Article:

Cotton, Matthew David orcid.org/0000-0002-8877-4822, Langford, Stephen, Kurie, Anne et al. (1 more author) (2025) A technology to solve the water-energy-food crisis? Mapping sociotechnical configurations of agrivoltaics using Q-methodology. Energy Research and Social Science. 103872. ISSN 2214-6296

https://doi.org/10.1016/j.erss.2024.103872

Energy Research & Social Science 119 (2025) 103872

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Original research article

A technology to solve the water-energy-food crisis? Mapping sociotechnical configurations of agrivoltaics using Q-methodology

Matthew Cotton [a,*], Stephen Langford [b], Anne Kuria [c], Karen Parkhill [b]

[a] *School of Social Sciences, Humanities and Law, Teesside University, Middlesbrough, UK*
[b] *Department of Environment and Geography, University of York, York, UK*
[c] *World Agroforestry Centre (ICRAF), Nairobi, Kenya*

ARTICLE INFO

Keywords:
Agrivoltaics
Q-methodology
Stakeholder perspectives
Rural livelihoods
Sociotechnical configurations

ABSTRACT

"Agrivoltaics" are solar photovoltaic panels mounted above productive farmland so that energy and food production can occur simultaneously on the same plot. Agrivoltaics are proffered as a means to reduce food-energy land use conflicts, and to ameliorate rural community opposition to ground-mounted solar farms. In this study we examine the socio-economic and environmental claims around agrivoltaics as a set of competing sociotechnical configurations, assessed through a Q-methodology and qualitative analysis of 30 responses from technical, NGO and social opposition respondents from 14 different countries. We find three emergent sociotechnical configurations, labelled: 1) Agrivoltaics for livelihood diversification and poverty alleviation; 2) Opposing agrivoltaics – asserting community control and procedural justice, and 3) Scaling up a 'triple win' for agrivoltaics – centring innovation and ownership models. We identify strong support for agrivoltaics in livelihood diversification across rural communities, and for meeting multiple food, energy and water security goals simultaneously. However, stakeholder opposition from technological intrusion of agrivoltaics in rural places and a lack of consensus on what role governmental authorities, landowners and community cooperatives can play are key barriers to deployment and upscaling of this niche technology. We find that agrivoltaics can stimulate diverse sociotechnical configurations of energy and agriculture, with great potential for improving energy and food security, though issues of visual intrusion and perceived 'technology in the wrong place', lack of clarity on funding and planning models, and improper scales of governance and procedural injustice could potentially stymie rollout for both smallholders and larger agribusiness schemes.

1. Introduction

The urgent need to achieve Sustainable Development Goal 7 for clean, reliable, and low carbon energy systems requires innovative technological development to meet the needs of different geographies, biophysical conditions, and community relationships with land and natural resources. For rural and peri-urban communities, solar photovoltaics (hereafter SPV) are now a commercially mature technology for both small (household or farm) and large-scale (solar plant) applications to low carbon electricity generation [1]. One specific downside of SPV at scale is the large surface area of land needed for construction of solar plants. When SPV is constructed in rural areas this creates competition for productive agricultural land [2,3]. In this paper we assess a relatively new application of SPV termed *agrivoltaics* – a technology touted by proponents as a means to resolve agricultural and energy land use conflicts by using the same land for both applications simultaneously [4].

Agrivoltaics are hybrid co-located photovoltaics elevated on a mounted array, sometimes integrated with rainwater harvesting and irrigation systems [5,6] (where gutters collect rainwater from the panels and channel it to water storage for drip irrigation). The principle of agrivoltaics is to mount SPV above ground to allow for simultaneous crop production, livestock husbandry, or other food production uses (such as apiary) to occur beneath the panels [5,7]. As a novel application of SPV with consonant changes in the visual impact and place characteristics of rural communities, differences in land use governance practices, and the spatial orientation of energy production, agrivoltaics can potentially alter social relationships between heterogeneous 'publics', social organisations, planning authorities and technology use cases. As Walker and Cass [8] argue, such challenges raise new questions

---

[*] Corresponding author.
E-mail address: m.cotton@tees.ac.uk (M. Cotton).

https://doi.org/10.1016/j.erss.2024.103872
Received 20 December 2023; Received in revised form 21 November 2024; Accepted 28 November 2024

of meaning, differentiation, interrelation, and access, which they define as novel *sociotechnical configurations* of renewable energy technologies such as agrivoltaics. Sociotechnical configurations are, in the Walker and Cass [8] analysis, conceived of different combinations and assemblages of "the 'hardware' of engineered artefacts as being utilised within and through the co-dependent and co-evolving 'software' of its social organisation." In this paper, we explore perspectives on differentiated sociotechnical configurations of agrivoltaics using a Q-methodological approach, drawing upon input from agrivoltaics and SPV technical and social expertise from stakeholders in 14 countries.

2. Background to agrivoltaics

The falling cost of SPV coupled with a high solar potential across equatorial regions presents an important sustainable energy transition pathway for high and low-income nations, particularly for off-grid communities to which 'last-mile' access of centralised electricity generation is difficult due to challenges of cost, geography and infrastructure capacity [9,10]. Competition for land in regions with high solar potential between SPV and crop production is a critical concern for agriculturalists and energy policy makers across the world. SPV can be integrated with rooftop design in urban conurbations, either by retrofitting existing rooftops or integrating SPV design into new build properties [11]. However, for rural applications, large scale solar plants or solar farms have emerged as a profitable technological strategy for land owners [12,13], using broad tracts of land that would often otherwise be used for agricultural production [14,15]. Competition between food and energy production is thus of critical importance for sustainable land use planning under conditions of population growth and increased demands for nutrition and energy resources in urban and peri-urban regions. As with similar cases of food-energy conflict emerging in biofuel production [see for example [16]], agricultural land owners, environmental managers, planners and policy makers must balance issues of land and water availability, nutritional security, and electricity access in order to meet multiple sustainable development goals simultaneously. The resolution of this emergent water-energy-food (WEF) nexus and associated land use conflict is thus becoming a key environmental governance challenge in the 21st century [17,18] requiring new configurations of technological and social innovation.

Agrivoltaics enable agricultural production either beneath or between panels. Systems can involve different levels of technological complexity. Some designs use fixed panels mounted vertically or horizontally; others use mounted arrays with solar-tracking technology. Applications can also vary in design for different contexts, for example in open fields, greenhouses, or else as part of husbandry, apiary, or agroforestry schemes. The optimal design of agrivoltaics for different topography, crop or livestock types, community dynamics and geographic regions is an ongoing research and development concern [19]. However, irrespective of the design approach, agrivoltaics provide opportunities for rural livelihood diversification with the expansion of farm income through energy production, whilst maintaining simultaneous agricultural productivity [20–22]. The synergistic effect of meeting multiple sustainable development goals within one technological application is touted as the primary benefit of agrivoltaics deployment, and is of growing interest for global socio-economic development applications [23–25] across agricultural regions in the Global South [26–29]. However, agrivoltaics remain a niche socio-technical transition at the time of writing, with the majority of systems in research or demonstration stages and situated in the Global North [30]. The scaling up of agrivoltaics and application to commercial-scale agricultural and energy production across the world is therefore a key ongoing agribusiness, research impact and social development concern [31], requiring further examination of the social, economic and environmental impacts of their application.

Agrivoltaics are shown to have a range of potential socio-environmental benefits. These include: reduced soil temperature and reduced soil evaporation [32] due to shading from mounted panels. Improvements in soil moisture retention from the shading that panels provide can increase the late season biomass of forages [33] whilst creating overall improvements to the health of degraded soils [34,35]. Climate and air pollution-related benefits are derived primarily from reduced fossil fuel resource use in electricity production [36,37], notably when agrivoltaics systems replace diesel generators for farm electricity needs. Agrivoltaics can also improve the energy and water efficiency of farm irrigation practices when combined with rainwater harvesting and renewables-powered irrigation [38].

Though concerns have been raised about agricultural productivity for crop production under conditions of reduced sunlight [39,40], research shows that if crop varieties are used that do not need constant direct sunlight in order to grow well, agrivoltaics can actually improve yields under certain conditions. The reduced light from panels improves radiation interception efficiency (RIE) which can be beneficial to some cultivated produce, for example lettuce [41]. The shelter provided by panels also provides (limited) extreme weather protection for produce and for livestock, with potential to increase farm financial stability under conditions of growing volatility in weather conditions due to anthropogenic climate change [42]. Overall, when agrivoltaics is combined with shade tolerant crop varieties, yield losses can be minimised and crop price stability maintained if planned effectively [43]. Moreover, applications to sheep farming or cattle grazing beneath or between panels do not suffer these negative impacts. Potential economic benefits to farmers and farm communities therefore must balance between the costs associated with panel construction, maintenance, and decommissioning against the net benefits to farmer livelihood resilience through agrivoltaics adoption. Though this is a potentially significant financial risk, early results seem promising for farmer livelihoods overall [44], and so interest in how to scale up agrivoltaics from niche technology to energy production at scale is ongoing.

