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Research paper

Geospatial assessment of elevated agrivoltaics on arable land in Europe to highlight the implications on design, land use and economic level

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ABSTRACT

Agrivoltaic systems (a combination of agricultural crop production and photovoltaics (PV) on the same land) have an increasing interest. Realizing this upcoming technology raises still many challenges at design, policy and economic level. This study addresses a geospatial methodology to quantify the important design and policy questions across Europe. An elevated agrivoltaic system on arable land is evaluated: three crop light requirements (shade-loving, shade-tolerant and shade-intolerant) are simulated at a spatial resolution of 25 km across the European Union (EU). As a result, this study gives insight into the needed optimal ground coverage ratio (GCR) of the agrivoltaic system for a specific place. Additionally, estimations of the energy production, levelized cost of energy (LCOE) and land equivalent ratio (LER) are performed in comparison with a separated system. The results of the study show that the location-dependent solar insolation and crop shade tolerance have a major influence on the financial competitiveness and usefulness of these systems, where a proper European policy system and implementation strategy is required. Finally, a technical study shows an increase in PV power of 1290 GWp (almost × 10 of the current EU's PV capacity) if potato cultivation alone (1% of the total arable agricultural area) is converted into agrivoltaic systems.

1. Introduction

The European Commission aims to make Europe the first carbon-neutral continent by 2050. The European Green Deal, a plan launched in 2020, established an ambitious package of measures in order to mitigate climate change. One of the first actions in this Green Deal is the 2030 Climate Target Plan, aiming to reduce 55% of the greenhouse gases by 2030 (European Green Deal, 2020).

Achieving a reduction of 55% greenhouse gases by 2030 requires an increased share of renewables to 40% of the gross final consumption. The power sector needs to further be decarbonized; around two-thirds of the EU's electricity should be supplied by renewables while fossil fuels would generate less than 20%.

Large-scale PV systems have already a long proven record with benefits of green, cheap and reliable electricity production. However, an inherent limit to solar energy production is its capacity factor (10%–25%); solar energy systems only generate power during daylight, preferably with a sun unobstructed by clouds and no shade from trees and building structures (Kaspar et al., 2019). This low capacity factor results in a rather small share of PV generation (3.6%, 2017 data European Commission, 2020) in comparison with the total electrical energy production in the EU. Several studies suggest that the technical potential of rooftop PV (Huld et al., 2018) and ground-mounted PV (EU, 2019) on marginal land will suffice to reach the ambitions of installed PV power. However, in order to massively increase the share of PV, alternative places to install PV are being considered such as building integrated PV, floating PV, solar carports, road-integrated PV, urban PV and vehicle integrated PV.

One promising application, evaluated in this study, is the use of agrivoltaic systems (Goetzberger and Zastrow, 1982). These dual land use systems combine both food (crop) and energy production on the same (crop)land. Agrivoltaic systems can be divided into two types of structures (DIN, 2021; Willockx et al., 2020b) as shown in Fig. 1: elevated (overhead) structures where agricultural machinery can drive below and ground-based structures where agriculture machinery can drive in between. The design of ground-based structures is constrained by practical limitations: the minimum interrow distance is limited by the width of the agricultural machinery while the direction is fixed by the cultivation direction. In contrast, elevated structures, which are evaluated in this study, give the opportunity to make much denser systems independently from the dimensions of the machinery.

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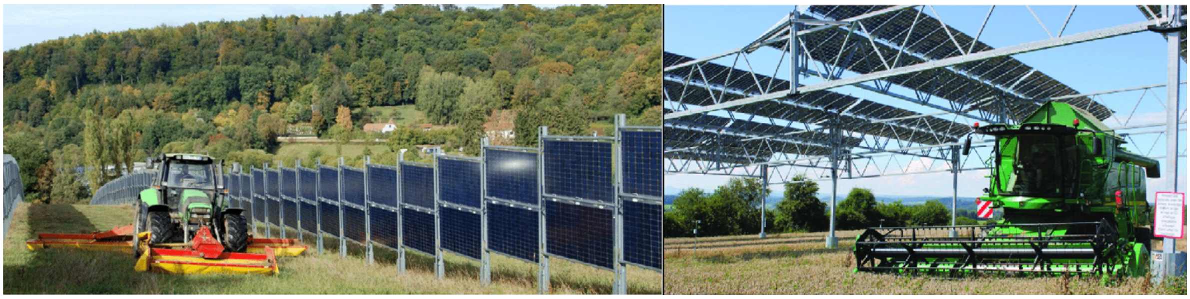

Fig. 1. Example of two different agrivoltaic structures: left, a vertical ground-based structure provided by Next2sun (Next2sun, 2021) and right, a elevated structure from the German pilot in Heggelbach (Fraunhofer, 2016).

In addition to the structure classification, agrivoltaics can be classified according to the crop land purpose: arable land (temporary field crops, meadows for mowing or pasture) and permanent crop land (crops that occupy the land for long periods such as fruits). The theoretical potential seems high; crop land accounts for almost one third of te European territory (32%) (Land cover, 2021), where 28.2% is used as arable land 3.8% is used for permanent crops. The focus of this study will be the arable land, given its large share in comparison with permanent crops.

Preliminary results of agrivoltaics are mainly based on a few pilot sites across Europe; located in France (Montpellier) (Dupraz et al., 2011; Sun Agri, 2021; Valle et al., 2017), Northern Italy (Piacenza) (Amaducci et al., 2018), Germany (Hechelbach) (Trommsdorff et al., 2021), the Netherlands (BayWa re, 2021) and Belgium (Willockx et al., 2020a). The early results show an increased spatial land efficiency (Dupraz et al., 2011), reduced evapotranspiration (with savings on irrigation) (Elamri et al., 2018; Barron-Gafford et al., 2019; Marrou et al., 2013a) and additional crop protection against extreme weather conditions (such as hail, rain, sunburn and drought Aroca-Delgado et al., 2018). Besides these positive effects, the deployment of the first agrivoltaic systems showed also the multi-disciplinary complexity to further (commercially) expand this dual-land use system across Europe; First of all, PV deployers are not aware how the (location specific) design influences the crop yield, risking to impact the food security. Indeed, the pilot sites across Europe show how the design differs with respect to the local climatic conditions. For example, the ground PV coverage ratio (GCR), defined as the ratio between the surface area and the cultivated ground surface, for the same crop-type in the Montpellier is around 50% (Marrou et al., 2013b), while the German pilot in Heggelbach (APV, 2016) has a GCR of 35%. Additionally, there is an argument on the visual landscape and the additional (investment) cost (Schindele et al., 2020) in comparison with separated (ground-mounted PV + mono culture) production systems, since these installations must comply with the farming practices (resulting in probably more steel and/or smaller PV densities). Lastly, there is a lack of clear (national) implementation policy guidelines. The question arises of (the more expensive) agrivoltaic systems do have a benefit (and additional subsidies are justified) in comparison with separated production systems across the whole European Union. To facilitate this decision process, this study evaluates following questions, including technical, cost and environmental aspects:

- What are the required technical specifications for a sustainable agrivoltaic system according to my location and crop type?
- What is the potential energy production? Does it differs with traditional ground-mounted PV systems?
- What are the benefits of the agrivoltaic system compared to separated production?
- At which cost can agrivoltaics be implemented (in comparison with ground-mounted PV)?

As explained, a few studies tried to solve these questions only evaluating one specific location (Amaducci et al., 2018; Trommsdorff et al., 2021; Dinesh and Pearce, 2016). However, – to the best of our knowledge – this is the first effort that explores the agrivoltaic potential at a large scale.

Solving these questions on a gridded level across Europe will help to better evaluate the potential of agrivoltaics or separated PV production, prioritizing specific regions and crops types. To do so, this study proposes the use of 3 Key Performance Indicators (KPIs) explained in Section 2. These KPIs are simulated and visualized at detailed grid level (25 km resolution) in Section 2.4 based on the desired light level for shade-loving, shade-tolerant and shade-intolerant field crops (Beck et al., 2012).

Finally, one case study explores the technical potential including the cultivated area of potatoes. The results of these objective key performance indicators are crucial in efficient policy-making within the renewable energy support scheme and the Common Agricultural Policy (CAP).

2. Methodology

The aim of this study is to evaluate the potential of elevated agrivoltaics on a gridded level. We therefore specify a general methodology, as visualized in Fig. 2, consisting out of four important steps.

In the first step (Section 2.1), the area of interest is discretized in small areas (grid cells), with unique environmental, climate and agricultural parameters. The next step (Section 2.2) defines the agrivoltaic, reference ground-mounted PV construction and crop type. It is important that not all dimensions of the agrivoltaic structure are fixed, since every crop type/variety and location have a unique light (shade level) requirement and consequently system design. In step 3, described in Section 2.3, a unique algorithm calculates for all grid cells the optimal agrivoltaic dimensions, based on the local (climatic) parameters and desired crop light level to have a sustained crop growth. Once the optimal dimensions are calculated, the following KPIs to address the research questions of this study are estimated (explained in Section 2.4):

- power capacity (kWp/ha) and energy production (MWh/ha/year)
- the benefits in comparison with separated production: land equivalent ratio (LER) & GCR (%)
- levelized cost of energy (LCOE) (€c/kWh)

No agricultural indicator is mentioned, since this study assumes the use of a crop light requirement that optimizes the agricultural yield (i.e. minimum of yield losses and additional (quality) benefits due to the reduced risk on sunburn).

