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The spatial potential for agrivoltaics to address energy-agriculture land use conflicts in Great Britain

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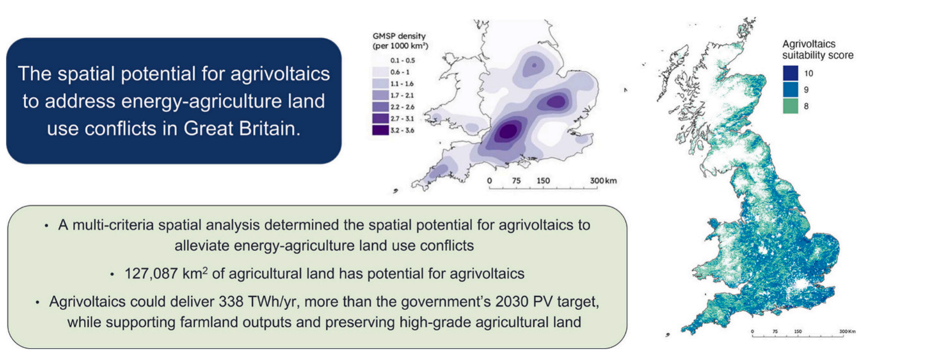
HIGHLIGHTS

- An MCSA determined the optimal location for agrivoltaic systems in Great Britain.
- 127,087 km^2 of agricultural land has potential for agrivoltaics.
- Agrivoltaics could deliver 338 TWh/yr while supporting high-grade farmland outputs.

GRAPHICAL ABSTRACT



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ABSTRACT

Ground-mounted solar parks provide much needed low-carbon electricity, but their development is increasingly conflicting with other land uses, such as agriculture, and their visual intrusion on agricultural landscapes and possible impact on food production is causing increasing public concern. Agrivoltaics has been proven across Europe to produce food and electricity concomitantly, but its potential to alleviate land use conflicts in Great Britain is yet to be explored. This study quantifies the extent that existing solar parks overlap with different grades of agricultural land, and forecasts where PV-agriculture land use conflicts may occur in the future. Where agrivoltaics could alleviate these conflicts is determined based on expert stakeholder insights, revealing that this technology could theoretically generate 338 TWh/year while maintaining outputs from 20,272 km^2 of high-grade farmland. Some agrivoltaic designs reduce evaporative water loss, and this study highlights where this would be beneficial for regions facing water scarcity. The spatial suitability of different cropland classifications is also shown. This study provides the first spatial assessment of the potential for large scale PV infrastructure to be developed in synergy rather than in conflict with agriculture in Great Britain.

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Nomenclature

Abbreviations

AA	arable agriculture
AV	agrivoltaics
BMV	best and most versatile
GHG	greenhouse gas
GHI	global horizontal solar irradiation
GMSP	ground-mounted solar park
LER	land equivalent ratio
MACR	mean absolute change rate
MCSA	multicriteria spatial analysis
PAR	photosynthetically active radiation
PV	photovoltaics
UK	United Kingdom

Units

°C	degrees Celsius
°E	degrees east
°N	degrees north
°W	degrees west
$GWh\cdot MW^{-1}\cdot yr^{-1}$	Gigawatt hours per Megawatt per year
GWp	Gigawatt peak
km^2	kilometre squared
$kWh\cdot m^{-2}\cdot day^{-1}$	kilowatt hours per metre squared per day
m	metre
mm	millimetre
TWh	Terawatt hour
$TWh\cdot yr^{-1}$	Terawatt hours per year

1. Introduction

To combat the critical challenge of climate change [1], the UK government has set a "Net Zero" target to be carbon neutral by 2050, with an interim target of reducing greenhouse gas (GHG) emissions by 78 % by 2035 [2]. This will require major transitions across all sectors, particularly energy and agriculture, which contribute 19 % and 12 %, respectively [3], to the country's total GHG emissions. To meet the 2035 emissions target, the UK must decarbonise electricity generation by rapidly deploying renewable energy technologies; the UK Government has committed to plans for a zero-carbon electricity system by 2030 [4]. Solar photovoltaics (PV) and wind energy are forecast to provide 75–90 % of electricity in 2035, up from just 3.3 % and 0.6 % respectively in 2021 [3,5]. This expansion is necessary to meet the expected 50 % increase in electricity demand, from 334 TWh in 2021 to 500 TWh by 2035 [5]. Deployment of PV has been growing steadily over the past decade, and to help meet its 2030 "clean power commitments", the new UK government aims to triple PV capacity from 16.9 GWp to 50 GWp by 2030 [6]. However, developing this infrastructure will require up to 662 km^2 of additional land [7], potentially conflicting with other land uses such as agriculture.

Solar PV and agriculture generally have similar land requirements - abundant sunlight and relatively flat ground - meaning the most suitable land for PV is often identified as having high agricultural potential [8]. Large scale solar parks provide the cost-effective means of delivering high generation capacities needed to meet the Government's ambitions for renewable energy production, but non-agricultural or low-grade agricultural land is often not suitable for PV because of incompatible terrain and/or excessive distance to a grid connection point. Hence, planning permission for solar parks can be granted for high-grade agricultural land, particularly when the developer can demonstrate high electricity generation potential, minimised development costs and consequently lower electricity prices, or if the proposal encourages biodiversity improvements [2]. While delivering much-needed low carbon electricity, deployment of solar parks could therefore conflict with agricultural land, particularly problematic for land designated as "best and most versatile" (BMV) agricultural land in England and Wales, and "arable agriculture" (AA) in Scotland. This raises the urgent need to balance electricity generation targets with agricultural production - which accounts for 70 % of land [9].

The UK is not self-sufficient in food production and relies heavily on imports to meet demand [3], and this reliance has become increasingly precarious following Brexit due to workforce losses and supply chain disruptions [10]. Additionally, price instability due to political tensions, such as the Russia-Ukraine war, have further compromised the accessibility and affordability of food [11]. The detrimental impacts of increasingly unpredictable rainfall and extreme weather events associated with climate change on agricultural productivity [5] further highlights the increasing threats to food security as well as the need to invest in low-carbon technologies to reduce GHG emissions and thereby mitigate climate extremes. Preserving farmland is vital for maintaining food production, improving domestic food security, and increasing resilience against external events that disrupt supply [12]. The growing need to develop both renewable energy infrastructure and food security consequently raises an urgent challenge: how can we best use our land for both food and electricity production? Multifunctional land use innovations that reduce emissions while delivering both food and electricity production are urgently needed.

Agrivoltaics is an emerging application of PV technologies where agriculture and PV are integrated, producing food and electricity on the same area of land. It offers a promising solution to mitigate land use trade-offs between food and electricity production, and it has been tested and proven in mainland Europe [13–17], Africa [18], Australia [19], Asia [20,21], South America [22], and the US [23,24], with research and commercial interest growing exponentially [25,26]. Common designs for agrivoltaics include livestock grazing within solar parks, solar panels raised above cropland - either fixed or tracking, and vertical bifacial solar panels interspaced with arable land [27–30]. Semi-transparent and wavelength-selective panels are also being researched for agrivoltaic application [31–34]. Each design has different effects on the local microclimates. For example, raised PV notably reduces evaporative water loss from underlying crops and soil due to partial shading of solar radiation [25], while vertical bifacial PV acts as a slight wind break [35]. The reductions in evaporative water loss from solar radiation-driven latent heat flux consequently lowers irrigation needs [24,36,37], potentially benefiting many farmers as precipitation patterns become increasingly unpredictable due to climate change [38]. Rainwater harvesting can be incorporated to capture and store runoff from the panels to be used as irrigation when needed [18,25]. Such water conservation is especially important during heatwaves; the heatwave during summer 2022 led to fruit and vegetable losses [3,39]. Conversely, agrivoltaics can offer protection from heavy rain or hail events. Thus, it can increase resilience against both temperature and precipitation extremes [40].

