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Room for renewables: A GIS-based agrivoltaics site suitability analysis in urbanized landscapes

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HIGHLIGHTS

find the best AV locations.

able for agrivoltaics.

A R T L C L E I N F O

Multi criteria decision analysis

Editor: Paul Crosson

Keywords: Site selection

Agrivoltaics

Potential analysis

voltaic suitability scores.

be identified using GIS-MCDA.

· Crop type is a key determinant of agri-

performance.

GRAPHICAL ABSTRACT



ABSTRACT

CONTEXT: Flanders, a densely populated region in Belgium, faces challenges in balancing agricultural production with renewable energy targets. Agrivoltaic systems combine solar energy and agricultural activity on the same field and can increase land productivity while simultaneously expanding the share of renewables. However, its potential and implications for the region is geographically complex.

Abbreviations: AHP, Analytic Hierarchy Process; AV, Agrivoltaics; BD72, Belgian Lambert 72; FOD, Federale Overheidsdienst (Federal Public Service); GHI, Global Horizontal Irradiance; GIS, Geographic Information System; HSAT, Horizontal Single Axis Tracker; IPCC, Intergovernmental Panel on Climate Change; MADM, Multi-Attribute Decision Making; MCDA, Multi-Criteria Decision Analysis; MWh/ha, Megawatt-hour per hectare; PV, Photovoltaic; SAW, Simple Additive Weighing; VEKA, Vlaams Energie- en Klimaatagentschap (Flemish Energy and Climate Agency); VITO, Vlaamse Instelling voor Technologisch Onderzoek (Flemish Institute for Technological Research).

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Dual land use Renewable energy

OBJECTIVE: This research aims to assess the suitability of Flanders' 658,000 ha agricultural land for agrivoltaic systems, using a geographical multi criteria decision analysis (MCDA), considering environmental, technical, agronomic, and cultural criteria to optimize land use for simultaneous food and energy production.

METHODS: We describe a Geographic information system Multiple-criteria decision analysis (GIS-MCDA) using QGis-software. Expert stakeholder input was incorporated by applying the pairwise comparison method from the analytical hierarchical process (AHP). Criterion weights are applied to seven classifiers: irradiance, soil suitability, slope, orientation (aspect), crop type, flood risk and distance to roads/grid. Areas with particular societal, ecological, economic, and historical importance are excluded. The resulting scores are then placed in their agronomic and energy context.

RESULTS AND CONCLUSION: Our analysis indicates that 60.4 % of Flanders' farmland is well suited for agrivoltaic development, and that 9 % of farmland under AV would suffice to meet future energy targets in combination with rooftop PV. After our analysis, 11.5 % of total agricultural land was classified as less suitable, 28.74 % as somewhat suitable, 19.40 % as suitable and 12.22 % as very suitable.

SIGNIFICANCE: Transitioning away from fossil fuels requires a multi-facetted approach. Agrivoltaic systems can contribute to this shift, opening up additional land without significantly compromising farm revenue. This study presents insights into the feasibility and geographic potential of agrivoltaic systems in densely populated regions with intensive agriculture like Flanders and can serve as a base for future discussion regarding dual land use planning decisions locally and abroad.

1. Introduction

Transitioning away from fossil fuels and nuclear power requires a shift toward renewable, low-impact energy sources. Currently, Flanders imports 65 % of its energy (Nationale Klimaatcommissie, 2023) with sustainable sources accounting for just 10 % of the total (Vlaams Energie- en Klimaatagentschap (VEKA), 2024). The target to completely transition to a carbon neutral electricity mix by 2050, and shift to a more electrically powered society has been set (Vlaamse regering, 2019). Additionally, in Belgium, the nuclear exit is scheduled for 2035, further putting strain on the current reliance on fossil fuels (FOD Economie et al., 2021).

As of 2024, the Belgian renewable electricity is primarily composed of wind power as well as rooftop solar production. Belgium's geology limits the potential of geothermal or hydroelectric power, but there has been a notable rise in wind power over the past decade (FOD Economie K.M.O. Middenstand en Energie, 2023). Solar energy production has predominantly expanded on rooftops, whereas ground mounted utility scale solar projects have been slow to develop (Goigne and Van Evercooren, 2024), facing a number of barriers (Van Opstal and Smeets, 2022). Nevertheless, solar photovoltaic (PV) has the potential to become the majority global energy source (Victoria et al., 2021).

Agrivoltaics (AV), a system that combines renewable energy production and agricultural activities, has emerged as a novel approach to enhance land productivity while addressing climate change (IPCC, 2022). First conceived in 1982 (Goetzberger and Zastrow, 1982), crops were proposed as a secondary revenue to utilize the formerly neglected area between solar modules. Since the revival of AV in Europe in 2011 (Dupraz et al., 2011), increasing priority has been given to crop yields under AV. By safeguarding crop yield, vast areas of agricultural land may become available for sustainable energy production whilst maintaining their agronomic value.

AV production systems should be individually tailored to specific crops, taking into account location, climate, and the corresponding agronomic and electrical potential. Additionally, AV specific crop management strategies should be implemented, tailored to the system dimensions and solar panel layout. The DIN SPEC 91434 (Deutsches Institut für Normung, 2021) classifies agrivoltaic systems in two categories: crop production may be done either below elevated PV or between vertically oriented bifacial PV module with or without tracking systems. Nevertheless, the most appropriate AV design and its implementation often remain unclear, despite its large potential (Ali Khan Niazi and Victoria, 2023).

While common for PV and wind, AV-specific site suitability studies are limited in number. Willockx et al. (2022) investigated the larger European context for general AV potential. However, this study used a much coarser scale. In Japan, a Geographical Information System (GIS) study on AV established 'good AV practices' and makes a case-study for Ine town in Kyoto Prefecture (Nakata and Ogata, 2023). However, only marginal farmland was selected for AV expansion without considering additional geographic inputs. Elkadeem et al. (2024) described an AV specific GIS Multi-Criteria Decision Analysis (MCDA) method for the Swedish territory, based on a number of criteria such as irradiance, precipitation, water stress and seasonal evapotranspiration revealing 8.6 % of the country's total area as suitable for AV systems. A comparable approach, integrating elements from the analytical hierarchical process (AHP) for AV site selection was taken for the Gunungkidul Regency in Indonesia (Tri Nugroho et al., 2024). Here, criteria including climate, land use, grid connectivity and water features nearby were integrated alongside a number of constraints. Recently, Fattoruso et al. (2024) also compiled a comprehensive range of criteria (land use, GHI, elevation, slope, distances to power lines...) in a GIS-MCDA using the AHP method for southern Italy, and identified 65 % of the Italian agricultural landscape as potentially suitable for AV, and a study of the Canadian AV potential revealed that only 1 % of farmland should transition to AV to capture Canada's energy need (Jamil et al., 2023). Our analysis specifically explores the region of Flanders in the north of Belgium. In doing so, it aims to assess AV suitability and potential in a high-density region.

