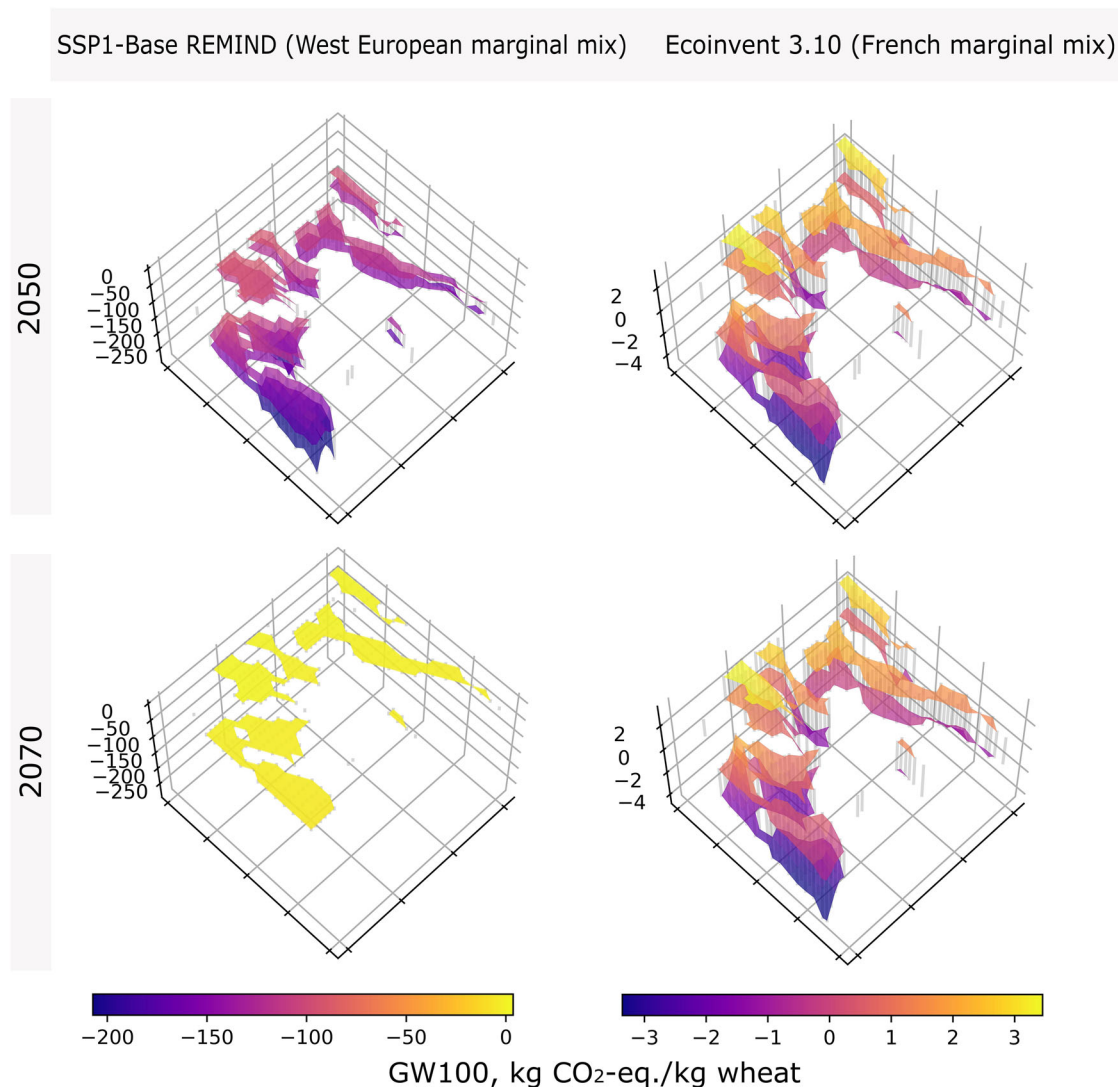


Fig. 4 | Three-dimensional overlay of two surfaces representing the interquartile range (from first to third quartile) of GW100 impact values for 1 kg of agrivoltaic (AV) wheat, for background scenarios SSP1-Base REMIND and for the current

background database. For the latter, the background remains the same for 2050 and 2070, and only local agro-climatic factors change. Reference AV system mounting structures are considered. The color scales differ between the two columns.

than by local agro-climatic factors (cf. Supplementary Information I.5.4 for details).