The most appropriate design for each installation will depend on the local agricultural, environmental and socio-economic context [41,42]. Agrivoltaics with sheep grazing is already deployed in the UK, whilst crops similar to those grown in the UK have proven viable for cultivation in agrivoltaic systems elsewhere in Europe, including: leafy greens [14], potatoes [13], cereal crops [43], soft fruits [44] and fruit trees [45]. Agrivoltaics have also been implemented in northern European locations where there are similar or more challenging climates for agriculture than in the UK [46]. A recent land productivity and economic viability model shows promise for a selection of crops combined with raised fixed-tilt and vertical bifacial agrivoltaic systems [47]. However, it is currently unknown where the technology could be implemented to mitigate land use conflicts in Great Britain. This is a key knowledge gap as such conflicts between renewable energy and alternative uses is an increasingly pressing issue in the UK, and controversy around large solar parks and associated transmission infrastructure is intensifying [48–50].

This study investigates the following research questions:

1. **Photovoltaics**: What is the spatial distribution of existing solar parks? To what extent do they overlap with different grades of agricultural land and hence where are potential PV-agriculture land use conflicts likely to occur?
2. **Agrivoltaics:** What is the spatial distribution of areas with potential for agrivoltaics? Where could it alleviate land use conflicts? To what extent do different cropland classifications overlap spatially with different agrivoltaic suitability scores?
3. **Resolving critical challenges:** Where could agrivoltaics mitigate the most pressing land use conflicts, i.e. those with high-grade agricultural land specifically? Given predictions of the impact of climate change on rainfall, where could agrivoltaics be situated in regions facing water scarcity?

2. Methods

1.1 *Study area*

The study area selected was Great Britain, comprising England, Scotland, and Wales. Northern Ireland was excluded due to a lack of data compatibility. The study region covers 228,948 km^2, located 49.95°N to 58.67°N and − 6.23°W to 1.76°E. Mean incoming global horizontal solar irradiation (GHI) ranges from 1.2 to 3.2 kWh·m^{-2}·day^{-1} [51], with a mean of 3.8 h of sunshine a day, which varies throughout the year from 1.5 h in January to 5.6 h in July [52]. It is topographically diverse, ranging from flat lowlands and rolling hills to coastal plains, cliffs, and rugged mountains – the highest peak is 1345 m, and the average elevation is 162 m. The temperate maritime climate sees cool wet winters between October and March and warm wet summers between April and September, with a 1991–2020 mean air temperature range of 3.9 °C in January to 15.3 °C in July [52]. Temperatures can exceed 32 °C in the Southeast of England in summer and drop below −15 °C in Scotland in the winter [52]. Extreme weather conditions are becoming more frequent, with rainfall becoming more unpredictable [5], flooding events more severe [5], and heatwave temperatures surpassing 40 °C [53]. The country receives 900–1360 mm of precipitation annually and 23.7 days of snowfall, predominantly in Scotland. Mean annual GHI and the regions studied are shown in Fig. 1.

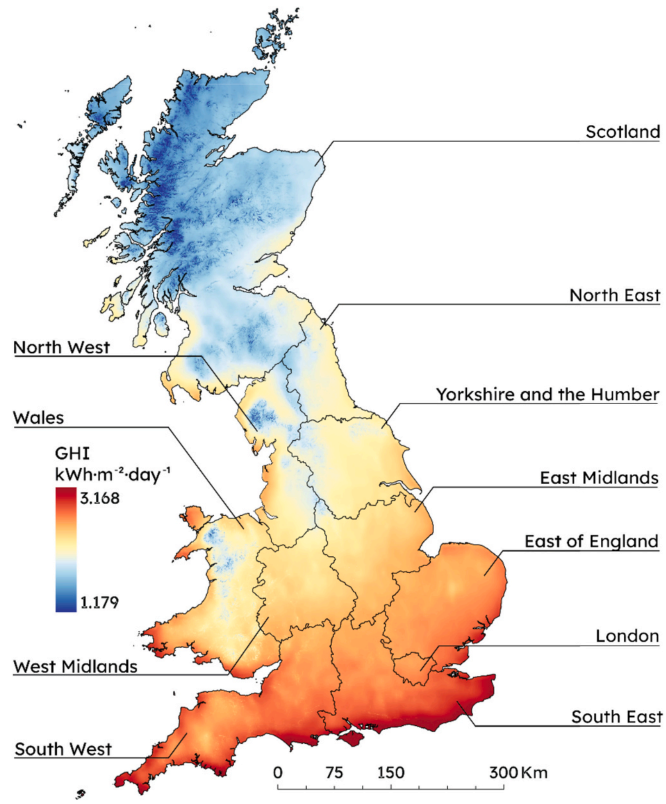


Fig. 1. Global horizontal irradiation. The GHI across the 11 regions of Great Britain.

2.1. *Spatially explicit multi-criteria analyses*

Two spatially explicit multi-criteria suitability analyses were conducted to assess the land use suitability (hereafter suitability) for photovoltaic and agrivoltaic development in Great Britain using ArcGIS Pro (ESRI, version 3.2.2). The PV suitability analysis describes the most suitable land in Great Britain for conventional ground-mounted solar parks, while the agrivoltaics suitability analysis describes the most suitable land in Great Britain for agrivoltaics, including both crops and animal grazing applications, based on physical parameters. The aim of the agrivoltaics suitability model is to determine the best location for agrivoltaics to mitigate land use conflicts. The model does not assess system performance nor compatibility with different crops. The data layers used in the analyses, along with their application and sources, are described in Suppl. mat. Table 1. Due to variations in data resolution, capture methods and the inclusion of some water bodies there is a < 0.001 % discrepancy between the reported size of Great Britain (228,948 km^2) [54], and the spatial data (229,093 km^2). The latter is used for the purpose of this study.

2.1.1. *Model input factors and rules*

A literature review was conducted to determine the input factors for the multi-criteria analysis. The search strategy implemented included a combination of key terms related to solar energy and site selection methods. The Boolean operators OR and AND were used to capture a wide range of relevant literature. For example, the search string (“solar” OR “photovoltaics” OR “PV”) AND (“site selection” OR “suitability analysis” OR “multi-criteria analysis”, OR “multicriteria analysis”) was used. The selected factors for both analyses were intentionally kept general to provide a broad overview of suitability for a range of PV applications and designs, rather than being specific to a particular use case. The input factors for determining PV potential were distance to grid connection (including connection capacity, where substations with available capacity were prioritised), theoretical photovoltaic energy output (PVOUT) [55], slope, and aspect [56]. The same factors, with the addition of agricultural land classification [57–59], were used to determine agrivoltaic suitability. Urban and forested areas, larger water bodies, and slopes above 11 % were excluded from both analyses as land unsuitable for PV. Each input factor was assigned a model influence “rule”, developed from the literature, to determine the way it influences the models. The model processes are shown in Fig. 2.

2.1.2. *Weighting factors: expert elicitation*

The weighting of each input factor in the model was determined by pairwise comparisons completed by 23 relevant experts: nine from energy development, research, and solar monitoring to inform the PV suitability analysis; and 14 from agrivoltaic research and development to inform the agrivoltaic suitability analysis. The pairwise comparison compared every combination of applicable input factor pairs using a simplified four-point scale to assess the relative importance of one input factor over another [60]. The expert derived weights, shown in Suppl. mat. Table 2, were determined by aggregating the individual scores for each factor and normalising them to the sum of all scores.

