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Land-use and European power system transition to carbon neutrality: implications, challenges and optimal mix

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ABSTRACT

This study aims to assess the amount of land needed by the transition towards carbon neutrality of the European power system in 2050. We endogenized the land variable in eTIMES-EU, a long term planning model for the interconnected EU power system. We then assess the impact of explicit constraints on land use on the optimal trajectory and portfolio to meet carbon neutrality.

Keywords: Land-use, Power system, Europe, TIMES, Energy planning

1. INTRODUCTION

Reaching carbon neutrality in 2050 requires a transition of the electrical system with the phase out of fossils and an increase of the share of low-carbon technologies. Nonetheless, renewable energy sources (RES) tend to have a lower power density than fossils, which implies an increase in the land dedicated to electricity production. This dimension used to be overlooked but gained interest in the last decade. [1] proposes an estimate of the land occupied by the energy sector in the US, [2] studied the impact of a constraint on available land for the power system in the Canadian province of Alberta. Land-use is also assessed in life cycle analysis (LCA) studies applied to electricity production technologies.

A better consideration of land-use in prospective scenarios enables to quantify the land needed for the infrastructures but also to anticipate potential bottlenecks coming from a lack of both land and acceptance. Indeed, the development of new RES projects has an impact in terms of conflicts of use, artificialization and modification of landscapes. Therefore, considering land-use embraces both technical and social acceptance dimensions.

[1] and [2] focused on the US and Alberta but we did not find any study which explores the land-use implications of the future European power system while taking into account the electricity trading dimension and a collectively shared decarbonization goal. This study proposes to fill this gap by providing an original approach thanks to a detailed description of the power system at a country scale and a large and diverse technological environment. This paper aims to answer two questions: how much land the European electrical system needs to achieve carbon neutrality in 2050 and is there any possibilities to minimize this value? These questions are addressed by assessing conditions, in terms of implementations of technologies, required to meet the constraints while giving an estimate of the land that is necessary to reach carbon neutrality. We also explored the impact of the land constraint on relations between countries in terms of electricity exchanges and constraint transfers.

2. METHODOLOGY

2.1 Land-use metrics

A quantitative comparison of the land footprint for different technologies requires to have an explicit and objective definition of land-use. This notion can be defined as the land occupied by the electricity infrastructures. There are two widely used metrics: total land-use and direct land-use. We can mention also the visibility but it is not suitable to properly discuss questions of acceptance or conflicts of use. [3] are proposing in their literature review a definition of these metrics and compare values for some RES. Total land-use for a given project is the area used by the installation. For instance, this surface can be bounded by a fence or the land rented by the operator. The direct land-use refers to the land directly used by the project and is usually smaller than the total land-use. It includes power facilities, buildings and access roads but does not

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consider the space unused in between. Visibility zone is more subjective because it depends on both the terrain and the observer's perception.

The choice of one metric between these three belongs to the modeler and depends on the topic one wants to address. Artificialization, conflicts of use and acceptability are linked but none of these metrics are suitable to treat at the same time these three dimensions. Direct land-use should be preferred for artificialization but does not represent well the other questions. For example, direct land-use applied to onshore wind does not represent the land sprawl because the space between turbines is not considered.

We chose to consider the total land-use because we found this was the metric that best quantify the land needed for energy production from an energy planner perspective. We reused most of the total land-use values proposed by [2] which itself considered values from [1]. We checked that these values were not challenged recently. We found that the order of magnitude were confirmed for most of the technologies by [4] and by [3] for RES.

