



HAL
open science

Interactions between land and grid development in the transition to a decarbonized European power system

Victor Guillot, Gildas Siggini, Edi Assoumou

► To cite this version:

Victor Guillot, Gildas Siggini, Edi Assoumou. Interactions between land and grid development in the transition to a decarbonized European power system. *Energy Policy*, 2023, 175, pp.113470. <10.1016/j.enpol.2023.113470>. <hal-03986792>

HAL Id: hal-03986792

<https://hal.science/hal-03986792v1>

Submitted on 31 Mar 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC 4.0 - Attribution - Non-commercial use - International License

Interactions between land and grid development in the transition to a decarbonized European power system

Victor Guillot*, Gildas Siggini, Edi Assoumou

MINES Paris-PSL University, CMA - Centre for Applied Mathematics, Rue C. Daunesse, 06904 Sophia Antipolis, France

*Corresponding author: victor.guillot@minesparis.psl.eu

Highlights

- Limited total discounted cost increase in a scenario with no land expansion
- Interconnections development modifies land and investments distribution
- Cooperation at European scale challenged by opposing national interests

Abstract

The decarbonization of the European electricity system by 2050 will involve replacing fossil fuels with low-carbon energies, in particular variable renewable energies, coupled with the development of the transmission network to ensure their integration at European scale. As these production modes have a lower energy density, their development will imply an increase in the amount of land dedicated to electricity production. This study investigates the links between an optimal decarbonization of the electricity system, land requirements, and the development strategy of interconnections. We study these interactions using eTIMES-EU, an energy system optimization model, by endogenously taking into account a land variable and testing two interconnection development plans. Our results show that it is possible to limit the land use of the network to its 2020 value for roughly a one percent higher total discounted cost, and that the development of interconnections changes the technologies to be installed on a European scale, but that it requires efficient and ambitious planning. Moreover, our results highlight disparities across countries in terms of space and investment that may constitute barriers to implementing this type of centralized development policy.

Keywords: TIMES, land, energy system modeling, carbon neutrality, power system planning

1. Introduction

The European Union (EU) is committed to achieving net carbon neutrality by 2050 and intends to significantly increase the share of renewables (European Parliament and Council of the European Union, 2021). Moreover, the electrification, combined with the potential for reducing greenhouse gas (GHG) emissions in this sector (European Commission et al., 2020) make the power system an essential factor in the decarbonization of the economy. While renewable energy systems (RES) have the advantage of emitting less GHG than fossil fuels, their energy density is lower (van Zalk and Behrens, 2018). This larger land footprint raises concerns about a disorganized power system land sprawl if nothing is done to limit it. Although space resources are sufficient from a technical point of view, i.e. the RES potential is sufficient to supply Europe with electricity (Child et al., 2019), this observation neglects the complexity related to the use of space for electricity production. Indeed, a techno-economic approach overlooks social acceptance issues related to the use of space and conflicts of use, which are central to the transition of the electricity system (Busse and Siebert, 2018; Wolsink, 2018). Employing a notion of feasible potential that integrates social acceptance (McKenna et al., 2022) is more suitable for the spatial planning of energy systems. Another method that integrates social acceptance related to land involves employing tools to spatially allocate generation facilities in power system planning (Drechsler et al., 2017, 2011; Grimsrud et al., 2021; Koecklin et al., 2021).

Although the issue of space is starting to be addressed in academic research, the power system transformation plans made by national institutions rarely take this dimension into account. Yet research shows that if nothing is done to limit it, significant land space can be employed for energy purposes (Trainor et al., 2016) and that while action can be undertaken to reduce this land space, it requires ambitious planning decisions (Palmer-Wilson et al., 2019). (Scheller et al., 2021) carried out a survey among the energy system analysis community. They found that, in addition to equity and distributional impacts, the integration of land use issues into models is still at an early stage of development, despite the fact that it does not require making substantial changes to model structures.

Contrary to the interaction between GHG and electricity production, which is studied almost systematically in energy models, the link with land use is still poorly understood. Recent years have seen an increased number of studies on this subject, but the wide range of methods implemented in terms of space and time boundaries or

technologies considered makes it difficult to infer what concrete action to take in terms of power system development. Table 1 lists studies that focus on land use and energy system models.

The simplest method to consider the land footprint is to apply coefficients to different technologies in an ex-post manner for particular scenarios. Some studies examine land consumption in detail (Trainor et al., 2016), while others consider this variable among other indicators such as air pollution and employment (Jacobson et al., 2017); water use, GHG and material (Arent et al., 2014); and LCA categories (Berrill et al., 2016). A more sophisticated method is to study the impact of restrictions on available land by exogenously modifying the feasible potentials according to the definition (McKenna et al., 2022) of specific technologies, i.e. to reduce the economic potential to reflect a scarcity of the resource. This method is flexible and allows a detailed description of the restrictions related to a lack of acceptance or impact on biodiversity. (Wu et al., 2015) look at the development of the electric power system in California with environmental constraints. (Price et al., 2018) consider different potential values for variable RES for 20 zones in the UK by changing the distance to homes or the availability of agricultural land for generation facility installation. (Fälth et al., 2021) restrict solar and wind potentials for the North Africa and Middle East region. The variability in both hypotheses and regions covered make comparison between studies difficult. The latter method involves incorporating into an energy model an endogenous constraint on the area available for the power system. The model optimizes the power system so that the sum of areas used by different facilities is lower than a fixed value. The least-cost optimization is land-use neutral with respect to different technologies; the objective is to ensure that electricity demand is met while keeping the space consumption below a set value. (Palmer-Wilson et al., 2019) study decarbonization scenarios for the Alberta province (Canada) power system with different sets of constraints on space. (Tröndle, 2020) explores ways to limit the land footprint of the European power system for a technology mix including ground and rooftop PV, onshore and offshore wind, and a small proportion of hydro and bioenergy. (Chen et al., 2022) investigate the link between land use and GHG reduction in 13 European countries for the year 2040 by minimizing land use within a defined additional cost in comparison to a reference scenario. (Cook et al., 2022) analyze the implications of water and land constraints on a 100% renewable power system located in Amarillo, Texas in the USA.

Most studies rely on a single year simulation, which makes it impossible to investigate the influence of a land constraint on the power system's development over time. Moreover, these studies do not always include the same list of available technologies. To our knowledge, only (Palmer-Wilson et al., 2019) have studied decarbonization

scenarios of the power system between the current period and 2050 with an endogenous constraint on space. The authors find that the reduction of fossil technologies replaced by solar and wind leads to a tenfold land use increase in an unconstrained scenario. In addition, they point out that not allowing any land use increase leads to an 11% cost increase. However, the study is limited to a least-cost optimization for a single region in Canada, and interconnections are not considered. Studies involving an endogenous constraint on Europe are based on the optimization of a power system over one year, making it impossible to study the evolution of the system over time. Moreover, some of these studies do not cover all European countries. While some research considers the benefits of interconnections in terms of costs (Schlachtberger et al., 2017) or balancing management at different scales (Tröndle, 2020), these articles do not focus on the impact on space at the European scale.

Our work proposes to fill this gap by integrating a land variable in an energy optimization model that allows us to build scenarios that limit land sprawl while testing interconnection developments to investigate the land burden transfer between countries. The spatial dispatch of technologies along with the distributional effects are assessed at continental and national scales. We also look at the implication of interconnection development and land constraint on investment distribution.

The research questions that structure this work are: 1) How does the integration of land use in energy planning modify decarbonization pathways? 2) Which levers of action and choices in terms of technologies and development of interconnections take into account the consumption of land in decarbonization pathways? 3) What are the potential barriers to the implementation of a land use reduction policy?

The rest of the article is organized as follows: Section 2 describes the model and the method employed to incorporate a surface constraint. Section 3 gives the results, and section 4 proposes a discussion. Section 5 makes a conclusion and suggests the policy implications on the decarbonization of the power system.

Table 1 Literature review: studies considering land use and energy systems

| Article | Region | Energy sector | Time frame | Interconnection | Method | Land use as main topic of the study | Technology | Carbon objectives |
|-------------------------------------|------------------|-----------------------------|--------------------------|---------------------------------------|-----------------------|--|--------------------------------------|------------------------------------|
| (Ribeiro et al., 2013) | Portugal | Electricity | 2010-2020 | No | Ex-post computation | No | All except nuclear and ccs | None |
| (Arent et al., 2014) | US | Electricity | 2010 to 2050 | Yes | Ex-post computation | No | All | ~ -80% |
| (Hertwich et al., 2015) | World | Electricity | 2010 to 2050 | No | Ex-post computation | No, other LCA indicators | All except nuclear | No |
| (Wu et al., 2015) | California(US) | Electricity | One year 2050 | No | Potential restriction | Yes | All | -80% |
| (Konadu et al., 2015) | UK | Energy | 2018 to 2030, 2050 | No | Ex-post computation | Yes | Bioenergy land use only | -80% |
| (Trainor et al., 2016) | US | Energy | Comparison 2011 and 2040 | No | Ex-post computation | Yes | All | Carbon tax |
| (Berrill et al., 2016) | Europe | Electricity | One year 2050 | No (just transmission land footprint) | Ex-post computation | No, other LCA indicators | All except nuclear | Carbon tax |
| (Jacobson et al., 2017) | World | Energy | 2015 to 2050 | No | Ex-post computation | No | RES only | Neutral (no fossils) |
| (Price et al., 2018) | UK | Electricity | One year 2050 | Yes | Potential restriction | Yes with water | All | -80% |
| (Palmer-Wilson et al., 2019) | Alberta (Canada) | Electricity | 2015 to 2060 | No | Endogenous constraint | Yes | All | -90% |
| (Tröndle, 2020) | Europe | Electricity | One year | Yes | Endogenous constraint | Yes | RES only | Neutral (no fossils) |
| (Sasse and Trutnevyte, 2020) | Central Europe | Electricity | 2035 | Yes | Ex-post computation | No, land use as an indicator of equity with jobs and investments | All | No |
| (Wu et al., 2020) | Western US | Electricity | 2016-2050 | Yes | Potential restriction | Yes | PV, onshore wind and geothermal | -80% |
| (Price et al., 2020) | UK | Electricity | 2050 | No | Potential restriction | Yes, visual impact more precisely | All | 3Mt CO ₂ 2050 |
| (Fälth et al., 2021) | MENA | Electricity | One year 2040 | Yes | Potential restriction | Yes | All | CO ₂ neutral |
| (Heinrichs et al., 2021) | Germany | Energy and agriculture | 2015 to 2050 | No | Potential restriction | Yes | All, but bioenergy only for land use | -80% |
| (Pedersen et al., 2021) | Europe | Electricity | 1 year, greenfield | Yes | Ex-post computation | No, other socio economic metrics | RES + open cycle gas turbine | CO ₂ reduction explored |
| (Williams et al., 2021) | US | Energy | 2020 to 2050 | No | Potential restriction | No | All | Net zero 2050 |
| (Chen et al., 2022) | Northern Europe | Electricity, heat, hydrogen | 2040 | Yes | Endogenous constraint | Yes | All | Cap and tax |