Crop-demand-driven AV deployment

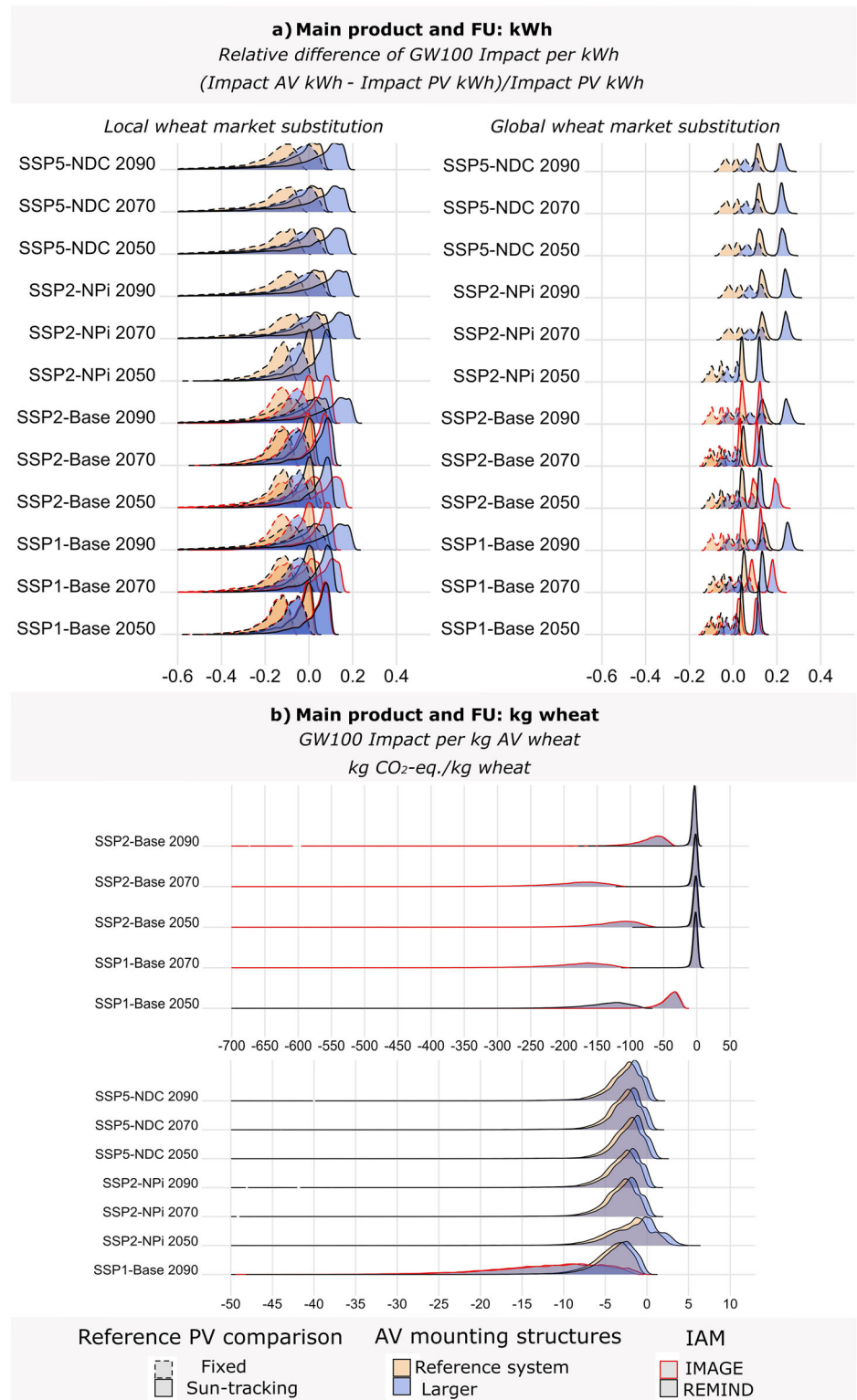
The environmental consequences of AV systems vary substantially depending on what drives their deployment—a distinction captured in consequential LCA by defining the system's main product (cf. Methods). When AV systems are implemented in response to crop demand—meaning that rising crop needs incentivize the joint expansion of both agricultural and electricity production—the results show that the climate benefits can be substantial. As illustrated in Fig. 4, under this crop-demand-driven deployment logic, the GW100 impact value per kilogram of AV-produced wheat can become strongly negative—that is, it leads to avoided emissions. In the most favorable case—using the IMAGE SSP1-Base background scenario for 2070—the impact reaches as low as -3467 kg CO₂-eq, with interquartile values ranging from -210 to -153 kg CO₂-eq. over the domain (cf. Fig. 5, Supplementary Data I.3, and Discussion).

