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Managing variable renewables with biomass in the European electricity system: Emission targets and investment preferences

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ABSTRACT

Biomass can help reaching climate goals in many sectors. In electricity generation it can complement variable renewables or, if coupled with carbon capture and storage (CCS), also provide negative emissions. This paper adds to the existing literature by focusing on the cost-efficiency of balancing variable renewables with biomass and by providing an indication on acceptance of these technologies. A dynamic optimization model is used to analyse the role of biomass in the European electricity system pending different emission targets for 2050. The results are compared with survey data on investment preferences for biomass technologies, and wind and solar power. The formulation of the emission target greatly influences the cost-efficient use of biomass, with more concentrated use observed, if bioenergy with CCS is allowed. This indicates that a Europe-wide emission target could be more cost-efficient than separate national targets. Both governmental and nongovernmental actors tend to be negative towards investing in biomass technologies, although with greater variation if combined with CCS, indicating possible challenges for implementation. Their attitudes towards wind and solar power are much more positive in all countries, supporting the continuation of the existing trend of an increasing share of variable renewables in the European electricity system.

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1. Introduction

UN climate policy aims to keep human-induced global warming well below 2 °C, aspiring to limit it to 1.5 °C. A task that entails radical global transformation of energy conversion and use. The power sector is one of the main sources of emitted anthropogenic greenhouse gases (GHGs), accounting for about 30% of the total global emissions [1]. This and several affordable alternative technologies to current production make it one of the main targets for emissions reductions. Furthermore, to achieve the 1.5 °C target set by the Paris Agreement, global net-negative emissions will likely be needed in the second half of the century, to compensate for the emissions in the first part of the century or for sectors that are difficult to mitigate completely, such as agriculture [2]. In several studies these negative emissions are at least partially provided by BioEnergy with Carbon Capture and Storage (BECCS) in the electricity sector both on global [3] and regional level [4]. Thus, the mid-century goal for the European electricity system can be either

to reach zero or negative emissions if the global climate goals are to be met. In November 2018, the European Commission proposed a new direction for the European climate and energy policy towards achieving net-zero emissions by 2050. This objective would replace the previous one, to reduce emissions by 80–95%, and is underpinned by possibilities to use negative emission technologies to compensate for a residual from sectors that are hard to decarbonize. In proposing this objective, the Commission calls for exploring “how biomass can be supplied in a sustainable way while enhancing our natural sink or in combination with carbon capture and storage that both can lead to increased negative emissions” [5].

While the literature on BECCS is increasing rapidly, it is also marked by several knowledge gaps. First, the dynamic relationship between BECCS and intermittent renewables is understudied. In recent years the share of low-carbon electricity generation from wind and solar sources has expanded significantly, and it is expected to continue to do so in the coming decades owing to decreasing costs [6] and policy incentives [7] that are fuelled by climate and energy security concerns. However, large-scale expansion of wind and solar power creates a new set of challenges related to power quality and balance, flow, and stability [8].

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The energy supplied from wind and solar technologies is variable in both the short and long terms. High levels of wind and solar power complicate systems operation by changing the shape of the residual load and exacerbating the uncertainty of supply. On the one hand, if significant amounts of intermittent capacity are installed in the system there may be an over-supply of electricity on windy and sunny days, which would result in periods of low electricity prices. On the other hand, when wind and solar power production is too low to meet the demand, other power plants must be deployed. Their full-load hours will, however, be reduced by wind and solar infeed, while requirements in relation to flexibility will increase compared to current thermal generation. Thus, the variability of solar and wind generation can be expected to have a strong influence on investment decisions in the electricity system over the coming decades.

Second, the effect of demand for negative emissions on the system value of biomass is highly uncertain. Biomass could be used to complement wind and solar power and to manage variations and also provide negative emissions in combination with CCS. However, biomass is a limited resource and there are significant uncertainties related to how much of it can be provided to the energy system in a sustainable manner both in Europe [9] and globally [10]. Furthermore, it is uncertain as to where in the energy system the available biomass should be used [11]. Mitigation may be more difficult in sectors other than electricity generation, such as fuel production for aviation, or biomass may simply be needed as a feedstock for products, such as plastics. Therefore, the value of biomass in electricity system and how it is affected by the demand for negative emissions needs further examination.

Third, there is an undersupply of more finely granular mid-term regional scenarios compared to global long-term scenarios. In a recent review of the state of art in investigation of 100% renewable energy systems Hansen et al. [12] state that "Energy System Models (ESMs) with higher resolutions than Integrated Assessment Models (IAMs) could recalculate the technical feasibility of suggested pathways. Furthermore, IAMs do not account in sufficient detail for energy system flexibility effects, which is an area of expertise within ESMs. These measures might include BECCU (BioEnergy with Carbon Capture and Utilization) or DACCU (Direct Air Capture with Carbon Utilization), more described as Power-to-X. In addition, negative CO₂ emissions, based on BECCS and DACCS (storage instead of utilization) is a field to which ESMs can contribute with a deeper energy system understanding of these climate change mitigation options, which may be needed" (p. 476). A few attempts have been made in that direction. A previous study conducted by Johansson, Lehtveer and Göransson [13], which assessed the value of biomass for variation management in selected European regions with different wind and solar resources found that biomass has a high value up to approx. 5% of the electricity generation. However, this study did not consider variation management via trade among different regions nor had hydro power available. Trade with regions in possession of large amount of hydro power especially could potentially reduce the value of biomass in the electricity system. Yet, trade is limited by network capacity for which expansion must be weighed against different production allocations. Mesfun et al. [14] investigate the expansion of intermittent electricity in European system using a spatially explicit model but don't consider the option of negative emissions and its effect on the system. It is thus unclear what is the role of biomass in European electricity system while aiming for fulfilment of climate targets and where it would be most useful from the variations management perspective.

Finally, adoption of biomass in the electricity sector, and investments in BECCS, are also pending policy incentives [15]. Several national as well as EU-wide policy instruments are in force to deliver European energy security and climate mitigation objectives

[16]. These instruments are often designed to internalize costs of environmental degradation and reduce reliance on imported energy sources. As such, they alter the competitiveness of different technologies in the energy sector. Policy instruments for BECCS are almost entirely lacking, especially demand-pull policy instruments [17]. How the sector is regulated is pending political priorities that in turn is partly based on views among politicians and their constituencies. A broad set of actors, such as businesses, civil society organizations, academicians, and sub-national governments, influence policy development in the European countries and the EU. A further understanding of these views on bioenergy and BECCS is thus needed.

This paper contributes to filling the current knowledge gap by answering three research questions:

- What is the cost optimal allocation of biomass in the European electricity system considering the differences in variable renewable resources and cost of expanding transmission lines?
- How do different emission targets, including net-negative emission targets, influence the European electricity system?
- How do these results compare with investment preferences for bioenergy with and without carbon capture and storage (CCS) in selected countries, situated in view of preferences for investments in intermittent renewables?