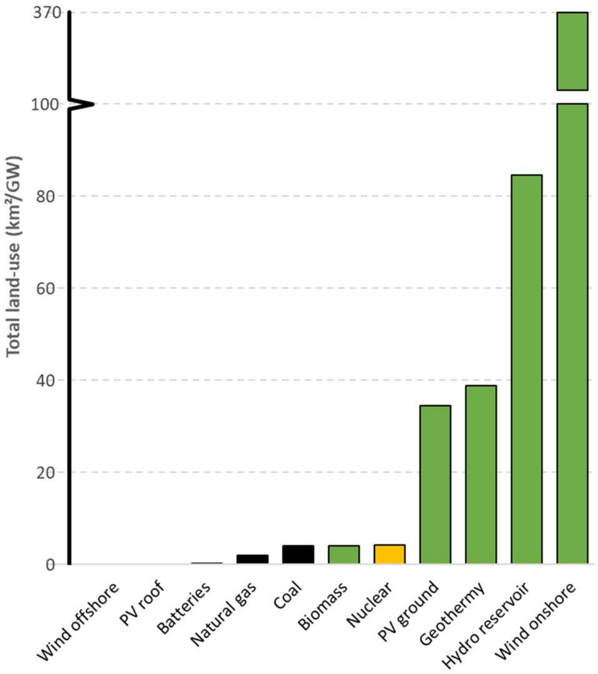

Fig. 1. Total land-use of common technologies

2.2 Adding a land constraint in the optimization model

eTIMES-EU is a bottom-up optimization model which represents the European power system[5]. It considers the European Union continental countries plus Iceland, Norway, Switzerland and UK. The goal of this model is to assess scenarios on the power system transition. It makes investment and production decisions in order to minimize the total actualized cost of the system. This type of model is well suited for this study because the full description of technologies and relations between them enable a precise observation of a constraint on land.

The period going from 2016 to 2050 is sliced in 5-year periods, then each year is represented by 64 periods that consider seasons. Each period is made of two typical days which represent the week or the week-end. These days are sliced in 8 periods of three hours to capture the variability in capacity factors. The calibration of the starting year and technology assumptions are based on data coming from the EU commission, the ENTSO-E and the IEA.

The proposed methodology is to enhance a power system model that does not consider land-use as a driver of technology selection. The most relevant way to assess the impact of the land constraint was to endogenize it. We set a maximum area requirement for all technologies of the whole power system. Therefore, the model makes its investment and operational decisions in a manner that the total land-use does not exceed the constraint.

We set the maximum available land in 2050, then the value for each period is deducted with a linear interpolation between 2016 and 2050. As we don't consider all other usages of land, we capped the maximum area dedicated to electricity production at 20% of the total country area to avoid solutions that could be illogical for small states.

2.3 Scenario description

All scenarios are designed to reach carbon neutrality in 2050 and share a common base of hypotheses on technology costs and rate of deployment. Concerning the use of interconnections, they are installed and used in a cost optimal way. While countries could potentially limit the amount of electricity imported for sovereignty reasons, we did not reflect such non-technical constraints on the amount traded and describe an idealized fully cooperative cost optimal approach. What we investigate here is the effect of different land-use endowments on the design of carbon neutral trajectories. We studied 4 scenarios for the land constraint, all other parameters being equal. The reference scenario gives a base for comparison and does not have a constraint on land. Scenario "x1" does not allow an increase in land between 2016 and 2050. Scenarios "x2" and "x3" respectively allow a doubling and a threefold increase of the land impact between 2016 and 2050.

3. RESULTS AND DISCUSSIONS

3.1 Impact of the constraint on the mix

The model manages to find solutions for each set of constraint on the total land requirement. We found a multiplication by 4 of the land between the starting year and 2050 in the reference scenario. The total area is a little bit less than 260 000 km². For comparison the surface of the UK is a little less than 250 000 km² while Germany has a surface of nearly 360 000 km².

In each scenario we logically see a decline of the fossils share and an increase of RES in the production mix as the system moves towards carbon neutrality. The constraint seems to have an impact on the pace of these trends. The more stringent the land constraint is, the smaller the share of RES is in 2050. The difference is filled with thermal power plants like nuclear, combined cycle gas turbine (CCGT) and biomass. For instance, in the scenario “x1”, the production from nuclear and CCGT almost doubles in comparison to the reference scenario.

