IAM COMPACT

Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

Land-based policies to mitigate impacts of the energy transition in land use

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1 Motivation

IAM COMPACT is a Horizon Europe research project, with the objective to support the assessment of global climate goals, the collective progress towards them, and the feasibility space in delivering on those goals. It aims to involve relevant stakeholders in the process to help promote acceptable, robust, sustainable transitions, as well as to enhance trust on both ends, yielding outputs intelligible in terms of real-world implications and actionable in terms of concrete policy recommendations.

The rapid deployment of renewable energy technologies, particularly solar photovoltaic (PV) systems and bioenergy, has become a cornerstone of global efforts to reduce dependence on fossil fuels and advance international climate goals. Yet, this transition entails important trade-offs. This Policy Brief examines both energy sources, given their significance for land-use impacts and their central role in climate policy. It is not intended to compare them as equivalent options, since solar PV is markedly more land-efficient and generally more attractive. For instance, estimates suggest that the land footprint required to generate one unit of electricity from biomass can be up to 29 times larger than that of solar PV (Lovering et al., 2022). Similarly, Fehrenbach et al. (2023) find that electric vehicles powered by photovoltaics require only 2.5% of the arable land needed to achieve the same driving range using bioenergy.

Concerns also persist regarding the carbon profile of biomass. While wood is classified as a renewable resource, provided harvesting rates remain below reforestation rates, it is not always as low-carbon as assumed. When lifecycle emissions are considered, reliance on forest biomass (rather than residues from sawmills or paper mills) can, in some cases, result in higher carbon emissions than the fossil fuels it seeks to replace (Duffy et al., 2018; Norton et al., 2019). Nonetheless, biomass offers advantages over solar PV. It provides a continuous, dispatchable source of energy, mitigating the intermittency inherent in solar generation. This characteristic supports the requirement for a stable share of firm capacity, estimated at around 20% of total supply (Parrado-Hernando et al., 2021). Biomass may also play a strategic role in decarbonising sectors where direct electrification is technically or economically challenging, such as high-temperature industrial processes and heavy transport (IRENA, 2021).

Despite these differences, both technologies warrant close examination, as each contributes to the energy transition. A shared challenge lies in their substantial land requirements—direct in the case of solar parks, and often indirect for biomass extraction. Rising land demand from renewable energy deployment risks intensifying existing pressures on ecosystems, driving land-use change emissions, and sparking social and economic tensions over resource allocation.

For these reasons, integrating energy and land-use policies is increasingly recognised as essential. Without coordinated, forward-looking planning, renewable energy expansion may carry unintended environmental and socio-economic consequences. Robust and integrated policy frameworks are therefore needed to ensure that renewable energy deployment is spatially efficient and aligned with broader sustainability objectives, including biodiversity conservation, food security, and climate mitigation.

In this context, the workshop *"Land Use & Renewable Energy"*, reflected in this Policy Brief, brought together key stakeholders from institutions including the European Commission (DG AGRI), the European Environment Agency (EEA), Climate Action Network (CAN), IDDRI, and WWF European Policy Office. Stakeholders provided valuable insights into the multifaceted challenges of land-use and renewable energy deployment. These included concerns over environmental degradation, emissions associated with land use and land use change, socio-economic barriers to project development, gaps in existing policy instruments, and the need to measure cross-sectoral impacts. A detailed summary of recommendations is provided in Section 4 (*Policy Implications*).

Guided by stakeholder input and leveraging the capabilities of the WILIAM Integrated Assessment Model (IAM), this study aims to explore the complex interlinkages between renewable energy deployment, land use, and natural resource constraints. The overarching objective is to assess the impacts of expanding solar PV and bioenergy in

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the European Union (EU), with a particular focus on land-use competition, carbon emissions, and sustainable resource management. The key research questions addressed in this research are:

- What are the land-use implications of large-scale solar PV deployment in the EU?

  Particular attention is given to land competition and the impacts in terms of carbon emissions under different deployment scenarios

- How does an ambitious renewable energy scenario based on bioenergy (in particular, from biomass from forests) affect land demand (including impacts outside the EU), and put pressure on forest biomass and ecological boundaries?

  This question investigates the trade-offs between energy transition goals and ecological, societal and agricultural sustainability.