3. Agrivoltaics as socio-technical configurations

The purported environmental and economic benefits of agrivoltaics are shaped by the socio-cultural, regulatory, and political-institutional conditions in which the technology is funded, sited, deployed, used, maintained, and decommissioned. Agrivoltaics can be conceptualised as a type of *socio-technical configuration* [8] through which human and non-human elements interact to form new networks of not only energy and agricultural productivity, but also new associations, social practices, and economic and socio-environmental conditions. A *socio-technical configurations* approach assesses the complex array of social, cultural and technological interactions that (re)produce certain social practices, economic, political and institutional power structures and cultural relationships [45,46], such that as Cass and Walker argue [8]:

> "…renewable energy technologies not simply as a series of engineered artefacts performing energy conversions, but as configurations of the social and technical which have emerged contingently in particular contexts and which mirror wider social, economic and technical relations and processes."

Sociotechnical configurations of agrivoltaics might concern a range of factors and associated outcomes. For example: issues of how local energy democracy and decision-making influence technology choice commonly emerge in public dialogue [47]. Likewise industry lobbying might foster demand-side policy measures (such as R&D funding, subsidies to manufacturers or end users) which creates a 'supply push' that expands technology roll-out [48,49]. Conversely, social opposition over technological 'intrusion' to rural landscapes and consonant impacts to visual amenity, rural places and associated disruption to place identities and place attachment [50–52], ultimately leading to a cooling of political support and a key barrier to the scaling up of agrivoltaics. We assert therefore that an understanding of competing conceptions of the sociotechnical configurations of agrivoltaics is necessary to gauge how broader stakeholder groups will respond to this new technology in the marketplace and in the places in which these systems are built, ultimately influencing their relative success in moving beyond a niche technology in the future.

Initial research into the socio-technical configurations of agrivoltaics shows that the institutional arrangements between the farming community, investors, and the social impact of agrivoltaics deployment are expected to vary from high benefits, to a risk of severe poverty amongst affected farmers, depending upon how these relationships are managed [20]. Pascaris, Schelly and Pearce [53] found through qualitative social research with farmers, that common concerns raised relate to the productivity impacts, market uptake and expansion of agrivoltaics, compensatory mechanisms for lost income, and system design specifications for different scales, operating practices, and farmer livelihood strategies. The institutional and planning contexts in which agrivoltaics are deployed, as well as the environmental and energy justice considerations of the distribution of benefits and risks, decision-making capacity and community 'voice' are all crucial to effective implementation of energy transitions involving solar [54]. Evidence in the US shows that deployment of agrivoltaics may improve rural community support for solar power by reducing land use competition and improving overall productivity of the rural economy [55]. However, the energy justice dimensions of agrivoltaics are not simply related to the economic impact of new renewable energy systems on livelihoods and crop production, but also to the recognition of place-identities and place-attachments experienced by rural people living in the communities in which agrivoltaics are deployed. Moreover, agrivoltaics have the potential to produce changes in the social relationships of economic power (such as changes to the gendered relations implicit to agricultural work and profit) [56], to working practices and farmer relations (such as shading workers from the heat) [57], to energy system complexity and to energy autonomy [58,59] by shaping the outcomes of energy technology development towards self-sufficient rural community development [9]. Anticipating the impact of sociotechnical configurations of agrivoltaics deployment is therefore relevant to understanding their success towards the Sustainable Development Goals.

As a nascent renewable energy pathway suitable for a range of geographic and rural development contexts, agrivoltaics are subject to an emergent empirical social scientific analysis of stakeholder perceptions. Such studies include the perspectives of farm users [20,53], heterogeneous publics [55], technical experts [59], or else define emergent 'personas' as a method to articulate differing positions and facilitate stakeholder engagement [60] within agrivoltaic-affected case study regions. In this paper we broaden the scope of inquiry within this nascent field to explore the patterning of perspectives on the socio-technical configurations of agrivoltaics across stakeholder actors across different geographic contexts and with differing technological, planning and social impact expertise. The aim of the empirical analysis is therefore to map out the emergent sociotechnical configurations of risk, costs, benefits, and social relations that inform the deployment of agrivoltaics as a new category of renewable energy and agricultural systems. It is by fostering a better understanding of the nature of competing configurations within the complex environmental management and technology choice decisions over agrivoltaics that policy authorities can establish good governance practices and achieve energy justice in the deployment of novel niche energy and agricultural transitions.

4. Methodology

The social research method called *Q-methodology* has proved useful for exploring emergent consensus and divergence in underlying environmental and sociotechnical configurations amongst a range of stakeholder actors [61,62]. Q-methodology first developed by psychologist Stephenson [63], bridges qualitative and quantitative research approaches using a combination of factor analysis and interpretative analysis to reveal a series of idealised "accounts", "perspectives" or "discourses" (the terminology varies dependent on discipline) emerging from the rank-ordering of a series of pre-selected statements (the ranking process is called *Q-sorting*). In this case we present these accounts as distinct perspectives on the *sociotechnical configurations* of agrivoltaics – to understand the combinations of socio-economic, psycho-social, socio-cultural and technological components of the technology and how these act as determinants for "how, whether, and why" agrivoltaics are pursued [64].

Though originally a niche method in the psychological sciences, Q-method has gained popularity in the environmental social sciences given its capacity to delineate areas of agreement and conflict arising within contentious environmental management debates. Contrasted with so-called *R-method* (i.e. the more commonly-used quantitative social survey approach) which measures attitudes or shows predictive/explanatory powers amongst a demographically-representative population of respondents, Q-method studies aim to examine the inherent subjectivity surrounding a topic from the standpoint of the individual experiencing it [65]. Q-method therefore has value in mapping perspectives on the sociotechnical configurations of agrivoltaics emergent from a range of actor responses and identifying areas of consensus and dissensus within and between these configurations amongst heterogeneous stakeholder groups.

We use Q-method here to reveal a taxonomy of sociotechnical configurations of agrivoltaics emergent from stakeholder participant perspectives on these issues. These shared configurations are presented as a set of *factors* derived from statistical analysis. However, Q-method remains consonant with interpretive, constructionist/post-positivist social theory [66] because the factors are *interpreted* by the researcher assisted by additional qualitative evidence collected "post-Q-sort" to shape a narrative description of the factors themselves. It is in this way that we use Q-methodology to explore the emergent sociotechnical configurations.

5. Q-methodology in practice

We follow a range of standard procedures for the development of Q-method research [derived from 65, 67], namely to:

1. *Establish the "concourse"* of statements around the sociotechnical aspects of agrivoltaics.
2. *Derive a Q-set* – select a subset of statements from the concourse that captures the nature of the discourse surrounding agrivoltaics.
3. *Select the participants (P-set)* who will sort the statements.
4. Conduct Q-sorting process and collect post-sort qualitative data.
5. Conduct statistical analysis of completed Q-sorts.
6. Conduct qualitative interpretation of factors into a series of distinct sociotechnical configurations.
7. Explore the areas of agreement and disagreement between configurations.

5.1. Establish the "concourse" of statements

The *concourse* in this analysis is a collection of statements selected with the aim of capturing the nature of the debate surrounding agrivoltaics. In this phase, researchers collected a range of opinion statements on the phenomenon of interest, assembled in the manner of "a botanist collecting leaves or an entomologist bugs" [68], where the aim is to capture a diverse array of expressed perspectives across the corpus of materials collected [69]. Such statements are typically gathered from conversations, commentary, interviews, and literature, focusing on opinions rather than factual statements [70]. In this case we combined online searches of academic databases (SCOPUS, Google Scholar), conference proceedings (IEEE Xplore) NGO and policy documents (policycommons.net) using search terms "Agrivoltaics" OR "Agrovoltaics" OR "Agri-PV", OR "Agro-PV", OR "agri-solar" OR "agro-solar"– and supplemented with Boolean operators AND with “social”, “economic”, “cost”, “environmental”, as appropriate. In each case source documents were selected, read and subjective statements related to agrivoltaics extracted into a longlist. Secondly, we used secondary analysis of interview transcripts on the theme of agrivoltaics development from with stakeholders in Kenya, Tanzania, and Uganda (specifically where the statements were relevant to generalised sociotechnical configurations of agrivoltaics). As statements were collected each was thematically categorised. The collection of statements ended at a point of theoretical saturation (i.e. where new statements found did not yield new thematic categories, or else were duplications of previously collected statements [71].

The collected *concourse* comprised of 218 statements. We used a simple content analysis approach to assess the gathered statements into generalised themes (specifically: rural livelihoods, crop production and productivity, grid connectivity, environmental benefits, environmental impacts, energy generation, investment and finance, community decision-making, visual impacts, risk perceptions, social impacts, government policy, planning processes). We then use these as categories through which to sample statements used in the Q-sort process (to produce a smaller sub-set called the Q-set). Note that the concourse, the selected statements and their origin are not inherently valuable as research tools, rather the research value of Q-method lies in the method that collates and correlates individual responses and extracts idealised forms of discourse latent in the statement data provided to the individuals in the study [65,69].