| | | | | | | | | |
|----------------------------|-------------------|--------------------|------------------|------------|------------------------------|-----------------|------------|-------------------------|
| (Cook et al., 2022) | Amarillo, TX, USA | Electricity | One year | No | Endogenous constraint | Yes, with water | RES only | No direct GHG emissions |
| This study | Europe | Electricity | 2016-2050 | Yes | Endogenous constraint | Yes | All | Net zero 2050 |

2. Methodology

The study uses eTIMES-EU, a bottom-up, techno-economic model to evaluate decarbonization scenarios of the European electricity system. eTIMES-EU optimizes the installation and operation of the different electricity generation facilities according to the potentials of countries in order to meet electricity demand and reach net carbon neutrality in 2050. The model can be used to study transition paths of the power system from 2016 to 2050 for Europe. In order to take into account the use of space by the model we have modified the general structure to add an additional constraint. Also, we created two different interconnection development plans to study the interconnection-land link.

2.1. Integration of a land constraint in eTIMES-EU

eTIMES-EU is an optimization model belonging to the TIMES family (Loulou et al., 2016). The model determines the power system with the lowest total discounted cost for the period 2016-2050. The total cost is the sum of the investment, operation and maintenance costs for each technology. The model is based on a rich technological environment including thermal power plants (nuclear and fossil) and renewable energy with a distinction between ground and rooftop PV and onshore and offshore wind. The model also considers storage facilities (battery, pumped storage) which, together with other dispatchable production facilities, ensure that sufficient power is available during peak demand. The model features a detailed representation of H₂ production. H₂ can be used as energy storage or as a way to decarbonize electricity production. This can be done thanks to power-to-gas-to-power, or by using combined heat and power units fueled with synthetic natural gas. H₂ can be produced by steam methane reforming, water electrolysis, or biomass gasification. Carbon capture and sequestration (CCS) technologies are modeled for power and H₂ production. Negative emissions can be achieved with biomass power plants or H₂ production through biomass gasification. These two technologies are named BECCS in this article. The high level of detail of the model in terms of investment and technology use is particularly appropriate for the study of transition scenarios up to 2050.

The model optimizes power system development in one- and five-year increments for the period from 2016 to 2050. Each year is divided into 64 periods which consider seasonality, each of which is subdivided into representative

days (weekdays, weekends). Each day is split into eight three-hour periods. eTIMES-EU covers the EU countries (excluding Cyprus and Malta) as well as the UK, Norway, Switzerland and Iceland.

Techno-economic assumptions for new technologies are taken from (IEA, 2016). A calibration for the starting year for existing infrastructure is made with Eurostat data (European Commission et al., 2016) and (ENTSO-E, n.d.). Fuel cost assumptions are taken from (IEA, 2013). Most assumptions made to derive RES potentials come from (Simoes et al., 2013) and were complemented by JRC ENSPRESO data (Ruiz et al., 2019) for solar PV to distinguish the potential of centralized and decentralized systems. National electricity demands are inferred from (European Commission et al., 2016). These corresponds to the reference scenario of the European Commission based on population, economic growth, and energy efficiency gains. The demand increase for Europe is 25% from 2016 to 2050. Scenarios with higher demand corresponding to a 60% increase are also simulated in section 4.4.

eTIMES-EU allows electricity exchanges between different zones, and the model can choose to build interconnections. In this article, the word interconnection designates the network transfer capacity that links two national transmission grids. The interconnections allow cross-border electricity exchanges. The costs associated with interconnections are investment and operation costs. Assumptions concerning interconnections that can be built by the model come from the TYNDP2016 (ENTSO-E, 2016). National transmission networks are not modeled completely, which does not show any network modifications linked to a larger share of variable RES in the power system. A more detailed description of the model featuring input data in the annex can be found in (Simoes et al., 2021), which focuses on climate variability.

The choice of Europe and of the national power system for the geographical zones is justified by the fact that Europe represents a coherent geographical zone where countries interact with each other thanks to interconnections.

In order to study the influence of a constraint on available land for the power system, we added a space variable to the model. This variable is the sum of the land associated with each facility. For 2016, the value is calculated for a power system that was modeled based on historical data; then for each year, the model updates the variable according to the installation and decommissioning of power plants. For each of the model's decisions, the increment is equal to the product between the installed/removed power and the total footprint of the technology concerned. It is then possible to set limits on this variable to constrain the available area. The model must make investment choices that consider the use of space in addition to minimizing the total discounted cost. The way the constraint is

implemented means that all countries cooperate to decrease the total area while minimizing the total discounted cost and being subject to shared CO₂ constraints.

Thanks to the model's high level of disaggregation, technologies can be precisely differentiated in terms of the areas associated with the construction. This method is more general than one that restricts onshore wind and PV only.

The study uses the total footprint to characterize the space consumption associated with each technology. This quantity can be defined as the total area used by power generation facilities (including road access, spacing, and buildings) per unit of power (Ioannidis and Koutsoyiannis, 2020). This quantity is equal to the inverse of the power density. The values are larger than the direct footprint, which roughly corresponds to the surface area artificialized by the facilities. The difference is particularly large for onshore wind and smaller for ground PV. We retain the total footprint because it reflects more of a potential approach and better represents possible conflicts of use. If the space between the turbines allows other activities, such as agriculture, this space is important from an electricity production perspective, as additional turbines cannot be introduced because of wake effect. We do not consider areas related to fuel extraction or the transmission grid. Total footprint values are the same as those used by (Palmer-Wilson et al., 2019), which were mostly taken from (Trainor et al., 2016). Offshore wind and rooftop PV have footprints equal to zero because they are not installed directly on land.

2.2. Scenarios

The scenarios covered makes it possible to study the link between the decarbonization of the power system and its use of space, and to assess strategies for developing interconnections and their impact on land use and its distribution across Europe. All scenarios are constructed in such a way that the power system reaches net carbon neutrality in 2050. Land use and CO₂ objectives are common to all zones. To reach carbon neutrality, we set a cap on direct CO₂ emissions for the whole system. The cap value for each year is calculated thanks to a linear interpolation between real CO₂ emissions in 2016 and zero emissions in 2050. For each scenario, the optimal solution is the one which minimizes the total discounted cost.

In order to study the impact of the space constraint, we limit the area increase between 2020 and 2050 by setting a maximum surface value in 2050 which is a multiple of the total area in 2020. The multiples used are 1, 2 and 3. For instance, a multiplication by 1 of surfaces between 2020 and 2050 represents the limit case where the model is not

allowed to increase the amount of land dedicated to the power system. The trajectory between 2020 and 2050 is obtained using a linear interpolation. Tightening the land constraint gradually triggers technology substitutions.

Eight scenarios are covered in this study; the four principal cases are described in more detail in the results section. Each of these four scenarios is then completed by a variant that allows us to explore the impact of interconnections. In the remainder of the article *Reference* refers to an unconstrained land scenario and *x1*, *x2* and *x3* designate scenarios which authorize a multiplication of the land between 2020 and 2050 of respectively 1, 2 and 3.

The first set of 4 scenarios (*Reference*, *x1*, *x2* and *x3*) represents a situation where the relative use of interconnections in each country does not change radically apart from the adaptation to the demand increase. The ratio between annual imports and demand is fixed for all time periods at its 2016 value. In order to explore the effect of interconnections on land use, for each scenario we then add an alternative case where trade between countries is only restricted by technical specifications. This means that cost efficiency is preferred to ensuring a share of national production. Alternative scenarios are designated by the prefix *Alternative_*.

3. Results

The results show that there is an optimal solution for each combination of land use constraint and carbon neutrality objective. This section first presents the analysis of the results at the European level where all the indicators are aggregated. This general picture is further detailed in specific subsections that analyze geographical distributions of land use and investments, and the impact of interconnections in order to assess the relevance of the optimal solutions.