In terms of land-use, we found that onshore wind, photovoltaic (PV) ground and hydraulic reservoirs are in order of magnitude the three main contributors. The limit on the land available has a great impact on the capacity installed of onshore wind. We see that the increase of onshore wind capacity roughly follows the increase of land available. In the reference scenario the onshore wind capacity is multiplied by 4. The scenario “x1” is the only case where the constraint is so strong that the model chooses to reduce the installed capacity by not replacing the old turbines in order to gain few square kilometers and increase the PV ground share.

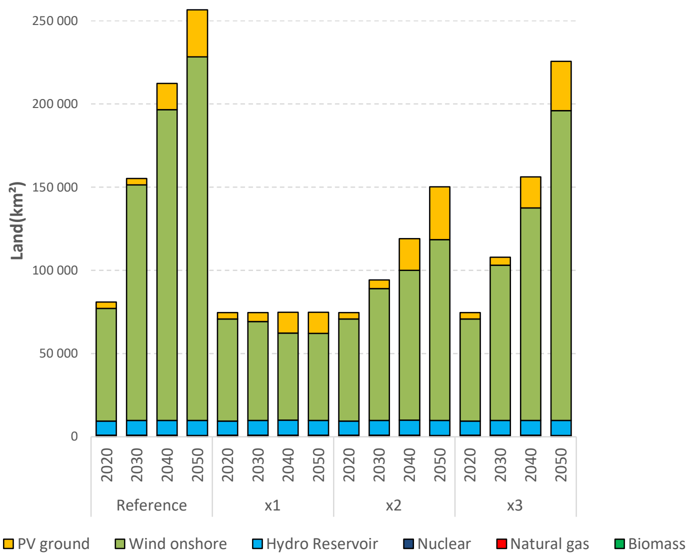

Fig. 2. Land-use of the four scenarios

If we look more closely at the selected technologies, we see that the system gradually shifts to low-carbon technologies that have a low total land-use. For RES, offshore wind and PV roof are interesting because their surface footprint is zero, however they are expensive and are kept for the scenario with a heavy constraint on the land. PV roof is used only in the scenario “x1”. The share of PV ground, hydraulic and bioenergies does not change significantly between scenarios, except for PV ground that can be replaced by PV roof.

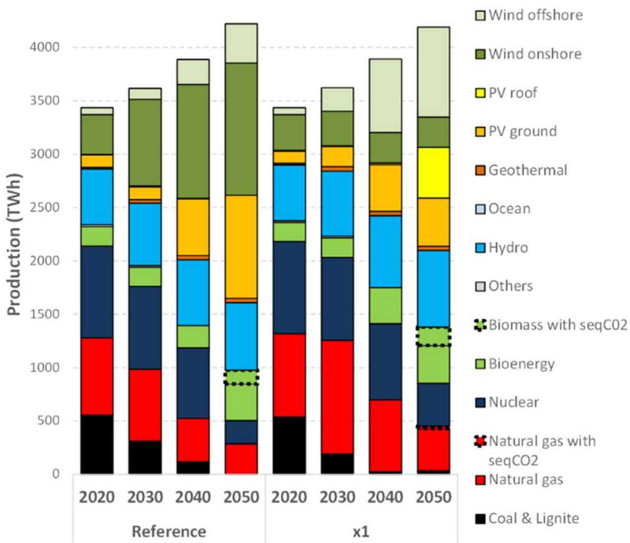

Fig. 3. Comparison of the production mix between the reference and the x1 scenarios

The system also relies on non-renewables technologies. While we observe a complete phase out of coal in 2030 for carbon neutrality, the share of CCGT is still significant and it increases with the constraint. Nuclear power follows the same trend, its share decreases over time, however production from nuclear increases with the constraint. Carbon Capture and Storage (CCS) plays a relevant role because it enables to compensate the emission of CCGT when it is associated with biomass. Its role increases with the constraint but we see a serious change in the scenario “x1”. The production of biomass with CCS doubles in comparison to the reference scenario and we have new capacities of

