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DOI
10.1016/j.energy.2024.133216

Publication date
2024

Document Version
Final published version

Published in
Energy

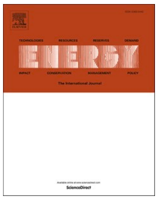
Citation (APA)
Béres, R., van der Wel, A., Fattahi, A., & van den Broek, M. (2024). The impact of national policies on Europe-wide power system transition towards net-zero 2050. *Energy*, *310*, Article 133216. https://doi.org/10.1016/j.energy.2024.133216

Energy 310 (2024) 133216

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



The impact of national policies on Europe-wide power system transition towards net-zero 2050

Rebeka Béres [a,*,1], Auke van der Wel [a,1], Amir Fattahi [b], Machteld van den Broek [c]

[a] University of Groningen, Energy and Sustainability Research Institute Groningen, 9747 AG, Groningen, the Netherlands
[b] TNO EMT, Motion Building Radarweg 60, 1043 NT, Amsterdam, the Netherlands
[c] Delft University of Technology, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628 BX, Delft, the Netherlands

ARTICLE INFO

Handling editor: X Zhang

Keywords:
EU policy
Power sector
Carbon-neutrality
Nuclear
Biomass
Power system modeling
policy analysis
energy system modelling
Europe
capacity expansion

ABSTRACT

This research aims to investigate the potential impact of national policies on the attainment of Europe's goal of achieving net-zero greenhouse gas emissions by 2050. Specifically, it analyses the effects of policies on the power sector, by evaluating capacity expansion portfolios, import reliance, and costs by 2050. A linear programming model, the IESA-EUPS, is utilized to optimize the expansion and operation of the power system, considering 28 nodes and hourly temporal resolution. The study includes five scenarios from 2020 to 2050, with varying levels of biomass and nuclear penetration based on existing member state policies. Results show that by 2050, changes mainly occur in the interplay between firm capacities and cross-border transmission levels. Limiting biomass can significantly increase nuclear energy generation, while enforcing all policies leads to a 40 % rise in cross-border transmission by 2050, due to imbalances between countries. Some member states, such as Spain and Finland, are less affected, whereas others are heavily reliant on firm nuclear capacities. Western European countries with strict biomass and nuclear restrictions may see a boost in nuclear installations in countries allowing it. Member states without both nuclear and biomass may rely more on variable renewables, resulting in surplus electricity and increased LCOE.

1. Introduction

To meet the temperature targets set by the Paris Agreement [1], the European Commission launched the Green Deal for Europe in 2019 [2]. This initiative aims for a 55 % reduction in greenhouse gas emissions by 2030 and carbon neutrality by 2050; these goals became legally binding in 2021 [2]. Given that the power sector contributed 22 % of anthropogenic greenhouse gas emissions in the EU in 2020 [3,4], the sector's transition is pivotal in achieving these targets.

While the EU member states (MS) are crafting individual energy and climate policies [5], aligning these policies with cost-optimal system designs from techno-economic studies is a challenge [6–9]. This disparity is particularly evident concerning the role of biomass and nuclear power, where political sensitivities, risk perceptions of nuclear incidents, waste management concerns, and environmental implications of biomass use and land competition play substantial roles [6,10]. For instance, Germany's policies limit biomass utilization and phase out nuclear power by 2023 [11], contrary to studies like [7–9], which highlight the importance of bioelectricity and nuclear generation, applying it large scale in Germany, 2050.

Despite some studies addressing policy measures [12–15], their focus remains on assessing broader EU-wide technology/resource restrictions, overlooking the impact of MS specific policies on the European power system's net-zero transition. The strict positions of certain MSs, such as restricting nuclear energy use or limiting biomass utilization, may result in significantly different implications for the entire European power system compared to outcomes based solely on technoeconomic analyses. This research gap is acknowledged by Sánchez Diéguez et al. [16], who calls for a comprehensive analysis of national policies.

This study aims to fill this gap by conducting an in-depth analysis of EU-level power system decarbonisation policies on MS level. By collecting and analysing current policy measures and combining it with a high temporal resolution and a brownfield modeling approach, the research provides insights into the long-term effects of national policies on the transition. Bistline [17] underscores the significance of high

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* Corresponding author.
E-mail address: r.j.beres@rug.nl (R. Béres).
[1] Shared first authorship with equal contributions.

https://doi.org/10.1016/j.energy.2024.133216
Received 9 May 2024; Received in revised form 14 August 2024; Accepted 17 September 2024

temporal resolution in policy analysis, especially given the increasing use of variable renewable electricity. Integrating these aspects can shed light on detailed implications of power system decarbonisation.

While there are studies exploring emission reduction feasibility through optimization models (Appendix L), none specifically model the national-level power sector transition using hourly resolution and a brownfield approach across the entire transitional period, accounting for climate policy constraints. Zappa et al. [9] propose viable 100 % renewable power systems by 2050, but without considering policy and existing capacity constraints. Similarly, van Zuijlen et al. [8] identify nuclear power and CCS as crucial, yet exclude policy and existing fleet constraints. Krakowski et al. [18] and Pleβmann & Blechinger [19] utilize brownfield methodologies, but with limitations in temporal resolution, and national scope. Although Schlachtberger et al. [15], explores the impact of some policy constraints on solar and wind potentials in the EU power sector in hourly resolution, the study excludes nuclear and biomass. Özdemir et al. [14] assess different renewable support schemes in the EU for 2030, using 50 representative days per year instead of chronological hourly data. However, the study employs uniform EU-level schemes across member states, neglecting coutry preferences. Furthermore, it solely focuses on 2030 without considering implications for a highly strict carbon-neutral setup in 2050.

In this context, Sánchez Diéguez et al. [16] adopt a brownfield approach with high temporal resolution to optimize capacity planning and multi-year dispatch for the Netherland's energy system. However, the EU-wide applicability of their findings remains uncertain due to the limited geographical scope.

By examining the influence of national policies on EU-wide net-zero transition by 2050, this study employs a novel capacity expansion model with cost-optimized policy scenarios spanning 2020–2050 with 7 milestone years on hourly resolution. While focusing on EU member states, it also considers Switzerland, the UK, and Norway for enhanced realism due to strong EU connections [20]. The term "Europe" refers to this geographic coverage herein.

2. Method

The main components of the method consist of a data inventory, analyses of country level policies on nuclear power, biomass and national net-zero targets to construct policy scenarios, and application of an energy system framework, IESA [16]. Model runs were performed with the objective of minimizing total costs while at the same time taking hourly dispatch into account for all modelled periods and included countries. Results then were analysed with regards to total and levelized system costs[2] generation portfolios and system adequacy. All cost assumptions are expressed in €$_{2019}$[3].

2.1. The model

We developed the IESA-EUPS model based on the IESA framework that is applied to assess cost-effective national-level power sector capacity expansion plannings for the countries in the Europe scope. IESA is an open-source linear programming model generator, with a brownfield approach, integrating policy and techno-economic constraints to minimize system costs throughout 2020–2050 [16]. Operating on 5-year intervals, it employs hourly technology dispatch for demand-supply equilibrium, resulting in 7 milestone years multiplied by 8760 time slices. The objective is to minimize net present value of total energy system costs including investments, variable and fixed operation and maintenance (O&M) costs, and costs for retrofitting and decommissioning [16]. This study focuses solely on the power sector, excluding other energy system components. While IESA-OPT already represents the European power sector, this study includes all European countries listed in Table 7 (see Appendix A) individually, updating their model inputs accordingly. Sánchez Diéguez et al. [16] provides a detailed formulation.

2.2. Input data and assumptions

2.2.1. Electricity demand

Modelled electricity demand (see Table 7, Appendix A) is integrated as yearly node-specific demand across periods. Total demand of Europe escalates from 3284 TWh (2020) to 4391 TWh (2050). Data originates from TYNDP [20], foreseeing long-term supply-demand trends through distinct scenarios. Our study employs the Global Ambition scenario's demand data, targeting 55 % reduction in 2030 and climate neutrality by 2050. This scenario anticipates increased demand due to electrification in transport, heat, and hydrogen production within a globally centralized transition approach. Demand growth estimation includes efficiency improvements in electric processes. Total yearly demand is combined with hourly electricity profiles to calculate demand per hour for each node. The electricity profiles, which show the percentage of yearly demand for each hour, are calculated based on actual hourly demand data per country in2019[3] from ENTSOe Transparency Platform [21].

2.2.2. Techno-economic assumptions of generators

The costs and CO_2 emissions associated with resources used for the thermoelectric generators in the model can be seen in Table 1. A maximum availability factor of 95 % was assumed.

Table 2 shows the techno-economic assumptions in 2030, 2040 and 2050 for all types of generators included in the model. To keep cost assumptions consistent across technologies, all investment, fixed and variable O&M costs are based on the technology assumptions used in the EU reference scenario 2020 [22]. A weighted average cost of capital of 8 % is used to annualize costs and include interest during construction. The discount rate used in the model is also 8 %. For some technologies, the costs are different for every modelled period due to assumed further technology development. Table 8 (Appendix B) shows the cost assumptions for 2020. For technoeconomic assumptions in 2025, 2035 and 2045, data from Table 2 is interpolated linearly.

Apart from building new capacity, the option was added to retrofit existing coal, gas, or biomass power plants into power plants that use the same fuel but include carbon capture and storage (CCS). Cost associated with this type of retrofit are equal to 60 % of the cost associated with a

Table 1
Fuel cost and CO2 emissions factors.

Technology	Emission factor (Mt CO_2/PJ)[a]	Fuel cost (M€/PJ)[b]			
		2020	**2030**	**2040**	**2050**
Waste[c,d]	0.1063	0.70	0.63	0.58	0.53
Biomass[c,e]	0.1096	5.44	5.19	5.06	4.82
Coal[f]	0.0983	2.09	3.05	3.38	3.6
Oil[f]	0.0733	6.93	8.91	9.85	10.3
Gas[f]	0.0566	6.73	8.1	8.96	9.27
Nuclear[f]	–	0.81	0.81	0.81	0.81

[a] *Based on the IESA-OPT-Netherlands model* [16].

[b] All costs are presented in €$_{2019}$.

[c] *Average costs across countries. In the model costs differ* per *country based on* [25].

[d] *Although the full emission factor is shown, waste is assumed to be 53 % CO_2-neutral based on* [16].

[e] *Biomass is assumed to be 100 % CO_2-neutral based on* [16]. *As such, the emission factor shown here is only used for calculating possible negative emissions when biomass capacity is combined with CCS (at a capture rate of 90 %).*

[f] *Based on the EU reference scenario 2020* [22].

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[2] Levelized costs are total system costs divided by final electricity consumption.

[3] 2019 was chosen because it is the most recent year that was not influenced by the Covid-19 pandemic.

Table 2
Technoeconomic assumptions of generators.

Technology	CAPEX (€/kW)[a,b]			Fixed O&M (€/kW-y)[b,c]			Variable O&M (€/MWh)[b,c]			Efficiency[f] (%)$_{2050}$	Life[d] (year)
	2030	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2050**	**-**
Coal old	2585	2585	2585	35	35	35	2.8	2.8	2.8	41 %	40
Coal new	2605	2595	2585	45	44	42	5.0	4.8	4.6	48 %	40
Coal CCS[g]	4910	4775	4630	65	62	61	18.2	14.3	11.7	40 %	40
CCGT old	675	670	670	20	20	20	2.3	2.3	2.3	58 %	30
CCGT	730	725	720	21	20	19	1.9	1.8	1.7	63 %	30
OCGT	415	415	410	12	12	12	2.1	2.1	2.1	38 %	25
CCGT CCS[g]	2210	2040	2040	38	35	34	7.8	6.6	5.5	53 %	30
Oil[d]	700	700	700	10	10	10	2.6	2.6	2.6	33 %	20
Waste	2035	2025	2015	44	42	39	0.8	0.8	0.8	34 %	20
Biomass	2265	2140	2140	40	39	38	3.6	3.6	3.6	38 %	30
Nuclear	6250	6100	5950	115	108	105	7.4	7.6	7.8	38 %	60
Hydro RoR	1670	1660	1650	8	8	8	0.0	0.0	0.0	–	50
Hydro Reservoirs	2100	2100	2100	26	26	26	0.3	0.3	0.3	–	50
Tide, wave, ocean	2665	2320	1975	33	28	24	0.1	0.1	0.1	–	80
Onshore wind	1080	1025	1000	14	12	12	0.2	0.2	0.2	–	30
Offshore wind[i]	2025	1965	1905	31	29	28	0.4	0.4	0.4	–	30
Solar[j]	500	485	470	14	10	9	0.0	0.0	0.0	–	30
Solar CSP	3060	2930	2800	99	87	77	0.1	0.1	0.1	–	25
Biomass + CCS[h,g]	5000	4495	4360	69	63	61	21.2	18.1	15.2	30 %	30

CCGT: combined cycle gas turbine, OCGT: open cycle gas turbine, CCS: carbon capture and storage, RoR: run of river, all costs are presented in €$_{2019}$.

[a] The CAPEX includes the overnight investment costs from the EU reference scenario 2020 [22]and interest during construction based on build time [9] and a discount rate of 8 %.

[b] All costs are presented in €$_{2019}$.

[c] Based on the EU reference scenario 2020 [22].

[d] Based on [8].

[e] Oil generator cost data is taken from the IESA-OPT-Netherlands model [16].