5.2. Derive a Q-set

It is necessary to reduce the broader concourse of qualitative statements about the subject of agrivoltaics to a manageable subset that can be presented to participants for sorting (what is sometimes referred to as the Q-set). Brown [70] argues that such a selective process is “*more art than science*” – there is no single approved sampling method applicable to all Q-method studies. We provided structure to the Q-set first by assessing the broader 218 statement set for duplication, then assessing the broad array of concourse themes, selecting a balance of statements within each category, ensuring a balance of ‘valence’ within the thematic categories (i.e., making sure that not all statements express positive or negative subjective/normative positions), and ensuring that all relevant perspectives are captured in an easy-to-understand manner. The statement selection was tested amongst the research group, then a small group ($n = 3$) of agrivoltaics specialists to ‘ground-truth’ the statements (i.e., make sure than none were misrepresented or missing) and through this iterative piloting a 34-statement selection was produced.

5.3. Selecting the participants (P-set)

Q-method studies use a relatively small number of participants (or P-set) typically a sample smaller than the number of statements in the Q-set (commonly in the 12–40 range) [72]. Our p-set was composed of *30 participants*. The P-set is intended to represent diversity of potential perspectives within its scope: “a structured sample of respondents who are theoretically relevant to the problem under consideration; for instance, persons who are expected to have a clear and distinct viewpoint regarding the problem” [67]. We used a combination of purposive and snowball sampling to establish a diverse group of specialist agrivoltaics stakeholders from academia, industry research and development, social movements, NGOs, and development agencies. These participants come from 14 different countries, though it must be noted that cross-national comparison between country perspectives is not the aim of the method.

5.4. Conduct Q-sorting process and collect post-sort qualitative data

30 completed Q-sorts were returned. Details of the stakeholder participants and their demographic characteristics are shown in Table 2. Q-sorting was conducted online using the Qsortware platform. Users were asked to first sort the statements into three groups – into those that they agreed, disagreed and were neutral/unsure about. Second, participants were asked to categorise the statements from the first three ‘piles’ into those that were *most similar to their perspective* (+4) to *least similar to their perspective* (−4), where 0 is neutral. Participants were tasked with sorting the statements into a forced quasi-normal distribution pattern in the Q-grid shown in Table 1. Once this process was complete, they each provided written qualitative feedback on their choice and patterning of statements within the Q-grid and upon their selection of statements at the poles (+4 and − 4). This additional feedback was used to provide context and nuance in the construction of the perspectives on agrivoltaic sociotechnical configurations described in the analysis stage.

5.5. Conduct statistical analysis of completed Q-sorts

Successfully completed Q-sorts were extracted and the output Excel file analysed using KADE software for Q-method statistical analysis [73]. Statistical analysis first established a correlation matrix of all completed Q-sorts. The resultant correlation matrix was then subject to Principal Components Analysis (PCA). PCA establishes the underlying structure of the data, illustrates the directions where there is the most variance and then reduces the number of variables by creating linear combinations that retain as much of the original measures’ variance as possible [74]. After an analysis of the scree plot of the Eigenvalues of principal components, a three-factor solution was retained and rotated using Varimax rotation. The three-factor solution explains 61 % of total variance. Factor loading is determined for each Q-sort. Varimax rotation ensures that each Q-sort has a high loading to only one of the factors, and that the factors are positioned in such a way that the final solution maximises the amount of study variance explained. Each of the three retained factors is statistically significant with an Eigenvalue >1.00 with at least two Q-sorts loading on each factor. Thus, the three-factor solution we present meets all the statistical criteria for validity.

Participant loadings on factors are shown in Table 2. Participants (each individual Q-sort) are numbered 1–30. Loadings on factors are marked in bold to show defining sorts for that factor, i.e. the exemplars that reveal the shared item pattern or configuration that is characteristic of that factor [75]. The statements and the factor array showing the relative ranking of each statement for each of the emergent sociotechnical configurations (A, B, or C) is shown in Table 3.

5.6. Conduct qualitative interpretation of factors

Factor interpretation involves presentation of a series of sociotechnical configurations of agrivoltaics – summaries that capture the nature of shared viewpoints on socio-economic, governance, technological and environmental aspects of the technology across the total Q-set, with each account distinguishing the nature of each factor. In essence these are composites formed from the aggregation of perspectives emerging from the factor analysis and shaped by the qualitative data to give ‘richness’ to the description of each idealised account. Each sociotechnical configuration is constructed through reference to the positioning of items in the relevant best-estimate factor arrays from stage 5 [75]. These configurations are produced using a procedure used by Stevenson [76] and Heath and Cotton [77]: the account makes reference to the statements ranked at +4 and − 4 for each factor, followed by the distinguishing statements [i.e. statements that were ranked significantly differently between a given factor and all other factors, and the statements that were not ranked differently by any factors, see: 72] including neutral statements, and then shaped and contextualised through reference to qualitative data collected from post-sort

Table 1
Structure of the Q-sorting grid.

	Least like my opinion				Neutral				Most like my opinion
Score	-4	-3	-2	-1	0	+1	+2	+3	+4
Number of statements sorted into column	2	3	4	5	7	5	4	3	2

Table 2
Q-sorting details and loading on factors.

				Perspective		
Participant no.	Origin country	Expressed Gender	Background or profession	A	B	C
1	UK	F	Involved in opposition movement against agricultural solar power.	−0.1131	**0.7937**	−0.2273
2	Germany	M	Renewables engineer	0.3201	−0.1767	**0.6241**
3	USA	M	Industrial researcher into agrivoltaics	**0.7257**	−0.3365	0.1844
4	USA	M	Energy research and development practitioner	0.5344	−0.266	**0.647**
5	Canada	M	Academic researcher on agrivoltaics	**0.6425**	−0.4089	0.4198
6	Sweden	M	Academic researcher on energy for development/NGO representative	**0.7392**	−0.3443	0.2951
7	USA	M	Academic and industry researcher on solar photovoltaics, and agrivoltaics	**0.6286**	−0.3518	0.3033
8	Spain	M	Industrial energy research and development	0.3022	−0.1982	0.1239
9	Italy	F	Agrivoltaics developer	**0.5982**	−0.3437	0.3548
10	Germany	M	Agrivoltaics project manager	**0.6939**	−0.083	0.3772
11	Kenya	M	Energy engineering company director	0.0194	0.133	**0.8892**
12	France	M	Project development manager for renewable energy	**0.7416**	0.0722	0.2912
13	Canada	M	Industry energy research and development practitioner	**0.692**	−0.2207	0.3757
14	UK	F	Industry energy research and development practitioner	**0.4514**	−0.0426	0.418
15	Belgium	M	Industry researcher in agrivoltaics	**0.5486**	0.4855	0.111
16	Indonesia	F	Academic researcher in agrivoltaics/NGO representative	**0.6004**	−0.3912	0.2705
17	Germany	M	Agrivoltaics project manager	**0.7401**	−0.4886	0.2537
18	UK	M	Agricultural scientist	−0.3933	**0.7159**	−0.2921
19	Germany	F	Academic researcher in solar photovoltaics	**0.7361**	−0.1725	0.0415
20	Denmark	F	Academic researcher in energy engineering	**0.8071**	0.0081	0.0027
21	USA	M	Academic researcher in energy planning	0.1916	−0.2619	**0.7528**
22	USA	F	Agricultural Solar Developer	**0.6858**	−0.1209	0.1808
23	Germany	F	Agrivoltaics engineer	0.4845	−0.4329	0.4235
24	UK	F	Retired former planner	−0.2025	**0.5404**	0.26
25	Germany	F	Industrial researcher in agrivoltaics	**0.4794**	−0.2642	−0.0095
26	Germany	F	Industrial Researcher in agrivoltaics	0.3932	0.1963	0.4095
27	Austria	F	Agricultural engineer	**0.8031**	−0.2908	0.3456
28	USA	F	Industry research and development in agrivoltaics	**0.6841**	−0.3482	0.3876
29	Japan	M	Policy analyst for solar planning	**0.8207**	−0.2709	0.2937
30	UK	F	Campaign Organiser for opposition to agricultural land use for solar energy	−0.1716	**0.8377**	−0.0593
Explanation of variance (%)				33	14	14

N.B. Numbers highlighted in **bold** represent defining sorts for the factor.

questionnaires, examining statements made by sorters that loaded on the respective factor under discussion.

5.7. Explore the areas of agreement and disagreement between configurations

Finally, factor interpretation involves consideration of statements which distinguish individual factors from one another (indicative of points of disagreement between different sociotechnical configurations), and those statements which do not distinguish between factors (and others indicative of points of agreement or consensus amongst competing stakeholder positions).

6. Findings

This results section describes the features of the three sociotechnical configurations that emerge. Each is given a brief descriptive moniker to capture the nature of the narrative produced, as follows:

A. Agrivoltaics for livelihood diversification and poverty alleviation
  - This configuration emphasises the role agrivoltaic systems in diversifying farmer incomes and improving the resilience agricultural livelihoods, whilst asserting that agrivoltaics will prove profitable without government assistance.

B. Opposing agrivoltaics – asserting community control and procedural justice
  - This configuration emphasises the visual and amenity impacts of agricultural solar power, is sceptical of agricultural and environmental benefit claims, and calls for local democratic involvement in energy planning across rural landscapes.