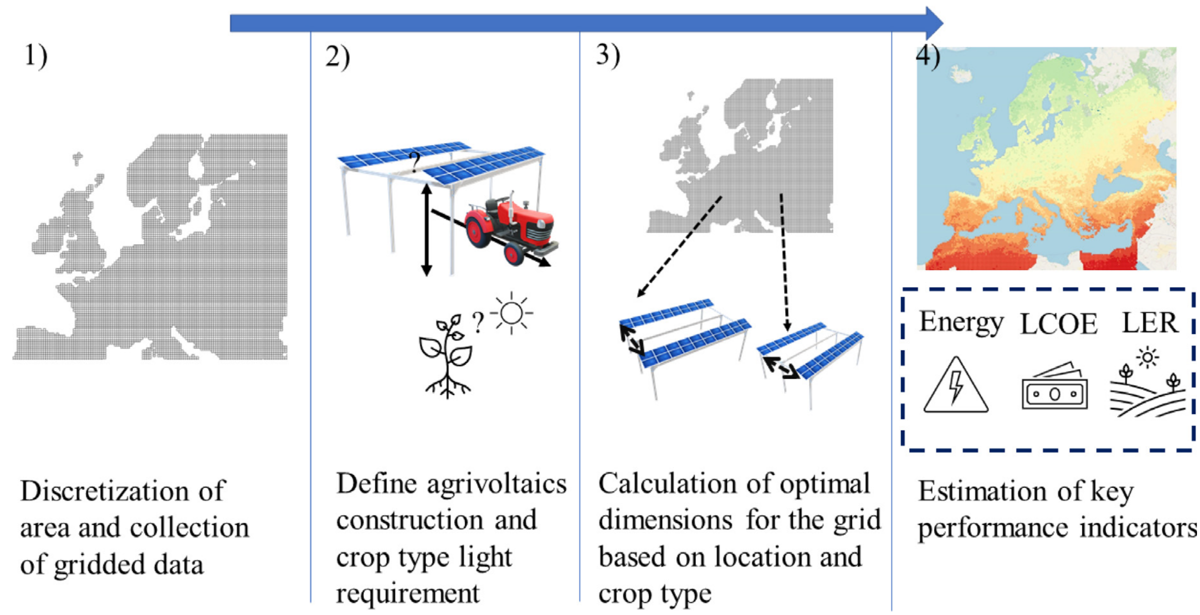

Fig. 2. The modeling structure, showing four important steps to assess the geospatial potential of agrivoltaics; (1) discretization of the grid (2) definition of agrivoltaics construction and crop type (3) calculation of optimal dimensions (4) estimation of key performance indicators.

2.1. Gridded data set

The weather data for this study has been collected by a custom-made python (Python Software Foundation, 2008) file, connecting to the PVGIS database by the json protocol. The European area is divided into grid cells of 25 km, matching the Lambert Equal Area projection. Every grid cell has unique meteorological data, representing median weather conditions over a multiyear (10 years) period. A typical meteorological year (TMY) is a set of hourly values for a given geographical location. For each month in the year, the data has been selected from the year that was considered most "typical" for that month (TMY, 2021).

Whereas energy production is mostly evaluated annually, the crop growth duration depends on each crop type and its start- (sowing or planting) and end dates (harvesting). Additionally, the cultivated area (ha) is also depending on the local specific conditions. This gridded information is averaged over 10 years and taken from the agri4cast data portal (AGRI4CAST, 2016) in the form of csv files.

2.2. Selection of the agrivoltaic structure, ground-mounted structure and crop type

2.2.1. Agrivoltaic structure

Following the definition of agrivoltaics, the first priority remains the continuous agricultural production. To be compliant with the farming practices and machinery (and to limit additional costs during the farming process such as working time and fuel), the height of the construction is considered to be 5 m while the distance between two vertical pillars is considered at 16 m. The module tilt is taken at 12° in order to limit the wind load and module self-shading effects independently from the chosen GCR. A lower wind load results in a lighter steel structure and requires a smaller (reversible) foundation (the use of concrete is not recommended, since it negatively impacts the soil) (Trommsdorff et al., 2021). The modules are considered bifacial, since its expected due to the height that the backside receives a large part of the reflected irradiance.

The ideal agrivoltaic system reduces the solar radiation until the crop light saturation point is reached, mitigating the excess of solar radiation that impacts the quality (tip burn or sunburn). In practice, the opaque modules cause not only a continuous reduction of the diffuse light (given by the sky view factors), also a discrete pattern of the direct light (the direct sun component) occurs as shown in Fig. 3. The reduction in diffuse light depends on the height of the modules and the density (i.e. the ground coverage ratio GCR) of the PV array, while the duration of the discrete pattern depends on the height and width of the modules, as visualized in Fig. 3. The same complexity in temporal PV shading can be found in photovoltaic greenhouses. Indeed, the importance of a dynamic and homogeneous light distribution has been reported by Yano et al. (2010), where a checkerboard formation improved the imbalanced spatial distribution of received sunlight energy in comparison with a straight line formation.

In contrast to the checkerboard formation, another option to have a homogeneous light distribution is the choice of orientation. This study assumes a 52.5° southwest orientation, as proposed in Trommsdorff et al. (2021) and Fraunhofer-Gesellschaft (2016), to further increase the homogeneity at the ground level. In this way, the light conditions are assumed equally for all crops below the agrivoltaic set-up.

Finally, the only free parameter is the row to row (R2R) distance (and thus the GCR, defined as width/R2R) impacting the shade level and energy production per land unit (MWh/ha) as visualized in Fig. 4.

2.2.2. Ground-mounted reference PV structure

Another option in comparison with agrivoltaic systems is the use of separated production systems (i.e. ground-mounted PV on cropland and crop production separately). Comparing both the separated and combined option is a complex task. In order to make a fair comparison, both the combined and separated system should have a similar impact on the environment (even after 20–30 years lifetime of a solar park). Indeed, as shown in Fig. 5, the left ground-mounted PV design covers a large area of the soil, limiting the water and sunlight availability. This can reduce the soil fertility and has a poor impact for biodiversity. According to the study of Wageningen and TNO (Aken, 2021), which examined 25 solar parks in the Netherlands, the best design with respect of soil quality and biodiversity is a South-facing solar park as can

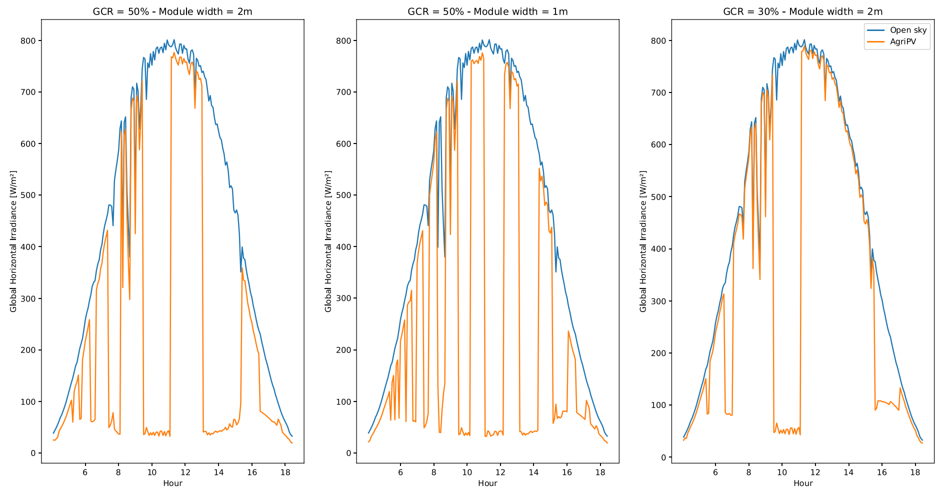

Fig. 3. The horizontal solar irradiance, measured in open sky and agrivoltaic (AgriPV) conditions. The reduction in diffuse light is visible by the continuous shift, while the direct component changes dynamically. A smaller width of the modules influences the period of shading (comparing the left and middle figure), while a lower GCR results in less periods of shade (comparing the left and right figure).

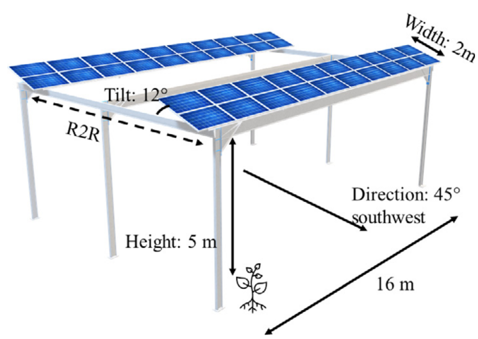

Fig. 4. The considered specific agrivoltaic system used in this study. The R2R (or GCR) is the only free parameter, impacting the shade level and energy production per unit of land.

Table 1
The geometrical lay-out of the reference ground-mounted PV plant.

GCR	0.55
Tilt	20°
Direction	South
Height	1.35 m

be seen in the right Fig. 5. It has a ground coverage of around 55% and the array width is advisable to be smaller than 4 m. In this way, most areas are receiving more than 50% of the sunlight, which is sufficient for (shade-tolerant) crop growth supplying organic matter and other nutrients to the soil. The integration of different plant species can result in an increased (pollinator) biodiversity (Blaydes et al., 2021) and habitat structures (PV magazine, 2022) with good management practices. Additionally, it has been showed that pollinating insects visited flowers regardless of the presence of the PV modules (Graham et al., 2021). The height for this ground-mounted PV system is taken at 2 m since no food crops are cultivated on this field, and the farming practices are less intensive in comparison with conventional agriculture. The specifications of the ground-mounted PV installation are presented in Table 1.

2.2.3. Crop choice and target light values

A major concern of agrivoltaic systems is the division of available solar energy between photosynthesis and photovoltaic conversion, impacting crop as well as energy yield compared to single land use.

