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Original research article

Agrivoltaics as a win-win for rural regions? Energy and environmental justice perspectives across Italy, Spain, Belgium, and the Netherlands

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A R T I C L E I N F O

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A B S T R A C T

Agrivoltaics integrates agricultural production with renewable electricity generation on the same land, addressing land-use conflicts while offering benefits for both sectors. However, as with other renewable energy technologies, its implementation risks reinforcing existing socioeconomic inequalities, such as unequal distribution of benefits, exclusion from decision-making, and marginalization of underrepresented voices. This could result in social and environmental harm, including landscape changes. To ensure a just energy transition, the implementation of agrivoltaics must tackle these challenges, balancing decarbonization goals with equity and inclusivity considerations. This study investigates experts' perceptions on the justice implications of agrivoltaics with insights from four European regions across Italy, Spain, Belgium and the Netherlands. Building on in-depth semi-structured interviews, this study conducts a comparative analysis of the perceived justice implications of agrivoltaics by applying an environmental and energy justice framework. The findings indicate that while agrivoltaics is perceived to offer economic benefits like additional revenue for farmers and indirect environmental benefits such as improved soil quality, it also raises social and ecological challenges, with benefits often favoring large-scale farmers, landowners, and investors over small farmers and local communities. Excluding small farmers, residents, and ecosystems from decision-making processes exacerbates power imbalances. Early stakeholder involvement can mitigate negative impacts and foster public support by empowering communities. Local engagement, energy communities, financial contributions, and biodiversity restoration efforts are key to restoring fairness. The findings highlight the need for justice-oriented policy frameworks and regulations to ensure an equitable distribution of benefits, inclusive decision-making, and appropriate compensation for any environmental or social harm resulting from agrivoltaics implementation. Future research directions should prioritize further analyses of the restorative justice principle within agrivoltaics. Emphasis should be placed on assessing its capacity to mitigate environmental and social externalities, thereby supporting a more just transition toward renewable energy in rural areas.

1. Introduction

The transition to renewable energy (RE) is a global imperative to reduce greenhouse gas (GHG) emissions and mitigate the climate crisis. Among RE technologies, solar photovoltaic (PV) stands out as one of the fastest-growing, driven by declining costs, increasing efficiency, and broad applicability, from small residential systems to large-scale PV plants [1]. Global solar PV capacity expanded by 87 % in 2023

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compared to 2022, with 447 GW of new installations—accounting for 78 % of all newly added renewable power capacity worldwide [2]. The rapid deployment of solar PV is expected to continue, driven by its technical and economic feasibility [3]. To achieve the European Union's (EU's) net-zero emissions goal by 2050, the REPowerEU plan aims to more than double solar PV capacity by 2025 and approach 600 GW by 2030. Meeting this target requires sustaining an average annual growth rate of 13 %, starting from an installed capacity of 260 GW in 2023 [4]. Yet, this expansion is challenged by the decreasing availability of suitable sites for solar PV installation and public opposition to ground-mounted photovoltaics (GMPV) [5]. This holds especially true in densely populated regions such as Europe, where land is in high demand and subject to multiple competing uses, impacting ecosystems and local communities [6]. A key concern is the competition between agriculture and energy production, raising questions about how to balance food security and agricultural land preservation while ensuring energy security.

Agrivoltaics may address these concerns by combining agriculture and solar PV electricity production on the same site [7]. It shows potential to generate a range of synergistic benefits from this combined land use [8]. For example, different studies suggest that agrivoltaics can help to maintain agricultural activity as the primary land function, ensuring food production [9] while simultaneously shading crops, improving soil water balance, and offering protection from extreme weather events [10]. At the same time, it supports biodiversity and reduces the visual impact compared to GMPV, alleviating nature- and landscape-related social concerns [11]. It may facilitate the harmonization of policies related to sustainable agriculture, the energy transition, rural development, and environmental and biodiversity protection in the pursuit of the targets set in the European Green Deal [12]. Agrivoltaics can also contribute to 14 of the United Nations' 17 Sustainable Development Goals [13,14]. In addition, agrivoltaics systems can generate additional income for rural communities from RE production and reliable crop yield, provided that such economic benefits are retained within rural communities also through land security [12].

Agrivoltaics' potential to reduce inequalities requires careful analysis, particularly in the context of large-scale implementation. Without thorough and proactive regulation and planning, these systems risk perpetuating or exacerbating existing disparities while striving to achieve decarbonization goals and resolve land-use conflicts between agriculture and energy production [15]. Although the deployment of agrivoltaics at scale can benefit from reduced capital costs and increased income from energy production [16], it entails environmental, landscape, and social implications that must be addressed to ensure the "just energy transition" targeted by the European Green Deal [17]. The risk of misusing agrivoltaics by changing agricultural land to primarily being used for RE generation is already becoming evident. Large-scale implementation may also lead to public resistance to agrivoltaics and negatively influence social acceptance of these systems by residents and local communities [18,19]. Literature on social or community acceptance of agrivoltaics and RE infrastructure identifies a variety of economic, financial, social, cultural, and emotive factors that shape support for or opposition to RE projects [20–22]. Perceived local externalities of RE, such as aesthetics, noise, and impacts on biodiversity and ecosystems, contribute to local resistance despite general support for renewables, leading to NIMBY (not in my backyard) movements [23]. Although these studies acknowledge RE projects' aspects of distributive or procedural justice, they do not consider the range of injustices involved in the energy transition, which may risk replicating past and current injustices of fossil fuel-based energy systems [24–26]. Modalities and pathways to implementing RE projects influence disparities among different stakeholders, affecting communities' social vulnerability to environmental impacts and their access to affordable and reliable RE [27]. This holds especially true for agrivoltaics, where social science research has focused on issues of social acceptance [28], while questions about justice have received little attention [17].

To close this gap, the current study builds upon both environmental and energy justice literature to explore the justice implications of agrivoltaics deployment in the EU based on expert interviews. Twenty in-depth interviews were conducted with experts in the solar industry and agricultural sector, local policymakers, social science academic researchers, and representatives of civil society to analyze perceptions concerning the justice implications of agrivoltaics across four regions of the EU: Catalonia in Spain, North Brabant in the Netherlands, South Tyrol in Italy, and Wallonia in Belgium. This study's specific intent was to empirically examine the three core dimensions of justice (distributional, procedural, recognitional) and add a fourth underexplored one (restorative) by combining environmental and energy justice frameworks and collecting experiences and perceptions related to agrivoltaics development in different European contexts. By analyzing experts' perceptions, this study aims to deepen the understanding of justice-related stances on agrivoltaics that may facilitate or hinder its implementation across different EU regions [29,30]. Using a qualitative approach, the research investigates justice as a complex and context-dependent topic, where outcomes are not yet fully visible or measurable, given the relatively early implementation of this technology. The results provide valuable insights for academics, policymakers, developers, and other stakeholders, highlighting opportunities for addressing justice-related concerns and building trust in the design of strategies for deploying agrivoltaics.

This paper is structured in five parts. Section 2 provides a literature review of agrivoltaics and the environmental and energy justice frameworks that grounded our work. Section 3 describes the interview process and the methodology used for data coding and analysis. Section 4 presents the results in terms of the distributional, procedural, recognitional, and restorative justice implications of agrivoltaics in the four regions. Section 5 discusses the results in the context of the theoretical framework, identifying the main justice implications related to agrivoltaics' roll-out identified by the interviewed experts, as well as distinct insights that emerged from the interviews. Section 6 concludes by providing recommendations for the future deployment of agrivoltaics and offering new insights for future research on agrivoltaics from a social science perspective.

2. Background

2.1. The emergence of agrivoltaics

The idea of integrating agriculture and PV systems on the same land emerged in the early 1980s, when the term "agrivoltaics" was introduced [31]. For decades, agrivoltaics remained a niche technology within the solar sector. However, it has recently gained attention for its potential to optimize land use for both energy production and agriculture [5]. As the concept spread globally, alternative terms emerged to describe this approach, including "agrovoltaics," "AgriPV," and "solar sharing" [32].

Agrivoltaics systems are classified into open and closed systems and can have different configurations depending on the crop type, PV module type, and specific site conditions [33]. Closed systems apply to greenhouse infrastructures, requiring a special system design to maximize solar light penetration without affecting crop yields [34]. Open systems are mounted on fields, and their design (vertical vs. horizontal, with fixed or single/dual-axis tracking) depends on the land use (arable land, grassland, horticulture, fruticulture) and farming operations [32]. Generally, agrivoltaics systems entail the following components: PV panels to generate electricity from sunlight, inverters to transform direct current electricity into alternating current electricity, energy storage systems to store excess electricity generated, control systems to manage the operation of PV panels and storage systems, civil foundation and supporting structure, crop management and infrastructure to integrate agricultural activities with electricity production, and finally monitoring systems [35]. Fig. 1 presents the main types of agrivoltaics system

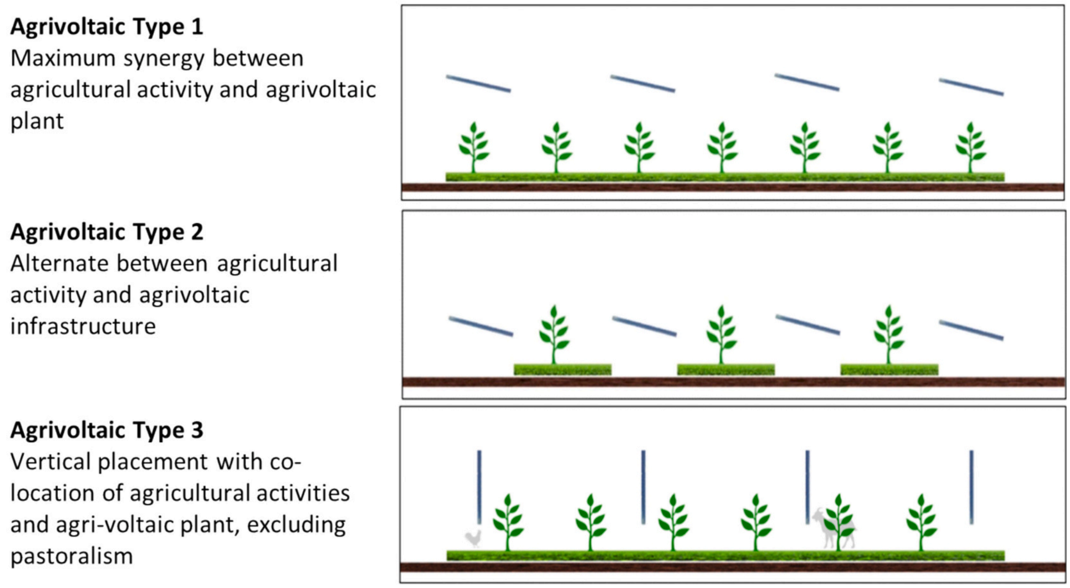

Fig. 1. Agrivoltaics system configurations based on ENEA [36].

configurations, as identified by the study.

Following the increasing adoption of open and closed agrivoltaics systems globally, academic interest in this technology has grown exponentially. While the topic generated fewer than ten publications annually before 2020, the field has since experienced a remarkable surge in the last four years, reaching 206 publications in 2024, according to our own analysis in Scopus (Fig. 2).