2. Methodology

The analysis consists of two parts. In first part the need for biomass in electricity system is estimated via using an electricity system model. The second part analyses investment preferences for biomass, solar and wind technologies collected via a survey.

2.1. Model study

To evaluate the need for biomass in European electricity system the ELINEPOD modelling package is used. The Electricity Systems Investment Model (ELIN) originally developed by Odenberger and Unger [18], has previously been used to study the transformation of the European electricity system to meet the policy targets on CO₂ emissions. The ELIN model is a bottom up, long-term, dynamic optimization model that optimizes the investments in the power sector and has partial coverage of heat sector via combined heat and power plants (CHPs) and heat pumps. The composition of electricity system is used as input to the Electric Power Dispatch (EPOD) model [19]. This model minimizes the operating cost on an hourly basis for a selected period (usually 1 year), thus being able to investigate variations from wind and solar resources. The system models use a comprehensive database as input to represent the existing electricity supply infrastructure (power plants) [20] and hourly wind and solar resources.

The ELINEPOD modelling package covers 27 EU member states (EU-27), i.e. all but Croatia, as well as Norway and Switzerland. For this study, the island states of Cyprus and Malta are excluded from the geographical scope, i.e. in total, this study covers 27 countries.¹ In the models, Europe is subdivided into 50 regions based on key bottlenecks in the transmission grid. The models minimize the cost of investments and operation of electricity and transmission

¹ Austria (AT), Belgium (BE), Bulgaria (BG), Czech Republic (CZ), Denmark (DK), Estonia (EE), Finland (FI), France (FR), Germany (DE), Greece (GR), Hungary (HU), Ireland (IE), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg (LU), the Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Slovakia (SK), Slovenia (SI), Spain (ES), Sweden (SE), Switzerland (CH), and the United Kingdom (GB).

capacity while meeting the electricity demand in each region. The ELIN model includes a constrain on carbon dioxide emissions which becomes gradually stricter over time and is further described below. The future investment options include on- and off-shore wind power, solar power, heat pumps, and different type of thermal plants (e.g., condensing, with carbon capture, and combined heat and power), which can be run on coal, lignite, natural gas, oil, biomass or waste. Biomass is considered as a uniform resource including both purpose-grown biomass and forest and agricultural residues, but biogenic waste is considered separately. For the cases considered, investments in new hydro power is not allowed due to political and environmental concerns. Nuclear power can expand up to ten times its current capacity in countries that have nuclear power. In other countries the expansion is not allowed. CO₂ storage is only allowed offshore and the cost of transporting the CO₂ is included in the model. The expenditure related to capital investment, operation and maintenance, as well as the technical lifetimes for different technologies, are presented in Table A.1 in Appendix A. In addition, to take heed of the fact that capturing 100% of the CO₂ in flue gases is extremely expensive, with the marginal abatement cost increasing dramatically for the last 10% points, the capture efficiency of CCS technologies is set to 90%. The development of electricity demand is based on the Energy Roadmap [21] assuming a moderate increase in electricity demand on average 26% between 2015 and 2050. The transmission network between regions is modelled according to current state considering existing expansion plans and their specific capacities. New investments between the regions are chosen by the model based on cost-efficiency. The planning horizon for the model is 2030–2050. Every decade until year 2050 is modelled with 240 h (30 representative days with 3 h time resolution) according to the approach suggested by Nahm-macher et al. [22] to capture the variability in load, wind and solar power. The demand profiles for electricity are based on ENTSO-E data, whereas wind and solar profiles are based on MERRA meteorological data.

For the current study, new bio-based generation technologies have been added to the ELINPOD package. Biomass-fuelled steam power plants with CCS (i.e. BECCS), as well as combined cycle gas turbines with CCS fuelled with bio-based methane (biomethane CCS) are modelled as negative emission technologies. The capture rate, additional costs for the CCS part, and efficiency penalties are assumed to be equal to their corresponding fossil-fuelled versions.

Since the amount and the cost of biomass that can be supplied sustainably and would be available to electricity system is highly uncertain, as demonstrated by Kluts et al. [9], this study refrains from assuming the cost-supply curve of biomass for the model runs and instead allows for unlimited biomass use at varied prices to illustrate the cost-efficient use of biomass for the electricity system. Based on previous research [13], four different price levels for biomass are tested: 20, 30, 50 and 100 €/MWh_{th} (megawatt hours of heat). The biomass price can be compared to the bioenergy index PIX (Pellet Nordic Index), which has remained rather stable within the range of 26–31 €/MWh_{th} over the past years [16]. To estimate the effect of negative emissions on the cost optimal allocation of biomass the model is run with three different emission scenarios: reaching zero emissions by 2050, meaning that no emissions from any part of the electricity system are allowed; reaching net-zero emissions by 2050, meaning that emissions in part of the electricity system can be offset by negative emissions in another, and; reaching net-negative (–10%) emissions compared to 1990 levels by 2050 amounting to ca 150 Mton of CO₂ sequestered. Combining these scenarios with biomass costs, thus, generates twelve different cases for the model analysis.

2.2. International Negotiations Survey

For comparing the model results with investment preferences in the regions in which bioenergy is playing an important role in the different scenarios, data from the International Negotiations Survey (INS) is used. The INS has previously been used to explore, for example, views on leadership in climate negotiations [23], allocation of climate finance [24], effort sharing [25], and alternative forums for tackling climate change [26]. The INS was initiated in 2007. By 2019, over 12 000 questionnaires had been completed.

Survey data on investment preferences in the energy supply sector were obtained through questionnaires distributed at five negotiating sessions of the UN Framework Convention on Climate Change (UNFCCC): the 42nd Subsidiary Bodies meeting in Bonn, June 2015 ($n = 134$); the 21st Conference of the Parties (COP) in Paris, December 2015 ($n = 577$); COP22 in Marrakech, November 2016 ($n = 892$); COP23 in Bonn, November 2017 ($n = 944$); and COP24 in Katowice, December 2018 ($n = 996$). In total, 3543 responses have been collected of which 1115 are from UNFCCC delegates residing in the 27 European countries focused in this article. The data used in this article builds on and extends previously used data on investment preferences [27]. The extended number of responses allows for a more finely granulated analysis, moving from global regional analysis to look at European domestic levels (see Table A.2 in Appendix A).