However, plants only use a small part of the global irradiance to carry out photosynthesis (Campillo et al., 2012): PAR (Photosynthetic Active Radiation, the spectral area between 400 and 700 nm). The ability to utilize incident light differs from plant to plant. In low light conditions the photosynthesis rate of a single leaf increases almost linear with the incident irradiation, but, depending on the plant species, the rate of photosynthesis saturates at a certain amount of Photosynthetic Photon Flux Density PPFD (the number of photosynthetically active photons that fall on a given surface each second, μmol/m^2/s) (Hall et al., 1999). PPFD intensities above this point (i.e. the light saturation point (LSP)) are not able to increase the photosynthesis rate. However, the incident single leaf PPFD depends on the position of the leaves (extinction coefficient) and the sun position, the nitrogen distribution and the (overlapping) leaf area (given by the Beer–Lambert equation Ponce de León and Bailey, 2019).

This study aims to simplify the impact of agrivoltaics on the crop yield; The PPFD at the horizontal top canopy level is considered as main changing environmental parameter, leading to the use of the daily light integral (DLI, mol/m^2/day) which is often applied in greenhouse lighting (Seginer et al., 2006). This parameter integrates the PPFD values in 24 h at the top height of the canopy, including the diurnal variation and day length. This study suggests to use the average DLI_{PS} (photosynthesis, mol/m^2/day), taking into account the needed amount of photons to have a "good and sustained" crop growth. Higher DLI_{PS} levels result in excess irradiation (full solar spectrum), not contributing to the crop growth; impacting negatively the quality effects or additional crop needs (e.g. photoinhibition Demmig-Adams and Adams, 2017 or larger crop temperatures and larger transpiration rates due to UV and infrared radiation FAO, 2019). Target values of DLI_{PS}, can be found in literature based on the crop photosynthesis saturation point, experimental data, or results from (mechanistic) modeling. Following the classification method and experimental results from Beck et al. (2012) and Barron-Gafford et al. (2019): three categories can be distinguished: shade-loving crops (+) such as leafy vegetables where the shade effect increases the leaf area, shade-tolerant crops (0) like potatoes and sugar beets and shade-intolerant crops (−) like maize.

2.3. The calculation of the GCR based on the desired light target

As explained before, the installation of solar modules results in shading of the ground during the daytime which changes

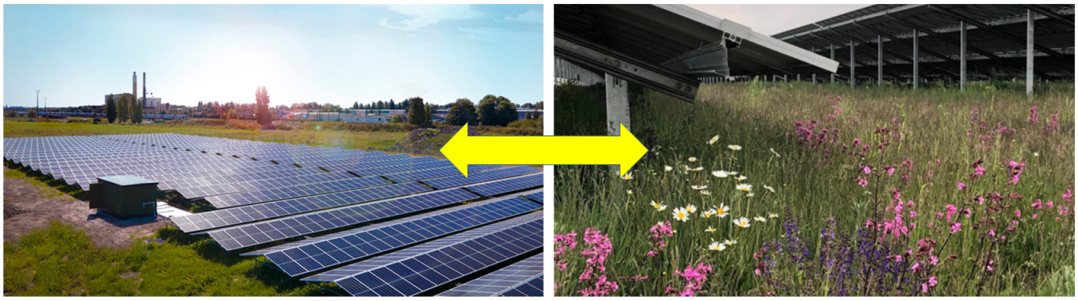

Fig. 5. Two types of reference ground-mounted PV systems. The left design is an industrial East/West lay-out, limiting water and sunlight for the soil, while the right design is a South facing lay-out, including measures for soil fertility and biodiversity (PV magazine, 2022).

temporally and spatially. The DLI_{PS} is considered as homogeneous due to the southwest orientation and landscape module position, however, small (monthly) variations between ground points are inevitable (Beck et al., 2012). Therefore, this study evaluates the DLI_{PS} for each point below the agrivoltaic set-up and timestep: Firstly, the evaluation surface (considered at the height of the canopy) is meshed, represented by a $n \times m$ (2D) matrix. Secondly, Perez model (Perez et al., 1990) is used to decompose the diffuse horizontal irradiance (DHI) from the TMY data into its isotropic I_{iso}, circumsolar I_{circ}, and horizon component I_{hor}. The solar irradiance is now represented by a direct and isotropic diffuse I_{iso} part. The direct part is represented by the direct normal irradiance (DNI) and the diffuse circumsolar region around the sun (I_{circ}). As a result, the horizontal canopy irradiance (HCI) is also divided into two parts and can be written as Eq. (1) for each coordinate (x,y) of the evaluation plane and each timestep (t) of the simulation period:

$$\mathrm{HCI}_{x,y,t} = \mathrm{HCI}_{\mathrm{diffuse},x,y,t} + \mathrm{HCI}_{\mathrm{direct},x,y,t} \tag{1}$$

Similar to the validated methodology of Marion et al. (2017), the direct component is calculated based on the sun position and module vertices, while the diffuse component is evaluated with (sky) view factors. Once the $\mathrm{HCI}_{x,y,t}$ is calculated, it is converted to the $\mathrm{PPFD}_{x,y,t}$ value. The relation between the solar irradiance (HCI) and the PPFD is not constant (varying between 0.4 and 0.6) and affected in time by several atmospheric processes (Rayleigh scattering, water vapor and ozone absorption) modeled by the solar elevation angle θ_{el} and the clearness index K_t in Eq. (2) (Ge et al., 2011).

$$\mathrm{PPFD} = -0.1248 + 0.0069\mathrm{HCI} + 0.0035\mathrm{HCI}\sin(\theta_{el}) - 0.0024\mathrm{HCI} \times K_t \tag{2}$$

The $\mathrm{PPFD}_{x,y,t}$ values are calculated every timestep and are finally integrated over the crop growth duration time and evaluation area to calculate the average DLI_{PS}.

The GCR (between 0 and 100%) impacts the shaded area and consequently the (average) DLI_{PS}. According to the desired DLI_{PS}, the algorithm calculates iteratively the corresponding GCR, used by following sections to calculate the energy, spatial and economic indicators.

2.4. Estimation of the key performance indicators

2.4.1. The energy production per unit of land

TMY weather files not only consist out of the DNI and DHI, it also contains the wind speed (at a height of 10 m) and the dry bulb temperature, which are used to calculate the PV yield. The assumed PV cells are bifacial, considered as key technology in agrivoltaic systems due to the additional energy gain and limited extra cost in comparison with monofacial cells. Firstly, in order to make a more accurate estimate of the PV yield, the wind speed at a height of 10 m is converted to the actual height at which the PV modules are located, using Hellman's law (Bañuelos-Ruedas et al., 2010), with a friction coefficient of 0.15.

Table 2
PVWatts DC model input parameters.

Parameter	
Module power	215 W/m^2
Bifaciality factor	0.7
Temperature coefficient γ	−0.002/°C
a (thermal model)	−3.47
b (thermal model)	−0.0594
ΔT (thermal model)	3 °C

Further, functions of the PVlib library (Holmgren et al., 2018) are used. The model starts by calculating every timestep the in-plane irradiance of the module's front- and rear side. The front side irradiance is calculated based on Perez's model, with input of the current DHI and DNI, agrivoltaic structure direction, module tilt and solar position. This in-plane irradiance is corrected by the angle of incidence (AOI) to account for reflection losses. The rear side irradiance is calculated based on the view factor model, described by Marion et al. (2017) where a fraction of the HCI is reflected due to the crop albedo (considered fixed at 0.2). The PVWatts DC power model is selected, where the module irradiance is converted into electricity $P_{DC,t}$ (kWh/m^2 module) decreasing linearly with the PV cell temperature. This cell temperature is calculated based on SAM's temperature model (King et al., 2004), influenced by the surrounding air temperature, wind speed and irradiance. All constants in the PVWatts and SAM model are given in Table 2.

In the final step the annual AC energy $Y_{\mathrm{electricity,PV}}$ per unit of land (MWh/ha/year), is estimated by integration of all hourly $P_{DC,t}$ model values and the use of the GCR, given by the algorithm in Section 2.3. In this estimation, a constant factor η_{losses} is used to take into account all possible power losses such as DC and AC cable losses, inverter losses, mismatch losses and PV soiling effects. This loss factor was calibrated at 10% by comparing the estimated energy yields with simulations of the PVSyst software.

$$Y_{\mathrm{electricity,PV}} = (100 - \eta_{\mathrm{losses}})/100 \times \int_{t=0}^{8760} P_{DC,t} \times \mathrm{GCR}\, dt \tag{3}$$

2.4.2. The spatial efficiency

When PV modules and crops are combined on the same land, land productivity increases. A term to evaluate this increased land productivity is the LER. The origin of this term was to compare mixed cropping systems with respect to sole crops. Later, LER was extended to agroforestry (land mixed with crops and trees) as well as agrivoltaics. The LER of an agrivoltaic system is defined as (Eq. (4)) (Trommsdorff et al., 2021):

$$\mathrm{LER} = \left(Y_{\mathrm{crop,AV}}/Y_{\mathrm{crop,FL}}\right) \times (100 - LL)/100 + \left(Y_{\mathrm{electricity,AV}}/Y_{\mathrm{electricity,PV}}\right) \tag{4}$$

Where the indices of the yield Y refer to the marketable yield (kg/ha) obtained in agrivoltaics (AV) and full light (FL) conditions and electrical yields (MWh/ha/year) obtained respectively under an agrivoltaics (AV) scenario and a reference PV plant (ground-mounted) that maximize electricity production with respect to environmental constraints. *LL* is the land loss due to the presence of the structural elements of the agrivoltaic structure.

As explained by the multi-year simulation analysis of Amaducci et al. (2018), the yield difference between agrivoltaic and full light conditions highly depends on the water availability and type of year. During years without irrigation and limited rain, the agrivoltaics tends to be higher than under full light. In contrast, under full irrigation or when rainfall satisfied crop water demand, yields are on average higher in full light than agrivoltaics. Nevertheless, it has been shown by the same study that under mild shading (20%–35% radiation reduction) the agrivoltaics yield was quite close to those obtained in full light. This can be explained by the light saturation point, where higher light levels are not increasing the photosynthesis rate (Schulz et al., 2019). It is clear that the LER values change according to the type of year (water availability, light saturation reached or not). Given that this study tries to give an "average" estimation over the lifetime of the agrivoltaic installation, and that the design is adapted to reach optimal $\mathrm{DLI_{PS}}$ light levels, it is assumed that the $\left(Y_{\mathrm{crop,AV}}/Y_{\mathrm{crop,FL}}\right)$ ratio is equal to one. Nevertheless, this ratio is decreased by the land loss, which reduces the amount of cultivated area.