[f] As the model only allows for one value for the resource-use efficiency across all modelled periods, the average efficiency from 2020, 2030, 2040 and 2050 is calculated based on the EU reference scenario 2020 [22].

[g] A capture ratio of 90 % is assumed for CCS plants based on [8]. CO_2 transport and storage costs (levelized costs per tonne CO_2 captured) are included in VOM costs of CCS technologies. Based on [80,81], for 2020 the cost is 60 €/t_{co2}, which reduces to 32 €/t_{co2} in 2050 (with linear reduction assumed between). It is assumed that the majority of transport and storage happens onshore.

[h] BECCS is not included in the base scenarios, due to uncertainty in future availability and in actual carbon removal potential [6]. Only used for 'BECCS inclusion' sensitivity analysis.

[I] Fixed foundation.

[j] Solar includes utility scale and rooftop.

newly build CCS plant of the same fuel type [9]. Retrofitting capacity from coal fired into biomass fired is also added as an option. Cost associated with this type of retrofit are set to 700 €/kW [9].

For all thermoelectric generators the startup time and costs were neglected; however, simplified ramp rates are considered with 10 % of total capacity of nuclear, and 50 % for bioenergy and coal. A maximum availability factor of 95 % was assumed. Although using biomass and waste as a resource causes CO_2 emissions, it is assumed that biomass is 100 % CO_2-neutral and waste is 53 % CO_2-neutral based on the IESA-OPT-Netherlands model [16]. It is assumed that there is no cost associated with emitting CO_2 as emissions are already forced out of the solution by the CO_2 emissions constraint.

2.2.3. *Existing capacity and planned decommissioning*

Fig. 1 displays current capacities and anticipated decommissioning in each modelled period, using the JRC-IDEES dataset [23]. We fixed the database capacities from 2015, in 2020 (the start date of the modeling period). To correct this, decommissioning data excludes capacities post-2015, with end-of-life before 2050. The resulting 2015 baseline discrepancy is mitigated by introducing additional capacity after 2020.

The JRC-IDEES dataset includes 30 generator types per country. Fossil generator aggregation is detailed in Table 10. Biomass and waste capacity grouping is separated based on ENTSOE capacity ratios [21], yielding separated capacities by country (Appendix E).

2.2.4. *Storage*

The storage options included in the model are pumped hydro storage, large scale electrochemical batteries, and underground hydrogen storage (see Table 3). Hydrogen storage cost includes the cost of salt cavern development, an electrolyser, and a hydrogen turbine based on van Zuijlen et al. [8]. The shifting range shows the period over which the model is allowed to shift generation to meet demand later by using a storage technology. The storage capacity for the battery is assumed to be 12 h [16] and the capacity of the H_2-battery is assumed to be 90 days [8]. The pumped hydro storage capacity differs per country, detailed breakdown of data and methodology is Appendix F: Resource potentials.

2.2.5. *Renewable energy potentials*

To prevent the model from using more resources than available in a country, an upper limit was added, based on resource availability by Ref. [24,25] (See detailed country level resource availability in Appendix H). Biomass[4] and waste potentials were taken from the ENSPRESO database [25]; solar and wind availability were taken from Hu et al. [24]. Solar, onshore wind and offshore wind hourly capacity factor portfolios are taken from Hersbach et al. [26]. The 0.25° × 0.25° spatial resolution from ERA5 [26] is aggregated to one single country level profile, with offshore and onshore wind only including grid cells

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[4] One could argue that biomass can also be imported from outside Europe or exchanged between countries within Europe. However, it was assumed that in net-zero 2050, biomass resources are needed locally and thus both options are excluded.

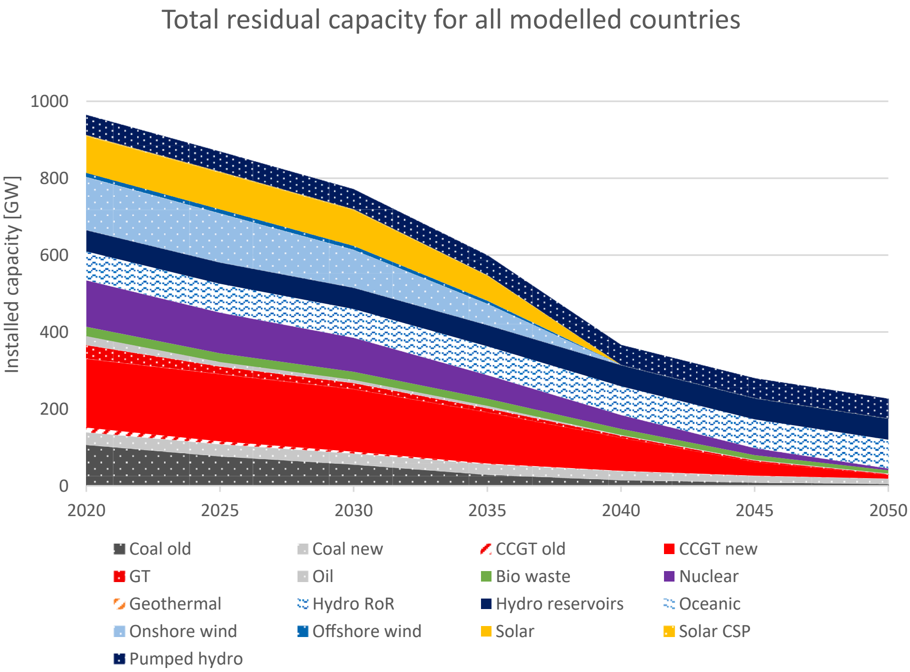

Fig. 1. *Aggregated vintage capacity of all countries in the Europe for the period 2020–2050* [23].

Table 3
Techno-economic parameters of storage options.

Technology	Roundtrip efficiency	Lifetime [y]	Shifting range[a]	Variable O&M (€/MWh)[b]	CAPEX (€/kW)[b]			Fixed O&M (€/kW-y)[b]		
					2030	**2040**	**2050**	**2030**	**2040**	**2050**
Pumped hydro storage[c]	85 %	60	1 year	5.1	4000	4000	4000	51	51	51
Electrochemical battery[d]	75 %	20	1 day	0.0	3600	2280	1800	26	15	13
H_2-battery[e]	41 %	20	1 year	1.6	2300	2100	2100	39	39	39

[a] The shifting range depicts the maximum period over which demand can be shifted using one of the flexibility options included in the model.

[b] All costs are presented in $€_{2019}$.

[c] *Based on* [8].

[d] *Based on the EU reference scenario 2020* [22] *assuming large-scale batteries with a storage capacity of 12 h.*

[e] *Based on* [8] *assuming the system with the smallest maximum power output (type III) and a storage capacity of 12 h. As no sectors other than the power sector are included in the model hydrogen can only be used to store electricity. The techno-economic assumptions shown here therefore assume a system where electricity is stored as hydrogen and then converted back into electricity again.*

with annual average capacity factor above 25 %. Coal, natural gas, oil, and uranium were perceived as abundant resources, assuming their global importability.

2.2.6. *Transmission capacity*

The transmission capacity between countries is added exogenously to the model and is based on TYNDP by ENTSOe, with unified European transmission capacity plans for 2030–2050 [20]. The cross-border capacity in 2020 is assumed to be equal to that in 2025 from Entsog & Entso-e [20]. The import/export CAPEX is set to 450 €/kW and the fixed operational costs are 50 €/kW [16]. For trading electricity between countries, 5 % transmission loss is assumed [16].

2.2.7. *Reserve margin and lost load*

Due to computational trade-offs, firm capacity or a minimum reserve margin was not included as a modelling constraint. To prevent modelling infeasibilities caused by constraints being too strict, the model was given the option to include loss of load in the solution. Based on estimates from Ref. [27], a variable cost of 10,000 €/MWh was assumed. This is the rounded average based on the country level estimates of the domestic consumer value of lost load found in the study.

2.2.8. *Allowed CO_2 emissions*

The total allowed CO_2 emissions are based on the targets set out in the European Green Deal, namely a 55 % reduction of emissions in 2030 compared to 1990 and a net-zero target for 2050 [2]. According to an impact assessment from the [28], a 55 % reduction requires a −65 % reduction target for the ETS-stationary sector when compared to 2005 levels. The method described in Schwenk-Nebbe et al. [29] was used to disaggregate reported emission data from the EEA [30] to find electricity related CO_2 emissions.[5] This data was used for the allowed CO_2 emissions in the first period and in 2030 and from then a linear reduction to zero by 2050 is assumed. The emission constraint pathway can be seen in Appendix G.

2.3. *Scenarios*

To measure the impact of national policy choices on the EU-wide transition towards net-zero, an in-depth policy analysis have been applied, with data collection of up to date member state (MS) policy standing on biomass and nuclear implementation, as well as MS level

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[5] As the model only includes the greenhouse gas CO_2, this is also the only greenhouse gas included in the calculation of the total allowed emissions.

CO_2 emission targets, from member state policies and long term strategies from governmental bodies (see Table 4). Nuclear and biomass policies were prioritized over other technologies due to heightened debates among member states about their inclusion in the energy transition [31]. Based on these policy measures, 5 core scenarios have been modelled: Reference (REF), Biomass polices (BIO), Nuclear policies (NUC), CO_2 emission policies (CO_2) and all policy combined (Allin). In REF, the transition is optimized for total cost without adding any policy restrictions on technology use (apart from resource availability constraints described in section 1.1.5 Renewable energy potentials**.** and overall EU emission reduction targets from section 1.1.8). The core scenarios are.

- **Reference (REF)** – Technoeconomic optimization of the power system transition without any policy restrictions (apart from resource availability constraints described in section 2.2.5, exclusion of biomass import/export and EU-wide emission reduction targets from section 1.1.8).
- **Biomass policy (BIO)** – In accordance with current member state (MS) policies as outlined in Table 4, biomass is prohibited in MSs where it is not a preferred component of their long-term energy strategy, or where it is favoured but not for electricity generation. Consequently, these MSs are prohibited from generating power from biomass after 2025 and are also restricted from exporting biomass to MSs that permit its use as stated in REF.
- **Nuclear policy (NUC)** – Based on up to date member state policy measures, presented on Table 4, nuclear power is set to zero from 2025 onwards for MSs that prohibit nuclear use or want to phase-out nuclear power in the short term. For all other countries nuclear power is freely optimized.
- **CO2 emission policy (CO2)** – Certain MSs have specific CO2 emission targets for the power generation sector with their own net-zero target years (see Table 4), which they must meet in addition to the EU-wide emission target.
- **All policy combined (Allin)** - BIO, NUC and CO2 combined

Table 4
Member state level policy assumptions for use of biomass and nuclear power and net-zero target.

Country	Biomass allowed?	Nuclear allowed?	Net-zero target year[g]:	Source Biomass/ Nuclear
Austria	Yes[a]	No[e]	2040	[48–50]
Belgium	No[c]	No[a]	2050	[51]
Bulgaria	Yes[a]	Yes[a]	/	[52]
Croatia	Yes[a]	Yes[a]	/	[82]
Czech Republic	Yes[a]	Yes[a]	/	[53]
Denmark	No[c]	No[e]	2030	[54,55]
Estonia	Yes[b]	Yes[b]	/	[56,57]
Finland	Yes[a]	Yes[a]	2035	[58,59]
France	No[c]	Yes[a]	2050	[60]
Germany	No[c]	No[e,f]	2035	[61]
Greece	Yes[a]	No[e]	2050	[62,63]
Hungary	Yes[a]	Yes[a]	/	[64]
Ireland	Yes[a]	No[e]	2050	[52]
Italy	No[c]	No[e]	2050	[55,65]
Latvia	Yes[b]	Yes	2050	[66]
Lithuania	Yes[a]	No[b]	2050	[67]
Luxembourg	Yes[a]	No[e]	2050	[68]
Poland	Yes[a]	Yes[a]	/	[69]
Portugal	No[c]	No[e]	2050	[70]
Romania	Yes[a]	Yes[a]	/	[71]
Slovakia	Yes[a]	Yes[e]	2050	[72]
Slovenia	Yes[a]	Yes[b]	2050	[73]
Spain	Yes[a]	No[f]	2050	[74]
Sweden	Yes[a]	Yes[a]	2040	[75]
United Kingdom	Yes[d]	Yes[a]	2035	[76]
Norway	No[b,c]	No[b]	2025	[77]
Switzerland	Yes[a]	No[f]	2050	[55,83]
Netherlands	No[c]	Yes[b]	2050	[78]

Data is based predominantly on energy and climate plans and long-term energy strategies published by member state Governmental bodies, see sources column.

[a] Preferred and increase expected.

[b] Not mentioned specifically/undecided.

[c] Biomass not preferred for electricity.

[d] Biomass + CCS preferred.

[e] Specifically against nuclear.

[f] Phase out preferred.

[g] *All the years of member state net-zero targets for the power sector are from IRENA* [84].

A more detailed version of Table 4 including more detailed explanation on what assumptions are based on can be found in Appendix H.

Sensitivity of results have been assessed in terms of nuclear, bioenergy and battery investment costs (± 50 % change), bioenergy with CCS (BECCS) inclusion, 100 % CCS capture rate, and different weather year portfolios.

