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Cropland and rooftops: the global undertapped potential for solar photovoltaics

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Abstract

The utilization of cropland and rooftops for solar photovoltaics (PVs) installation holds significant potential for enhancing global renewable energy capacity with the advantage of dual land-use. This study focuses on estimating the global area suitable for agrivoltaics (PV over crops) and rooftop PVs by employing open-access data, existing literature and simple numerical methods in a high spatial resolution of 10 km × 10 km. For agrivoltaics, the suitability is assessed with a systematic literature review on crop-dependent feasibility and profitability, especially for 18 major crops of the world. For rooftop PV, a non-linear curve-fitting method is developed, using the urban land cover to calculate the PV-suitable built-up areas. This method is then verified by comparing the results with open-access building footprints. The spatially resolved suitability assessment unveils 4.64 million km^2 of global PV-usable cropland corresponding to a geographic potential of about 217 Terawatts (TW) in an optimistic scenario and 0.21 million km^2 of rooftop-PV suitable area accounting for about 30.5 TW maximum installable power capacity. The estimated suitable area offers a vast playground for energy system analysts to undertake techno-economic assessments, and for technology modellers and policy makers to promote PV implementation globally with the vision of net-zero emissions in the future.

1. Introduction

Solar photovoltaic (PV) is one of the major technologies pioneering the energy transition to alleviate climate change and achieve the Paris Climate Convention goals [1]. Due to its scalability and ease of decentralization, the adoption potential of PV panels on a local scale is immense. In recent years, global land cover data [2, 3] shows an increasing trend in urbanization and cropland expansion. Installing PV on agricultural land [4] and buildings [5] promotes dual use of land while fueling the energy transition. It is thereby important to investigate the suitable areas for PV installation, especially on these land cover types.

PV systems with crops growing underneath the panels are commonly termed 'Agrivoltaics', 'Agro-PV', or 'APV' across the literature. Besides dual land use, solar panels can offer protection against extreme heat, hail, and wind. However, their shading effect may also affect crop yield. Therefore, to estimate the geographic potential of agrivoltaics, it is important to determine crop-specific suitability.

Different studies have explored the benefits of agrivoltaics for various crops. For example, the Fraunhofer Institute in Germany [4, 6–8] and other institutions [9–17] investigated the general suitability and benefits of agrivoltaics for various crops. Notable literature reviews from Weselek *et al* [13] and Laub *et al* [18] highlight the discrepancies in the suitability of different crops to shading. Such studies address a wide range of crops but are often insufficient when applied globally. To determine global suitable areas for agrivoltaics, investigating individual crops and incorporating up-to-date, comprehensive, and diverse literature are necessary.

For rooftop PV, several studies [19–23] and solar cadastral maps [24, 25] provide estimates of its potential with in-depth analysis of roof-slopes and shading effects. These studies typically employ high-resolution satellite data with computationally intensive techniques. While they are suitable for regional focuses, scaling to a global level is infeasible. Meanwhile, other studies employ different techniques e.g. using satellite-derived settlement maps [26, 27] to calculate built-up fractions based on land cover and socio-economic factors. Though settlement maps encompass large areas, they often carry large errors despite recent improvements [28]. Methods specific to calculating built-up and rooftop PV suitable areas by [29–31] are tailored to typical climatic and cultural assumptions and cannot be extended to a global scale. To our knowledge, so far, there is no open and global data for rooftop PV suitability, or even built-up areas. Recently, Joshi *et al* [32] calculated built-up areas at 10 km × 10 km resolution using machine learning. The analysis considers samples across the globe and shows merit in its simplicity. Although it addresses our focus, the reliability of the method is hampered by several inconsistencies. For instance, the method is based on Open Street Map (OSM) which is incomplete in many regions, and only a limited range of building density is considered in their evaluation. We build upon their ideas to estimate global suitable areas for rooftop PV.

The goal of this paper is to evaluate agricultural and urban areas suitable for PV on a global scale for modeling and analysing future energy systems. In this study, we offer:

1. Agrivoltaics:
   (a) A systematic literature review of over 140 studies to explore the shading response of major crops of the world
   (b) Global agrivoltaics suitability maps for three acceptance scenarios in 10 km × 10 km resolution [33].
2. Rooftop PV:
   (a) A simple and verified method to derive PV-suitable built-up area from urban land cover.
   (b) Global rooftop PV suitability maps in 10 km × 10 km resolution [33].

2. Methods

2.1. Agrivoltaics

Agrivoltaics are still in a nascent stage and require further experimentation and policy incentives before large-scale deployment. The current literature pool majorly focuses on experimental, regional field studies with observations on specific crop yields and economic trade-offs. Since the crop's suitability to shade is the driving factor in adopting agrivoltaics, we also investigate relevant literature on general shading effects. The following data forms the basis of our method.