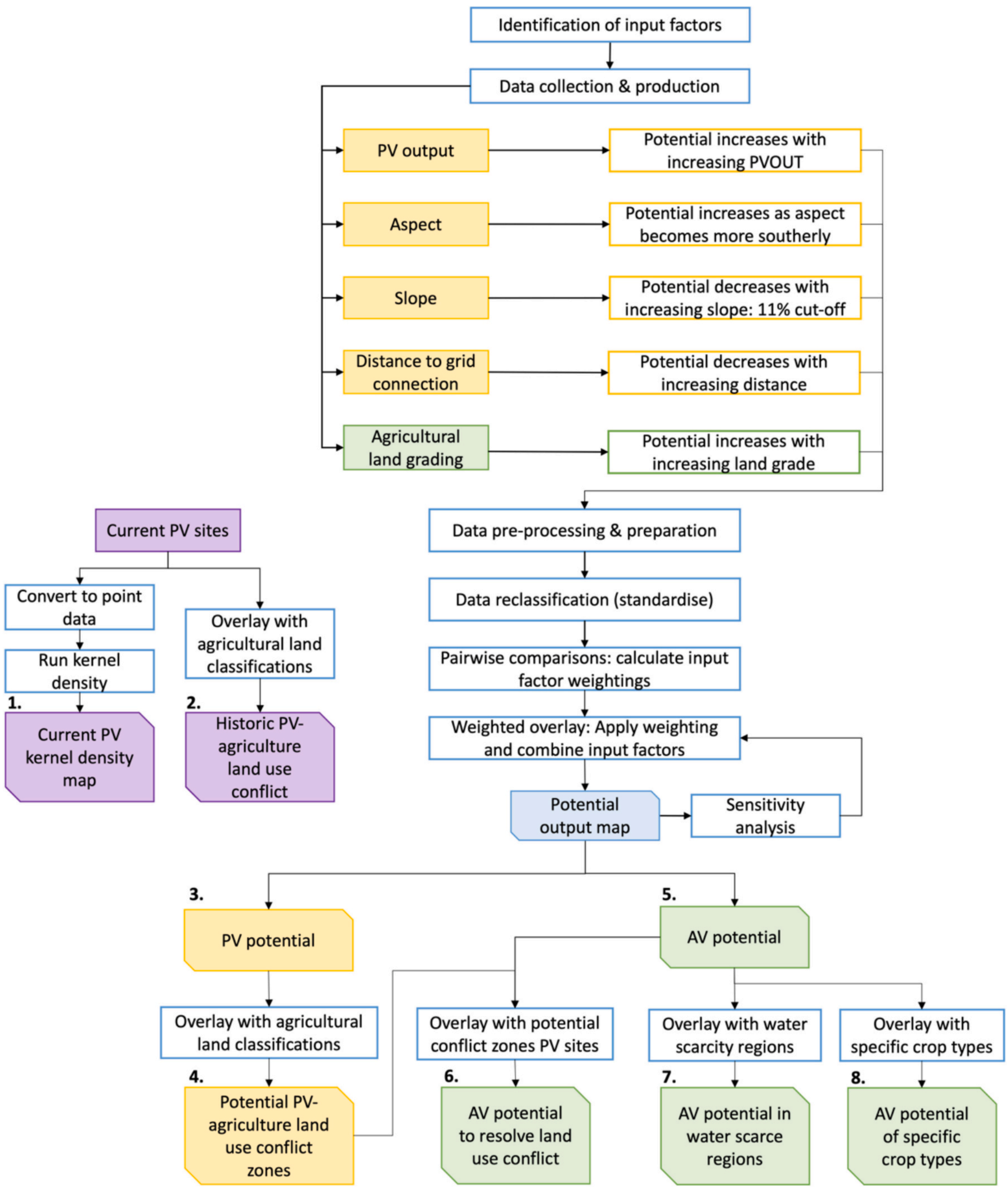


Fig. 2. The stages and processes implemented in the study. The numbered shapes are analysis outputs. Blue rectangles are steps or processes in the analysis. Coloured rectangles are input datasets: yellow relates to PV potential analysis, green relates to agrivoltaic (AV) potential analysis (note agrivoltaics potential analysis is inclusive of yellow), and purple relates to existing PV analysis. Yellow and green outlined rectangles represent input factor rules. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.1.3. *Validation and sensitivity analysis*

Intersection overlay analysis was used to correlate the locations of existing ground-mounted solar parks with our model's PV suitability scores, assessing the validity of the model's accuracy. A sensitivity analysis was conducted to evaluate the stability of the suitability pattern to variations in the expert stakeholder judgments [61]. This was achieved by assigning equal weightings to each of the original input factors in both the PV and agrivoltaics suitability analyses and comparing the equal-weighted outputs to the expert stakeholder outputs. To quantify the impact of the equal weightings, the mean absolute change rate (MACR) was calculated as the average of the absolute percentage change between the weighted and equal weighted suitability scores across all pixels [62]. For the agrivoltaics suitability analysis, the sensitivity of high and low suitability scores to variation in the weighting scheme was analysed by calculating the MACR separately for high suitability (original weighted suitability score at or above 75th percentile) and low suitability (original weighted suitability score at or below 25th percentile) pixels in each region. This highlighted any differences in the sensitivity of high and low suitability areas to changes in the weighting scheme.

2.2. Current solar park density

A kernel density map of the spatial distribution and density of existing solar parks was generated using the kernel density tool. This analysis fits a curved surface over each input point feature beginning at zero at the search radius distance and increasing in value with decreasing distance to the location of the point. The area (km^2) of the solar parks was included as the population field in the analysis. Higher values indicate areas with a higher density of PV site coverage. The output illustrates the spatial patterns and hotspots of currently installed PV in Great Britain.

2.3. Agrivoltaics to address PV-agriculture land use conflicts and support agriculture

Intersection overlay analysis was used to determine and quantify: a) where current PV systems have been developed on different grades of agricultural land; b) where potential future PV-agriculture land use conflicts are likely to occur by overlaying areas of high PV potential with agricultural land (this analysis was performed across all agricultural land and then separately for agricultural grades 1 and 2 only); c) where agrivoltaics could alleviate future PV-agriculture land use conflicts by overlaying high agrivoltaic suitability with potential PV-agriculture land use conflict zones; d) where agrivoltaics could be implemented in counties facing with water scarcity [63], and e) the agrivoltaic suitability of land currently used for different crop types. Based on available spatial data, the cropland classifications are: beet, field beans, grass, maize, oilseed rape, peas, potatoes, spring barley, spring oats, spring wheat, winter barley, winter oats, winter wheat, and "other" crops (other cereals, root crops, early potatoes, and vegetables, together with a small number of parcels which could not be classified) [64]. Determining system performance and specific crop compatibility given local environmental conditions is outside the scope of this country-wide spatial land use analysis.

The likelihood of future PV-agriculture land use conflicts is estimated by comparing the locations of high PV suitability with agricultural land. The study then "hones in" on subsets of this model to determine the spatial potential for agrivoltaics in three key areas of interest: 1) areas of potential conflict with high-grade agriculture; 2) areas facing water scarcity, where the water conservation benefits of agrivoltaics - most notable with raised systems – could support farmers water needs; and 3) where agrivoltaic suitability overlaps with major cropland. For the assessment of high-grade agriculture, agricultural land grades 1 and 2 are considered the "best and most versatile" (BMV) agricultural land in England and Wales, and "arable agriculture" (AA) in Scotland. While BMV also includes grades 3a and AA includes 3.1, data limitations prevented the separation of grade 3 land (where 60.2 % of ground-mounted solar parks are located) into its subclassifications. When a solar park planning application is filed for development on grade 3 land, a site-specific survey is completed to determine if the land is 3a or 3b and as such no large-scale dataset exists for further analysis. We therefore limit our discussion of BMV land and AA to agricultural land grades 1 and 2, where we are confident of the classification and where the greatest impacts on BMV land and AA will occur.

2.4. Inclusion and ethics statement

Relevant experts were recruited through academic, research and industry networks using a snowball sampling approach where recruited stakeholders suggested further participants. Biases within the selection process may be present due to the natural limited reach of the network and snowball effect. The survey was carried out in accordance with the University of Sheffield's ethics procedures, and approval for the survey was granted by the University's ethics committee. All participants gave informed consent for participation in the survey and use of the outputs for the stated research objectives.