Flanders represents one of the most populated regions in Europe (European Environment Agency, 2024). Together with the Randstad region surrounding Amsterdam in the Netherlands and the Ruhr area in Germany, it is distinguished from other radially expanding urban centers by a considerable proportion of built-up land in one interconnected cross-border area. The peri-urban context in Flanders is characterized by a high degree of urban sprawl (Vermeiren et al., 2018) and ribbon building (Vermeiren et al., 2022), scattered in between agricultural and industrial zones. This pattern results in a fragmented energy demand, and has to contend with an ageing electric distribution grid. At the same time, a variety of soil types (Marechal and Tavernier, 1974) and the temperate maritime climate make for a high yielding farming region. Agricultural land represents 45 % of the total Flemish area (Agentschap landbouw en zeevisserij, 2024), but is under pressure by expanding urban and industrial activities, challenging the preservation of existing farming operations (Beckers et al., 2020). Building upon the challenges posed by urbanization and the need for diversification in farming businesses (Pölling et al., 2016), AV systems can offer additional revenue streams and may also result in competitive energy production and stable crop yields (Agostini et al., 2021).

MCDA techniques are widely employed to select optimal locations for certain land uses based on a number of constraints and selection criteria. Often implementing pairwise comparison method from the AHP approach (Saaty, 1987), these criteria are balanced with each other to provide a single potential score for each alternative. This type of GIS based classification systems have been employed extensively in solar-PV site selection (Osorio-Aravena et al., 2022; Spyridonidou and Vagiona, 2023). By combining different geographic, spatially bound datasets, it is possible to assess areas of land for the desired effect and assign them a relative suitability score.

We aim to present a detailed assessment of the technical potential for agrivoltaic production in Flanders, an urbanized and fragmented landscape, using a GIS-based MCDA method. We include a number of criteria that have been identified by other AV site selection studies, and augment these with parcel-specific data on soil suitability as well as, among others, societal (heritage) and natural (flora and fauna value) constraints.

In this manuscript, we present a multi-attribute decision making (MADM) analysis for determining appropriate areas for AV systems in Flanders, where commercial AV systems are starting to emerge. We start by identifying techno-agro-socio-economic criteria applicable to AV suitability, assigning weights to the main evaluation criteria and defining restriction criteria for areas where AV would be unsuitable. We demonstrate that the AV production potential in Flanders shows no clear regional bias yet is highly dependent on the suitability of individual crops. While certain crops are more suitable for AV, our analysis reveals a remarkable consistency across the crop types. More than 60 % of each individual crop area attaining a similar suitability score, suggesting that agrivoltaic systems can be installed in a multitude of locations. The AV suitability map was used to calculate the electrical potential, with 9 % of cropland under AV being sufficient to meet Flanders' future sustainable energy goals.

2. Method

This study focuses on current agricultural land within the region of Flanders of Belgium (Fig. 1) where agricultural land makes up 48 % or 650,000 ha of the total 1,362,500 ha using the reference year 2022 and for which an extensive collection of geodatasets is available. We maintained the local EPSG: 31370 (BD72 / Belgian Lambert 72) coordinate reference system throughout this analysis and transformed input layers not adhering to this coordinate reference system to the same. Vector geodatasets were rasterized to a 10 m \times 10 m resolution. All mapping operations were performed in Qgis version 3.34.2 "Prizren" (QGIS Association, 2023).

To determine the most suitable locations in Flanders for the combined production of agricultural commodities and PV-electricity, we define a GIS-MADM method. Our classification of cropland for AV suitability is based on criteria identified from a literature study of AV and PV site selection research conducted abroad. Our method visualized below (Fig. 2) principally adapts the work described by Elkadeem et al. (2022), and utilizes criterion cutoffs from multiple solar and AV site selection studies as detailed in Table 1.

2.1. Data gathering, assigning crop and soil scores, identifying unsuitable areas and dataset assembly

In the initial step, the most recent relevant geodatasets on technical, socio-economic, natural, and agricultural criteria were identified and collected (Fig. 2 (1)). We include 7 criteria contributing to AV site suitability (Table 2). First, solar irradiance contributes the principal energy input for the AV system. Secondly, the fields agronomic characteristics are included. Due to its significance for crop potential, we assess soil suitability, taking into account the specific crops of our



Fig. 1. Geographic location of the study area of Flanders and the total available agricultural land. Insert: Flanders in its western european context (yellow) makes up the northern half of Belgium (red) and surrounds the Brussels capital region (hatched with diagonal lines, not included in study area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



Fig. 2. Flowchart of the used GIS-MADM methodology. Step (1): Data gathering and assembly. Step (2a): Assembling datasets, assigning crop and soil scores. Step (2b): Identifying unsuitable areas, assembly exclusion layer. Step (3): survey administration and processing. Step (4): Geodataset preparation. Step (5): Weighted overlav analysis.

Table 1

Weighted and scaled crop group suitability scores (between 0 and 1; 1 being better) following Asa'a et al. (2024) and Reher et al. (2024b) and clustered following Van Gossum et al. (2014).

Crop group	Scaled score (0-1)
Arable crops	0.4315
Fruit crops	1
Maize	0.1627
Grass (short cycle grazing or forage)	0.8630
Vegetables	0.4726

reference year and the classification system described by Van Gossum et al. (2014). By overlaying crop type for our reference year of 2022 with their soil suitability grid value, a crop dependent soil potential is determined for every pixel (Supplementary Table S 3). Then, both the field slope, as well as its aspect are assessed: level, or slightly sloped south oriented parcels are preferred and receive a favorable rating whereas steep or north facing plots are classed as unfavorable. Thirdly, the crop groups determined earlier for the soil parameter (Table S 3) are rated according to their AV crop suitability (Fig. 2 (2a). For this, a ranking of crop responses to shading was established based on an extended version of the meta-analysis by Asa'a et al. (2024) as well as on field trial results from the Belgian AV pilot sites (Reher et al., 2024a-c; Willockx et al., 2024) and practical considerations for AV cultivation (Supplementary Table S 1). Here, we integrate the crop's shade tolerance with an assessment of crop management, crop rotation and construction impact on a scale from "1" to "4" (higher is better). Crop management gets assigned a score of "1" when extensive agricultural machinery is required, up to a level of "4", in cases when minimal impact from machinery is expected in an AV context, or when cultivation is done entirely manually. Crop rotations are assigned "1" when three or more crops are commonly rotated. A score of "2" is assigned for short cycle rotations or forage crops, "3" for short-lifespan perennials such as blueberries and "4" for long-term perennial crops such as pomefruit.