The EarthStat database [34] openly provides area shares of about 171 crops in the world at 10 km × 10 km resolution.A study by Leff *et al* [35] estimated the global distribution of crops and concluded that over 80% of global agricultural land is used for 18 major crops as illustrated in table 1. All other crops are classified following [34] into 'fruits', 'other cereals', 'other roots', 'tree-nuts', and the remaining are put together into 'others' consisting of vegetables, melons, oil-crops, fiber, forage, etc. We undertake a systematic literature review for these 18 major crops and some minor crop categories. The details of the literature review are available in the supplementary material.

After a broad literature survey, we discovered that the effect of shading on crop yield varies with crop species, shading conditions, and climate. Hence, we propose to classify the crop as 'high (H)' or 'low(L)' suitable and broaden the meaning of suitability from yield to shade-response of plant's growth, and the potential for implementation. The following rules are applied to determine the suitability category for each crop:

(i) If most studies indicate positive or comparable yield outcomes due to shading, it is categorized as 'H'.
(ii) Conversely, if most studies indicate negative effects on crop quality, yield, or growth, it is categorized as 'L'.
(iii) If there is no particular inclination to benefit or loss:
   (a) Higher importance should be given to the studies that implement multiple experimental conditions (e.g. shading extent, regions, crop varieties) than single crop experiments.
   (b) If no relevant study is found, the decision of the crop with a similar growing environment is transferred to that crop.
   (c) If the decision is still unclear or when the available literature is inadequate, the category is by default 'L'.

In table 1, we summarize the relevant findings and indicate the categories allocated to the 18 major crops. The suitability of the minor crop groups is indicated in table 2.

To identify potentials for future energy systems, we consider three policy scenarios, namely 'conservative', 'neutral', and 'optimistic'. These scenarios indicate political and social acceptance and consequently different degrees of technological advancement of agrivoltaics. The optimistic scenario represents a highly favourable future for agrivoltaics, the neutral scenario assumes the continuation of current policies, and the conservative scenario represents a strict policy. For each scenario, we assign a suitability

Table 1. Overview of major global crops, their area shares, suitability categories, and supporting sources.

Crop	Area [35] (1000 km^2)	Cropland share (%)	Suitability	Supporting literature and remarks
Wheat	4028	22	H	• Reduction in yield [13, 36, 37] and limited price performance [17] • Enhanced plant growth and yield in hot and dry climatic conditions [13, 36–38] • Some varieties respond positively, even adapt to shading conditions [39–43]; possibility of limiting shade with bi-facial PV panels [6] • Commercial projects for winter wheat [11]
Maize	2271	13	H	• [44, 45] High yield with reduced soil water evaporation[46]; commercial projects [11] • Reduced yield [13, 18, 47]
Rice	1956	11	L	• Reduced yield [13, 45, 48–53] • Limited applicability [12, 54, 55]; low yield reduction with shade-tolerant varieties [56–61]
Barley	1580	9	H	• Negative impact on yield due to shading [42, 50] • Effects vary with shading extents, climatic conditions [18, 62] • Overall suitability for commercial applications [12]
Soybean	927	5	L	• Negative effects on yield due to shading [18, 45, 48, 50, 63–66] • Slight shading is beneficial [67] or may have insignificant yield effects [68]
Pulses	794	4	L	• Negative effects on yield for different pulses' varieties [18, 69–72] • Under limited shading conditions, selective crop varieties perform well [12, 73–76]
Cotton	534	3	L	• Negative effect on yield, from commercial applications [13, 77] • negligible effects on yield with some varieties [78]; positive effect in extreme hot weather conditions [16] (table 2)
Potato	501	3	H	• Increased yield under shading or climatic conditions [13, 18, 37, 48, 79–83] • ongoing projects [6, 16] • High price-performance ratio [17, 84], but negative effects on plant weight [85]
Sorghum	501	3	L	• No specific supporting literature, but considered similar to millet due to similar harvest areas [86]
Millet	331	2	H	• Negative effects on yield [6, 12, 87, 88] • Some varieties can be as high as two meters and are not considered suitable for agrivoltaics [15] • Studies on improving shade tolerance, or breeding shade-tolerant varieties [89, 90]

(Continued.)

Table 1. (Continued.)

Crop	Area [35] (1000 km^2)	Cropland share (%)	Suitability	Supporting literature and remarks
Sunflower	290	2	L	• Reduced yield [6, 12, 13] • Limited shading may be favourable in drought-prone areas [91]
Rye	288	2	H	• Effect of shading is not significant [6, 12, 45, 84], and may vary with extent of shading [18, 92]
Rapeseed/canola	283	2	H	• Insignificant effect on yield [6, 12, 43, 84, 93], high yield in varieties with high light use efficiency [94] • Plant growth in pre-flowering stages impacted adversely due to shading [95, 96], reduced oleic acid compositions [97]
Sugarcane	265	1	H	• Negligible effect on yield [16] and possible advantages with less evaporation [98, 99], especially in early growth stages [100], but may hinder growth later on [101]
Groundnut/peanut	247	1	L	• Shading degrades plant growth, quality, and yield [94, 102–105]
Cassava	235	1	L	• Negative effects due to shade [106–110] • Acceptable yield [12]
Sugar beet	154	1	L	• Limited Suitability [12] • Negative effects of shading [111–114]
Oil palm fruit	72	<1	L	• Unsuitability due to tree height • Shade suitability for seedlings [115, 116]; [13] indicated mixed shade effects
Major 18 crops	15 256	85		

factor, where 0 indicates no suitability of the area for agrivoltaics and 1 indicates 100% suitability.