The questionnaire was designed using a Likert-style response option format. Likert items measure attitudes toward options related to a stem statement, providing respondents with a bipolar weighting [28]. The respondents were asked to agree or disagree with the statement that, in their country of residence, investments in a long-term transition to low-carbon electricity generation should be directed towards a defined list of different technologies including, among others, bioenergy without CCS, BECCS, and solar and wind power. The response scale ranged from one (“disagree strongly”) to seven (“agree strongly”). This study follows the convention in the survey design literature of treating the middle option, “neither agree nor disagree,” as reflecting indifference or ambiguity rather than as indicating “don’t know” [29]. It should be noted that the so-called acquiescence bias – i.e. a tendency among respondents to agree rather than disagree with a Likert statement – likely generated a slightly more positive response pattern than if the attitudes had been measured using other means [30]. Although this has an important effect when measuring absolute preferences, when measuring relative preferences – as is done here – the positive bias can be expected to be equal for all Likert items and to have no effect on the results.

All valid responses from European delegates are subdivided according to the respondents’ country of residence. The INS data is non-normally distributed and ordinal, i.e. it is suitable for nonparametric statistical analysis. The nonparametric Kruskal-Wallis H test will be used in this analysis, a test that is appropriate when comparing differences among groups of more than two (i.e. country of residence). The test will be complemented with its equivalent for pairwise comparisons, i.e. the Mann-Whitney U test, for groups of two (i.e. actor type).

3. Results

The results description consists of two parts. In the first part, results from the electricity system model are presented. The second part analyses investment preferences for biomass, solar and wind technologies collected via the surveys.

3.1. Model results

The cost-efficient electricity generation at 2050 comprises mainly of onshore wind, solar PV, hydro and nuclear power for all studied cases (Fig. 1). The investment in bio-based technologies decrease as the price of biomass increases and are mainly replaced by offshore wind and batteries. When biomass fuelled technologies with CCS are available, some of the negative emissions are used (aside for meeting the emission requirement in -10% emissions case) to balance the emissions from use of gas power plants to provide flexibility to the system as well as other existing fossil fuel plants. At biomass price 100 €/MWh_{th} natural gas with CCS is deployed to minimize the need for biomass. In all cases, existing biomass fuelled steam power plants and combined heat and power plants (CHP) are used irrespective of the biomass price. Their operational hours, however, decrease with the increasing cost of biomass and with the availability of BECCS. The new investments in bio-based technologies are made in BECCS if available and in biogas plants if biomass is cheap (less than 50 €/MWh_{th}) or when BECCS is not available. The investments in biogas CCS plants will never become cost-efficient as their total capture rate per unit of biomass is lower than for BECCS plants. Investments in BECCS plants become concentrated into few countries (the Netherlands, Bulgaria, Romania), providing negative emissions also for other member states. The deployment of BECCS in Bulgaria and Romania is an

effect of the weather conditions as the region has low wind potential and more diffused solar radiation compared to other southern regions making solar PV less efficient. Therefore, these regions are best suited for investing in technologies that are most cost-efficient when operated continuously such as BECCS. The Netherlands on the other hand is located close to storage sites and has thus lower storage costs and is also relatively densely populated making it difficult to invest in large amounts of wind power while solar resources are relatively poor in the region. In the zero emission cases and low biomass price cases, the distribution of bio-based power plants is much more even in the system (Fig. 2).

Biomass provides only a small share of total electricity generated in all the scenarios. The highest share of bio-based electricity is reached when biomass is relatively cheap (20 €/MWh_{th}) and -10% emissions from 1990 levels is required (7% of electricity generation) or if zero emissions are required (5% of electricity generation). However, the amount is negligible if biomass is expensive (100 €/MWh_{th}) and emission target is set to zero or net-zero (0.5% of the electricity generation). The total amount of biomass used by the system varies between 0.2 and 2.9 EJs.

Varying the price of biomass influences the total amount of biomass in the system but regional distribution stays roughly the same for the zero emission cases. For the net-zero and negative emissions case the spread of biomass is increased with falling price. At 20 €/MWh_{th} price level all countries employ some biomass in

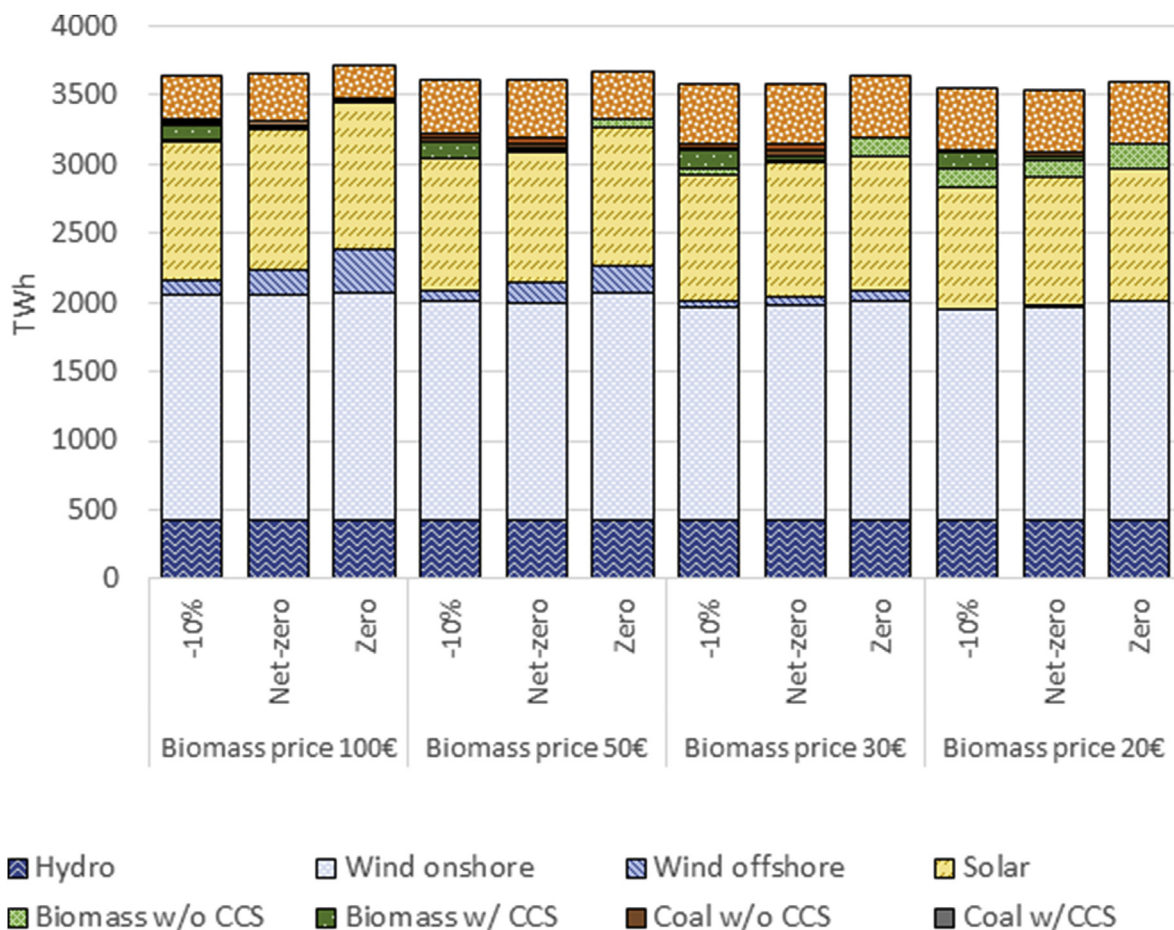


Fig. 1. Electricity generation in Europe by source in different cases at 2050.