3. Results

3.1. Existing solar park locations, photovoltaic suitability, and potential PV-agriculture land use conflicts

As of 2021, ground-mounted solar parks occupy 0.07 % (161 km^2) of the land area of Great Britain, but there is large variation between regions, with coverage ranging from 0.21 % in the South West to less than 0.01 % in Scotland and the North East (Fig. 3a; Suppl. mat. Table 3). Two thirds of solar parks are located in the South West, South East, and East of England. Most currently installed solar parks, 79.5 %, are situated on agricultural land graded 1–3 (Fig. 3b), with 19.3 % being located on BMV land grades 1 and 2, occupying 31 km^2 - more than double previous estimates [12].

172,287 km^2 (75.3 % of Great Britain) is found to have high suitability for PV (scores 8–10), and 9996 km^2 (4.4 % of the country) has the highest suitability (Fig. 4). Suitability generally increases towards the south - with the exception of London, where existing land uses such as parks, buildings, and roads render it largely unsuitable for ground-mounted solar parks. The South East has the greatest proportion of land with the highest PV suitability score, followed by the East of England, reflecting the high irradiance and great prevalence of flat land in these regions. Based on a conservative estimate of 0.02 km^2 utilised per MW of installed PV capacity [7], generating 1 $GWh \cdot MW^{-1} \cdot yr^{-1}$, the areas with the highest suitability for PV could generate 500 $TWh \cdot yr^{-1}$ - the entire forecast electricity consumption for the country in 2035 [5].

All existing solar parks are situated on land classified with a PV suitability score of 7 or above, and 68.5 % of solar parks are located on land with scores 9 and 10 (Suppl. mat. Table 4), despite only 38.2 % of Great Britain meeting this criterion. This validates our PV potential model for accurately predicting optimal locations for PV development.

Areas of high suitability for PV development frequently overlap with agricultural land, revealing substantial potential for PV-agriculture land use conflicts. Of land identified to have the highest suitability for PV, 92.6 % (9081 km^2) overlaps with agricultural land (grades 1 to 5). This overlap decreases as suitability for PV decreases, with 78.9 % (64,675 km^2) of the land with suitability score 9 and 66.7 % (53,876 km^2) of the land with suitability score 8 intersecting with agricultural land. This shows that the land most suitable for PV development tends to coincide with agricultural land. This trend suggests that without careful planning efforts, PV development could continue to disproportionately impact agricultural land.

23,593 km^2 (9.2 % of Great Britain) of areas of high suitability (scores 8–10) for PV overlaps with high-grade agricultural land (grades 1 and 2) (Fig. 5). The East of England has the most overlap, covering 6693 km^2, with 98.0 % of grade 1 agricultural land having high potential for conflict with PV. The West Midlands, East Midlands, and South West also have over 8194 km^2, combined, of potential high-grade agricultural land use conflict areas.

3.2. The spatial suitability for agrivoltaics

127,087 km^2 (55.5 % of Great Britain) has high spatial suitability for agrivoltaics, with 1570 km^2 (0.7 % of Great Britain) having the highest suitability, primarily located in the East of England and the South East (Fig. 6). Similarly to PV suitability, agrivoltaic suitability shows a southern and eastern trend. However, while the South East has the highest suitability for PV, it is the East of England that has the greatest agrivoltaic suitability. Considering an example where PV yield per hectare is reduced threefold to account for agricultural needs [16], agrivoltaics could theoretically generate 2118 $TWh \cdot yr^{-1}$ across all agricultural land use grades. This is more than four times the forecast electricity demand for 2035 in the UK.

Analysis of spatial overlap demonstrates that areas with high land use suitability (scores 8–10) for agrivoltaics strongly coincide with potential PV-agriculture conflict zones; 121,037 km^2 (95.2 %) of this

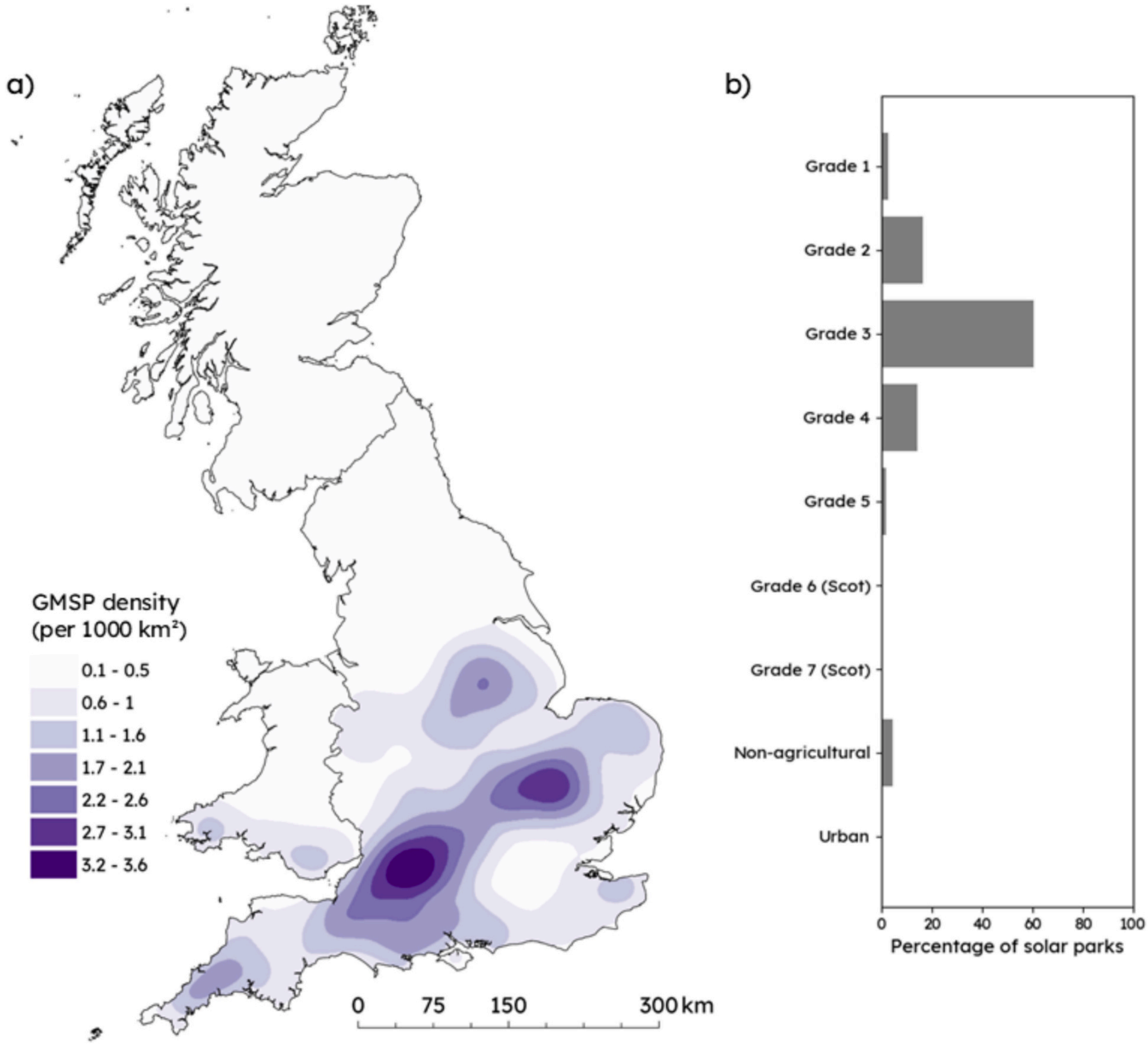


Fig. 3. Distribution of existing photovoltaic installations. a) The distribution density of existing ground-mounted solar parks (GMSPs) in Great Britain; higher values indicate areas with greater land coverage by solar parks. b) The percentage of solar park area distributed across different land classifications.

highly suitable land overlaps with areas of potential PV-agriculture conflict. This overlap is particularly evident at the highest suitability level, where almost all of the land achieving a suitability score of 10 coincides with potential land use conflict areas. The East of England, with its flat terrain and highly productive agricultural land, shows the greatest overlap between potential PV-agriculture conflict and high agrivoltaic suitability, followed by the South East and South West. While northern regions also demonstrate significant overlap, the relationship diminishes with northerly latitude, likely due to lower solar insolation and proportionally lower agricultural productivity per hectare. Applying the same threefold reduction in PV yield per hectare, agrivoltaics developed on potential PV-agriculture conflict areas could theoretically generate 2017 TWh·yr^{-1}. These results reveal a huge spatial potential for agrivoltaics to achieve PV capacity targets while mitigating the loss of agricultural land across Great Britain. This provides guidance on where agrivoltaics could potentially be located. Crop-specific compatibility with agrivoltaics - yet to be tested in Great Britain - will provide a more targeted assessment.