C. Scaling up a ‘triple win’ for agrivoltaics – centring innovation and ownership models
  - This configuration is supportive of a ‘triple win’ for agrivoltaics in reducing land use, increasing energy and improving farm profitability, whilst calling for greater research and innovation into panel design, and reducing government and community intervention that might stymie agrivoltaic uptake.

The following section provides a discursive analysis constructed from both the factor array, and qualitative feedback from participants whose Q-sorts correlate with the associated factor (correlations for configuration that define the factor are shown in bold in Table 2). Each narrative refers to the statement and its relative ranking for each factor/configuration in parentheses, e.g. (s1, +4).

6.1. Configuration A: Agrivoltaics for livelihood diversification and poverty alleviation

Configuration A is characterised by two discursive dimensions. The

Table 3
Composite factor array of the three perspectives.

No.	Statement	Perspective		
		A	B	C
1	I support agrivoltaics because they represent a “triple win” - they increase food production, renewable energy generation and reduce water use.	+4	−4	+4
2	I am concerned that agrivoltaics will lead to poor quality crops and lower yields.	−3	+3	−1
3	Agrivoltaics are only suitable for shade tolerant crops (e.g., berries) and so I am concerned that this will reduce farmer decision-making control over what they can produce.	−2	+2	+3
4	I am concerned that although agrivoltaics allow for some agriculture to occur, they would still damage farmer incomes due to a drop in food production.	−4	+2	−1
5	Sharing not competing for land use is the best way to achieve community support for solar power.	+3	0	+3
6	Agrivoltaics should be the first choice for improving electricity access for the poorest agricultural communities across the world.	−1	−1	0
7	Government coordinated feed-in-tariffs are the best mechanism to ensure the profitability of agrivoltaic systems.	0	−3	−3
8	I am concerned that elevating photovoltaics above ground makes them an eyesore, negatively impacting the beauty of the surrounding countryside.	−1	+3	+1
9	Agrivoltaics will only be an effective solution if there is further innovation and funding in panel design.	−1	0	+3
10	Electricity produced from agrivoltaic systems should be used to alleviate energy poverty and insecurity for the poorest communities.	+3	+1	0
11	Agrivoltaics are not economically viable on a large scale because the shade crops grown beneath them are only a tiny proportion of overall agricultural production.	−2	+1	−2
12	Agrivoltaic systems should be avoided because they are technologically complex – if the systems are damaged or break down there won’t be enough local professionals able to fix them.	−3	0	−3
13	Agrivoltaics are most effective when combined with livestock farming or beekeeping, i.e., allowing sheep to graze between the panels or hosting beehives to boost pollination.	−1	−2	+1
14	Agrivoltaic manufacturers need to inspire farmers to use agrivoltaics through education and outreach initiatives.	+2	−2	+2
15	Agrivoltaics should be designed as community-owned energy projects that share electricity across a local electricity grid.	+2	+1	0
16	Governing bodies should implement laws for farmers to maintain a minimum level of agricultural production on agrivoltaic-occupied land, or else the panels should be removed.	0	+2	−2
17	Agrivoltaics should be used to help combat desertification by reducing soil erosion and evaporation from marginal agricultural lands.	+2	0	−1
18	International aid organisations, donors and non-governmental organisations should prioritise agrivoltaic investment to improve sustainable development outcomes.	+1	−1	+4
19	Government investment in training for installing, maintaining, and repairing agrivoltaic systems is needed before roll-out of the technology occurs.	+1	0	0
20	Agrivoltaics are beneficial because they improve women’s involvement in high value agricultural production and decision-making.	0	−3	0
21	Agrivoltaics should be used because they diversify the revenue streams and livelihood strategies of vulnerable farmers.	+4	−1	+2
22	The cost of installing agrivoltaics should be subsided by government grants so that they can reach profitability quickly.	0	−2	−2
23	The high costs of elevation, mounting and maintenance mean that agrivoltaics will likely never be profitable.	−3	+1	−3
24	We should prioritise grid connections over agrivoltaics to improve the livelihoods of the poorest rural communities.	−1	+1	0
25	It is important to prioritise sustainable construction and engineering practices in the installation of agrivoltaic systems such as reducing the use of carbon-intensive steel and cement and reducing construction waste.	+2	+3	+2
26	We should avoid covering any crop land with solar panels - solar energy is only suitable for urban roof tops, barren land, or industrial zones.	−4	+4	−4
27	Installing agrivoltaics should be a democratic decision taken in consultation with the whole community, not just the landowner.	0	+4	−2
28	Agrivoltaics should be used to improve farmer health and safety by providing shaded working conditions.	0	−1	−1
29	I am concerned that agrivoltaics risk food safety from pathogens borne by wildlife incursion such as birds roosting on panels or rodents seeking shelter in the shade.	−2	0	−4
30	I am concerned that shaded crops under agrivoltaics will lead to poor quality food produce and food waste, as thinner leaf or fruit wall structures will lead to reduced shipping and shelf life.	−2	+2	+1
31	Agrivoltaics should be connected to provide electricity supply to national grid systems.	0	0	0
32	Agrivoltaics prioritised in areas of degraded land to improve the health of soil ecosystems.	+1	−1	+2
33	Agrivoltaics are valuable because they reduce users’ reliance on monopoly energy companies for their electricity needs.	+1	−3	+1
34	Agrivoltaics are valuable because they reduce energy price instability.	+1	−4	−1
35	Agrivoltaics are helpful in providing secondary economic benefits and income opportunities to marginalised rural communities through system installation, service, and maintenance jobs.	+3	−2	+1

N.B. The table shows each statement and the relative ranking of each statement by each composite factor.

first is a positive attitude towards the potential profitability of agrivoltaics and the second is an emphasis on the socio-economic and livelihood development benefits of such profitability. Like configuration *C* there is a strong sense that there is ‘triple win’ potential across the nexus of energy, food and water security (s1, +4). As proponents of configuration A state in the qualitative feedback on the Q-sorts (respectively)

> “AV addresses land-use conflict and it is the way forward to address the issues of food-energy-water nexus.” (Participant 3).

What distinguishes configuration A from configuration C is the emphasis on the economic development potential for privately owned agrivoltaics, and the capacity of the technology to enable rural poverty alleviation (s10, +3).

> “The triple win is the most compelling attribute of agrivoltaics. Diversification of income is also very important especially for vulnerable farmers who increasingly suffer from unpredictable weather conditions due to climate change.” (Participant 10).

Proponents of configuration A perceive agrivoltaics as a profitable technology, one that can help to diversify farmer livelihood strategies through the addition of energy generation to food production (s21, +4), and through the development of secondary economic benefits from a nascent agrivoltaics industry, such as the job growth around installation, maintenance and repair of panels and supporting infrastructure (s35, +3). As such there is confidence that agrivoltaics systems will be profitable (s26, −4) despite any potential drop in agricultural productivity, with agrivoltaics off-setting losses of food production (s4, −4).

In contrast to configuration B, there was little concern over potential agricultural impacts due to lower crop yields (s2, −3), crop quality (s30, −2), or the risks of crop pathogens (s29, −1). Collectively this shows that proponents of configuration A view that the suspected impact to agricultural productivity, crop quality and rural livelihood strategy are low, and that energy service benefits from agrivoltaics will outweigh the costs or risks to existing livelihood strategies, particularly under conditions of dangerous climate change:

> "Facing climate change and more extreme weather events getting an additional income from electricity production is important to help farmers stay farmers." (Participant 12).

The second dimension to configuration A concerns ownership, decision-making autonomy and government involvement in agrivoltaics costs and profitability. It is notable that proponents of configuration A remain neutral on issues of government involvement in subsidising agrivoltaics systems, specifically on direct subsidy (s22, 0), and on feed-in tariffs (s7, 0). In the context of the positive expectations around profitability and socio-economic development, this shows that proponents of configuration A are likely to believe that agrivoltaics will prove profitable without subsidisation or 'boosterism' from government funds. What is also interesting is the neutrality around issues of decision-making at the farm or community scale. For example, there is little concern for farmers having diminished decision-making control over crop planting strategies (s3, −2), with neutral positions on issues such as the decision-making empowerment of women (s20, 0), or of broader communities (s27, 0). It is notable therefore that proponents of configuration A remain relatively neutral on issues of *procedural, recognition* or *participative* environmental and energy justice, whilst remaining positive about the *distributional* justice benefits of energy and food production to rural communities.

6.2. *Configuration B: Opposing agrivoltaics – asserting community control and procedural justice*

Configuration B is characterised by an anti-solar position related to the use of agricultural land for energy production. Of concern is the industrialisation of rural places through construction, with solar technology deemed only suitable for urban or industrial landscapes (s26, +4). As two sorters loading on configuration B state in the qualitative feedback (respectively):

> "Solar energy installations are best suited to rooftops, car parks, and motorway embankments etcetera. We can live without electricity but not without food, therefore food production must take the highest priority." (Participant 1).
>
> "Given that land is a finite resource and that there are many demands on the land -– food production, wildlife, environmental improvements, housing, health and well-being etc. -– countries need to ensure there is adequate regulation to minimise land use conflicts. Solar PV can be deployed easily on existing built surfaces or car parks or brownfield sites and this should be used before we consider solar on greenfield land. (Participant 24).