These exceptionally low values are driven by the substitution of high-emission marginal electricity by the co-produced AV electricity. When the marginal electricity being substituted has a low emission factor—such as the current French marginal mix at 0.035 kg CO₂-eq. per kWh—the net climate

benefit narrows considerably. Under these conditions for the year 2070, the impact per kilogram of AV wheat ranges from -56 kg to $+6$ kg CO₂-eq. (Q1 = -1.38 , Q3 = $+1.65$; cf. Figures 4 and 5 and Supplementary Data I.3). These findings highlight the dominant role played by both the emission intensity of the marginal electricity and the electricity yield of the AV system. Because AV wheat is co-produced with a substantial amount of electricity, small changes in electricity emissions can result in large shifts in the overall climate impact—especially in southern regions, where crop yields are relatively low and electricity yields are high. Over the long term, the climate benefit of crop-demand driven AV deployment is more sensitive to changes in the electricity side of the system than to variations in crop yield (see Fig. 4 and Supplementary Information I.5.4). In fact, the environmental impact per kilogram of AV wheat will converge to that of conventional wheat with similar yields when the substituted marginal electricity has the same emission profile as the AV electricity component.

As previously emphasized, it is crucial to understand that such climate benefits are not intrinsic to AV systems and products but to systemic responses of the productive and economic system to specific demands signals. These responses are conditioned by the state of the economic system and the AV business model, and hence by assumptions about the future

Fig. 5 | Distributions of all relative impact differences per kWh (when main product) (a) and all agrivoltaic (AV) wheat impact values (when main product) (b) across the entire studied domain. Background databases with short- and long-lasting demand changes are merged into single curves, as they overlapped and could not be shown (cf. Methods and Supplementary Information I.4, Supplementary Data I.3). FU Functional Unit, IAM Integrated Assessment Model, PV Photovoltaic.



electricity mix. Currently, crop-demand-driven AV deployment is not particularly plausible as further developed in the discussion.

Figure 5 further emphasizes the sensitivity of crop-demand-driven AV systems to the marginal electricity mix. The long-tailed distributions—especially for southern Spain—capture the large spread in outcomes, reflecting variations across SSPs, IAMs, years, and modeling assumptions. Figure 5a presents the distribution of relative climate impacts for electricity-demand driven deployment, while Fig. 5b shows the absolute impacts of AV

wheat under crop-demand driven deployment. Together, they provide a compact overview of the uncertainty and potential benefits of AV systems across the full range of the spatial, temporal, and systemic conditions considered.

Discussion

This study shows that AV systems can deliver substantial global warming mitigation benefits under specific conditions in the Mediterranean region.

When deployed in response to electricity demand, AV systems can reduce climate impacts by up to 50% on average in Spain, particularly in high-yield solar regions. By contrast, in France—excluding some coastal areas—AV deployment typically results in slightly higher impacts than conventional PV, with increases of up to 10% on average. In the other regions of the studied domain, AV systems offer no consistent advantage. Across scenarios, however, AV systems equipped with sun-tracking panels systematically outperform fixed-tilt PV configurations. Crucially, minimizing the use of high-impact materials—especially steel and aluminum in mounting structures—is essential to preserving AV's comparative advantage³². In this sense, innovations such as tensile structures, minimizing the structural needs per m² of panel are particularly relevant¹⁹. Maintaining minimal mounting structures is even more critical for other impact categories that are not directly studied here, such as mineral resource scarcity (cf. Supplementary information I.7.1 and Supplementary Data I.5). Indeed, the additional steel and aluminum structures mobilized by the AV system, even for the smallest structures, make its kWh worse by 33% on average than for the conventional PV system over the whole domain, even in the south of Spain (25%) (ReCiPe 2016, surplus ore potential, in kg Cu-eq.). Even when compared to fixed PV structures, the AV kWh still performs worse by 9% on average in 2090. This detrimental result extends to the situation in which crop is the main product, as crop-demand driven AV systems yield a positive impact for surplus ore potential while the substitution induced large negative results for climate change. This confirms the previous results demonstrating stricter requirements applying to the mounting structures for AV systems to perform better than conventional PV for mineral resource scarcity³². While the model behaviors demonstrated for climate change hold, different impact categories are associated with distinct maps of performances, as the threshold above which higher material and land intensities are compensated by the agronomic gains varies. For instance, only a comparison to fixed conventional PV allows a less impactful AV kWh for freshwater ecotoxicity (ReCiPe 2016, freshwater ecotoxicity, kg 1,4-DCB eq.) by 2% on average over the domain.