The sensitivity analysis showed relatively small changes in suitability scores when the equal weighting was applied for both PV and agrivoltaics (Suppl. mat. Figs. 1 and 2), suggesting the results are robust and that the overall suitability classifications are reasonably reliable despite changes in weighting.

All cropland classifications are situated on land with a mean agrivoltaics suitability score greater than 8, with beets having the highest mean score and grass having the lowest (Fig. 7). Despite that, grass is grown over a much greater area, and so in absolute terms offers more locations designated as highly suitable for agrivoltaics in terms of land use. Winter wheat, like grass, covers a relatively large area, but unlike grass these areas also have a relatively high agrivoltaics suitability score, and winter wheat has the greatest area coverage of the highest suitability score. While every crop is grown on some land with a suitability score of 10, winter wheat is the most notable, covering 365 km^2, with only grass covering a similar area (307 km^2). Winter oats have the lowest coverage of score 10 and cover the smallest area overall. Despite beets, field beans, and peas covering less land overall, they have the highest average suitability scores, indicating they are mostly grown in areas highly suitable for agrivoltaics to alleviate PV-agriculture land use conflicts. Potatoes have the greatest proportion of cultivation area in the top suitability category, being grown in areas particularly suitable for agrivoltaics to mitigate land use conflicts (Fig. 7 and Supp. mat. Table 5).

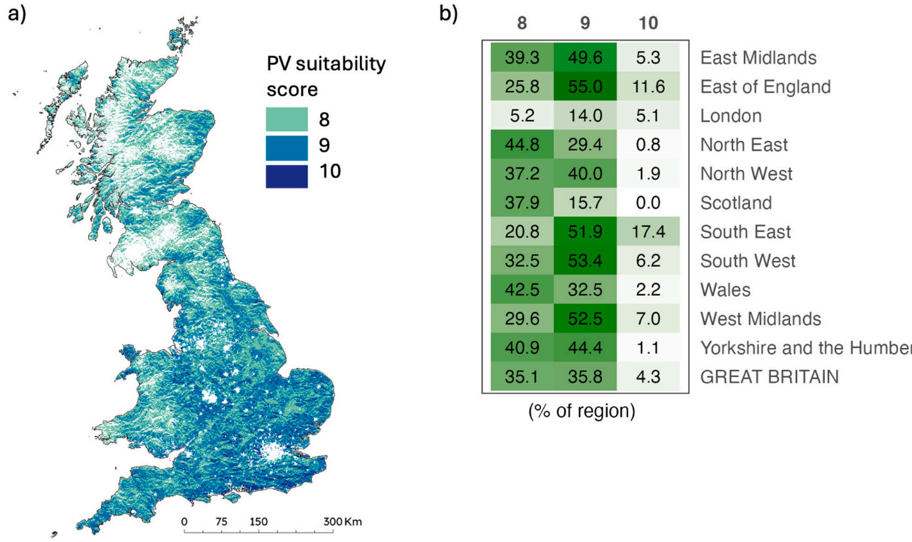


Fig. 4. Photovoltaic suitability across Great Britain. a) Land areas with high suitability (suitability score of 8 or higher) for PV, and b) the distribution of high suitability scores for each region as a percentage of a region's total area.

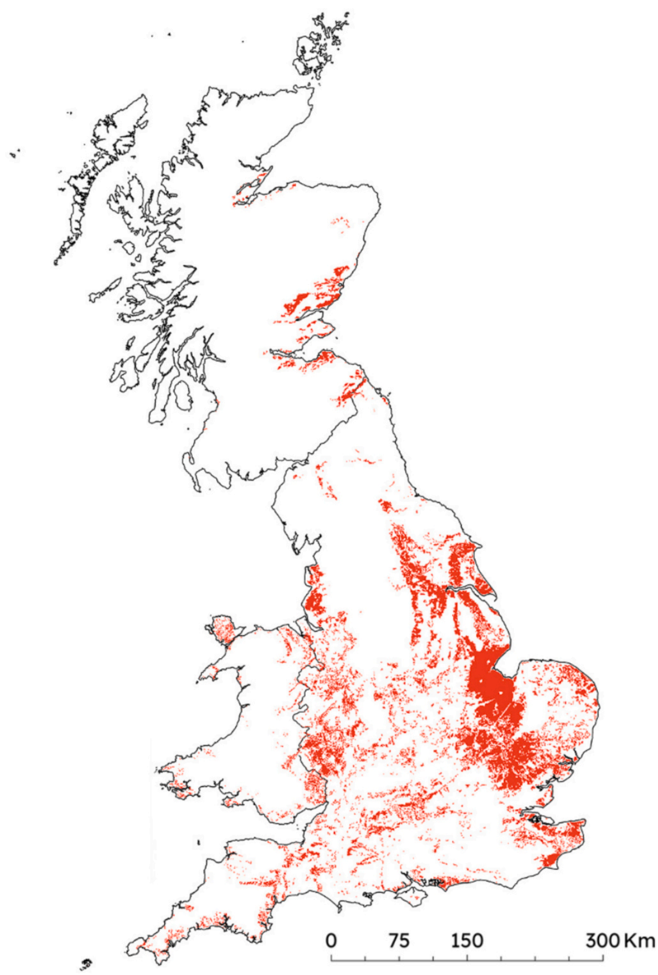


Fig. 5. Potential for land use conflicts between PV and high-grade agricultural land. The overlaps, in red, between areas with high suitability (suitability scores 8–10) for PV and high-grade agricultural land (grades 1 and 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3. Resolving critical challenges

3.3.1. Mitigating land use conflicts with high-grade agricultural land

20,272 km^2 (8.9 % of Great Britain) of potential PV-agriculture conflict areas on grades 1 and 2 agricultural land - where land use conflicts are especially contentious with the public - has high spatial suitability for agrivoltaics (Fig. 8). Developing agrivoltaics here could theoretically generate approximately 338 $TWh \cdot yr^{-1}$, approximately 6.8 times the government's PV capacity target for 2030. 80 % of these conflict areas are located on land achieving agrivoltaic suitability scores of 9 and 10, 69 % and 11 % respectively. The East of England has the largest coverage (6120 km^2) of high agrivoltaic suitability on these sensitive conflict areas. In this region, 91.4 % of said conflict areas also have high suitability for agrivoltaics, demonstrating significant potential for agrivoltaics to help resolve land use conflicts in these key agricultural areas. Other regions show significant potential for agrivoltaics to resolve conflicts on high grade agricultural land, including the East Midlands (2932 km^2), Yorkshire and the Humber (2368 km^2), and the South East (2235 km^2).