- Which policy mechanisms can mitigate the adverse impacts of land-intensive renewable energy expansion while aligning with climate and energy objectives?

The study examines the potential benefits of integrated energy and land-use policy frameworks and explores how such policies could improve planning, resource efficiency, and sustainability outcomes.

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1. Scenario Design

This study applies a scenario-based approach using the Integrated Assessment Model (IAM) WILIAM to assess the impacts of renewable energy deployment on land use and the environment, with a specific focus on solar PV and forest-based bioenergy. The primary objective is to evaluate the consequences of deploying these energy sources at the EU level under current policy frameworks, highlighting trade-offs related to land competition, biophysical constraints, and associated carbon emissions. The study also investigates the role of land-based policies in mitigating potential negative effects.

The IAM employed, WILIAM, was developed under the H2020 LOCOMOTION project and builds on the MEDEAS model architecture (Capellán-Pérez et al., 2020). WILIAM integrates energy, land, and climate systems at the global scale, with regional disaggregation including the EU, China, and Latin America, among others. This integrated structure enables the joint assessment of land–energy policy interactions and quantifies their implications for emissions (Mediavilla et al., 2024). The model incorporates land-based measures such as forest protection, improved forest management, and afforestation.

The analysis presented in this Policy Brief is structured in two parts. The first examines the implications of high biomass penetration in the energy system, with a particular focus on potential biophysical limits across energy, food, and conservation demands. The second investigates the impacts of large-scale solar PV deployment on land use at the EU level. Both analyses rely on two reference scenarios: a baseline scenario, capturing current trends, and an NDC-LTT scenario, which integrates existing EU energy policies (see Figure 1). For each analysis, additional policy scenarios are developed by applying land-based measures to counteract negative impacts. The main characteristics of all scenarios are summarised in Table 1.

A. **Analysis of bioenergy penetration in EU:** the following scenarios have been developed:
    1. Baseline: Business-As-Usual (BAU) scenario, where historic trends continue.
    2. NDC-LTT scenario: which includes short and long-term policy ambition set by EU countries. It encompasses ambitious policies for the penetration of renewable energy such as solar PV and bioenergy. Also, the NDC-LTT already envisages the protection of primary and managed forests as well as some reforestation based on current EU policies. It is worth mentioning that the reforestation considered is distributed equally between natural forests and plantations, maintaining same ecosystem balance observed in 2005. However, it is essential to emphasise that any afforestation efforts should be preceded by careful site-specific assessments to ensure they deliver ecological benefits. This aspect goes beyond the current WILIAM capabilities.
    3. NDC-LTT-Self-Sufficiency: land-based policies are applied focused on EU forest preservation, including limits on forest biomass extraction and relocating roundwood production to ensure self-sufficiency
    4. NDC-LTT-Afforestation: a more ambitious afforestation policy is applied with respect to NDC-LTT scenario in order to offset the impacts of increased demand for biomass.

B. **Analysis of the impacts of solar PV penetration in EU[1]:** the following scenarios have been developed:
    1. Baseline: Business-As-Usual (BAU) scenario, where historic trends continue. Same as the one in the analysis A).
    2. NDC-LTT scenario: which includes short and long-term policy ambition set by EU countries (same

[1] Assumption/hypothesis made for the analysis of solar PV on land: The installation of solar panels has been restricted to areas with a net energy ratio of 8:1 or higher. This implies that PV installations provide, over their lifetime, eight times the amount of energy needed to produce them.

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scenario that the one used in the analysis A))

3. Baseline- land-based policies: in this scenario land-based policies associated to the deployment of solar PV on land are applied. In particular: 1) siting of solar PV panels prioritizing those areas with lower carbon stocks and less ecological value, and 2) protecting specific land use types from solar PV deployment that could increase land competition (e.g. cropland or forestland).

4. NDC-LTT- land-based policies: as in the previous scenario, land-based policies associated to the deployment of solar PV on land are applied over an NDC-LTT scenario.