The environmental performance of electricity-demand-driven AV systems is also highly sensitive to the type of crop market substitution assumed. Substitution of local wheat yields more favorable outcomes than global substitution, as it aligns with three reinforcing factors: high solar productivity, yield gains from partial shading, and the substitution of low-yield, high-impact conventional wheat. Assuming local substitution is particularly relevant, and is likely to happen under policy frameworks prioritizing food sovereignty and reduced agricultural imports—objectives increasingly reflected in the evolving European Common Agricultural Policy³³. However, the high benefits of this substitution for southern European locations would also prevail if the substituted global wheat also stemmed from similar low-yield regions. Indeed, a global wheat market scenario unaffected by climate change was assumed in this study, producing relatively low reference impacts, but this assumption should be considered in the context of the regionalization of the global market. If AV-induced yield increases were to enable exports to low-yield regions particularly affected by climate change—such as North Africa, already the leading importer of EU wheat³⁴—comparable benefits to substituting local wheat could still arise.

With France being the EU's leading wheat exporter, and Italy and Spain being net importers³⁴, the current specific trade markets do not particularly foster the synergy associated with the reinforcing factors mentioned above. Low AV-induced yield benefits in France lead to little substitution of high-impact crops, while large AV-induced yield effects entail large substitution of imports from locations with higher yields and lower impacts. With future climate change, geopolitics and trade policies remaining uncertain, prospective trade modeling would be necessary to better estimate the balance between local and global production shifts in response to AV deployment³⁵. Consequently, the climate impact of electricity-driven AV systems likely lies between those derived from local and global-market assumptions.

When AV systems are deployed in response to crop demand, their climate benefits hinge on the characteristics of the avoided marginal

electricity production. The more carbon intensive the substituted electricity, the greater the potential benefit. Hence, the use of nationally resolved, prospective marginal electricity mixes would be necessary: the prospective European mix applied in this study is notably more carbon-intensive than, for example, the current French mix. Assuming progressive decarbonizing of the electricity production, the mitigation potential of crop-driven AV deployment is expected to decline—emphasizing the importance of near-term implementation to maximize benefits.

Importantly, electricity- and crop-demand-driven AV deployments correspond to distinct consequential LCA frameworks, each rooted in different economic logics. Following established heuristics³⁶, the main product in such systems is defined as the one whose marginal revenue exceeds the marginal cost of the co-production process. Under this principle, crop-demand-driven AV systems would be more viable in futures characterized by high agricultural prices and relatively low electricity prices—an increasingly plausible future in the context of climate change and the global energy transition. If this context arose, it could plausibly happen simultaneously with the previously mentioned decarbonizing of the electricity sector, thus decreasing the benefits of the occurring substitution.

This context is not likely under the current circumstances, such as in France, where AV deployment is largely electricity-demand-driven. Installations are typically initiated by energy-sector actors seeking to expand PV capacity on farmland, with a legal framework³⁷ ensuring that crop yield does not fall by more than 10% and landowners receiving rental income. This aligns with the state objectives articulated in the Multi-Annual Energy Plan, which positions AV systems as a tool for meeting national renewable energy targets⁸. However, the way in which such objectives are translated into national policies and regulatory frameworks varies across countries. For instance, Italy and Spain have adopted legal and policy frameworks for supporting AV deployment that differ from those implemented in France³⁸. While it is beyond the scope of this work to discuss whether specific legal frameworks imply a crop or electricity-demand driven deployment, this study purposely explores both economic perspectives so that the results can inform interpretation across contexts, also acknowledging that the underlying policy landscapes are evolving, remain uncertain and must be critically informed^{18,33}. Overall, the work disentangles the multiple factors that drive AV comparative environmental performance so that results can be generalized carefully according to agroclimatic (i.e., AV relative benefits, electric and crop yields, which are common to most semi-arid Mediterranean regions), technological (i.e., relative material intensity for mounting structures), market (i.e., substituted marginal electricity or crops), regulatory (i.e., demand driver), and prospective socioeconomic (i.e., global SSP) contexts.