The first motivation for this opposition is a combination of what we might term food sovereignty, self-sufficiency, and sustainability. As one proponent states:

> "By reducing the amount of solar energy for plant growth we reduce the ability of plants to capture carbon dioxide and hence we increase global warming." (Participant 18).

The second perceived negative is the aesthetic impact of agrivoltaics on the landscape (s8, +3) (it is interesting that support remains for grid connected electricity for rural communities (s24, +1) though these would also have potential negative aesthetic impacts through the construction of electricity towers and lines).

As with many social movements of opposition towards energy technologies there is a strong concern around potential procedural injustices related to siting and construction, particularly in rural communities. There is strong support amongst proponents of this configuration for direct democracy through consultation with the whole community in advance of energy technology siting decisions (s27, +4). As proponents of configuration B state (respectively):

> "The voices and concerns of farmers should be heard without undue influence of developers and others who stand to profit from agrivoltaic systems." (Participant 30).
>
> "Any projects that affect local communities should be subject of consensus from that community." (Participant 1).

Proponents of B also argue that if agrivoltaics is supported through democratic decision-making, that this technology would be best delivered through a community energy ownership model (s15, +1), rather than through private ownership and feed-in tariffs (s7, −3), donor investment (s18, −1), direct government grants or subsidies (s22, −2) or government boosterism by encouraging farmer uptake of the new technology (s14, −2). As one proponent states:

> "I don't believe that Government money should be spent on ensuring profitability of agrivoltaics. If the system is unviable or unprofitable it should not be operating. Subsidies of inefficient, unviable, unprofitable systems are not sustainable and detract from other more suitable projects." (Participant 24).

Broader scepticism over the positive value of agrivoltaics deployment covers a range of purported benefits. In stark contrast to configuration A, there is a strong rejection of the "triple win" framing of agrivoltaics systems (s1, −4), such that the purported water, land security (s32, −1), food security, livelihood diversification (s21, −1), energy autonomy (s33, −3), profitability (s23, +1) and energy security (s34, −4), benefits not accepted by proponents of this configuration. Other secondary socio-economic and welfare benefits such as improving women's involvement in agricultural production (s20, −3), local economic growth through secondary service support mechanism (s35, −2) or farm worker welfare through shading (s28, −1) were similarly unconvincing. Those aligned to configuration B show concern for the overall impact of agrivoltaics on the quality and quantity of agricultural production, in terms of reductions in crop quality (s2, +3; s30, +2), farmer income (s4, +2), farmer decision-making autonomy over planting practices (s3, +2), and they maintain that agrivoltaics are also unsuitable for combination with livestock farming or apiary (s13, −2) production. Thus, it is the combination of perceived negative aesthetic, socio-economic and land use impacts that characterise the social opposition to agrivoltaics present in this configuration.

6.3. *Configuration C: Scaling up a 'triple win' for agrivoltaics –centring innovation and ownership models*

Configuration C, like A, supports agrivoltaics as a triple win approach to food, energy and water security (s1, +4), with confidence that solar panels are an appropriate technology for use on agricultural land (s26, −4), and that they will gain farmer support by allowing sharing of, rather than competition for, land use (s5, +3) and demonstrating positive environmental benefits in reducing land degradation (s32, +2). As one participant loading on configuration C states:

> "As research and pilot plant studies have proven to my satisfaction that triple win is possible." (Participant 4).

However, there are some subtle differences in the ways in which this positive support is expressed and justified. Specifically, configuration C is characterised by a pro-technological innovation, anti-government intervention, and private ownership/decision-making approach to agrivoltaics development.

Notable amongst proponents of configuration C is a confidence in the income diversification potential of AV systems for farmers (s21, +2). This is in a way that reduces farmer reliance on monopolised/centralised grid connections for electricity access (s33, +1) and provides overall farm profitability through supplementing crop production with energy generation (s11, −2). For some energy generation is seen as the only way to save smaller farms. As one proponent states:

> “I live in a rural area with many small farms and know how a high percentage struggle to make ends meet and have seen many farms cease production altogether in favour of leasing out the land for solar panels.” (Participant 21).

Income diversification extends to positive support for the secondary economic benefits gained through AV construction, service and maintenance employment derived from system management (s35, +1) which alleviates concerns about the construction or maintenance costs that might damage the profitability of farms (s23, −3).

In terms of the systems themselves, proponents of configuration C support further innovation in both panel design (s9, +3) and construction sustainability (s25, +2) and have confidence in the capacity of support organisations/workers to maintain panel efficiency and profitability (s12, −3). There is strong support for further innovation in improving panel efficiency and reducing shading impacts on crop production, though these issues are posited as issues of both panel design and construction placement. As two participants loading on configuration C state respectively:

> “With the right spacing and tracking strategies we can ensure impact on crop growth is minimal.” (Participant 2).

> “I currently agree that high light requiring crops suffer under opaque photovoltaic systems. However spectral light sharing techniques can assist in improving crop yields further and that’s where material and engineering innovations are key.” (Participant 21).

What is notable in configuration C is a lack of support for different kinds of external intervention in agrivoltaics uptake. For example, there is little support for government intervention to ensure farm profitability in the face of construction (s16, −2), or to support construction through different forms of subsidy such as feed-in tariffs (s7, −3), and they remain neutral on issues such as government investment in training (s19, 0). As one participant states:

> “Win-Win solutions are the most favoured deals. When we share resources and negotiate as partners and equal stakeholders, rather than competitors, this gives confidence and positive acceptance of projects by the community. [Agrivoltaics] is then seen by the community as value-addition to their land rather than loss of land.”

It is also notable there is little support for community consultation or involvement in decision-making on site selection (s27, −2), and a neutral stance on community ownership of agrivoltaics (s15, 0), though interestingly there is a stronger support for international donor, NGO, and aid organisation involvement in agrivoltaics uptake and deployment (s18, +4).

6.4. *Consensus and dissensus within and between configurations*

The analysis reveals discursive consensus and dissensus between the three emergent sociotechnical configurations. Agrivoltaics can be described as socially and ethically contentious technologies [78], in which their deployment creates new landscapes of economic, social and environmental benefits and risks. Managing the sociotechnical configurations of such changes requires processes of dialogue, debate, and compromise amongst competing stakeholder voices to achieve good governance of technology implementation as agricultural managers, rural communities, technology developers and planning authorities adapt to this new technology. Q-methodology is valuable in its capacity to identify points of consensus and dissensus and disagreement within the broader discourse surrounding agrivoltaic sociotechnical configurations. The results show which statements either distinguish between sociotechnical configurations (i.e. points of potential conflict) or do not (indicating points of consensus between competing perspectives). In the following section we aim to inform future stakeholder engagement and further empirical analysis of agrivoltaics – specifically in areas of consensus building. These are sometimes referred to as “quick wins” – issues where stakeholder conflict is less likely to occur, and areas of disagreement that would require further examination through qualitative and quantitative social research, facilitated dialogue and engagement with broader stakeholder networks to resolve competing positions [79]. These issues around which consensus and dissensus emerge are discussed in the following section, with reference to the statements and relative rankings for each sociotechnical configuration in parentheses e.g. (s25: A + 2. B + 3. C + 2).

6.5. *Areas of potential stakeholder consensus*

The strongest positive consensus across all three sociotechnical configurations was the importance of supply chain sustainability, prioritising sustainable construction and engineering practises in the installation of agrivoltaic systems such as reducing the use of carbon intensive steel and cement and reducing construction waste (s25: A + 2, B + 3, C + 2). Stakeholder consensus on providing cradle-to-grave sustainability within the production, deployment, use and decommissioning is therefore a key concern – one seen in other sustainability transition pathways in which a move towards low carbon technology may increase or reduce associated negative environmental consequences, for example from mining activity for copper, uranium or rare earth mineral, or from the disposal of electronic waste [see for example: [80,81]. Establishing upfront a lifecycle impact assessment of agrivoltaics at the point of promotion to policy authorities and farming communities is therefore a key mechanism to ensure the justice and social acceptance of agrivoltaics as a sociotechnical configuration of renewable energy production and agricultural practice.

There was also a broad positive consensus that agrivoltaics should benefit the local ‘energy community’. This could take the form of community owned energy projects with electricity shared across a local grid (s15: A + 2, B + 1, C0) which as seen in other cases, tends to improve social acceptance outcomes for controversial renewable energy projects [82,83]. Though there was support for community energy, the method of connection and energy sharing was less clear. The configurations remain somewhat agnostic about the importance of agrivoltaics being connected to grid systems (s31: A0, B0, C0), this strategy being a first choice for improving electricity access to poorer agricultural communities (s6: A-1, B-1, C0) and so this was seen as a priority to provide grid connections over agrivoltaics to these communities (s24: A-1, B + 1, C0). In each case, there was consensus that government investment in training in all aspects of agrivoltaics systems before rollout of the technology occurred (s19: A + 1, B0, C0) is of critical importance to its success.