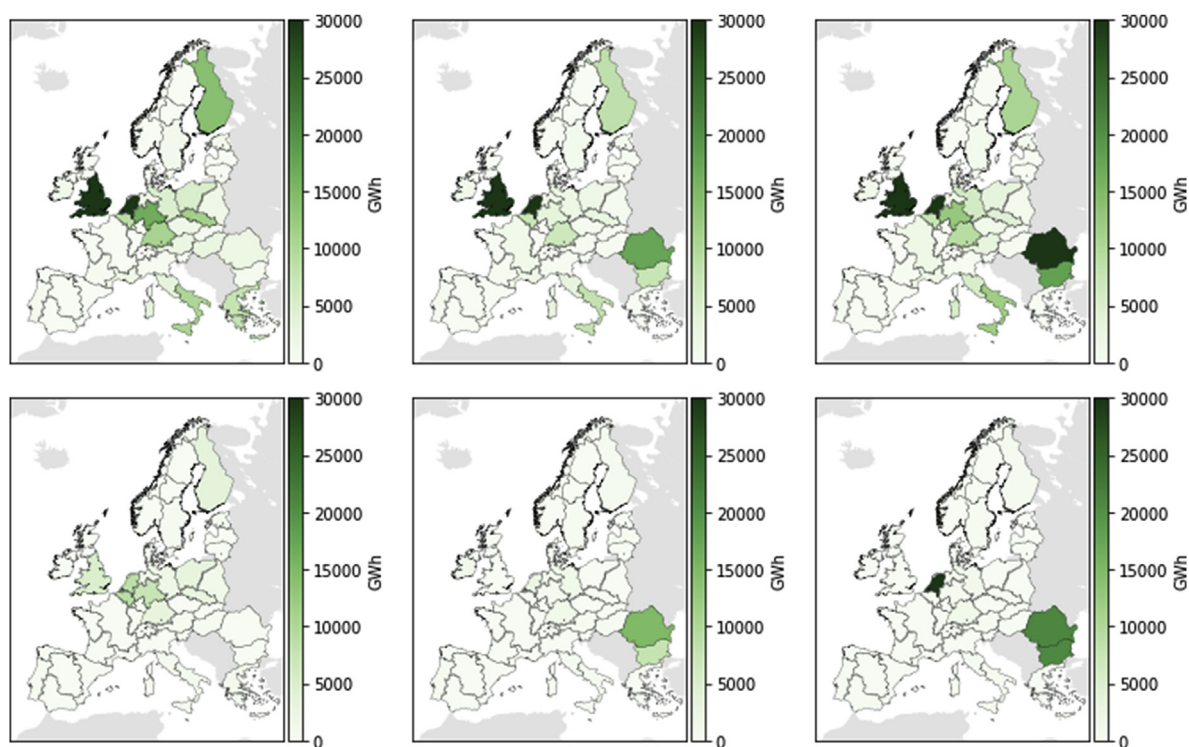


Fig. 2. Electricity generation from biomass at 2050 in different regions in GWh_{el} . From left to right: zero, net-zero and -10% emissions with biomass price $20 \text{ €/MWh}_{\text{th}}$ in the upper row and $50 \text{ €/MWh}_{\text{th}}$ in the lower row. The colour scale has been normalized between 0 and 30 000 GWh_{el} , but the generation in the Netherlands reaches up to 80 000 GWh_{el} in -10% cases. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

their electricity system. The exceptions are hydro power rich regions in Sweden and Norway. One can also note that even when biomass cost is very high ($100 \text{ €/MWh}_{\text{th}}$), it is still cost-efficient for the system to use some biomass in existing facilities or in BECCS plants. Contrary to common findings, competition among investments for biomass and nuclear power is not observed as the latter does not become profitable. Instead the lower price of biomass enables the extended use of existing nuclear power plants. As it is rather costly to start up and shut down nuclear power plants, having biomass available at low cost provides cheaper variation management options and thus enables to run nuclear power for longer consecutive periods compared to cases when variation management is more expensive and it is cost-efficient to shut down or postpone the start-up of nuclear power for longer periods. Instead, in the cases examined in this paper, biomass and offshore wind are competing for investments. The investments in batteries and heat pumps are also increased with higher biomass costs providing additional variation management options.

Requiring zero emissions from all parts of the electricity system also increases the need of transmission capacity compared to other cases (Fig. 3) as it excludes the use of natural gas compensated by negative emissions from BECCS for balancing purposes. Biomass that is used instead is mainly deployed in biogas plants with higher investment costs. Thus, it is cost-efficient to run biogas turbines for fewer hours and invest in transmission instead to manage variations. Similarly, lower biomass price makes the larger spread in biomass technologies cost-efficient and reduces the need for investments in transmission. A slight increase compared to net-zero target can also be observed in -10% cases when a larger part of capacity consists of BECCS plants that are operated more like base

load to provide negative emissions at lower price.

Increasing the cost of biomass has a relatively small effect on total system cost if zero or net-zero emissions are set as targets (Fig. 4). This is due to other variation management options available that can replace bio-based technologies although at somewhat higher cost. When negative emissions are required biomass must be used as there are no other negative emissions technologies available in this model. Therefore, the total cost will also increase significantly. Implementing direct air capture could be another option for providing negative emissions but the cost of it is highly uncertain and would also create a new energy demand that needs to be factored in.

3.2. Survey results

To analyse the attitudes towards biomass based technologies, the responses from countries that are allocated high share of BECCS by the model but also countries that have a high potential biomass resource according to de Wit and Faaij [31] are investigated. The attitudes for biomass technologies without CCS are leaning towards negative in most of the analysed countries with exception of Sweden and France. Combining bioenergy with CCS, i.e. BECCS, increases the agreement that bioenergy should be targeted for investments significantly in Great Britain and Italy but reduces it in for example Spain, Denmark and Sweden. Close to all respondents, regardless of country of residence, agree that investments should target solar and wind. Wind is favoured slightly higher than solar in most countries except in France, Italy and Spain (Fig. 5).

