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Mitigation of land-related impacts of solar deployment in the European Union through land planning policies

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ABSTRACT

Solar power is space-intensive and will contribute to intensify land competition, a factor typically not captured by models. This study uses the Integrated Assessment Model WILIAM which explicitly represents the land use changes driven by solar energy expansion through a hard link of its energy and land modules including net energy restrictions. A Green Growth type transition is simulated for the European Union with a high renewable energy share target in electricity mix by 2050, testing different land use planning policies.

The results show that a rapid deployment of solar power in land without land policies can intensify land use conflicts and increase associated land use change emissions. Land-use requirements for solar would be 1–1.4 % of total land (corresponding to 55–75 % of urban land), which could be problematic locally. The implementation of land-use protection and land siting policies could reduce 23 % of total land occupied bv solar photovoltaics panels (with respect to forest and cropland the area occupied could be reduced up to 88 %), and 23–47 % of the land use change associated emissions with respect to a scenario where not policies are applied. These results show the importance of integrating land use and energy planning policies to alleviate the undesired impacts.

1. Introduction

Global land resources are critical to reach climate objectives, being also essential to sustain life [1] and even recognised as a “planet boundary” [2]. On the other hand, the urgency of the climate change challenge implies the design of ambition mitigation policies, being renewable energies key. Given that today ~80 % of final energy is supplied by fossil fuels, this will require a very large expansion of new renewable energy infrastructure that, due to the lower power density of renewables, tends to occupy more area than fossil fuels [3]. For solar photovoltaics (PV), power densities ranging 2–10 W_e/m^2 (~11.4–57.1 m2/MWh/year) have been reported in the literature for the total power plant facility [4] (range due to geographical differences in solar irradiance [3,5]).

Recent studies show that Utility-Scale Solar Energy (USSE) installations are often sited in agricultural land (e.g. more than 30 % in EU [6] and 28 % in California in croplands and pastures [7]) due to specific conditions: flat, typically close to the electrical grid due to proximity to inhabited areas, large and cleared parcels, and higher solar power production potential [8]. However, if the siting of solar plants is only based on the goal of maximizing production [9], it could worsen land-use conflicts [10], affecting other sectors as agriculture, and amplifying negative effects on biodiversity [11] and Greenhouse Gas (GHG) emissions from land-use change [12].

Hence, the analysis of the synergies and trade-offs between land, energy and ecology are necessary [13]. This brings to light the need to design appropriate land-based policies in a context of fast solar deployment [14]. The following ones are gaining importance: 1) land siting policies of USSE installations incentivising a) the built environment [15], such as rooftops PV [16], b) degraded lands, or c) non-human utilizable land, as water surfaces with floating solar photovoltaic panels [17], 2) agrivoltaics systems that allow to use the same area of land for USSE installations and agriculture [18], 3) solar energy park design with land management practices [19]to maximise the supply of ecosystem services [20], 4) land protection policies to assure biodiversity

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Nomenclature

Abbreviations

C	Carbon
CO_2	Carbon Dioxide
EROImin	Minimum Energy Return on Energy Invested
EROIpou	EROI to the point of use
EROIst	EROI standard
EU	European Union
GHG	Greenhouse Gas
GIS	Geographic Information Systems
IAM	Integrated Assessment Model
LUC	Land Use Change
LUE	Land Use Efficiency
LULUCF	Land Use, Land-Use Change and Forestry
PV	Photovoltaics
RES	Renewable Energy Sources
SM	Supplementary Material
USSE	Utility-Scale Solar Energy
VRES	Variable Renewable Energy Sources

protection, and avoid pressure over productive land types [21], or 5) repowering: upgrading or retrofitting, thus reusing existing land sites [22].

Scenarios and models are recognised as effective tools capable of evaluating the impacts over time of deep decarbonisation scenarios. In particular, Integrated Assessment Models (IAMs) are powerful tools widely used for the design of climate change mitigation pathways [23] that integrate climate, environment, human and social components being able to analyse how these multiple complex dimensions interact [24]. IAMs can evaluate different sectoral policies in combination, as e.g. assessing potential synergies and trade-offs when combining land management and energy policies, including underperforming [25]. Nevertheless, IAMs and also specific sectoral energy and land use models, usually do not consider in their land use competition analyses the potential constraints driven by the deployment of solar energy on land, remaining understudied this issue from a quantitative point of view. Past analysis of impacts on renewable energy have been focused on bioenergy, as with GLOBIOM–MESSAGE model [26]. Just a few studies have analysed this issue in a quantitative manner (see Table 1 below).

However recently the land use requirements of solar energy has taken more relevance because 1) the share of solar energy in future scenarios are high (even 60–90 %), meaning that the expected electricity energy demand cannot be fulfilled occupying urban areas or roof-tops [6], and in the case of specific world regions like the European Union (EU), which is small and densely populated, this can result in a shortage of suitable land sites for installing PV [6] 2) has less power density than fossil fuels [31] being its value lower that initially estimated [27], and 3) although the potential global land use conflicts due to the energy transition had been already anticipated [27], now they are of increasing interest at local and at larger spatial scales (e.g. the Conservation Plan in California [32]). At local scale rural conflicts are already occurring [33], being the cause for the adoption of policy barriers to the siting of solar farms. This is due to the lack of appropriate land use planning from governments regulating the integration of renewable energy projects to landscapes [34].

This article intends to shed lights on these issues, as a complementation and continuation of the previous studies, by showing the results of the multiregional model WILIAM IAM (*Within Limits Integrated Assessment Model*), a dynamic simulation model including links between energy, land, climate and socio-economy systems, being capable of quantifying the land use related impacts of solar energy deployment capturing regional heterogeneities in a context of deep energy decarbonisation scenarios. The objective of this paper are (1) to anticipate vulnerabilities related to land-use requirements of the deployment of solar in land, 2) analyse potential trade-offs between energy and other land-resources and to 3) analyse land siting and protection policies that can counteract the potential negative consequences. In contrast to previous studies mentioned above and to conventional general or partial equilibrium models, WILIAM includes biophysical, economic, social and technological restrictions, not imposing neither equilibrium nor optimization, thus including a more realistic approach to energy substitution and land resource allocation [35]. It considers the potential and limits of energy resources based on land use constraints and the Energy Return on Energy Invested (EROI) as indicator which is an unexplored topic [36]. Also, WILIAM examines the sustainability potential of other land-resources (food, wood extraction) and past dynamics in the land competition, rather than on the basis of maximizing economic profit as in the case of GCAM [6]. In addition, although GCAM tracks total land cover change by period it does not provide information about what type of land use is changed to another as WILIAM does, which is key for knowing where solar capacity is built. WILIAM particularities allows to integrate better the concepts of "sustainable potential" or "sustainable limits" of solar energy.

Table 1

Overview of relevant works quantifying land use requirements and impacts of solar energy deployment.