In LER, the environmental effects (soil fertility, biodiversity, and eco-system) are not integrated and that may be considered as a limitation of the expression to evaluate the efficiency of the combined system. To encounter this problem, this study assumes that the reference and agrivoltaic PV systems have minimal negative impact on the environment, as described in Section 2.2. For the calculation of $\left(Y_{\mathrm{electricity,AV}}/Y_{\mathrm{electricity,PV}}\right)$, the same bifacial PV modeling parameters are assumed.

2.4.3. The LCOE

In order to evaluate the economic feasibility of the agrivoltaic installation different economic indicators such as the price-performance indicator exist (Schindele et al., 2020). However, considering that the $\mathrm{DLI_{PS}}$ requirement is reached, no large (financial) quality and quantity crop losses are expected. Additionally, the agrivoltaic structure is adapted to the farming practices and no change in operational costs is expected (working time, extra fuel, more pesticides). Consequently, the main financial indicator, usable to compare different elevated agrivoltaic installations with field crops across Europe is the LCOE (Branker et al., 2011):

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{N} \frac{\mathrm{OPEX}}{(1+\mathrm{WACC})^t}}{\sum_{t=1}^{N} \frac{Y_{\mathrm{electricity,AV}}(1-d^t)}{(1+\mathrm{WACC})^t}} \tag{5}$$

The total cost of the installation can be divided into capital expenditures (CAPEX) and operating expenses (OPEX). The CAPEX is then divided into two factors, a variable cost for the area, depending on the land consumption and a variable cost depending on the installed PV capacity. The variable cost for the area (€/m^2) considers the cost for the cabling and the mechanical structural basis. These costs are difficult to find in literature and are based on a Belgian pilot project at TransFarm (Lovenjoel) from the KU Leuven, part of the Flemish Agrivoltaics TETRA project (TETRA Agrivoltaics, 2022). The variable cost for the PV capacity (€/Wp) includes the modules, inverters, upperstructure, cables and connection cost. The detailed costs are provided in Table 3. Finally, we define the OPEX as 1.1% of the initial CAPEX, due to the synergetic effect of the dual land use (Schindele et al., 2020). As shown in Eq. (5), the annual cash flows are discounted using the Weighted Average Cost of Capital (WACC). A WACC of 6% is being used for all of Europe (Bódis et al., 2019). Finally, we use a degradation rate *d* of 1% to account for the ageing of the PV panels and calculate the LCOE over a time period *N* of 25 years. In contrast to the costs of agrivoltaic systems, the CAPEX costs of the (ecological exploited) ground-mounted systems is assumed in this study at 0.8 €/Wp, while the OPEX costs are slightly higher due to more field maintenance and fencing, resulting in 2.5% of the initial CAPEX.

3. Results

The objective of this paper is to investigate the potential of agrivoltaics across Europe. To do so, a unique gridded methodology is proposed, where three different KPIs are estimated based on the desired crop light level. In order to evaluate the impact of the assumed crop type/variety, three target $\mathrm{DLI_{PS}}$ levels were simulated between March and October (similar to the study of Cossu et al. (2020)): 12 mol/m^2/day for the shade-loving (leafy) crops like lettuce (Baumbauer et al., 2019), 16 mol/m^2/day for the shade-tolerant crops such as potatoes (Schulz et al., 2019) and 25 mol/m^2/day for the shade-intolerant crops like maize (Trecker, 2018).

The resulted gridded KPIs are used to address the following questions, and are made available in the Zenodo repository (https://doi.org/10.5281/zenodo.6752301). Interactive maps are available at https://iiw.kuleuven.be/apps/agrivoltaics/maps.html.

3.1. What are the required technical specifications for a sustainable agrivoltaic system according to my location and crop type?

One important parameter in technical agrivoltaic designs is the GCR, impacting the shade level and power capacity (energy production). This is also confirmed by the study of Amaducci et al. (2018), which showed that the radiation reduction was more affected by the GCR than the module management. Based on the three $\mathrm{DLI_{PS}}$ levels, which are simulating three different crop types, the GCR is expressed across Europe. Not surprisingly, Fig. 6 clearly shows that the GCR increases with increasing solar insolation level (see Fig. 7 where the average daily HCI for the crop season is shown). This increase is enhanced by the geographical latitude: due to higher sun elevation angles, shade fractions and consequently average light reductions are smaller. In contrast, the GCR drops significantly for the Northern half of Europe, especially for the $\mathrm{DLI_{PS}}$ requirement of 25 mol/m^2/day, where the GCR tends to be nearly zero. This result is in line with current crop growth strategies: light needy crops (tomatoes, fruits, ...) are mostly cultivated in the South whereas in the Northern part winter crops are available. The GCR expresses the PV cell area with respect to the cultivated area. If a low GCR is required to meet a specific $\mathrm{DLI_{PS}}$ level, but the area of needed protection against hail or heavy rain is larger, semi-transparent modules (spaced c-Si cells with transparent backsheet or glass–glass modules) come in as the perfect solution (Gorjian et al., 2022; Willockx et al., 2020a).

It is also shown that for one specific location the GCR significantly changes related to the chosen shade tolerance of the crop. Consequently, caution should be taken in the field crop rotation

Table 3
CAPEX inputs for agrivoltaic installations.

	Land cost	Peak cost
Bifacial PV modules		0.33 €/Wp (Module Price Index, 2021)
Balance of system upperstructure		0.47 €/Wp (Cossu et al., 2021)
Steel for mechanical basis	30 €/m^2 (TETRA Agrivoltaics, 2022)	
Site preparation and installation	20 €/m^2 (TETRA Agrivoltaics, 2022)	

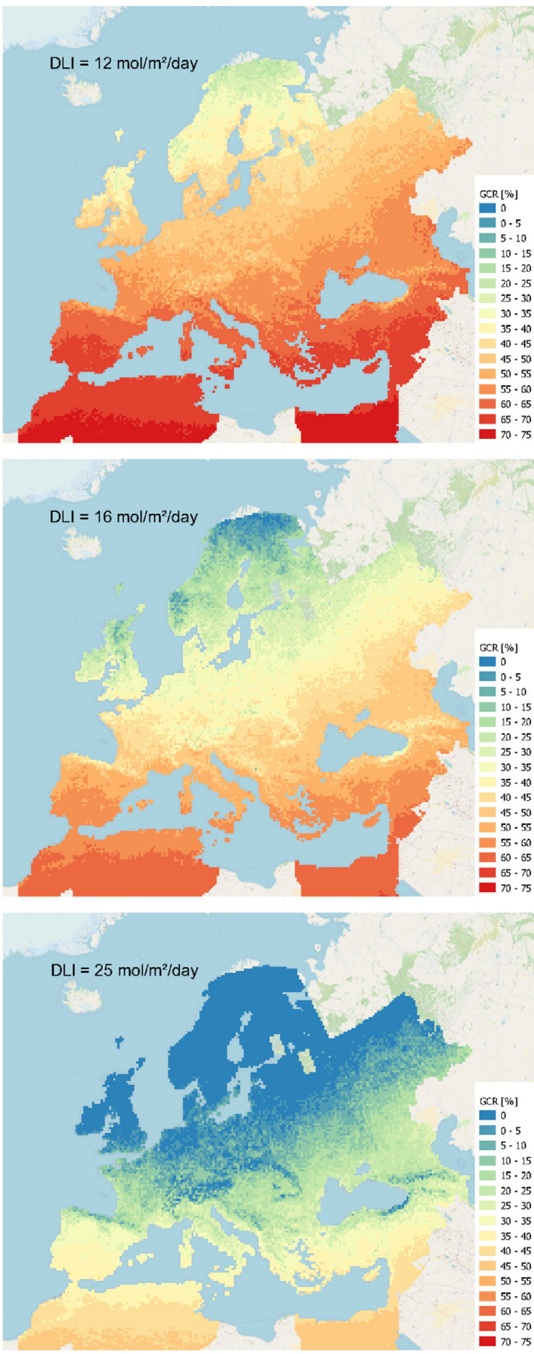

Fig. 6. The estimated GCR for three DLI_{PS} requirement levels. The GCR increases with rising solar insolation levels and crop shade tolerance.

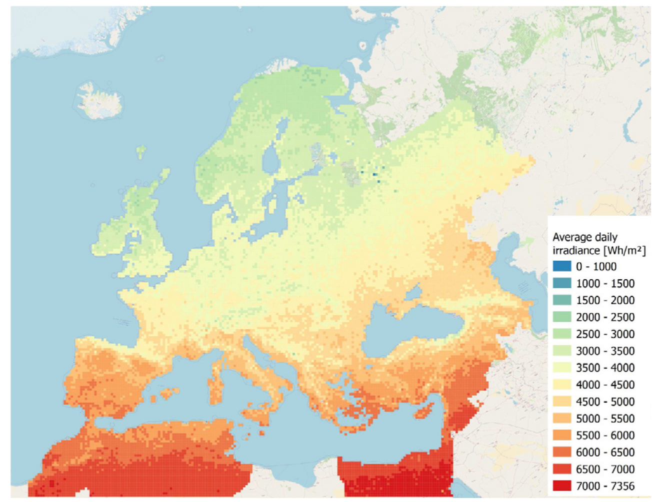

Fig. 7. The averaged daily HCI in open field conditions.

system: a fixed agrivoltaic system (with fixed GCR) will need every year a crop with similar light requirements.