Finally, the type of AV construction required is ranked by estimated module density and cost. High, shade sensitive crops are assigned "1", intermediate or extensive shade sensitive crops are assigned "2", shade sensitive perennials are assigned "3" and more shade tolerant perennials are assigned "4". These scores are then weighted with the shade tolerance and normalized 0–1 (Table 1). Fourth, flood prone areas are marked as less favorable due to the increased risk of soil texture degradation. Finally, we assess whether a location is likely to be a near a major grid connection. Because for Flanders this data is not freely available, we use the approximation from Elkadeem et al. (2022) whereby a 5000 m buffer is applied to the main roads. Eventually, every one of these criteria is assigned an expert-based score regarding its technical (un)suitability, normalized between 0 and 1 to determine their relative weights. Table S 2 lists the geodatasets sources in detail.

To delineate areas unsuitable for AV systems due to other criteria (Table 3), a Boolean (TRUE / FALSE) exclusion map was created (Fig. 2 (2b), result in Fig. S 7). To start, areas classed as roadway are excluded. Similarly, close proximity to high-voltage infrastructure (above- and belowground, <100 m) is considered detrimental for construction. Any area with heritage or monument status is excluded. Also, locations interfering with highly biodiverse or valuable flora are avoided. Agricultural land already occupied by another construction type (building, greenhouse...) or high-stem orchards (Table S 4) is also excluded. Finally, protected permanent grasslands, classified as 'vulnerable' (grassland not managed or maintained) are deemed ineligible.

2.2. Survey administration and processing

In order to assess the relative significance of the aforementioned criteria, we determined criterion weights that were subsequently assigned to the respective criteria in Table 2 (Fig. 2 (3)). Briefly, a panel of 33 anonymized experts with established AV familiarity compared the 7 selected criteria in pairs, each rated from -9 to 9. All 21 criterion pairs were presented in a random order. The expert panel was composed of

Table 2

Criteria contributing to the suitability for AV and their classification according to relative suitability fraction. Suitability classification ranging from 0 (not suitable) to 1 (most suitable).

Criteria	Level	Classification (1: suitable, 0: not suitable)	Geodatasets (Table S 2)
Global horizontal irradiance (GHI)		$\begin{array}{l} \text{Max} = 3.05 \text{ kWh} \\ \text{m}^{-2} \text{ d}^{-1} \text{:} 1 \\ \text{Other: fraction of 1} \\ \text{scaled to GHI} \end{array}$	Derived from Global Solar Atlas (World Bank Group, 2023)
Crop specific soil suitability		Cat1: very suitable: 1 Cat2: Suitable: 0.8 Cat3: Somewhat suitable: 0.6 Cat4: Less suitable: 0.4 Cat5: Not suitable: 0.15	Based on the 'present physical suitability' score for each crop group from the NARA-T 2014 (Van Gossum et al., 2014), matched to the annual declaration of planted crop type for 2022 (Departement Landbouw en Visserij, 2022)
Slope	>10 %	>10 %: 0 <10 %: 1	Calculated from digital terrain model (Agentschap Digitaal Vlaanderen, 2014). 5–10 % are common for PV-site selection (Díaz-Cuevas et al., 2021; Katkar et al., 2021; Osorio-Aravena et al., 2022; Spyridonidou and Vagiona, 2023).
Aspect (direction of slope)	North	337.5° < <i>N</i> < 22.5° and > 2 % slope: 0 Other: 1	Calculated from digital terrain model (Agentschap Digitaal Vlaanderen, 2014) based on (Elkadeem et al., 2024 and Saraswat et al., 2021).
Crop		Fruit: 1 Grass: 0.86 Vegetables 0.47 Arable crops 0.43 Maize: 0.16	Assessment of crop shade tolerance, agronomic suitability, constraints due to crop rotations and ease of AV construction based on expert assessment (Asa'a et al., 2024) (Supplementary Table S 1)
Flood risk		Effectively flood- prone area: 0 Other areas: 1	Derived from Vlaamse Vlaamse Milieumaatschappij, 2017
Distance to		< 5 km: 1	Derived from Elkadeem et al.
inain roads		> 5 KM: U	(2022).

Table 3

Exclusion criteria for AV suitability (negative selection layer).

Criteria	Classification (Table S 2, Table S 4)	Source
Roadways	Intersects with roadways	(Agentschap Digitaal
		Vlaanderen, 2023)
Electrical grid	Within 100 m from high voltage	(Van Duijnhoven et al.,
	grid	2018)
Protected	Matches 'protected monument,	(Agentschap Onroerend
landscapes	-archeological site, -city or	Erfgoed, 2017;
	village view, old landscape	Spyridonidou and Vagiona,
	relics, or woody vegetation with	2023)
	heritage value, historical	
	gardens or -landscapes, or	
	UNESCO world heritage areas.'	
Natural value	Contains 'very valuable' flora in	(De Knijf et al., 2010;
	the biological valuation map	Instituut voor Natuur- en
		Bosonderzoek, 2023).
Crops under	Contains Greenhouses and	(Departement Landbouw en
permanent	growth rooms (Supplementary	Visserij, 2022)
cover	Table S 4).	
Protected	Any area classified as	(Agentschap voor Natuur en
permanent	'vulnerable' as well as high stem	Bos, 2019; Spyridonidou
grasslands	orchards (Supplementary	and Vagiona, 2023)
	Table S 4)	

people with agricultural, PV and energy backgrounds, as well as policy makers, technical advisors, and researchers, all with prior experience in AV systems. After removing incomplete or invalid assessments, 30 responses were retained. While this pairwise comparison method was inspired by the Analytic Hierarchy Process (AHP), it was used solely for determining weights ('preferences') for each of the 7 criteria that retain equal hierarchy. Processing of the survey responses was performed using R version 4.2.3 - "Shortstop Beagle" (R Core Team, 2023) and RStudio 2023.03.0 Build 386 "Cherry Blossom" (RStudio Team, 2020) using the AHP package by Cho (2019). Individual preferences were calculated to assess the uniformity of responses. Data analysis was visualized using the ggplot2 (Wickham, 2016), ggprism (Dawson, 2023) and export (Wenseleers and Vanderaa, 2020) packages.