The suitability factors are presented in table 3. For crop category L, the implementation of agrivoltaics is expected to decrease crop yield, thus we consider a suitability factor of 0 for both neutral and conservative scenarios. However, in the optimistic scenario, a value of 0.15 is assigned based on the regulation proposed by the German Institute for Standardization (DIN), which regulates that at least 85% of the agricultural land should be reserved for conventional agricultural purposes [150]. For crop category 'H', we assign the suitability factor of 0.15 for the conservative scenario based on the same reason, while a value of 0.25 is assigned for the neutral scenario based on current policy preparations in countries where incentives are provided to farmers for agrivoltaic implementation provided yields stay above a limit i.e. 66% in Germany [150] and 80% in Japan [56]. Finally, the optimistic scenario assigns a suitability factor of 0.5 for category 'H', taking into account the potential for significant increases in the suitability of agrivoltaics because of technological advancements and the development of more shade-tolerant crop varieties.

Additionally, since the PV module density for agrivoltaics is lower than a standard open-field PV module, we propose a reduction factor of 0.8 to account for the decrease in installable power capacity per unit area. The harvested area share of every major crop and minor crop group are used as weights in every 10 km × 10 km pixel to calculate an overall suitability factor in each pixel. The factors are then multiplied with cropland cover data [3] to obtain Agrivoltaic area potential maps for all scenarios.

2.2. Rooftop PV

For rooftop PV, we use urban areas from land cover data to distinguish available built-up areas for PV installation. It is necessary to exclude areas such as roads, railways, and buildings with special uses, for example, buildings of religious or historic significance like monuments. Since only a fraction of the remaining areas is suitable for PV installation, assigning rooftop PV suitability solely as urban land cover data is not sufficient.

To estimate the available rooftop areas for PV installation, we propose that the available rooftop area for PV installation is equivalent to the built-up area which is correlated with the urban density in a given region. Then, we develop a numerical model to investigate the relationship between built-up areas and urban density in various geographical regions

Table 2. Description of minor crop groups, their suitability categories, and supporting sources.

Crop group	Crops included	Suitability	Supporting Literature and remarks
Fruits	apple, apricot, avocado, banana, blueberry, carob, cashew apple, cherry, cranberry, currant, date, fig, gooseberry, grape, grapefruit, kiwi, lemonlime, mango, orange, papaya, peach, pear, persimmon, pineapple, plantain, plum, quince, raspberry, sour cherry, strawberry, tangerine, mandarine, clementine, and other fruits	H	• Positive effects of shading on mango [13, 117], strawberry [18, 118], black currants [18, 119], dwarf banana [120], grapes [18, 121, 122], apple [18, 123, 124], kiwi [13], black berry [13, 18], blue berry [18], lemon [18], orange [18] • Effects of shading vary depending on the specific type of crop but still have high yield outcomes (strawberry [18], blueberry [13], lime [125]
other cereals	buckwheat, canary seed, fonio, mixed grain, oats, quinoa, triticale	L	• Negative effect on yield [18, 92, 126–128] • Positive effect of shading on grain weight [129] and seedlings [130]
other roots	taro, yam, yautia, other tubers	H	• Positive or insignificant effects on plant growth and yield seen for taro [81, 87, 88, 109, 131, 132], cocoyam [133], yam [131, 134, 135] • Negative effects on tannia [109], yam [109], some crop yield loss according to [18]
tree-nuts	almond, brazilnut, cashew, chestnut, hazelnut, pistachio, walnut	L	Average plant height is too high for agrivoltaics, but may work with seedlings as in oil palm in table 1
others	abaca, agave, alfalfa, anise, areca, artichoke, asparagus, beet, cabbage, carrot, castor, cauliflower, chilli, cinnamon, clove, clover, cocoa, coconut, coffee, cucumber, eggplant, flax, garlic, ginger, bean and corn greens, green pea, green onion, hemp, hop, jute, kapok, karite, kolanut, lettuce, linseed, mate, melons, mixedgrass, mushroom, mustard, nutmeg, oilseed, okra, olive, onion, pepper, peppermint, pimento, poppy, pumpkin, pyrethrum, ramie, rubber, safflower, sesame, sisal, spinach, stringbean, tea, tobacco, tomato, tung, turnip, vanilla, watermelon etc	L	• Negative effects on crop yield, growth or quality for leafy vegetables (lettuce, spinach, basil, alfalfa) [18], sweet potato [106, 109, 136–138], chilli [139], tomato [140], eggplant [87] • Effects of shading are positive or not significant for lettuce [141], cucumber [141], spinach [84], salad [84], tomato [13, 142, 143], coffee [13, 144], sweet pepper [13, 18], squash [18], bell pepper [18, 145], olive [146], chilli pepper [81, 87, 143], cacao [147], vanilla [148], eggplant [81], cowpea [149] • Existing projects [13] for tomato, watermelon, eggplant, cabbage, cucumber, celery

Table 3. Weighting factors for scenarios and corresponding scores.