Although this study integrates a broad set of uncertainties, future research would benefit from incorporating additional land surface models—such as those within the Agricultural Model Intercomparison and Improvement Project (AgMIP)—to compare agronomic projections under alternative climate trajectories³⁹. Here, the ORCHIDEE model was used to simulate generic wheat production, but alternative models could better reflect local soil properties and farming practices.

In addition, the analysis assumes that yield variations are driven exclusively by climatic and geographic factors, while life cycle inventory (LCI) inputs are held constant. This simplification overlooks potential changes in management practices and environmental interactions. For instance, the altered microclimate beneath AV structures may influence soil carbon dynamics relative to conventional cropping systems. The present work does not account for such possible differences in local carbon accumulation or emission processes between these systems. Using the same ORCHIDEE-AV model, Rapella et al.⁴⁰ investigated the effects of AV systems on nitrogen use efficiency (NUE), showing context-dependent responses but an overall improvement. These results suggest that AV deployment may require a specific rescaling of the different LCI inputs and outputs, as fertilizer use per unit of output could potentially decrease further than for the other inputs. However, biophysical models alone cannot provide prospective LCIs without assumptions regarding farmers' responses. Given the observed biophysical effects, farmers may either intensify

practices—leveraging higher NUE to increase yields per unit of fertilizer—or maintain current yields while reducing inputs. Similarly, focusing on non-irrigated crops avoids introducing assumptions about irrigation adaptation strategies. Where irrigation is available, climate change impacts can be partially mitigated through increased water use, effectively substituting additional greenhouse gas emissions with higher water demand. These limitations could be addressed in follow-up studies, as more knowledge on farmers' responses becomes available.

Although ORCHIDEE-AV has been applied to C4 crops such as maize¹⁶, this study focuses on C3 crops, as the tropical origin of C4 species makes them particularly dependent on irrigation during summer, and hence less appropriate for the European-wide evaluation carried out in this study. Maize, the most irrigated crop in France⁴¹, is unlikely to expand in southern Europe without substantial irrigation. Modeling such systems would therefore require explicit representation of adaptive farming practices. For example, Zang et al.⁴² showed that a projected 26% yield loss for U.S. maize in the Ogallala aquifer region could be offset by a 67% increase in irrigation. Similarly to the limitation tackled above, addressing these considerations would require biophysical models capable of simulating adaptive management (e.g., process-based crop models⁴³), potentially complemented by agent-based modeling approaches⁴⁴ to capture how farmers' decisions evolve under economic, social, and behavioral conditions. These limitations, however, do not undermine the overall findings. The sensitivity of results to agricultural input levels remains low compared to parameters associated with the PV system, as previously reported³² and confirmed by the global sensitivity analysis (cf. Supplementary Information I.6). Assuming a homogeneous scaling of the LCI therefore constitutes a reasonable approximation, enabling robust conclusions regarding overall impact patterns within this consequential framework, where outcomes are primarily driven by crop and electricity yields, market assumptions, and PV material requirements.

AV and PV installations are assumed to occupy similar land types, defined by their potential net primary productivity (see the indirect land use change [iLUC] model in the methodology and SI I.2.2). The comparison would differ if, for example, a PV system were deployed on forested land (increasing its impact) or on built-up areas (reducing it). Van de Ven et al.⁴⁵ showed that modeling assumptions about local carbon dynamics associated with PV deployment can strongly influence the impact per kWh. Additionally, AV systems could affect nutrient cycles⁴⁶, while increasing temperatures and drought stress may require adjustments to irrigation or fertilization regimes. Furthermore, the NPP-based iLUC model considers indirect climate change effects due to competition on the global land market, but not the other effects associated with the induced land use changes such as biodiversity loss, water use etc. Moreover, the analysis includes both AV and conventional systems across the entire domain, regardless of economic feasibility. While southern Spain, for example, already observes unirrigated wheat yields below 500 kg/ha⁴⁷, the agricultural component of AV systems may arguably become economically nonviable in the future, potentially favoring conventional PV deployment (from an electricity-demand-driven perspective) or greater reliance on imports (from a crop-demand-driven perspective). Integrating such viability constraints into future modeling frameworks would help refine deployment assessments. Extreme positive or negative impact values in the very south of Spain thus show potential impacts for systems that may not realistically persist under such adverse conditions. If they did, the production volume for crops would also be very low, which would induce an overall minor positive impact in the case of crop-driven AV.