3.1. Influence of the land constraint on the whole power system

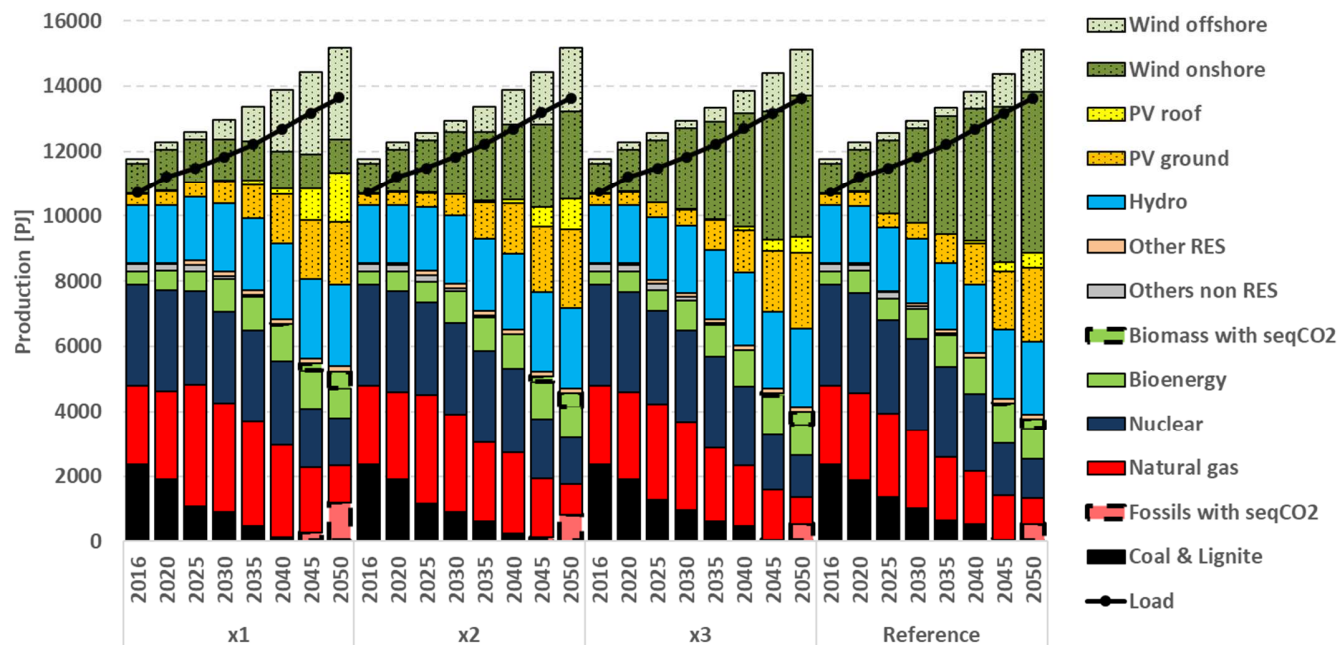


Figure 1 European generation mixes for *x1*, *x2*, *x3* and Reference scenarios, shares of variable RES (dotted background) and dispatchable sources (plain background) are distinguished. *x1* refers to the scenario where there is no land use increase, *x2* refers to the scenario where land use is multiplied by two between 2020 and 2050, *x3* refers to the scenario where land-use is multiplied by 3 between 2020 and 2050.

3.1.1. Generation mix

Figure 1 shows the evolution of the generation mix for the European power system for the *x1*, *x2*, *x3* and *Reference* scenarios. For all scenarios, the direct CO₂ emission constraint is materialized by the decrease in the share of fossil fuels from 40% to 15% of the total production in the *x1* and from 40% to 8% in the *Reference* scenario. The technologies that are still present are, in equal proportion, natural gas, and fossil fuels equipped with CCS. Coal production is almost equal to zero in all scenarios by 2045. The more stringent the land constraint, the higher the share of fossils in the generation mix. The last direct CO₂ emissions associated with these fossil-based technologies are reduced when equipped with CCS and compensated by BECCS in order to reach carbon neutrality in 2050. The share of nuclear power decreases in all scenarios: it is divided by three in the *Reference* scenario and accounts for

8% of the total production in 2050. Its share is divided by two in the *x1* scenario and accounts for 10% of the total production in 2050.

The decrease in technologies based on fossil and nuclear energy is compensated by an increase in the share of wind and, to a lesser extent, of PV. These two technologies account for roughly 60% and 50% in the *Reference* and *x1* scenarios respectively in 2050. While the global share of RES tends to slightly decrease as the land constraint increases, results show a high sensitivity of the share of these technologies. The optimal solution of land-constrained scenarios favors technologies with low total footprints, like offshore wind and rooftop PV, and reduces the amount of electricity produced by onshore wind and ground PV. For instance, onshore wind contributes up to roughly 30% of the total electricity production in the *Reference* scenario and only 7% in the *x1* scenario. On the contrary, rooftop PV production in 2050 is almost three times higher in the *x1* scenario than in the *Reference* scenario and offshore wind production in 2050 is almost twice as high in the *x1* scenario as in the *Reference* scenario.

More generally, the results show that a stricter land constraint tends to reduce the share of variable RES and slow down the decrease of dispatchable technologies in the generation mix.

3.1.2. Installed capacity

Figure 2 shows the installed capacities for the *x1*, *x2*, *x3* and *Reference* scenarios. Installed capacity follows similar trends to those of production. Installed nuclear capacity is roughly halved in all scenarios between 2020 and 2050. The *x1* scenario is the case with the highest installed capacity in 2050, with 59 GW, unlike the *Reference* scenario with 47 GW. This 12 GW difference corresponds to roughly 8 EPR reactors (1600MW). The general decrease in nuclear capacity implies that some nuclear power plants will be shut down while others will be renewed. CCS for fossil fuels and biomass reacts similarly to the land constraint. Capacity equipped with CCS increases with the constraint, the *x1* scenario has 73 GW of CCS installed, while the *Reference* scenario has 37 GW installed. This 36 GW is significant, it corresponds to the equipment of 72 sites with a capacity of 500 MW across Europe.

3.2. Concerning variable RES, onshore wind is the technology that is the most affected. Its high land footprint is a disadvantage as the land constraint becomes stronger. Installed capacity in 2050 in the Reference scenario is equal to roughly 670 GW, and drops to around 140 GW in the x1 scenario. The results show that the land constraint modifies the trend for the installation of onshore wind capacities depending on the scenario. The onshore wind installed capacity is multiplied by roughly 4 between 2020 and 2050 in the Reference scenario while it slightly decreases in the x1 scenario. For

all other variable RES and scenarios, the total capacity installed increases over time. The development of rooftop PV increases gradually depending on the constraint and reaches 110 GW in 2050 in the Reference scenario and is at its maximum in the x1 scenario with around 380 GW installed. The difference is less pronounced concerning installed capacity between scenarios for ground PV. The installed capacity difference in 2050 between the x1 and Reference scenarios is equal to 110 GW, which should be compared to the 600 GW installed in 2050 in the Reference

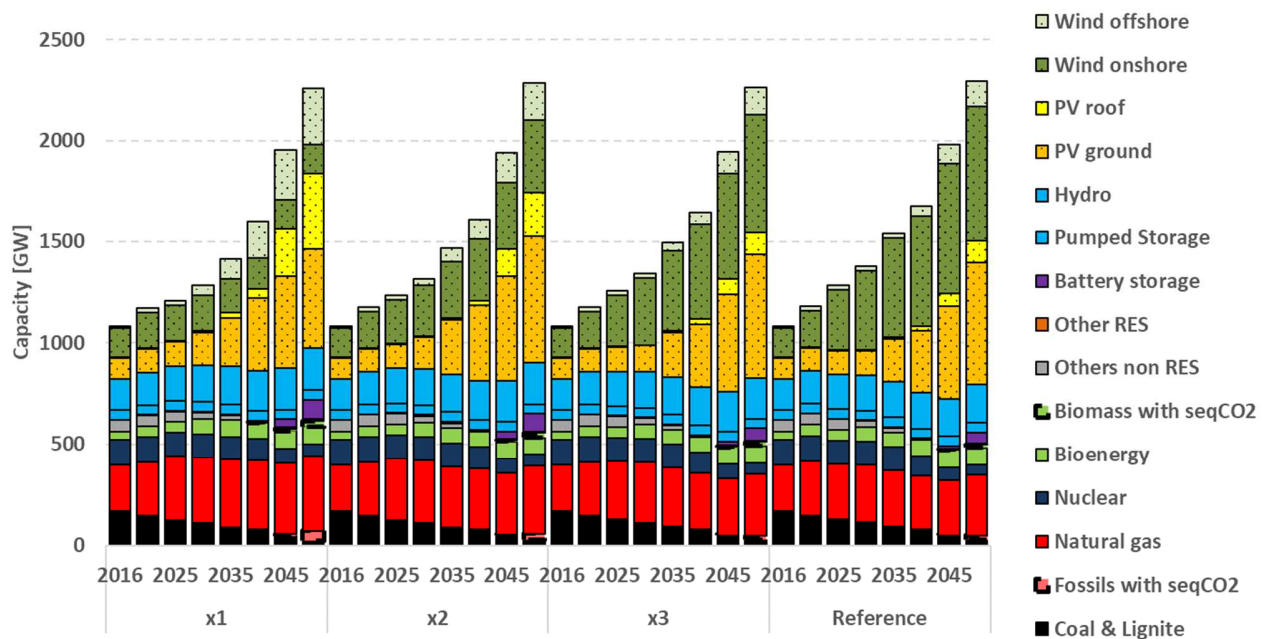


Figure 2 Installed capacities for x1, x2, x3 and Reference scenarios, shares of variable RES (dotted background) and dispatchable sources (plain background) are distinguished. x1 refers to the scenario where there is no land-use increase, x2 refers to the scenario where land use is multiplied by two between 2020 and 2050, x3 refers to the scenario where land use is multiplied by 3 between 2020 and 2050.

scenario. National specificities and interactions between countries under the land constraint

Looking at the global situation tends to underestimate the difficulty of implementing specific power system development. The aggregation of values for the whole of Europe hides specific situations in which cooperation between all of the actors might not be guaranteed. The least-cost optimization with perfect foresight used in this study means that the optimal solution is reached for the whole zone and may create situations where countries can

win or lose in terms of land use or investments. These differences may motivate countries or energy utilities to defend development schemes that fulfill their interests. These diverging interests might be even more challenging than the extra cost of the system, which is rather limited. The following sub-sections further detail the optimal solutions by examining national situations.