	Conservative	Neutral	Optimistic
L	0	0	0.15
H	0.15	0.25	0.5

based on the building footprints derived from OSM. For this purpose, we choose administrative areas derived from the Database of Global Administrative Areas (GADM) [151], an open-source database that provides administrative area maps for all countries.

To ensure the quality of data derived from the crowd-sourced OSM, we cross-check them with satellite data in selected study areas. In total, we analyse 202 administrative regions of varying sizes with acceptable OSM data quality spanning 46 countries across all continents except Antarctica as figure 1 shows. To calculate the built-up area in each administrative region, we utilize OSM*nx*, a python package for analysing geo-spatial geometries from OSM [152]. In the calculation, we also exclude certain building types that are deemed unsuitable for PV installations, including terrace, cathedral, church, chapel, monastery, mosque, religious, shrine, synagogue, temple, stadium, and ruins.

In addition, we also calculate the total area and urban density in each administrative region. Urban density is determined as the average urban fraction within an administrative area and is calculated from Copernicus Land Cover Data [3]. As depicted in

Figure 1. Distribution of administrative region samples.

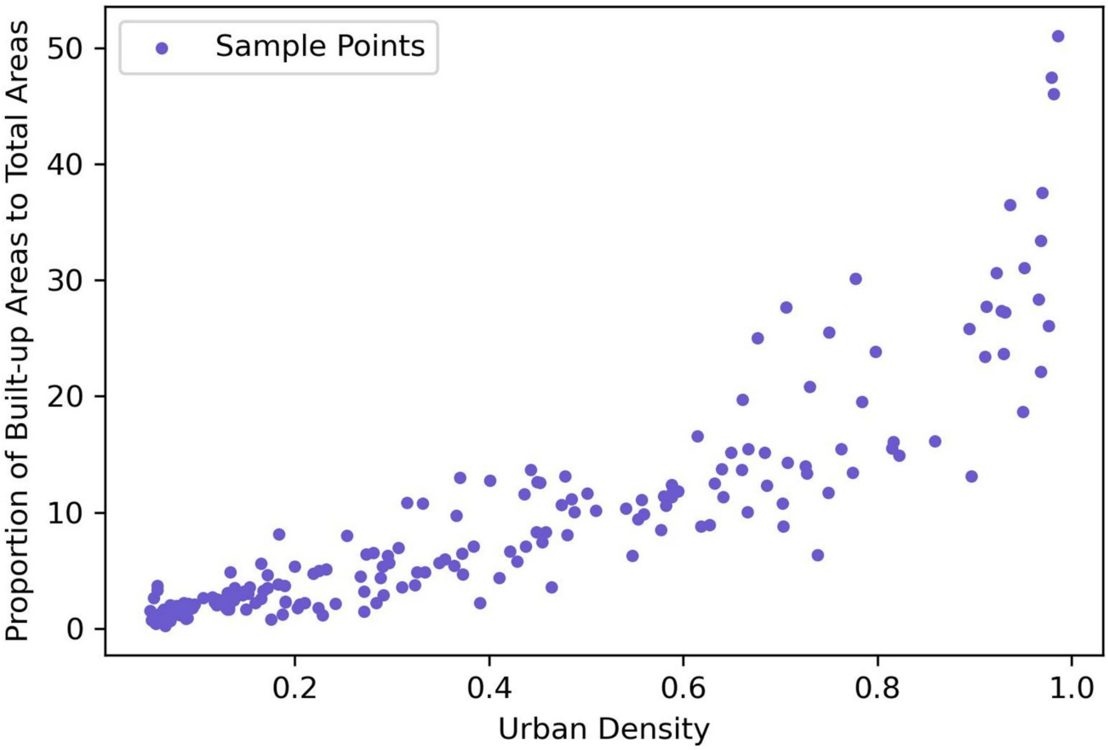
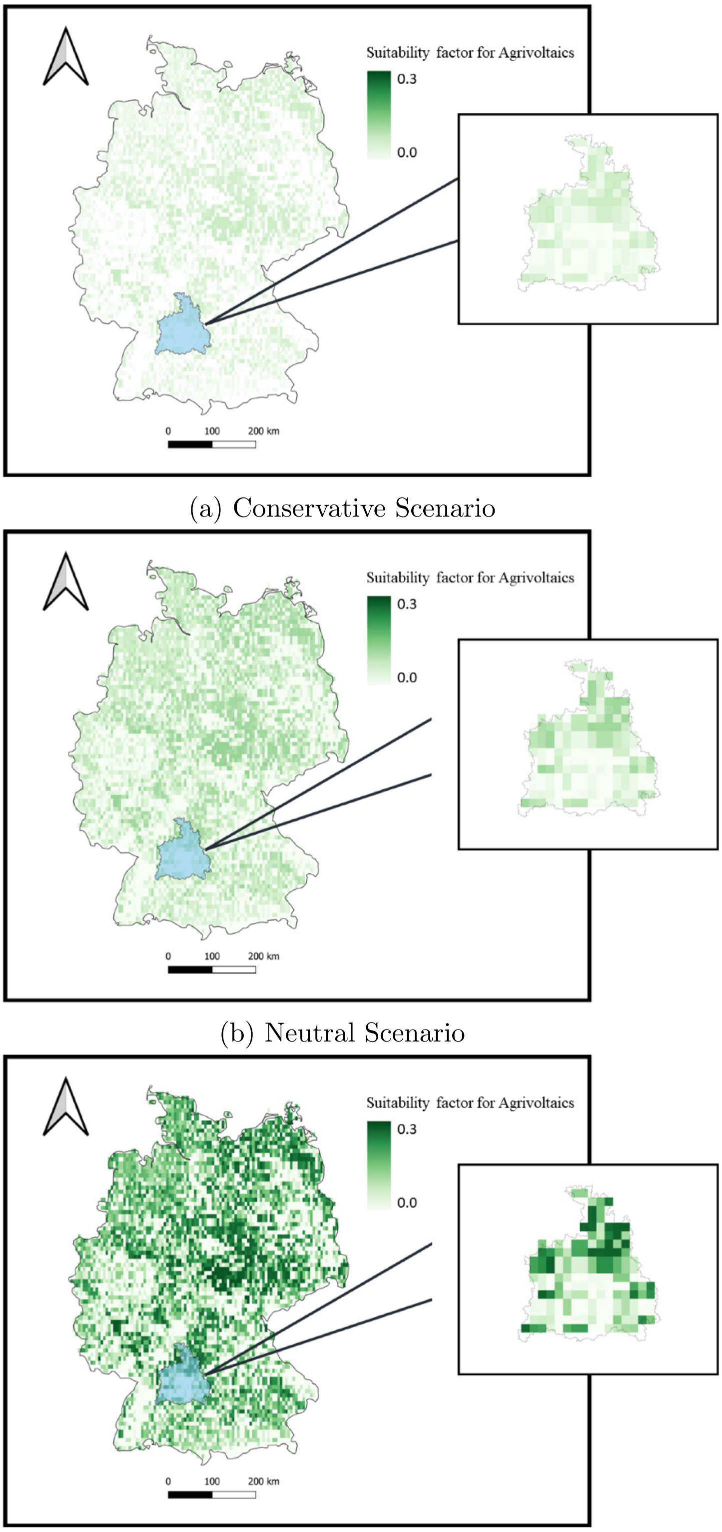