Despite these limitations, the extensive scenario and sensitivity analyses conducted in this study—and in earlier model explorations³²—support the robustness of key spatial trends and orders of magnitude. The results offer actionable insights for both research and policy, showing how AV systems' global warming impacts are shaped by the interplay of structural design choices, site-specific agro-climatic conditions, and the dynamics of local and global markets for electricity and crops.

Although this complexity is substantial, the emergence of geographically consistent patterns across scenarios and years enables the identification of priority regions for AV deployment—guiding technical planning and regulatory frameworks. It is essential to emphasize, however, that the global warming impact represents just one facet of sustainability. While the analyzed behaviors can extend to other impact categories with caution as previously studied³², some impacts assessment may require more detailed tracking of water and nutrient fluxes. Even outside the LCA framework, broader environmental and social considerations must also be addressed, particularly given that AV systems straddle two sectors—agriculture and energy—with divergent goals, values, and governance structures^{8,48,49}.

Methods

This study combined prospective climate, economic, and agronomic modeling to evaluate the global warming impact of large-scale AV deployment across southern Europe. The methodology integrated (i) a parameterized consequential LCA model for AV systems, (ii) prospective consequential background LCI databases projecting economic evolution through the 21st century, and (iii) spatially explicit simulations of crop and electricity yields generated by the ORCHIDEE-AV model. An overview of the methodological framework is provided in Fig. 6.

Consequential LCA modeling

This study adopted a consequential LCA framework to quantify the system-wide environmental impacts induced by marginal changes in demand, reflecting both economic and biophysical cause–effect relationships^{26,50}. Multifunctionality—that is, the joint production of electricity and crops—was resolved through system expansion via substitution. Depending on whether electricity or crops were considered the main product (i.e., the driver of deployment), the co-produced output substituted its marginal counterpart (conventional wheat or marginal electricity)—that is, it avoided its production. The net environmental impact was calculated as the sum of all inputs and emissions associated with the AV system minus those of the substituted marginal product.

The functional unit was either 1 kWh of electricity or 1 kg of wheat at the farm's gate. This modeling approach builds on the parameterized PV LCA model developed by Besseau et al.⁵¹, who revised the ecoinvent inventories for photovoltaics after establishing that they were obsolete, and incorporates agricultural life cycle data from the ecoinvent 3.10 consequential background database. AV systems were modeled using bifacial single-crystal silicon PV modules mounted on horizontal single-axis trackers.

The LCI of each AV system was constructed for a 30-year lifetime, consistent with PV industry standards. For each year X , the LCI includes total expected electricity and average crop output over $(X, X + 30)$, using yield estimates from the ORCHIDEE-AV model. Two types of mounting structures were considered: a reference 2.5 m galvanized steel frame based on a demonstrator at the SIRTa observatory (IPSL, Palaiseau, France)³², and an alternative design with increased material use (steel, cement, aluminum) to accommodate higher panels (cf. Supplementary Information I.2.1). Indirect land use change (iLUC) impacts^{53,54} were also incorporated, using the model based on a global market for net primary productivity (NPP0) proposed by Schmidt et al.⁵⁵ (cf. Supplementary Information I.2.2).

The climate impact metric used was the global warming potential over a 100-year horizon (GW100), following the ReCiPe 2016 methodology⁵⁶. AV electricity was compared against PV with either sun-tracking, thus maintaining the same modeled electric yield as AV, or fixed-tilt configurations. Panel density differed between AV (0.44 m² panel/m² ground) and PV (0.76 m²/m²). AV crop production was compared to conventional wheat grown in the same location. All comparisons are reported as relative impact differences with regard to the conventional reference. The foreground AV consequential LCA model has been fully described and analyzed in Jouannais et al.³², to which the reader is referred for a detailed explanation.