3.2.1. Land use distribution: the land constraint reduces the difference between countries

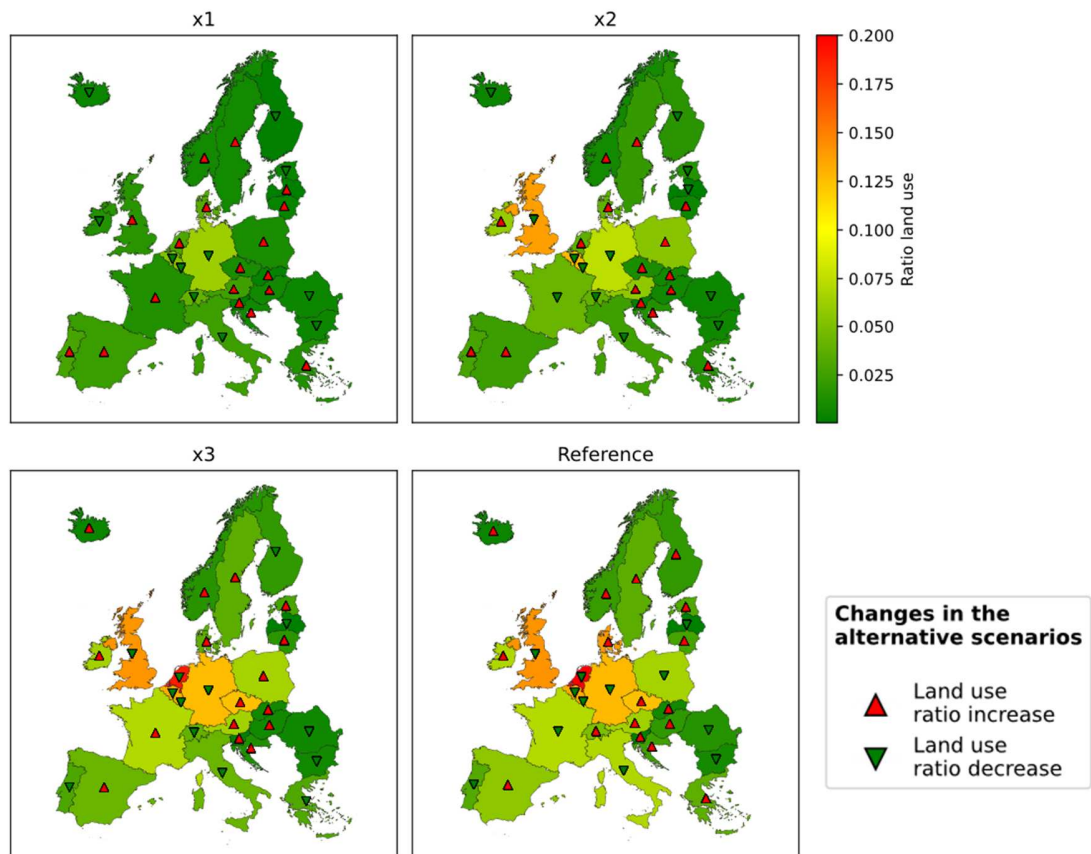


Figure 3 Geographical distribution of land use in 2050. The ratio is equal to the land dedicated to energy production divided by the total country area. Upward triangles (red) denote a land use ratio increase with development of interconnections and downward triangles (green) show a decrease. x1 refers to the scenario where there is no land-use increase, x2 refers to the scenario where land use is multiplied by two between 2020 and 2050, x3 refers to the scenario where land use is multiplied by 3 between 2020 and 2050.

Figure 3 shows the distribution of the surface dedicated to electricity production by country in 2050. It is noteworthy that in the reference cases, the ratio between the land used for electricity production and the total area is significant

for some countries. This is particularly the case for countries with a large onshore wind potential, such as Belgium, the UK, and the Netherlands, where the land ratio is equal to 13, 14 and 20% respectively in the *Reference* scenario. These ratios correspond to absolute values of roughly 4,000, 35,000 and 8,000 km² respectively. The countries with the highest ratio are not those with the highest absolute land use. The absolute land use values for Germany and France in the *Reference* scenario are respectively 45,000 and 39,000 km², while their ratios are equal to 13 and 7%. The main effect of adding an area constraint is to reduce the national land use ratio. Luxembourg is the country with the highest land use ratio, which is equal to 9% in the *x1* scenario. In other words, the land constraint tends to enhance equity related to the ratio of land use among countries.

The influence of interconnections varies according to the country. In some countries, the impact of the use of interconnection is insensitive to the land constraint. For instance, countries like Germany and Belgium always have an interest in terms of land use when trade is optimized. On the contrary, in countries like Spain and Denmark, land use increases when exchanges are not limited. One of the reasons is that countries with lower potential can outsource production from neighboring countries when exchanges are not limited. The last category gathers countries that are affected differently depending on the land use constraint. For example, Portugal's ratio decreases in the *Reference* and *x3* scenarios but increases in the two other cases.

3.2.2. Influence of interconnections: improving efficiency increases trade imbalances

Figure 4 shows the distribution of trade and the balance between imports and exports for each country in 2050. The difference between the two interconnection operation schemes is visual. The optimal solution makes significant use of electricity exchanges between countries in the case of unrestricted exchanges, especially in Western Europe. Trading is intense around Germany, which imports roughly 230 TWh in 2050 from neighboring countries in the *Alternative* scenario compared to 30 TWh in the *Reference* scenario. This trade increase is enabled by the development of interconnections. The *Alternative* scenario has an additional 27 GW of interconnections compared to the *Reference* scenario.

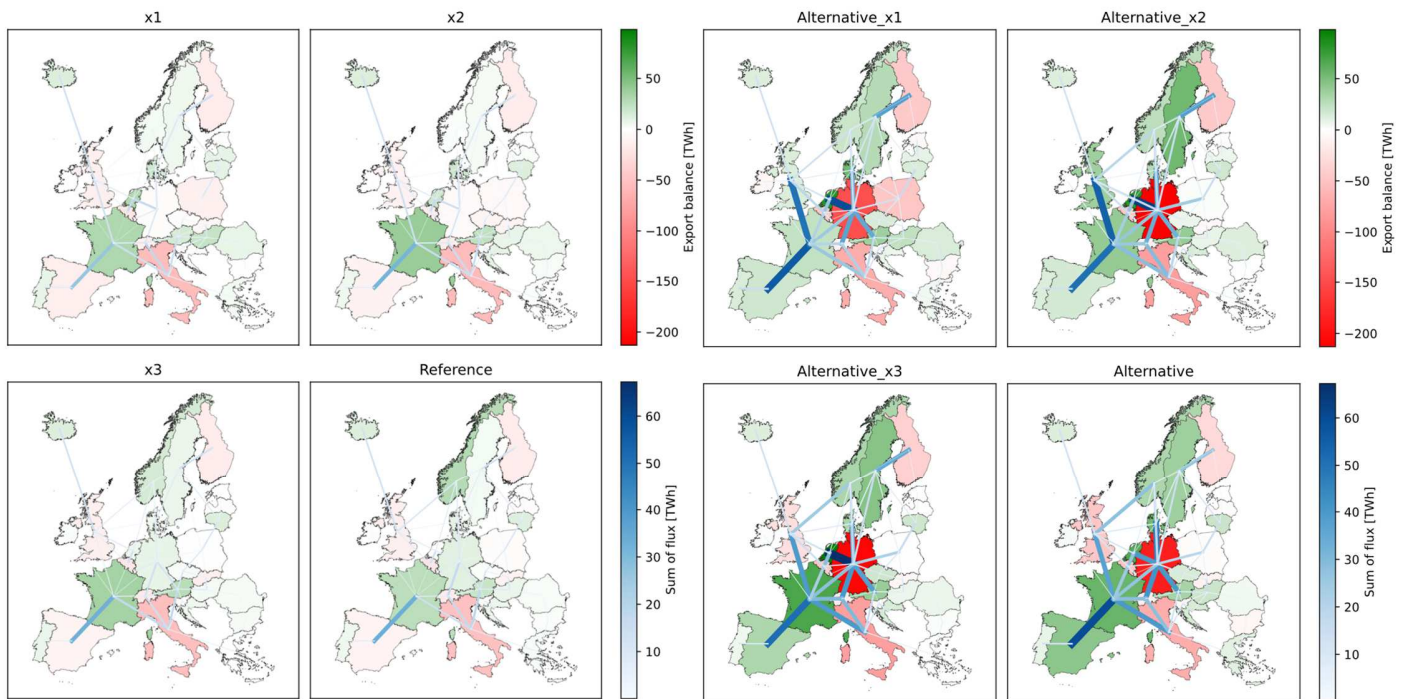


Figure 4 Electricity trades, map background for the difference between exports and imports and lines for the sum of electricity flows in 2050. The four left-hand squares are the main scenarios, the right-hand squares are the alternative scenarios where national imports are limited to 2016 levels. x1 refers to the scenario where there is no land use increase, x2 refers to the scenario where land use is multiplied by two between 2020 and 2050, x3 refers to the scenario where land use is multiplied by 3 between 2020 and 2050.

Interconnections tend to spatially concentrate production, so that countries with the highest potential produce more and can increase the value of their production through trade. For instance, the Netherlands exports around 35% of its total production in 2050 in the *Alternative* scenario and Denmark about 60% of its total production. This also implies that exporters will have to endure the disadvantages of energy production that is not limited to land use. The land constraint does not significantly affect the trading schemes, except for the UK. The constraint has an impact on volumes but not on the direction of the exchanges.