2.3. Geodatasets preparation and weighted overlay analysis

Next, in step four, the suitability basemaps for the individual criteria were generated using Qgis's raster calculator, classifying pixels as either positively (1) or negatively (0) associated with AV's potential or according to its crop, soil, or irradiance score (fraction between 1 and 0) (Fig. 2 (4)).

The fifth step uses a weighted overlay analysis to generate the final suitability map for AV systems (Fig. 2 (5)). Each alternative (i) (10 m \times 10 m pixel) is assigned a suitability score, based on the Simple Additive Weighing (SAW) method (Eq. 1), which involves multiplying the criterion weights by their respective criterion values. Here, we also apply the Boolean restriction value to exclude areas that do not meet minimum suitability, yielding the total available cropland area for AV along with its classification.

$$AV \, score_i = \sum_{j=1}^n C_j * S_j * X_j$$

Equation 1: Simple Additive Weighting (SAW) for each pixel i, calculated using classification C (the normalized score for each criterion), relative significance S (the weight assigned to each criterion) and X (exclusion layer score). This equation provides an AV score for each pixel based on the weighted contributions of each criterion.

Then, the respective areas of individual crop types affected by each selection layer was quantified to gain insights into the principle contributing criteria per crop.

2.4. Electric potential estimation

To estimate agrivoltaic system's energetic potential across Flanders, we combined both agronomic and energy factors from the GIS-based analysis (Fig. 2 (6)). As taken into account for the crop specific suitability scores (Supplementary Table S 1), each crop varies in technical compatibility depending on the AV system type (e.g., vertical, horizontal, or tracking configurations (see supplementary Fig. S 18)). By placing these technical constraints and potential AV configurations (cf. Deutsches Institut für Normung (2021)) in their local perspective, we identified regionally relevant preferences and priorities (Ali Khan Niazi and Victoria, 2023), which we translated to the Flemish context using our AV suitability maps. All electrical yields are calculated based on typical meteorological year (TMY) data and bifacial modules.

Where crop groups were composed of multiple scenarios, we split the technical options equally across all categories.

For these crops, we compare an equal distribution of area among the three technologies: interspaced ground mounted, vertical bifacial and horizontal single axis tracker (HSAT). All three AV system types show technical merit, yet it is still unclear which technology would be installed at large scale in the Flemish context. This decision is not only influenced by technical parameters but also by socio-economical constraints and policy decisions that are currently absent. This uncertainty about construction type is present for arable crops as well as grass and vegetables. Maize, which scored lowest in AV suitability for Flanders, faces unique technical challenges within AV systems due to its height and potential for module shading in vertical bifacial or low mounted tracking setups. Instead, we identified an elevated horizontal single-axis tracking AV system as the best alternative for maize, enabling adequate light penetration. While the elevated HSAT system carries a higher capital expenditure (CAPEX), its enhanced energy yield and profitability within the GIS-mapped suitability zones make it the plausible AV design for maize in Flanders (Asa'a et al., 2024).

Fruit crops are assigned to two similar scenarios depending on row spacing and height: pome fruit production at a row spacing of 3.5 m, under east-west, semitransparent C—Si modules at a 45 % transparency degree (Willockx et al., 2024), and other fruit spaced 3 m, at a 50 % transparency level under a similarly oriented setup.

3. Results

3.1. Fragmentation in Flanders' landscape significantly reduces AV site availability

Agricultural land makes up 45 % of the Flemish area. As shown in Fig. 1, it is apparent that agricultural activity takes place across the whole area. The areas with a mixed weight impact on AV site suitability are equally scattered throughout the landscape. Parcels with a high slope or undesirable aspect (orientation of the slope facing North) as well as plots potentially susceptible to flooding impact a large portion of agricultural land. While the southern regions are hillier, plots with northern aspect are spread throughout. Flood prone areas are nearly all fluvial – following the main rivers and streams (Fig. S 3). The remaining criteria show a smaller spatial overlap with the different cropping areas (Fig. S 4, Fig. S 5, Fig. S 6), overall negatively impacting less than 10 % of land each (Table 4).

Fig. S 5 reveals that the 5 km buffer to all main roads (along which the main distribution grid is located) is distributed across all of Flanders, only excluding some minor areas near the borders and the less densely populated regions. Flood sensitivity, distance to roads, elevated slopes and north facing aspects impact between 0.7 % and 11 % of the various cropping areas. A notable exception is the influence of 'aspect' on the arable crops, of which over 22 % are planted on fields with a northern slope (Table 4).

Across the Flemish region, a variety in crop specific soil quality exists. The analysis reveals that despite, some coastal regions with sandy soils or potential salinity issues, high quality soils are dominant (Table 4, Fig. S 6).

Due to its relatively small size, solar irradiance differs little across the Flemish landscape. The highest irradiance levels are found around the coast to the west (Fig. S 4), but overall, only a 7 % difference in global

Table 4

Area and fractions of agricultural land (%) negatively impacted by the categorical discrete selection criteria (grid access, flood proneness, aspect, and slope), and affected per soil suitability class (categorical; following Van Gossum et al. (2014)); and area and fraction agricultural land associated with the exclusion layer (Boolean selection) in Flanders.

Criterion	Area impacted (ha)	% agricultural land impacted
Grid access = 0	32392	4.92 %
Flood prone $= 0$	39302	5.97 %
Aspect = 0	70801	10.75 %
Slope = 0	14727	2.24 %
Soil suitability = 0	49676	7.54 %
Soil suitability = 0,15	7735	1.17 %
Soil suitability $=$ 0,4	52870	8.02 %
Soil suitability = 0,6	134645	20.44 %
Soil suitability = 0,8	179331	27.22 %
Soil suitability = 1	234598	35.61 %
Exclusion layer = TRUE	177544	26.95 %
Total agricultural area	658856	



Fig. 3. Cropping area (ha) per irradiance level (fraction of maximal irradiance, 3.05 kWh m⁻² d⁻¹) in Flanders relative to total crop area. Mean = 0.965 % = 2,94 kWh m⁻² d⁻¹. Locally estimated scatterplot smoothing (loess) used for fitting the curves to individual datapoints.

horizontal irradiance across the full year exists. Fig. 3 highlights the irradiance level distribution across the agricultural landscape, noting a mean value of 2.94 kWh m⁻² d⁻¹, and 95 % of area receiving between 2.88 and 3.00 kWh m⁻² d⁻¹.

Agrivoltaics also has to contend with the highly fragmented land use in Flanders. With regard to the exclusion zones, both fauna and heritage areas are relatively large, but a great number of smaller zones are also excluded due to flora or protected grassland classification. Nevertheless, many of these areas fall outside agricultural land and therefore do not directly impact the AV potential (Fig. S 2). Yet, out of all areas designated as agricultural land in this study (658,856 ha), 26.95 % or 177,544 ha are deemed unsuitable due to these exclusion zones.