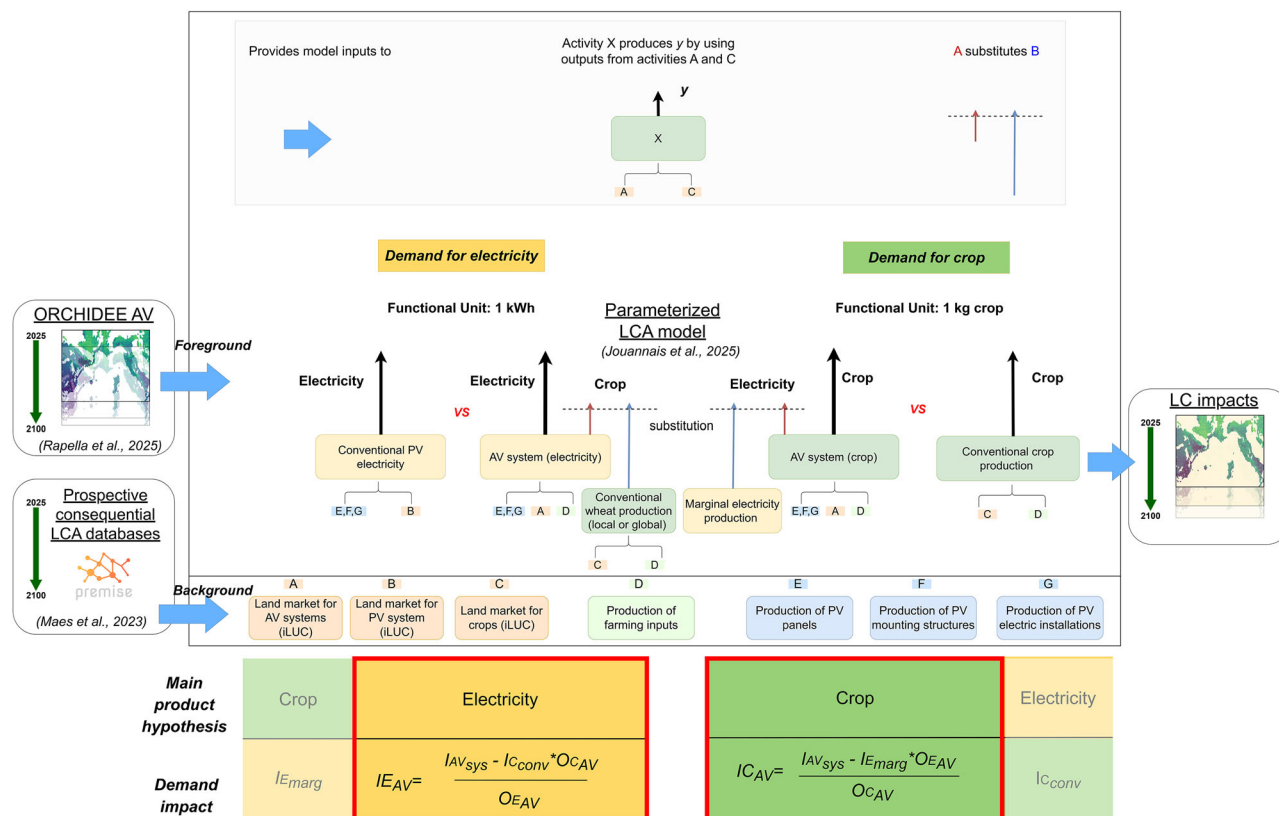


Fig. 6 | Overview of the methodology, consequential perspectives, and associated impact calculations. In the present work, only situations in which the demand concerns the main product of the agrivoltaic (AV) system are considered. Thus, when electricity is the main product, the analysis considers electricity demand; when crops are the main product, it considers crop demand. In the former case, the functional unit (FU) is 1 kWh of electricity. The impact per FU of electricity produced by the AV system (IE_{AV} [impact unit. kWh⁻¹]) is calculated as the total impact of the AV system (IAV_{sys} [impact unit]) minus the impact avoided through its

output (OC_{AV} [kg]), calculated as OC_{AV} multiplied by the impact of producing 1 kg of conventional crop (IC_{conv} [impact unit. kg⁻¹]). The resulting net impact is then divided by the AV system's electricity output (OE_{AV} [kWh]) to express the result per functional unit. The same approach is applied symmetrically when crops are the main product: the impact of the AV system is offset by the impact avoided through its electricity output, calculated using the impact of 1 kWh of marginal electricity on the market (IE_{marg} , impact unit. kWh⁻¹).

Background modeling: SSPs, IAMs, and RCP scenarios

Prospective consequential background LCI databases were developed using the consequential version of the premise Python library^{31,57}, which modifies the ecoinvent 3.10 consequential database to reflect long-term global socio-economic and technological evolutions. These evolutions are simulated by IAMs, which differ in structure and optimization logic²⁹.