Table 1. Scenario design characteristics: Concept and land-based sustainability policies

Scenario	Concept	Afforestation	Primary Forest Protection	Managed Forest Protection	Biomass Extraction Limit	Forestry Self-Sufficiency	Solar PV siting policies	Land protected from solar PV
Baseline	Continue historic Trends	None	None	None	None	None	None	None
NDC- LTT	High bioenergy and solar PV penetration	Medium	High	Medium	Low	None	None	None
ANALYSIS OF BIOENERGY PENETRATION IN EU								
NDC-LTT-Self-Sufficiency	High bioenergy use with biomass only from EU forests, and solar PV penetration	Medium	High	Medium	High	High	None	None
NDC-LTT-Afforestation	High bioenergy use with biomass only from EU forests, reforestation, and solar PV penetration	High	High	Medium	High	High	None	None
ANALYSIS OF SOLAR PV PENETRATION IN EU								
Baseline-land-based policies	Continue historic Trends and apply land-based policies	None	Just from solar PV	None	None	None	Yes. Prioritising less carbon rich areas	Yes. Protecting forest and cropland
NDC-LTT-land-based policies	High bioenergy and solar PV penetration and apply land-based policies	Medium	High	High	Low	None	Yes. Prioritising less carbon rich areas	Yes. Protecting forests and cropland

2 Model Results

2.1 Greenhouse gas emissions

In both studies (A) analysis of bioenergy and (B) solar PV penetration in EU the model obtains an ambitious penetration of both types of energy for the NDC-LTT scenario. This can be seen in the following plots, where the increase in bioenergy is shown in green, whereas the increase in solar PV penetration appears in light yellow:

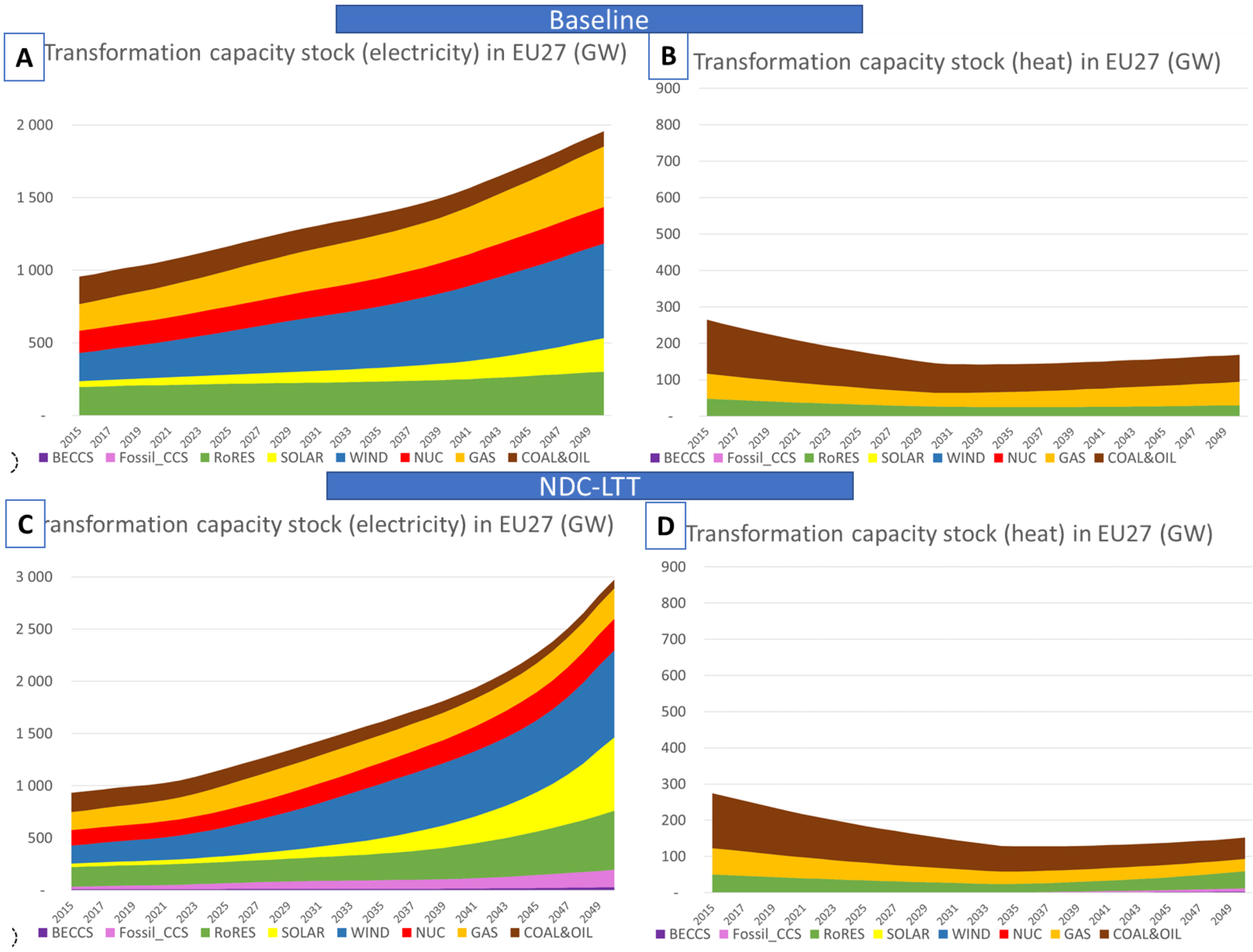

Figure 1. Higher penetration of solar PV energy (light yellow) and bioenergy (green) in the NDC-LTT scenario (figures 1C and 1D) with respect to the baseline scenario (BAU) (Figures 1A and 1B).

In terms of emissions, Figure 2 shows that the policies in the NDC-LTT scenario reduce emissions compared to the baseline (although it should be noted that the emissions are just stabilised). However, it should be noted that in other parts of the world the effects are the opposite (e.g. in CHINA, the emissions increase by 0,91%, while EASOC (East Asia and Oceania) increases in the NDC-LTT by 1,1 %, and LATAM region (Latin America) increases by 2,64 %).

Regarding emissions, it should be noted that WILIAM also calculates carbon emissions from the LULUCF sector (Land Use, Land Use Change and Forestry emissions), although it does not yet account for "indirect" emissions associated with biomass, such those from the manufacturing stages, energy emissions related to the forestry sector, etc. Incorporating all these emissions is already being considered for further improvements of the model, as doing so would provide really valuable information to clarify the real net impact of bioenergy on climate.

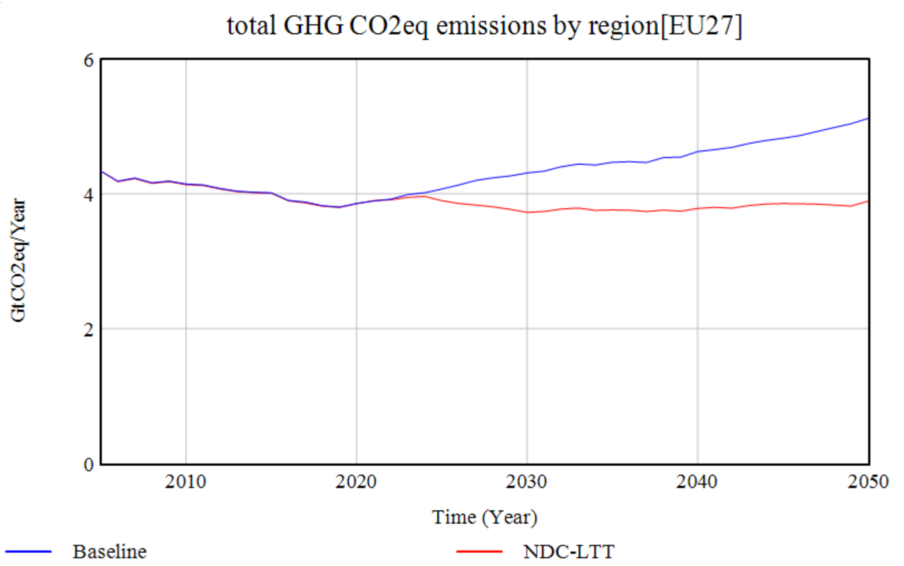

Figure 2. Comparison in terms of total emissions in CO_2 equivalent between the baseline and the NCD-LTT scenarios in EU

2.2 Bioenergy penetration in the EU

Figure 3A allows to observe the increase in bioenergy demand in the European Union under **the NDC-LTT Scenario** compared to **the Baseline.** The growth of wood demanded is especially reflected in energy uses and, to a lesser extent, in industrial ones, as shown in Figure 3B.