6.6. *Areas of potential stakeholder dissensus*

The greatest levels of disagreement concern emerge between configuration B contrasted with configurations A and C. This disagreement reflects a relative sense of benefit-versus-threat of agrivoltaics to rural communities as perceived by each stakeholder group. Only configuration A was not concerned that the aesthetic impact of elevated panels, with configurations B&C both highlighting potential impact to amenity values (s8: A-1, B + 3, C + 1). Agrivoltaics, like other forms of renewable energy in rural communities, can create a sense of technological intrusion which disrupts interpersonal place attachment and place identity amongst community members in rural places [52], stimulating social opposition as a form of place protective action. From the Q-sorting process it’s clear that this type of opposition is likely to occur in certain communities during the rollout of agrivoltaics due to the perceived negative socio cultural and aesthetic impacts that occur. This leads to a broader disagreement about whether the countryside is an appropriate place for photovoltaic solar cells – in essence whether this is an urban or rural technology (s26: A-4, B + 4, C-4). We see in this data a strong division between heterogeneous stakeholder representatives on an appropriate spatial strategy for photovoltaic implementation, with agrivoltaics potentially exacerbating rural land use conflicts amongst solar proponents and opponents, between those that support agrivoltaics as a triple win (s1: A + 4, B-4, C + 4), and those that do not. As an issue of procedural energy justice, supporters of configuration B seek a strong democratic mandate across the community, before implementation, in contrast to the other configurations for whom decision-making authority is much less clear.

7. Discussion

Agrivoltaics are lauded in the literatures on energy for sustainable development as a *triple win* across the nexus of water, energy, food: solar panels produce renewable energy reducing reliance on fossil fuels and biomass for energy services, the elevation of photovoltaic cells allows simultaneous farming activity beneath the panels, and the shade reduces water loss from the soil leading to substantive economic and environmental benefits [e.g. [84]]. As a technological solution across the WEF nexus, agrivoltaics shows promise in alleviating food-energy land use conflicts, and increasing the social acceptability of solar photovoltaic deployment within rural communities that might otherwise contest such developments [56]. However, in our Q methodological evaluation of the sociotechnical configurations of agrivoltaics, we find a more nuanced picture of social acceptance, development potential, socioeconomic impact, and environmental justice amongst a diverse stakeholder population.

In contrast to the highly positive attitude taken towards agrivoltaics' potential seen in some academic, industry and policy circles [5], the three configurations emerging from the Q-method and qualitative analysis show a mixed level of support and engagement with the technology as both a climate change mitigation pathway, and as a means to diversify and build economic resilience within rural communities. Through the sorting of statements, and qualitative feedback on agrivoltaics, we identified three emergent sociotechnical configurations of agrivoltaic systems. Configuration A emphasises the potential of the technology for livelihood diversification, with proponents sharing the broader enthusiasm for the technology expressed within certain engineering and policy circles. The primary perceived benefit for proponents of configuration A comes from the technology's capacity to sustainably diversify income streams for vulnerable farmers and thus create alternative agricultural livelihood strategies for land-owners in the face of extreme weather events, volatile fossil fuel prices, ecological disruption, and changing farming practices, mirroring the perspectives shown in other studies of agrivoltaics amongst farmer-stakeholders and solar panel developers emphasise the productivity benefits for rural communities in terms of income diversification, improving access to electricity, and achieving greater economic stability [43,85]. In this respect we find that configuration A is representative of the dominant worldview of agrivoltaic proponents and supporters within technical and engineering disciplines, who seek the expansion of agrivoltaics to smallholder farms, motivated by the perceived socioeconomic development and climate resilience benefits for rural actors.

Proponents of configuration C are similarly supportive of agrivoltaics but do so for a subtly different reason – asserting that agrivoltaics are a profitable innovation not just for smallholder farmers who might be suffering economic vulnerability but also to large agribusinesses seeking to expand their operations and reduce the on-farm costs of energy. Proponents of configuration C assert that the technology will be profitable without government intervention and thus are supportive of market solutions to scaling up the technology, in contrast to some of the existing literature on agrivoltaic finance, that warn of high capital expenditure risks, financing, marketing and regulatory challenges that act as barriers to uptake [86]. If we present configuration A as representative of support for agrivoltaics for social development through clean energy technology uptake, climate adaptation and agricultural productivity maximisation coupled with livelihood diversity, then configuration C is more *techno-centric* and *'boosterist'* in character – emphasising profitability, research and design innovation and market support as key messages in the scaling up of agrivoltaic systems. There is a clear sense in support for this configuration, that further system design innovation is needed to meet the diverse geographic and market needs of different farming communities. Thus there is a call amongst proponents of configuration C, not for market subsidy in panel uptake per se, but as seen in some aspects of the academic and policy literatures [87], a call for increased research and development spending on panel and array design, from which the market will decide amongst these available technology options for deployment in different farming contexts.

Finally, configuration B stands in stark contrast to the other two supportive stances, defining the character of social opposition towards agrivoltaics technology. This configuration rejects the positive socioeconomic benefits expressed in configurations A and C, and emphasises most strongly the risks and disbenefits of agrivoltaics stemming from *technological intrusion* from solar power into rural landscapes and consequently a threat to rural place identities and place attachments [52]. Running through this configuration is the message that *any* rural solar panels are 'technology in the wrong place', that even the potential double use of the same land for farming and energy does not assuage concerns about its effect upon place character and the subjective experience of rural landscapes. This configuration thus stands in contrast to similar studies of agrivoltaics that emphasise how the technology might alleviate social opposition by diversifying rural land use productivity and ameliorating food-versus-energy conflicts that emerge in rural communities that adopt traditional ground-mounted solar farms [55,59].

This diversity in perspectives amongst our sample, reveals a lack of consensus on the decision-making and governance structures needed to provide a just and socially responsive agrivoltaics strategy. There is no clear consensus on the role of government in supporting agrivoltaics financially (through feed in tariffs or other forms of subsidy support), nor is there consensus on the appropriate scale of decision-making necessary to ensure ongoing social support to the technology (what might be termed a social license to operate). There is a lack of clear consensus on whether decisions on agrivoltaics implementation, funding and up-scaling should be taken by private owners, community groups, or elected officials. Greater clarity and further research activity is needed to define what an appropriate agrivoltaics governance framework should look like, which governmental bodies, tariff and subsidy arrangements should be in place and how local community involvement in decision-making fits with a broader narrative of energy justice, fair energy planning systems and justice for rural communities in terms of climate change mitigation and adaptation strategy.

8. Conclusions

In this Q-methodological study of stakeholder perspectives we identify three different sociotechnical configurations representing three competing visions of agrivoltaics development. First, is a positive response to agrivoltaics as a climate resilience and rural development strategy, second, as an opportunity for a market-led agribusiness venture with government support for panel innovation, and third, as a type of technological intrusion into rural community life. We conclude that, contrary to some of the more positive rhetoric around agrivoltaics emerging engineering and policy networks, the technology will not be a panacea to the types of land use conflict that are currently emerging between food and energy production land uses in rural communities if disagreement on fundamental aspects of funding, siting and planning are not resolved at the point at which agrivoltaics are developed at scale across rural landscapes. Thus as a normative conclusion from our research, the promotion of an agrivoltaics-led sustainable transition pathway could aim for what Cotton [88] terms ‘scalar parity’ in the decision-process, i.e. that procedural environmental justice in agrivoltaic implementation can be achieved by working to find the point at which different scales and geographies of decision-making authority and community representatives can meet on equal footing to define a shared vision of where agrivoltaics fit into rural landscapes, communities and livelihood strategies. In practice this means bringing together individual landowners, community organisations, local authorities and implementing bodies at an appropriate decision point where the process and outcomes of decision-making on agrivoltaics implementation can be shared across a stakeholder network, and thus the outcomes mutually supported (if not universally agreed). The successful scaling-up of agrivoltaics from niche agricultural technology to broader sustainable development pathway in rural energy and agricultural production is dependent upon finding an appropriate mechanism to ensure such procedural justice for rural communities. Only then can the apparent “triple win” for the natural environment and farming communities be realised.

CRediT authorship contribution statement

Matthew Cotton: Writing – original draft, Supervision, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Stephen Langford:** Writing – review & editing, Investigation. **Anne Kuria:** Investigation. **Karen Parkhill:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Matthew Cotton reports financial support was provided by UKRI Global Challenges Research Fund. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research is funded through the “Harvesting the sun twice: Enhancing livelihoods in East African agricultural communities through innovations in solar energy” project funded by the United Kingdom Research and Innovation (UKRI) Global Challenges Research Fund. Grant reference: ES/T006293/1.

Thanks go to Professor Sue Hartley, Dr. Richard Randle-Boggis, Prof. Steve Cinderby, Dr. Christine Lamanna and all other members of the project team, and to all of the participants who took part in the research.

Data availability

Data will be made available on request.