Methodology	Geographical scope	Objectives	References
Top-down	Global	Estimation of solar energy maximum techno-sustainable potential	[27]
WoLiM Economy-Energy-Environment model. System Dynamics.	Global	Evaluating future energy scenarios based on [27]	[28]
Multi-regional input-output model and estimations	40 countries	Assess land requirements and its related vulnerabilities in 100 % solar electricity scenarios	[3]
Modelling suitable areas/high resolution datasets	National: California, Southest Asia	Examine land use trade-offs of renewable energy development	[29,30]
GCAM IAM	Europe, India and Japan-South-Korea	Estimate land cover impacts and related Land Use Change (LUC) emissions	[6]

In this article, the effects of rapid solar energy expansion under a Green Growth transition paradigm for four hypothetical scenarios are quantified in combination with specific land-based policies. The study is concentrated in the European Union (EU-27), being this a continent with ambitious renewable electricity targets [37], and at the same time a small and densely populated [22]which has been identified in previous research as potentially vulnerable regarding suitable land for installing new PV infrastructures [6], even not feasible for most EU-27 countries under a 100 % solar energy scenario [3].

2. Materials and methods

In this section first, an overview of the modelling framework is presented: WILIAM IAM, then it is explained the modelling of the link between solar PV capacities and their land requirements, including the dynamic allocation of land uses and the land-based policies modelling, and, in terms of impacts, the method to compute the related LUC emissions is reported.

2.1. Overview of the general method

For this study WILIAM IAM, which is designed applying System Dynamics, has been used. See more information in Supplementary Material (SM) Section 1.1. A detailed description is available in Refs. [38, 39].

A method is developed and modelled in WILIAM capable to quantify the interactions between the land demanded for the deployment of solar power in energy transition scenarios, and the use of land to provide other ecosystems services. Also the emissions associated to LUC have been calculated. The method considers the EROI: ratio of the energy delivered from a process divided by the energy required to get it over its lifetime [40], indicating the net energy to society [41]. It accounts for the fact that the potential of solar PV depends on the minimum EROI (EROImin) [42] considered needed to run society as we know it [43].

The modelling consists of four main parts.

1. Feedback between Energy and Land modules: considering potential shortages of land use for solar energy deployment, and therefore constrains to the expansion.
2. In the “Energy” module: a certain capacity of solar PV is demanded. It includes a method for the calculation of the land requirements of solar power deployment.
3. In the “Land” module”: dynamic modelling of LUC, capable of being influenced also by land-based policies. It checks if there is land available for solar PV.
4. Estimation of LUC emissions due to solar energy deployment on land.

2.2. Overview of the modelling of the link between solar PV capacities and their land requirements

Fig. 1 shows how the “Land” and “Energy” modules are linked to capture the impacts of solar energy deployment on land. First, the Energy module quantifies the expansion of energy capacity, and distributes this new capacity (MW/year) among the different types of energy for electricity generation.

Secondly, the “Energy” module calculates the land required (km^2/year) for the deployment of this new additional solar power capacity based on the dynamic Land Use Efficiency (LUE) estimated depending on the region, the EROImin and the PV technologies (MW/km^2). The LUE is a metric that indicates the relationship between the power capacity (W) of the energy infrastructure and the total area occupied by the installation [44]. The EROI standard (EROI$_{st}$) boundary is applied, which includes the on-site and offsite energy requirements to get the energy (e.g. build, operate and maintain a power plant).

This new land required for solar power installations enters into the “Land” module which assesses if there is enough suitable area for this use, considering land-based policies applied. The “Land” module eventually sends a signal of “stress” to the “Energy” module to reduce the electricity demand and therefore adapt to the new situation in case two types of “limits” are surpassed: a) a biophysical limit of not available land (land scarcity) is reached (absolute limit, calculated inside the “Land” module) and b) a specific defined criteria exceeded (indicator or limit to be defined by a user, as for example, a decision-maker).

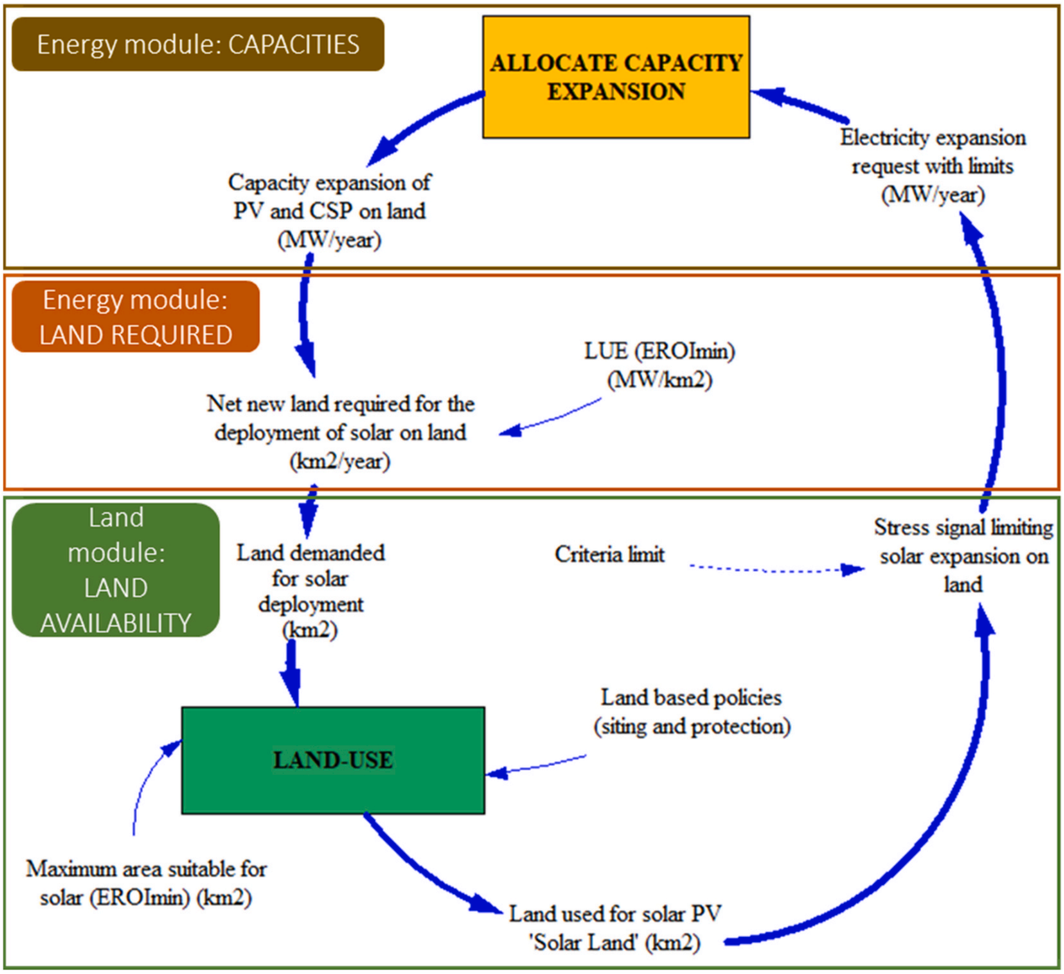

Fig. 1. Diagram of the interactions between “Energy” and “Land” modules for solar PV on ground. Feedback of available land for the solar capacity expansion. The specific criteria (limit) that can be defined by a user is represented with a dotted arrow. Source: own elaboration.