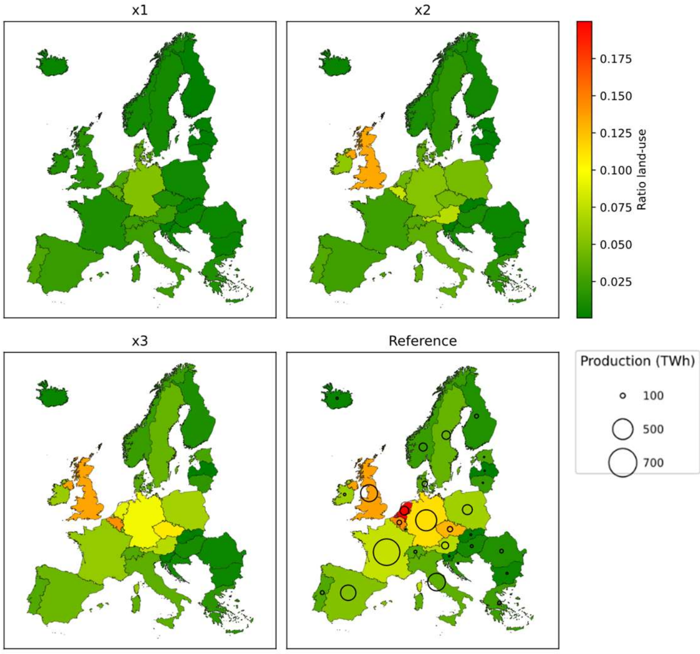

Fig. 4. Ratio of the land dedicated to electricity production divided by the total land of each country in 2050

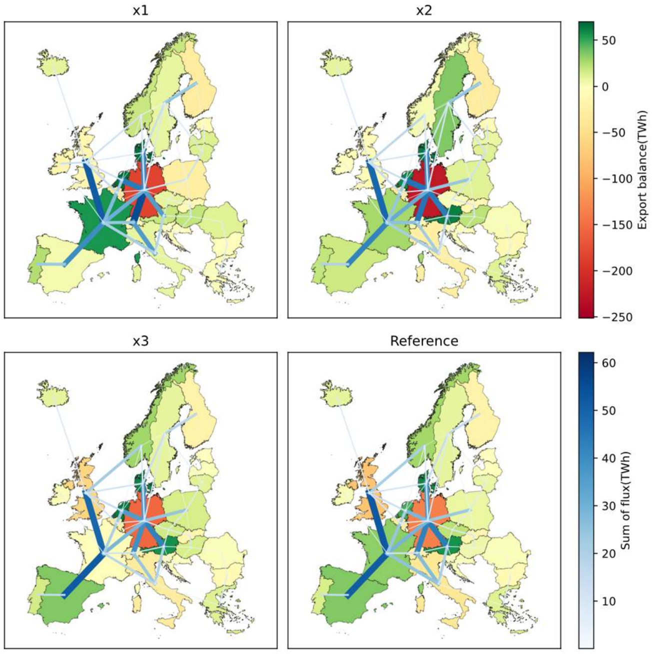

Fig. 5. Balance between exportation and importation and exchange flux between countries in 2050

CCGT and coal that are equipped with CCS in the scenario “x1”.

It is worth to note that the system tends to be more centralized when the constraint is strong. In other words, the most constrained scenarios have a smaller number of production facilities that are bigger, like thermal power plants or onshore windfarms.