3. Results

3.1. Overall impact of selected policy measures on europe region

Introducing the selected three member state level policy measures impacts the entire power system in the Europe region. Significant deviations in solar and wind capacity expansion, as well as the use of natural gas and coal, occur during the transition period 2030–2040 when policy measures are implemented. However, by the net-zero target year 2050, substantial variations are primarily observed in the interplay between firm capacities (nuclear energy, bioenergy, and batteries) and the levels of cross-border transmission. Main impacts in more detail include:

- Total power system capacities from 2020 to 2050 experience an average 2.2-fold increase across scenarios in Europe, while total annual generation only increases by about 30 % in the same period, as shown on Fig. 2. There is minor deviation in total capacities across scenarios; however, the mix of technologies show considerable differences from 2030 onwards.
- The transition period of 2030–2040 utilizes considerable 350–450 TWh/year natural gas and 25–290 TWh/year coal (Fig. 2). Before the complete retirement of fossil fuels in 2050, natural gas power plants undergo a 40 % average capacity increase by 2040 across scenarios, as shown on Fig. 3, where changes compared to REF scenario are highlighted. Even in scenarios with member state-level CO_2 emission targets, where seven countries achieve net-zero by or before 2040, there is a 20 % increase in natural gas power plant capacities. These capacities are decommissioned in 2050 due to the zero emission constraint, revealing that low CAPEX OCGT is cost-competitive for installation even for a 10-year transition period. Up until 2030, various policy scenarios show no significant impact on capacity portfolio development. However, by 2040, significant changes occur, particularly with the introduction of member state-level CO_2 targets. This results in a 15 % increase in solar capacity, a 17 % decrease in gas capacity compared to the Reference (REF) scenario, and the installation of 17 GW of battery capacity.
- Variable renewable energy (vRES), including solar, onshore wind, and offshore wind, remain largely unchanged despite the introduction of member state policy measures in Europe (Fig. 2). Although there is a 20 % increase in solar generation and 8 % increase in offshore wind generation in the Allin policy scenario in 2040, compared to REF, all other deviation remain between ±5 % compared to the REF scenario.
- Bioenergy and nuclear dynamics are the most impacted by the policy measures (Fig. 3). In the BIO scenario, member state-level bioenergy

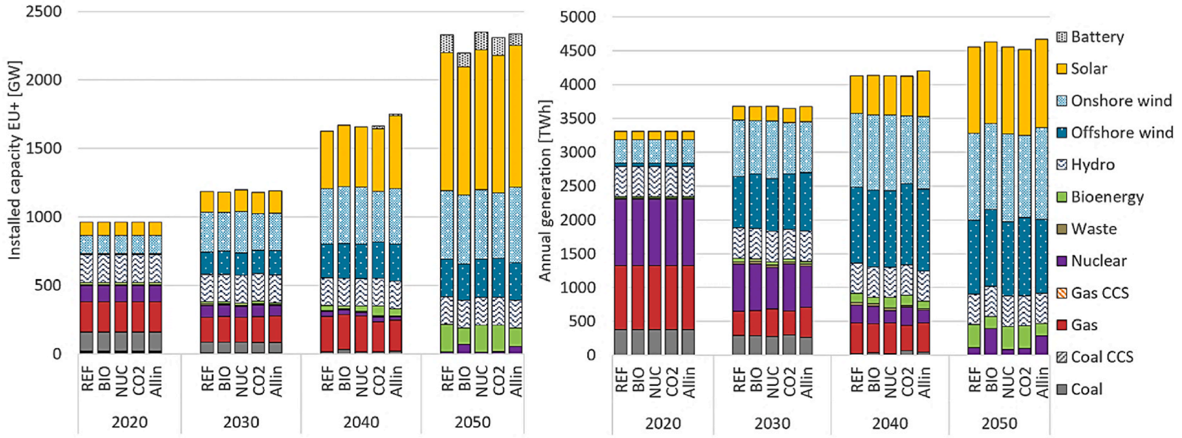

Fig. 2. Installed capacities [GW] on the left and their annual generation [TWh/year] on the right in the Europe region in the Reference scenario (REF) the three policy measures separately: No bioenergy in member states with comparable policy (BIO), no nuclear in member states where nuclear is discouraged by policy (NUC), member state level net-zero targets with their specific year (CO2), and these three policy measures combined (Allin). CCS: carbon capture and storage.

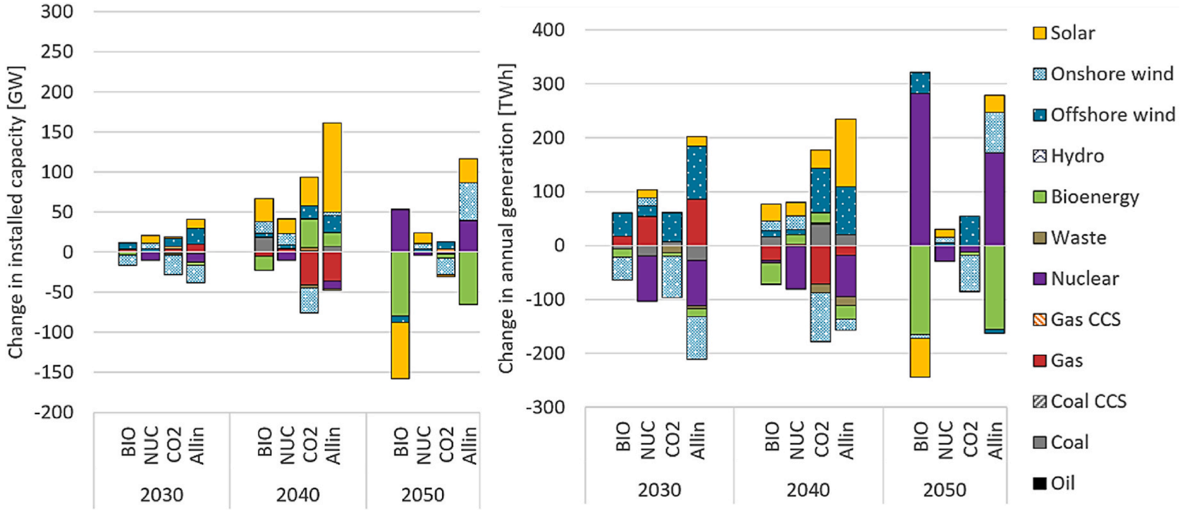

Fig. 3. Change in capacities on the left and in annual generation on the right in policy scenarios, compared to REF the three policy measures separately: No bioenergy in member states with comparable policy (BIO), no nuclear in member states where nuclear is discouraged by policy (NUC), member state level net-zero targets with their specific year (CO2), and these three policy measures combined (Allin). CCS: carbon capture and storage.

restrictions lead to a 50 % decrease in bioenergy utilization and a threefold increase in nuclear utilization compared to the REF scenario in 2050. The increased nuclear utilization is accompanied by a slight reduction in the use of solar PV and battery installations due to the baseload nature of nuclear power, making costly batteries less necessary.

- In the Allin scenario, which combines all policy measures, the significant increase in nuclear generation observed in the BIO scenario drops back by 30 %. Nevertheless, there is still a 2.5-fold increase in nuclear utilization compared to the REF scenario. In parallel, solar and onshore wind generation slightly increase, while the need for batteries decreases. This is attributed to the optimal placement of nuclear capacities, benefiting from cross-border electricity transmission between regions with high nuclear and high vRES capacities, as evidenced by a 40 % increase in cross-border transmission in the Allin policy scenario. Nuclear generation only constitutes a maximum of 9 % of total generation in the BIO scenario, and bioenergy reaches a maximum of 7 % despite the significant changes in their interplay.
- In terms of costs, the Allin scenario incurs the highest expenses, with a 4 % increase in total system costs (2020–2050) and a 6 % increase in annual average Levelized Cost of Electricity (LCOE) in 2050 compared to the REF scenario, as shown on Table 5. This is primarily driven by a 9 % increase in capital investments and fixed operational costs, offset by a 30 % decrease in variable costs. The capital-intensive nature of nuclear power and the decreasing variable costs associated with bioenergy contribute to this cost dynamic.
- The share of variable renewable energy sources (vRES) in total generation significantly rises to 78%–81 % in 2050, with the highest share observed in the nuclear-restricted policy scenario (NUC), compared to a mere 16 % in 2020. However, this high share of vRES raises concerns about insufficient reserve margins,[6] potentially leading to adequacy issues. Nonetheless, the unserved energy factor aligns with the reliability standard of 0.002 % [27], ranging between 0.002 and 0.003 % (Table 5).
- Biomass utilization ranges from 1.7 to 3.2 EJ/year across scenarios (Table 5), representing about 80 % of the maximum potential. Even in the most restricted Allin policy scenario, only 79 % of available

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[6] Total firm capacity in the study does not reach peak load, while according to Ref. [40], firm capacity should be 7–17 % over the peak load for reliability.

Table 5
Selected relevant power system performance indicators: total and levelized costs, share of vRES (solar and wind), total cross boarder transmission, biomass utilization and unserved energy.

	Total costs (2020–2050)	LCOE in 2050	Share vRES 2050	vRES curtailment 2050	Cross-border transmission	Biomass use 2050	Unserved energy 2050
	Bln €$_{2019}$	€$_{2019}$/MWh	%	%	TWh/year	EJ/year	%
REF	3061	106.4	80 %	8 %	172	3.2	0.003 %
BIO	3084	109.7	78 %	6 %	212	1.7	0.003 %
NUC	3084	107.7	81 %	8 %	179	3.2	0.003 %
CO2	3106	106.2	80 %	8 %	173	3.2	0.003 %
Allin	3180	112.4	80 %	9 %	245	1.8	0.002 %

biomass is utilized. This is attributed to country-specific and biomass type-specific pricing, ranging from 3 to 8 EUR/EJ depending on the country. For instance, one of the most expensive biomass sources in Spain, priced at 7.7 EUR/EJ, utilizes less than 50 % of its available potential.

- Significant changes in cross-border transmission can be observed due to the applied policy measures. Scenarios characterized by biomass restrictions and heightened nuclear capacities, such as BIO and Allin, undergo substantial increase of 25 % and 40 % in cross-border transmission when contrasted with the REF scenario. This is most likely due to increasing differences in member state level capacity portfolios and generation capabilities, requiring more support between countries.

3.2. Member state level impact of policy measures in 2050

Policy measures introduced for power system optimization not only affect the overall Europe region power system portfolios but also significantly impact member state-level power system portfolios and dynamics. In the Western European region, where stringent bioenergy and nuclear restrictions coincide with ambitious member state net-zero targets, simultaneous exclusion of nuclear and bioenergy leads to heightened nuclear installations in countries allowing nuclear (see Fig. 4 with county level generation portfolios). Notably, the Netherlands and France, surrounded by countries excluding nuclear from their long-term plans, experience a total nuclear capacity of 48 GW in 2050 in the Allin policy scenario. Moreover, member states excluding both nuclear and biomass while pursuing net-zero targets witness a substantial surge in solar and wind generation (Fig. 6), resulting in increased annual generation and electricity exports to neighbouring countries. Examples are Germany, Italy, Denmark, and Portugal, where strict policies transform these nations with the most restrictions into crucial energy exporters in their region. However, these changes in the energy mix also correspond to increased LCOE in these member states (Fig. 7). More detailed breakdown of results revealed that:

- The least affected countries are the ones with no policy restrictions, including Spain (only nuclear exclusion), Finland, and Ireland, as well as the Eastern European bloc comprising Poland, Czech Republic, Slovakia, Hungary, Romania, and Bulgaria, as shown on Fig. 4. However, certain countries without policy restrictions, like the UK, experienced impacts from other member states' policies. For instance, the UK witnessed increases in nuclear and offshore wind capacities, even though neither biomass nor nuclear is restricted.
- Germany undergoes a substantial transformation in net cross-border transmission, transitioning from a net-importer in the REF scenario to a net-exporter in the Allin policy scenario (Fig. 4). This shift underscores the considerable impact of Member State policies on regional energy dynamics. In the Allin policy scenario, Germany becomes a significant producer, exporting 18 % of its electricity production in the Allin policy scenario to neighbouring countries. This results in a decrease in net export capacity of major exporters, such as France and Spain, with Austria also transitioning from a net-exporter to a net-importer in the Allin policy scenario.