2.3. Land requirements of solar power deployment

The net land requirements of solar power installations, associated to the production and the transformation phase (energy generation plants), are calculated dynamically in terms of LUE (MW/km^2),

LUE of solar power is endogenously computed depending on the region and the dynamic PV (photovoltaic) module efficiency of each of the PV subtechnologies modelled: monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si), Copper indium gallium selenide (CIGS) and Cadmium telluride (CdTe) [45]. This estimation has been performed based on the data for each PV subtechnology for the year 2021 from Ref. [46] considering an annual efficiency improvement of 2 % with respect to the value of previous year from the year 2005. In the design of future scenarios a constant increase of 0,255 % each year (absolute) is considered based on past information from Refs. [46,47], future scenarios from Ref. [48], and the industrial module efficiency limiting value [49]. See more details in Section 1.2. in SM.

In the estimation of LUE, the geographical characteristics of each region of WILIAM have been considered, as the panel spacing to avoid excessive shadowing depends on the latitude. This is based on Dupont method [36], which uses Geographic Information Systems (GIS) grid-cell methodology at global level to asses solar energy potential considering EROImin,st. The area occupied is converted to LUE adapting the method developed in Ref. [6], considering the following factors (see more details in (SM): Section 1.2.).

- Land occupied by panels based on solar irradiance. This depends on the EROImin criteria.
- Packing factor: ratio between the PV panels or heliostats and the ground area required for arrays' installation [50]. It depends on the average latitude of the region.
- Generator-to-system area ratio: relation between the area covered by PV panels and heliostats and the entire area delimited by the site boundary of the power plant. Aligned with [6], a value of 0.7 is considered from the 0.7–0.85 reported [50], assuming a more likely development of larger-size plants [27].

For the estimation of net new land requirements of solar power installations, the "repowering sites" are given priority.

Finally, PV in rooftop is also included via the share of rooftop area to urban area, set to 1.5 %. Data of PV rooftop for mono-Si panels is used since it is the best-efficiency technology. The remaining PV rooftop potential is recalculated considering PV subtechnology split as well as Urban land area.

2.4. Dynamic allocation of land uses, and land-based policies modelling

WILIAM module includes three environmental modules: Land, Water and Climate (more information in SM, Section 1.3). The "Land" module, is in charge of providing with the LUC and allocating the land among several uses. The 12 land uses types defined are: Cropland Rainfed and Irrigated, Forest Managed, Forest Primary and Forest Plantations, Shrubland, Grasslands, Urban, Wetland, Other Land (bare areas without vegetation), Snow and Ice Waterbodies, and also a specific defined land use type where solar energy power is deployed: "Solar Land".

The allocation of land uses and LUC is based on 1) the demand for land, 2) past trends, 3) constrains, and 4) policies. For more detail of how land use dynamics are modelled see SM Section 1.4.

Firstly, land use demand (from food consumption, population growth, solar energy, biomass etc.) is defined at the regional level of WILIAM (9 economic regions of the world), considering that part of the land products (e.g. food, bioenergy, etc.) are traded internationally. It uses signals such as the shortage of land products and energy that allows to calculate the land stress for several uses.

Secondly, for defining past dynamics for "Solar Land", the initial shares, which indicate the prior land use types that have been occupied by "Solar Land", have been studied applying GIS techniques analyzing the allocation of current solar power capacity. This analysis has been done for each of the 9 regions of WILIAM [51] and it is based on data processed from the "Global Database of Power Plants" [52,53] combined with land cover data from Globcover Portal [54]. The analysis shows that in EU, the 55 % of the area occupied by solar PV panels was previously Cropland (see SM Section 1.5. Table 2 , for the rest of the "initial shares" of Solar Land). In the case of the solar power allocated in "waterbodies" the data of current floating PV panels capacity installed has been also considered [55].

Thirdly, the "Land" module allocates the Solar Land demanded based on the percentage (share) of suitable area. This suitable area for Solar Land has been determined through GIS techniques, and depending on the EROImin considered (equation (1)). See in SM Section 1.6 Table 3 the results of reduced land area suitable for an EROImin of 5:1(the one used in the posterior analysis) with respect to not EROImin considered for EU-27.

$$share\_(area\ suitable\ by\ EROImin) = \left(area\ by\ LC\ type_{>EROImin}\right) \Big/ (total\ area\ by\ LCtype) \tag{1}$$

Finally, the land-based policies modelled are.

- Repowering: assumed by default in the model.
- Installations of USSE in rooftops: as a share of urban area.
- Land use protection policies: specific land use types are protected and not changed to "Solar Land".
- Land use siting of solar power: it indicates in which land use types "Solar Land" (solar infrastructure) would be preferably installed.

2.5. Land use change emissions

LUC associated emissions due to the deployment of solar land are calculated. Emissions from agriculture and Land Use, Land-Use Change and Forestry (LULUCF) emissions are endogenously calculated in WILIAM following the (IPCC, 2006) guidelines [56]. See SM Section 1.7 for main equations.

3. Definition of scenario cases

The results of the analysis proceed from the simulation of different cases or scenarios with WILIAM model. For the objective of this paper the scenarios follow a Green Growth (GG)/Green Deal narrative.

Two different analyses have been developed: a) four scenarios analysing the influence of different solar potentials (dependent on EROImin, st threshold) and the impacts of land-based policies application, assuming the same energy demand scenario (GG) and b) a sensitivity analysis (Monte Carlo) that studies the impact of the variation of a specific relative criteria that limits solar energy expansion.

3.1. Overview of scenario components

The scenarios have been chosen based on three main characteristics explained in more detailed in the respective subsections.

- GG scenario development basis: narrative with high RES penetration.
- Different solar potential in EU: to analyse the effects of considering EROImin.
- Different land-based policies: to analyse the effects of land siting and land use protection policies.

3.1.1. *GG scenario development: energy demand*

A GG scenario has been developed and integrated into WILIAM model. Energy demand in WILIAM is determined by the interaction between the goods and services demand generated in the economy module for final consumption of households and production of firms and the technologies to supply the necessary energy demand in the energy module, including factors of efficiencies, fuel shifts, etc. [57]. In this work the implications for solar land of high penetration of Renewable Energy Sources (RES) for electricity in a context of increased electrification in production sectors, as well as assuming an increase in electricity for supplying green H2 to be used as feedstock in the industry [58], have been explored. Policies start from 2025. For more information see Section 2.1 of SM.

This is a scenario aiming at replicating current EU policies to analyse the solar land impacts, and should not be interpreted as a recommendation from the authors.

3.1.2. *Solar potential in EU*

For this study, the results of no EROImin threshold have been compared with an EROImin,st of 5:1 to analyse the influence of integrating a performance constraint to the potential. This is a low limit from the point of view of the metabolism of society [59], but we select it since of the built-in EROImin,st thresholds in WILIAM (0, 2, 3, 5, 8, 10, 12 and 15:1), it is the highest which provides potential spread along most EU members, and hence it is more in line with current policies.