A Kruskal-Wallis test provides no evidence that country of origin influences respondents' views of whether to direct

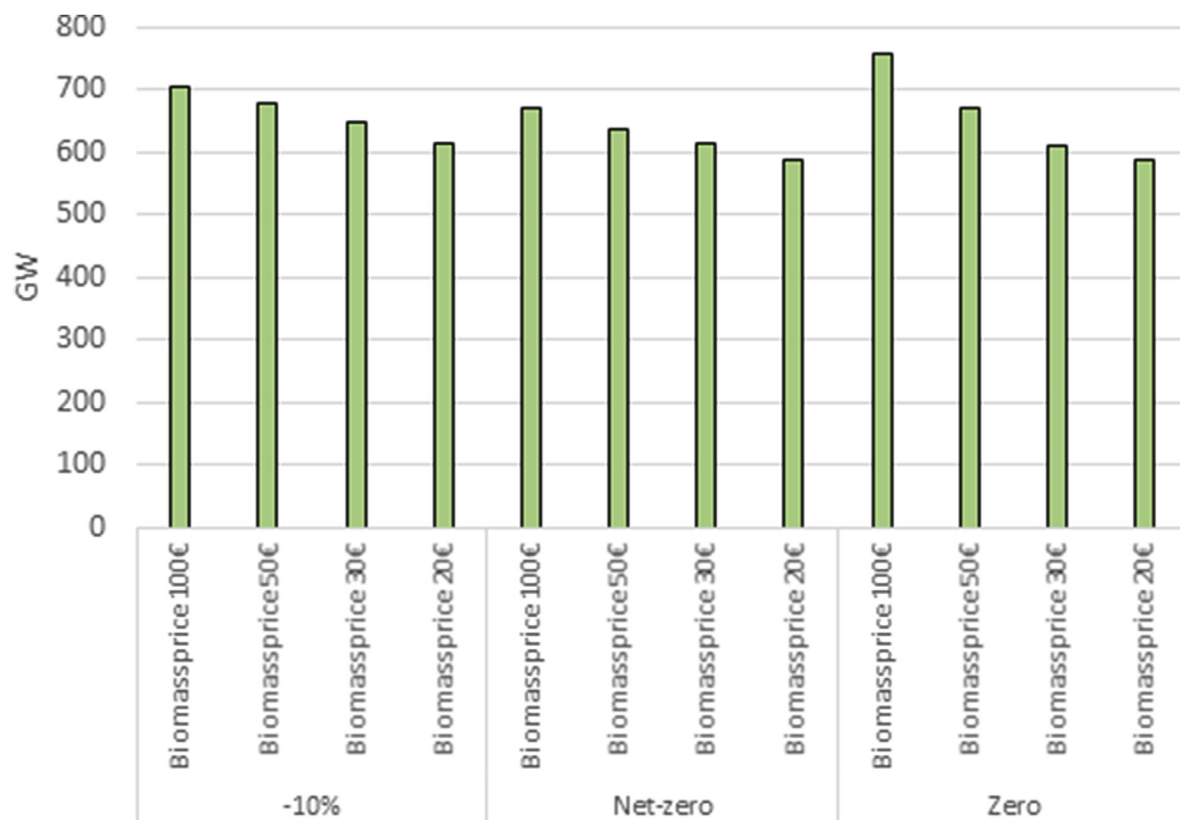


Fig. 3. New investments in grid capacity in different cases over the modelled period (2021–2050).

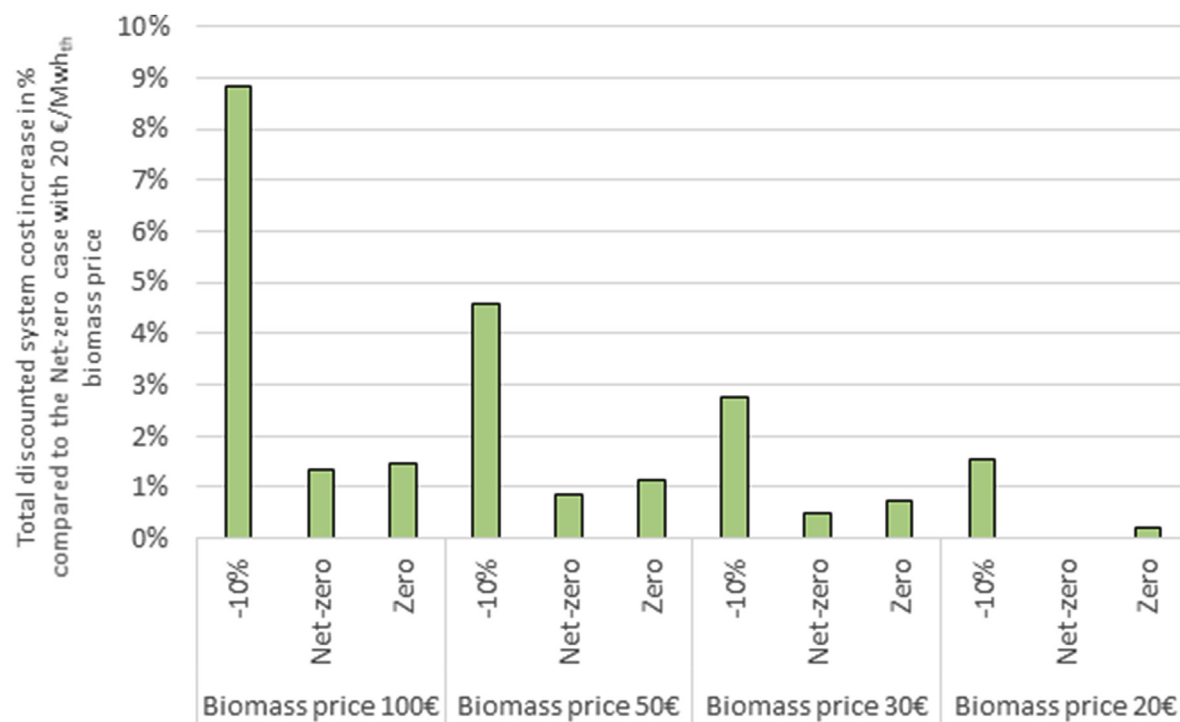


Fig. 4. Differences in total discounted system costs between cases. Note that the anomalies are relative to the reference case of a net-zero emissions target with a 20 €/MWh_{th} biomass price (i.e. the least costly scenario).