Comparing the simulated GCRs with existing elevated agrivoltaic pilots show a high similarity: the German pilot situated in Heggelbach (APV, 2016), cultivating potatoes and wheat (DLI_{PS} = 16 mol/m^2/day), has a GCR of 35% while the France pilot in Montpellier has a GCR of 50% (Marrou et al., 2013b) for the same crop type. For the simulation study in Piacenza (Italy) with maize (Amaducci et al., 2018), the optimal GCR without yield losses was 13% (ST1 scenario), which is in line with the GCR on the DLI_{PS} = 25 mol/m^2/day map (15%–20%). Another study (Cossu et al., 2020), evaluating a photovoltaic greenhouse in Sardinia (Italy), showed that medium light species (such as asparagus) with an optimal DLI lower than 17 mol/m^2/day and low light crops can be cultivated with a GCR up to 60%, which is exactly the simulated GCR in the 16 mol/m^2/day map. However, the limited number of existing pilots make it difficult to validate all estimated GCRs. Therefore, we assess the GCR maps based on (shaded) results of major field crop types across Europe:

- Root crops (potatoes): the study of Schulz et al. (2019) showed that shading had no significant influence on the potato quality and yield if the DLI_{PS} = 16 mol/m^2/day requirement is reached, resulting in shade levels of 50% shade at latitudes lower than 35°N while with every increase of 10°N the accepted shade levels have to be halved. These shade levels are compliant with the simulations of the GCR in our study.
- Cereals (wheat and barley): the study of Arenas-Corraliza et al. (2019) showed that current commercialized wheat and barley cultivars have sufficient plasticity for adaptation to shade. In their analysis in the Mediterranean area (high irradiance conditions), the grain yield at 10% and 50% shade levels showed comparable results. In contrast, at lower solar insolation conditions (−35%), grain yield decreased under 20%–30% shade level. These results are in line with our DLI_{PS} approach, simulating a higher GCR (and shade level) at places with a higher insolation level.

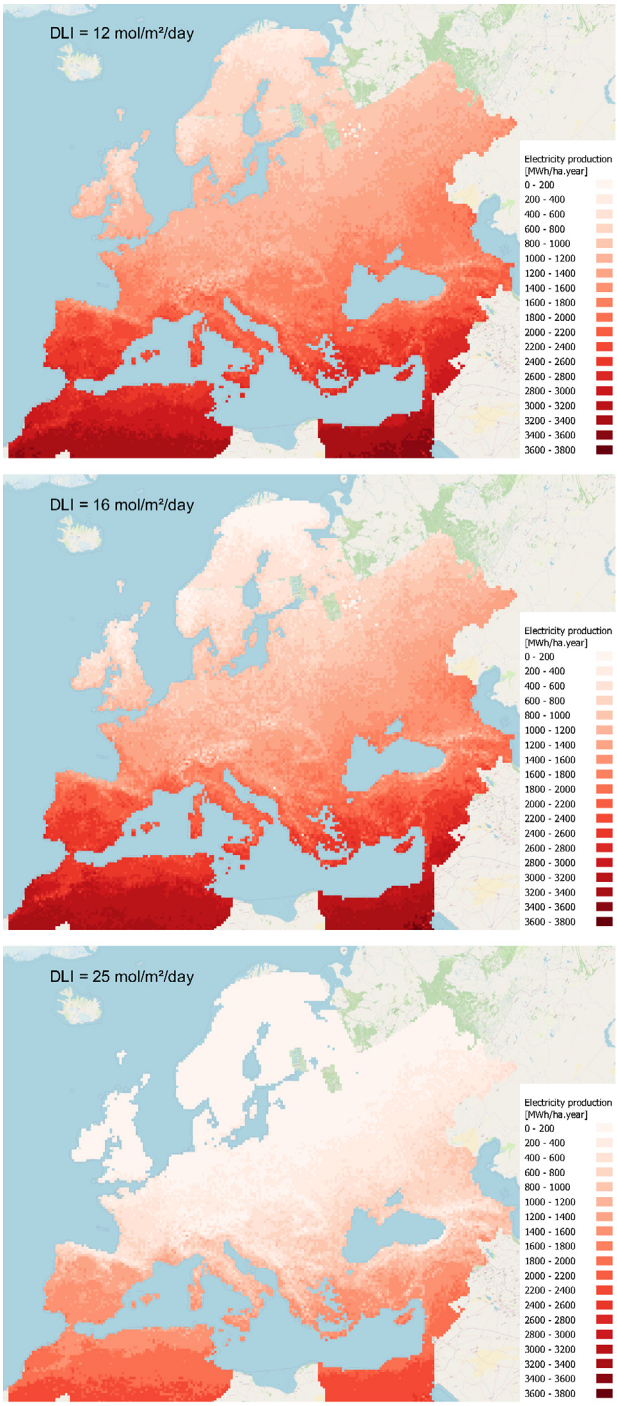

Fig. 8. The simulated annual electricity production for three DLI_{PS} requirement levels per ha of land. The electricity production per unit of land is massive for Southern countries due to their high capacity factor and power capacity (shade requirement (GCR)).

3.2. What is the potential energy production? does it differs with traditional ground-mounted PV systems?

This question is particularly interesting for each member state separately. Each member state has a national binding renewable energy target, and wants to know the possible energy production per unit of crop land. For agrivoltaic systems, the high GCR and capacity factor in the South (Bódis et al., 2019) results in a massive potential on the annual energy per land area (MWh/ha/year) production as shown in Fig. 8. In contrast, due the lower capacity factor and GCR, the energy is almost 5 times lower in the Northern countries for one specific light target. Consequently, this means that for the same amount of generated energy, 5 times more (crop) land will be needed in the Northern countries in comparison with the Southern countries. Additionally, Fig. 8 shows also the increase in energy production per land area regarding the shade-tolerance of the crop. Indeed, a higher shade-tolerance and higher GCR results in a higher energy production per unit of land. Subsequent, for the same amount of needed energy, less agrivoltaic land area is needed, resulting in a reduced impact on the visual landscape. The impact on the visual landscape (and social acceptance) should not be underestimated as shown by various studies (O'Neil, 2020; van der Horst, 2007), and could be a reason to prioritize shade-loving or shade-tolerant crops.

The same reasoning about the impact on landscape can be made in comparison with ground-mounted PV systems. As shown in Fig. 9, there is a difference between the energy generated by the ground-mounted PV and agrivoltaic system. In the South, due to the elevated agrivoltaic structure (resulting in more diffuse light that can penetrate and smaller shade fractions), larger GCRs (and a higher energy production per unit of land) are possible in comparison with a ground-based PV system for an equal soil impact. Indeed, the ground-based PV systems are constrained by the GCR since the low height result in higher shade levels. This means that there is less area needed to generate the same amount of energy. In contrast, in the Northern countries where agrivoltaic systems have a lower GCR, ground-mounted PV systems generate more energy per unit of land, meaning that there is less impacted crop land needed for the same amount of generated energy.

3.3. What are the benefits of the agrivoltaic system compared to separated production

To answer this question, we address three main benefits found from the literature review in the introduction:

- less evapotranspiration which saves irrigation (water)
- increased spatial efficiency
- the reduction of plastics or nets which are common in crop protection systems.

3.3.1. The water reduction

Irrigation accounts for 70% of total global water withdrawals (Gao et al., 2021). Water is a valuable good, and the increasing drought periods (typically in the South of Europe) will cause a competition between different sectors. To promote efficient agricultural production, it is necessary to ensure water security and to realize efficient water use (Gao et al., 2021). One option to reduce the need for irrigation, is the reduction of the evapotranspiration rate. Following the Penman–Monteith relation (McNaughton and Jarvis, 1984), there is a high correlation between evapotranspiration rate and solar radiation. Consequently, the highest water savings will occur for the largest PV ground coverage ratios as visualized in Fig. 6, while a low GCR will result in almost no effect on the evapotranspiration rate.

3.3.2. Increased spatial efficiency

The present analysis shows the gridded LER values in Fig. 10. The LER increases by rising solar insolation level and crop shade tolerance. As explained, there is a seasonal variability of the LER, sensitive to the type of year. The simulated LER values can therefore not be considered as fixed during the lifetime of the agrivoltaic installation, and give more an estimation of its average value based on the TMY weather data. Additionally, these LER values are not considering the positive (economic) crop (quality) benefits, for example, due to the protection against

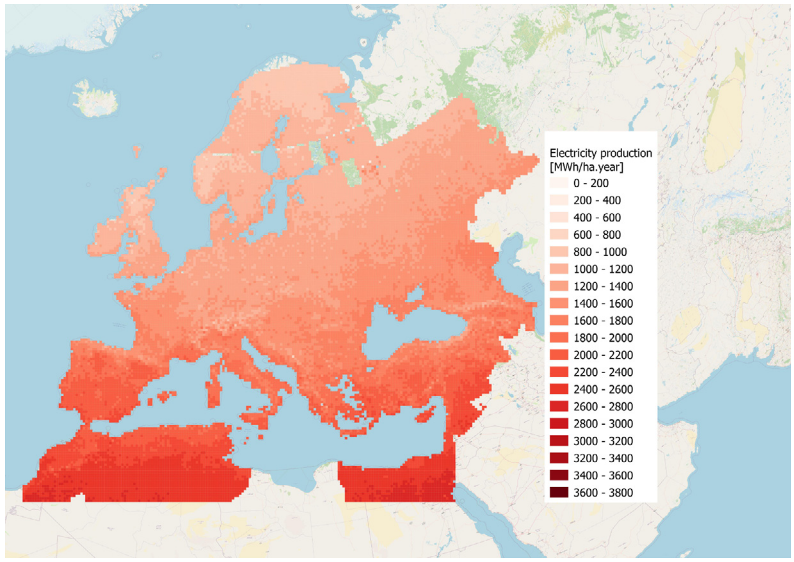

Fig. 9. The simulated annual electricity production for a ground-mounted PV system per unit of land.

extreme weather events (hail or sunburn), which are more likely in future due to global warming. Moreover, the reference PV system is considered as fixed for all regions, but the design (such as the tilt angle) can differ concerning the latitude and local engineering/grid requirements.