3.2 Land constraint and electricity exchanges

eTIMES-EU has a detailed spatial resolution which gives the opportunity for an original approach on the study of the dynamic of exchanges between countries. We found that it is Western Europe countries which will bear most of the effort in terms of land. One has to keep in mind that these countries are also the biggest electricity consumers and their mix tend to have a higher share of onshore wind in comparison to the other area of Europe. Nonetheless, the distribution is different if we look on the ratio between the space dedicated to electricity over the total area of a country. Small countries like the Netherlands and Belgium can have to devote more than ten percent of their total area to produce electricity in the reference scenario (Fig 4). This effort can be loosened up with a higher land constraint.

It is worth to note that eTIMES-EU optimizes the use of the potential at a European scale. For instance, we tend to see that most of PV capacities are built in the Southern part of Europe and offshore wind turbines on the North-western part of Europe. Some countries will be specialized in one technology. For instance for all scenarios the share of offshore wind in Denmark’s production will be a little bit less than 80% in 2050 and this share is about 2/3 for the Netherlands in the scenario “x1”.

The study of imports/exports shows that the constraint does not have a significant impact on the volumes. Germany concentrates most of exchanges in the four scenarios (Fig 5). It heavily relies on its neighbors for its electricity consumption. In all scenarios, Germany imports around 200 TWh of electricity in 2050 (Fig 5), in comparison it has imported 40 TWh and exported 73 TWh in 2019. One way to see it is that in a fully cooperative mode, Germany prefers to delegate to other countries the electricity production due to the distribution of RES potential. Indeed, one has to keep in mind that the hypothesis on the cooperation is very permissive and represents an ideal situation where exchanges are very easy. The constraint has a slight impact overall except for Spain, Italy and the UK which tend to reduce the gap between imports and exports when the constraint increases.

3.3 Discussion and feasibility of the measures

Even though the model finds a solution for each scenario, there are other necessary conditions to achieve the implementation of electricity production mix. To integrate the land constraint, the model compares the costs of each technologies adjusted with its total land-use. By doing so, some technologies like PV roof which are normally more expensive become competitive.

Nevertheless, rates of deployment imposed by the model are sometimes extremely ambitious and may become bottlenecks to the achievement of objectives. For instance, the scenario “x1” requires to build roughly 40GW of CCS in Europe between 2030 and 2050, knowing that this technology is not very developed at an industrial scale today. Moreover, current infrastructures that have a 30-year lifetime will have to be replaced by 2050, which will eventually increase the amount of capacity to install in this period. The non-respect of these conditions will lead to both an overshoot of the land dedicated to electricity and the failure to reach carbon neutrality. In addition, one has to keep in mind that a stricter constraint on one technology requires to rely on other technologies that are more expensive and sometimes more controversial. For instance, giving up nuclear or CCS will likely rise the overall costs.

The volume of biomass-based technologies is important and countries might face challenges to provide these amounts of biomass only for electricity production. There are other energy sources like biofuels and usages in heating and cooling sectors which partly rely on biomass. Biomass feedstocks might be used in priority for usage that are not easily electrified.

It is worth to mention the model mocks a situation of an ideal cooperation between countries. eTIMES-EU computes an optimal solution for the entire zone while in reality each country tries to optimize its own costs. For instance, one may object that some countries will not be willing to install supplementary capacities on their land and coasts to export to their neighbors. Conversely, it is not certain that countries will accept to heavily rely on its neighbors for electricity production.

4. CONCLUSION

This study shows that there is an interest to consider the land-use in scenarios that model energy transition pathways. By incorporating land-use constraints in a detailed EU wide model we quantified the possible impacts of land use limitations on the optimal power mix in each country and the level of electricity trades. Restricted land availability affects the trade-off between renewable solutions by favoring PV instead of onshore wind. It also increases the share of thermal solution from 23% to 33%, which is enabled by a higher role of CCS, nuclear and CCGT. By evaluating feasible mix under various land related constraints, our analysis is a contribution to a better integration of externalities of power systems in the design of low carbon futures.

Yet there are others externalities like material criticity, or jobs that are also worthy of interest. They are left beyond the scope of this study and are avenues for future work.

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