However, this surge has been heavily skewed toward technical disciplines. As Fig. 3 illustrates, most studies concentrate on engineering and natural science perspectives, such as system design optimization, land-use efficiency, and assessment of agrivoltaics' environmental and economic impacts [14,37,38]. Studies like those by Amaducci et al. [10] and Dinesh and Pearce [9] emphasize technical approaches, exploring solar panel configurations for crop resilience, energy efficiency, and climate change mitigation, which highlight the field's preference for technical perspectives. While valuable and necessary in investigating a technological innovation such as agrivoltaics, a focus on technical approaches risks overshadowing crucial questions about the societal dimensions of agrivoltaics. In fact, publications within the social sciences account for only about 5 % of the total.

Research on social implications has thus far been confined mainly to issues of public acceptance or resistance to agrivoltaics [19,25,39–42]. For example, Levenda et al. [25] identify key drivers of social acceptance of RE production technologies more broadly, including concerns over negative externalities generated by RE infrastructure and inadequate inclusiveness more widely. Pascaris et al. [28] highlight how agrivoltaics may strengthen community acceptance by providing dual-use land benefits for both agriculture and energy production, while Cotton et al. [43] caution against viewing agrivoltaics as a universal solution, pointing to complexity in its support, social involvement, and benefit distribution. Despite these contributions, the social science literature remains narrow in scope, often reducing the social

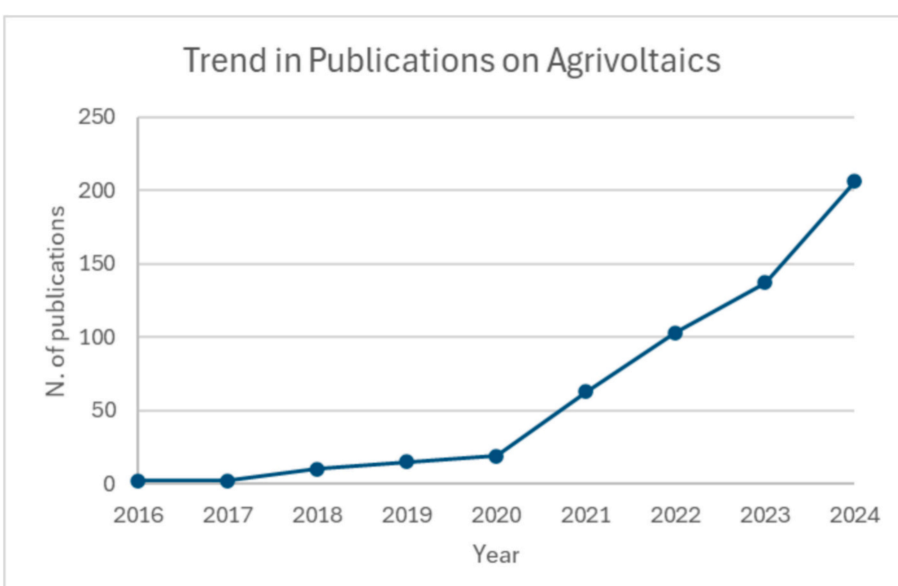

Fig. 2. Trend in research publications on the topic of agrivoltaics, own research in Scopus, using the keywords "agrivoltaic," "agrovoltaic," "agriPV," "agri-PV," "agri-photovoltaic," "agriphotovoltaic," and "agri photovoltaic" searched within article title, abstract, and keywords.

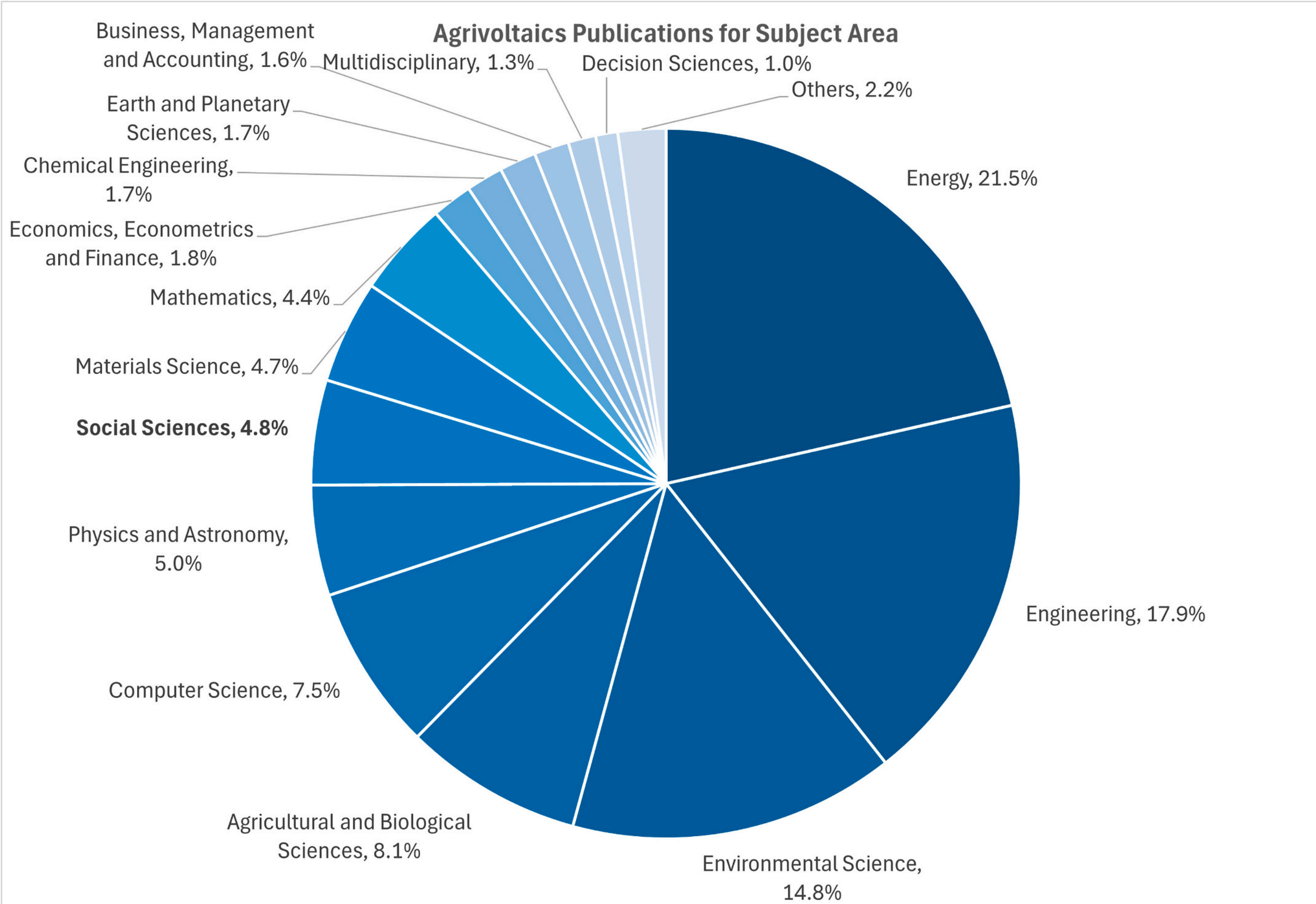

Fig. 3. Research publications on the topic of agrivoltaics, shown by subject area. Same sample of publications used to show rising publication trend (Fig. 2).

implications of agrivoltaics to questions of social acceptance and public engagement, without a deeper exploration of broader equity and inclusivity considerations under a just transition framework. Addressing these gaps is urgent: As agrivoltaics scales globally, overlooking its social dimensions risks reproducing existing inequalities, constraining public legitimacy, and limiting its transformative potential.

2.2. *Environmental and energy justice*

Environmental justice and energy justice frameworks offer complementary perspectives on addressing inequalities and exclusion in the socio-ecological transformation toward RE systems, like the implementation of agrivoltaics systems. Although justice frameworks have been widely applied to RE infrastructure and projects [25,44], their application to agrivoltaics remains largely unexplored. This study contributes to the literature by examining agrivoltaics through the lens of both environmental and energy justice frameworks, applying the four justice tenets—distributional, procedural, recognitional, and restorative (Fig. 4).

On the one hand, U.S. environmental justice scholarship, deeply rooted in the movement that emerged in the 1970s, advocates for vulnerable groups disproportionately affected by the unequal distribution of environmental externalities, such as air, water, and land pollution [45,46]. On the other hand, European scholars have expanded this perspective by moving beyond a sole focus on vulnerable groups to examine the broader interconnections between socioeconomic conditions, environmental harms and benefits, and public health [47]. In sustainability transition research, environmental justice is typically defined as the equitable distribution of and protection from environmental hazards, fair access to natural resources and their benefits, and concrete and inclusive participation in decision-making processes [25,46,48]. Environmental justice focuses on finding a balance between the social and ecological dimensions involved in the transition [45].

The energy justice framework serves as an analytical lens to assess injustices—unfairness and inequalities—produced by energy systems and the energy transition within society [49]. It embraces the concept of a just transition, addressing the shift to RE sources in energy production and consumption. This approach aims to balance GHG emissions mitigation goals with the preservation of individual well-being, community cohesion [45], inclusivity and representation in decision-making processes [46], as well as addressing inequalities in the affordability, accessibility, and environmental impacts of RE [50].

While energy justice can be seen as an extension of environmental justice [46], it differentiates itself by focusing specifically on energy systems and aiming to support decision-making [48]. Nevertheless, it has been criticized for prioritizing the identification of injustices rather than providing concrete justice-oriented solutions [46]. Both environmental and energy justice frameworks generally encompass three core tenets: distributional, procedural, and recognitional justice [46,51]. However, different scholarships expand upon these with additional tenets, including restoration or restorative [26,45,51], cosmopolitan or cosmopolitanism [26,49,51], and cognitive justice [51].

This study reviews and applies the three core tenets—distributional, procedural, and recognitional justice—while also incorporating restorative justice, a less explored yet highly relevant dimension in the context of agrivoltaics.