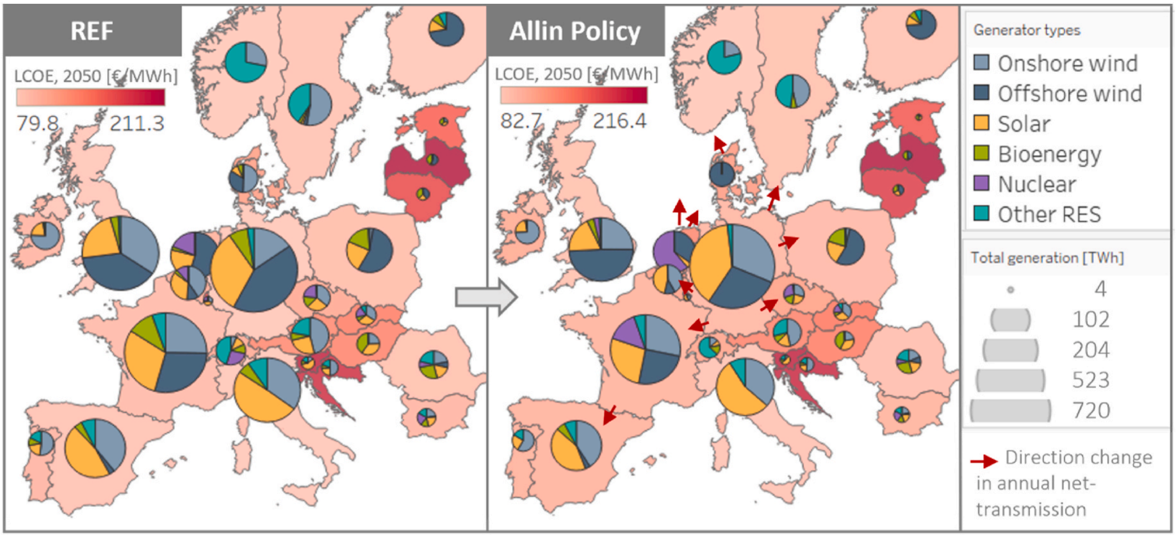

Fig. 4. Member state level energy generation mix on pie chart and average annual levelized cost of electricity (LCOE) on the heatmap for the REF scenario on the left and the Allin policy scenario on the right. Red arrows only show the new direction of annual net-cross border transmissions, where the direction of net-transmission changed compared to REF, in case direction change did not occur between countries, arrow is not included Note that extensive nuclear generation in the Netherlands is a result of high upper limit for thermal generators (250 GW regardless of technology or country). The study has also conducted a scenario with 8 GW maximum nuclear capacity in the Netherlands to show a more policy aligned scenario, attached in Appendix K. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

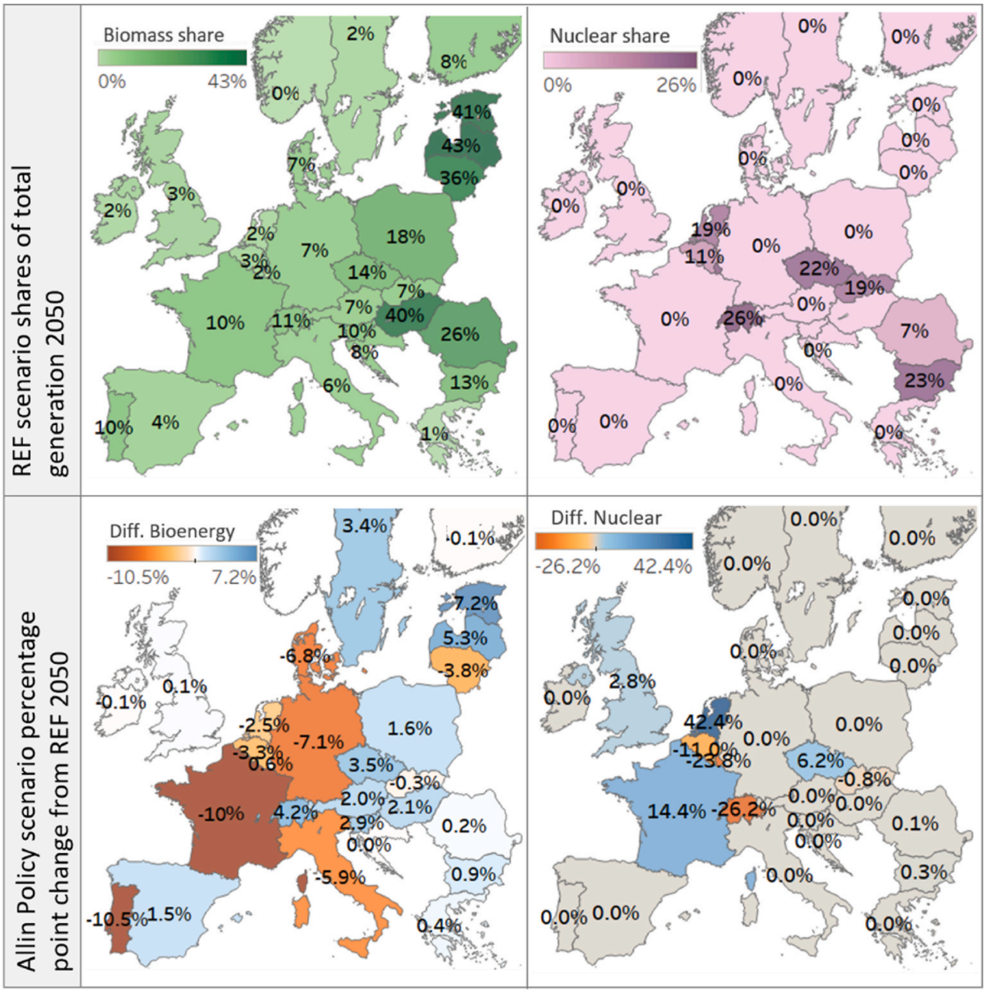

Fig. 5. Share of biomass (left) and nuclear (right) in total annual generation in 2050 per country. The top row shows results from the reference scenario and the bottom row shows the percentage point change in the Allin policy scenario, compared to REF.

- Primarily Eastern European countries exhibit the highest share of biomass in power generation, ranging from 1 % to 44 %, and they are unaffected by biomass restrictions (Fig. 5). Conversely, countries like France, Germany, and Portugal, with significant bioenergy shares in the REF scenario, with 10 %, 7 % and 10 %, respectively, experience a reduction to zero in the Allin policy scenario due to their biomass restricting policies. Sweden and Spain stand out as the only countries where bioenergy utilization increases noticeably, with 3.4 % point and 1.5 % point respectively.
- In the REF scenario, the Benelux region extensively adopts nuclear power, particularly in the Netherlands with 7.2 GW, Belgium with 2.2 GW, and Luxembourg with 0.3 GW in 2050. However, the Allin policy scenario imposes restrictions, including the ‘no nuclear’ policy of Belgium and Luxemburg, leading to a significant shift in nuclear installations of 30.2 GW to the Netherlands, which becomes a net-exporter. Existing energy modeling studies conducted on the Netherlands suggest a maximum nuclear capacity ranging from 5 to 12.5 GW [32–35]. In comparison, the proposed 30 GW capacity is significantly higher. The Allin policy scenario, tested with an upper limit of an average 8 GW based on these studies, resulted in a portion of nuclear capacity relocating to France (6 GW) and the UK (4 GW). However, under this scenario, overall European nuclear capacity decreases by 25 % when the Netherlands is constrained to 8 GW. More details of this additional scenario are in Appendix K.
- The substantial 30 GW capacity proposed in this study serves as evidence of the considerable impact of member state policies on nuclear capacity distribution, rather than a recommendation for future action. Additionally, Fattahi et al. [32] highlight the high sensitivity of nuclear capacity expansion decisions in the Netherlands to CAPEX and weather year assumptions. These factors are further examined in sensitivity analysis.
- The Eastern European countries with nuclear installations in the REF scenario experience minimal changes in the Allin policy scenario, while Switzerland witnesses a reduction in nuclear capacity, replaced by electricity imports from neighbouring countries.
- Significant impact is also exhibited in the shares and distribution of solar and wind generation, when policies targeting biomass, nuclear, and net-zero goals are included (Fig. 6). Germany sees the most significant 2.7 fold increase in onshore generation (110 TWh to 300 TWh) and 58 % increase in solar generation (230 TWh to 370 TWh) in 2050, changing from REF to Allin policy scenario. On the other hand, Spain and France experience a slight reduction in the share of solar and wind due to increased biomass and nuclear utilization, respectively. Central European countries like Austria, Czech Republic, and Slovenia witness substantial decreases of approximately 40%–50 % in the share of solar and wind, compensated by increased imports to meet electricity demand. In Austria, this significant decrease in solar and wind generation is replaced by 80 % increase in import, resulting in 50 % of Austria’s electricity demand met by import (Fig. 7).
- The levelized cost of electricity (LCOE) rises notably in the Netherlands by 30 %, Germany by 14 %, and Spain 7 % when all

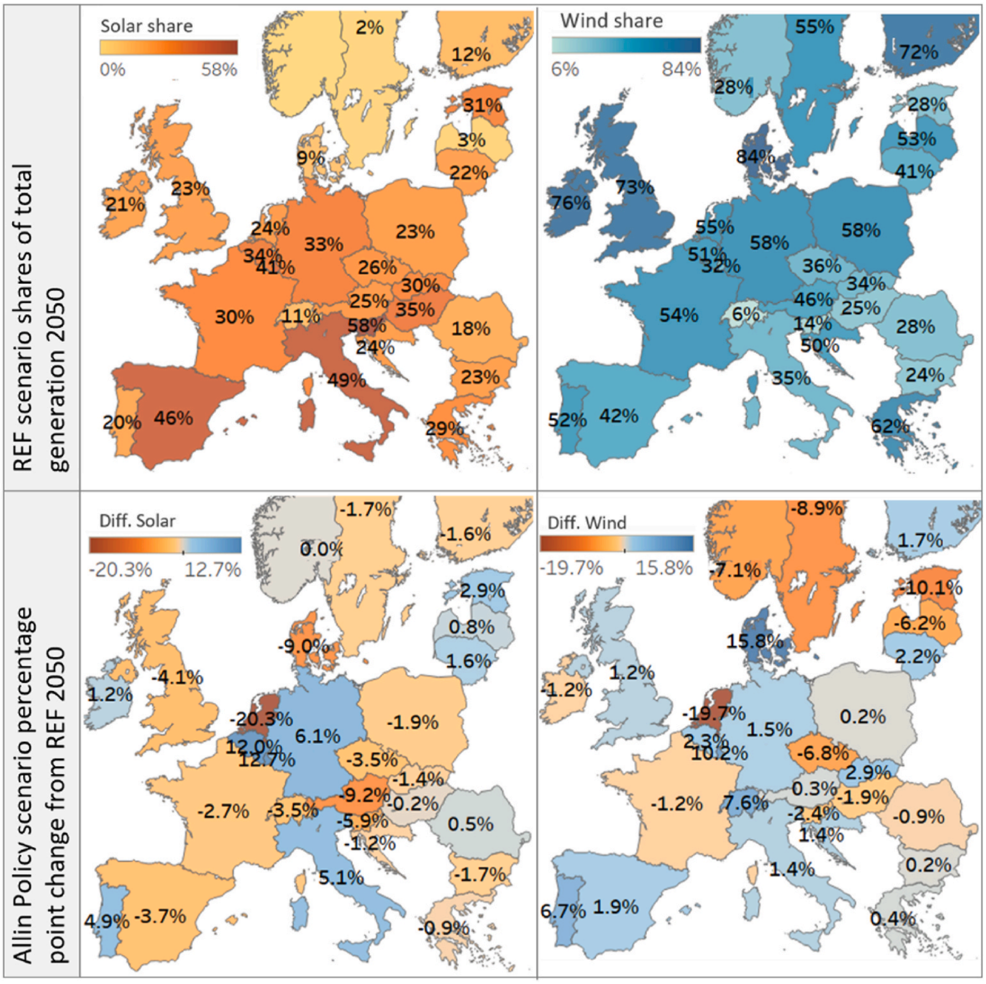

Fig. 6. - Share of solar (left) and offshore + onshore wind (right) in total annual generation in 2050 per country. The top row shows results from the reference scenario and the bottom row shows the percentage point change in the Allin policy scenario, compared to REF.

policy measures are introduced. In the Baltic region, the highest LCOEs range from 161 to 216 €/MWh in the Reference (REF) scenario, and this elevated cost persists in the Allin policy scenario (Fig. 7). LCOE quantifies the annualized average cost of electricity generation per member state. It differs from market price, yet offers a standardized metric for comparing the competitiveness of national power systems.

- The UK and Ireland experience the highest renewable energy (RE) curtailment, encompassing both solar and wind, in 2050 across all scenarios (Fig. 7). This is attributed to a substantial share of wind generation, while these countries are somewhat isolated from EU countries, posing limitations transmitting excess electricity. Southern countries with high solar penetration witness 7 %–11 % curtailment in the REF scenario. This curtailment intensifies in the Policy scenario for Italy and Portugal due to an even greater solar generation, with a 7.4 percentage point and 5.4 percentage point increase, respectively. The Netherlands stands out with the most notable decrease in RE curtailment, primarily driven by a significant reduction in solar and onshore wind penetration.

4. Sensitivity analysis

In the result section it was shown how restrictions on biomass and nuclear power and CO_2 emission targets contribute to the transition, with results showing the greatest impact on the interplay between bioenergy, nuclear and battery deployment and their interaction with cross border transmission. Thus, considering the uncertainty surrounding the future advancements in the costs of nuclear power, bioenergy and batteries, the sensitivity of these prices were tested on the REF scenario. Furthermore, this study has assessed the effects of incorporating BECCS technology or a 100 % CO_2 capture rate on all CCS. BECCS offers carbon removal capabilities, while a 100 % capture rate ensures carbon neutrality, which may enable fossil fuel use in the power system, thus potentially altering the power mix. Also, the impact of choosing different weather years is tested. Hence, the sensitivity runs include.

- ±50 % change on nuclear CAPEX
- ±50 % change on bioenergy CAPEX
- ±50 % change on battery CAPEX
- Option for BECCS (bioenergy with CCS) with 90 % capture rate
- 100 % capture rate on gas + CCS and coal + CCS (while BECCS is excluded)
- Testing with a ‘good’ and ‘bad’ weather years: 2019 and 2010 (based on [6])

Sensitivity analysis has revealed the following results.

- Capacity portfolios prove to be robust in high nuclear CAPEX, low bioenergy CAPEX and low battery capex sensitivity runs, although in low battery CAPEX, battery capacity increases by 50 %, the rest remains relatively similar compared to REF scenario (see Fig. 8and Fig. 9).