3.2. Criteria weights reveal a preference for both solar and agricultural interests

Our expert panel was composed of members from various backgrounds. It included farmers, agricultural advisors, PV-industry professionals and academic researchers. A number of technical experts in renewable energy and policy makers also participated. Given the relatively high number of respondents (30), this diverse panel exhibited a certain degree of variability with regard to their responses. Despite these differences, overall criteria mean (Table 5) provide an accurate illustration of perceived importance for the combined agricultural and energy system. The variability of individual criteria scores is illustrated in Supplementary Fig. S 1. Both solar irradiance and distance to roads as well as crop type stand out as relatively more important. Slope, soil quality or flood risk are regarded as lower priority.

3.3. AV systems hold potential across the whole of Flanders

By calculating the simple additive weights (Eq. 1), we eventually obtained an agrivoltaic site suitability map for Flanders (Fig. 4). Agricultural plots in exclusion areas (Table 3) are scattered throughout (pink).

We zoom in on two AV pioneering production systems in Belgium,

Table 5 Mean criterion weights (n = 30) and standard errors for various selection criteria in the agrivoltaic system evaluation. Normalized to $\sum = 1$.

Criterion	Criterion weight \pm se
Global horizontal irradiance	0.204 ± 0.020
Crop specific soil suitability	0.095 ± 0.018
Slope	0.104 ± 0.008
Aspect (direction of slope)	0.120 ± 0.021
Crop	0.182 ± 0.021
Flood risk	0.121 ± 0.009
Distance to main roads	0.174 ± 0.018



Fig. 4. AV suitability score distribution across Flanders (A) for all crop types (based on map inventories of 2022) after exclusion of the Boolean exclusion layer (pink). Two AV test-sites are located and shown as a close-up map. (site 1) A pear orchard pilot site with overhead horizontal PV in Bierbeek (B) and (site 2) an arable pilot site with tracking and vertical bifacial PV in Grembergen (C). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

namely two KU Leuven AV pilot sites, one in Bierbeek (Fig. 4B, site 1) (Reher et al., 2024c; Willockx et al., 2024) and one in Grembergen (Fig. 4C, site 2) (Reher et al., 2024a; Willockx et al., 2023). Both of these experimental sites received favorable AV scores, comparable to the maximum achievable for their respective crop types, being pear and sugar beet. In Bierbeek (Fig. 4B), a patchwork landscape of arable fields and pome fruit crops is visible, where pale and dark green alternate, respectively. The undulating landscape generates some unsuitable areas to the south-west of our field due to north-facing slopes. The Grembergen site (Fig. 4C) is surrounded by arable fields, which are impacted to a limited extent by the nearby Scheldevallei national park floodplains to the East.

3.4. Agrivoltaic suitability scores are highly crop dependent

A classification of the AV scores per crop type and their specific localization is shown in Fig. 5. The high-resolution maps of the agrivoltaics suitability map for each crop type are shown in Supplementary Fig. S 8–12. These detailed maps show for each crop type that a sizable portion of the available farmland is suitable for AV implementation according to our calculations.

When we plot the AV suitability score per crop type against the area (Fig. 6), we observed that, regardless of the crop type, a very similar pattern emerges where the majority of fields obtain relatively high scores, while rapidly decreasing for the lower AV scores (Fig. 6A). Despite this similarity in distribution shape, absolute AV ratings remain different between crop types. Arable crops (Fig. 6B) have a relatively

good score, but one should take into account crop rotations which might complicate the AV system design. Fruit crops (Fig. 6C) stand out as remarkably more suitable for AV than the others, attaining scores above 0.9. The AV suitability levels of cultivated grass (Fig. 6D) is also high, and it covers a much larger total area compared to fruit crops, hence has a larger total AV potential. Maize (Fig. 6E) has the lowest AV suitability score and also has to contend with alternating crops. Vegetables (Fig. 6F) are well suited, but their total area for AV potential is much smaller.

Zooming in on the difference between maximal crop-specific AV suitability scores, Fig. 7 reveals that the score ranking is independent of the total cultivation area. Here, the cropland area percentile is shown alongside their average AV suitability score. Crop suitability reveals a line graph with two distinct segments: on the upper end (higher area percentiles), we observe a very gradual change in AV score, while for the lower values (lower area percentiles), AV scores drop rapidly. Note that individual crop types plateau at very different AV scores. The bending points (crop-specific maximum potential limit) of the crop-specific AV suitability scores, are summarized in Supplementary Table S 6.

Across all crops (Fig. 7, grey dotted line), AV scores increase gradually above a score of 0.8. We propose that an AV suitability score of 0.8 should be considered as a practical lower border for AV site selection for two reasons: (1) a significant portion of land exceeds these values and, (2) while technically not excluded by the negative selection layer, much stricter design constraints are expected for fields with low suitability scores. However, to get a more holistic view, we grouped the AV suitability scores in suitability groups per crop type ranging from very



Fig. 5. Individual crop types with AV potential score after analysis. A: arable crops, B: fruit, C: grass, D: maize, E: vegetables.



1.1 1.0 Average of AV score 0.9 0.8 All crops Arable 0.7 Fruit Grass 0.6 Maize Vegetables 0.5 0 ź 50 100 15 **Total area percentile**

Fig. 7. Average AV scores normalized for equal-area percentiles per crop type. Dashed line: average across all crops. Green: arable crops. Purple: fruit crops. Dark blue: grass. Light blue: maize. Magenta: vegetable crops. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Crop area distribution in relation to the AV suitability score per crop. A: Overall score, B: Arable crops, C: Fruit crops, D: Grassland, E: Maize, F: Vegetables.

Table 6

Total and potential AV area per crop type after exclusion layer (left), grouped according to equally spaced suitability classes above the drop-off AV suitability score for the overall 'all crop' AV suitability. % for suitability scores (right) as a fraction of total overall crop area before selection.