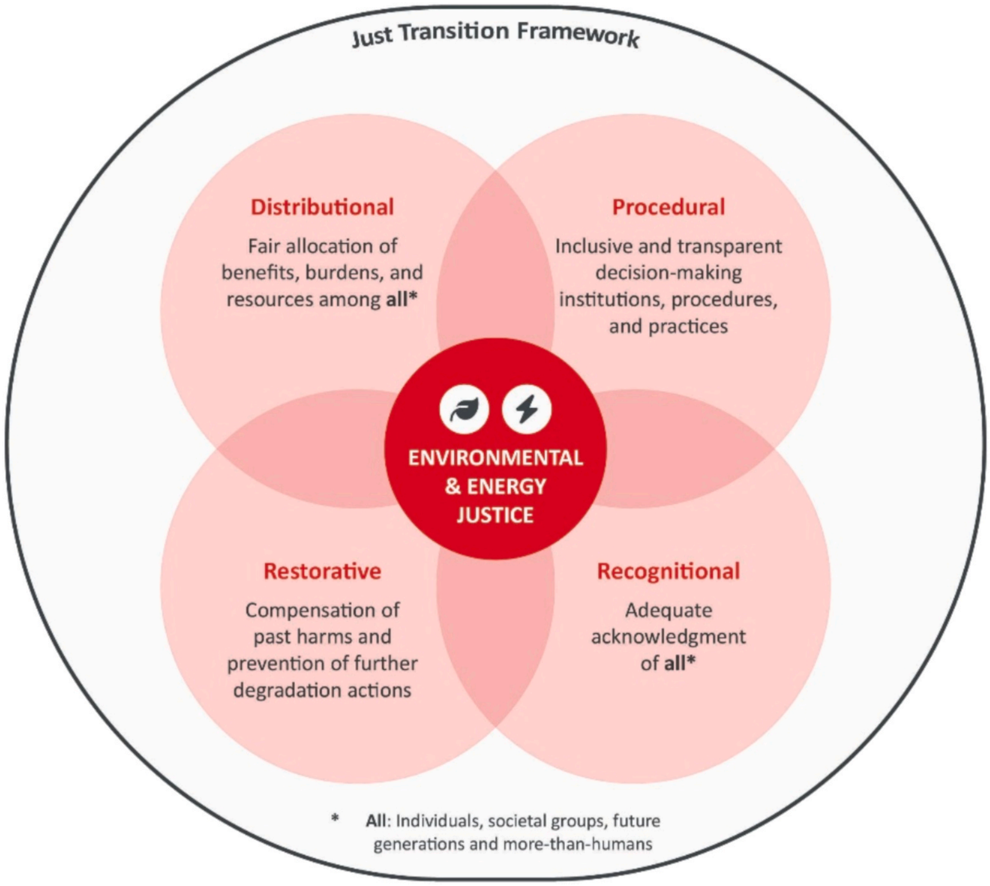

Fig. 4. Conceptual diagram illustrating the Just Transition framework, along with the energy justice and environmental justice frameworks, highlighting all the tenets used for the conceptual grounding and analysis in this study.

The distributional tenet addresses the fairness of the allocation of benefits, burdens, and resources within society, emphasizing the need for an equitable distribution of both environmental and energy-related costs, benefits, and impacts. Currently, environmental externalities and the burdens of energy production and consumption disproportionately impact different social groups, while a privileged minority receives most of the benefits [45]. Within the environmental justice framework, distributional justice has been closely linked to the spatial and social patterns of environmental harm. Studies have demonstrated that negative environmental externalities, such as pollution and land degradation, often affect communities based on proximity criteria, which in turn are strongly correlated with ethnicity and race [25,45]. In the framework of energy justice, distributional justice highlights the unequal distribution of burdens and benefits within fossil-fuel-based, centralized energy systems [46]. This perspective underscores the importance of ensuring access to affordable RE, directly related to issues of energy poverty and energy vulnerability [45]. Furthermore, it advocates for the fair allocation of both the advantages of RE access and the costs associated with its production [26,49].

The procedural justice tenet focuses on identifying who is involved in decision-making processes and how they engage with these processes [49] to ensure fairness, inclusivity, and transparency in decision-making institutions, procedures, and practices by enabling meaningful participation from all stakeholders. However, barriers to non-discrimination and inclusivity persist, limiting the ability of some groups to influence decision-making effectively. Within the environmental justice framework, procedural justice is often examined in relation to the siting of new infrastructure, such as dams and nuclear waste disposal sites, which frequently spark opposition movements [45]. Injustices arise when less-powerful groups are excluded from decision-making processes, preventing them from voicing concerns and shaping outcomes while bearing negative landscape changes and environmental impacts [25]. The energy justice framework shifts the focus from merely reducing or avoiding conflicts related to new infrastructure to actively designing engagement processes that integrate communities into decision-making. This approach seeks to enhance public acceptance of RE projects [45], ensure equitable outcomes in the energy transition [49], and strengthen the legitimacy of this process [26].

The recognitional tenet of justice emphasizes the need for adequate acknowledgment of all individuals and societal groups, ensuring that their identities, needs, and contributions are valued and respected [52]. Within the environmental justice framework, recognitional justice is a fundamental precondition for achieving a fairer distribution of environmental benefits and burdens, as well as for fostering more inclusive and democratic decision-making [46]. Discriminatory factors such as indigeneity, race, class, and gender have been identified as key determinants of environmental injustice, influencing who bears the costs of environmental harm and who has access to environmental goods [25]. In the framework of energy justice, recognition focuses on identifying and acknowledging the rights and needs of vulnerable [49] and marginalized communities [26], emphasizing that the energy transition should improve their conditions rather than exacerbate existing inequalities [49]. In both frameworks, scholars have also urged a broader application of recognitional justice by considering nonhuman subjects—such as ecosystems and biodiversity—when identifying neglected groups and their needs, acknowledging the vast impacts of energy systems on the environment [25,53,54], or challenging the constructed separation between human and non-human nature [55].

Building on this call to extend justice considerations beyond humans to past and present generations, the restorative tenet emerges as a

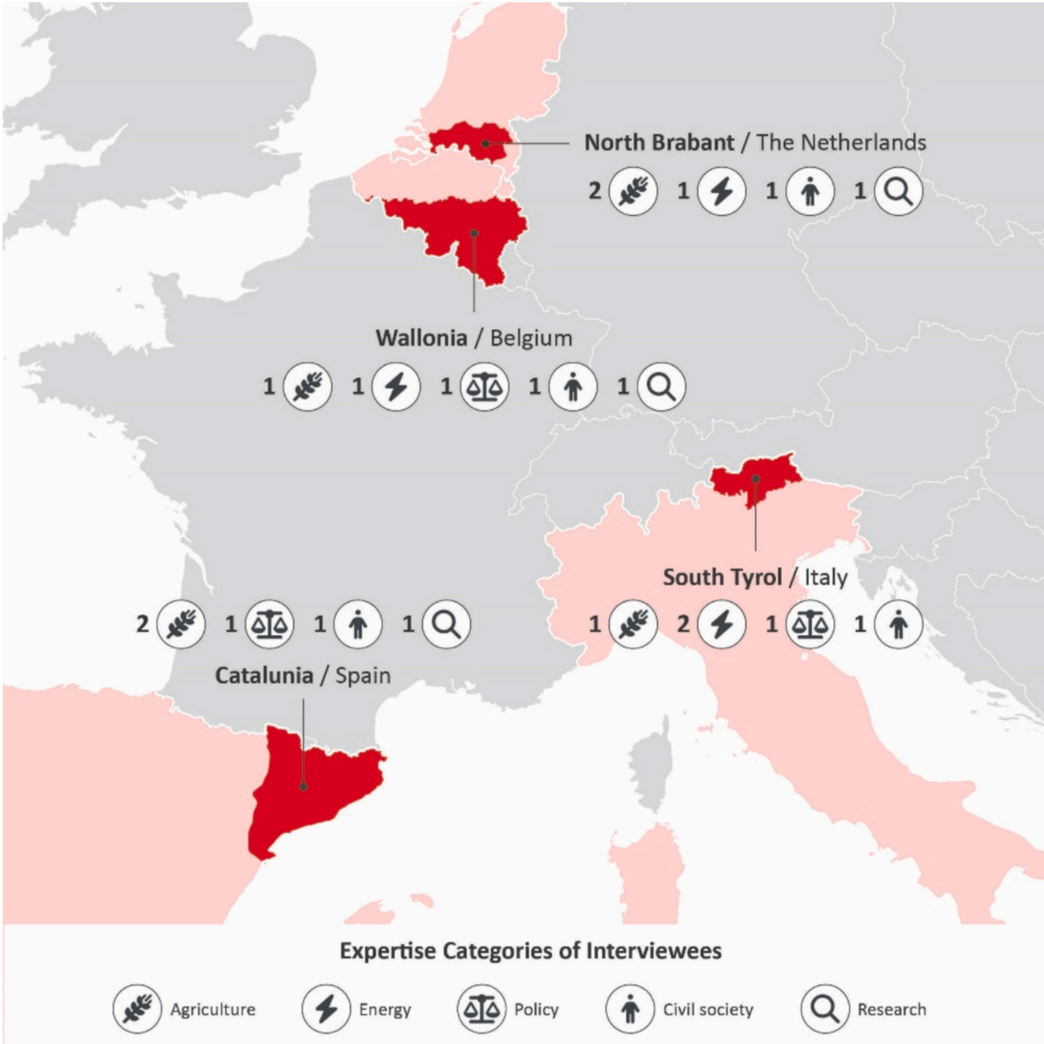

Fig. 5. Map of the case study regions in Europe. The number and sectors of expertise of the interviewees in each region are also provided.

crucial complement to the three traditional justice dimensions, as it not only addresses past harms inflicted on humans and nonhumans but also guides future preventive actions to mitigate further degradation and damages. The restorative dimension of a just transition originates from the demands of U.S. trade union movements, which called for the restoration of jobs lost due to the delocalization of fossil fuel-intensive industries [45]. Restorative justice is closely linked to procedural justice, as engagement and participation play a key role in rebuilding trust between affected communities and those responsible for harm. Rather than focusing solely on punishing offenders, its primary aim is to repair the damage inflicted on individuals, communities, and ecosystems [45,56,57]. While restorative justice addresses past environmental, social, and climate-related damages, it also serves a preventive function by identifying areas where future harm can be mitigated [45]. Additionally, it calls for the recognition of more-than-human entities, advocating for terminology that reflects a non-anthropocentric perspective and ensuring fair representation—or a designated representative—to speak on their behalf [54,56,57].

Within the environmental justice framework, restorative justice primarily focuses on repairing environmental damage caused by heavy industrial activities and hazardous waste contamination, particularly in local soil and water [45,56]. This perspective also emphasizes private and public entities' responsibility to remediate environmental degradation and restore affected ecosystems. In the energy justice framework, restorative justice focuses on the polluter-pays principle, holding energy providers accountable for the harm they cause [45]. In the context of the energy transition, this accountability extends to ensuring that those who have profited from RE production contribute to restoring ecological balance and compensating for both environmental and socioeconomic damages.

As this concise yet comprehensive literature review demonstrates, justice frameworks have been extensively applied to RE infrastructure and projects. However, their application to agrivoltaics remains largely overlooked. To date, only very few studies explicitly address this gap. An early study applies the three core tenets of energy justice to conduct a comparative analysis of the agrivoltaics sector, laws, and policies in the USA, Australia, and Japan [17]. A second one [58] examines the perspectives of farmers and solar developers on agrivoltaics in the USA, applying the three core tenets of energy justice. However, it finds that the practice is predominantly framed as solar leasing of farmland, rather than as a genuine integration of agricultural and energy production. However, both these works' analyses are situated in socioeconomic, regulatory, and geographical contexts that differ significantly from the European setting addressed in the current study. Moreover, both studies apply only the energy justice framework and focus on the three core tenets—distributional, procedural, and recognitional justice—without considering restorative justice, which this study includes as a fourth dimension. The recent integration of the restorative justice tenet within the environmental and energy justice frameworks requires advancing both its conceptual clarity and empirical application. Recently, the

Table 1
Overview of key environmental, economic, and energy indicators across the four case studies.