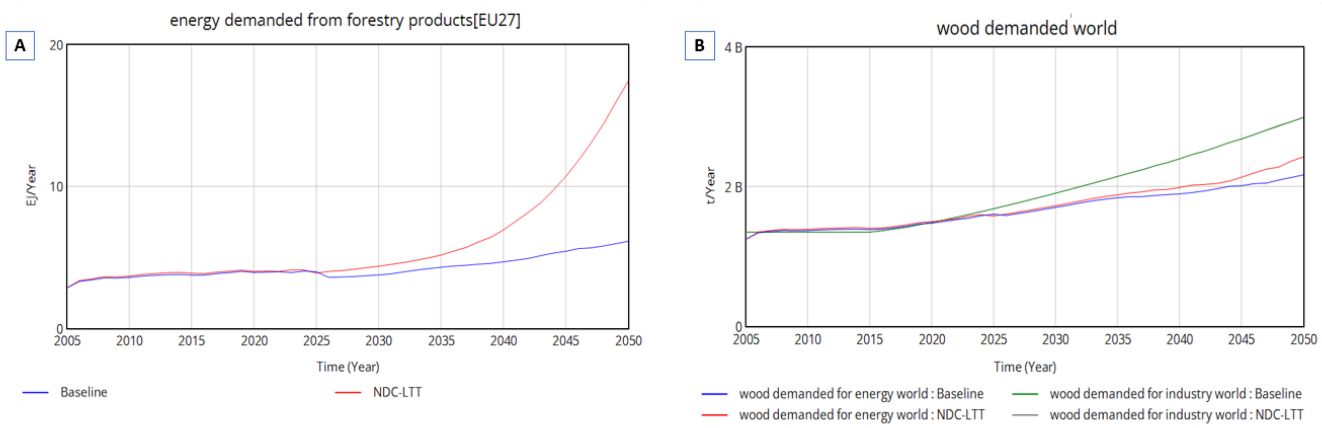

Figure 3. Demand for (A) energy from forestry product in EU27; and (B) wood for energy and industry globally

Although moderate afforestation in the **NDC-LTT Scenario** (by 2050, new planted forests should represent 7% of the managed area in 2005) improves the status of EU's forest stock, this remains a concern because of its decline from 2035 onwards (steeper in **Baseline**), as noticeable in Figure 4A. Moreover, as global demand remains constant and the distribution of supply does not change, stocks in other regions worsen under **the NDC-LTT Scenario** (Figure 4B).

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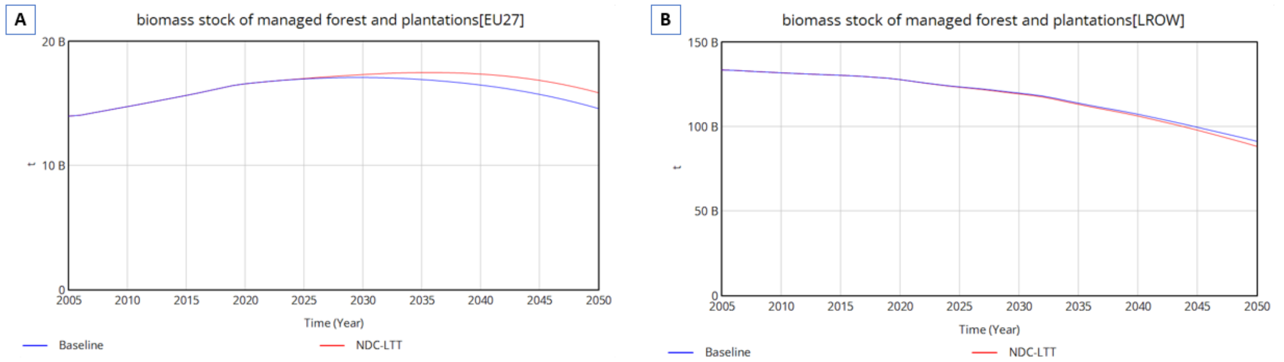

Figure 4. Biomass stock of managed forest and plantations in (A) EU27; and (B) LROW

Therefore, these two initial simulations highlight the need for more intensive afforestation policies together with a limitation of forest stock removals, which should avoid drawing from developing regions to meet growing demand.