Figure 2. Scatter plot for urban density and the proportion of built-up areas.

figure 2, we can observe a clear exponential correlation between urban density and the proportion of built-up area. To establish this non-linear relationship, we apply curve-fitting using *scipy* python package which utilizes 'least square' to minimize the sum of squares of nonlinear functions [153]. To evaluate the performance of the curve-fitting equations, three statistical metrics are considered: root mean square error (RMSE), Pearson correlation of coefficient (PCC) [154] and R2 score.

3. Results and discussion

Here, we present and discuss the resulting suitability for agrivoltaics and rooftop PV using Copernicus Land cover data from 2018 [3]. Since land use changes develop slowly, we can safely make our scenario assumptions by considering present topography. For rooftop PV, the following section entails also a segment on validation. Afterwards, we address the limitations and scope for improvement.



(a) Conservative Scenario

(b) Neutral Scenario

(c) Optimistic Scenario

Figure 3. Suitability factors for Agrivoltaics in Germany and administrative NUTS-2 region (10 km × 10 km).

3.1. Suitability factors for agrivoltaics

The aggregated suitability factor for agrivoltaics in different scenarios is illustrated in figure 3 for Germany and the administrative NUTS-2 region of Stuttgart in southern Germany. Since the harvested area of every crop per pixel is accounted for, the effects of crop rotation, inter-cropping and regional distribution of crops are inherently considered in the estimation of suitability.

Considering about 17 million km^2 of cropland in the world [35, 155], this makes about 4.64 million km^2 cropland suitable for agrivoltaics in the