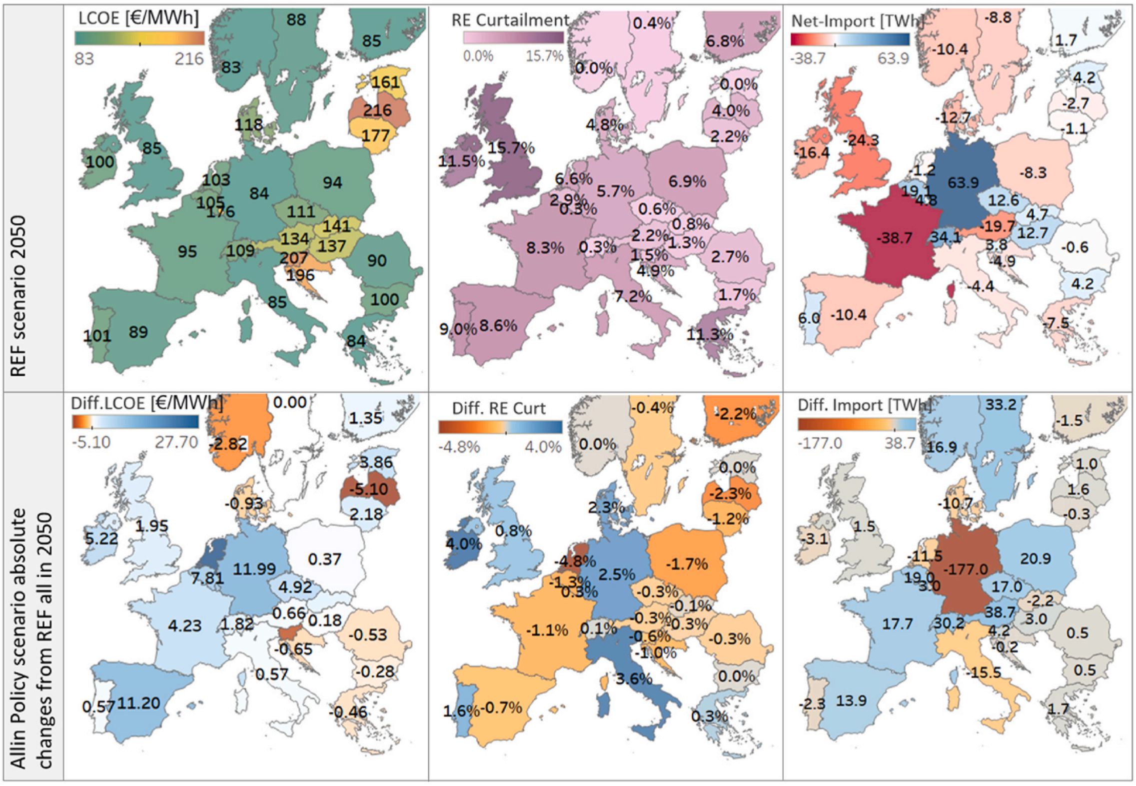

Fig. 7. Important power system indicators, including levelized cost of electricity (LCOE) on the left, RE (solar and onshore + offshore wind) curtailment as a percentage of total RE annual generation on the middle, and annual net-import in TWh on the right all country level in 2050. On the top row, results of the REF scenario can be seen and on the bottom row, The absolute change in the Allin policy scenario compared to REF. RE curtailment change is expressed in percentage points LCOE quantifies the annualized average cost of electricity generation per member state. It differs from market price, yet offers a standardized metric for comparing the competitiveness of national power systems. Appendix M shows import-export between countries in TWh.

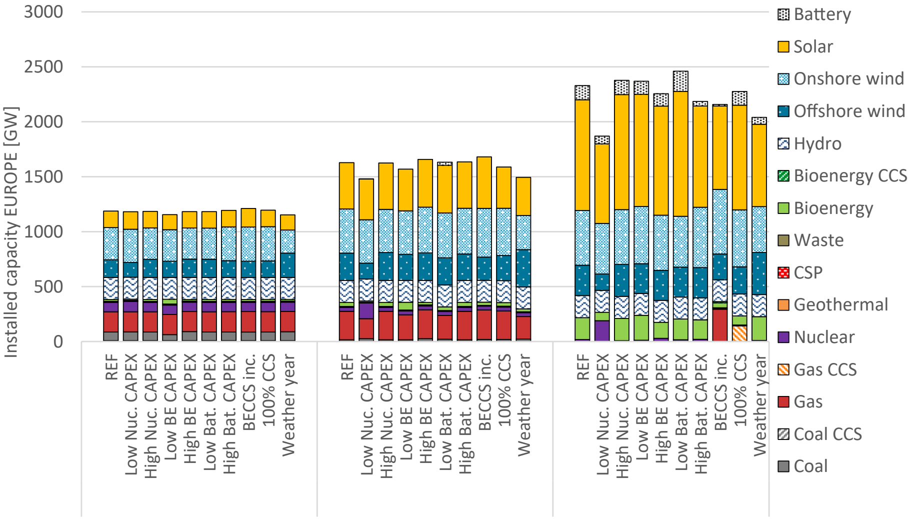

Fig. 8. Sensitivity analysis results on total Europe capacity portfolios in GW for the 9 sensitivity runs plus REF scenario.

- The model is highly sensitive to lowering nuclear CAPEX with total installed capacity decreases by over 25 % compared to REF. With 190 GW installed nuclear, solar and wind capacities decrease. When BECCS is included, 94 TWh BECCS production with resulting negative emissions is observed, allowing 290 TWh of natural gas generation from 290 GW installed combined cycle gas turbine in 2050. Sensitivity run with 100 % CCS capture rate results in 180 GW of combined cycle gas with CCS, while this technology has not been built before (see Fig. 8).
- The choice of different weather years had significant impacts solar and wind capacities significantly, with 25 % decrease in solar capacity installation, 16 % decrease in onshore wind capacity installation and approximately 40 % increase in offshore wind capacity installation (see Fig. 8). However, these weather years had no impact on the interplay between nuclear, bioenergy and cross-boarder transmission (see Table 6).
- Total system costs only deviate by ±4 % in the sensitivity runs, compared to the reference case. LCOE also proved to be robust to

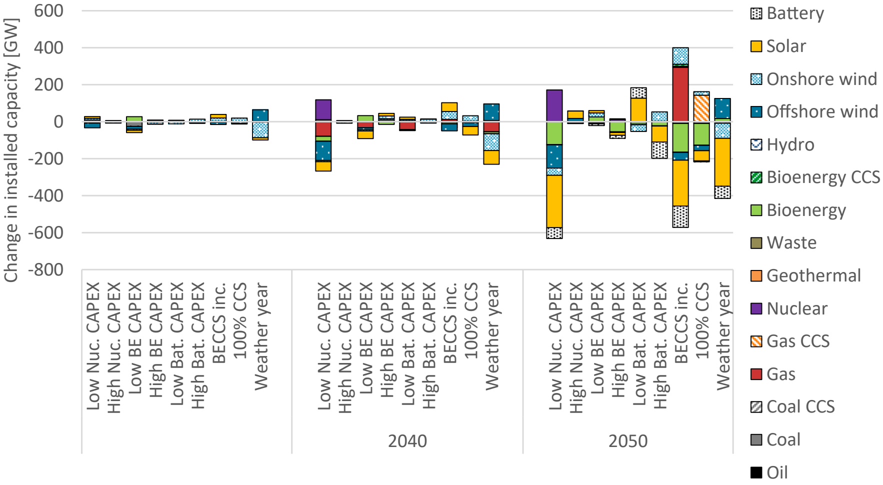

Fig. 9. Differences in capacity portfolios in the Europe region in GW compared to the REF scenario.

Table 6
Important power system performance indicators in the REF and 9 sensitivity scenarios.

	Total costs	LCOE	Biomass use	Unserved energy
	Bln EUR	EUR/MWh	EJ/yr2050	%
REF	3061	106	3.2	0.003 %
Low Nuc. CAPEX	3020	105	0.6	0.002 %
High Nuc. CAPEX	3171	107	3.3	0.003 %
Low BE CAPEX	3015	102	3.6	0.003 %
High BE CAPEX	3092	110	2.6	0.004 %
Low Bat. CAPEX	3043	103	2.9	0.002 %
High Bat. CAPEX	3070	108	3.2	0.006 %
BECCS inc.	3011	99	3.0	0.001 %
100 % CCS	3051	104	2.7	0.004 %
Weather year	3019	103	2.8	0.004 %

Additional results of the sensitivity analysis can be seen in Appendix J.

these changes, with largest impact in BECCS inclusion scenario, where LCOE decreased by 7 % in 2050 (see Table 6).

- Biomass utilization also shows robustness in sensitivity runs, except for Low Nuclear CAPEX scenario, where biomass utilization decreases by over 80 % (see Table 6).
- Unserved energy factor increases significant 0.006 % in High Battery CAPEX scenario. Due to a 32 % reduction in battery capacity also reduces flexibility options and increases unserved energy. With BECCS inclusion the added combined gas turbine capacity increases the available flexibility and reduces unserved energy to 0.001 % (see Table 6).

5. Discussion

5.1. Limitations

This study conducted a sensitivity analysis to evaluate the impact of key variables. However, the findings should be interpreted within the following limitations:

- Demand hourly profiles for each country are based on the single year 2019. Increased electric vehicle and heat pump usage may elevate electricity demand peaks [36]. However, incorporating higher peak demand profiles is anticipated to amplify impacts on the generation portfolio and costs, given the limited options for dispatchable or flexible capacity in a policy-restricted pathway.
- The spatial resolution of the study is copper plate country level with cross-border transmission. Disregarding sub-national transmission constraints, transmission flows may exceed national grid capacities. Countries like the Netherlands serve as crucial hubs for transmitting electricity across Europe, necessitating further sub-national grid modelling [8].
- Modeling vRES hourly generation is based on a single weather year without a firm-capacity constraint, potentially underestimating the necessary flexible and dispatchable capacity [37]. This, along with changes in demand profiles, is expected to amplify the impacts of policy restrictions.
- Exclusion of startup/shutdown time of thermal generators may overestimate the flexibility of thermal generators [38]. However, the most impacted nuclear power plants are considered baseload power in this study, thus start up and shut down protocols would have minimal impact on the results [39].
- The study excludes reserve capacity margin constraints due to computational complexity, resulting in 10%–20 % lower firm capacities in 2050 compared to peak load (reference on reserve margins) [40]. This absence may lead to power system inadequacy in adverse weather conditions. Enforcing the constraint is expected to increase battery, nuclear, and bioenergy capacities for backup, with the least capital-intensive bioenergy and battery likely contributing to the required 200 GW firm capacity. Since installed firm capacity is similar across scenarios in 2050, additional capacities are expected to have a comparable impact, thereby not significantly altering the main conclusions.
- The model focuses solely on the power sector, potentially overlooking interactions with other energy sectors, like biomass distribution, combined heat and power solutions, or hydrogen sector coupling [12]. To address biomass demand in other sectors, we use conservative assumptions, limited trade considerations, and include only power-specific crops. The highest annual biomass use across scenarios is 3.2 EJ, while Mandley et al. [41] suggests a 2050 technical potential of 9–24 EJ, leaving room for additional biomass use in other sectors. The potential role of hydrogen in sector coupling warrants further research. While this study interpolated the net-zero CO_2 emissions constraint to the power sector, including other energy sectors under the net-zero constraint could change the power sector's emission allocations.
- The model in this study assumes perfect foresight, minimizing total costs over the full period. While a myopic approach could impact total system costs, scenario comparisons for the same year (mostly

2050) with the same modeling approach suggest this is unlikely to alter the outcome.

- Technology and cost developments towards 2050 remains highly uncertain and may affect technology deployment. However, sensitivity analysis on uncertain cost and technology developments reveals that adjusting these assumptions does not significantly alter the results, except for nuclear. Low nuclear CAPEX significantly reduced the role of solar, offshore wind, batteries and bioenergy. Additionally, fleet decommissioning is uncertain, particularly with potential nuclear lifetime extensions. If granted, the existing nuclear fleet could operate beyond 2050 contrary to our decommissioning assumptions potentially leading to different results.
- Policy measures are dynamic, subject to change over time. Therefore, these policy scenarios should be considered a snapshot of time, when the study was conducted in 2022–2023. There are some countries, with steady policy on technology exclusion, such as Germany's nuclear phase out policy standing for decades [42]. In contrast, countries like the Netherlands demonstrating varying nuclear policy while the study was conducted. Despite potential future policy changes, the main conclusions on how member state policies impact surrounding countries or the entire region can be implemented.