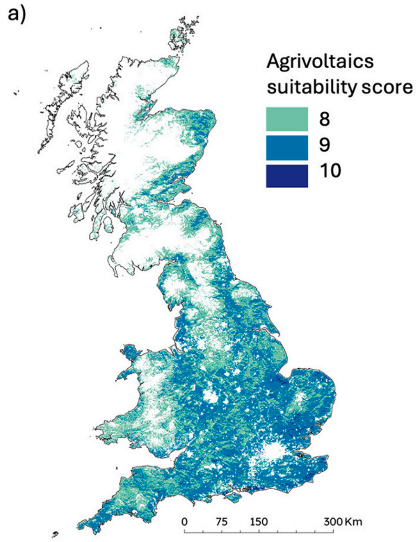
3.3.2. Agrivoltaics in regions faced by water scarcity

Our analysis also highlights significant overlap between areas of high agrivoltaics spatial potential and those facing water scarcity, covering over 45,000 km^2 - more than half of the area (Fig. 9). Here, the positive effects of solar panels on water conservation – most notable with raised agrivoltaics systems – could have additional benefits for farmers struggling with water loss.

4. Discussion

4.1. Existing solar park locations, overlaps with agriculture, and photovoltaic suitability

Up to 662 km^2, 0.3 % of Great Britain, will be required to install the 33.1 GWp of PV needed to reach the UK Government's installed capacity target of 50 GWp by 2030, and significantly more land will be required to achieve "Net Zero" carbon neutrality by 2050. While rooftop solar avoids land use change, ground-mounted solar can be deployed quicker with larger capacities. Most areas with high suitability for PV overlap with agricultural land so are likely to generate future land use conflicts between PV and agriculture, including high grade agricultural land. However, our findings, which align with a previous study on PV



b)

8	9	10	
39.3	50.2	0.8	East Midlands
17.4	65.8	3.3	East of England
12.3	1.0	0.0	London
35.2	18.4	0.0	North East
25.8	0.2	0.0	North West
17.8	5.1	0.0	Scotland
18.3	59.4	3.1	South East
37.6	48.4	0.7	South West
38.9	16.5	0.2	Wales
34.0	52.1	0.1	West Midlands
38.7	34.4	0.0	Yorkshire and the Humber
26.7	28.1	0.7	GREAT BRITAIN

(% of region)

Fig. 6. Agrivoltaic spatial suitability across Great Britain. a) Land areas with high suitability (suitability score of 8 or higher) for agrivoltaics on all agricultural land grades, and b) the distribution of high suitability scores for each region as a percentage of a region's total area.

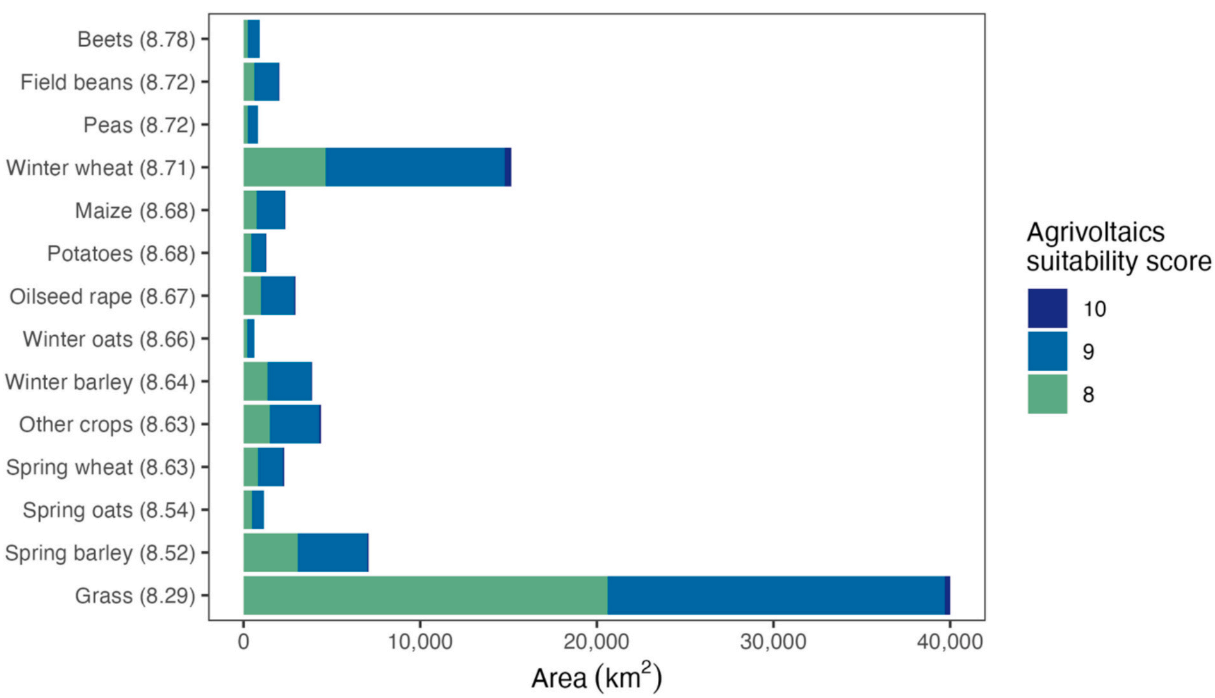
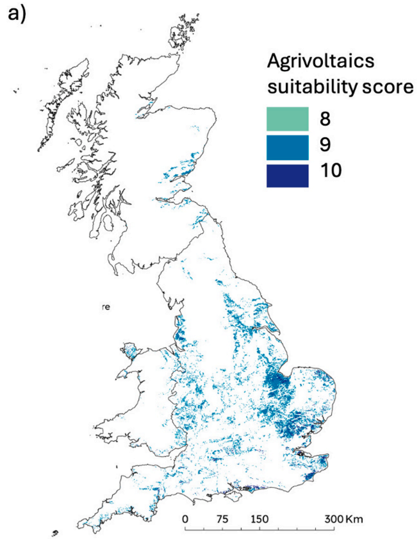


Fig. 7. Agrivoltaic land use suitability scores for areas cultivated for major crops. The area of different crops grown on land classified with a land use suitability score of eight or higher for agrivoltaics. The mean land use suitability score for each crop's cultivation area is shown in brackets.

potential of the UK [7], also demonstrate that the distribution of potential conflict areas does not follow the same spatial pattern as PV potential, highlighting that having the highest potential for PV in an area does not necessarily lead to that area having the highest likelihood for PV-agriculture land use conflict. Hence our analysis can inform where PV can be developed while avoiding the greatest impacts on agriculture, e.g. with high grade agriculture. Despite the South East and East of England - characterised by relatively flat land and high solar insolation - having the greatest suitability for PV, most solar parks so far have been developed in the South West. This could be to avoid conflicts with high-grade agriculture, which contributes a greater proportion of land in the east. However, this situation is changing, with most of the planned large solar parks likely to be sited in the south and east [65,66] (see below) so the ongoing siting of solar parks on agricultural land, particularly on best and most versatile land (BMV, i.e. agricultural land grades 1-3a), raises concerns about the impacts on food production and security.

The high potential for PV-agriculture conflicts identified in the East of England is particularly concerning given this region has already experienced the largest loss of BMV land compared to any other region [12]. The disproportionate loss of the most productive land here, coupled with the high potential for PV-agriculture conflicts and the national commitment to expanding solar [65], suggests the trend of losing BMV land is likely to continue, resulting in high-grade agricultural land being converted to solar parks - the loss of which could reduce food production and other agricultural outputs in the region. If solar



b)

8	9	10	
4.4	12.9	1.4	East Midlands
6.6	21.1	4.3	East of England
0.0	1.7	0.9	London
0.2	1.3	0.0	North East
1.4	4.6	0.6	North West
0.1	0.9	0.0	Scotland
2.2	6.8	2.7	South East
1.6	5.2	0.8	South West
0.9	3.0	0.4	Wales
2.5	11.1	1.6	West Midlands
3.7	11.3	0.3	Yorkshire and the Humber
1.8	6.1	1.0	GREAT BRITAIN

(% of region)

Fig. 8. Agrivoltaic spatial suitability in PV-high-grade agricultural land use conflict areas. a) Land areas with high suitability (suitability score of 8 or higher) for agrivoltaics where PV-agriculture land use conflicts occur on high-grade (grades 1–2) agricultural land, and b) the distribution of high suitability scores for each region as a percentage of a region's total area.