Rooftop potential is considered to be shared by solar PV and solar thermal. The share of the rooftop for solar PV and solar thermal considered is 50 % of the estimated available roofs for both options [51].

3.1.3. *Land-based policies considered*

In the scenarios two different policies have been applied from 2025 in EU-27.

1. Land siting policies for solar power: For planning where the energy infrastructure should be placed. The objectives are to 1) prioritize the siting of solar power energy infrastructure in the “Other land” type, i.e, in bare areas or with sparse vegetation, and therefore with less carbon (C) emissions associated to LUC. And 2) to avoid potential land use conflicts occupying productive land uses or natural areas as “Cropland” and “Forest land”.
2. Land use protection policies: Cropland and Forest Land are protected from solar power installations. This is based on the same criteria considered for “solar land sitting policies”, i.e. avoid potential resources-related and C emissions.

3.2. *Scenarios defined for comparison*

Below the four scenarios are described.

1. **Unlimited solar land GG**: Scenario developed for comparison purposes. The feedback between Energy and Land modules is deactivated, meaning that the expansion rate of solar power energy is not constrained by land availability restrictions. No EROImin threshold considered for solar potential.
2. **Limited EROI5 GG**: It allows to compare the effects of Scenario 1 (no EROI min) with more realistic scenarios where the suitable area is reduced due to EROImin. Feedback Energy-Land is activated. The EROImin threshold of 5:1 is considered.
3. **Limited EROI5 GG with solar land siting policies**: Land use sitting policies are applied in the EU-27 from 2025. “Other Land” is prioritized, to 1) select areas with less C emissions, and 2) to avoid potential land use conflicts occupying productive land uses. Feedback Energy-Land is activated with an EROImin (5:1).
4. **Limited solar land EROI5 GG with protection of specific land uses**: Cropland and Forest Land are protected from solar power installations from 2025 based on the same criteria considered in the Scenario 3. Feedback Energy-Land is activated with an EROImin (5:1).

In the following Table 2 a summary of the four scenarios is presented.

Table 2

Summary of the characteristics of the scenarios used for this study.

		Energy demand scenario	Land restrictions (Energy-Land feedback)	EROI min	Land use siting policies of solar power	Land use protection policies
1	Unlimited solar land GG	GG	No		No	No
2	Limited_EROI5_GG	GG	Yes	5:1	No	No
3	Limited_EROI5_GG with solar land siting policies	GG	Yes	5:1	Yes -Starts: 2025 -75 % Other Land -12,5 % in Shrubland -12,5 % in Grassland	No
4	Limited_EROI5 GG with protection of specific land uses	GG	Yes	5:1	No	Yes. - Starts: 2025 - Forest Land protected Cropland protected

3.3. Sensitivity analysis considering a limiting criteria to "solar land" expansion

A sensitivity analysis considering a relative limiting criteria to solar land expansion has been conducted, acknowledging that in EU there are regional and local differences. This allows a deeper understanding of the implications of the feedback between Energy and Land modules.

The criteria considered here is the maximum value of the ratio between "Solar Land" and "Urban Land", representing how much land with relation to the urban area of a region could be dedicated to solar PV:

$$Max.\ value\ of \rightarrow\ share\ solar\_urban\ (t) = (area\ of\ Solar\ Land\ (t)\ )\ /\ (area\ of\ Urban\ Land\ (t)) \tag{10}$$

Urban land is just taken as a reference to set the limitation, chosen as a comparative reference of environmental impacts and of land use conflicts [60], especially with cropland [61]. Taking different ratios any land limitation can be tested. Controlling this ratio can support the anticipation of potential future land use conflicts in scenarios of rapid solar energy deployment.

In case of activating the solar PV land availability feedback between Land and Energy modules, if the limit defined for this criteria or assumption is surpassed the stress signal reduces the capacity growth of solar energy in land, and the energy system reacts installing other technologies.

Bearing in mind that for defining the maximum value of this criteria there is large uncertainty, for this sensitivity analysis (Monte Carlo experiment), a wide range has been taken to test the potential impact of this limit on the results. Specifically, the input is varied under a uniform probability distribution from 0.35 to 0.8 (i.e., assumption of maximum 35 % of solar land with respect to urban land, that could be increased to 80 %). Table 3 shows the characteristics of the experiment.

Table 3
Summary of the characteristics of the sensitivity analysis.

Experiment aspects	Input parameter characteristics		Scenario characteristics				
	Input parameter	Range of the input	Energy demand scenario	Land restrictions (Energy-Land feedback)	EROI min	Land use planning policies of solar power	Land use protection policies
-200 simulations -Uniform distribution	Max. value of share solar-urban	0.35–0.8	GG	Yes	No EROI min	No	No