Crop	Total crop area (ha)	Potentially suitable	Total potential area (ha)	Less suit (<0.8) (l total)	able ha, % of	Somewhat (0.8 > < (ha, % of	t suitable (0.867) total)	Suitable (< 0.933) total)	0.867 > (ha, % of	Very suit (>0.933) total)	able) (ha, % of
Fruit	17,929	84.34 %	15,121	453	0.07 %	1210	0.18 %	1814	0.28 %	11,643	1.77 %
Grass	224,868	63.60 %	143,021	8581	1.30 %	14,302	2.17 %	41,476	6.30 %	78,661	11.94~%
Vegetables	34,277	79.50 %	27,250	2725	0.41 %	12,535	1.90 %	11,990	1.82~%	0	0,.00 %
Arable	201,594	73.22 %	147,614	20,666	3.14 %	47,236	7.17 %	79,711	12.10~%	0	0.00 %
Maize	180,188	81.46 %	146,783	24,953	3.79 %	121,830	18.49%	0	0.00 %	0	0.00 %
Total	658,856	71.86 %	473,440	75,750	11.50 %	189,376	28.74%	127,829	19.40 %	80,484	12.22~%

suitable (AV score > 0.933) to less suitable (< 0.800) and calculated the areas and their percentages suitable for AV (Table 6) for each category. This analysis revealed that, despite fruit reaching the highest absolute AV potential score, nearly 10 % of the total area in the best category was made up of grassland. In the second group of 'suitable' areas, arable crops represent the largest land area. The bulk of the maize crop falls in the 'somewhat suitable' class, making up almost a fifth of the land. This reveals that of total available area and absolute AV score are only limitedly related, despite being valuable for priority assessment.

3.5. Potential AV land can cover all of Flanders' electrical needs

Table 7 highlights the total potential electrical capacity and yields per year for the various candidate AV systems, based on the areas and crop scores exceeding the 0.8 AV suitability score cutoff. The theoretical production potential of agrivoltaics in Flanders amounts to a total of 217 TWh per year. This is over four times Flanders' current annual electricity demand of 50.5 TWh (Vlaams Energie- en Klimaatagentschap, n.d.). For reference, the maximal attainable electrical yield using traditional ground-mounted PV is also given.

Despite attaining the worst AV crop suitability score, the widespread cultivation of maize, coupled to the high electric production of its corresponding HSAT AV system makes it more attractive. Grass and arable crops represent approximately equal weights at 18.86 % and 17.8 % of total agricultural land. Despite being highly prioritized in practice, soft fruit such as raspberries are only able to contribute a very small fraction of total capacity. Hence, when weighed for their energy potential, a variety of AV crop production systems show merit.

4. Discussion

4.1. Flanders' agricultural land can be widely suitable for AV implementation

The variety of AV systems provides a promising toolbox for achieving the dual goal of renewable energy production and agricultural resilience. Our analysis, combining a GIS-MADM methodology with estimations of currently attainable PV yields, identifies the technical potential of AV in Flanders. We identify a significant portion of Flanders' farmland as suitable for AV development. While this study focuses on Flanders, its methodology and findings could be adapted to other regions with similar geographical, agricultural and solar energy features. For example, our overall potential (60.4 %) closely approaches Fattoruso et al. (2024) results (65 %) for the Italian context. Nevertheless, we expect a discrepancy between this theoretical potential and a more limited actual deployment based on additional factors outside of this study, such as societal acceptance, technical challanges, or economic feasibility (Sacchelli et al., 2016; Ketzer et al., 2019; Torma and Aschemann-Witzel, 2023).

Certain crops, notably fruits and grass, emerge as more compatible with AV systems, likely due to their tolerance to partial shading and their cultivation systems. Grass for forage is managed in a semiextensive way, requiring fewer interventions. On the contrary, fruit crop production is highly manual or uses small agricultural vehicles. These approaches to AV implementation suggest that crop-specific designs are essential for supporting agricultural yield alongside energy production.

A continuing evolution of the PV design for AV is noted. Early studies focused principally on elevated systems (Dupraz et al., 2011; Weselek et al., 2019). Newer types of elevated horizontal tracking systems and ground-mounted vertical bi-facial systems are expanding the AV systems catalogue (Asa'a et al., 2024; Sponagel et al., 2024). Bearing in mind continuous improvements in solar panel technologies, future evolutions may lead to new design philosophies. We assume that a variety of AV systems will develop based on the specific local use-case, with crop type being a dominant driver, as shade levels experienced by the crops remain a fixed factor for any solar setup in AV.

4.2. A variety of criteria have a comparable impact on AV site suitability scores in Flanders

The total cultivation area per crop in Flanders is remarkably consistent year to year, specifically for fruits, (Agentschap landbouw en zeevisserij, 2024) which supports the feasibility of (quasi) permanent AV systems in perennial crops. Despite the varied criteria included in this work, the challenge of a site-specific AV system design remains.

Identifying the major contributing criteria that determine the AV site suitability score is challenging, as many variables are either correlated or confounding. Differences in crop type stand out as particularly impactful for technical AV potential. Crop selection has the ability to change the resulting AV score in our analysis up to 0.152 when comparing minimum and maximum scores. Crop type and shade tolerance go hand in hand and have an important effect on AV system design. Soil type and crop selection are also tightly intertwined. The metaanalysis by Laub et al. (2022) suggests that fruits and some vegetables could partially benefit from shade while most arable crops, and especially maize and grains suffer more. These shade benefits for berries are also highlighted by Hermelink et al. (2024), but are not equal for all berry types.

Given the varied nature of crop responses to AV systems, it is clear that a one-size-fits-all approach to scoring AV suitability will favor certain crops over others, despite the total available area we identified (Table 6). For arable crops, crop rotations are essential to maintain soil and environmental health (Bowles et al., 2020). In their work, Sponagel et al. (2024) used the CropRota model (Schönhart et al., 2011) that generates crop rotations based on agronomic criteria and observed land use from the past to account for this.

Exploring the individual spatial overlap with agricultural land for the remaining criteria, revealed no particularly hard cutoffs for a single criterion in our study. While most selection criteria had a similar moderate impact on the eventual AV suitability score, a notable exception to this is the influence of a field's aspect for arable crops. We attribute this largely to the importance of arable farming in the southern part of Flanders, where the terrain is more undulating and therefore more likely to have a northern aspect. A level of uncertainty about grid connectivity remains in our analysis. More restrictive distances were proposed by