	Landscape	Land use	GDP per capita	Main sectors	Agriculture	RE (per year)	Decarbonization targets (2030, 2050)	PV production (2023)
South Tyrol (Italy)	Alpine and Dolomite mountains	Forested areas Alpine pastures Agriculture	€46,000	Tourism, Agriculture, Manufacturing, Services	Apple orchard, Vineyards, Dairy farming	6.6 TWh of RE production, 88 % from hydropower	CO_2 emissions reduction of 55 % by 2030 75 % of RE production by 2030	344 GWh [61]
Catalonia (Spain)	Pyrenees Mediterranean coastline Fertile central plains	Urban areas Industrial zones Agricultural land Protected natural areas	€32,500	Industry (automotive, chemical, pharmaceutical, food processing), Services, Tourism	Horticulture, Olives, Vineyards, Fruits	29.9 TWh of production of wind and solar power	Reduction of 30.3 % of primary energy by 2050	400.2 GWh [62,63]
Wallonia (Belgium)	Rolling hills Forests River valleys	Agriculture Urban areas Forests	€34,500	Industry (steel, coal, glass, mechanical engineering, biotechnology), Services, Agriculture	Dairy farming, livestock, cereals	19 TWh of RE manly from wind and PV	CO_2 emissions reduction of 55 % by 2030 28 % of RE production by 2030 and 5100 GWh of PV production per year	1603.4 GWh [64]
North Brabant (Netherlands)	Rural areas, consisting of farmland, woodland and rivers	Agriculture Built-up areas Forests	€55,000	Agriculture, Food processing, Electronics	Sweetcorn, Wheat, Sugar beet, Livestock	3.4 TWh production of solar and wind power in 2022	A 49 % reduction in GHG emissions by 2030 (vs. 1990) and 95 % by 2050.	3372 GWh [65]

restorative potential of agrivoltaics has been reviewed, highlighting that when combined with conservation agriculture practices, agrivoltaics can simultaneously support agricultural and energy production while enhancing environmental conditions [59]. Agrivoltaics provides a particularly suitable empirical context for applying the restorative justice tenet, as it inherently bridges societal and ecological dimensions. Building on this foundation, the present study is a pioneering effort that explicitly applies the restorative justice principle within the justice framework to the context of agrivoltaics.

The analysis focuses on four European case studies to provide region-specific insights, which together contribute to a more comprehensive understanding of the justice implications of agrivoltaics. Additionally, this research explores an often-overlooked justice implication of agrivoltaics: its impact on landscapes. Several studies have examined how agrivoltaics influences perceived landscape quality [18,19,33,40,42,60] and its subsequent effects on social acceptance and opposition [58]. However, the landscape implications of agrivoltaics have yet to be examined from an environmental and energy justice perspective. This study seeks to bridge that gap.

3. Material and methods

3.1. Case studies

A case-study approach was used to examine the justice implications of agrivoltaics in Europe. Four regions were selected based on two common criteria: longstanding agricultural sectors, and ongoing political debates on agrivoltaics as a technological solution to balance local decarbonization targets with agricultural production and landscape preservation. The inclusion of four distinct regions as case studies provided a comprehensive perspective on the diverse justice implications emerging across varying geographical and socioeconomic contexts, thereby enhancing the study's analytical depth and generalizability. Fig. 5 shows their location within the European context, while Table 1 provides an overview of key environmental, economic and energy characteristics of the four case study regions.

South Tyrol is an autonomous province located in northern Italy with a total area of 7400 km^2 [66]. Agriculture is a leading sector in the region, with farming associations playing a significant role in local agricultural policymaking. In South Tyrol—according to the provincial law on the "Use of energy from renewable sources"—PV panels may only be installed on buildings and roofs and along some road areas [67]. Agrivoltaics encounters political resistance stemming from concerns that it may disrupt the region's traditional agricultural landscape, a cornerstone of its tourism economy. Provincial legislation from 2024 prohibits agrivoltaics systems, allowing installations only for research purposes [68].

Catalonia is an autonomous community in northeastern Spain, covering approximately 32,108 km^2. Agriculture has long been a key sector in the region, and the agrifood sector plays a vital role in its economy, accounting for 20 % of Catalonia's GDP. In April 2024, the Catalan government issued a technical guideline to establish criteria for integrating solar energy generation with agricultural activities on the same land. This initiative aims to promote a balanced implementation of agrivoltaics while preserving agricultural practices and the landscape. It does so by requiring a minimum agricultural yield of at least 60 % relative to reference values and prohibiting significant land-use changes, such as converting orchards into pasture.

Wallonia is one of the three regions of Belgium, located in the southern part of the country. With a total area of 16,901 km^2, it has a widespread agricultural sector that plays a leading role in the regional economy, encompassing dairy farming, livestock, and cereals. In 2024, regional policymakers debated a possible approval of agrivoltaics pilot projects [69] through the release of a white paper resulting from a stakeholder dialogue including agricultural organizations and PV project promoters. The specific guidelines on the pilot projects are expected to be released during the 2024–2029 legislature by the newly formed government.

North Brabant, located in the southern part of the Netherlands, is a region characterized by a mix of rural landscapes and small urban centers. It has a total area of 5000 km^2 and a relatively low population density compared to other Dutch provinces. The area has a well-established primary sector, including both agriculture and livestock farming, which plays a crucial role in the local economy [70]. The political landscape in North Brabant is increasingly supportive of agrivoltaics, with the aim of meeting decarbonization targets while fostering innovation in land use [71]. Nonetheless, an ongoing debate persists about the extent to which agrivoltaics development can coexist with preserving agricultural productivity and the visual quality of the rural landscape.

3.2. Data collection

In each region, data were collected via semi-structured expert interviews based on an interview protocol grounded in the environmental and energy justice theoretical frameworks. Interviewees were selected for their expertise across five categories: agriculture, energy, policy, civil society, and research. These categories reflect key stakeholder groups that either influence or are affected by the development of agrivoltaics [28], and were identified based on literature on innovation adoption and stakeholder perceptions in energy transitions [72–74]. Specifically, they include: (i) representatives of farmer associations, project managers, and agronomists ("Agriculture"), who are central to decisions regarding agrivoltaics implementation on farmland; (ii) representatives of renewable energy industry developers ("Energy"), responsible for the integration of RE infrastructure on farmland; (iii) policymakers ("Policy"), who design regulations to guide the energy transition in general and the implementation of agrivoltaics in particular; (iv) representatives of NGOs or citizens' associations located near landscapes suitable for agrivoltaics ("Civil Society"), who do not directly implement agrivoltaics but are impacted by its deployment and can be involved in the overall governance of the system; and (v) researchers ("Research"), who contribute different disciplinary perspectives to the field. Although individual farmers were not interviewed, the inclusion of farmer association representatives allowed for the collection of collective perspectives from the farming community. Experts were chosen through purposive sampling to align with the qualitative design of the research, seeking to gather in-depth insights from knowledgeable interviewees [75]. The sampling strategy targeted individuals with demonstrated expertise in agrivoltaics at local or national levels, including their professional roles, research and work experience, and practical knowledge of agrivoltaics implementation. This approach was specifically chosen to ensure interviewees could provide detailed, contextually informed perspectives on the justice implications of agrivoltaics deployment, which required both technical understanding of the technology and awareness of its broader socioeconomic impacts. Initial expert contacts were provided by representatives of national agrivoltaics networks, approached by the principal investigators of this study. A snowball sampling strategy was subsequently employed, whereby interviewees recommended additional experts engaged in agrivoltaics. Interviews were conducted with those who responded to the invitation email and were available to participate, resulting in 20 interviews out of 53 contacts. The interview protocol was structured in five sections (Annex 2), providing flexibility to accommodate interviewees' expertise and the case-study specificities. Section (A) invited the interviewee to share their professional background and experiences with agrivoltaics. Section (B) asked for definitions of agrivoltaics. Section (C) presented three different configurations of agrivoltaics systems (Fig. 1), assessing their perceived landscape impact. Section (D) explored the distributional, procedural, recognitional, and restorative justice implications related to agrivoltaics projects, based on experts' perceptions. Section (E) collected any additional insights provided by the interviewee. While this study focuses specifically on the justice implications of agrivoltaics (primarily Sections A and D), following experts' opinions, the complete protocol is presented for methodological transparency. Responses provided in the framework of other sections of the interview (Sections B, C, and E—not explicitly addressing the topic of justice) often contained implicit justice-related content that informed the overall analysis, showing the interconnection between technical understanding and broader conceptualization and experience of justice in relation to agrivoltaics. When possible, the interviews were conducted in the interviewees' native languages and then translated into English for data analysis. In total, 20 semi-structured interviews were conducted between summer 2023 and spring 2024.

3.3. Data analysis

The interviews' transcripts were translated into English, then formatted and anonymized in compliance with EU GDPR.[1] The transcripts were systematized in four different codebooks—one for each country—and relevant information for the five sections of the protocol (A–E) was extracted, including both the original and the paraphrased text. Interviewee identification codes—consisting of the acronym of the country the region belongs to (IT, ES, NL, BE) and the first letter of the sector of expertise ("A" for Agriculture, "E" for Energy, "P" for Policy, "CS" for Civil Society, "R" for Research)[2]—were assigned manually to the interviewees, for a total of 20 univocal codes. Annex I provides an overview of the list of interviews and related codes, and the expertise sector and role of each expert interviewed.

Macro-codes were also created for each specific question within the five sections and then merged with the interviewee codes (e.g., A.1. IT_E_1_01, A.1.IT_E_1_02, A.2.IT_E_1_01, etc.). A set of keywords—and their description—was finally listed for each excerpt and matched with the codes in a comparative analysis matrix. Four researchers independently coded the transcripts in the four codebooks and periodically compared and refined the codebooks to agree on the final codes in the aggregated codebook (Annex 3).

4. Results

This section presents the insights provided by the interviewees related to the distributional, procedural, recognitional, and restorative justice implications of agrivoltaics. The inclusion of four different regions as case studies and of five different expertise fields enabled the collection of a multitude of perspectives on agrivoltaics informing its justice implications of agrivoltaics that arise from various geographical and socio-economic European contexts as well as sectors. The analysis of the interviewed experts' interviews perspectives on agrivoltaics revealed both common themes and some key differences, providing a comprehensive understanding of the possible justice implications of agrivoltaics. An overview of key insights of commonalities and differences in perceptions across case studies and expertise fields is displayed in Figs. 6 and 7, respectively.

4.1. Distributional justice

Among the distributional effects of agrivoltaics, experts predominantly highlighted potential economic and environmental benefits but also stressed economic, social, and environmental costs. Expected economic benefits entail additional revenue for farmers through sales of

[1] The General Data Protection Regulation (GDPR) is a European Union regulation that came into effect on May 25, 2018, designed to protect individuals' personal data and privacy. It sets out rules for how organizations must collect, store, process, and share the personal data of individuals within the EU. The GDPR emphasizes transparency, accountability, and the rights of individuals over their data, including the right to access, rectify, or delete their data. It applies to any organization that handles the data of EU residents. Noncompliance can lead to significant penalties. In the framework of this study, all participants signed an informed consent form that explained to participants the purpose of the research and asked for voluntary consent to participate.

[2] In cases where the same affiliation occurred more than once within a case study (e.g., Agriculture in the Netherlands and Spain; Energy in Italy), we included a differentiating number.