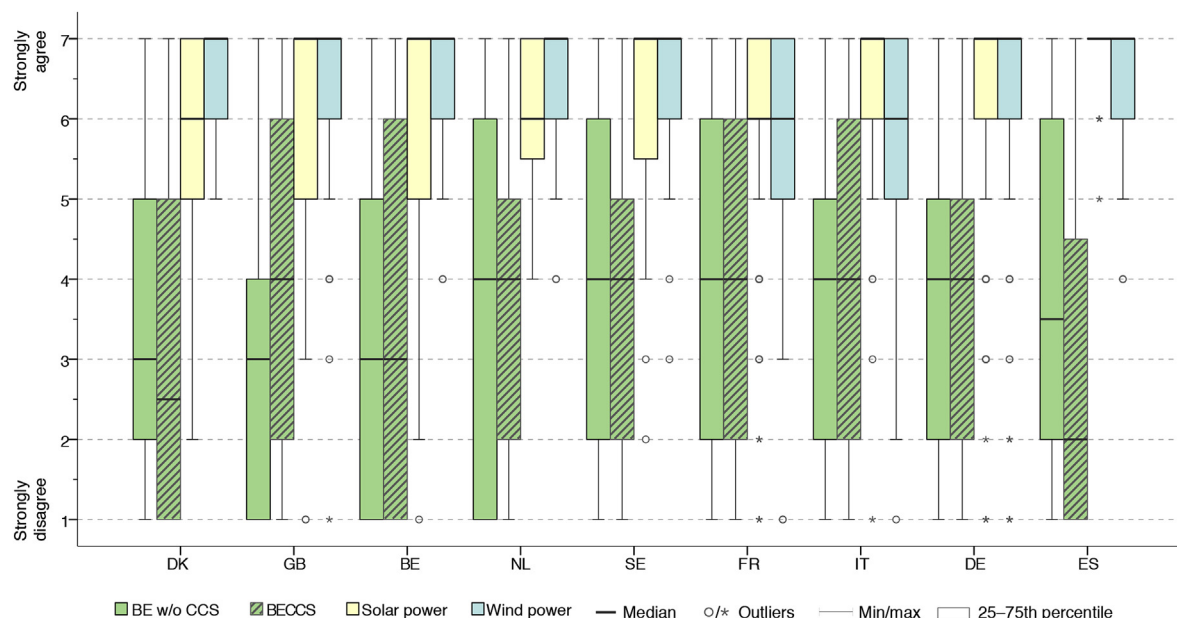


Fig. 5. Attitudes of UN climate change conference delegates, from the selected countries, towards directing investments in a long-term transition to low-carbon electricity generation to bioenergy without carbon capture and storage (BE w/o CCS), BECCS, solar power, and wind power. Note that the number of respondents residing in Bulgaria (BG) and Romania (RO) are limited and have therefore been excluded from the figure.

investments towards BECCS. For most countries, the respondents neither agree nor disagree that such should be done, with a slight tendency to lean towards disagreeing.

The same test provides evidence that country of origin influences respondents' views of whether to direct investments towards bioenergy without CCS ($p = .001$), solar power ($p = .026$), and wind power ($p = .008$). Pairwise comparisons ($p < .05$) reveal a statistically significant lower agreement that investments should target: 1) bioenergy without CCS among respondents residing in Great Britain compared to in Sweden, France, Italy and Germany, and also in Belgium compared to in France and Germany; 2) solar power among respondents residing in all countries except Italy compared to in Spain, but also in Denmark compared to in Germany and Italy, and; 3) wind power among respondents residing in Italy and France compared to in Great Britain, Denmark, and the Netherlands, and also in France compared to Belgium and Spain.

A Mann-Whitney U test also reveals that governmental actors are generally more in favour of both bioenergy without CCS ($p = .021$) and BECCS ($p = .000$) compared to nongovernmental (NGO) actors across all the selected countries represented in Fig. 5. Among the various NGOs, representatives of environmental NGOs are the most skeptical towards BECCS. The same test provides no evidence for differences in views among governmental and NGO actors in regard to solar and wind power.

4. Discussion

The future cost-efficient use of biomass in an European electricity system based on variable renewables is relatively small as also identified by Mesfun et al. [14]. Different biomass technologies are not equal when it comes to variation management as demonstrated also by Johansson, Lehtveer and Göransson [13]. BECCS technologies that are needed to create negative emissions are costly to use for variation management due to high capital costs

that requires running under close to full load to increase cost-efficiency. Thus, requiring negative emissions instead of just carbon neutrality affects the cost-optimal allocation of biomass use in European electricity system. But as shown here negative emissions can be cost-efficient in zero emission systems due to the enabling the use of existing fossil capacity. Contrary to the previous study [13] this study finds that the system value of biomass is limited even at low price levels (20 €/MWh_{th}), reaching at its max 5% of electricity generation if no negative emissions requirement is posed on the system. This is due to the added variation management possibilities via trade and hydro power use. However, some biomass is still cost-efficient for the system even at 100 €/MWh_{th} due to existing bio-based power plants as these investments are seen as a sunk cost and thus only operational costs need to be covered for cost-efficiency.

The results show that it is cost-efficient to have concentrated generation of negative emissions in a few countries. This has an advantage of using variable renewables where their resource potential is greatest and could also reduce the cost of infrastructure needed to transport and store CO₂. While this result holds from the techno-economic point of view, the real implementation would require rules for dividing negative emissions as current EU emission targets are set on country bases. Here benefits of co-operation must be weighed against the political feasibility – it is likely easier to implement targets on country level. Furthermore, some regions, especially the Netherlands would need to rely on biomass import from other regions, the cost of this extra transport is not considered in this study.

When applying these results to other regions it should be kept in mind that Europe is a rather unique region in the world with good conditions for wind power and relatively poor resources for solar power. As wind variation patterns tend to be rather long (several weeks) biomass as a dispatchable resource is well suited for managing them. A region where main source of variability is

solar power with variations that are mainly on daily scale not seasonal, is therefore expected to have lower benefit of employing biomass and higher benefit from battery technologies. However, requiring negative emissions from the electricity system would likely result in similar patterns as seen in this study.

When situating these model results in context of survey results, they align well in terms of an expanding share of intermittent renewables yet less so in terms of investing to make bioelectricity with or without CCS capable of delivering electricity when solar and wind infeed is low. Solar and wind power has undergone a tremendous expansion in since the beginning of the present century. This development has been spurred by costs reductions, which in combination with the fact that the technologies have been proven functional and commercial, provide a positive narrative for wind and solar that helps explain why the respondents favour them for investments. The positive narrative and trend is further underpinned by renewable energy policies in Europe, such as quota obligations and tradable green certificates and the EU's emissions trading system [32], as well as feed-in tariffs and the European Wind Initiative's €6 billion R&D funding [33], yet the European response pattern is mirrored also globally, combined with similarities in global expansion rates for intermittent renewables [34].

Respondents residing in countries with relatively larger potentials for and installed capacities of solar power, such as Spain and Italy, are also statistically significantly more positive towards solar than the other respondents. A similar pattern is visible for wind power, with respondents residing in Great Britain being among the most positive, mirrored in high potentials and one of the highest shares of European installed wind capacity. Respondents residing in France constitute an exception. Even if France has a high share of the European installed wind power capacity, French respondents are generally less positive than others towards directing investments into wind power. Although this can be explained by the French tendency to oppose wind power more generally [35], it should be noted that the French respondents' relatively lower support for wind power does not mean that they are against targeting wind power for investments. Almost 75% of the French respondents agree that investments should target wind power, i.e. much more than for bioenergy and BECCS (see Fig. 5).