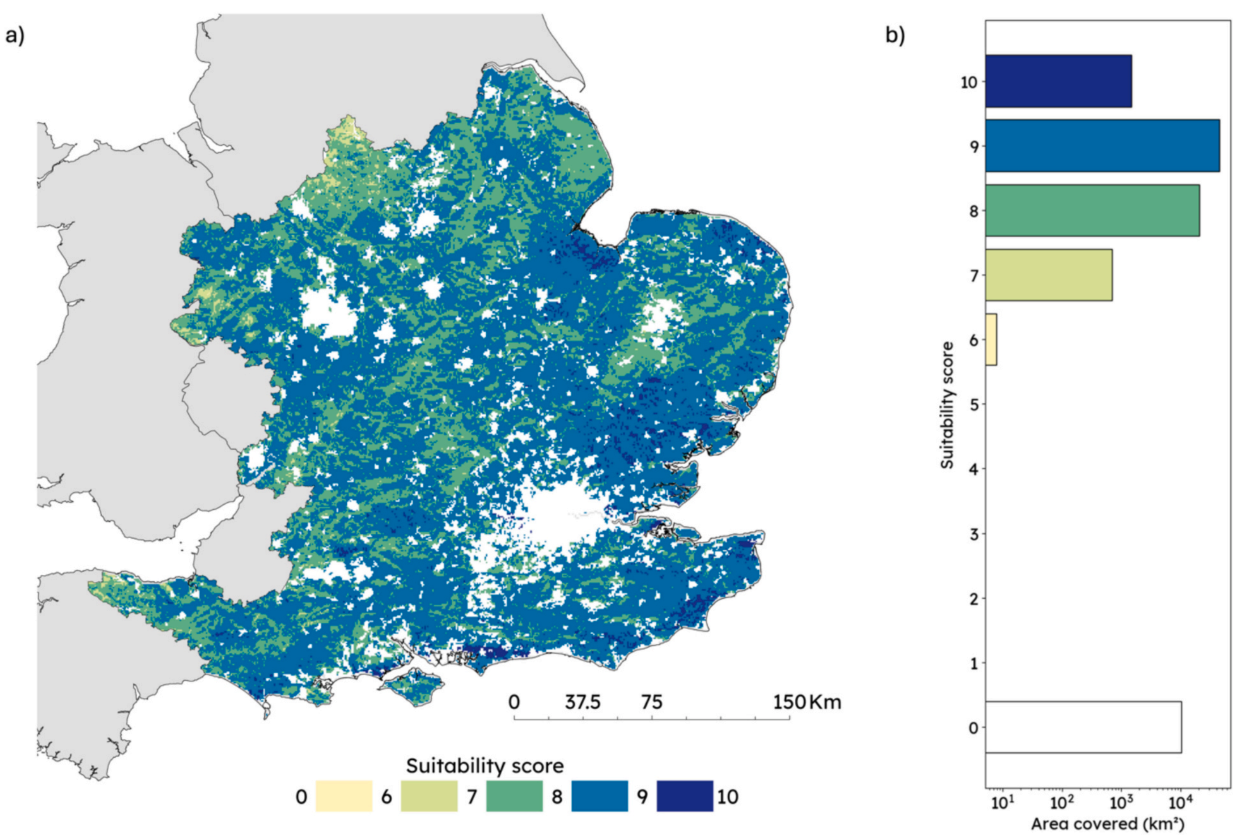


Fig. 9. Agrivoltaic spatial suitability in regions facing water scarcity. a) Suitability across farmland in regions of southern England threatened by water scarcity, and b) the area coverage in these regions for the different agrivoltaic suitability scores.

park installations continue to follow regional trends, up to 115 km^2 of land in the East of England could be required to achieve the 50 GWp target. This region contributes 28 %, 33 % and 29 % of Englands entire production of wheat, potatoes and field vegetables, respectively [67] and so if this additional solar infrastructure were developed proportionally across these three crops, for example, it could reduce the production of each crop by 2.4 %, over 103 km^2, 6 km^2 and 5 km^2, respectfully. This potential loss of agricultural land highlights the far-reaching consequences for food security should land used for these nationally significant crops be converted for ground-mounted solar park use only.

Best and most versatile land is often used for fruit and vegetable production [12], so the loss of such land could necessitate greater importation to meet demand; imported fruits and vegetables are often more greenhouse gas intensive, resulting in an increase in the carbon footprint of British food systems [68]. This demonstrates a trade-off between sustainability aims: reductions in GHG emissions from low carbon electricity generation at the expense of higher emissions in the food system e.g. from transport. With 48 % of the population already concerned about the environmental impact of their food [69], it is crucial that further PV development acknowledges these widespread concerns by minimising the conversion of BMV land. As such, the development of agrivoltaics rather than conventional PV in these areas could contribute to overall reductions in GHG emissions, rather than outsourcing them to other countries [70,71].

4.2. Agrivoltaics as a solution to PV-agriculture land use conflicts

Our analysis shows agrivoltaics could meet the government's PV capacity target several times over, bolstering low carbon electricity generation with minimal agricultural land conversion. This is also considering variations in area capacities, as agrivoltaic technologies have lower MW capacities per hectare compared to conventional south-facing fixed-tilt systems.

Land use conflicts are likely to occur in the south and east of England in particular, where PV suitability is high and where much of Britain's intensive arable agricultural production occurs. It is in these regions where the construction of "nationally significant infrastructure project" solar parks are being announced [65,66]. Agrivoltaics could alleviate these conflicts by maintaining some of the agricultural outputs whilst generating solar electricity. Our findings align with the productivity and economic modelling results found by Garrod, A. et al. [47] and the modelling evaluation of tracking bifacial agrivoltaics by Hussain, S.N. and Ghosh, A. [72], which generally found the net present value (i.e the total value of an asset or investment) of agrivoltaics and the yields of electricity and potatoes to increase towards the south. In more northern and western locations, where suitability is moderate and land use conflicts with high-grade agriculture are less pressing, agrivoltaics could still alleviate these land use conflicts. Agrivoltaic systems combined with livestock are already present across northern and western locations, demonstrating success cases for co-use of land for electricity generation and agriculture in these regions, and siting agrivoltaics with livestock on lower quality agricultural land could be a way to mitigate yield reductions on highly productive land [73]. The National Farmers' Union has shown support for such "multi-functional land use", emphasising the new opportunities for agrivoltaics following recent technological developments, including their contribution to enabling farmers to diversify their income [74,75]. This income diversification is increasingly popular, with an estimated 70 % of UK solar parks being owned or hosted by farmers [76] due to the relative stability of electricity sales compared to the fluctuating economic returns of traditional agriculture [77].

The loss of agricultural land is one of the most cited reasons for planning permission for solar parks to be rejected or contested by local communities [78,79], highlighting the importance of land use conflicts in undermining community acceptance of this technology and hence targets for solar electricity production. Similar difficulties were seen in the case of onshore wind farms, where community backlash resulted in the removal of government subsidies [80]. Reducing the impact of solar development on agricultural land could be one important component of public acceptance of PV expansion; indeed, a study in the US found that 81.8 % of survey respondents would be more likely to support solar developments if they were integrated with agricultural production [81]. However, other aspects of social acceptance, such as the visual impacts of PV infrastructure or lack of consultation, remain a challenge [82,83]. Agrivoltaics, as a PV technology, can have substantial visual impacts that disrupt both visual views and emotional connections to a landscape [84–86], not least because they typically require larger structures to accommodate agriculture, and/or cover wider areas per MW due to reduced panel coverage [16]. This issue is complex, as there are many design options that have different visual impacts and capacities per hectare. The acceptance of this technology therefore relies on the sensitive integration of agrivoltaics into landscapes. This integration will be shaped by project size, local topography, and surrounding features such as forests [73].