lectrical potential	of candidate AV systen	ns for different crop ty _l	pes in Flanders and their	total potential AV ele	ectrical capacity and yield.			
Crop type	System Type	% of designs likely in this category	PV-specific electrical yield (kWh/ kWp)	Installed PV capacity (kWp/ha)	Annual electrical yield capacity (MWh/ha)	Potential area (AV suitability score > 0.8) (ha)	Potential annual electrical yield (GWh)	Fraction of total annual electrical yield (%)
Fruit (pear,	Elevated	100 %	956	660	630	13,348,55	8410	3.87
apple)	semitransparent							
Fruit	Elevated	100 %	956	578	552	1319,75	7289	3.35
(raspberries)	semitransparent							
Grass	Interspaced ground	33 %	1040	450	468	44,814	20,973	9.65
	mounted							
	Vertical bifacial	33 %	835	450	376	44,814	16,850	7.75
	HSAT	33 %	1245	450	560	44,814	25,096	11.55
Vegetables	Interspaced ground	33 %	1040	450	468	8175	3826	1.76
	mounted							
	Vertical bifacial	33 %	835	450	376	8175	3074	1.41
	HSAT	33 %	1245	450	560	8175	4578	2.11
Arable crops	Interspaced ground	33 %	1040	450	468	42,316	19,804	9.11
	mounted							
	Vertical bifacial	33 %	835	450	376	42,316	15,530	7.15
	HSAT	33 %	1245	450	560	42,316	23,697	10.90
Maize	Elevated HSAT	100 %	1245	450	560	121,831	68,225	32.39
Total AV				193,06 GWp		422,414	217 TWh	
potential								
Max PV	South inclined	100 %	1040	1210	1258		829 TWh	

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Sacchelli et al. (2016), but they applied this to all roads in their geodataset; including minor roads. If we consider the smaller buffers from Sacchelli et al. (2016), and apply them to Flanders' main road network, smaller overlaps with agricultural land emerge (5000 m: 95.30 %; 1200 m: 46.50 %; 700 m: 28.50 %; 200 m: 7.20 %). Due to the significant age of some local distribution networks in Flanders, we chose to focus on main roads only (where the grid is likely more up to date). Alternatively, using the grid operator's geodatasets in the analysis, would help to improve the grid connectivity criterion. Although unavailable for indepth offline analysis, a limited geographical dataset of distribution network was recently made available online (Fluvius System Operator cv, 2023). This online tool reveals that grid connectivity is rarely a technically limiting factor for the Flemish context, but depending on distance to substations, it might remain an economical barrier. Despite not being available for offline access, their platform corroborates the assumption made in this analysis regarding grid connectivity (Fig. S 5), confirming a wide-reaching cover of potential new feed-in connections.

Another consideration is the ambiguous perception of AV on marginal lands versus areas with high intrinsic productivity capacity. In this analysis, the 'soil suitability' criterion appeared to have only limited effect on AV site suitability. Despite this, marginal land is expected to have a lower absolute yield loss under AV, due to its intrinsic lower potential caused by other limiting factors. However, using AV on marginal land may reduce yields below an agronomic minimum, leading to a situation where the crop is simply maintained to meet legislation that currently prohibits ground-mounted PV. A critical consideration in this regard is the available yield buffer between the minimally acceptable vield and the benchmark vield. When using a 'Field-Specific Maximum Yield', we might prioritize AV implementation on the least productive lands, as their absolute shade losses may be minimal due to other limiting factors. If we consider the 'Region-Wide Average Yield', focus may shift toward more productive lands, where agricultural productivity has a greater buffer before dropping to unacceptable levels. As such, one could argue that AV is better suited for valuable agricultural areas, while marginal land should be prioritized for other uses.

4.3. AV sites may help meet renewable energy and crop needs while remaining profitable

To accommodate the projected changes in the energy landscape, Belgium's installed electricity system capacity will need to increase more than fivefold from 2020 to 2050, reaching over 135 GW, with renewable sources accounting for over 90 % of this capacity (EnergyVille, 2024). Currently, installed PV capacity in Flanders amounts to 6.65 GWp, installed capacity is projected to reach 8.9 GWp by the end of 2030. However, to stay on track with the 2050 net-zero goals, Flanders will need to nearly quadruple its PV capacity to reach 20 GW by 2030 (EnergyVille, 2024).

With extensive electrification, it is estimated that 91.7 TWh of electricity will need to be generated by solar installations by 2050 (EnergyVille, 2024). A significant portion of this can come from rooftop installations, with a potential capacity of 72 GWp, sufficient to produce approximately 62 TWh per year (Vlaamse Instelling voor Technologisch Onderzoek, VITO). Consequently, only 29.7 TWh would need to be supplied by other installations such as agrivoltaics, accounting for only 13.7 % of the theoretical agrivoltaics energy potential in Flanders. This would require agrivoltaics to be installed on approximately 9 % of Flanders' total agricultural area.

Future evaluations of AV potential for contributing to this demand should consider the energetic gains and cost-benefit analysis of AV systems compared to other methods of expanding solar capacity. A possible indicator to compare different AV and PV designs, is the levelized cost of electricity (LCOE) (Agostini et al., 2021). The LCOE divides the lifetime system costs and integrates it over the power generated across the lifespan. For AV systems, the LCOE decreases as crops become more shade tolerant. This tolerance allows for denser PV panel setups,

Table

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which increases energy output without adding to fixed structural costs thus decreasing the LCOE (Willockx et al., 2022).

The overall economic balance of an AV system, considering both energy and agricultural elements is a complex interplay between geographic, management and design choices. Gross margins per hectare for PV and agriculture are remarkably different. Also, between crop types, large variation in revenue per hectare exist. An extensive economic analysis for AV farms in Germany was described by Feuerbacher et al. (2021). Despite a significant decrease in crop contribution margins, cereals and vegetables may be profitable under AV. Given the risk of yield reductions for any AV crop in the temperate regions, Feuerbacher et al. (2021) propose low-value crops as more appropriate for a similar PV benefit. The crop contribution margin of low-value crops decreases numerically less than for high-value crops. In their assessment, fruit crops are rated as relatively less promising due to their small area, with the exception of berries. Conversely, arable AV systems are often more invasive in the landscape than lower AV systems above fruit orchards, which typically already have established cover systems (plastics or hail netting).

4.4. Suitability of AV sites is also influenced by local, societal or policy considerations

The evolution of land use classes in Flanders from 2013 to 2022 shows a significant increase in houses and gardens, as well as arable land, while agricultural grassland has experienced the largest decline. These shifts also underscore the necessity for agrivoltaic system designs to be adapted to changing land use patterns in the future (Poelmans et al., 2023). Also, other legal and societal limitations can impact local deployment of AV. For example, the public perception and resistance (visual impact, NIMBY, wildlife concerns...) toward AV systems by multiple stakeholders play a crucial role in their adoption (Torma and Aschemann-Witzel, 2023). Contrarily, AV produce can be perceived as a favorable alternative, as a study by Ha et al. (2024), reported that over 40 % of respondents indicated a willingness to pay a premium for agrivoltaic produce. AV systems are also considered more favorably by the public than ground mounted PV (Ketzer et al., 2019), but are still considered lower priority than roof mount alternatives. Additionally, the uncertainty of environmental impacts of AV systems can sometimes be a bottleneck.