5.2. Policy and research implications

Exploring policy implications and comparison to similar literature allows deeper interpretation of our results:

- The results demonstrate minimal impact on countries without specific policies restricting nuclear or biomass. However, significant effects emerge when neighbouring countries collectively phase out nuclear energy. In the Benelux region, despite nuclear installations in all three countries in the REF scenario, Belgium and Luxembourg's long-term exclusion of nuclear prompts the Netherlands to substantially increase nuclear capacities and export to neighbouring countries. Likewise, in France, when nuclear phase-out is mandated in Belgium, Germany, and Switzerland, France increases nuclear capacity from zero in REF to 17 GW in the Allin policy scenario. Member states should carefully consider this crucial policy implication before opting to exclude nuclear from their long-term plans. This technology shifting to neighbouring counties phenomenon cannot be observed with bioenergy.
- With policy measures included in the optimization, results align more closely with some countries' long-term strategies. Despite the REF scenario decommissioning all nuclear in France by 2045, the inclusion of policy measures retains 18 GW of nuclear capacity in 2050, bringing the results in line with current policies [43]. In the Allin policy scenario, Denmark's focus on offshore wind aligns with its long-term strategy of significant expansion and exporting to neighbouring countries. Denmark aims to install 13 GW offshore wind by 2030 [44], while the model installs 16 GW in 2030, increasing to 18 GW in 2050 in the Allin policy scenario, while in the REF scenario, offshore wind only reaches 2 GW in 2030 and 6 GW by 2050. Germany's planned 71 GW onshore wind by 2030 [42] contrasts with the REF scenario, where only 29 GW is installed. The Allin policy scenario raises this to 80 GW in 2030 and 118 GW in 2050.
- Some countries ended up with highly different generation mix from their long term strategies. Although the Netherlands do not exclude nuclear in their electricity mix, long term strategies only foresee minor contribution of about 10%–13 % to the electricity mix by 2050. While the REF scenario shows a comparable share of 16 %, this increases to approximately 60 % when policy measures are included, making the model outcomes highly inconsistent with Dutch strategies [45].
- There is inconsistency in the role of nuclear across studies. Compared to other hourly resolution power system optimization studies, the 17 GW nuclear capacity for Europe in 2050 is significantly lower than the approximately 100 GW in van Zuijlen et al. [8] and 200 GW in Zappa et al. [9]. This discrepancy may be attributed to the higher assumed costs for solar and wind capacity in those studies, resulting in a higher LCOE for these technologies. Consequently, nuclear becomes a more cost-efficient option than the combination of solar, wind, and dispatchable backup capacity identified as cost-optimal in this study. Pietzcker et al. [7], employing similar cost assumptions for solar and wind as in this study, also concludes that new nuclear plant additions are not cost-efficient after 2025. Another similarity between the method used by Pietzcker et al. [7] and this study is the modeling of the transition from 2020 to 2050, considering existing capacity. In contrast [8,9], only model 2050 and exclude existing capacity. Furthermore, Zappa et al. [9] includes a firm-capacity constraint, a factor not considered in this study.
- Costs in this study are comparable but somewhat higher than those reported by Ref. [8,9]. Zappa et al. [9] reports specific electricity costs of 99 €/MWh, including start-up and emission costs, which are excluded in this study. [8]) estimates total annualized system costs, resulting in electricity costs of 98–101 €/MWh, inclusive of start-up costs and excluding unserved energy costs. In the REF scenario of this study, costs were found to be 102 €/MWh, indicating a slightly higher range compared to these studies, considering the absence of start-up and emission costs.

6. Conclusion and policy implications

This study models the transition to a net-zero power system from 2020 to 2050 in the Europe region, incorporating three crucial policy measures: the future use of nuclear and biomass, and member state-level individual net-zero targets. The objective is to provide policymakers and stakeholders with unbiased insights into member state-level policy dynamics and optimal European capacity expansion strategies, avoiding value judgment or attempts to predict the future. Results highlight the substantial impact of policy measures on the power system transition, with significant deviations in solar and wind capacity expansion, natural gas, and coal use during the 2030–2040 transition period. However, by 2050, variations primarily occur in the interplay between firm capacities (nuclear energy, bioenergy, and batteries) and cross-border transmission levels only. Least affected countries include Spain, Finland, Ireland, and the Eastern European bloc, with no policy restrictions. In Western Europe, stringent bioenergy and nuclear restrictions, coupled with ambitious net-zero targets, result in heightened nuclear installations in countries allowing nuclear. The Netherlands and France, surrounded by nuclear-excluding countries, experience a total nuclear capacity of 48 GW in 2050 in the Allin policy scenario. Member states excluding both nuclear and biomass while pursuing net-zero targets witness an increase in solar and wind generation, becoming significant energy exporters, e.g., Germany, Italy, Denmark, and Portugal. However, these changes correspond to increased LCOE in these member states.

Capacity portfolios prove robust in high nuclear CAPEX, low bioenergy CAPEX, and low battery CAPEX sensitivity runs. However, low nuclear CAPEX scenarios result in a 25 % decrease in total installed capacity, decreasing mainly solar and wind capacities. Power system portfolios and policy implications may differ if nuclear CAPEX significantly decreases, BECCS is included, or CCS reaches 100 % capture rate.

Overall, policy implications can be drawn from this study, emphasizing minimal impact on countries without specific nuclear or biomass restrictions, while significant effects emerge when neighbouring countries collectively phase out nuclear energy. In the Benelux region, despite nuclear installations in all three countries in the REF scenario, Belgium and Luxemburg nuclear exclusion prompts the Netherlands to increase nuclear capacities and export. Likewise, in France, nuclear phase-out in neighbouring countries prompts an increase from zero to 17 GW in the Allin policy scenario. Countries with all three policy restrictions become solar and wind powerhouses, exporting significantly, although at a higher LCOE. Results for some countries align more closely with long-term strategies in scenarios with policy measures, emphasizing crucial policy implications.

Further research should explore interactions with other energy sectors, including sector coupling via hydrogen, carbon capture and storage, and possible negative emissions in the power system under varying policy implications.

CRediT authorship contribution statement

Rebeka Béres: Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Auke van der Wel:** Validation, Methodology, Data curation, Conceptualization. **Amir Fattahi:** Validation, Software, Methodology, Investigation. **Machteld van den Broek:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Conceptualization.

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.

Data availability

Data will be made available on request.

Acknowledgement

We extend our gratitude to Manuel Sanchez Dieguez for his invaluable assistance in model development. Furthermore, we express our gratitude to Mark Fazekas for kindly sharing his expert insights on data visualization, enhancing the quality of the graphs presented in this work.

Appendix. 8

Appendix A. Electricity demand

Table 7
- Projections of electricity demand by country in TWh based on the Global Ambition scenario from TYNDP ENTSOe [20].

Country	2020[a]	2025[a]	2030	2035[a]	2040	2045[a]	2050
Austria	74	80	85	91	98	101	104
Belgium	87	95	103	108	114	118	122
Bulgaria	33	34	34	34	35	35	35
Croatia	17	17	18	18	18	19	21
Czech Republic	58	61	65	68	71	73	75
Denmark	40	44	49	52	56	58	61
Estonia	8	8	8	8	9	9	9
Finland	94	101	108	116	124	125	125
France	468	496	523	547	571	584	598
Germany	571	611	651	686	720	746	771
Greece	56	56	56	58	59	61	63
Hungary	39	42	45	48	50	53	56
Ireland	36	41	46	49	52	54	56
Italy	312	315	318	335	352	370	388
Latvia	8	8	9	9	9	9	10
Lithuania	11	12	12	12	12	13	13
Luxembourg	7	8	8	9	10	10	11
Poland	150	160	171	178	184	192	200
Portugal	53	54	55	57	59	61	63
Romania	52	56	61	64	68	73	77
Slovakia	28	30	32	33	34	37	39
Slovenia	14	15	15	16	16	17	17
Spain	264	271	279	288	298	309	321
Sweden	138	141	144	148	152	154	156
United Kingdom	339	358	377	438	498	518	537
Norway[b]	136	138	139	141	143	144	146
Switzerland[b]	60	66	73	79	86	92	99
Netherlands	131	151	171	182	193	206	219
Total	3284	3468	3654	3872	4090	4240	4391

[a] Because [20] contains only the years 2015, 2030, 2040 and 2050 other periods in the model are interpolated linearly.

[b] *Because both Norway and Switzerland are not in Ref.* [20]*, demand of these two countries is taken from* Ref. [16].

Appendix B. Evolution of cost of generators over modelled period

Table 8
Technoeconomic assumptions of power generators in Europe for start year 2020

Technology 2020	CAPEX (€/kW)[11]	Fixed O&M (€/kW-y)[b]	Variable O&M (€/MWh)[b]	Build time [y][1]	Lifetime [y]	Resource-use efficiency [%][1]
Coal old	2585	35	2.8	4	40	41 %
Coal new	2655	47	5.2	4	40	48 %
Coal CCS	5145	69	20.9	5	40	34 %
CCGT old	695	20	2.3	3	30	58 %
CCGT	755	22	2.0	3	30	61 %
OCGT	430	12	2.1	1	25	38 %
CCGT + CCS	2130	41	9.7	4	30	46 %
Oil[1]	700	10	2.6		20	33 %
Waste	1920	52	0.8	3	20	34 %
Biomass	2520	47	3.6	3	30	38 %
Biomass + CCS	5510	81	25.1	4	30	30 %
Nuclear	6400	120	6.4	7	60	38 %
Geothermal	3950	110	0.1	3	35	–
Hydro RoR	1715	9	0.0		50	–
Hydro Reservoirs	2100	26	0.3		50	–
Tide, wave, and ocean	4270	40	0.1		80	–
Onshore wind	1135	14	0.2	1	30	–
Offshore wind	2135	42	0.4	1	30	–
Solar	570	17	0.0	1	30	–
Solar CSP	3675	113	0.1	2	25	–

CCGT: combined cycle gas turbine, OCGT: open cycle gas turbine, CCS: carbon capture and storage, RoR: run of river.

[a] *The CAPEX includes the overnight investment costs from the EU reference scenario 2020* [22] *and interest during construction based on build time and a discount rate of 8 %.*

[b] All costs are presented in $€_{2019}$.

[c] *Based on the EU reference scenario 2020* [22].

[d] *Based on* [8].

[e] *Oil generator cost data is taken from the IESA-OPT-Netherlands model* [16].

[f] *As the model only allows for one value for the resource-use efficiency across all modelled periods, the average efficiency from 2020, 2030, 2040 and 2050 is calculated based on the EU reference scenario 2020* [22].

[g] *A capture ratio of 90 % is assumed for CCS plants based on* [8]. *CO_2 transport and storage costs (levelized costs* per *tonne CO2 captured) are included in VOM costs of CCS technologies. Based on IEA (2030), for 2020 the cost is 60 €/t_{co2}, which reduces to 32 €/t_{co2} in 2050 (with linear reduction assumed between). It is assumed that the majority of transport and storage happens onshore.*

[h] BECCS is not included in the base scenarios. Only used for ‘BECCS inclusion’ sensitivity analysis.

Table 9
Cost assumptions of generators

Technology	CAPEX (€/kW)[a] [b]			Fixed O&M (€/kW-y)[b] [c]			Variable O&M (€/MWh)[b] [c]		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Coal old	2585	2585	2585	35	35	35	2.8	2.8	2.8
Coal new	2605	2595	2585	45	44	42	5.0	4.8	4.6
Coal CCS	6710	6575	6430	65	62	61	8.6	7.1	6.9
CCGT old	675	670	670	20	20	20	2.3	2.3	2.3
CCGT	730	725	720	21	20	19	1.9	1.8	1.7
GT	415	415	410	12	12	12	2.1	2.1	2.1
Gas CCS	2780	2610	2610	38	35	34	6.5	6.4	6.3
Oil[d]	700	700	700	10	10	10	2.6	2.6	2.6
Waste	2035	2025	2015	44	42	39	0.8	0.8	0.8
Biomass	2265	2140	2140	40	39	38	3.6	3.6	3.6
Biomass + CCS	6655	6150	6015	69	63	61	9.4	9.3	9.3
Nuclear	5950	5950	5950	115	108	105	7.4	7.6	7.8
Geothermal	3350	3155	2960	95	100	105	0.1	0.1	0.1
Hydro RoR	1670	1660	1650	8	8	8	0.0	0.0	0.0
Hydro Reservoirs	2100	2100	2100	26	26	26	0.3	0.3	0.3
Tide, wave, and ocean	2665	2320	1975	33	28	24	0.1	0.1	0.1
Onshore wind	1080	1025	1000	14	12	12	0.2	0.2	0.2
Offshore wind	2025	1965	1905	31	29	28	0.4	0.4	0.4
Solar	500	485	470	14	10	9	0.0	0.0	0.0
Solar CSP	3060	2930	2800	99	87	77	0.1	0.1	0.1

[a] *The CAPEX includes the overnight investment costs from the EU reference scenario 2020* [22] *and interest during construction based on build time and a discount rate of 8 %.*

[b] All costs are presented in $€_{2019}$.

[c] *Based on the EU reference scenario 2020* [22].

[d] *Oil generator cost data is taken from the IESA-OPT-Netherlands model* [16].