References

[1] J. Khan, M.H. Arsalan, Solar power technologies for sustainable electricity generation–a review, Renew. Sust. Energ. Rev. 55 (2016) 414–425.
[2] D.-J. Van de Ven, I. Capellan-Peréz, I. Arto, I. Cazcarro, C. de Castro, P. Patel, M. Gonzalez-Eguino, The potential land requirements and related land use change emissions of solar energy, Sci. Rep. 11 (1) (2021) 1–12.
[3] R.R. Hernandez, M.K. Hoffacker, C.B. Field, Land-use efficiency of big solar, Environ. Sci. Technol. 48 (2) (2014) 1315–1323.
[4] C. Taguta, T.L. Dirwai, A. Senzanje, A. Sikka, T. Mabhaudhi, Sustainable irrigation technologies: a water-energy-food (WEF) nexus perspective towards achieving more crop per drop per joule per hectare, Environ. Res. Lett. 17 (7) (2022) 073003.
[5] G.A. Barron-Gafford, M.A. Pavao-Zuckerman, R.L. Minor, L.F. Sutter, I. Barnett-Moreno, D.T. Blackett, M. Thompson, K. Dimond, A.K. Gerlak, G.P. Nabhan, Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands, Nature Sustainability 2 (9) (2019) 848–855.
[6] S. Amaducci, X. Yin, M. Colauzzi, Agrivoltaic systems to optimise land use for electric energy production, Appl. Energy 220 (2018) 545–561.
[7] M.A. Al Mamun, P. Dargusch, D. Wadley, N.A. Zulkarnain, A.A. Aziz, A review of research on agrivoltaic systems, Renew. Sust. Energ. Rev. 161 (2022).
[8] G. Walker, N. Cass, Carbon reduction, ‘the public’ and renewable energy: engaging with socio-technical configurations, Area 39 (4) (2007) 458–469.
[9] D. Salite, M. Cotton, J. Kirshner, Enabling uptake of off-grid solar: the case of Mozambique, Climate and Energy 39 (5) (2022) 18–25.
[10] R. Milani, L.C. Couto, R. Soria, A. Szklo, A.F. Lucena, Promoting social development in developing countries through solar thermal power plants, J. Clean. Prod. 246 (2020).
[11] S. Freitas, C. Catita, P. Redweik, M.C. Brito, Modelling solar potential in the urban environment: state-of-the-art review, Renew. Sust. Energ. Rev. 41 (2015) 915–931.
[12] S. Seyam, I. Dincer, M. Agelin-Chaab, Development of a clean power plant integrated with a solar farm for a sustainable community, Energy Convers. Manag. 225 (2020) 113434.
[13] P. Jones, D. Comfort, D. Hillier, Spotlight on solar farms, J. Public Aff. 15 (1) (2015) 14–21.
[14] E.H. Adeh, S.P. Good, M. Calaf, C.W. Higgins, Solar PV power potential is greatest over croplands, Sci. Rep. 9 (1) (2019) 11442.
[15] L. Dias, J.P. Gouveia, P. Lourenço, J. Seixas, Interplay between the potential of photovoltaic systems and agricultural land use, Land Use Policy 81 (2019) 725–735.
[16] J. Tomei, R. Helliwell, Food versus fuel? Going beyond biofuels, Land Use Policy 56 (2016) 320–326.
[17] N.X. Thinh, G. Arlt, B. Heber, J. Hennersdorf, I. Lehmann, Evaluation of urban land-use structures with a view to sustainable development, Environ. Impact Assess. Rev. 22 (5) (2002) 475–492.
[18] I.B. Turner, C.M. Pansino, M.J. de Lemos, Land–energy–food Nexus: competition and societal impact of land use for sustainable energy and food production—a review, J. Energy Resour. Technol. 145 (11) (2023) 110802.
[19] M. Kumpanalaisatit, W. Setthapun, H. Sintuya, A. Pattiya, S.N. Jansri, Current status of agrivoltaic systems and their benefits to energy, food, environment, economy, and society, Sustainable Production and Consumption 33 (2022) 952–963.
[20] M. Trommsdorff, M. Vorast, N. Durga, S. Padwardhan, Potential of agrivoltaics to contribute to socio-economic sustainability: A case study in Maharashtra/India, in: AIP Conference Proceedings, AIP Publishing, 2021.
[21] A. Feuerbacher, T. Herrmann, S. Neuenfeldt, M. Laub, A. Gocht, Estimating the economics and adoption potential of agrivoltaics in Germany using a farm-level bottom-up approach, Renew. Sust. Energ. Rev. 168 (2022) 112784.
[22] R. Randle-Boggis, G. Barron-Gafford, A. Kimaro, C. Lamanna, C. Macharia, J. Maro, A. Mbele, S. Hartley, Harvesting the sun twice: energy, food and water benefits from agrivoltaics in East Africa, Renew. Sust. Energ. Rev. 208 (2025) 115066.
[23] L.J. Walston, T. Barley, I. Bhandari, B. Campbell, J. McCall, H.M. Hartmann, A. G. Dolezal, Opportunities for agrivoltaic systems to achieve synergistic food-energy-environmental needs and address sustainability goals, Frontiers in Sustainable Food Systems 6 (2022).
[24] C. Toledo, A. Scognamiglio, Agrivoltaic systems design and assessment: a critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns), Sustainability 13 (12) (2021).
[25] N.C. Giri, R.C. Mohanty, Design of agrivoltaic system to optimize land use for clean energy-food production: a socio-economic and environmental assessment, Clean Techn. Environ. Policy 24 (8) (2022) 2595–2606.
[26] P. Gese, F.M. Martínez-Conde, G. Ramírez-Sagner, F. Dinter, Agrivoltaic in Chile—Integrative Solution to Use Efficiently Land for Food and Energy Production and Generating Potential Synergy Effects Shown by a Pilot Plant in Metropolitan Region, Proceedings of the International Conference on Solar Heating and Cooling for Buildings and Industry (SHC), Santiago de Chile, Chile, 2019, pp. 3–7.
[27] R.J. Randle-Boggis, E. Lara, J. Onyango, E.J. Temu, S.E. Hartley, Agrivoltaics in East Africa: opportunities and challenges, AIP Conf. Proc. 2361 (1) (2021).
[28] J. MacDonald, L. Probst, J.R. Cladera, Opportunities and challenges for scaling agrivoltaics in rural and urban Africa, in: AIP Conference Proceedings, AIP Publishing, 2022.
[29] S. Cinderby, K.A. Parkhill, S. Langford, C. Muhoza, Harnessing the sun for agriculture: pathways to the successful expansion of Agrivoltaic systems in East Africa, Energy Res. Soc. Sci. 116 (2024) 103657.
[30] T. Sekiyama, A. Nagashima, Solar sharing for both food and clean energy production: performance of agrivoltaic systems for corn, a typical shade-intolerant crop, Environments 6 (6) (2019) 65.
[31] N. Gomez-Casanovas, P. Mwebaze, M. Khanna, B. Branham, A. Time, E.H. DeLucia, C.J. Bernacchi, A.K. Knapp, M.J. Hoque, X. Du, Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production, Cell Reports Physical Science 4 (2023).
[32] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, J. Wery, Microclimate under agrivoltaic systems: is crop growth rate affected in the partial shade of solar panels? Agric. For. Meteorol. 177 (15) (2013) 117–132.
[33] P. Santra, P.C. Pande, S. Kumar, D. Mishra, R.K. Singh, Agri-voltaics or solar farming: the concept of integrating solar PV based electricity generation and crop production in a single land use system, International Journal of Renewable Energy Research 7 (2017) 694–699.
[34] E. Hassanpour Adeh, J.S. Selker, C.W. Higgins, Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency, PLoS One 13 (11) (2018).

[35] A.A.A. Omer, W. Liu, M. Li, J. Zheng, F. Zhang, X. Zhang, S.O.H. Mohammed, L. Fan, Z. Liu, F. Chen, Water evaporation reduction by the agrivoltaic systems development, Sol. Energy 247 (2022) 13–23.

[36] M. Wagner, J. Lask, A. Kiesel, I. Lewandowski, A. Weselek, P. Högy, M. Trommsdorff, M.-A. Schnaiker, A. Bauerle, Agrivoltaics: the environmental impacts of combining food crop cultivation and solar energy generation, Agronomy 13 (2) (2023) 299.

[37] A.S. Pascaris, R. Handler, C. Schelly, J.M. Pearce, Life cycle assessment of pasture-based agrivoltaic systems: emissions and energy use of integrated rabbit production, Cleaner and Responsible Consumption 3 (2021).

[38] F. Chekired, A. Richa, S. Touil, B. Bingwa, Energy yield evaluation of a rainwater harvesting system using a novel agrophotovoltaics design, Desalin. Water Treat. 255 (2022) 27–33.

[39] M. Graham, S. Ates, A.P. Melathopoulos, A.R. Moldenke, S.J. DeBano, L.R. Best, C. W. Higgins, Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem, Sci. Rep. 11 (1) (2021) 7452.

[40] L.A. Shepard, C.W. Higgins, K.W. Proctor, Agrivoltaics: modeling the relative importance of longwave radiation from solar panels, PLoS One 17 (10) (2022).