This also holds true more generally. The statistically significant influence of country of residence on respondents' investment priorities for wind and solar power, although relevant and explainable, should be seen in context of the fact that an overwhelming majority of the respondents favour such investments in all of the countries surveyed.

Bioelectricity, on the other hand, constitutes only a small fraction of the European power generation capacity. The bioelectricity trend is also relatively stable whereas wind and solar power contributes substantial and rapidly increasing shares. This reality is likely mirrored in many respondents' acquaintance with power production options, which in turn may help explain the relatively higher response rate on the wind and solar survey items compare to bioenergy with or without CCS (see Table A.2). Lower acquaintance may also contribute to the lesser priority given to investments in bioenergy and BECCS, a response pattern that for BECCS is likely further explained by the technology's relative complexity and lower maturity, which introduces greater challenges and risks.

The results also show that governmental and NGO respondents are equally supportive of directing investments into wind and solar power, and that NGOs give statistically significant lower support for bioelectricity both with and without CCS. These differences are also detectable on global scale and have previously been explained by NGOs, especially environmental NGOs, traditional role as government watchdog, whereas the latter are responsible for delivering

on climate policy objectives [36]. The position of respondents from European environmental NGOs is therefore understandable, well attuned with the sometimes rather harsh critique of unsustainable biomass production as well as of fossil CCS' potential to prolong the fossil era.

In general, the survey's response pattern indicates that investment priorities may be path dependent. In other words, it seems easier for the respondents both to relate to existing deployment patterns and experiences as well as trends and expectations than to imagine larger reconfigurations of the European electricity production system. Such dynamics also find support in the transition literature that repeatedly report on routine reproduction of socio-technical regime [37] as well as active regime resistance to more radical change [38].

4.1. Availability of sustainable biomass in Europe

In this study has assumed unlimited biomass availability at different prices. This assumption was made due to high uncertainty in the amount of biomass that can be supplied sustainably and due to the competition for biomass among sectors. Allowing unlimited amount of biomass enables an analysis of the variability management and emission target related drivers of deploying biomass in electricity system separate from supply issues. As an alternative to domestic supply, biomass can be bought from either other regions inside EU or from countries outside of EU thus extending the available supply, however the extra costs such biomass transport would need are not included in this paper.

Several studies have tried to estimate the potential of biomass in Europe, see Kluts et al. [9]. However, many of these analysis include only some types of biomass (dedicated crops, agricultural and forest residues, woody biomass) or do not consider the sustainability aspect of biomass production. Based on the coverage comparison with three studies that have considered variety of biomass sources and/or sustainability aspects was chosen. De Wit and Faaij [31] estimate the techno-economic potential of biomass feedstock in EU to be around 10.5 EJ in 2030 with the largest potential being in France, Germany, Poland and Romania. Benelux countries have a very small potential. Elbersen et al. [39] consider also the sustainability implications and arrive at 2.1 EJ at 2030 including woody and grassy biomass. The main potential is found to be in France, Romania, Germany and Spain. Böttcher et al. [40] estimate the potential for large variety of biomass sources including also sustainability criteria. They find that about 8.6 EJ of biomass to be available at 2030 from agricultural and forest production with France, Germany, Poland and Sweden having the largest potentials.

The scenarios produced in this study indicate that biomass could be cost-effectively used in the electricity system in the Netherlands, Romania and Bulgaria if negative emissions are an option and mainly in Belgium, Germany, Finland, Italy, Poland and the UK depending on the biomass price. These regions lack hydro power as a balancing energy source and in case of Bulgaria and Romania also lack good wind resources. Biogas plants are often invested in central Europe in regions that have good transmission possibilities to several other regions and can thus maximize the balancing effect. However, it should be kept in mind that other consideration such as biomass availability may alter that allocation.

The identified potentials for European biomass by De Wit and Faaij [31], Elbersen et al. [39] and Böttcher et al. [40] correlate well with the survey results. Respondents residing in countries with greater potential, i.e. France, Germany, Spain and Sweden, generally favours bioenergy without CCS higher than in other countries, especially compared to respondents residing in Belgium and Great Britain. This strengthens the path-dependency hypothesis presented above, i.e. that the trends as well as familiarity of existing

and forecasted electricity production partially shape views on investment priorities. The uncertainties related to the capacity to supply sustainable biomass resources to meet future demands, a lively debated topic, may also explain the lower preferences for bioelectricity than intermittent renewables.

It is unclear how much sustainable biomass production in Europe can be increased and as seen above also estimates for 2030 vary greatly. Following the estimate of 8.6 EJ given by Böttcher et al. [40] up to 33% of biomass available could be used in electricity sector if the price is low and negative emissions from the electricity system are required. However, as little as 2% of the biomass could be cost-effectively used in electricity system if the price is high.

4.2. Model limitations

Although the ELINEPOD model framework allows for analysis of the cost-optimal allocation of investments, this model as well as all other models, provides a simplified representation of reality in several ways, which should be kept in mind while interpreting the results.

While ELINEPOD captures the need for high voltage direct current (HVDC) grid development it does not analyse the investments needed in local grid developments nor the congestion that may occur there. Therefore, the total investments needed in the grid are likely to be higher than presented here but since the amount of electricity from variable renewables, which is one of the main drivers of the grid expansion, is high in all studied cases, it is not expected to influence the findings.

Converting electricity to hydrogen at the time of high solar and wind infeed times, storing it and converting it back to electricity could be a possible replacement to bioenergy in variation management. This hypothesis was tested in the model but not found to have no significant effect. This is due to two reasons. First, the model used here looks at the development of European electricity system from current state to specified target at 2050 considering the existing capacities. However, due to this time horizon, the investment part of the model has a more limited representation of intra year variations (30 representative days). This captures well the daily variations of wind and solar power and daily storage needs; however, long-term storage, such as hydrogen storage, is somewhat less well represented in this type of models and may thus be undervalued. Studies that show large role of hydrogen to electricity often use green field models that only consider investments for one year but are then able to run the whole year with high time resolution thus capturing better the long-term storage effects but missing out on the transition aspects (e.g. Ref. [41]). These models may also use more limited geographical scope and thus undervalue the benefits of trade in the variation management (e.g. Ref. [42]).

Secondly, the efficiency of electricity-hydrogen-electricity conversion is rather low (ca 35–45%) and requires significant investments in electrolyzers, hydrogen storage and fuel cells. This means that using hydrogen for electricity production is most likely to be viable option when biomass price is high and there are no negative emissions in the system that can be used to compensate for the use of natural gas. Thus, addition of fuel cells to model can be expected to affect only few of the cases presented here. Furthermore, for reaching net-negative emissions from electricity system BECCS is required and would be, as also shown in the

results, the main driver of using biomass in the electricity system. Production of hydrogen from electricity becomes a more interesting option due to the need to decarbonize other sectors such as long-distance transport, or industrial processes such as steel making. If investments in hydrogen production and storage are mainly taken to satisfy these demands, using some of the hydrogen to produce electricity could also become a more attractive option. The current version of the model includes limited interaction with other sectors such as heat, transport and industry focusing on heat. Large scale electrification of these sectors can provide additional means to handle variability and thus reduce the need for biomass use as well as for combinations of BECCS and natural gas. On the other hand, increased electricity demand may also increase the need for biomass as some of the technologies providing variation management, such as hydro power, are difficult to expand. Furthermore, integration of new demands is likely to significantly change the demand profile. These effects require further investigation. However, the results of the current study help to interpret the scenarios presented in the literature thus far as well as to provide insights of the main driving forces for biomass adoption.