3.2.3. Investment distribution: the emergence of winners and losers with the land constraint

The challenges related to investments are twofold. While Europe has an interest in developing a least-cost power system, countries have an interest in attracting investments. Indeed, thanks to specific pricing, exports can cover the cost of additional investments for exporting countries while benefiting from economic spill-overs in terms of employment and investments related to the additional capacities.

3.2.3.1. Total cost

Table 2 Absolute and relative difference of total discounted cost from the reference scenario

| Scenario | Absolute difference from <i>Reference</i> scenario [G€] | Relative difference from <i>Reference</i> scenario |
|--------------------|--|---|
| <i>x1</i> | 76 | 1.3% |
| <i>x2</i> | 28 | 0.5% |
| <i>x3</i> | 6 | 0.1% |
| <i>Alternative</i> | -14 | -0.2% |

Table 2 gives the absolute and relative differences from the *Reference* case in terms of total discounted cost and total cost for the year 2050. We can see that costs gradually increase when the constraint on land becomes stricter. The extra cost of the land constraint in the *x1* scenario reaches 76 billion euros for the whole system and time period. The relative cost difference between the *x1* scenario and the *Reference* scenario is 1.3%, which is rather limited in comparison to the severity of the land constraint. In other words, there it is possible to drastically reduce the land footprint of the power system with a limited extra cost. Nonetheless, this requires the full cooperation of every country and effective planning of the power system development. Developing the use of interconnections lowers the total system cost of roughly 14 billion euros in the *Alternative* scenario compared to the *Reference* scenario.

3.2.3.2. Overall investments

Figure 5 gives the absolute total investments (activity, fixed operation, and maintenance and investments costs) in 2050 and the difference with the *Reference* in the other scenarios. It can be seen that countries are not equal in the face of constraints and that interests diverge according to network development policies. Total investments have consequences at two levels: first, they generate an expense for consumers, who pay for the power system and are looking for affordable electricity. Second, they create economic spillovers for countries, such as job creation, or tax and trade revenues. The model computes the total discounted cost for the whole zone, which means that it provides the cheapest solution for consumers in a fully cooperative mode. Nonetheless, the spatial distribution of investments may vary according to interconnection use and land constraints. In other words, some policies may favor or

disadvantage a country in terms of investments. Countries may push for a particular policy that favors their economic interests and thus deviate the transition pathways from a fully cooperative mode.

Absolute investments in 2050 are located in countries with the highest demand, like Germany and France, which respectively attract around 51 and 41 billion euros in the *Reference* scenario. The investment differences between the *Reference* scenario and the constrained scenarios tend to increase when the constraint becomes more stringent. Some countries, like the Netherlands and Spain attract more and more investments when the constraint increases, while countries like Italy and Norway tend to lose investments. These differences can be significant in terms of percentage; for instance, investments in Norway are divided by 1.6 between the *Reference* and *x1* scenarios.

The impact of interconnections on investments has similarities with their effects on land use. Countries like Spain and Denmark, which are subject to a land use increase when trade is not limited, also attract more investments. On the contrary, countries like Germany and Belgium, which are subject to a land use decrease when trade is not restricted, see their national investments decrease.

3.2.3.3. Investments by technology and country

Figure 6 gives the difference between investments (activity, fixed operation, and maintenance and investment costs) and the *Reference* scenario for different technologies in 2050. Similar to national investments, changes in the

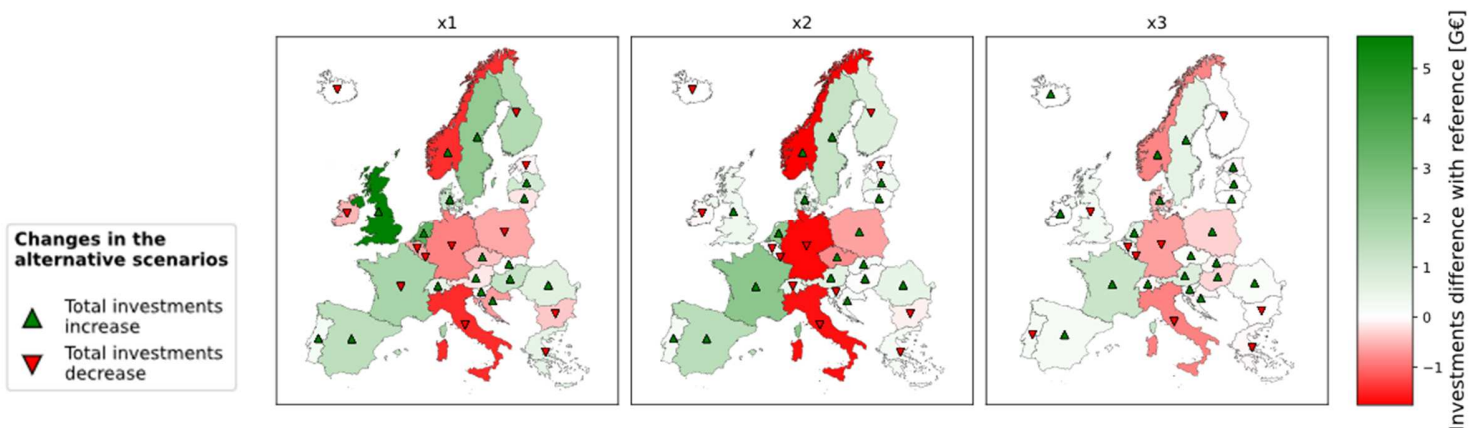


Figure 5 Geographical distribution of total investments difference with the *Reference scenario* in 2050. .

Upward triangles (red) denote a land use ratio increase with development of interconnections and downward triangles (green) show a decrease. x1 refers to the scenario where there is no land use increase, x2 refers to the scenario where land use is multiplied by two between 2020 and 2050, x3 refers to the scenario where land use is multiplied by 3 between 2020 and 2050.

amount invested may have an impact on industries that may either be advantaged or disadvantaged.

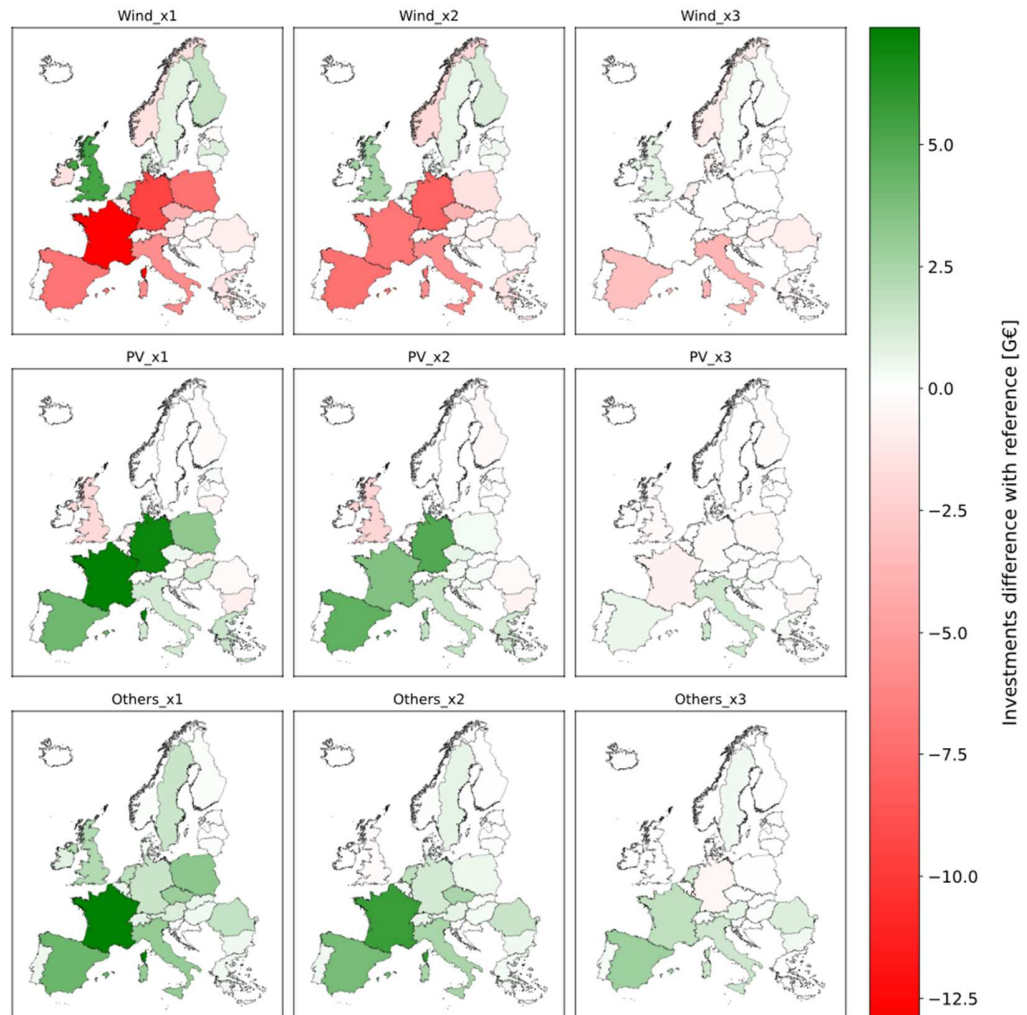


Figure 6 Difference between geographical distribution of total investments and the *Reference scenario* by technology in 2050. x1 refers to the scenario where there is no land-use increase, x2 refers to the scenario where land use is multiplied by two between 2020 and 2050, x3 refers to the scenario where land use is multiplied by 3 between 2020 and 2050.