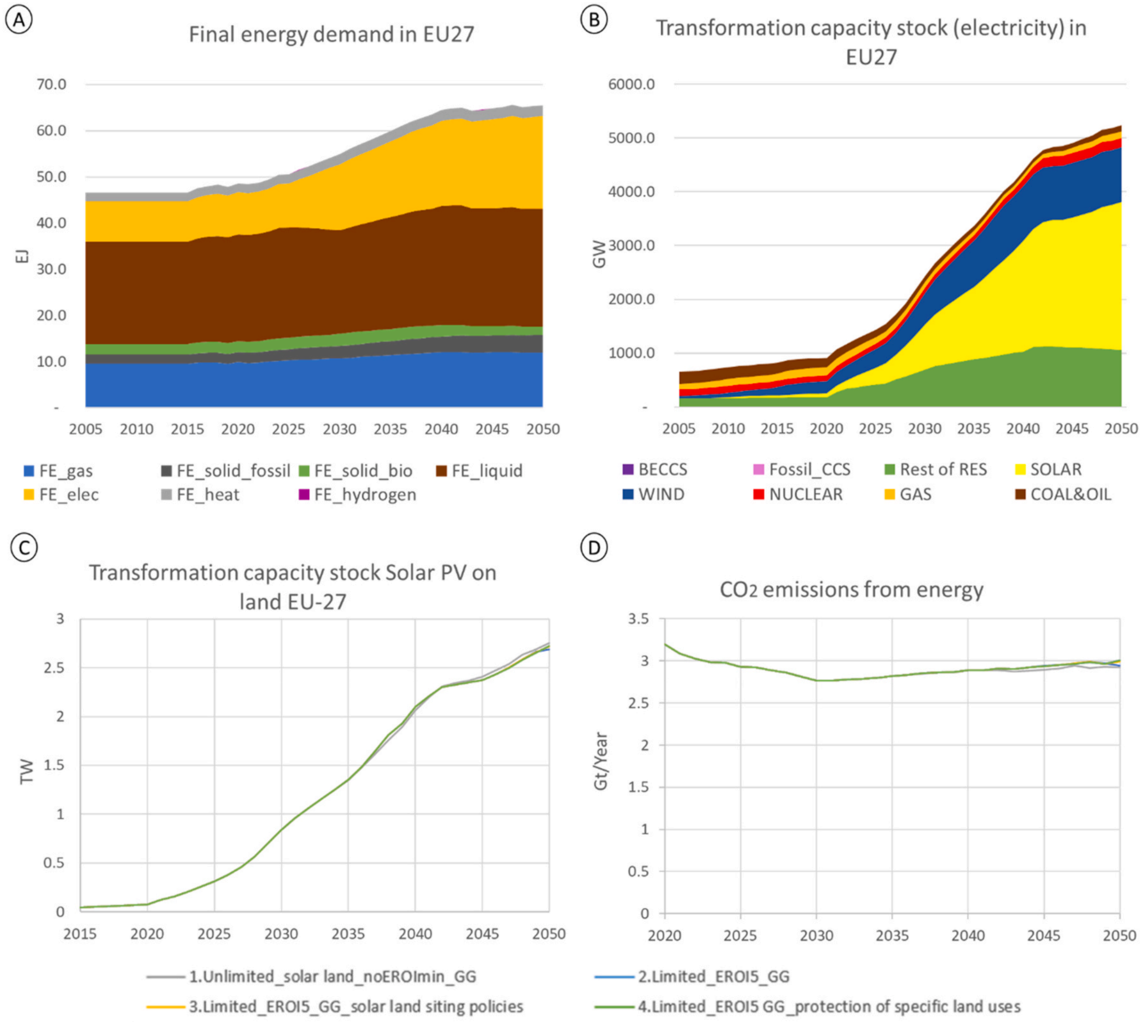

Fig. 2. Evolution of the final energy demand (A) the installed capacity stock of electricity (B), and the transformation capacity stock of Solar PV for each of the scenarios (C) in EU-27 in the GG scenario.

4. Results

This section shows the results obtained with WILIAM model applying the scenarios described and those from the sensitivity analysis. The analysis is focused in EU-27 until 2050.

4.1. Results: scenarios

The results related to the four scenarios defined (see Table 2) are presented below.

4.1.1. Energy. Final energy demand and installed transformation capacity stock of electricity in EU-27

Fig. 2A shows the final energy demand in EU-27, with electricity (FE_elec) reaching 31 % of the final energy demand by 2050. Fig. 2B shows the evolution of the capacity stock of electricity, where solar energy reaches a high share (approx. 54 % in 2050, corresponding 51,3 % to solar PV on land).

Fig. 2C shows the evolution of the capacity stock of solar PV that is calculated considering the new transformation capacity of solar PV, and the one that is decommissioned. The results of the four scenarios shows very little differences. This is because in these scenarios, biophysical constraints (land scarcity to solar PV deployment) still not appear, neither a sustainable criteria that limits the land available is applied. The only difference is the type of land where the solar PV panels are deployed. Therefore, the feedback between Energy-Land is not operating, and the capacity stock of Solar PV is not constrained. Finally, Fig. 2D represents the evolution of carbon dioxide (CO_2) emissions from energy, which are not reduced given to the continued energy demand increase of the GG scenario and the fact that the transition to RES in other sectors than electricity and passenger transport is not modelled.

4.1.2. Land. Type of land uses occupied by “solar land”

In Fig. 3A it is possible to analyse the total land occupied by solar PV infrastructure. In this case there are clearer differences among scenarios. The first scenario occupies much more land than the other three. This is because in the rest of scenarios an EROImin is considered of 5:1, and therefore, the locations where solar land are deployed are constrained to those “with better net energy balance”, meaning that the land necessary to be occupied to obtain the same energy power is smaller, i.e, the LUE (MW/km^2) is bigger in the scenarios 2, 3 y 4. The rest of differences among scenarios 2, 3 and 4 are also due to the difference in LUE, due to the fact that the distribution among land use types is different. In Fig. 3B the ratio of solar-urban is represented justifying the range of (0,35-0,8) used for this parameter in the sensitivity analysis (see Section 4.2).

Also, it is important to analyse the type of land use that converts to “Solar land”, i.e., in which type of land use the solar PV infrastructure is deployed.

Before policies are applied the distribution between different types of land use are the same among scenarios, being cropland rainfed where most solar PV infrastructure is allocated (see Materials and Methods). The results show (Fig. 4) different distributions of land use types covered by Solar Land in EU-27 for each Scenario:

- *Scen 1: Unlimited solar land GG*: The distribution among land use types is uniform over the years following past trends.
- *Scen 2: Limited EROI5 GG.* The area suitable considering an EROImin is reduced as locations with “better net energy balance” are chosen, and therefore, the area occupied is smaller. By 2050 part of the Solar Land is reallocated to “Other land” (negative values) because the decommissioning of PV is greater than the new capacity installation.
- *Scen 3: Limited EROI5_GG with solar land siting policies.* The distribution is guided by the policy applied: prioritization of “Other land” (75 %), followed by “Shrubland” and “Grassland” (12,5 %).
- *Scen 4: Limited EROI5 GG with protection of specific land uses.* Cropland and Forest Land are protected. This causes the increase of the “share” of the rest of land uses used for solar deployment. In this case, “Other land” is not prioritized.

See SM Section 3.1 for an overview of the LUC to solar PV with respect to the initial land use area (2005), which reflect the different percentages of land use type occupied according to the scenarios. See SM Section 3.2 for checking the evolution of the remaining land suitable for solar land PV for the different scenarios and the related remaining potential capacity (GW) for solar PV.

4.1.3. Land. Competition with other land uses and impact on land products

In this section the evolution of different Land Use types that are of interest due to the land-resources they provide are shown to illustrate the effect of the land-based policies.

Fig. 5A shows that the scenarios where land-based policies are applied require less cropland. With respect to the Scenario 1, around 7800 km^2 are saved in the Scenario 2 (23,5 %), and of 29600 km^2 approx. in Scenarios 3 and 4 (88,9 %) in 2050.

In the case of Forest Land (Fig. 5B) for 2050 the forest area not occupied with PV with respect to the Scenario 1 is of 3060 km for Scenario 2 and of 11500 approx. for Scenarios 3 and 4 (23,5 % and 88,9 % of reduction respectively).