The **NDC-LTT-Self-Sufficiency Scenario** reduces biomass stock removals progressively increasing protection until full protection in 2050, and limits them only to regional forests to reduce adverse impacts on other global regions. Figure 5A shows how the stock starts to increase towards the end of the simulation due to the restrictions on removals. However, in Figure 5B it can be seen how these constraints affect the harvested roundwood, making it impossible to satisfy the European demand for biomass.

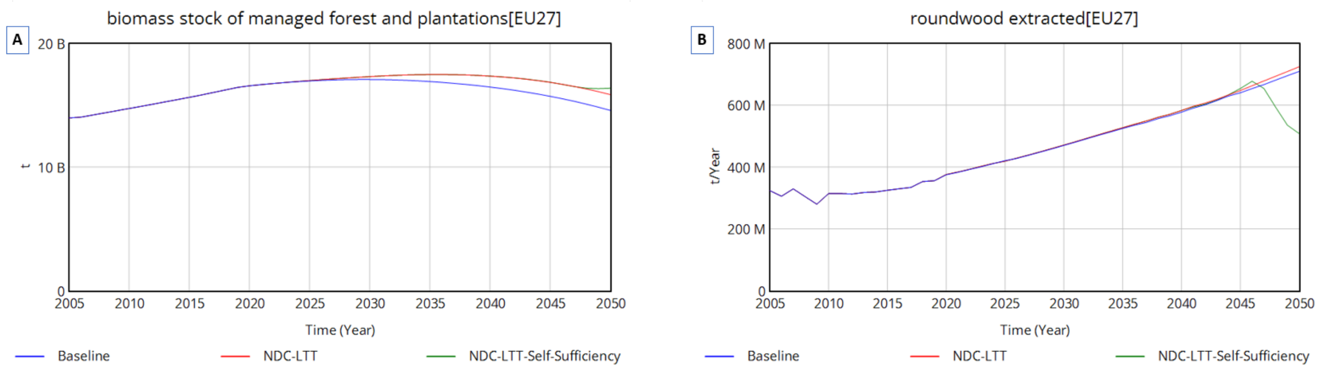

Figure 5. Comparison in EU27 of (A) biomass stock of managed forest and plantations; and (B) roundwood extracted, under three scenarios.

Finally, in order to try to meet this unfulfilled demand while maintaining certain restrictions on removals, the **NDC-LTT-Afforestation Scenario** focuses on greatly increasing reforestation, reaching a new planted area equal to 24% of the managed forest extent in 2005. As a result, the largest stock of managed forest is observed among the scenarios, preventing its decline until 2045, as well as satisfying demand (Figure 6A). The main drawback of this scenario, as shown in Figure 6B, is that forest land starts to compete slightly with cropland, which must be reduced to meet all policy specifications, a risk that might increase in the longer term.

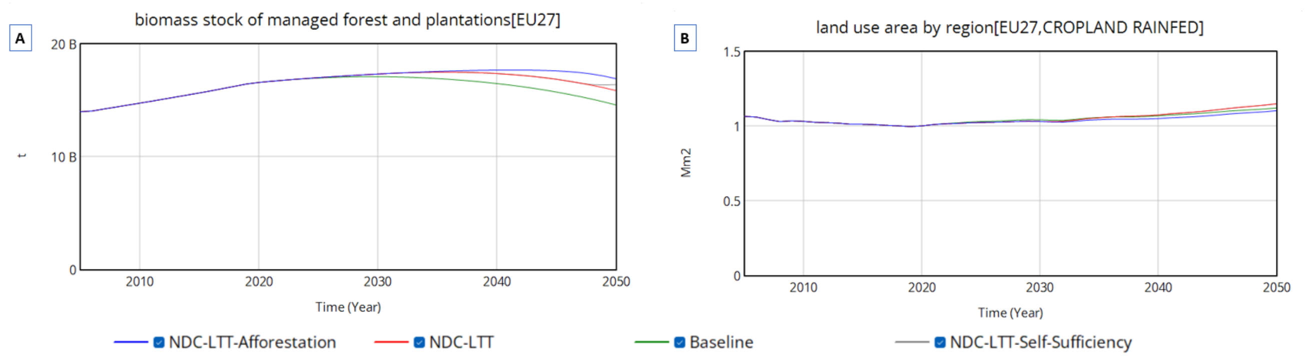

Figure 6. (A) Comparison of biomass stock of managed forests and plantations in EU27 under all scenarios. (B) Rainfed cropland extension in EU27 under all scenarios

3.3 Solar PV penetration in the EU

In this case, the impacts can be seen clearly in the area of land directly occupied by solar PV panels, which comes from different type of land uses. Particularly, approx. the 55% of solar PV panels are allocated in cropland (rainfed) aligned with past dynamics of solar deployment found in EU (Ferreras-Alonso et al., 2024).