Wagner et al. (2024) surveyed farmers regarding their perception toward AV. While the added income from PV was regarded favorably, the uncertain legal framework and expected bureaucracy are considered a barrier. The discrepancies in legal framework across countries with established AV legislation is highlighted by Dupraz (2023), who also highlights the limited number of legal frameworks for AV across the globe. Currently, both farmers and investors face the challenge of lacking legislative frameworks. The need for a comprehensive stakeholder engagement strategy is raised by Torma and Aschemann-Witzel (2023). This proposed strategy should address concerns early on in the design phase and emphasize the benefits of agrivoltaics. The interaction with policymakers and local stakeholders during that time can help to create a more welcoming environment for agrivoltaic integration in densely populated areas such as Flanders.

4.5. Suitable sites for AV are plentiful, providing sustainable development options

While the fragmentation of the Flemish landscape might restrict large-scale AV systems and could result in more costly systems, it also entails a relatively close proximity to end-users. Nevertheless, often broken-up land ownership necessitates careful consideration of longterm exploitation agreements. According to Ketzer et al. (2019) AV plants should preferentially be owned and operated by local energy cooperatives or the farmers themselves. Given this perspective, small- or medium scale installations that fit with this urbanized context could be a promising implementation. In the light of the decentralized ambitions to use renewable and local energy sources, AV systems may elevate energy resilience at the community level, if economic viability and stakeholders' participation are well considered.

4.6. Future directions for AV site selection in Flanders

While our findings highlight a large potential for AV site selection in Flanders, some other elements must be addressed to facilitate the practical application of our GIS-MCDA model. Notably, limited access to data on grid connectivity restricts AV planning beyond small scale initiatives. While grid-connection studies are available for individual projects (*Fluvius System Operator cv*, 2023), such data remains inaccessible for broader offline analyses, limiting our assessment for clustered or high-capacity systems. Despite the extensive availability of high-quality geodata, better data accessibility of utility information would enable more comprehensive planning for AV at a regional level.

Methodologically, our study emphasizes spatial and agronomic suitability. It currently lacks explicit integration of economic, social, and environmental factors beyond our survey's impact. These concerns will be essential for specific AV deployment decisions. Questions about profitability, such as whether both energy and agricultural components of AV systems should be profitable independently, or only as a whole, need to be answered. Additionally, parcel size requirements impose further constraints. While potentially viable on a company-level, smaller parcels may limit the economic feasibility of grid-tied AV installations. Additionally, the inclusion of elements such as parcel shape would be of interest. Land ownership also plays a role in AV viability, as ownership or lease agreements influence the long-term profitability of sites.

Going forward, a more comprehensive economic assessment of the Flemish AV context could boost the economic potential of AV and establish a base of trust for long-term property and financing agreements. To facilitate AV implementation in Flanders, government agencies and stakeholders could prioritize pilot programs that focus on high-potential crops and AV configurations with demonstrated economic benefit. Early engagement with local farmers appears to be crucial.

While we applied an AV suitability threshold of 0.8 in this study, future work might refine this by identifying crop-specific suitability thresholds, preferably based on multiyear field-trial data, rather than crop group specific cutoffs. This could yield more tailored boundary conditions for aligning both crop-specific agronomic and economic needs. Development of more shade tolerant cultivars could also help maximize the AV suitability potential. Given the diversity in crop requirements and the importance of crop rotations, a one-size-fits-all approach is impractical. Further work would benefit from the inclusion of crop yield data and rotation schemes, shedding additional light on crop-specific suitability for AV.

Finally, a comprehensive legal framework, currently absent in Flanders, could offer essential security for investors by delimiting the boundary conditions for sustainable and socially acceptable AV development. Financial support, such as subsidies for shade-tolerant crops or AV infrastructure, could further encourage AV expansion in areas with the highest potential and help support Flanders' renewable energy and sustainable agriculture targets.

5. Conclusion

This study assessed the technical potential for agrivoltaic (AV) production in Flanders, an urbanized and fragmented region, with the aim to identify locations where AV systems are likely to perform best and how the energy produced can complement Flanders' greening targets.

Using a GIS-based multi-criteria decision analysis, we incorporated location-specific criteria such as solar irradiance, slope, aspect and grid access as well as indicators of agricultural potential such as soil suitability and crop shade tolerance in a site-suitability study. Additionally, we consider a number of constraints related to heritage and biodiversity, as well as restricted agricultural land use because of constructions or protected crop types.

Our results show that AV systems can be implemented widely across Flanders, with over 60 % of each crop type (arable, maize, vegetable, fruit and grass) achieving similar suitability scores. This consistency across crop types highlights the versatility of AV systems and suggests a wide range of AV systems can be considered. Furthermore, our findings indicate that AV could play a key role in meeting Flanders' renewable energy targets, with just 9 % of total farmland being sufficient to achieve the region's 2050 energy goals, in combination with planned rooftop solar.

To refine our region-wide study and guide decision-making on design and investment, several parcel-specific analyses are recommended. These include assessing the impact of parcel size, shape, ownership, and local energy demands, as well as conducting a grid integration study to determine the engineering boundary conditions of potential AV systems. From a farmer's perspective, compatibility with farming practices place further constraints on construction designs. We also believe an investigation of AV-specific crop yield and rotations, which may differ from conventional farming practices, would help evaluate the crop potential across the system's lifespan. Additionally, as Flanders establishes its legal framework for AV, the integration of stakeholder perspectives should be closely regarded. Evaluating a fields proximity to residential areas and investigating location-specific public acceptance will be crucial. Finally, a site-specific economic analysis should consider the minimally legally acceptable crop yields while exploring varied energy revenue models to further hone in on an all-encompassing AV suitability score assessment.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used OpenAI's ChatGPT 4 in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Thomas Reher: Writing - review & editing, Writing - original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. Cas Lavaert: Writing - review & editing, Methodology, Investigation, Formal analysis, Data curation. Sam Ottoy: Writing review & editing, Supervision, Software, Methodology, Investigation, Formal analysis. Johan A. Martens: Writing - review & editing, Supervision, Resources, Project administration, Funding acquisition. Jos Van Orshoven: Writing - review & editing, Supervision, Software, Project administration, Funding acquisition. Jan Cappelle: Writing review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. Jan Diels: Writing - review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. Bram Van de Poel: Writing - review & editing, Writing - original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104266.

Data availability

Research data will be made available at https://rdr.kuleuven.be/ with DOI: https://doi.org/10.48804/ZUYGT5

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