[41] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, Y. Ferard, Combining solar photovoltaic panels and food crops for optimising land use: towards new agrivoltaic schemes, Renew. Energy 36 (10) (2011) 2725–2732.

[42] R.I. Cuppari, C.W. Higgins, G.W. Characklis, Agrivoltaics and weather risk: a diversification strategy for landowners, Appl. Energy 291 (2021).

[43] H. Dinesh, J.M. Pearce, The potential of agrivoltaic systems, Renew. Sust. Energ. Rev. 54 (2016) 299–308.

[44] A. Agostini, M. Colauzzi, S. Amaducci, Innovative agrivoltaic systems to produce sustainable energy: an economic and environmental assessment, Appl. Energy 281 (2021).

[45] J.M. Wittmayer, T. de Geus, B. Pel, F. Avelino, S. Hielscher, T. Hoppe, S. Mühlemeier, A. Stasik, S. Oxenaar, K.S. Rogge, Beyond instrumentalism: broadening the understanding of social innovation in socio-technical energy systems, Energy Res. Soc. Sci. 70 (2020).

[46] C. Büscher, J. Schippl, P. Sumpf, Energy as a Sociotechnical Problem: An Interdisciplinary Perspective on Control, Change, and Action in Energy Transitions, Routledge, Abingdon, 2018.

[47] A.M. Levenda, J. Richter, T. Miller, E. Fisher, Regional sociotechnical imaginaries and the governance of energy innovations, Futures 109 (2019) 181–191.

[48] J. Hoppmann, The role of deployment policies in fostering innovation for clean energy technologies: insights from the solar photovoltaic industry, Bus. Soc. 54 (4) (2015) 540–558.

[49] M. Cotton, Planning, infrastructure and low carbon energy, in: S. Davoudi, R. Cowell, I. White, H. Blanco (Eds.), Routeledge Companion to Environmental Planning and Sustainability2019, pp. 248–256.

[50] P. Roddis, K. Roelich, K. Tran, S. Carver, M. Dallimer, G. Ziv, What shapes community acceptance of large-scale solar farms? A case study of the UK's first 'nationally significant'solar farm, Sol. Energy 209 (2020) 235–244.

[51] J. Nicholls, Technological intrusion and communicative renewal: the case of two rural solar farm developments in the UK, Energy Policy 139 (2020).

[52] P. Devine-Wright, Y. Howes, Disruption to place attachment and the protection of restorative environments: a wind energy case study, J. Environ. Psychol. 30 (3) (2010) 271–280.

[53] A.S. Pascaris, C. Schelly, J.M. Pearce, A first investigation of agriculture sector perspectives on the opportunities and barriers for agrivoltaics, Agronomy 10 (12) (2020) 1885.

[54] B.K. Sovacool, M. Martiskainen, A. Hook, L. Baker, Decarbonization and its discontents: a critical energy justice perspective on four low-carbon transitions, Clim. Chang. 155 (2019) 581–619.

[55] A.S. Pascaris, C. Schelly, M. Rouleau, J.M. Pearce, Do agrivoltaics improve public support for solar? A survey on perceptions, preferences, and priorities, Green Technol. Resil. Sustain. 2 (1) (2022) 8.

[56] A.S. Pascaris, C. Schelly, L. Burnham, J.M. Pearce, Integrating solar energy with agriculture: industry perspectives on the market, community, and socio-political dimensions of agrivoltaics, Energy Res. Soc. Sci. 75 (2021) 102023.

[57] B. Willockx, B. Herteleer, B. Ronsijn, B. Uytterhaegen, J. Cappelle, A standardized classification and performance indicators of agrivoltaic systems, EU PVSEC Proceedings 2020 (2020) 1–4.

[58] H. Scheer, Energy Autonomy: The Economic, Social and Technological Case for Renewable Energy, Earthscan, London, 2012.

[59] G. Torma, J. Aschemann-Witzel, Social acceptance of dual land use approaches: Stakeholders' perceptions of the drivers and barriers confronting agrivoltaics diffusion, J. Rural. Stud. 97 (2023) 610–625.

[60] G. Torma, J. Aschemann-Witzel, Sparking stakeholder support: creating personas for renewable energy innovation adoption based on qualitative data analysis, Energy Res. Soc. Sci. 109 (2024) 103407.

[61] L. Seghezzo, G. Sneegas, W. Jepson, C. Brannstrom, S. Beckner, K. Lee, The use and potential of Q method in environmental planning and management, Journal of Environmental Planning and Management (forthcoming) 1–27.

[62] P. Robbins, R. Krueger, Beyond bias? The promise and limits of Q method in human geography, The Professional Geographer 52 (4) (2000) 636–648.

[63] W. Stephenson, Application of Q-method to the measurement of public opinion, the, Psychol. Rec. 14 (1964) 265–273.

[64] C. Giotitsas, P.H. Nardelli, S. Williamson, A. Roos, E. Pournaras, V. Kostakis, Energy governance as a commons: engineering alternative socio-technical configurations, Energy Res. Soc. Sci. 84 (2022).

[65] S.R. Brown, Q methodology and qualitative research, Qual. Health Res. 6 (4) (1996) 501–512.

[66] D. Durning, The transition from traditional to postpositivist policy analysis: a role for Q-methodology, J. Policy Anal. Manage. 18 (3) (1999) 389–410.

[67] J. Van Exel, G. De Graaf, Q Methodology: A Sneak Preview. www.jobvanexel.nl, 2005.

[68] S.R. Brown, Q Methodology in Research on Political Decision Making, Oxford University Press, New York, Oxford Research Encyclopedia of Politics, 2019, p. 30.

[69] B. McKeown, D. Thomas, Q Methodology, Sage, London, 1988.

[70] S. Brown, A primer on Q methodology, Operant Subjectivity 16 (1993) 91–138.

[71] J.B. Paige, K.H. Morin, Q-sample construction: a critical step for a Q-methodological study, West. J. Nurs. Res. 38 (1) (2016) 96–110.

[72] T. Webler, S. Danielson, S. Tuler, Using Q Method to Reveal Social Perspectives in Environmental Research, Social and Environmental Research Institute, Greenfield MA, 2009.

[73] S. Banasick, KADE: a desktop application for Q methodology, Journal of Open Source Software 4 (36) (2019) 1360.

[74] J.M. Conway, A.I. Huffcutt, A review and evaluation of exploratory factor analysis practices in organizational research, Organ. Res. Methods 6 (2) (2003) 147–168.

[75] S. Watts, P. Stenner, Doing Q Methodological Research: Theory, Method & Interpretation, Sage, London, 2012.

[76] H. Stevenson, Contemporary discourses of green political economy: a Q method analysis, J. Environ. Policy Plan. (2015) 1–21.

[77] A. Heath, M. Cotton, Responsibility, engagement, and policy strategy for ocean plastic waste management: a Q-method study of stakeholder perspectives, J. Environ. Plan. Manag. 65 (13) (2022) 2412–2435.

[78] M. Cotton, Ethics and Technology Assessment: A Participatory Approach, Springer, Heidelberg, 2014.

[79] G.O. Aigbe, M. Cotton, L.C. Stringer, Global gas flaring and energy justice: an empirical ethics analysis of stakeholder perspectives, Energy Res. Soc. Sci. 99 (2023).

[80] M.-O.P. Fortier, L. Teron, T.G. Reames, D.T. Munardy, B.M. Sullivan, Introduction to evaluating energy justice across the life cycle: a social life cycle assessment approach, Appl. Energy 236 (2019) 211–219.

[81] J. Krane, R. Idel, More transitions, less risk: how renewable energy reduces risks from mining, trade and political dependence, Energy Res. Soc. Sci. 82 (2021) 102311.

[82] S. Ruggiero, T. Onkila, V. Kuittinen, Realizing the social acceptance of community renewable energy: a process-outcome analysis of stakeholder influence, Energy Research & Social, Science 4 (2014) 53–63.

[83] P. Vuichard, A. Stauch, N. Dällenbach, Individual or collective? Community investment, local taxes, and the social acceptance of wind energy in Switzerland, Energy Res. Soc. Sci. 58 (2019).

[84] T. Lombardo, Agrivoltaics Provide Food, Power and Money: A Triple Win, 2021. https://www.engineering.com/agrivoltaics-provide-food-power-and-money-a-triple-win/. (Accessed 03.03.2024.

[85] B. Valle, T. Simonneau, F. Sourd, P. Pechier, P. Hamard, T. Frisson, M. Ryckewaert, A. Christophe, Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops, Appl. Energy 206 (2017) 1495–1507.

[86] N. Adelhardt, J. Berneiser, Risk analysis for agrivoltaic projects in rural farming communities in SSA, Appl. Energy 362 (2024) 122933.

[87] S. Gorjian, F.J. Jamshidian, A. Gorjian, H. Faridi, M. Vafaei, F. Zhang, W. Liu, P. E. Campana, Technological advancements and research prospects of innovative concentrating agrivoltaics, Appl. Energy 337 (2023) 120799.

[88] M. Cotton, Environmental justice as scalar parity: lessons from nuclear waste management, Soc. Justice Res 31 (2018) 238–259.