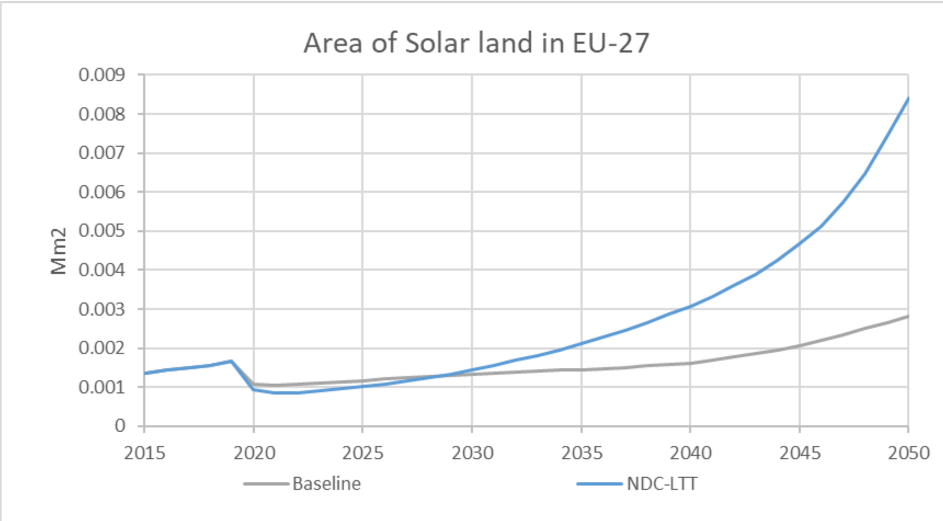

Figure 7. Area occupied by solar PV infrastructure in the baseline and the NDC-LTT scenarios.

To avoid negative impacts of this deployment of solar PV, we developed the scenarios explained previously, in which land-based policies are applied: solar sitting and specific land use types protected from solar PV occupation. Figure 8 shows that the area occupied by solar PV deployed on land use types with productive uses, like cropland and forest land are reduced, and therefore potential negative impacts reduced, including land competition (e.g. competition for food, wood, etc.). Furthermore, forest land plays a crucial role in maintaining ecological balance and serves as a significant carbon reservoir.

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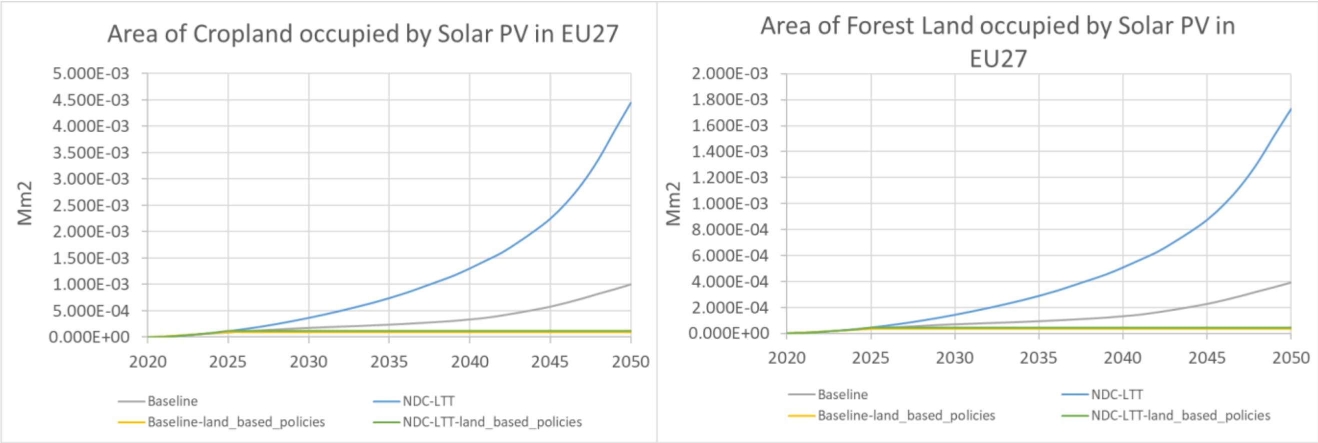

Figure 8. Evolution of other productive land use types occupied by solar PV for the different scenarios in EU-27.