Nevertheless, the present single-scenario analysis highlights the risk of agrivoltaic systems; depending on the type of crop, land loss (considered at 10%) due to the structural elements and specific place, there is no spatial advantage of the dual land use guaranteed (LER < 1). This means that separate production of agriculture and PV will result in the same amount of food and energy production.

In contrast, in the South, LER values greater than 2 can be found. This can be explained by the sustainable LER definition where both the ground-mounted PV and agrivoltaics system are considered to provide minimal (negative) impact on soil fertility and biodiversity. Because the ground-mounted PV structure is placed much lower, diffuse and direct sunlight is not able to reach all areas of the ground level, explaining the limit on the GCR (of 55%) and the energy production per unit of land. By placing the agrivoltaics system at a height of 5 m, a higher GCR is possible (resulting in a larger energy production potential), since the diffuse light will be able to penetrate a larger area below the PV array.

Generally spoken, the LER will be lower (1) for places with low solar insolation levels and (2) for crop types that require high DLI_{PS} levels as shown by Fig. 10. For the highest light requirement (average $DLI_{PS} = 25$ mol/m^2/day), spatial advantages in comparison with a separated production system are not guaranteed for the Northern half of Europe.

3.3.3. Reduction of plastics

Another advantage of agrivoltaics is the reduction of existing crop protection systems. These protection systems can be mostly found for (high-value) permanent crops, however, in the Mediterranean area with high radiation levels, also fields crops can benefit from shade nets and plastic tunnels (Pardossi et al., 2004). The replacement of these plastic tunnels by agrivoltaic systems has a positive benefit for the environment; as plastics have been observed to negatively affect humans and the environment: due to their potential toxicity and interaction with distinct species, including humans, at different biological levels (Rodrigues et al., 2019).

3.4. At which cost can agrivoltaics be implemented (in comparison with ground-mounted PV)?

As visualized in Fig. 11, the LCOE decreases with regard to the shade tolerance of the crop. The lower light requirement results in a larger GCR and subsequent larger power capacity and energy generation for the same amount of fixed structural costs. However, there is also an optimal LCOE design possible, illustrated in South-Spain. The lowest LCOE can be found in the 16 mol/m^2/day map. A lower light requirement (12 mol/m^2/day), and consequently higher PV density and investment cost, will result for this case in a higher LCOE, due to a lower PV efficiency caused by module self-shading and marginal bifacial gain. In contrast, a higher light requirement (25 mol/m^2/day), results in a lower PV density and higher PV efficiency, but again an increased LCOE, due to the initial cost of the steel structure. It is therefore shown that the cost plays an important role in the sustainable deployment of agrivoltaics: it can lead to a cultivation shift and impact on the food security, where farmers try to optimize their revenues and income diversification by the cultivation of shade-tolerant crops and not of shade-intolerant types (like maize); This effect is also highlighted by the study of Sekiyama and Nagashima (2019b). They showed that the total annual revenue from a high-density agrivoltaic installation with corn harvest was 8.3 times larger than the reference situation, whereas that of the low-density configuration was only 4.7 times larger although that the corn harvest in the low-density case was lower. Consequently, there is a likely event that farmers or PV deployers try to optimize the total economic profit, with a too high GCR for the specific crop type. This study therefore suggest the need for minimum DLI_{PS} or GCR target values, obliged by the local policymakers.

It is known that the LCOE is very sensitive to its input assumptions (Branker et al., 2011). For example, the cost of the steel structure will depend on the local conditions such as wind speed (wind load), soil stability etc. Also, the WACC values vary over a wide spectrum: from 3.5% (Germany) up to 11%–12% in countries of Eastern Europe (Bódis et al., 2019). However, our results are in line with reported values in literature: €0.093 per kWh in Germany (PV Magazine, 2021a) and €0.0815/kWh in France (PV Magazine, 2021b). Nevertheless, following a sensitivity analysis at three locations for an equal DLI_{PS} requirement of 16 mol/m^2/day, the advantage of a high power capacity (kWp/ha) in the South is clear. Indeed, in Fig. 12, CAPEX, OPEX and WACC are varied with

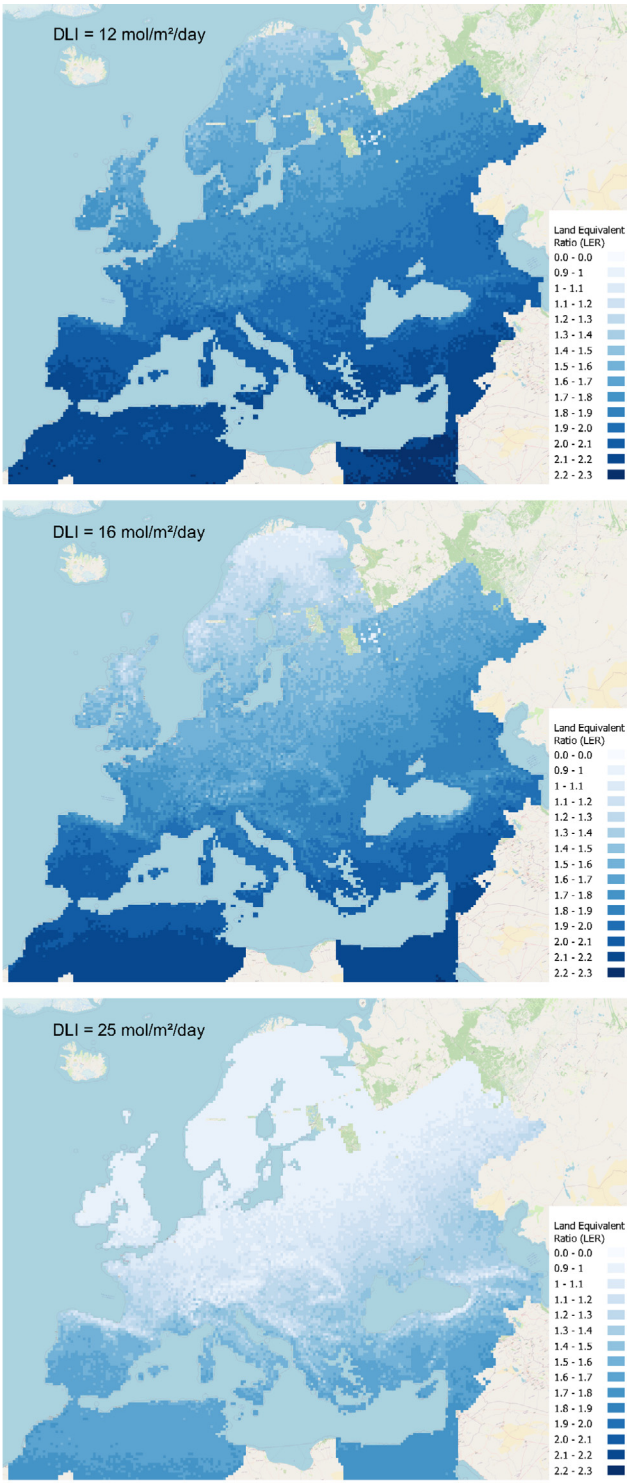

Fig. 10. Expected LER values, showing the risk of a small spatial improvement in comparison with a separated production system for Northern countries and high DLI_{PS} requirements.

25%. Because of the higher capacity factor and GCR in the South, initial CAPEX costs are divided over a (much) larger amount of energy, resulting in a minor absolute change in the LCOE. Consequently, LCOE prices are almost 3 times lower in comparison with the installation in the North. The same reasoning applies in comparison with ground-mounted PV installations. The price

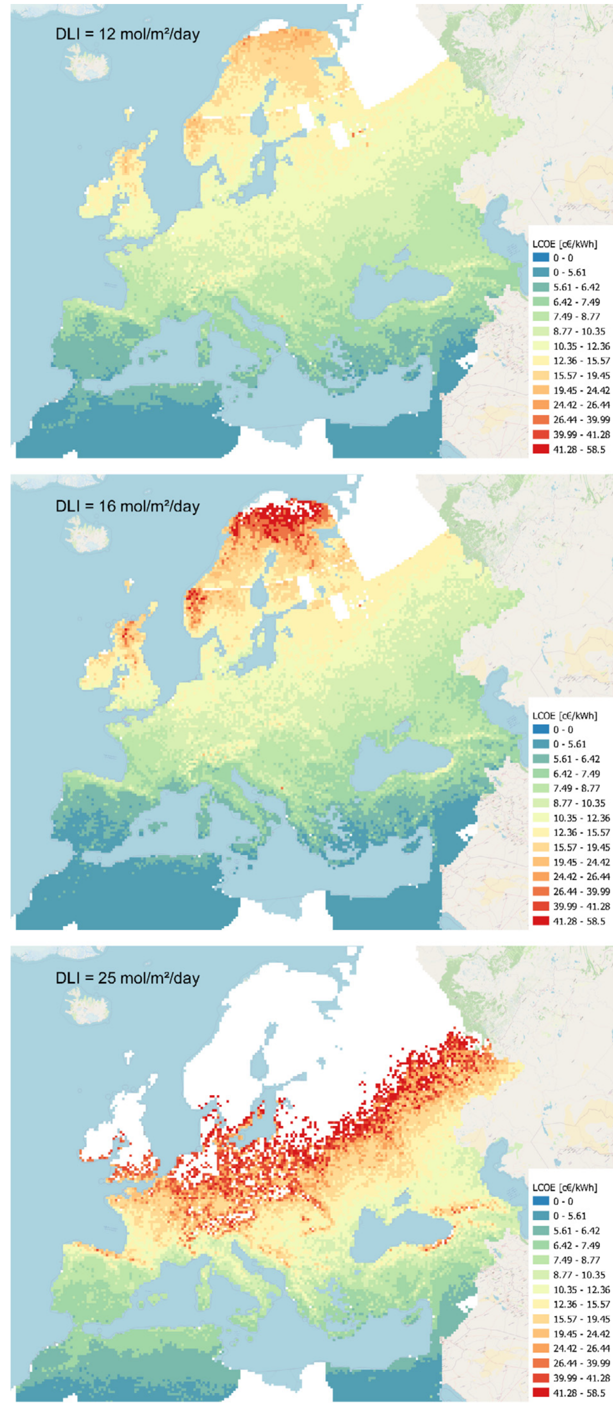

Fig. 11. LCOE values based on a specific agrivoltaic system with a fixed structural cost. Shade-intolerant crops and consequently a low-dense agrivoltaic system results in too high CAPEX costs in contrast to the annual energy production. The massive energy production per unit of land for shade-loving crops in the South results in competitive wholesale prices around €50/MWh.