The gradual reduction of onshore wind when the constraint increases is reflected in investments in wind technologies. Countries with a high offshore potential like the UK, the Netherlands, and Denmark manage to take advantage of this potential when the constraint is tightened, while countries that mainly rely on onshore wind in the *Reference* case like France and Germany lose up to 13 and 9 billion euros of investments respectively in the *x1*

scenario compared to the *Reference* scenario. This investment loss is partially compensated by the installation of PV, while only a limited number of countries lose investments in the constrained scenarios. The wind technology decrease is compensated by the installation of dispatchable technologies gathered in the category *Others*. While every country has positive investments, France concentrates a significant part of the increase, with an 7 billion-euro difference between the *x1* and *Reference* scenarios. This is partially related to the slower decrease in the share of nuclear when the constraint become stronger.

4. Discussion

The results show that it is possible to achieve carbon neutrality under strong constraints on available space. However, achieving these objectives requires important decisions to be made in terms of planning and development of energy sources. Moreover, the decarbonization of the electricity system and the control of the power system land sprawl can only be achieved with significant cooperation between countries. The least-cost model reflects an ideal case where all countries work together to achieve the objectives by taking advantage of each other's strengths. Nonetheless, the modeling tends to overlook other aspects, such as distributional effects, which may make it more complicated to achieve.

(Bolwig et al., 2020) show that it is possible to improve the modeling by considering other aspects related to social acceptance, such as changes in consumer electricity prices or differences in producer revenues, by taking into account the level of interconnection. More specifically on land use, (Sasse and Trutnevyte, 2020) evaluate changes in system cost, land use, and employment among other indicators by region for Central European countries. Like (Chen et al., 2022), they are also interested in changes in investment by technology.

In this study, we propose to focus on technical feasibility, the impact of land constraints, and the impact of interconnections on the spatial distribution of land use and investments.

4.1. Comparison with (Palmer-Wilson et al., 2019)

Comparing this study with (Palmer-Wilson et al., 2019) is difficult, since Europe is much bigger and more populated than the Alberta province, and thus involves modeling different interconnections and different RES potential. While we identify similar trends on the impact of a land constraint on onshore wind and rooftop PV, there is a significant difference in terms of cost increase in the constrained cases. These authors found that a scenario that does not allow any land increase is 11% more expensive than the unconstrained cost. Our study finds only a 1.3% difference. While

this may be seen as a dramatic difference, several arguments explain this gap. First, our study includes low-carbon technologies with low land footprints, like offshore wind and nuclear, which are not considered in (Palmer-Wilson et al., 2019). Second, the nature of the power system in the starting year is different in the two studies. In (Palmer-Wilson et al., 2019), the power system heavily relies on conventional technologies and the total land use is little less than 1,000 km² in the starting year. In comparison, the total land use is equal to a little more than 80,000 km² for Europe in 2020; this gives the model more room to reduce onshore wind capacities to free up space to install technologies with a lower land footprint.

Lastly, there are specific locations where high variations in the total discounted cost can be seen between scenarios. For instance, there is a 24% difference in the Danish total discounted cost between the *Reference* and *xI* scenarios. Denmark and Alberta are comparable in terms of population.

4.2. Feasibility of implied investment pace

Highly land-constrained scenarios require the use of a significant amount of low-carbon and low total footprint technologies. However, the capacities to be installed are particularly high for some technologies, such as offshore wind and rooftop PV. For rooftop PV, more than 300 GW must be installed within 10 years at European scale in the *xI* scenario. As a comparison, the historical annual maximum total PV installation was achieved in Italy in 2011 with a little less than 10GW. For offshore wind, the increase is more gradual, reaching around 280 GW installed in 2050 in the *xI* scenarios. Today, the largest offshore wind farm in Europe is Hornsea 1 (2020) in the UK with an installed capacity of 1.2GW. Thus, to keep up the pace, it would be necessary to install about 8 projects equivalent to Hornsea 1 every year.

Moreover, some technologies, such as CCS, must be used in most constrained scenarios to both reduce the emissions of part of the natural gas and compensate with BECCS the emissions of the remaining natural gas not equipped with CCS. From 2040 to 2050, around 73 GW need to be built in the *xI* scenario. Today, CCS is not developed on a large scale in Europe. There are no industrial sites in Europe other than those related to gas production operating on a large scale in 2022 (Global CCS Institute, 2022). Moreover, this technology faces social acceptance issues in some places (L'Orange Seigo et al., 2014). CCS equipment for power generation will also be in competition with other industry sectors that are more difficult to decarbonize than the power sector. The use of interconnections can limit the need for CCS by allowing better integration of variable RES and a decrease in the

share of dispatchable technologies. However, the trade-off is that it requires an even more ambitious program for rooftop PV and offshore wind.

4.3. The level of cooperation shapes the future power system

The analysis of total system costs shows that cooperation on electricity production tends to reduce costs by increasing trade. Nonetheless, the development of interconnections modifies the nature of the power system and its operation in the future. It enables countries to rely on neighbors that have better RES potential and that can capitalize on it at the same time. However, the location of infrastructures and investment distribution change in this case, which can discourage countries from fully cooperating. The notion of cooperation is central to power grid parameters like total cost and land use, investments, and cost distribution. The multiple actors that contribute to the development of the power system may associate the word “cooperation” with different meanings. There is a need to further define this notion in order to secure a transition that will achieve carbon neutrality with a limited land use increase while satisfying national interests.

Some key elements can already be identified by this study. The limitation of land use, and more generally infrastructure installations, seems difficult to align with attracting national investments and will call for trade-offs. In the case where interconnections are developed, countries like Denmark and the Netherlands that have the ability to build new infrastructures to export to their neighbors can attract more investments, but at the expense of increased land use.

4.4. The influence of biomass availability and the level of demand

The scenarios described above show an increased role of biomass, which is also a source of negative emissions. While the methodology described in this analysis could apply to land use linked to biomass feedstock, it opens specific quantification uncertainties that are left outside the scope for the sake of clarity. The allocation of the land use linked to biomass is not straightforward and likely country-dependent. The value depends on the amount of material coming from waste or energy crops (e.g. short rotation coppice) and the type of crops over the horizon. Allocating the amount of land between energy and non-energy uses and accounting for trade of biomass add another layer of complexity. Not taking into consideration biomass land use is a strong assumption that may lead to an optimistic vision of biomass usage in our result. To partially explore the effect of this optimistic vision, all the

scenarios are simulated with a lower biomass availability. The scenarios with the suffix *_lowBIO* refer to the situation where biomass availability is halved compared to the *Reference* scenario.

A similar approach is used for the discussion of future electricity demands. The main scenarios are based on a 25% electricity demand increase from 2016 to 2050. This might be a low estimate in case of considerable electrification and high use of electric vehicles, and highlights the benefits of sector coupling. Since the consistent treatment of land use implications for the whole energy system was beyond the scope of this work, the influence of demand on the results was simply investigated here by adding variant scenarios with a higher demand. The scenarios with the suffix *_highDEM* refer to cases where the total demand increases by roughly 60% from 2016 to 2050.

Table 3 Production by technology for all scenarios in 2050

| Production [PJ] | Technology Coal & Lignite | Fossils with seqCO2 | Natural gas | Nuclear | Bioenergy | Biomass with seqCO2 | Other RES | Hydro | PV ground | PV roof | Wind onshore | Wind offshore |
|------------------------|---------------------------------|---------------------------|----------------|---------|-----------|---------------------------|--------------|-------|--------------|------------|-----------------|------------------|
| x1 | 30 | 1163 | 1149 | 1444 | 932 | 496 | 181 | 2505 | 1925 | 1503 | 1024 | 2829 |
| x2 | 38 | 782 | 925 | 1444 | 966 | 415 | 146 | 2465 | 2413 | 924 | 2715 | 1943 |
| x3 | 36 | 490 | 834 | 1277 | 968 | 374 | 147 | 2418 | 2312 | 483 | 4373 | 1398 |
| Reference | 33 | 506 | 804 | 1176 | 971 | 282 | 147 | 2226 | 2252 | 480 | 4941 | 1305 |
| Alternative_x1 | 34 | 1277 | 981 | 1444 | 968 | 448 | 146 | 2518 | 2009 | 1264 | 1024 | 3085 |
| Alternative_x2 | 40 | 444 | 824 | 1444 | 982 | 376 | 146 | 2489 | 2230 | 1080 | 2825 | 2312 |
| Alternative_x3 | 39 | 78 | 728 | 1254 | 1000 | 336 | 140 | 2456 | 2079 | 656 | 4481 | 1884 |
| Alternative | 42 | 43 | 708 | 1168 | 986 | 327 | 140 | 2255 | 2083 | 587 | 5221 | 1545 |
| x1_highDEM | 9 | 2891 | 1441 | 1871 | 959 | 603 | 404 | 2555 | 1824 | 2131 | 1021 | 3215 |
| x2_highDEM | 39 | 1703 | 1502 | 1441 | 798 | 660 | 230 | 2581 | 3363 | 1794 | 2362 | 3131 |
| x3_highDEM | 42 | 974 | 1268 | 1443 | 861 | 562 | 175 | 2563 | 3311 | 1485 | 4108 | 2752 |
| Reference_highDEM | 43 | 771 | 1193 | 1438 | 850 | 525 | 169 | 2318 | 2994 | 1154 | 5814 | 2201 |
| Alternative_x1_highDEM | 21 | 3143 | 2044 | 1443 | 630 | 827 | 410 | 2617 | 2035 | 2141 | 1024 | 3262 |
| Alternative_x2_highDEM | 40 | 1880 | 1435 | 1444 | 799 | 634 | 169 | 2567 | 3089 | 1698 | 2657 | 3189 |
| Alternative_x3_highDEM | 42 | 1066 | 1096 | 1444 | 929 | 489 | 157 | 2544 | 2819 | 1489 | 4361 | 3084 |
| Alternative_highDEM | 42 | 912 | 870 | 1412 | 988 | 401 | 140 | 2314 | 2496 | 1012 | 6029 | 2875 |
| x1_lowBIO | 5 | 1713 | 1400 | 1479 | 114 | 409 | 282 | 2519 | 1543 | 1926 | 1056 | 3133 |
| x2_lowBIO | 0 | 470 | 1335 | 1444 | 140 | 409 | 155 | 2460 | 2586 | 1326 | 2558 | 2768 |
| x3_lowBIO | 1 | 240 | 1273 | 1437 | 149 | 404 | 146 | 2454 | 2498 | 834 | 4295 | 1862 |
| Reference_lowBIO | 2 | 195 | 1296 | 1282 | 144 | 397 | 146 | 2190 | 2342 | 861 | 5048 | 1660 |
| Alternative_x1_lowBIO | 0 | 1077 | 1299 | 1444 | 181 | 654 | 207 | 2550 | 1975 | 1625 | 1024 | 3031 |
| Alternative_x2_lowBIO | 0 | 194 | 1331 | 1444 | 132 | 428 | 158 | 2507 | 2183 | 1348 | 2814 | 2918 |
| Alternative_x3_lowBIO | 2 | 53 | 1264 | 1444 | 150 | 392 | 146 | 2502 | 2050 | 1012 | 4434 | 2131 |
| Alternative_lowBIO | 6 | 0 | 1330 | 1266 | 130 | 412 | 146 | 2213 | 2153 | 781 | 5391 | 1722 |