Fig. 5C shows the effects on the land related products (food and wood), and therefore the land-use competition consequences. Approx. 0,93 and 0,94 % more land products available ($\sim4*10^8$ of tonnes) in Scenario 3 and 4 respectively with respect Scenario 1 in the period from

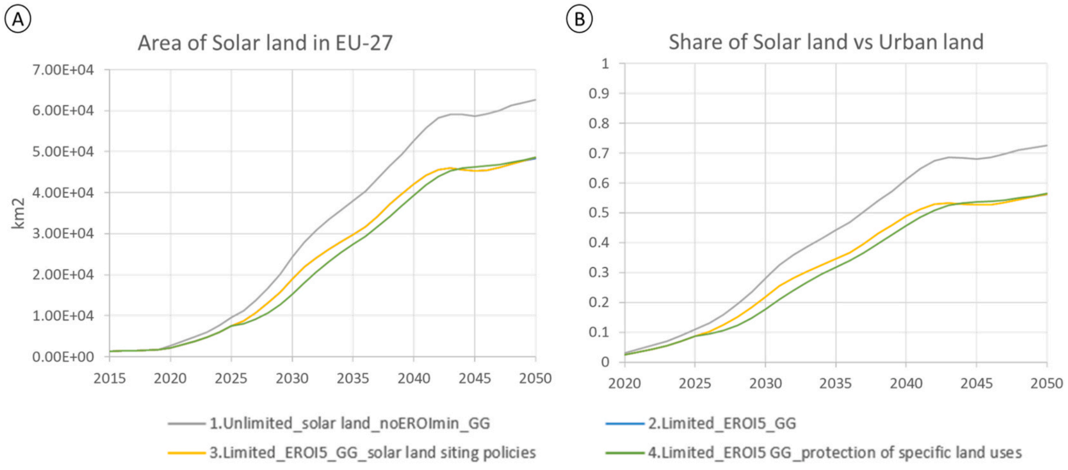

Fig. 3. Area occupied by solar PV infrastructure in the four scenarios, and the ratio between “Solar Land” and “Urban Land”.

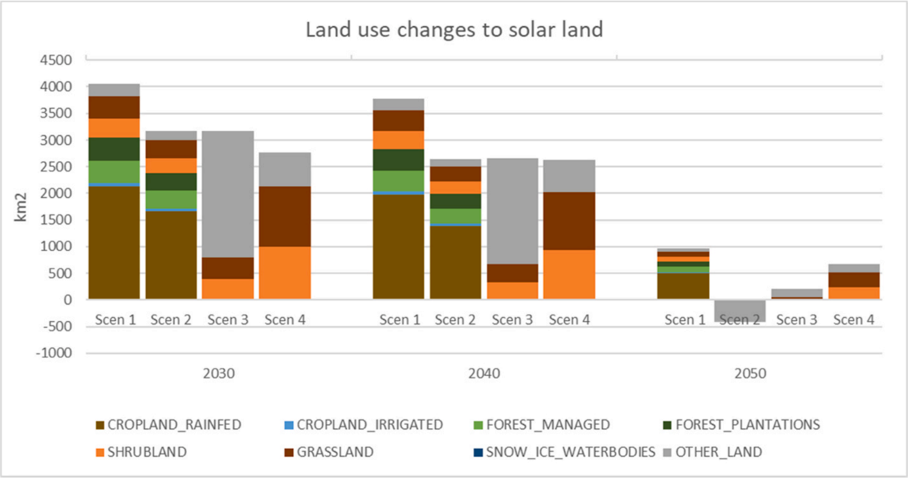

Fig. 4. From which land-use type and quantity of land is changed to solar land in the four scenarios, in three years: 2030, 2040, 2050.

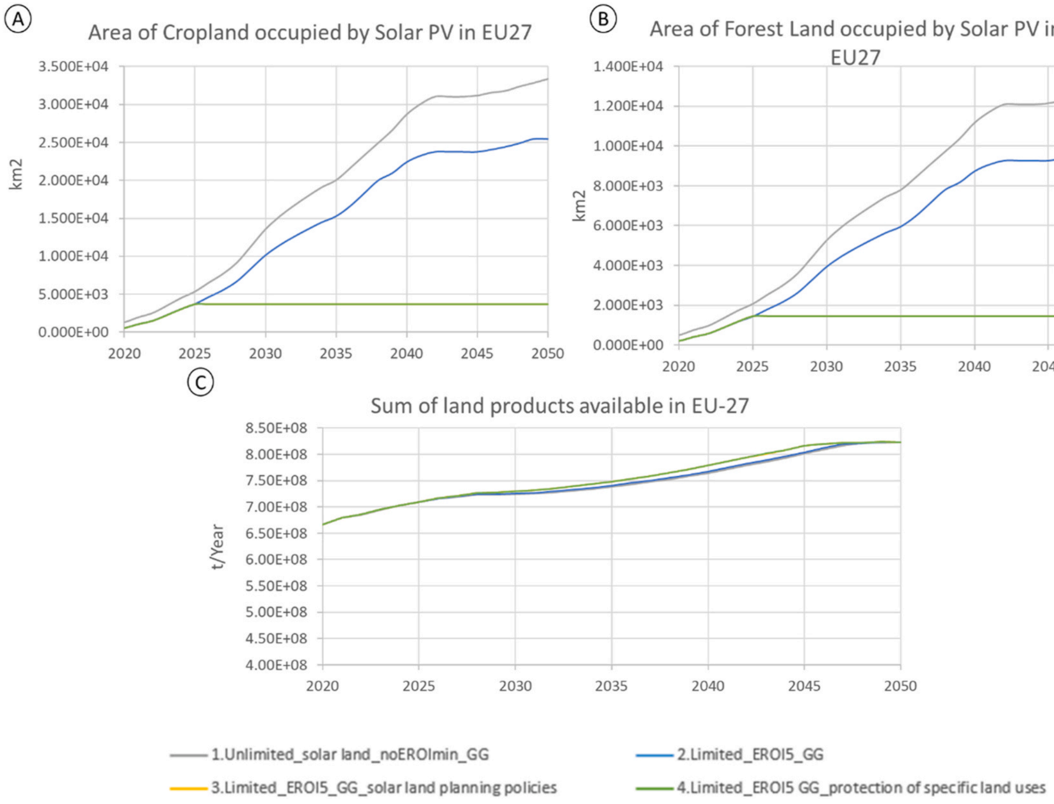

Fig. 5. Evolution of other land uses and its related products for each scenario in EU-27.

2020 to 2050.

Table 4
LUC emissions associated to the deployment of solar PV on land.

	Cumulated carbon emissions (GtC) 2020–2050	% of emissions with respect to Scenario 1
1.Unlimited solar land GG	0.60	100 %
2.Limited_EROI5_GG	0.46	77 %
3.Limited_EROI5_GG_solar land planning policies	0.32	53 %
4.Limited solar land EROI8 GG with protection of specific land uses	0.42	71 %

4.1.4. *Land. Land use change emissions*

Table 4 shows the cumulated LUC carbon emissions due to the deployment of solar land in the four scenarios.

The results show that all the scenarios save LUC carbon emissions with respect to the “Unlimited” scenario. In policy-based scenarios, the solar land sitting policy is more effective than protection policies, as the sitting policy directly recommends where to deploy the new infrastructure, being “Other land” prioritized (bare and sparsely vegetated areas). It is necessary to clarify that these emissions (LUC due to the deployment of solar energy) are just 0,8-1,5 % of the total cumulated anthropogenic C emissions between 2020 and 2050.