The lifecycle and operation of agrivoltaics also differ from conventionally-implemented ground-mounted solar parks, as integrating PV into agricultural settings can subject the panels to more challenging conditions such as greater dust soiling, potentially increasing corrosion [87]. Whilst this study establishes the high potential of implementing agrivoltaics to mitigate PV-agriculture land use conflicts across Great Britain, assessing the social and sustainability aspects of such implementation requires further research.

4.3. Agrivoltaics in regions facing water scarcity and application with crop types

Agrivoltaic systems, especially raised systems, are a practical solution to the escalating challenge of increasing water use efficiency in agricultural systems. As water scarcity is projected to worsen [88], technologies which reduce evaporative water losses from agricultural land and thus enabling farmers to get more 'crop per drop' will become essential [89]. Irrigation use is increasing in Great Britain [90], especially for crops like potatoes, carrots, and cauliflower, due to quality, consistency, and continuity demands placed on farmers by supermarkets, as well as increasingly frequent hot weather and more unpredictable rainfall [91]. Implementing appropriately designed agrivoltaic systems in regions facing water scarcity could potentially maintain crop quality requirements whilst reducing water use compared to open field agriculture.

Potato cultivation is a good example of these benefits. Potato cultivation increasingly relies on irrigation, so the generally high suitability for agrivoltaics on potato cropland supports the suggestion that agrivoltaics could be a valuable tool in reducing water consumption in this crop. Potatoes have grown viably under agrivoltaic shading in Germany [13], where yields increased by 11 % during hot dry conditions [92], demonstrating the ability of agrivoltaic systems to buffer potato production against climate extremes. However, under less water stressed conditions, potato production under agrivoltaics was reduced. A further study from Korea found most growth and yield parameters for potatoes were similar under agrivoltaics compared to full sun conditions, with plant height showing the only significant difference [93]. This suggests potato yields may be maintained in agrivoltaic systems under some contexts and thus should be tested in the UK. Modelling of potato yields in specific locations in the UK has taken the first step towards realising this potential, showing examples of where potato yields may perform better or worse with different static and tracking agrivoltaic designs [72]. Water stress also heavily impacts crop marketability: for example, drought stresses reduce common bean size and thus may lead to failure to meet the standards required for sale for human consumption [94]. Reduced water loss as a result of agrivoltaic shading [24,36,37] could mitigate this effect and thus reduce food waste. However, a study of legumes in a temperate region in South Korea showed some yield losses [20], and so further studies with relevant field bean crops in the UK are needed to understand the compatibility with agrivoltaics.

Lettuce, one of the most commonly tested crops in agrivoltaic systems [14,37,95], is also one of the main fresh vegetables grown in the UK [96]. Yield impacts vary, ranging from large increases to losses, with larger losses typically observed in regions with lower solar radiation. These crops fall within the 'other' category in our analysis, showing some overlap with high suitability land and thus potential for integration with agrivoltaic systems, meriting further exploration. Greenhouse-integrated agrivoltaics with tomatoes have been studied [97–99], which could be particularly relevant in Great Britain as they are already grown under protected cultivation. However, given the relatively low solar radiation in Great Britain and the variable yield impacts observed in other regions, careful consideration of system design would be needed to optimise for both crop and electricity production.

Wheat, a major crop in Great Britain, has the second greatest area coverage of high agrivoltaics suitability, after grass, and it is primarily grown in the East of England. Further, one third of production is in drought-threatened areas. Agrivoltaics has been shown to mitigate drought effects on wheat in Germany [100], although the effects of reduced photosynthetically active radiation (PAR) under raised agrivoltaic systems when water is not restricted may reduce yields, particularly in average grain weight [101]. However, the overall land productivity, typically reported as the land equivalent ratio (LER), is most likely to increase when accounting for the combined outputs for both energy and agriculture [13,17,47,101]. Vertical bifacial agrivoltaic systems have less impact on PAR and do not place height restrictions on agricultural machinery, so may be more appropriate for cereal and potato crops in places where irrigation is sufficient and machinery taller than PV height restrictions is used [102,103]. Where raised systems are implemented, PV-tracker systems can be programmed to improve PAR coverage for underlying crops at crucial growth periods during the day, although this will partially reduce electricity yield [101,103,104]. Vertical agrivoltaic systems have shown promise for compatibility with sugar beet in Belgium [101], another key crop grown in the East of England with high area suitability for agrivoltaics.

Grassland presents the greatest overall area for agrivoltaics due to its extensive land coverage, although with much coverage in the north of Great Britain, where PV suitability is generally lower, it has the lowest mean agrivoltaics suitability score of the cropland studied. This type of application has been demonstrated with grazing livestock already, and with careful site selection considering local environmental and social contexts it could provide a large land area needed for several utility-scale solar parks. With such large scale infrastructure it is crucial that agriculture and ecosystem services are maintained and promoted along with the solar parks [105,106].

4.4. Limitations and need for further research

The findings and conclusions presented in this study are based on modelling spatial data and expert stakeholder inputs. The weighting of each layer was determined by relevant experts from a range of scientific and industry backgrounds, and this could vary for other stakeholders. While we assess the spatial potential for PV and agrivoltaics, including the actual economic performance of such systems in terms of electricity generation and, in the case of agrivoltaics, food production, into our analysis requires further empirical research that is yet to be conducted in Great Britain. Further, our model shows where agrivoltaics could potentially alleviate PV-agriculture land use conflicts, but which design would be most appropriate and indeed whether such systems would be economically viable necessitates field testing of different designs with different crops/livestock and across a range of agricultural contexts; again, such supporting experimental evidence is lacking for Great Britain.

This study shows where agrivoltaics could potentially alleviate PV-agriculture land use conflicts on different cropland, but, while agrivoltaic compatibility with some of these crops has been evidenced elsewhere in Europe, performance has not yet been investigated in Great Britain. Additionally, the CEH cropland classifications do not account for future crop rotation. As such, agrivoltaic developments would likely need to accommodate multiple crop types throughout the system's lifetime. Additionally, other land use types not considered in this study may prove to be incompatible with agrivoltaic development, such as protected landscapes.

5. Conclusion

Utility scale solar parks are urgently needed to generate low-carbon, renewable electricity, thus reducing greenhouse gas emissions from the energy sector while meeting a growing electricity demand. Doing so will require significant land use change. This research provides valuable guidance for decision-makers, such as the UK government, in assessing where PV has a high potential for land use conflicts with agriculture, where agrivoltaics could alleviate those conflicts, where grid reinforcement is needed, and strategically planning energy infrastructure development for cross-sectoral benefits. Most existing solar parks are concentrated on agricultural land in the South West, South East and East of England, and this trend of placing PV on agricultural land in these regions is likely to continue given the government's commitment to bolstering PV capacity and the strong overlaps between areas highly suitable for PV and agricultural land, particularly high grade agricultural land. Agrivoltaics could alleviate PV-agriculture land use conflicts while advancing towards PV goals, with the greatest benefits for mitigating conflicts with high-grade agriculture in the East of England, followed closely by the South East and South West. The multifunctional land use technology could surpass the government's clean power commitments while maintaining outputs from agricultural land and, in some locations, alleviate the detrimental effects of drought on food security and boost sustainable agricultural practices in the face of climate change. Given the pressing land use issues and food and energy security needs in Great Britain, implementing such a multifunctional land use technology could contribute to several government objectives while minimising trade-offs between them, and enable the UK to realise the cross-sectoral benefits agrivoltaic systems have delivered elsewhere in Europe.

CRediT authorship contribution statement

Talitha H. Neesham-McTiernan: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Richard J. Randle-Boggis:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Alastair R. Buckley:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Sue E. Hartley:** Writing – review & editing, Methodology, 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 A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2025.125527.

Data availability

All spatial data layers are publicly available, and the sources are described in the Supplementary material Table 1. Results data will be made available upon request.

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