Appendix C. Existing capacity in 2020

Table 10
Assumed existing capacity in 2020 for each country in the EU25 + 3 aggregated by type [MW] [23]

Country	Total	Coal old	Coal new	CCGT old	CCGT new	GT	Oil	Bio waste	Nuclear	RoR	Reservoirs	PHS	Solar	Onshore wind	Offshore wind	Geothermal	Ocean
Austria	23905	600	405	110	3685	1130	270	725		5520	2800	5235	935	2490		1	
Belgium	20485	50		1030	4460	1255	135	905	5925	95	25	1310	3120	1465	710		
Bulgaria	11295	3765		85	45	380	65	25	1975	490	1720	1015	1030	700			
Croatia	3985	210		6	625	365	65	35		515	1395	300	50	420			
Czech Republic	19610	7450	630	250	975	1235	35	135	4290	355	735	1170	2070	280			
Denmark	13040	1995	2575	335	485	1000	335	715		5	0		780	3550	1260		
Estonia	2085	1315				105	265	90		8				300			
Finland	15750	3625	560	35	1480	450	415	2180	2750	1890	1365		15	975	8		
France	125715	3935		1235	7155	1720	6360	1395	61370	8660	9690	6980	6765	10210		1	240
Germany	183150	28280	19380	2450	18140	8630	1420	2295	8105	4450	140	6805	39245	40490	3295	25	
Greece	18300	3040	660	270	5035	100	1105	25		180	2515	700	2605	2065		1	
Hungary	6885	65		550	2685	360	430	235	2000	30	30		170	330			
Ireland	9655	1185		365	3915	345	785	100		75	160	290	2	2410	25		
Italy	111360	2810	3195	935	41630	5760	5390	855		5000	9540	7675	18900	9115		555	0
Latvia	2920	25		2	980	180	8	65		50			2	70			
Lithuania	3345			20	500	780	630	30		120		760	70	435			
Luxembourg	1610			9		70	1	25		35		1295	115	60			
Poland	33650	21970	1700	55	1720	465	35	340		540	50	1780	110	4885			
Portugal	19655	1765		505	4105	205	885	550		2555	1905	1785	445	4930		17	1
Romania	21515	5415		30	1885	1035	145	16	1410	1530	5110	370	1325	3245			
Slovakia	7120	465		5	810	580	13	250	1940	165	1440	915	535	4			
Slovenia	3020	345		325		35	75	8	690	390	725	180	240	5			
Spain	98960	7765	335	980	27530	2955	1635	645	7005	4420	9700	5935	7155	22895	5		0
Sweden	18975	140		195	495	245	710	3375	6700	555	15725	100	105	5585	205		
United Kingdom	87025	9530		1545	33550	1245	1330	2130	9485	555	1220	2745	9535	9060	5090		3
Norway[a]	36310				1410						33780	1120					
Switzerland[a]	20920						400	10	3380	4030	8150	3990	920	40			
Netherlands	28055		2190	1490	12340	3605		3130	485	35			1515	2910	355		1
Total	948300	105745	31630	12820	175640	34235	22940	20290	117510	42260	107920	52455	97759	128924	10953	600	245

[a] *Switzerland and Norway are not included in the database because they were not part of the EU in 2015. Therefore their existing capacities are taken from* Ref. [21].

Appendix D. Aggregation of technologies from dataset

Table 11
Aggregation of dataset technologies into modelled technologies

Technology type model	Technology type dataset
Coal old	Fluidized bed combustion coal Steam turbine coal Fluidized bed combustion lignite Steam turbine lignite
Coal new	Integrated gasification combined cycle coal Supercritical steam turbine coal Integrated gasification combined cycle lignite Supercritical steam turbine lignite
CCGT old	Gas turbine gas
CCGT new	Gas turbine combined cycle gas
GT	Steam turbine gas Internal combustion engine gas Derived gas fired power plants Refinery gas fired power plants
Oil	Diesel oil fired power plants Fuel oil fired power plants

Appendix E. Disaggregating biomass and waste capacities

Because the installed capacities of generators that use biomass or waste are one category in the JRC-IDEES database [23], the installed capacities were disaggregated (see table below). This was done by calculating the percentage of waste based capacity vs the percentage of biomass based capacity that is installed in each country according to Ref. [21]. These percentages were then multiplied with the combined waste/biomass capacity from the JRC-IDEES database which results in the disaggregated capacities that were used in the model (Table 11).

Table 12
Disaggregation of waste and biomass based generators based on [21,23]

Country	Fraction		Capacity [MW]		
	Waste	Biomass	Waste & biomass	Waste	Biomass
Austria	23 %	77 %	725	168	557
Belgium	36 %	64 %	905	325	580
Bulgaria	8 %	93 %	25	2	23
Croatia	6 %	94 %	35	2	33
Czech Republic	20 %	80 %	135	26	109
Denmark	17 %	83 %	715	122	593
Estonia	11 %	89 %	90	10	80
Finland	8 %	92 %	2180	176	2004
France	0 %	100 %	1395		1395
Germany	17 %	83 %	2295	395	1900
Greece	0 %	100 %	25		25
Hungary	20 %	80 %	235	46	189
Ireland	0 %	100 %	100		100
Italy	7 %	93 %	855	64	791
Latvia	0 %	100 %	65		65
Lithuania	18 %	82 %	30	6	25
Luxembourg	31 %	69 %	25	8	17
Poland	0 %	100 %	340		340
Portugal	0 %	100 %	550		550
Romania	0 %	100 %	16		16
Slovakia	0 %	100 %	250		250
Slovenia	62 %	38 %	8	5	3
Spain	49 %	51 %	645	319	326
Sweden	0 %	100 %	3375		3375
United Kingdom	0 %	100 %	2130		2130
Norway	0 %	100 %			
Switzerland	0 %	100 %	10		10
Netherlands	62 %	38 %	3130	1932	1198

Appendix F: Resource potentials

Table 11 provides an overview of the assumptions for solar and wind availability including their capacity factors for each country, and Table 12 provides an overview for both biomass and waste. For energy from hydro (hydro reservoirs, run-of-river, or pumped storage), the maximum allowed capacity was set to today's levels, seen in Table 9 (Appendix C). This was based on the assumption that this technology already reached full maturity in Europe [9]. Table 15 shows hydro discharge capacities and capacity factors by country. Oceanic energy (tidal and currents) was also set to its current capacity. This was done because it is currently such a small scale technology that it is uncertain if it is going to be a technology of major use in 2050 [46]. Lastly, the geothermal energy potential is based on the same method used in Ref. [9], meaning 50 GW of total deployment is allowed which is allocated to countries based on their geothermal potential.

Table 13
Resource potentials and capacity factors of solar and wind energy for all modelled periods unless otherwise stated

Country	Solar PV[a]		Solar CSP		Onshore wind[b]		Offshore wind[b]	
	Max. potential [GW]	Capacity factor[c]	Max. potential [GW]	Capacity factor[c]	Max. potential [GW]	Capacity factor	Max. potential [GW]	Capacity factor[d]
Austria	73	14 %			44	29 %		
Belgium	52	13 %			5	30 %	0	57 %
Bulgaria	149	17 %			7	27 %	13	44 %
Croatia	50	16 %	0.03	16 %	8	30 %	16	37 %
Czech Republic	112	13 %			48	28 %		
Denmark	76	13 %			83	36 %	129	57 %
Estonia	28	12 %			35	28 %	15	56 %
Finland	36	12 %			38	29 %	110	55 %
France	815	15 %	8	15 %	646	29 %	132	52 %
Germany	494	13 %			116	29 %	80	54 %
Greece	152	20 %	5	20 %	104	33 %	2	43 %
Hungary	161	16 %			26	26 %		
Ireland	113	12 %			164	45 %	103	63 %
Italy	432	17 %	11	17 %	81	28 %	28	39 %
Latvia	48	12 %			64	29 %	53	56 %
Lithuania	93	12 %			123	30 %	15	56 %
Luxembourg	3	13 %			0	30 %		
Poland	447	13 %			370	28 %	80	55 %
Portugal	55	15 %	37	15 %	6	28 %	7	44 %
Romania	381	16 %			32	26 %	69	46 %
Slovakia	60	14 %			16	27 %		
Slovenia	18	15 %			0	27 %		
Spain	410	18 %	248	18 %	333	28 %	20	42 %
Sweden	71	12 %			154	34 %	194	54 %
United Kingdom	347	12 %			420	38 %	643	59 %
Norway[e]	71	2 %			110	34 %		54 %
Switzerland[e]	73	14 %			6	29 %		
Netherlands	67	13 %			43	32 %	87	57 %
Total/average	4887	14 %	307	14 %	3082	30 %	1796	51 %

[a] solar and wind capacities based on [24].

[b] The 'Reference – large turbines' scenario was chosen from the Enspreso database. Furthermore, a minimum capacity factor of 25 % was assumed, as with a lower capacity factor an investment would not be made.

[c] The country level capacity factors found in the Enspreso database were increased so that the average of all countries taken together is equal to the EU-average that is projected by the [47] as this projection is more up to date. (seems optimistic for e.g. NL. I expect that with more PV also less favourable locations, positions, and angles are used.

[d] The offshore wind capacity factor for all countries is assumed to increase by 15 % in 2050 compared to 2020 due to technology development [47]. The increase is assumed to be linear between 2020 and 2050. (in this table do you show the 2020 or 2050 numbers?).

[e] Because both Norway and Switzerland are not in the Enspreso database, their numbers are assumed to be equal to their neighbouring countries (Sweden and Austria).

Table 14
Resource potential of biomass and waste for all countries included based on [25] [PJ]

Country	Biomass[a]				Waste[b]			
	2020	2030	2040	2050	2020	2030	2040	2050
Austria	92	96	94	93	8	8	9	9
Belgium	81	89	83	76	31	33	36	40
Bulgaria	85	79	75	77	2	2	2	3
Croatia	23	21	20	18	0	0	0	0
Czech Republic	108	108	98	94	2	3	3	3
Denmark	74	73	72	71	17	18	19	20
Estonia	41	39	27	26	2	2	2	3
Finland	79	83	89	96	10	11	12	12
France	705	764	731	704	58	62	64	66
Germany	512	571	563	561	96	92	87	83
Greece	38	38	40	41	2	2	3	3
Hungary	194	191	191	191	6	7	7	7
Ireland	25	24	20	16	1	1	2	2
Italy	301	290	276	261	22	24	25	26
Latvia	55	56	53	49	0	1	1	1
Lithuania	72	76	68	59	1	1	1	1
Luxembourg	1	1	1	1	0	0	0	0

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Table 14 (*continued*)

Country	Biomass[a]				Waste[b]			
	2020	2030	2040	2050	2020	2030	2040	2050
Poland	326	358	355	352	17	19	20	21
Portugal	65	66	67	70	9	9	10	10
Romania	362	375	354	330	6	6	7	7
Slovakia	41	42	36	29	2	3	3	3
Slovenia	18	19	18	16	1	1	1	1
Spain	360	380	391	408	20	22	23	24
Sweden	149	156	160	164	21	22	23	24
United Kingdom	191	208	203	197	12	13	15	17
Norway[b]	149	156	160	164	21	22	23	24
Switzerland[b]	92	96	94	93	8	8	9	9
Netherlands	86	95	92	89	36	37	37	38
Total	4325	4550	4431	4346	411	429	444	457

[a] Years that are in between the mentioned periods are interpolated linearly.

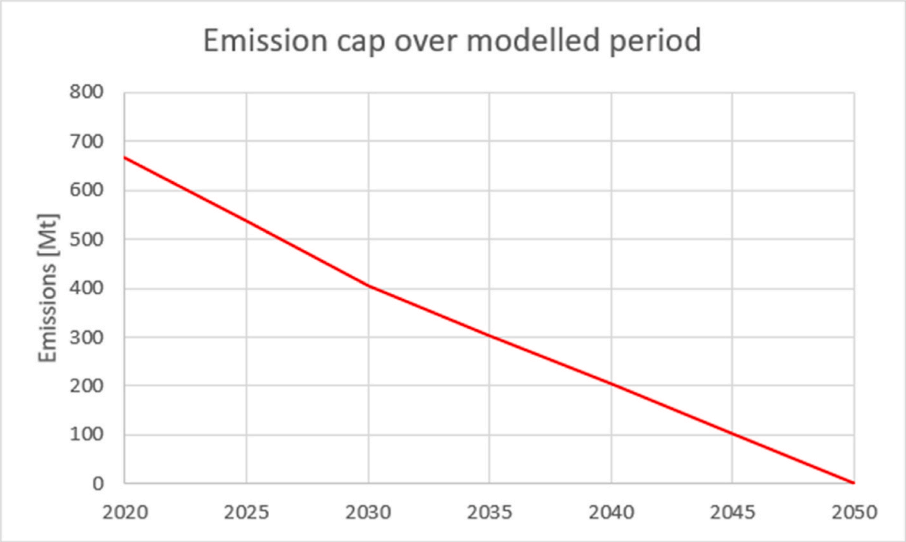
[b] Because both Norway and Switzerland are not in the Enspreso database, their numbers are assumed to be equal to their neighbouring countries (Sweden and Austria).

Table 15
Hydro availability input data

Country	Hydro pumped storage[a]		Hydro Reservoirs[a]			Run-of-river[a]	
	Discharge capacity (hours)	Installed capacity (MW)	Discharge capacity (hours)	Capacity factor	Installed capacity (MW)	Capacity factor	Installed capacity (MW)
Austria	329	5235	272	9 %	2800	58 %	5520
Belgium	4	1310				32 %	95
Bulgaria	261	1015	490	24 %	1720	43 %	490
Croatia	61	300	1467	24 %	1395	43 %	515
Czech Republic	5	1170	3	13 %	735	29 %	355
Denmark						45 %	5
Estonia						22 %	8
Finland			4054	43 %	1365	22 %	1890
France	14	6980	1032	22 %	9690	21 %	8660
Germany	113	6805	1814	6 %	140	45 %	4450
Greece	6	700	1392	24 %	2515	43 %	180
Hungary			1467	24 %	30	43 %	30
Ireland	6	290				33 %	75
Italy	53	7675	592	25 %	9540	46 %	5000
Latvia						22 %	50
Lithuania	14	760				22 %	120
Luxembourg	4	1295				32 %	35
Poland	4	1780	16	15 %	50	32 %	450
Portugal	1101	1785	623	28 %	1905	27 %	2555
Romania	247	370	419	24 %	5110	43 %	1530
Slovakia	54	915				35 %	165
Slovenia	14	180				43 %	390
Spain	1058	5935	1221	22 %	9700	20 %	4420
Sweden			2114	51 %	15725	22 %	555
United Kingdom						33 %	555
Norway	2575	1120	2575	40 %	33780		
Switzerland	168	3990	1000	29 %	8150	48 %	4030
Netherlands						29 %	35

[a] Discharge capacities and capacity factors by country based on De Felice (2020).