difference between the ground-mounted PV systems and agrivoltaics (DLI_{PS} = 16 mol/m^2/day) is visualized in Fig. 13, and is mainly affected by the CAPEX. If the generated energy over the lifetime is high (in the South), the impact of this increased CAPEX cost is much lower (LCOE+15%) than in the North (LCOE+00%) where the generated energy is 5 times lower. Further cost reductions on the mechanical (base) structure (less steel material for equal mechanical load) and the choice of shade-loving crops

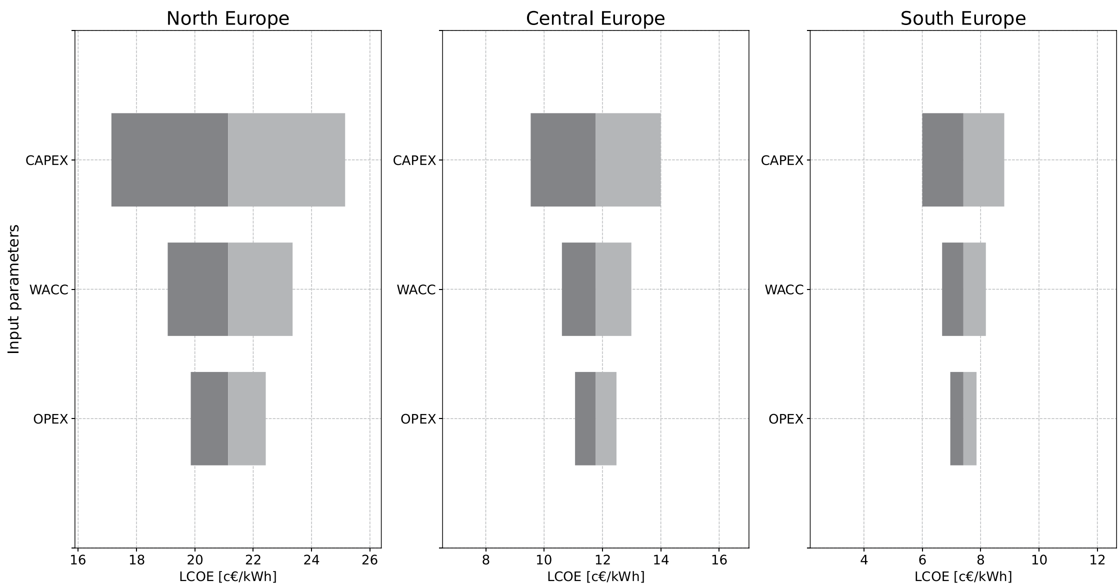

Fig. 12. Tornado plot showing the sensitivity of the LCOE at three different locations in Europe (latitude 60–40–35). At lower latitudes, CAPEX costs are divided over a higher amount of energy, resulting in a minor influence on absolute LCOE values. In contrast, the absolute value of the LCOE in the North is much more dependent on the CAPEX cost.

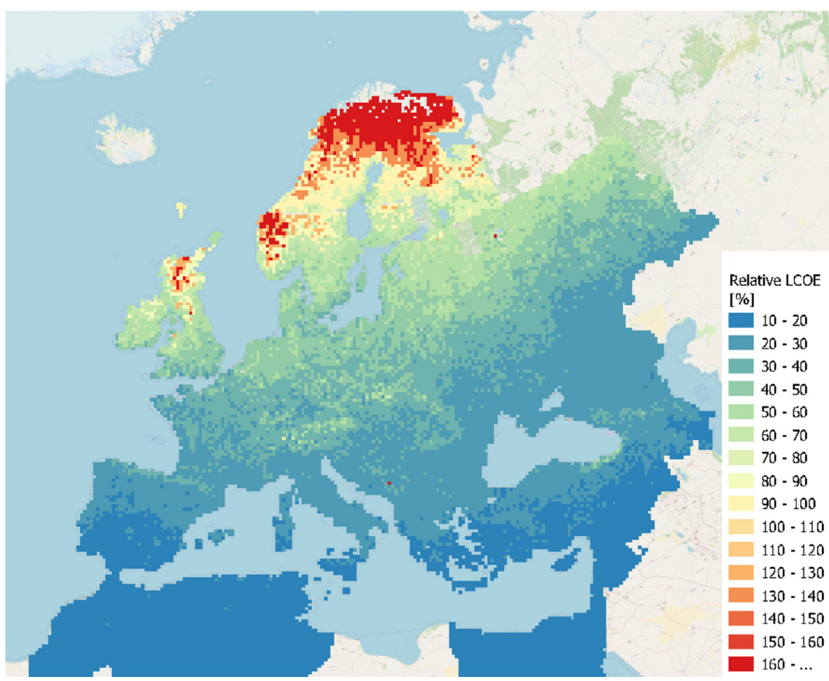

Fig. 13. The estimated difference between the LCOE for a ground-mounted PV system and an elevated agrivoltaic system designed for a DLI of 16 mol/m^2/day. The LCOE of a ground-mounted system is always lower, however, the relative difference in the South is only 15% while in the North the deviation can be larger than 100%.

(higher GCR for the same base structure), will only improve its competitiveness with traditional ground-mounted PV.

As pointed out, the low GCR and the low capacity factor result in the Northern countries to a high LCOE, sensitive to the CAPEX costs of the steel structures. This leads to a first thought of unlikely investments in agrivoltaics. However, the real market competitiveness depends on the local WACC, taxes, and business model (retail price for self-consumption or spot price for purchase power agreement (PPA)/energy injection). Also, countries can boost their competitiveness by direct and indirect support schemes like an increased Feed in Tariff (FIT). The question also arises if elevated agrivoltaic systems are suitable for all regions of the EU. Places with a low GCR and low capacity factor are maybe better with ground-based systems (like the vertical bifacial structure) with a large interrow distance, where less protection against high sun radiation is required, but protection against strong wind can be an added value. These systems would limit the needed amount of construction steel and investment (CAPEX) cost, increasing its price competitiveness.

3.5. The technical potential based on a case study with potatoes

Although that previous indicators clearly show the advantages for the Southern countries, the production of certain crops is

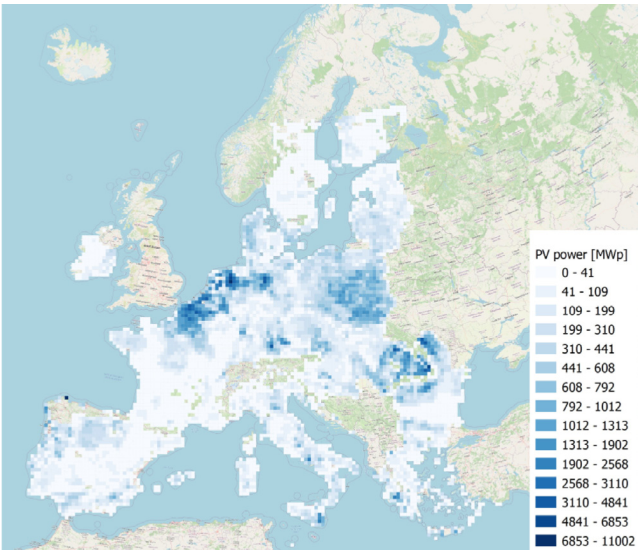

Fig. 14. The power of agrivoltaic potato cultivation, considering the available area and needed DLI_{PS} of 16 mol/m^2/day.

sometimes concentrated in other regions (due to other favorable environmental factors). This is illustrated with a case study focusing on potatoes. Potatoes are considered as shade-tolerant (C3 crop) for different shade levels (Schulz et al., 2019) and grown on 1.7 million hectares (only 1% of the total utilized agricultural area (Land cover, 2021)). The largest areas and consequently available power production is situated in Belgium–Netherlands–Germany–Poland and Romania (see Fig. 14). However, the total European agrivoltaic potential would be 1290 GWp (with an annual production of 1590 GWh, visualized in Fig. 15), which is almost 10 times larger than the current European solar PV capacity (EU, 2019). Given that the net electricity generation in the EU was 2 780 TWh in 2019, it is therefore clearly shown that even a small percentage of agrivoltaic systems could boost drastically the EU renewable production. However, the absolute technical potential (MWp) is mainly impacted by the existing cultivated area of a specific crop type and its shade-tolerance, where permanent grassland and cereals have the largest share and potential in the European union.