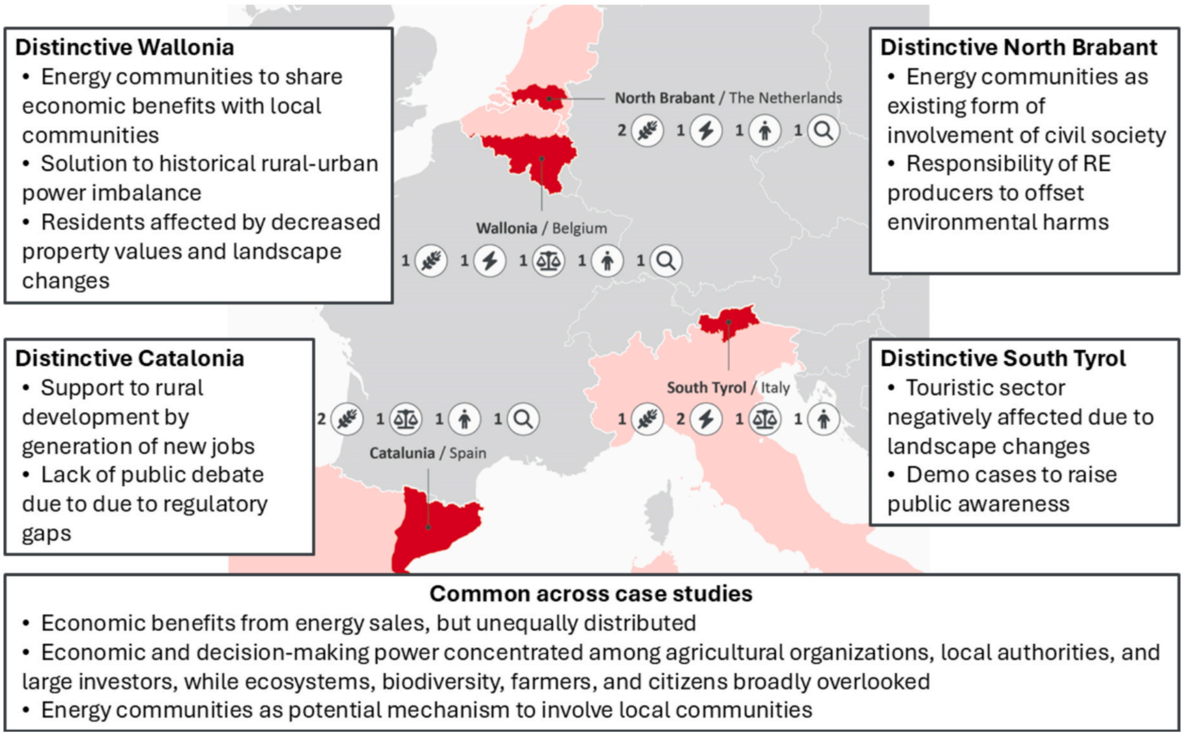

Fig. 6. Common and distinctive insights into the justice implications of agrivoltaics that emerged from expert interviews, from the perspectives of case studies.

electricity generated by agrivoltaics systems (IT_P, IT_A, ES_CS, ES_A_1, ES_R, NL_CS, NL_R, BE_A, BE_E, BE_R), and savings from electricity self-consumption (ES_CS, ES_R, BE_A) or from energy sharing in local energy communities[3] (ES_P, BE_CS, BE_R, BE_P). Residents, energy providers, and investors could gain financially by participating as shareholders in agrivoltaics projects (BE_P, BE_A).

The energy generated is primarily for self-consumption, shared with neighbors, or sold back to the grid, contributing to increased income or savings for the farmer. (ES_R).

At the same time, the installation of agrivoltaics systems and the related maintenance and support services are expected to support rural development by generating new job opportunities for local communities, at least as perceived by researchers, civil society organizations and some policy-makers (ES_CS, ES_R, ES_P, BE_R).

Experts highlighted several environmental benefits of agrivoltaics, including climate change mitigation (IT_A, BE_E, BE_P), land quality improvement, and biodiversity enhancement. These systems were considered to enhance soil water retention by providing additional shade (ES_P, BE_R), or by preventing or mitigating floods (BE_P). By reducing excessive solar exposure (IT_A, ES_CS, ES_A_2, ES_P, BE_A, BE_CS, BE_E), they were expected to optimize microclimate conditions (BE_CS), potentially boosting agricultural production (IT_A). Additionally, interviewees from the energy sector emphasize how agrivoltaics supports local ecosystems by providing shade (IT_E_1, BE_E) and benefiting wildlife, including birds and bats (BE_E).

Several experts raised concerns about the costs associated with implementing agrivoltaics systems. Feared economic costs include higher management and maintenance expenses compared to conventional PV installations as highlighted by civil society experts (NL_CS, BE_A, BE_CS), increased land prices due to speculation and land pressure as especially emphasized by agriculture experts (IT_A, BE_A), and uncertainties about agricultural productivity as stressed by policy-makers (IT_P). Assumed social costs involve subsidies funded through taxation (NL_CS), landscape changes (ES_CS), potential social conflicts among neighbors (NL_CS, NL_A_2, BE_R), and foreign ownership of agrivoltaics projects (NL_CS). The perceived environmental costs include biodiversity loss (ES_CS); negative impacts on fauna (ES_CS, BE_A); negative impacts on soil (NL_R), such as the risk of too much shade negatively impacting agricultural production (IT_P, IT_CS, BE_CS) or of the PV panels impairing water percolation (BE_P); and the environmental impact of extracting critical materials for PV panel production (NL_CS).

From a justice perspective, concerns emerged about the inequitable distribution of benefits and costs among investors, power plant owners, and local communities, stressing potential imbalances between stakeholders who may be unfairly advantaged or disadvantaged by agrivoltaics:

… this introduces a challenge of inequality, as the benefits from RE investments, such as agrivoltaics, might not be evenly distributed. The critical question is who invests in these renewables and who receives the returns on investment. (BE_P).

Another expert suggested how the benefits from agrivoltaics could be equitably distributed:

The goal should be to ensure that agrivoltaics doesn't just benefit a few individuals but supports the broader community, potentially through the development of energy cooperatives or community energy schemes. This approach could provide a more equitable distribution of the benefits derived from agrivoltaics. (BE_R).

Agrivoltaics are also perceived as an opportunity to tackle historical power and economic inequalities between urban and rural areas:

Historically, cities have held sway over rural areas, largely because the countryside has been a source of sustenance for urban populations. Now, we're increasingly looking to rural areas to also power our cities through RE sources like agrivoltaics. … It's evident that farmers, who

[3] The concept of an energy community was mentioned several times during the expert interviews. By "energy community," we refer in this study—as formalized under EU law in the two dedicated Directives—to initiatives based on voluntary and open participation whose shareholders or members are citizens, local authorities, or small enterprises, located in the proximity of the renewable energy projects owned and developed by that community, and with the purpose to provide environmental, economic, or social community benefits to its members or the local areas where it operates [76,77].

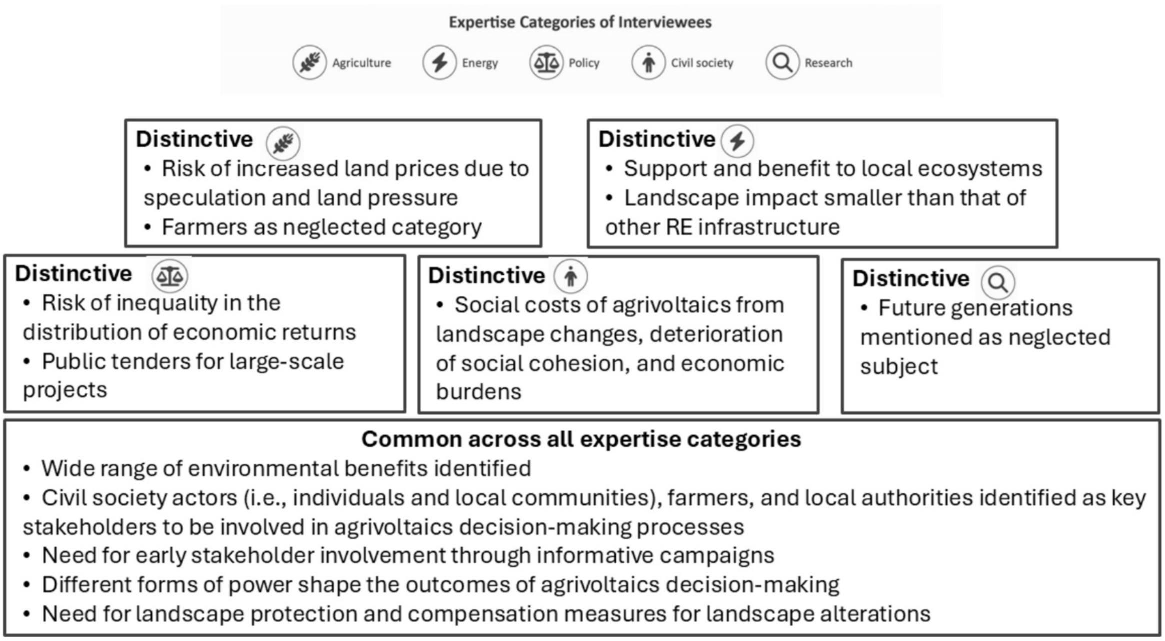

Fig. 7. Common and distinctive insights into the justice implications of agrivoltaics that emerged from expert interviews, from the perspectives of expertise categories.

have historically been undercompensated, could significantly benefit from the new revenue streams that agrivoltaics could offer. (BE_R).

The group most cited based on the interviewed experts' perceptions as having the most to gain includes farmers who decide to implement agrivoltaics to benefit from additional revenue (IT_CS, NL_E, BE_R) and related subsidies (BE_CS, BE_E). Landowners (IT_P, BE_R) and large farmers are assumed to benefit the most, since they can take advantage of economies of scale and lower costs (IT_E_2, BE_R), while small farmers may benefit from easier authorization procedures (IT_E_2). Investors or shareholders of agrivoltaics projects with investment capital (IT_A, ES_CS, BE_A, BE_P), such as energy producers, are described as benefiting from agrivoltaics' immediate economic returns without bearing the medium- to long-term costs that farmers face, such as maintenance and end-of-life costs (ES_CS, BE_A). Such costs include preserving the land for future generations:

While energy specialists might make decisions based on a business plan, a farmer has to consider the future of his whole family and future generations. (BE_A).

The local community of residents can gain from being involved in an energy community and energy-sharing practices (BE_CS, BE_E, BE_P). This would be even more significant for vulnerable citizens (BE_P), such as those in energy poverty conditions.

In contrast, some individuals are perceived as being disadvantaged. This includes farmers who do not implement agrivoltaics for various reasons and as a result do not receive economic subsidies for agrivoltaics and, more broadly, miss out on the additional economic benefits it provides (ES_A_1, BE_CS, BE_E). It also includes those farmers who rent the land they cultivate and cannot decide to implement agrivoltaics (IT_A, BE_R), as well as small farmers who may lack the initial capital (IT_E_2, ES_CS, BE_R). Additionally, big energy suppliers could be disadvantaged by local energy production from agrivoltaics via an expected reduction of their revenues (BE_P). Finally, residents could face disadvantages from the implementation of agrivoltaics systems if their property values decrease due to proximity to agrivoltaics fields (BE_CS), if they are affected by changes to the landscape (BE_P), or if they work in tourism and rely on traditional landscapes—their primary asset—which may be compromised (IT_P).