Appendix G: CO2 emission cap over modelled period



Maximum allowed CO_2 emissions for each modelled period. Numbers calculated based on [5,30]

Appendix H. Policy analysis

In the attached table it is explained what the assumptions on national use of biomass and nuclear power as well as national net-zero targets are based on. All member state level net zero targets are based on.

Country	Biomass allowed?	Based on:	Nuclear allowed?	Based on:	Net-zero by:
Austria	Yes	Increase expected [48–50]	No	Specifically mentioned in Refs. [48–50]	2030
Belgium	No	Only apply biomass where it has the highest value. Only waste streams are burned [51]	No	Specifically mentioned in NECP [51]	2050
Bulgaria	Yes	Increase expected [52]	Yes	Specifically mentioned in NECP [52]	/
Croatia	Yes	Farmers are promoted to grow biomass for energy [53]	Yes	Specifically mentioned in NECP [53]	/
Czech Republic	Yes	Increase expected [54,55]	Yes	Specifically mentioned in NECP MENDELEY CITATION PLACEHOLDER 73	/
Denmark	No increase	No increase expected as biomass is already + -50 % of energy mix [54,55]	No	National law forbids nuclear power plants to be build [54,55]	2030
Estonia	Yes	Not stated that it is used, also not strongly stated that it is used specifically for power sector [56,57]	/	Considering the possibility to build SMR's [56,57]	/
Finland	Yes	Will still be used and promoted, also in the electricity sector [58,59]	Yes	Specifically mentioned in NECP [58,59]	2035
France	No	As biomass is a scarce resource it is only used where it is most needed [60]	Yes	European Commission analysis of NECP MENDELEY [60]	2050
Germany	No	Biomass use is in a downward trend and in 2050 there will not be significant use anymore [61]	No	Specifically mentioned in NECP MENDELEY CITATION PLACEHOLDER 88	2035
Greece	Yes	Increase expected [62]	No	No plans to build new nuclear power plants [63]	2050
Hungary	Yes	Increase expected [64]	Yes	Specifically mentioned in NECP [64]	/
Ireland	Yes	Increase expected, first for co-firing and later retrofit plants to fully run on biomass [52]	No	Specifically mentioned in NECP [52]	2050
Italy	No	Biomass will mostly be used for heating [55,65]	No	National referendum has forbidden new nuclear builds in Ref. [55,65]	2050
Latvia	Yes	Not excluded [66]	/	Nothing stated [66]	2050
Lithuania	Yes	Increase expected [67]	No	Parliament does not foresee development in the future [67]	2050
Luxembourg	Yes	Increase expected [68]	No	Specifically mentioned in NECP [68]	2050
Poland	Yes	Increase expected [69]	Yes	Specifically mentioned in NECP [69]	/
Portugal	No	Careful with use of biomass in power sector, will eventually decrease its use [70]	No	Specifically mentioned in NECP [70]	2050
Romania	Yes	Seen as an important resource [71]	Yes	Specifically mentioned in NECP [71]	/
Slovakia	Yes	Increase expected [72]	Yes	Specifically mentioned in NECP [72]	2050
Slovenia	Yes	Increase expected [73]	/	Still undecided [73]	2050
Spain	Yes	Increase expected [74]	No	Specifically mentioned in NECP [74]	2050

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(*continued*)

Country	Biomass allowed?	Based on:	Nuclear allowed?	Based on:	Net-zero by:
Sweden	Yes	Important in transition to fossil-free. Already plays an important role in power sector [75].	Yes	Specifically mentioned in NECP [75]	2040
United Kingdom	Only combined with CCS	Large scale biomass-based electricity generation only supported with addition of CCS [76]	Yes	Specifically mentioned in NECP [76]	2035
Norway	No	Little focus on bioenergy for power as their electricity system is already mostly renewable (hydropower) [77]	/	Not forbidden or endorsed [77]	2025
Switzerland	Yes	Use biomass to increase energy security and decrease GHG emissions [55]	No	Phase-out after referendum [55]	2050
Netherlands	No	Only use for high grade applications where there are few/no alternatives [78]	/	Still undecided [78]	2050

Appendix I. National electricity costs in 2050 for REF and REF+

Electricity costs by country [€/MWh]		
	REF	REF+
Austria	187	185
Belgium	161	201
Bulgaria	138	134
Croatia	157	154
Czech Republic	142	134
Denmark	123	130
Estonia	271	277
Finland	85	87
France	90	93
Germany	102	118
Greece	76	75
Hungary	182	175
Ireland	77	87
Italy	80	82
Latvia	236	235
Lithuania	221	245
Luxembourg	374	622
Poland	91	85
Portugal	124	131
Romania	103	88
Slovakia	200	197
Slovenia	422	395
Spain	82	82
Sweden	100	97
United Kingdom	75	91
Norway	89	91
Switzerland	217	197
Netherlands	85	98

Appendix J. Sensitivity analysis additional results

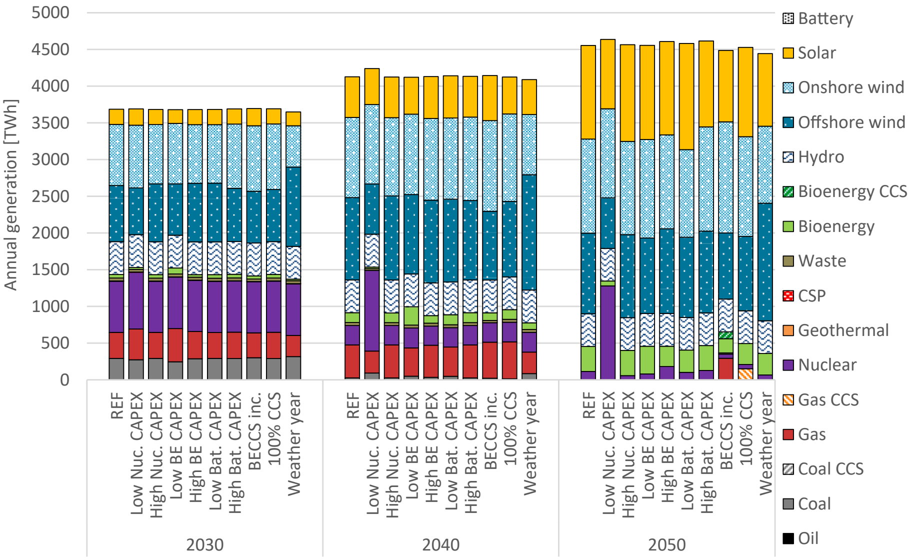


Fig. 10. Sensitivity analysis results on total Europe generation portfolios in TWh/year for the 9 sensitivity runs plus REF scenario

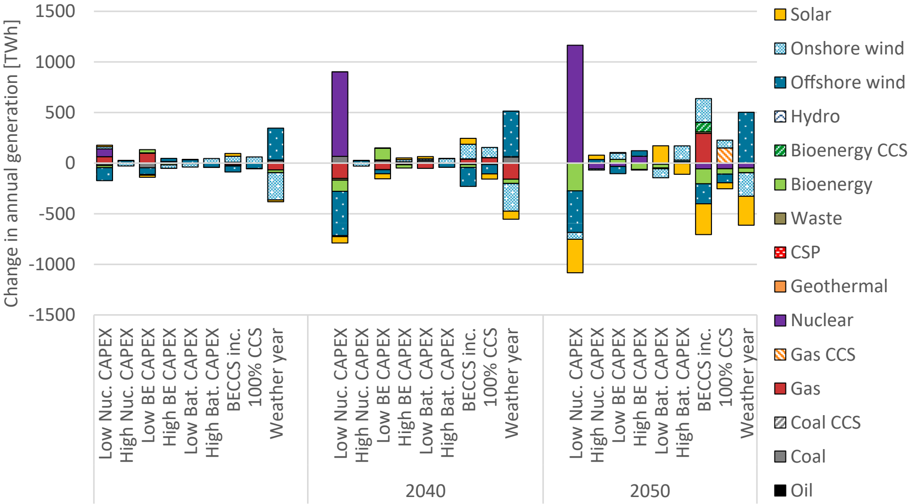
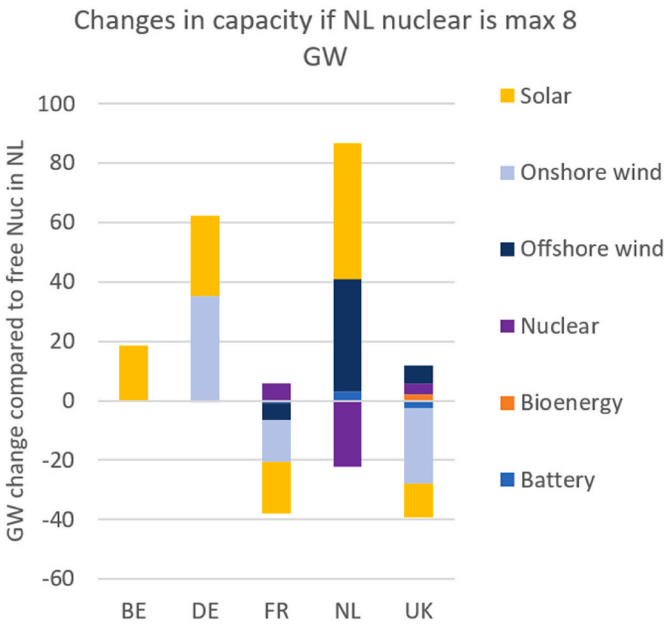


Fig. 11. Differences in generation portfolios in the Europe region in TWh compared to the REF scenario

Appendix K. – Additional scenario with constrained nuclear in the Netherlands

Based on existing energy modeling studies conducted on the Netherlands suggesting a maximum nuclear capacity ranging from 5 to 12.5 GW [32–35], a maximum 8 GW of nuclear is enforced in the Netherlands. The main changes in the results can be seen on figure below.



Although total system costs only increase by 1 % in this scenario, unserved energy factor uncreases from 0.0016 % to 0.005 % [85].

Appendix L. Overview of methods used in similar studies

Authors	Research topic	Model used	Geographical scope	Time resolution	Time scale	Type	Policies included
[8]	Robust power system consistent with the Paris Agreement	PLEXOS	Western Europe, countries modelled as individual nodes	Hourly	2050	Greenfield	Yes
[9]	Feasibility of a 100 % renewable European power system in 2050	PLEXOS	EU + NO, CH and UK, countries modelled as individual nodes	Hourly	2050	Greenfield	No
[79]	Integration of intermittent renewables	PLEXOS	Western Europe, countries modelled as individual nodes	Hourly	2050	Greenfield	No
[18]	Integration of intermittent renewables	TIMES	France	4-hourly	2012–2050 divided over 13 periods	Brownfield	No
[19]	Decarbonisation pathways of South-East Europe	Elesplan-m	Europe, countries are clustered into regions	Hourly	2016–2050 using 5 year timesteps	Brownfield	No
[16]	Decarbonisation pathway of a national integrated energy system	IESA-OPT	Netherlands[a]	Hourly	2020–2050	Brownfield	Yes

[a] This study also includes European countries with some clustered regions. However, the power sector capacities of these countries are exogenously defined.

Appendix M. Annual Electricity Import-Export

Table 16
Annual Import-Export in 2050 under the REF Scenario (TWh). Columns represent the country of origin for imports, and rows represent the destination country.

	AT	BE	BG	CH	CZ	DE	DK	EE	EL	ES	FI	FR	GB	HR	HU	IE	IT	LT	LU	LV	NL	NO	PL	PT	RO	SE	SI	SK
AT				1.7	1.4	17.2									1.8		4.5										1.4	
BE						1.4						16.4	8.2						0.6		8.2							
BG									5.1																1.2			
CH	4.4					15.4						21.2					14.7											
CZ	3.5					7.6																	7.5					1.1
DE	22.0	2.2		14.4	3.1		15.9					16.7	11.1						1.4		15.5	6.3	8.0			15.0		
DK						3.9							9.9								1.3	9.5				8.7		
EE											2.7									2.2								
EL			1.8														2.5											
ES												20.1												2.3				
FI								0.9														2.1				11.1		
FR		7.4		3.7		7.3				23.5			24.5			3.1	12.9		0.4									
GB		2.1				3.8	6.5					21.9				15.3					3.1	9.6						
HR															0.2												0.5	
HU	5.5													2.5											4.0		1.8	4.0
IE												1.7	4.1															
IT	4.2			9.7					5.0			12.9															1.2	
LT																				1.4			1.8			1.4		
LU		2.1				2.5						1.5																
LV								0.7										0.8										
NL		6.4				7.6	2.0						10.8									2.6						
NO						3.4	7.8				1.1		12.3								2.4					6.5		
PL					2.7	5.3												3.8								5.9		2.6
PT										6.9																		
RO			1.3												3.5													
SE						6.9	10.9				9.1							0.8				11.2	2.9					
SI	3.6													2.0	0.4		1.7											
SK					2.7										2.1								6.5					

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