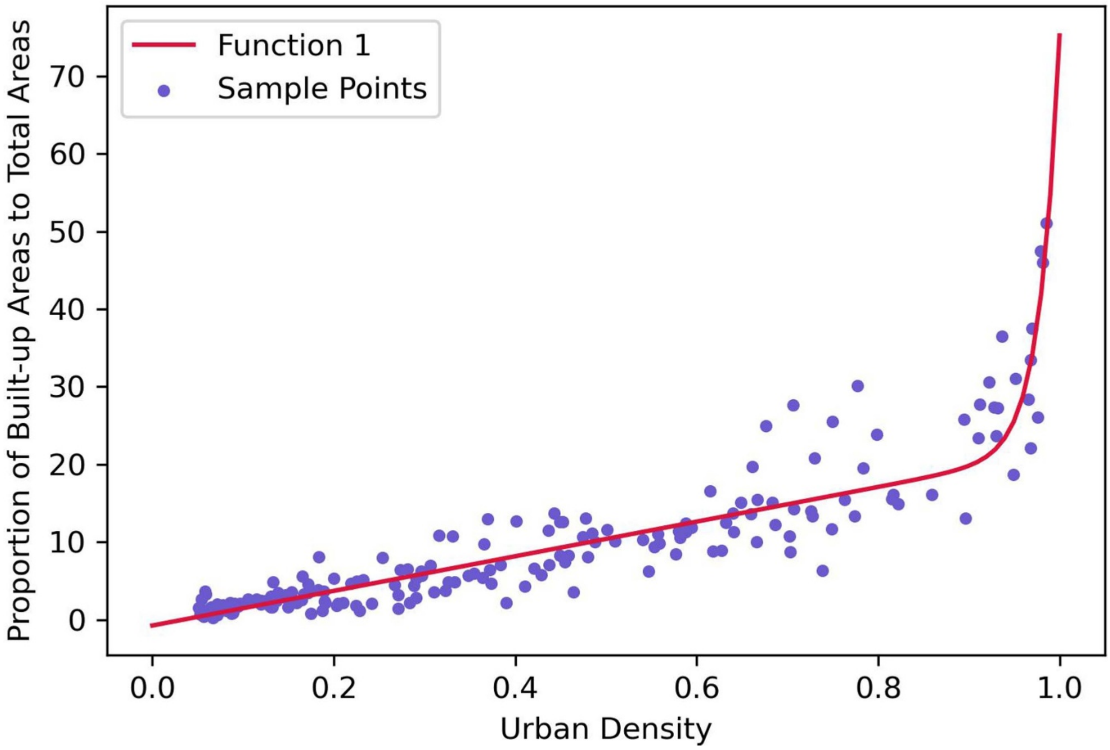


Figure 4. curve-fitting results.

optimistic scenario, about 1.69 million km^2 in the neutral and 1.02 million km^2 in the conservative scenarios. A simple conversion from the available area from the map to power capacity [156] (equations (8), (9)) indicates a global maximum installable capacity of about 217 Terrawatts (TW) in the optimistic scenario, 79 TW in neutral and 48 TW in the conservative scenario.

3.2. Suitability factors for rooftop PV

To ensure the robustness and accuracy of our model in determining the correlation between urban density and the proportion of built-up area, we split our data into 70% training and 30% testing data. Leveraging the observed exponential curve, we select the curve-fitting function to be a combination of the exponential and linear functions. Following the least square optimization process, the respective coefficients for this function are presented in equation (1). Our statistical evaluations indicate an RMSE of 3.578, a PCC of 0.920, and an R2 score of 0.838. The resulting curve-fitting function is further illustrated with data points in figure 4. Based on our calculation, the estimated total built-up area (excluding special buildings) across the globe is 0.43 million km^2.

$$F = 2.728 \cdot 10^{-19} \times e^{46.728 \cdot x} + 22.300 \cdot x - 0.746 \quad (1)$$

However, the suitable rooftop area for PV is a fraction of the built-up area. Different studies have different values for this fraction, ranging from 0.40 to 0.66 [32, 156–163]. In this paper, we consider a reduction factor of **0.5** to account for roof inclinations, chimneys, windows, and maintenance space. The suitable area for rooftop PV therefore is about 0.21 km^2, theoretically translating [156] to 30.5 TW maximum installable power capacity.

The final rooftop PV suitability map is generated on a 10 km × 10 km grid using the urban area land cover [3]. As an illustration, the suitability map for rooftop PV for Germany and the administrative NUTS-2 region of Stuttgart are presented in figure 5.

3.2.1. Validation

To validate our curve-fitting model, we compare our model results to the Microsoft AI building footprints, which provide open building footprint data [164]. Despite its large coverage, compared with satellite images, we still find incompleteness for certain regions in some countries. Hence, we filter the administrative areas with high-quality Microsoft AI data by comparing them manually with satellite images. The bias of the built-up area between Microsoft AI and our prediction is calculated and presented in figure 6.

From this bias plot, we can observe that for most administrative areas, biases between our curve-fitting results and the Microsoft AI building footprint acceptably range from −2.5 to 2.5 km^2. From the negative bias, we can tell that our method tends