This study used projections from two widely used IAMs: REMIND (optimization-based) and IMAGE (simulation-based). Both models are constrained to produce scenarios consistent with Representative Concentration Pathway 4.5 (RCP 4.5), a stabilization pathway that limits radiative forcing to 4.5 W/m² by 2100. These pathways were aligned with three SSPs—SSP1 (Sustainability), SSP2 (Middle of the Road), and SSP5 (Fossil-fueled Development)—explored under different policy assumptions that constrain the IAMs (Base, NPI: National Policies Implemented, NDC: Nationally Determined Contributions), resulting in six scenario combinations: SSP1_Base_IMAGE, SSP1_Base_REMIND, SSP2_Base_REMIND, SSP2_NPI_REMIND, SSP2_Base_IMAGE, SSP5_NDC_REMIND. For each SSP-Policy-IAM combination, two marginal supplier identification algorithms were applied: (i) a short-term slope method (2-year window), and (ii) a long-term area method (5-year window), yielding a total of 12 background LCI databases for each simulation year (2050, 2070, 2090)⁵⁷. Results using the original ecoinvent 3.10 database are also reported for isolating foreground model sensitivity.

The ORCHIDEE-AV model

Crop and electricity yields were simulated using ORCHIDEE-AV, a coupled land surface–PV model described in detail by Rapella et al.¹⁶. The PV module simulated horizontally aligned, single-axis sun-tracking panels—shown to optimize yields in Mediterranean climates. When operating in the sun-tracking configuration, for both conventional and AV systems, an additional constraint in the tracking system is added to avoid PV rows' self-shading⁵⁸. Both electric yields (kWh.m⁻² panel) for sun-tracking conventional and AV systems are therefore identical for a same location. The model was driven by high-resolution regional climate projections from the EURO-CORDEX ensemble (0.11° × 0.11° grid), covering the region [6.55°W–17.45°E, 35.85°N–47.05°N] from 2007 to 2098. The climate ensemble included nine GCM/RCM combinations consistent with RCP 4.5. A 100-year spin-up using the 2007–2016 decade repeated ten times stabilizes the model's carbon pools. Transient simulations were then run with atmospheric CO₂ concentrations from the RCP 4.5 pathway. The model assumed 100% C3 crop cover (representative of wheat without irrigation), and the results were restricted to grid cells with >10% agricultural coverage. To convert simulated net primary productivity (NPP) to grain yield, we calibrated the model using average NPP over the French territory obtained from ERA5-Land climate reanalysis data⁵⁹ and average French wheat yields over 2010–2020, generating an empirical distribution of 10 annual NPP-to-yield conversion factors (see simulation plan hereafter).

Simulation plan, uncertainty, and sensitivity analysis

To reduce spatial complexity, the ORCHIDEE domain was aggregated to 283 representative locations. For each location, year, background scenario, AV structure type, and crop market assumption (local vs. global), 180 climate impact values were calculated (9 climate models $\times$ 20 stochastic draws). Two parameters were sampled stochastically: (i) the weighted potential NPP (local/global NPP0 ratio), as input to the iLUC model⁵⁵, sampled from average values across Mediterranean countries; and (ii) the NPP-to-yield conversion factor, drawn from the 10-year empirical distribution.

A global sensitivity analysis was conducted using Borgonovo's delta index⁶⁰, which was applied to the full parameterized foreground model. A total of 50,000 parameter sets were sampled from uniform distributions ($\pm 25\%$ for uncertain values without empirical data), focusing on one background scenario (SSP1-Base REMIND, short-term marginal mix, 2070). This approach quantifies the influence of each parameter on the variability of impact outcomes, including both absolute and relative results. All simulations were performed using Brightway 2.5⁶¹ for life cycle modeling, premise³¹ for database transformation, and SALib⁶² for sensitivity analysis. The full code and data are publicly available in the project repository⁶³.

Data availability

The data allowing reproduction of the results is fully available at https://github.com/PJGilmw/Future_Medit_AV⁶³.

Code availability

The code allowing reproduction of the results is fully available at https://github.com/PJGilmw/Future_Medit_AV⁶³.

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Author contributions

P.J. developed the assessment protocol and convened the author team. L.R. performed ORCHIDEE simulations. M.D., P.D., N.V., M.M. and L.R. contributed sectoral knowledge and text. P.J. wrote the paper and all authors approved the final manuscript.

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Competing interests

The authors declare no competing interests.

Additional information

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