In addition, the carbon emissions related to Land Use Change due to the deployment of solar PV on land are reduced in scenarios where land-based policies are applied with respect "baseline" and "NDC-LTT" scenarios where land-based policies are not applied (see Table 2 below). The baseline scenario has less carbon emissions associated with respect NDC-LTT scenario due to the fact that the land occupied by solar PV panels is less as the penetration of solar PV energy is not so ambitious.

Table 2. Land Use Change emissions associated to the deployment of solar PV on land.

	Cumulated carbon emissions (GtC) 2020–2050 (associated to the deployment of solar PV on land)	% of carbon emissions with respect to Baseline and NDC-LTT scenario
Baseline	0.02	100%
Baseline- land-based policies	0.009	59%
NDC-LTT	0.06	100%
NDC-LTT- land-based policies	0.035	55%

3 Policy Implications

Our study analyses the impacts of the energy transition in land use. We include not only those related to land use change emissions, but also to land use competition which can compromise the repercussions on land-related products that are necessary for energy and non-energy purposes. Although the transition to renewable energy including bioenergy and solar PV deployment reduces GHG emissions (NDC-LTT scenario), there are indirect impacts that can be avoided or reduced when applying integrated energy and land policies.

Ambitious bioenergy requirements. Challenges & Solutions

The analysis of the impacts of bioenergy (from forest biomass) penetration in the system, highlights the critical need to align bioenergy deployment strategies with land-use sustainability objectives, particularly in the context of rising demand for forest biomass. Without stronger policy action, the European Union risks increasing pressure on global forest resources and exacerbating deforestation in vulnerable regions, such as Latin America, Sub-Saharan Africa, and Southeast Asia, as it already happened with the indirect Land Use Change (iLUC) issue of biofuels.[2]

- Scenarios based on historical trends foresee a considerable decline in EU forestry stock beyond 2030 of about 15% over 20 years. This loss raises a number of environmental concerns, as forests are the major carbon sink.
- High bioenergy scenarios increase forest biomass demand, requiring afforestation efforts beyond current policies. Forest protection alone leads to unmet demand and stock decline after 2035.
- Regional self-sufficiency policies reduce pressure on global forests but trigger land-use conflicts in Europe, especially with cropland, highlighting the need for integrated land-use planning.
- Conditioning bioenergy targets on land sustainability metrics, such as forest stock trends and sustainable management, can help ensure renewable goals align with ecological boundaries.

Ambitious solar PV deployment on land. Challenges & Solutions

In the analysis of solar PV impacts, the findings highlight the critical need to align the deployment of solar PV in line with a NDC-LTT scenario with land-based policies so that the impact can be reduced. This is in line with the conclusions drawn in the study (Ferreras-Alonso et al., 2024), which highlight how a high ambitious penetration of solar PV deployment in the EU can effect land use.

- In the scenario NDC-LTT where solar PV is deployed according to current EU policies, the land area required for installations increases. If current trends continue, a large proportion of this expansion will occur on rainfed cropland. This process has two main repercussions: increased land-use competition and higher emissions associated with land-use change.
- Implementing guidelines that determine where solar energy project can be built (solar sitting policies), restricting the deployment on sensitive land-use types avoid negative side effects. By limiting solar installations on cropland and forested areas, we can alleviate land competition (e.g. land for agriculture, biomass or timber production).

[2] https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en

- Integrating energy and land-use planning by restricting land-sensitive use types: prioritising deployment on lower-carbon, less ecologically significant land (e.g. degraded areas, heavily modified, or abandoned areas with low biodiversity and ecosystems service provision such as eroded fields) further reduces carbon emissions linked to land-use change and also impacts on ecosystems and biodiversity.

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Policy Brief

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In a nutshell

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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