The impact of agrivoltaics on the landscape was mentioned by all interviewed experts, highlighting its complexity in relation to distributional aspects. On the one hand, agrivoltaics was perceived to have a smaller landscape impact than other RE production infrastructure, such as wind turbines (BE_E) and GMPV (IT_E_1). According to some experts, agrivoltaics is necessary to move away from fossil fuels, and its impact on the landscape is a cost to be paid to achieve the energy transition (IT_P, ES_A_1, ES_R, ES_A_2). On the other hand, such costs risk being unequally distributed, affecting residents, local communities, and key rural economic sectors such as tourism to a greater extent (IT_P, IT_CS). The value of the landscape was highly perceived by the experts in all case studies. They stated that the traditional agricultural landscape was connected to cultural identity and a sense of belonging (IT_E_2, BE_CS) and to human well-being (IT_P, ES_CS) and uniquely characterized the specific European regions (IT_E_2, BE_A). Yet, according to some experts, rural and urban residents hold divergent perspectives and experience different impacts resulting from changes to agricultural landscapes. In the Dutch case study, urban residents were described as having a romanticized, bucolic view of these landscapes, valuing them primarily for their recreational benefits and generally opposing transformative changes that alter their natural aesthetics (NL_CS, NL_R). In contrast, rural residents employed in agriculture were described as perceiving these landscapes as productive spaces and being more receptive to transformative changes that could provide additional income (IT_E_2, NL_CS, NL_R). Meanwhile, residents and local communities not engaged in agriculture were reported to bear the negative consequences of landscape changes without receiving any direct benefits and lacking meaningful influence over the decision-making process regarding these changes (BE_E, BE_P, NL_A_2).

4.2. *Procedural justice*

Experts identified several forms of civil society involvement in agrivoltaics decision-making, both existing and desired. One considered key mechanism is the establishment of energy communities (IT_E_1, ES_P, NL_A_2, BE_A), enabling local communities to actively participate in agrivoltaics projects. However, among the four case-study regions, only North Brabant has implemented an energy community that owns a system connected to an agrivoltaics project, while in the other regions, this remains a potential but unimplemented approach. Another suggested form of public engagement involves periodic local markets or community gardens, where residents can participate in the agricultural production of agrivoltaics systems (IT_E_1, BE_CS), fostering a sense of community and facilitating knowledge exchange. Additionally, experts highlighted the importance of a sustained and comprehensive informational process to communicate the benefits of agrivoltaics, which could help secure public support for such projects (BE_CS, BE_E, BE_P). Furthermore, citizens can be involved as shareholders in agrivoltaics initiatives (BE_P). In Catalonia, discussions on agrivoltaics have not yet engaged civil society (ES_P), primarily due to a lack of information, clear definitions of agrivoltaics, and specific regulations (ES_R).

In general, the discussion on agrivoltaics seems to be at a very early stage and happening in closed fora in all case-study regions. Experts were asked to list the stakeholders who need to be involved in the discussion. Civil society was the most cited, including individual citizens (IT_A, ES_CS, BE_R, BE_P), local communities (IT_E_1, IT_E_2, NL_E, BE_CS, BE_E, BE_R), residents involved in energy communities (IT_E_1, IT_A, ES_CS, BE_A), civil society organizations (IT_E_2) such as organizations working with people affected by energy poverty (BE_P), and environmental organizations (IT_P, IT_A, NL_A_1, NL_CS, NL_R).

… in my opinion, when planning to install an agrivoltaics system, it is important to involve local people, those from the municipality itself and nearby areas—to discuss and potentially identify the most suitable location. (IT_A).

Stakeholders in the agricultural sector were also cited, including farmers (IT_A, NL_CS, NL_A_2, BE_E, BE_R), local small-scale farmers (BE_CS), and breeders (BE_A), organized in agricultural associations and cooperatives (IT_P, IT_A, ES_CS, ES_P, BE_E, BE_P). Local policymakers and local authorities were frequently mentioned (IT_A, IT_E_2, ES_CS, ES_A_2, NL_CS, BE_A, BE_E, BE_R, BE_P) as mediators and warrantors of public goods and needs (BE_A). In particular, environmental authorities were considered essential in the Belgian case study to find suitable locations for agrivoltaics systems and avoid negative environmental impacts (BE_CS, BE_E). Local authorities responsible for landscape urbanism (ES_A_2, NL_R, BE_E), the agricultural department (ES_A_2), the department of tourism (IT_P) and even archaeology (BE_E), regional authorities (BE_R), and national and European institutions (IT_E_1, BE_P) were also deemed important. For the energy sector (BE_E), energy providers (BE_P) and distribution system operators (BE_R, BE_P) were mentioned. Other stakeholder categories include private sector organizations (IT_P, IT_A, ES_A_2, BE_P), tourism organizations (IT_P), and investment cooperatives (BE_P).

Regarding the timing of stakeholder involvement in agrivoltaics decision-making, experts emphasized that it should begin from the very outset (NL_R, BE_A, BE_E). As for the modalities of involvement, they highlighted a wide range of formats corresponding to different levels of participation [78]. These include, for example, informative campaigns aimed at disseminating knowledge about the implications of agrivoltaics for various stakeholder groups—such as farmers and citizens (IT_A, IT_E_2, IT_CS, BE_E)—as well as addressing potential concerns (BE_A).

Engage local communities in awareness activities of this kind—genuine knowledge-sharing initiatives that help them understand the benefits. Often, residents are not fully aware of what an agrivoltaics system actually is. They may speak based on hearsay or what they read in newspapers, which unfortunately can often be inaccurate. This makes it easy for citizens or businesses outside the sector to have a distorted understanding of these systems. (IT_E_2).

In this regard, building demo cases could help to raise awareness about agrivoltaics (IT_E_2, IT_CS), and apps and digital tools were suggested as a rapid form of information sharing (NL_E). Co-design participatory activities were mentioned, where stakeholders actively contribute to the decision-making process (NL_CS, NL_R, BE_R), such as focus groups with local communities to identify suitable areas for agrivoltaics (IT_P, IT_A, NL_CS, BE_R). Another possible activity to gather opinions from different stakeholders could be to conduct interviews (IT_A). Finally, public tenders could be employed for large-scale agrivoltaics projects, with public offers by potential investors (BE_P).

Participatory approaches, including stakeholder involvement in the co-design of agrivoltaics systems, were suggested to be employed to mitigate the potential negative landscape impacts identified by experts. Such engagement can help address resistance and opposition from residents and local communities. The active involvement of local populations is recommended as a mitigation measure, also through initiatives such as participation in power plant ownership or energy communities (ES_CS, NL_CS, NL_A_2, BE_A, BE_E). Additional measures include compensation mechanisms, such as economic contributions to municipalities for community projects (IT_CS).

4.3. Recognitional justice

Regarding the recognitional effects of agrivoltaics, experts identified individuals or groups whose needs are either acknowledged or overlooked in its implementation, along with the underlying reasons for these disparities. Interviews with experts highlighted the role of power dynamics, revealing that those with the ability to influence agrivoltaics decision-making are more likely to have their needs and perspectives considered in the process. Those are agricultural organizations that defend the agricultural stakes (IT_A, ES_P, BE_E), large investors (ES_R, ES_P, NL_A_2), some categories of farmers (NL_CS) such as landowners (BE_A) and elderly farmers (NL_E, NL_A_2), and local authorities (IT_A, BE_E). Finally, in some innovative projects based on participation and co-design, residents are also involved and heard (NL_R). The drivers of such recognition include the power to influence the authorization of agrivoltaics projects (NL_CS, BE_E), economic power (ES_P, NL_A_2, NL_R), land ownership (BE_A, NL_CS), time to participate in local decision-making (NL_E), and the need to leave no one behind and find a balance among all interests (BE_E).

In the realm of agrivoltaics, the most influential group by far is the farmers' organization. They essentially hold the key to whether agrivoltaics projects can proceed. It's virtually impossible for local governments or other authorities to make decisions about agricultural lands without the consent of these organizations. (BE_E).

Among those whose needs and interests are currently being neglected in the decision-making processes concerning agrivoltaics, farmers in general were cited (ES_A_1, ES_A_2) as being neglected or even oppressed by national governments that prioritize RE production over agriculture (NL_A_1, BE_A), along with some more specific categories, such as sheep breeders (BE_A) and young farmers and entrepreneurs (NL_A_2). Moreover, citizens are often excluded from discussions concerning agrivoltaics (IT_A, NL_CS), even if their houses' value may depreciate (BE_CS), and broader societal concerns are neglected (NL_R). Finally, the experts identified two critical yet neglected stakeholders: future generations and ecosystems. Future generations are considered to have the right to a protected environment (BE_R). Ecosystems and biodiversity (IT_CS, ES_CS, ES_A_2, ES_P, NL_CS, NL_R, BE_CS, BE_R) are described as deserving of conservation, particularly against the potential ecological degradation caused by intensive farming and monoculture. In the interviews, ecologists emerged as advocates for this stakeholder (ES_P, NL_CS, BE_CS). Although environmental rights are recognized in policy, their practical implementation is inadequate (IT_P, NL_R). If managed sustainably, agrivoltaics were perceived to support and foster ecosystem biodiversity and soil quality (NL_A_2, NL_R, BE_R), especially when paired with sustainable agricultural models such as agroecology (BE_R).

From a landscape perspective, experts identified several critical areas that required protection and should remain untouched. These included environmentally and culturally significant landscapes, such as natural protected areas (ES_R, NL_CS, BE_CS, BE_R); cultural heritage sites (NL_R); historical centers (BE_CS); high-mountain valleys; regionally distinctive agricultural landscapes with high agronomic value (IT_E_1, BE_A), such as vineyards in South Tyrol, olive crops in Catalonia, trees, hedges, and community buildings in Wallonia; and peri-urban areas used for recreational purposes by citizens.

4.4. Restorative justice

From a restorative justice perspective, the transition to RE production should be pursued in harmony with the environment, ensuring that those who economically benefit from solar energy production compensate for any negative environmental impacts (NL_A_1). In the context of agrivoltaics, compensation measures for landscape alterations can take various forms. One mentioned approach is to foster local engagement through membership in an energy community or co-ownership of the agrivoltaics system (NL_CS, NL_A_2, BE_A, BE_E), allowing communities negatively affected by the energy transition to gain a sense of empowerment, ownership, and agency through agrivoltaics. Another strategy to mitigate visual impacts involves planting vegetation, such as trees or hedgerows that shield PV panels from street view (IT_A, BE_A, BE_P). This measure not only is thought to reduce the perceived landscape degradation but can also enhance local biodiversity, supporting both flora and fauna (IT_A). Additionally, financial compensation can serve as a restorative measure, with direct monetary contributions provided to affected local communities and municipalities (IT_P, IT_E_2, IT_CS, NL_R). Such compensation acknowledges the social and environmental costs borne by these communities and aims to restore fairness in the distribution of benefits and burdens associated with agrivoltaics projects.

5. Discussion

5.1. Distributional justice

From a distributional justice perspective, across all case studies and expertise fields, it emerged that the benefits of agrivoltaics, especially the economic ones, must be carefully managed to ensure equitable access to them and prevent the emergence of new inequalities. While agrivoltaics has the potential to enhance economic, social, and environmental outcomes, it also risks exacerbating disparities, as benefits and costs are often distributed unevenly among stakeholders. In agrivoltaics, large farmers, landowners, and investors tend to gain disproportionate economic advantages generated by the sale of the RE produced by the system, whereas small farmers, tenants, residents, and local communities may be excluded [26]. These imbalances must be addressed in the planning, design and implementation of new agrivoltaics systems in order to avoid creating new power imbalances, above all within the agricultural sector.