5. Conclusions

Biomass is an important resource that can help reaching climate targets in many sectors. If used in electricity generation, biomass can complement variable renewables as well as provide negative emissions if coupled with carbon capture and storage technologies. This paper investigates the need for biomass in the electricity system based on different emission requirements posed on the electricity system (zero, net-zero and negative) and compare the results with investment preferences for biomass technologies in selected countries.

If only the emissions in the electricity sector are regulated, BECCS in combination with natural gas plants is the cost-efficient complement to variable renewables. This should be kept in mind when designing policies. Also, how the emission target is formulated has a large impact on the cost-efficient use of biomass: when negative emissions are possible in the system, biomass use becomes very concentrated in countries with poor variable renewable resources indicating that EU-wide emission targets would be preferable to national targets. Requiring zero emissions from all parts of the electricity system, however, facilitates larger geographic spread of bio-based technologies to balance the variable renewables and also increases the cost-efficiency of transmission investments as bio-based technologies are more costly to manage variations with than gas turbines that can be used in combination with BECCS.

Survey respondents are generally of the view that investments for the long-term transitioning of European electricity systems, towards low-carbon configurations, should primarily target variable renewables, especially wind power in western and northern Europe and solar in southern Europe. Bio-based electricity production, with or without CCS, generally receives low priority for investments, without which at least BECCS would find it hard to prove commerciality without strong regulatory environments. While the view that biomass should be targeted for investments remain generally low among respondents from surveyed countries, adding a CCS component to biomass power technologies can make bioenergy both more and less accepted within a specific country.

Between countries, however, country of residence does not influence views on BECCS. BECCS constitutes an exception to the general rule that actor type does not influence investment priorities. NGOs are consistently more skeptical to investing in BECCS than representatives of governments, indicating that controversies around BECCS have been far from resolved.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Input and survey data

Table A.1

Technology investment, operational and maintenance costs (O&M) and life-times of some of the key technologies available in the ELIN model at 2050.

	Life-time [Years]	Investment cost at 2050 ^a [€/kW _{el}]	Fixed O&M cost ^a [€/kW _{el} /yr]	Variable O&M ^a cost [€/kWh _{el} /yr]
Coal				
Condense	40	2050	44.91	2.1
CHP/BP	40	2050	44.91	2.1
CCS	40	3018	105.46	2.1
CCS + bio-cofiring	40	3418	107.60	2.1
Natural gas				
GT	30	466	15.65	0.4
CCGT	30	932	17.33	0.8
CHP/BP	30	1210	32.05	0.7
CCS	30	1626	40.25	2.1
Nuclear				
Nuclear	60	4124	153.70	0.0
Bio & waste				
Condense	40	2049	54.23	2.1
GT	30	466	7.92	0.7
CCGT	30	932	12.96	0.8
Waste	40	6520	235.87	2.1
CHP/BP	40	3260	105.46	2.1
BECCS	40	3314	105.46	2.1
Intermittent renewables				
Wind (onshore)	30	1290	12.6	1.1
Wind (offshore)	30	2384	3.60	1.1
Solar PV	40	418	6.50	1.1
Small hydro	75	3633	65.94	1.0
Batteries				
Per kWh	25	79	—	—
Per kW	25	68	0.54	—

^a The values shown for investment costs and the fixed/variable O&M costs are based on the World Energy Outlook assumptions of the IEA from the 2018 edition [43] and have been extrapolated to Year 2050. Investment costs for intermittent renewable technologies are obtained from the Danish Energy Agency (<https://ens.dk/en/our-services/projections-and-models/technology-data>).

Table A.2

Number of cases (respondents from the selected countries) by variable (i.e. that investments in a long-term transition to low-carbon electricity generation should be directed towards specific technologies).

		Cases			
		Valid		Missing	
		N	%	N	%
BE w/o CCS	Belgium (BE)	60	80.0	15	20.0
	Bulgaria (BG)	3	100.0	0	0.0
	Germany (DE)	199	78.3	55	21.7
	Denmark (DK)	26	81.3	6	18.8
	Spain (ES)	18	64.3	10	35.7
	France (FR)	155	82.9	32	17.1
	Great Britain (GB)	96	78.0	27	22.0
	Italy (IT)	32	72.7	12	27.3
	The Netherlands (NL)	34	79.1	9	20.9
	Romania (RO)	6	100.0	0	0.0
	Sweden (SE)	49	89.1	6	10.9
	<i>Total</i>	678	79.8	172	20.2
BECCS	BE	59	78.7	16	21.3
	BG	3	100.0	0	0.0
	DE	199	78.3	55	21.7
	DK	26	81.3	6	18.8
	ES	20	71.4	8	28.6
	FR	146	78.1	41	21.9
	GB	100	81.3	23	18.7
	IT	33	75.0	11	25.0
	NL	35	81.4	8	18.6
	RO	4	66.7	2	33.3
	SE	51	92.7	4	7.3
	<i>Total</i>	676	79.5	174	20.5
Solar	BE	69	92.0	6	8.0
	BG	3	100.0	0	0.0
	DE	236	92.9	18	7.1
	DK	30	93.8	2	6.3
	ES	26	92.9	2	7.1
	FR	173	92.5	14	7.5
	GB	113	91.9	10	8.1
	IT	38	86.4	6	13.6
	NL	39	90.7	4	9.3
	RO	6	100.0	0	0.0
	SE	52	94.5	3	5.5
	<i>Total</i>	785	92.4	65	7.6
Wind	BE	68	90.7	7	9.3
	BG	3	100.0	0	0.0
	DE	235	92.5	19	7.5
	DK	30	93.8	2	6.3
	ES	26	92.9	2	7.1
	FR	170	90.9	17	9.1
	GB	113	91.9	10	8.1
	IT	37	84.1	7	15.9
	NL	38	88.4	5	11.6
	RO	5	83.3	1	16.7
	SE	54	98.2	1	1.8
	<i>Total</i>	779	91.6	71	8.4

Author contributions

Mariliis Lehtveer: Conceptualization, Methodology - modelling, Formal analysis -modelling, Writing - original draft Mathias Fridahl: Investigation - surveys, Formal analysis -surveys, Writing - original draft.

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