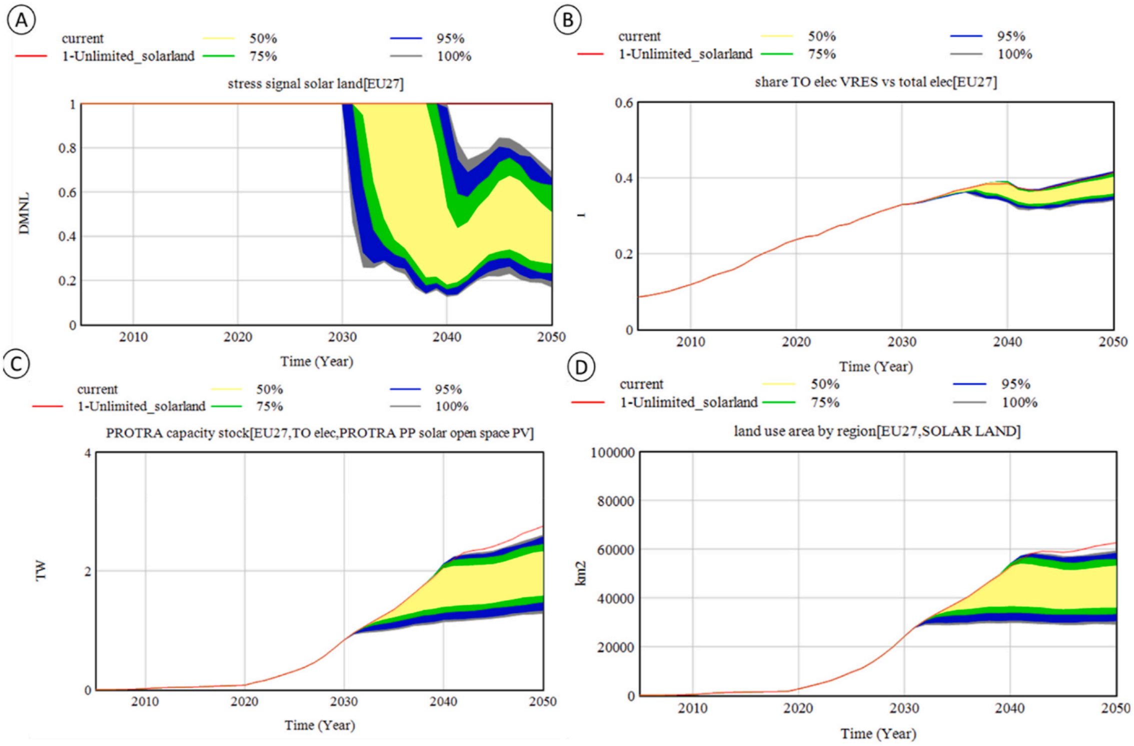

Fig. 6. Evolution of different variables in EU-27 under the sensitivity analysis made to the criteria of "maximum value of the share of solar land with respect urban land": A) the "stress signal", B) of the electricity mix in EU-27 (share of variable renewables), C) of the capacity stock of solar PV in ground, and D) of the evolution of the land occupied by solar PV infrastructure.

4.2. Results: sensitivity analysis considering a limiting criteria to "solar land" expansion

The results are very sensitive to the limiting criteria (maximum value of the ratio between "Solar Land" and "Urban Land" between 35 % and 80 %). From 2030 the P50 of the stress signal ranges 20–60 %, i.e., in half of the simulations the capacity expansion of solar PV on ground is reduced between 20 and 60 % with relation to the case without the limiting criteria (Scenario 1-Unlimited-red line) (Fig. 6A). This has relevant impacts on the land used for solar PV (Fig. 6 D) and on the PV capacity stock (Fig. 6C): P50 of solar capacity is 1.59–2.33 TW, while it reaches 2.75 TW in Scenario 1 Unlimited, a reduction of 15–42 %. The effect of the parameter in the electricity mix is smaller (Fig. 6 B) given the presence of other technologies contributing to Variable Renewable Energy Sources (VRES). Overall, the results show that under specific policies the capacity expansion of solar PV can be significantly constrained without affecting much RES penetration, although the eventual side-effects are not investigated further here.

5. Discussion

No relevant limitations of land in absolute terms are found in our study in the deployment of solar PV in a GG scenario for EU-27; however, this does not mean that land-use conflicts could not be an issue with solar PV expansion. If a socio-political criteria is considered, the stress signal does enter into operation significantly reducing the energy capacity growth of solar energy (*see Section 4.2*). However, this is limited by the scope of the analysis applied to a very large region (EU-27) since real tensions tend to appear locally. For analysing local conflicts more resolution of the model is needed, and to introduce socio-economic local contextual factors [62] with participatory processes [63].

5.1. EROImin and land-based policies limit the solar power potential but reduce impacts

Land needs to be managed strategically from a sustainability perspective [64] to avoid potential land use competition challenges or negative environmental impacts [65]. The results show that siting solar energy infrastructure in deep decarbonisation scenarios in EU-27 can limit negative impacts, in line with other studies [29]. When considering an EROImin treshold, and therefore, locations with better "net energy balance", the land required for solar PV is reduced, and the impacts with respect a scenario not considering EROImin. However, the areas suitable are also reduced with respect a scenario with no EROImin: 63%–94 % for an EROImin of 5:1 depending on the type of land. This consideration together with land-based policies reduce the negative impacts, but also suitable land area, and therefore the remaining solar power potential.

In terms of GHG emissions, the Scenario 3 (siting policies) has higher positive effects (57 % of LUC emissions avoided) with respect to Scenario 4 of land protection policies (29 % of emissions avoided). LUC emissions range is from 0,6 to 0,32 GtC in the period 2020–2050. The land occupied by 2050 of solar land ranges from 62600 km^2 in the Scenario 1 to approx. 48300 km^2 by 2050 (23 % reduced) in the rest of the scenarios where the criteria to EROImin is applied. The results in the Unlimited Scenario 1 shows the reality on how solar energy is being deployed in land in EU-27: not land-planning or effective siting policies are being applied at large scale, nor the locations with the best "net energy balance" are chosen, and the 54 % of the area occupied by solar PV panels is being installed in "Cropland".

The results are broadly consistent with those from the literature. On this side, the average value of the required land area for utility-scale PV (22-17 km^2/GW) is in line with the literature (19 km^2/GW) [66]. In addition, in Van de Ven et al., 2021 [6], the results for a similar solar penetration scenario (PWh in 2050) of approx. 1,7 PWh are aligned with our ranges (see Table of comparison in Section 2.3 in SM)