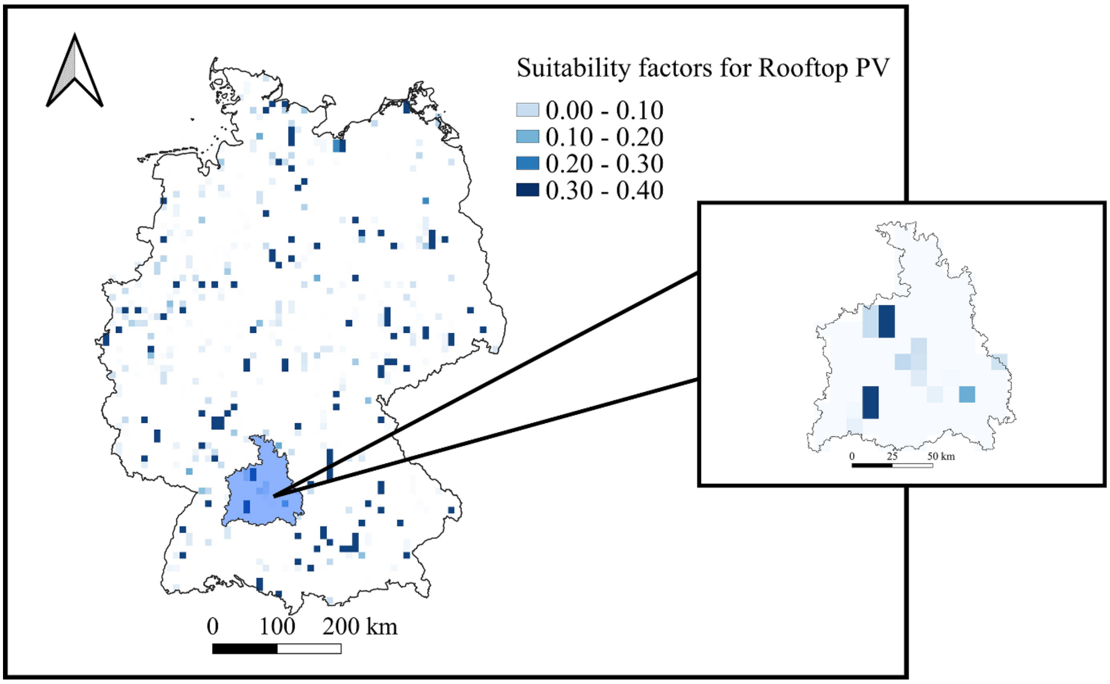


Figure 5. Suitability factors for Rooftop PV in Germany and administrative NUTS-2 region (10 km × 10 km).

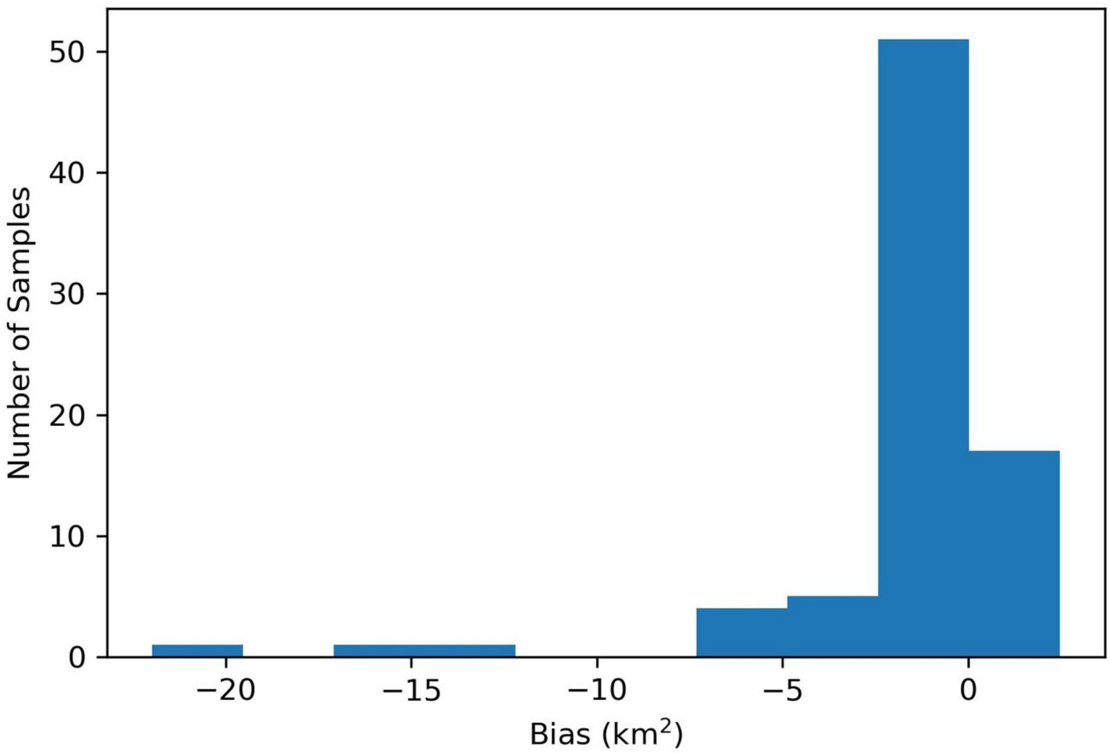


Figure 6. Bias between built-up area calculated by curve-fitting and Microsoft AI building footprints.

to underestimate the built-up area. This is because we exclude varieties of building types in OSM built-up area calculations. Meanwhile, some samples have large negative biases and are clearly underestimating the built-up area. To further investigate this problem, we examine the relationship between RMSE, urban density, and total area as shown in figure 7. We discover that most samples with a large RMSE (marked as excluded in figure 7) between our curve-fitting and the Microsoft AI building footprint have either very