Beyond direct financial gains, agrivoltaics can offer additional economic benefits to farmers through improved agricultural productivity, driven by enhanced soil and microclimatic conditions under PV panels. However, agricultural experts raised concerns about the increasing value of agricultural land, which may lead to price speculation in the land market, as well as the potential decline in residential property values due to landscape changes. In addition, all interviewed experts—apart from those in the energy field—underscored the potential for negative environmental effects if agrivoltaic projects are poorly planned or managed. Policy experts suggested that residents and the tourism sector are more likely to be harmed by the landscape transformations introduced by agrivoltaics, whereas farmers generally welcome these changes, as they are associated with increased revenue.

To maximize both economic and environmental benefits at the local level, there seems to be a common agreement among interviewed experts that agrivoltaics projects should prioritize affordable and clean energy provision for local communities, prioritizing vulnerable households suffering from energy poverty, and ensure a more equitable distribution of returns among project stakeholders. Farmers could play a pivotal role in initiating community-driven agrivoltaics projects, fostering both environmental benefits, i.e., decarbonization of local energy systems, and social benefits, including strengthening community cohesion in rural areas. In fact, Belgian interviewees emphasized the role of agrivoltaics in addressing rural inequalities, but also raised concerns about the viability of such projects in the medium to long term due to high maintenance costs. Finally, regulatory gaps might hamper community initiatives and public engagement, as in the Catalonian case.

5.2. Procedural justice

When planning new agrivoltaics initiatives, developers should actively identify and engage local stakeholders whose interests may be affected; in fact, proximity is confirmed as being a key component of justice when new RE infrastructure is to be realized [45]. Inclusion can be facilitated through mechanisms such as the establishment of local energy communities to reduce energy costs or co-investment schemes to enhance financial participation from the local community. Energy communities were widely recognized by the interviewed experts as a model to both involve local communities and share the benefits generated by agrivoltaics, especially with vulnerable residents.

Emerging at a critical moment in the European context, agrivoltaics can empower rural communities by fostering a bottom-up approach to RE development. By taking ownership of RE production, rural areas and communities can enhance their agricultural and energy resilience, advancing the energy transition while safeguarding farmers' rights. However, to be truly effective, agrivoltaics must balance ambitious RE targets with agricultural productivity, ensuring a mutually beneficial synergy rather than one sector prevailing over the other. In fact, Belgian interviewed experts identified agrivoltaics as an opportunity to address structural and historical rural–urban power imbalances by empowering rural areas and economically compensating the agricultural sector for its contribution to the decarbonization of the energy system. However, decision-making processes in agrivoltaics are already shaped by existing power structures, favoring those with economic power or the ability to affect decisions. This raises concerns about reinforcing inequalities within the agricultural sector, particularly between landowners and tenants or large and small and young farmers. Additionally, there is a risk of perpetuating broader systemic disparities, where energy production is prioritized over agricultural sustainability, and urban interests continue to overshadow rural needs. Ensuring an inclusive and fair governance framework for agrivoltaics at all levels is therefore essential to prevent the concentration of benefits among a limited group of already privileged stakeholders while marginalizing others.

Ensuring procedural justice is essential for fostering inclusive decision-making in agrivoltaics projects and mitigating social opposition and conflicts that could destabilize rural communities and exacerbate urban–rural disparities. Across all four regions, participatory approaches, pilot projects, digital tools, informational events, and co-design activities were identified as key strategies for promoting informed and inclusive decision-making. Informational campaigns were endorsed by experts from every field, whereas participatory co-design was highlighted by all experts through the interviews except those in the energy sector. Agrivoltaics system designs should prioritize agricultural yield considerations, with a strong emphasis on developing simulation tools that incorporate educational components to support farmers in understanding field-level impacts. Pilot sites, which provide real-world data and permit the development of evidence-based scenarios, play a crucial role in building trust and credibility for project scaling and replication. This could overcome the current mistrust that agricultural associations have in agrivoltaics in some geographical contexts, such as Belgium. Recognizing procedural justice in agrivoltaics could also generate co-benefits for both system owners and host communities, including new employment opportunities, enhanced local energy resilience, and increased engagement in the decarbonization process.

5.3. Recognitional justice

Adhering to the principle of recognitional justice requires ensuring that all voices are heard, particularly those of overlooked and marginalized stakeholders, who may be affected by agrivoltaics projects. Future generations, residents, small and young farmers, as well as biodiversity and natural ecosystems were identified by the experts as frequently overlooked groups. It is worth noting that farmers were identified as a neglected group only by agricultural experts, suggesting that their vulnerability is not fully recognized outside the agricultural community. Conversely, the idea that future generations risk exclusion was advanced solely by research experts, while energy experts were the only ones not to mention ecosystems and biodiversity as current neglected subjects. These insights underscore how disciplinary perspectives shape perceptions of who needs to be represented in the agrivoltaics' decision-making process. Acknowledging the needs and concerns of these groups is essential for fostering justice in agrivoltaics and preventing the perpetuation of the power imbalances and injustices that characterized fossil fuel-based energy systems, as well as some RE transition processes in the last decades. To promote recognition, participation and representation mechanisms should be designed to accommodate the specific needs of these stakeholders. For instance, on the one hand, young farmers with children may face barriers to engagement, necessitating tailored approaches that facilitate their inclusion in decision-making and mitigate their sense of exclusion. On the other hand, future generations and nonhuman entities—who lack direct representation—require stewardship by present actors who can advocate for their interests in decision-making processes [56].

5.4. *Restorative justice*

From a restorative justice perspective, those who profit from RE production by realizing agrivoltaics systems should be held accountable for any social and environmental harm they may cause, i.e., any material or immaterial damage to present and future local communities and ecosystems. This includes contributing to the restoration of ecological balance and compensating for negative environmental externalities, such as landscape alterations, which have been identified as a key concern in all case studies in agrivoltaics implementation. Agrivoltaics is an emerging practice in Europe, with few existing projects but great uptake potential. For existing projects, it is pivotal to identify and mitigate any already occurring harm [79]. A thorough assessment of the environmental and social impacts of any existing agrivoltaics project should be realized by local competent authorities as the first step, to be followed by an inclusive and participatory process to define how damages are to be repaired by the perpetrator [45,56,79]. Moreover, for future initiatives, to prevent any possible harm and build social trust in agrivoltaics [79], regulatory authorities could integrate mandatory biodiversity restoration areas or other compensatory measures into agrivoltaics system design already in the planning phase, helping address the potential impacts on both human and nonhuman entities. Additionally, some burdens associated with agrivoltaics may only become apparent in the future, such as the challenges of dismantling infrastructure at the end of its lifecycle, underlining the importance of looking at the whole energy life-cycle [26]. Experts emphasized the importance of intertemporal and intergenerational responsibility in ensuring that future generations are not unfairly burdened by the long-term impacts of agrivoltaics projects.

6. Conclusions

This study investigated the justice implications of agrivoltaics by applying environmental and energy justice principles and gathering insights from experts across four EU regions through 20 in-depth interviews. Agrivoltaics is perceived to offer both economic and environmental benefits and costs, which, however, are not equitably distributed. Key benefits include additional revenue from energy sales, savings from electricity self-consumption, support for local development and communities—particularly through energy-sharing initiatives—and improvements in environmental conditions and land value. The burdens include present and future costs of management and maintenance of the system, risk of land price speculation, environmental degradation, and reduced agricultural productivity. The distribution of these impacts is perceived to be uneven, with large farmers and landowners benefiting the most, while small farmers, tenants, and local residents—particularly those affected by landscape changes—face significant disadvantages. Based on the analysis of the results, viable paths for addressing justice-related expectations were identified. Just decision-making processes should be inclusive from the outset, incorporating both informative campaigns and participatory co-design to ensure broad stakeholder engagement. Energy communities are perceived to offer a valuable mechanism for redistributing benefits and empowering local communities. Residents, local authorities, and farmers are key stakeholders to be actively involved in decision-making to acknowledge concerns and build trust around agrivoltaics. However, current processes are perceived to be largely influenced by agricultural organizations, local authorities, and large investors, while the needs and rights of ecosystems, farmers, citizens, and future generations are often overlooked. Agrivoltaics must be conceived and implemented with careful attention to a dual responsibility—both toward neglected subjects (human and more-than-human) and across temporal scales—by preventing future social and environmental harm, and ensuring that when such impacts do occur, restorative measures are taken to repair damage to affected communities and ecosystems. To foster a just energy transition, agrivoltaics also must neither create new power imbalances nor reinforce existing inequalities—whether between urban and rural areas, between the energy and agricultural sectors, or within the agricultural sector itself.

To pursue distributional justice in agrivoltaics and avoid perpetuating power imbalances or creating new ones, regulatory measures should address land ownership and rental prices. Public subsidies and incentive mechanisms designed with consideration of inclusion are perceived as essential to prevent unfair competition, particularly between tenant and small-scale farmers versus landowners and large agricultural enterprises, as well as between multinational and local energy companies. Aligning local regulatory frameworks with national and European legislation is also expected to be critical to counter foreign investments that may disadvantage local farmers and entrepreneurs. Additionally, fostering energy communities in synergy with agrivoltaics systems is perceived to promote a more equitable distribution of benefits by enabling local energy sharing and allowing residents to participate as both consumers and producers.

To ensure procedural and recognitional justice, all relevant stakeholders must be involved in the decision-making process at multiple levels. This includes both the development of local regulations—ensuring a tailored application of European and national policies within regional economic systems—and the design of agrivoltaics projects. Particular attention should be given to the inclusion of traditionally excluded groups through participatory activities in local communities, also through mandatory representation of subjects who literally lack a voice. Raising awareness through informative events and campaigns is perceived as a key action to empower stakeholders across sectors, equipping them with the knowledge necessary to engage in meaningful discussions and express their concerns. Strengthening scientific and local knowledge emerges as crucial for building trust in agrivoltaics. Expanding demonstration sites is expected to provide empirical data, real-world case studies, and evidence-based scenarios to support project scaling and replication. Ensuring stringent regulations on crop production and quality is expected to further enhance support from the agricultural sector.

Environmental and landscape planning authorities should oversee the identification of suitable sites for agrivoltaics projects to prevent adverse effects on local communities and ecosystems. Additionally, clear guidelines should be established for restoration measures to address any environmental or social harm caused by project implementation that cannot be prevented.

Integrating these justice considerations into agrivoltaics planning and governance requires the development of decision-making tools to help policymakers and practitioners operationalize justice principles in project design and implementation. Given that the case study regions examined in this research have the autonomy to approve or halt agrivoltaics projects through their regulatory frameworks, they play a crucial role in shaping a just energy transition and setting a precedent for systematic change.

This study used a qualitative approach to analyze justice-related implications of agrivoltaics based on experts' opinions. The use of 20 semi-structured interviews across European regions supported the investigation of a complex, context-dependent topic such as justice. Engaging with experts from diverse regional contexts enriched the analysis by capturing a broad range of perspectives shaped by different policy environments, sociocultural conditions, and experiences of agrivoltaics deployment. By focusing on expert insights, our study identified potential justice concerns and opportunities that can inform the design and future deployment of agrivoltaics in ways that are perceived as fair, inclusive, and balanced.