5.2. Limitations and further work

- The modelling approach has very low geographical resolution (EU at a whole) and is not a grid-based model: although it uses exogenously GIS information, it is not possible to allocate the outputs of the current version of the model in specific grid-cells. Finally, considered the potential conflicts in EU-27 region, it would be interesting to focus in specific countries and regions where the analysis and land conflicts could be exacerbated. In this respect, WILIAM has a higher granularity in the case of EU region for some specific modules (such as the economic), and the analysis of suitable areas for PV depending on EROImin,st done it is also detailed at country level, so increasing resolution would be feasibly with some adaptations and improvements in the energy and land modules.
- Not accounting for grid requirements and accessibility issues: a critical constraint when assessing the viability of new solar plants is the proximity of the grid [67]. Including required grid expansion in the analysis would increase the land footprint of solar PV plants as well as allow to expand the EROI boundary to the point of use ($EROI_{pou}$), which would impact the potential by discarding those areas too far from existing grids. In fact, first calculations show that accounting for the transmission losses and the energy investments associated to the grids implies a large gap between the $EROI_{st}$ and $EROI_{pou}$ levels [68])
- Not fully dynamic solar potential: The Dupont's method [36] assumes that the technical characteristics and performance factors of solar PV remain constant over time. This makes that for the same solar irradiance the EROI in a given point remains constant over time (constant both the efficiency in the numerator and the energy investments per installed capacity in the denominator). However, the EROI of the technology can vary in the future (efficiency improvement, energy requirements increase for mining materials when ore decreases, curtailment due to VRES penetration, etc).
- Not accounting for LUC related to mining: (1) of metals for RES capacities as they have higher material intensities than fossil fuels [69–71] - and (2) avoided mining of fossil fuels in the future. Also, cumulated extraction of metals will tend to reduce ore grade in the future and hence, increase energy intensity [72], impacts on land and environment [73], and the geographical scale due to global supply-chains. These complexities are out of the scope of the current work.
- Limited portfolio of land-based policies: further future work could expand the analysis including: 1) solar land management practices, 2) agrivoltaic systems, 3) a deeper prospective analysis of the future potential of technological improvements such as testing different scenarios targeting specific PV efficiencies and (4) include grid expansion. Other prospective analysis can be done by testing different prioritization of solar PV in rooftops, and of floating solar panels.
- Expand the ecological and social implications beyond GHG emissions (such as on jobs, or specific biodiversity indicators).

Special attention requires the issue of EROI in this work. The EROImin,st threshold of 5:1, although corresponds with a spread potential of solar PV over EU Member States and hence it is in line with actual EU policies, it is below the minimum thresholds identified in the literature to sustain modern complex societies [59], and represents in fact an area of increasing risk for the feasibility of the system [74]. Yet, the uncertainties around these estimates are high, and the reduced availability of discretionary energy, as intermediary operations become less efficient, is a gradual non-linear process with increasing and cascade consequences over time. In addition, the EROImin depends also ultimately on social decisions [68]. Few works have dealt with this: some applying different methodologies [42,75–77] have suggested a EROIst, min of the system of 10–15:1. Dupont method delivers potential for EU with an EROImin,st of 8:1 (not for the threshold 10:1). With the EROImin,st of 8:1 the potential would be concentrated in the south of EU-27 (see SM Sections 1.6 and 3.3 for the results with this EROImin). which seems politically unrealistic in at least 3 ways: (1) goes against current policies of decentralizing power supply, (2) would likely face tremendous social opposition in the border areas where transmission lines should be concentrated, and (3) the transmission of such high amounts of electricity would imply a dip in the overall EROIpou.

Finally, it should be highlighted that the energy demand scenario used in this work has been developed to analyse expected solar land impacts under current policies, and shouldn't be interpreted as a recommendation from the authors. In order to design a sustainable energy scenario many aspects left out in this paper should be integrated, which are beyond the scope of the current research: mineral requirements, socioeconomic and net energy metabolic effects of using such a low threshold for solar PV potential (EROImin = 5:1), or the transition to RES in other sectors than electricity and a more ambitious scenario for transport (eg., see Fig. 2 where emissions are far to reach net zero by 2050). That exercise is a very ambitious currently ongoing work requiring the joint contribution of WILIAM developers. The latter also means that a more ambitious transition scenario based on electrification would imply higher solar PV land footprints than the ones presented here.

6. Conclusions

In this work the impacts on land of high penetration solar energy scenarios in EU27, and the effects of land-based policies that can counteract the potential negative impacts, including competition with other land-resources, have been studied, which is not usually considered by IAMs, and just few studies have analysed it in a quantitative manner. Also, for the analysis of solar energy potential the EROImin and land use constraints has been considered which is an unexplored topic. The results show that land-use required for solar would be 1–1.4 % of total land in the EU (an equivalent of at least 55%–75 % of the urban surface), which could be problematic locally despite our model does not have sufficient resolution to analyse it. Also, it was found that normally solar PV energy infrastructure are sit without an adequate planning not considering the potential ecological impact and land-use conflicts, neither net energy balance. Cropland areas are today predominantly chosen for allocating solar PV. If maintained this tendency in the future, solar energy deployment can have significant local impacts in terms of land-resources, jobs displacements, etc.

The design of energy transition policies needs integrated responses, including land governance, which can enhance social acceptance of new solar plants. The land-based policies presented in this article are: 1) siting of energy infrastructures considering a minimum net energy return (EROIst,min), 2) repowering, 3) installations in rooftops, 4) siting policies of solar PV in specific land types and 5) land protection policies. They all show positive impacts related to land resources and emissions, with some different tendencies, having the siting of policies higher positive effects on LUC emissions than land protection.

As EU-27 has been analysed as a whole region, a deeper analysis with more resolution, would result, in potentially detecting inequalities and worse impacts at country and local level. Another key point for further work is related with the definition of the EROImin due to the close relationship between solar potential and the EROImin threshold. On the one hand, including grids requirements will tend to reduce the effective potential, on the other hand there are many uncertainties to define the EROImin for sustaining modern complex systems. It is also important to have in mind that the impacts computed here are likely lower bounds of the current dominant transition narrative, given that a more ambitious transition scenario based on electrification would imply higher solar PV capacities.

In order to avoid potential land constrains and negative social and ecological impacts it is needed to plan beforehand the allocation of solar PV infrastructure on land. Integrated responses should be applied the sooner as possible to be effective as the energy transition occurs and it is deployed in our society.

CRediT authorship contribution statement

Noelia Ferreras-Alonso: Writing – original draft, Software, Investigation, Conceptualization. **Iñigo Capellán-Pérez:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Conceptualization. **Alexandros Adam:** Writing – review & editing, Methodology, Investigation. **Ignacio de Blas:** Validation, Software. **Margarita Mediavilla:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Noelia Ferreras-Alonso reports financial support was provided by Horizon 2020 research and innovation programme under grant agreement No 821105. Inigo Capellan Perez reports financial support was provided by Horizon 2020 research and innovation programme under grant agreement No 821105. Alexandros Adam reports financial support was provided by Horizon 2020 research and innovation programme under grant agreement No 821105. Margarita Mediavilla reports financial support was provided by Horizon 2020 research and innovation programme under grant agreement No 821105. Inigo Capellan Perez reports financial support was provided by Ministry of Economy and Competitiveness Spain. Noelia Ferreras Alonso has patent MIT License (MIT) licensed to WILIAM_1.2 (Vensim version) Copyright 2023 LOCOMOTION Consortia. Inigo Capellan Perez has patent MIT License (MIT) licensed to WILIAM_1.2 (Vensim version) Copyright 2023 LOCOMOTION Consortia. Alexandros Adam has patent MIT License (MIT) licensed to WILIAM_1.2 (Vensim version) Copyright 2023 LOCOMOTION Consortia. Margarita Mediavilla has patent MIT License (MIT) licensed to WILIAM_1.2 (Vensim version) Copyright 2023 LOCOMOTION Consortia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.131617.

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