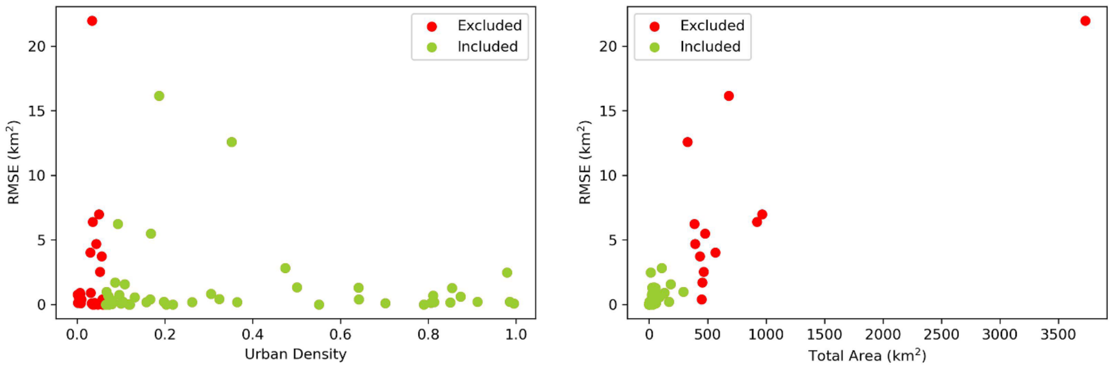


Figure 7. Scatter plot between RMSE and urban density and total area.

low urban densities or very large total areas. Therefore, we exclude samples with urban density smaller than 0.06 and total area bigger than 300 km^2. By excluding these samples, the RMSE between our curve-fitting results and the Microsoft AI building footprint decreases from 3.804 to 0.782, the PCC increases from 0.892 to 0.979, and the R2 score from 0.707 to 0.952.

3.3. Limitations and future work

As our focus lies on estimating the geographic potential through the generalized area suitability factors, our analysis does not incorporate techno-economic, political, or social effects, such as land use changes, economic value of land, or local shading effect. For agrivoltaics, the scenarios and suitability take limited consideration of the farmers' needs. Here, we assume only the best case that the farmers will always respond well to the government's incentives and cooperate when there is a positive effect on crops. Therefore, the resulting data does not represent realisable potential for agrivoltaics or rooftop PV, but the theoretical potential derived from the available and suitable areas.

The suitability factors are assumptions based on current trends in policy, previous experience, and judgment, and we suppose these assumptions are acceptable in the research domain of future energy. There are considerable uncertainties in our estimations for the future, with evolving technological and socio-political dynamics. Addressing these underlying uncertainties is still an open point, and is beyond the scope of the study.

For agrivoltaics, we conduct a systematic literature review that covered various crops. However, this review process is performed for only major crops and a few minor crops with significant harvest areas in the world. We acknowledge that certain categories, such as 'fruit' and 'others', contain a vast number of crops, which challenges our review process. The literature review is not comprehensive for every cultivable crop, but still sufficient enough to conclude agrivoltaic suitability.

In rooftop PV analysis, we examined a range of climatic, social, and economic factors, including mean annual and seasonal temperatures, Human Development Index, population density, etc. to identify their correlations to built-up areas. However, due to the limited and non-homogeneous set of samples and available data, no firm correlation was established. Hence, a clear and simplistic approach to the observed correlation is applied. The method can be extended when better data becomes available.

Meanwhile, our validation process reveals that the curve-fitting function does not provide reliable results when the study area has an urban density smaller than 0.06 or a total area bigger than 300 km^2. Consequently, the final suitability is calculated globally in 10 km $\times$ 10 km grids. Additionally, since our focus is to calculate the built-up area suitable for rooftop-PV, the estimated area from curve-fitting excludes certain building types and should not be mistaken as the overall built-up area.

4. Conclusion

In this study, we investigate two growing land cover categories, cropland and urban areas to identify global suitable areas for installing agrivoltaics and rooftop PV while promoting dual land use.

Since the feasibility and profitability of agrivoltaics vary with crop types, with a systematic literature review we assign a suitability type to every major crop category at a 10 km $\times$ 10 km resolution. We propose suitability factors for three future scenarios representing technological development and acceptance. In an optimistic scenario, this accounts for a global 4.64 million km^2 suitable area for agrivoltaics equivalent to a maximum installable power capacity of 217 TW.

For rooftop PV, we observe that the built-up fraction within administrative areas is highly correlated to the urban area. Therefore, we develop a non-linear curve-fitting model with OSM samples across the world. Using this model, we estimate 0.21 million km^2 of rooftop PV-suitable area globally, accounting for 30.5 TW geographic potential.

These global geographical estimates indicate the vast theoretical potential of solar PV on just two land cover types. By incorporating land-use dynamics, socio-economics, policy and meteorological factors, a more accurate, realisable potential can be estimated on local and regional scales. The examination of geographic potential itself can be enhanced with better quality of data and by exploring social and technological uncertainties. This study and the resulting open-access data provide a strong basis to promote corresponding energy research even in countries with limited data provisions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: 10.5281/zenodo.7467883. We provide global 10 km × 10 km maps of built-up area and suitability factors for agrivoltaics and rooftop PV. All data used in this study are openly available, relevant files are provided as supplementary material.

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