Table 3 gives the production in 2050 by technology for the main scenarios and the variant on biomass and demand.

Lowering the biomass availability forces the model to keep biomass fuel mainly for BECCS which allows negative

emissions. The comparison shows that biomass reduction is replaced by offshore wind and rooftop PV and to a lesser extent by nuclear and fossils with CCS. Ground PV and onshore wind also contribute to replacing biomass when the land constraint is not too restrictive.

Overall, a higher demand emphasizes the trends exposed in section 3. Low carbon with small land footprint technologies are favored when the constraint is tightened. Fossils equipped with CCS, offshore wind, rooftop PV and nuclear are used to meet the demand increase. Technologies like hydro or biomass do not change significantly compared to the main scenarios because they reached their maximum potential.

4.5. Limitations of this work

The results given by the model are not predictions of the future but give valuable insights on the land-use implications linked to energy transition. This study does not focus on the subnational dispatch of capacities, and the development of some technologies may have local consequences and acceptance issues, like visual impacts or land use competition. The rationale behind this modeling choice is that energy objectives are set either at EU or national government level. Nonetheless, in some countries, geographical specificities are hidden by country-size representation. For instance, considering France as a single zone does not allow the model to express North/South load factor differences for PV and wind, which may have an impact on the location of wind turbines and PV panels throughout the country. The analysis is performed here at the country level and increasing the spatial and temporal resolution of the model could potentially help derive insights at the subnational level. Nonetheless, there is a trade-off between spatial resolution and computation time, especially for perfect foresight models considering transition pathways. TIMES models treat the intertemporal investment problem with great consistency but, despite the distinction of 64 annual time slices in eTIMES-EU, the modeling of the power system operation is typically not as detailed as with an hourly unit commitment over successive years.

The land use values consider the space between the infrastructures, resulting in significant values for onshore wind. However, the large area between turbines can be used for other activities, such as farming. Ground base PV also allows the combination of crop and energy production using agrophotovoltaic systems (Weselek et al., 2019). This method consists in installing PV panels that allow farming activities between or underneath a row of panels. The power density of agrophotovoltaic is lower than utility-scale projects but allows food production. It is also possible to build PV wind hybrid systems (Khare et al., 2016) to densify electricity production by using the free space

between turbines to install PV panels. Altogether, these methods can be helpful to handle the land use increase by either combining electricity production with other use or densifying electricity production.

Another approximation is that the model does not consider internal transmission networks and more generally the transmission grid footprint. Grid connections and reinforcements may affect the cost and total footprint of the whole power system and slightly modify the nature of the optimal solution.

Finally, although these issues were explored in a simplified manner in the sensitivity analysis performed above, the treatment of land use impacts linked to fuel processing and the implications of higher electricity demand with more sector coupling could be improved and endogenised.

5. Conclusion and policy implications

This paper explores interactions between decarbonization objectives, surface constraints, and interconnection development at the European scale. The analysis is carried out at European and national levels and aims at identifying important elements to be taken into account for the development of the power system. This work goes beyond a least-cost optimization of decarbonization scenarios by adding an endogenous constraint on land.

At the European scale, the results show that it is possible to contain the land footprint of the power system by limiting the construction of onshore wind power and by favoring low-carbon technologies with a small total footprint, such as offshore wind, nuclear, CCS-equipped thermal power plants and, in the most constrained cases, rooftop PV. This induces competition between alternative renewable electricity production routes that impact excess electricity production and trade between countries. In more detail, limiting the land use increase by twofold in 30 years can be done with a 0.5% increase in the total discounted cost and leave flexibility in achieving the objectives. On the other hand, not allowing any increase in the land area dedicated to electricity production raises more questions in terms of development options. Deployment rates are high and trajectories for some countries require significant planning with ambitious objectives. For instance, it requires building 380 GW of rooftop PV and 280 GW of offshore wind by 2050 for the whole Europe.

Greater development of interconnections allows better integration of variable RES at a European scale. On the national level, some countries have an interest in developing interconnections to benefit from the renewable potential of better endowed neighbors. Overall, interconnections are cost efficient but foster the spatial concentration of facilities in a least-cost optimization paradigm.

In addition to technical issues linked to limiting the power system's land footprint, the way investments' spatial distribution is affected in the most constrained cases may encourage countries to make trade-offs between land-use and the development of infrastructures, which brings economic benefits.

6. Acknowledgements

This work was supported by the Chair Modeling for sustainable development, driven by Mines Paris - PSL and École des Ponts ParisTech, supported by ADEME, EDF, GRTgaz, RTE, SCHNEIDER ELECTRIC, TotalEnergies and the French ministry of ecological and solidarity transition.

7. References

- Arent, D., Pless, J., Mai, T., Wiser, R., Hand, M., Baldwin, S., Heath, G., Macknick, J., Bazilian, M., Schlosser, A., Denholm, P., 2014. Implications of high renewable electricity penetration in the U.S. for water use, greenhouse gas emissions, land-use, and materials supply. *Applied Energy* 123, 368–377. <https://doi.org/10.1016/j.apenergy.2013.12.022>
- Berrill, P., Arvesen, A., Scholz, Y., Gils, H.C., Hertwich, E.G., 2016. Environmental impacts of high penetration renewable energy scenarios for Europe. *Environmental Research Letters* 11. <https://doi.org/10.1088/1748-9326/11/1/014012>
- Bolwig, S., Bolkesjø, T.F., Klitkou, A., Lund, P.D., Bergaentzlé, C., Borch, K., Olsen, O.J., Kirkerud, J.G., Chen, Y., Gunkel, P.A., Skytte, K., 2020. Climate-friendly but socially rejected energy-transition pathways: The integration of techno-economic and socio-technical approaches in the Nordic-Baltic region. *Energy Research & Social Science* 67, 101559. <https://doi.org/10.1016/j.erss.2020.101559>
- Busse, M., Siebert, R., 2018. Acceptance studies in the field of land use—A critical and systematic review to advance the conceptualization of acceptance and acceptability. *Land Use Policy* 76, 235–245. <https://doi.org/10.1016/j.landusepol.2018.05.016>
- Chen, Y., Kirkerud, J.G., Bolkesjø, T.F., 2022. Balancing GHG mitigation and land-use conflicts: Alternative Northern European energy system scenarios. *Applied Energy* 310, 118557. <https://doi.org/10.1016/j.apenergy.2022.118557>
- Child, M., Kemfert, C., Bogdanov, D., Breyer, C., 2019. Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy* 139, 80–101. <https://doi.org/10.1016/j.renene.2019.02.077>
- Cook, J., Di Martino, M., Allen, R.C., Pistikopoulos, E.N., Avraamidou, S., 2022. A decision-making framework for the optimal design of renewable energy systems under energy-water-land nexus considerations. *Science of The Total Environment* 827, 154185. <https://doi.org/10.1016/j.scitotenv.2022.154185>
- Drechsler, M., Egerer, J., Lange, M., Masurowski, F., Meyerhoff, J., Oehlmann, M., 2017. Efficient and equitable spatial allocation of renewable power plants at the country scale. *Nat Energy* 2, 1–9. <https://doi.org/10.1038/nenergy.2017.124>
- Drechsler, M., Ohl, C., Meyerhoff, J., Eichhorn, M., Monsees, J., 2011. Combining spatial modeling and choice experiments for the optimal spatial allocation of wind turbines. *Energy Policy* 39, 3845–3854. <https://doi.org/10.1016/j.enpol.2011.04.015>
- ENTSO-E, 2016. TYNDP2016 - Project Map [WWW Document]. URL <https://tyndp.entsoe.eu/2016/map/> (accessed 2.4.22).
- ENTSO-E, n.d. ENTSO-E European Network for Transmission System Operators Transparency Platform [WWW Document]. URL <https://transparency.entsoe.eu/> (accessed 7.6.21).
- European Commission, Directorate-General for Climate Action, Directorate-General for Energy, Directorate-General for Mobility and Transport, Zampara, M., Obersteiner, M., Evangelopoulou, S., De Vita, A.,