Although this study aimed to capture diverse agricultural, climatic, and socioeconomic contexts by selecting case studies with varying crop types, land morphologies, and agrivoltaics system designs (e.g., open vs. closed, vertical vs. horizontal), it does not fully encompass the wide range of conditions across Europe. Additionally, the research design included five interviews per case study, each representing a different area of expertise—energy, policy, agriculture, civil society, and research. However, conducting multiple interviews per expertise area within each case study would have strengthened the findings by ensuring greater adherence to the principle of data saturation. Future research should further explore the potential and implications of restorative justice in agrivoltaics, particularly its potential to address negative environmental and social externalities both in the present and in the future, ensuring a more just RE transition in rural areas.

In conclusion, agrivoltaics presents a promising technological solution for addressing decarbonization challenges while optimizing land use and generating co-benefits for agricultural production. However, the development of agrivoltaics requires well-designed policy frameworks and regulations that ensure an equitable distribution of benefits, establish mechanisms for democratic and inclusive decision-making, integrate diverse stakeholder needs and interests, and provide compensation for any environmental or social harm resulting from its implementation.

CRediT authorship contribution statement

Silvia Tomasi: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Chiara Pellegrini:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Francesca Gaspari:** Writing – review & editing, Writing – original draft, Formal analysis. **Simone Vitale:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Marcel Macarulla Martí:** Writing – original draft, Investigation. **Anna Gras:** Writing – review & editing, Writing – original draft, Investigation. **Sonja Gantioler:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Annex 1. List of the transcription codes and other information.

Interview code	Interviewee sector	Interviewee role
IT_E_1	Energy	Agrivoltaics company manager
IT_P	Policy	Local policymaker of the landscape and nature department
IT_A	Agriculture	Local farmer association representative
IT_E_2	Energy	Agrivoltaics consultant
IT_CS	Civil society	Environmental protection association representative
ES_CS	Civil society	Manager of natural agricultural park
ES_A_1	Agriculture	CEO and founder of an agricultural company
ES_R	Research	Professor in engineering
ES_A_2	Agriculture	Director of an agricultural cooperative
ES_P	Policy	Local policymaker of the agricultural department
NL_E	Energy	Senior researcher and consultant in PV and agrivoltaics system engineering
NL_A_1	Agriculture	Greenhouse growing expert
NL_CS	Civil society	CEO and founder of a design association specialized in co-creation for RE projects
NL_A_2	Agriculture	Project manager of farmers and horticulturist association
NL_R	Research	PhD student working on Agri-PV and landscape
BE_A	Agriculture	Local farmer association representative
BE_CS	Civil society	Agronomist with experience in international cooperation and EU funded projects
BE_E	Energy	Partner and co-founder of a PV start-up
BE_R	Research	Academic researcher in the field of social sciences
BE_P	Policy	Local policymaker

Appendix 2. Annex 2. Interview Protocol.

Section A - Ice-breaking question.

Can you briefly introduce yourself and present your work/activities within [area of expertise and its connection to the topic of agrivoltaics] (where do you work, in what role, what issues do you deal with, what path of study and professionalism led you to deal with these issues)?

Section B - Definition of agrivoltaics.

B.1 – Free definitions of agrivoltaics

1. Can you describe your prior experience or familiarity with agrivoltaics before this interview?
2. What do you mean by agrivoltaics?

B.2 – Perceived difference between PV on agricultural land and agrivoltaics, advantages and disadvantages of both.

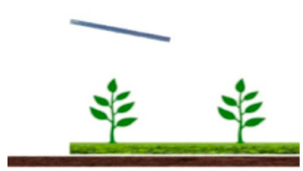
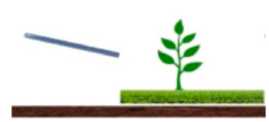
3. What is the difference between photovoltaic on agricultural land and agrivoltaics? What are the advantages and disadvantages of both?

B.3 – Perceived importance of agrivoltaics.

4. In your opinion, what is the importance of agrivoltaics?

B.4 – Most suitable configuration.

There are different configurations of agrivoltaics systems:

Type 1	Type 2	Type 3
The positioning (i.e., height above the ground) of the modules allows for the continuity of agricultural activities both under and between the PV modules, promoting dual land use, and maximum and synergistic integration between the PV system and the crop. For example, the modules can protect crops from excessive shading and weather events such as heavy rain and hail.	The positioning of the modules from the ground does not allow agricultural activities to take place below the PV modules although it allows for combined land use, with a lower degree of integration between the PV system and the crop than the previous one.	The placement of PV modules is vertical, not significantly affecting crop possibilities, but the height of the modules may affect the degree of connection and use of the area, namely the possible passage of animals, with implications on the use of the area for livestock-related activities.
		
Agrivoltaic Type 1, maximum synergy between agricultural activity and agrivoltaic plant (Source: ENEA)	*Agrivoltaic Type 2, alternation between agricultural activity and agrivoltaic plant (Source: ENEA)*	*Agrivoltaic Type 3, vertical placement with co-location of agricultural activities and agrivoltaics plant (Source: ENEA)*

5. Which spatial configuration do you most agree with in talking about agrivoltaics?

B.4 – Implications or limitations of each configuration.

6. What are the implications in terms of deployment or limitations of agrivoltaics systems related to one or the other configuration?
   6.1 Are there differences in terms of social and environmental impacts?
   6.2 If so, due to what?
   6.3 Are there differences in terms of production, both on the agricultural production and energy production side?
   6.4 If so, due to what?
7. What are the current policies at the local, national, and international levels that support the practice of agrivoltaics? Are there also policies that are limiting instead?

[Additional questions intended to be asked].

Section C – Agrivoltaics and landscape

One of the most discussed issues related to the presence of PV modules on agricultural land is the possible impact on the landscape.

C.1 – Perceived value of the landscape.

8. What value do you think the landscape has?

C.2 – Untouchable/inviolable/unchangeable aspects of the landscape.

9. What aspects of the landscape are in your opinion untouchable/inviolable/unchangeable and why?

C.3 – Perceived impacts of agrivoltaics on the landscape.

10. In your view and experience, what kind of impact, if any, does the introduction of PV modules on agricultural land have on the landscape?

C.4 – More suitable landscapes/areas for agrivoltaics.

11. In the landscape you know, which areas would be most suitable for the creation of agrivoltaics systems and why? Specifically, in what type of agrarian landscape do you think photovoltaic modules would be most integrable? For example, in arable landscapes (cereal fields, wheat, corn, canola, sunflowers, forages); vineyards, olive groves, orchards, greenhouses

C.5 – Perceived impacts of landscape change on people.

12. What are the effects of a landscape change on those who experience that landscape (permanently or for short periods)?

C.6. Possible compensation for landscape change.

13. Would there be, and if so what kind of compensation that people (e.g., neighbouring area residents) would be willing to accept for a changing landscape as a result of the deployment of agrivoltaics systems (e.g., utility bill discount, new rows of trees in other agricultural areas)?

[Show here the four pictures of the different agrivoltaic configurations (three types agrivoltaic and ground photovoltaic)].

Fig. 1. Agrivoltaic Type 1.

Fig. 2. Agrivoltaic Type 2.

Fig. 3. Agrivoltaic Type 3.

Fig. 4. Ground-based photovoltaics

14. Which image do you prefer? For what reason?
15. Which is best integrated with the landscape?

Section D – Environmental justice implications.
D.1/D.2/D.3 Meaning of environmental justice referred to agrivoltaics and perceived environmental and social impacts of agrivoltaics.

16. What do you associate with the concept of/what does environmental and social justice mean to you in reference to agrivoltaics systems?

D.4 – Distributional effects

17. Can you give me some examples of benefits of implementing agrivoltaics systems?
18. And what are the costs, also understood as negative impacts?
19. In this distribution of costs and benefits, who is advantaged and who is disadvantaged? Who can be considered more vulnerable to negative impacts?

D.5 – Recognitional effects

20. Are there some people or groups of individuals whose needs/interests to date are recognized more than others? For what reasons are they more recognized to date?
21. Are there people or groups of individuals whose needs/interests to date are neglected? For what reasons are they to date excluded?
22. Beyond identifying individuals or groups of individuals who are discriminated against or ignored currently, are there other subjects whose needs are often put on the back burner, e.g., the natural environment/ecosystems/biodiversity? Are there ecosystem rights?

D.6 – Procedural effects

23. Are you aware of any forms of civil society involvement (e.g., citizens, local communities, environmental organizations, consumer groups, other – if so, please specify) regarding the agrivoltaic discussion?
24. Which stakeholders do you think should be involved?
25. When and how should involvement be carried out (e.g., identifying where to install agrivoltaics systems, what kind of systems to install, when to install them, etc.)?
26. How much is having streamlined administrative procedures likely to have a negative impact on regulating the establishment of agrivoltaics systems?

[Additional questions intended to be asked].
Section E – Final cues

27. The interview is ending: do you have any final thoughts or would you like to say more?
28. Can you think of another expert you think is important for us to interview?
29. Finally, can you point us to potential stakeholders regarding the [*name of example cited in the interview*] demo site to invite to future interviews?

Appendix 3. Annex 3.

Interview #	Original text/Excerpt	Paraphrased/synthetized text	Code
Section A – Ice-breaking question			
A.1 Sector and role			
Section B – Definition of agrivoltaics			
B.1 Free definitions			
B.2 Perceived difference between PV on agricultural land and agrivoltaics, advantages and disadvantages of both			
B.3 Perceived importance of agrivoltaics			
B.4 Most suitable configuration			
B.5 Implications or limitations of each configuration			
Section C – Agrivoltaics and landscape			

(*continued on next page*)

(*continued*)

Interview #	Original text/Excerpt	Paraphrased/synthetized text	Code
C.1 Perceived value of the landscape			
C.2. Untouchable/inviolable/unchangeable aspects of the landscape			
C.3. Perceived impacts of agrivoltaics on the landscape			
C.4. More suitable landscapes/areas for agrivoltaics			
C.5. Perceived impacts of landscape change on people			
C.6. Possible compensation for landscape change			
Section D – Justice implications of Agrivoltaics			
D.1. Meaning of environmental justice referred to agrivoltaics			
D.2. Meaning of social justice referred to agrivoltaics			
D.3. Perceived environmental and social impacts of agrivoltaics			
D.4. Distributional effects			
D.4.1. Examples of benefits and costs			
D.4.2. Who is advantaged and who disadvantaged in their distribution			
D.4.3. More vulnerable groups or individuals			
D.5. Recognitional effects			
D.5.1. Examples of people or groups of individuals whose needs/interests are more recognized			
D.5.2. Reasons/drivers of recognition			
D.5.3. Examples of people or groups of individuals whose needs/interests are neglected			
D.5.4. Reasons/drivers of negligence			
D.5.5. Other neglected subjects (e.g., the natural environment/ecosystems/biodiversity)			
D.5.6. Ecosystems rights			
D.6. Procedural effects			
D.6.1. Forms of civil society involvement in agrivoltaics decision making (e.g., citizens, local communities, environmental organizations, consumer groups, other)			
D.6.2. Stakeholders to be involved			
D.6.3. When and how should involvement be carried out			
D.6.4. Impact of streamlined administrative procedures on regulation			
Section E – Final cues			

Appendix 4. Annex 4.

Acronym	Meaning
BE	Belgium
ES	Spain
EU	European Union
GHG	Greenhouse gas
GMPV	Ground-mounted photovoltaics
GW	Gigawatts
IT	Italy
NL	The Netherlands
PV	Solar photovoltaic
RE	Renewable energy

Data availability

The authors do not have permission to share data.

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