4. Implications of the crop impact indicators and socio-technic implementation issues

This study uses the DLI_{PS} as agrivoltaic crop impact indicator while other microclimatic effects such as air humidity and temperature are considered as minor effects (Marrou et al., 2013b). Conducting an equal DLI_{PS} target throughout Europe means a difference in shade level for every location (the ratio of light availability in agrivoltaic and open field conditions), which can have an important impact on the diffuse/direct and consequently the crop growth behavior. Indeed, not only does the amount of PPFD influences the crops' total photosynthesis rate: also water availability (Baslam et al., 2020), nitrogen content, leaf temperature, diffuse ratio (Li et al., 2016), R/FR ratio affects the ability of the crop to create assimilates. The use of a dynamic mechanistic crop model is needed to simulate the exact amount of biomass concerning these spatial and temporal changing variables. Although mechanistic crop models exist (GECROS Yin and Laar, 2005, STICS Brisson et al., 1998 etc.), little information is given how the default crop parameters (calibrated in shade free conditions) must be adjusted in respect of the shade level created by agrivoltaics. Various experiments show the effect of plants as living organisms. Some species react with shade avoiding behavior morphological and phenological changes (such as increased leaf area, change in extinction coefficient, number of leaves), improving their radiation interception efficiency and light use efficiency, resulting in the need to re-calibrate these models (for each crop-type and variety) in agrivoltaic conditions (Marrou et al., 2013b). Additionally, some subroutines, created in light of a shade-free environment (for example the leaf expansion) need to be re-modeled. Given the (unknown) complex shaded behavior of crops for different shade levels, utilizing and calibrating (Wallach et al., 2021) these mechanistic models, results in a time-intensive and high uncertain process, where more specialized research is needed. Therefore, the use of DLI_{PS} target values is currently the best (least uncertain) option to examine a geospatial assessment.

On the other hand, the implementation of agrivoltaics also leads to technical challenges: the high penetration of agrivoltaic systems into distribution networks located in rural (agricultural) areas may lead to stability issues and overvoltage problems. This can be partially solved by the increased load due to farm electrification. Additionally, excess solar power production is curtailed (Bird et al., 2016), however, regarding the large power potential, hydrogen production or storage with batteries could be a better option. Technological advancements in power electronics and the need to further decarbonize our world (power-to-X, electrical vehicles, heat pumps), may support higher PV penetrations by directly use of the excess energy in distributed generation systems. Smart inverters with advanced protection algorithms (Baeckeland et al., 2020) will help to stabilize the grid by controlling the reactive power and consequently grid voltage.

Lastly, the use of these elevated agrivoltaic installations, with a height of 5 m, could also have an impact on the visual landscape aspect and consequently the Not In My Backyard (NIMBY) effect. A sustainable landscape vision is therefore needed as described by Toledo and Scognamiglio (2021).

Only the evaluation of all important indicators (crop light requirement, protection against extreme weather conditions, land use, price competitiveness, reduction on water and plastic use) will lead to a sustainable deployment of agrivoltaic systems in the future across Europe. It is the task of the policy maker to optimize the social benefit and to provide a framework that attracts investors for the right PV application (ecological ground-mounted PV or agrivoltaics).

5. Conclusions

In order to realize a sustainable energy transition in Europe, additional PV systems are needed. One promising application with a huge theoretical potential is agrivoltaics on arable land: the combination of crop and PV production on the same land. Realizing this multidisciplinary system raises multiple challenges and questions.

- What are the required technical specifications for a sustainable agrivoltaic system according to my location and crop type?
- What is the potential energy production? Does it differs with traditional ground-mounted PV systems?
- What are the benefits of the agrivoltaic system compared to separated production?
- At which cost can agrivoltaics be implemented (in comparison with ground-mounted PV)?

This work proposed three key performance indicators, simulated at detailed EU grid level, focusing on elevated agrivoltaic systems applied on arable land and compliant with the farming practices. Three different light requirements (crop types) are examined, leading to the following main conclusions:

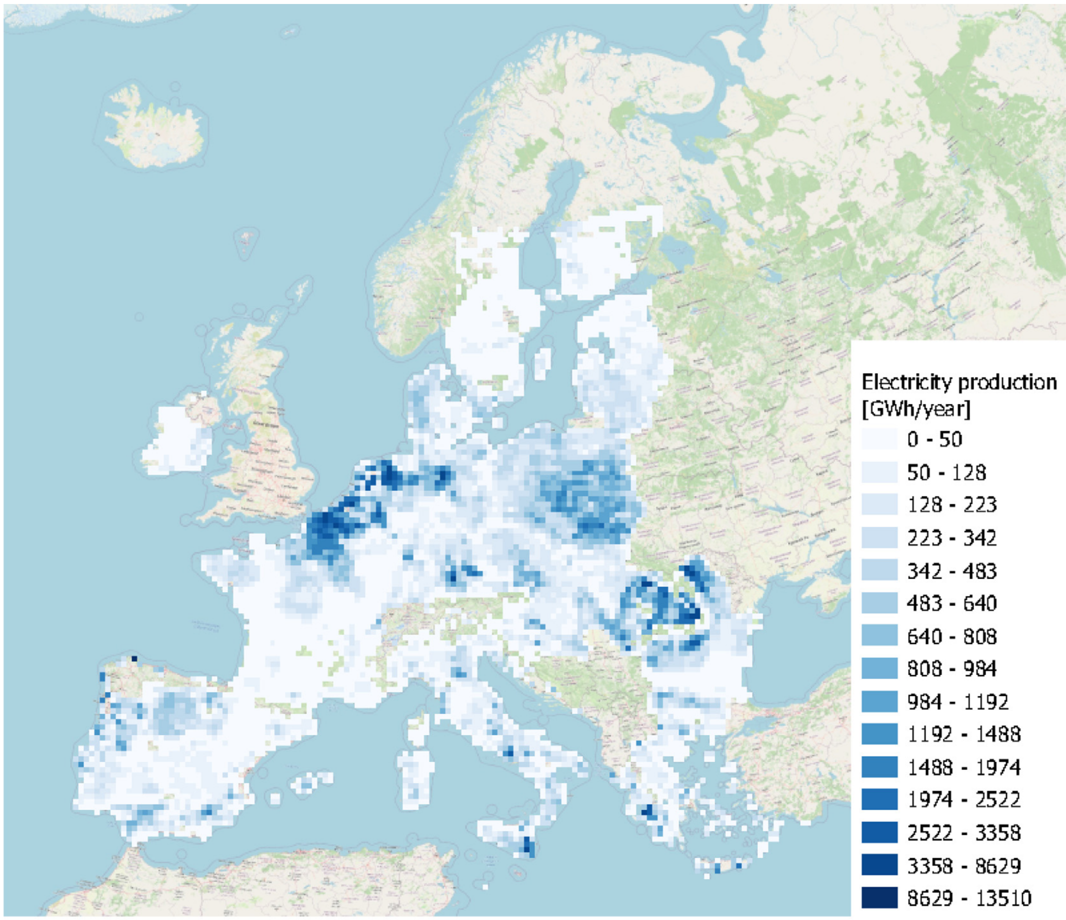

Fig. 15. The annual electricity production of agrivoltaic potato cultivation, considering the available cultivation area and needed DLI_{PS} of 17 mol/m^2/day.

(i) The GCR increases significantly for shade-tolerant crops (category 0) and places with a high insolation level;
(ii) (Varieties of) field crops in a fixed agrivoltaic crop rotation system must be carefully selected concerning their shade (in)tolerance in order to have a guaranteed sustainable agricultural system during the lifespan of the installation;
(iii) Agrivoltaic installations are financially more attractive and competitive for shade-loving crops (like leafy vegetables), leading to a risk that farmers will shift their production system and less shade-intolerant crops will be cultivated;
(iv) From a general economic point of view, agrivoltaics becomes cheaper in the South due to the higher capacity factor and higher ground coverage ratio (more solar irradiation and smaller shade fractions). However, there is an optimal design where an increase in PV density not leads to a lower levelized cost of energy due to the lower specific energy production (kWh/kWp) caused by module self-shade effects and minimal bifacial gains.
(v) Due to the limited available solar insolation in the Northern countries, ground coverage ratios of agrivoltaic installations are generally low. In contrast, the ground coverage ratios in the South are higher. Consequently, ground-based agrivoltaic systems with larger interrow distances will be more suitable in Northern countries, being more competitive, while elevated systems with larger coverage ratios have a vast potential in the South as crop (shade) protection system;

Important for policy makers is that all (social) costs must be including in the decision between combined or separated production. The (investment) cost of traditional ground-mounted PV farms stays in all situations lower than agrivoltaic systems. However, in some regions and dependent on the crop type, the added (social) benefits (water reduction, plastic reduction, land optimization and visual impact on landscape) of agrivoltaics is higher than separated production systems. On the other hand, for places with limited extreme weather events (limited years of drought, hail), annual solar insolation (where shade results in crop losses), or land constraints, the separated production systems outperforms the combined agrivoltaic system. Therefore, every member state should weigh the usefulness of agrivoltaic installations in comparison with ecological exploited ground-mounted PV farms and should establish guidelines on the maximum PV ground coverage ratio before implementing agrivoltaic support schemes; Although that our simulations are in line with other research results, more (long-term) field data of all effects of agrivoltaic systems is needed to better facilitate this important decision.

A case study focusing on potato cultivation showed the immense potential and importance of research of agrivoltaic systems across Europe: agrivoltaic potato cultivation uses 1% of the available agricultural area and could lead to an increased capacity of 1290 GWp which is tenfold of the current EU PV capacity. The absolute technical potential (MWp) is many times higher and mainly impacted by the existing cultivated area of a specific crop type where permanent grassland and cereals have the largest share. Nevertheless, important challenges remain to be addressed in terms of research on crop growth (modeling) and clear policy implementation guidelines.

CRediT authorship contribution statement

Brecht Willockx: Methodology, Software simulation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Cas Lavaert:** Software simulation, Visualization, Writing – review & editing. **Jan Cappelle:** Formal analysis, Supervision.

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.

Data availability

Datasets related to this article can be found at https://doi.org/10.5281/zenodo.6752301, an open-source online data repository hosted at Zenodo.

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