- Winiwarter, W., Witzke, H.-P., Tsani, S., Kesting, M., Paroussos, L., Höglund-Isaksson, L., Papadopoulos, D., Capros, P., Kannavou, M., Siskos, P., Tasios, N., Kouvaritakis, N., Karkatsoulis, P., Fragkos, P., Gomez-Sanabria, A., Petropoulos, A., Havlík, P., Frank, S., Purohit, P., Fragiadakis, K., Forsell, N., Gusti, M., Nakos, C., 2016. EU reference scenario 2016: energy, transport and GHG emissions : trends to 2050. Publications Office of the European Union, LU.
- European Commission, Joint Research Centre, Keramidas, K., Tamba, M., Diaz-Vazquez, A., Wen, X., Chai, Q., Van Dingenen, R., Tchung-Ming, S., Krause, J., Vandyck, T., Soria-Ramirez, A., Fu, S., Weitzel, M., 2020. Global energy and climate outlook 2019 : electrification for the low-carbon transition: the role of electrification in low-carbon pathways, with a global and regional focus on EU and China. Publications Office. <https://doi.org/10.2760/58255>
- European Parliament, Council of the European Union, 2021. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), OJ L.
- Fälth, H.E., Atsmon, D., Reichenberg, L., Verendel, V., 2021. MENA compared to Europe: The influence of land use, nuclear power, and transmission expansion on renewable electricity system costs. *Energy Strategy Reviews* 33, 100590. <https://doi.org/10.1016/j.esr.2020.100590>
- Global CCS Institute, 2022. Facilities - Global CCS Institute [WWW Document]. URL <https://co2re.co/FacilityData> (accessed 2.4.22).
- Grimsrud, K., Hagem, C., Lind, A., Lindhjem, H., 2021. Efficient spatial distribution of wind power plants given environmental externalities due to turbines and grids. *Energy Economics* 102, 105487. <https://doi.org/10.1016/j.eneco.2021.105487>
- Heinrichs, H.U., Mourao, Z., Venghaus, S., Konadu, D., Gillessen, B., Vögele, S., Linszen, J., Allwood, J., Kuckshinrichs, W., Robinius, M., Stolten, D., 2021. Analysing the water and land system impacts of Germany's future energy system. *Renewable and Sustainable Energy Reviews* 150, 111469. <https://doi.org/10.1016/j.rser.2021.111469>
- Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proc Natl Acad Sci USA* 112, 6277–6282. <https://doi.org/10.1073/pnas.1312753111>
- IEA, 2016. World Energy Outlook 2016. Paris.
- IEA, 2013. World Energy Outlook 2013. Paris.
- Ioannidis, R., Koutsoyiannis, D., 2020. A review of land use, visibility and public perception of renewable energy in the context of landscape impact. *Applied Energy* 276, 115367. <https://doi.org/10.1016/j.apenergy.2020.115367>
- Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A.F., Goodman, S.C., Chapman, W.E., Cameron, M.A., Bozonnat, C., Chobadi, L., Clonts, H.A., Enevoldsen, P., Erwin, J.R., Fobi, S.N., Goldstrom, O.K., Hennessy, E.M., Liu, J., Lo, J., Meyer, C.B., Morris, S.B., Moy, K.R., O'Neill, P.L., Petkov, I., Redfern, S., Schucker, R., Sontag, M.A., Wang, J., Weiner, E., Yachanin, A.S., 2017. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* 1, 108–121. <https://doi.org/10.1016/j.joule.2017.07.005>
- Khare, V., Nema, S., Baredar, P., 2016. Solar–wind hybrid renewable energy system: A review. *Renewable and Sustainable Energy Reviews* 58, 23–33. <https://doi.org/10.1016/j.rser.2015.12.223>
- Koecklin, M.T., Longoria, G., Fitiwi, D.Z., DeCarolis, J.F., Curtis, J., 2021. Public acceptance of renewable electricity generation and transmission network developments: Insights from Ireland. *Energy Policy* 151, 112185. <https://doi.org/10.1016/j.enpol.2021.112185>
- Konadu, D.D., Mourão, Z.S., Allwood, J.M., Richards, K.S., Kopec, G., McMahon, R., Fenner, R., 2015. Land use implications of future energy system trajectories—The case of the UK 2050 Carbon Plan. *Energy Policy* 86, 328–337. <https://doi.org/10.1016/j.enpol.2015.07.008>
- L'Orange Seigo, S., Dohle, S., Siegrist, M., 2014. Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews* 38, 848–863. <https://doi.org/10.1016/j.rser.2014.07.017>
- Loulou, R., Goldstein, G., Kanudia, A., Lettita, A., Remme, U., 2016. Documentation for the TIMES Model PART I: TIMES concepts and theory.
- McKenna, R., Pfenninger, S., Heinrichs, H., Schmidt, J., Staffell, I., Bauer, C., Gruber, K., Hahmann, A.N., Jansen, M., Klingler, M., Landwehr, N., Larsén, X.G., Lilliestam, J., Pickering, B., Robinius, M., Tröndle, T., Turkovska, O., Wehrle, S., Weinand, J.M., Wohland, J., 2022. High-resolution large-scale onshore wind

- energy assessments: A review of potential definitions, methodologies and future research needs. *Renewable Energy* 182, 659–684. <https://doi.org/10.1016/j.renene.2021.10.027>
- Palmer-Wilson, K., Donald, J., Robertson, B., Lyseng, B., Keller, V., Fowler, M., Wade, C., Scholtysik, S., Wild, P., Rowe, A., 2019. Impact of land requirements on electricity system decarbonisation pathways. *Energy Policy* 129, 193–205. <https://doi.org/10.1016/j.enpol.2019.01.071>
- Pedersen, T.T., Victoria, M., Rasmussen, M.G., Andresen, G.B., 2021. Modeling all alternative solutions for highly renewable energy systems. *Energy* 234, 121294. <https://doi.org/10.1016/j.energy.2021.121294>
- Price, J., Mainzer, K., Petrović, S., Zeyringer, M., McKenna, R., 2020. The implications of landscape visual impact on future highly renewable power systems: a case study for Great Britain. *IEEE Transactions on Power Systems* 1–1. <https://doi.org/10.1109/TPWRS.2020.2992061>
- Price, J., Zeyringer, M., Konadu, D., Sobral Mourão, Z., Moore, A., Sharp, E., 2018. Low carbon electricity systems for Great Britain in 2050: An energy-land-water perspective. *Applied Energy* 228, 928–941. <https://doi.org/10.1016/j.apenergy.2018.06.127>
- Ribeiro, F., Ferreira, P., Araújo, M., 2013. Evaluating future scenarios for the power generation sector using a Multi-Criteria Decision Analysis (MCDA) tool: The Portuguese case. *Energy* 52, 126–136. <https://doi.org/10.1016/j.energy.2012.12.036>
- Ruiz, C.P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla, L.F., Kober, T., Badger, J., Volker, P., Elbersen, B., Brosowski, A., Thrän, D., Jonsson, K., 2019. ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials [WWW Document]. JRC Publications Repository. URL <https://publications.jrc.ec.europa.eu/repository/handle/JRC116900> (accessed 10.3.22).
- Sasse, J.-P., Trutnevte, E., 2020. Regional impacts of electricity system transition in Central Europe until 2035. *Nat Commun* 11, 4972. <https://doi.org/10.1038/s41467-020-18812-y>
- Scheller, F., Wiese, F., Weinand, J.M., Dominković, D.F., McKenna, R., 2021. An expert survey to assess the current status and future challenges of energy system analysis. *Smart Energy* 4, 100057. <https://doi.org/10.1016/j.segy.2021.100057>
- Schlachtberger, D.P., Brown, T., Schramm, S., Greiner, M., 2017. The benefits of cooperation in a highly renewable European electricity network. *Energy* 134, 469–481. <https://doi.org/10.1016/j.energy.2017.06.004>
- Simoës, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., Peteves, S., European Commission, Joint Research Centre, Institute for Energy and Transport, 2013. The JRC-EU-TIMES model: assessing the long-term role of the SET plan energy technologies. Publications Office, Luxembourg.
- Trainor, A.M., McDonald, R.I., Fargione, J., 2016. Energy Sprawl Is the Largest Driver of Land Use Change in United States. *PLOS ONE* 11, e0162269. <https://doi.org/10.1371/journal.pone.0162269>
- Tröndle, T., 2020. Supply-side options to reduce land requirements of fully renewable electricity in Europe. *PLOS ONE* 15, e0236958. <https://doi.org/10.1371/journal.pone.0236958>
- van Zalk, J., Behrens, P., 2018. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy* 123, 83–91. <https://doi.org/10.1016/j.enpol.2018.08.023>
- Weselek, A., Ehmann, A., Zikeli, S., Lewandowski, I., Schindele, S., Högy, P., 2019. Agrophotovoltaic systems: applications, challenges, and opportunities. A review. *Agron. Sustain. Dev.* 39, 35. <https://doi.org/10.1007/s13593-019-0581-3>
- Williams, J.H., Jones, R.A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., Torn, M.S., 2021. Carbon-Neutral Pathways for the United States. *AGU Advances* 2, e2020AV000284. <https://doi.org/10.1029/2020AV000284>
- Wolsink, M., 2018. Co-production in distributed generation: renewable energy and creating space for fitting infrastructure within landscapes. *Landscape Research* 43, 542–561. <https://doi.org/10.1080/01426397.2017.1358360>
- Wu, G.C., Leslie, E., Sawyerr, O., Cameron, D.R., Brand, E., Cohen, B., Allen, D., Ochoa, M., Olson, A., 2020. Low-impact land use pathways to deep decarbonization of electricity. *Environ. Res. Lett.* 15, 074044. <https://doi.org/10.1088/1748-9326/ab87d1>
- Wu, G.C., Torn, M.S., Williams, J.H., 2015. Incorporating Land-Use Requirements and Environmental Constraints in Low-Carbon Electricity Planning for California. *Environ. Sci. Technol.* 49, 2013–2021. <https://doi.org/10.1021/es502979v>