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The open source electricity Model Base for Europe - An engagement framework for open and transparent European energy modelling

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ABSTRACT

The transition to a low carbon energy system as laid out in the Paris Agreement and the European Green Deal presents challenges that involve society at all levels from planners to consumers. A key challenge is the communication across these levels. Tools to foster engagement and discussion between the different actors are open-source models with a low threshold for uptake. This paper presents the Open-Source electricity Model Base for Europe an electricity sector engagement model covering all member states of the EU, Norway, Switzerland and the United Kingdom. Built in OSeMOSYS and available on GitHub, the model provides a starting point into energy systems modelling and can be further developed in a collaborative manner. It enables non-experts to develop an understanding of energy systems models and energy planning. Thereby, it can serve as an engagement tool to carry the debate on the future of the European power system beyond the academy, which might contribute to finding societal consensus on how to decarbonise our energy system. The model allows dynamic power sector expansion analysis of the European power system till 2050. It can be used for scenario analysis and is expandable to other sectors to analyse the benefits of sector coupling.

1. Introduction

In the European Green Deal of the European Commission (EC) the EU commits itself to net zero greenhouse gas (GHG) emissions in 2050 and a decoupling of growth from resource use [1]. 35% of the energy-related CO2 emissions in the EU originate from the power and heat sector, thereby it is the largest source of energy-related emissions [2]. In 2017 the EU electricity sector had a carbon intensity of 294 gCO2/kWh [3]. This relates to 936 million tonnes of CO2, which are about 25% of the CO2 emission in the EU, while only representing 21% of the final energy demand in the EU [4]. For comparison heating and cooling represent approximately 50% of the final energy demand in the EU [5]. To reduce these emissions by 2050 or even earlier to net zero while maintaining secure and affordable electricity supply, thorough energy planning is needed.

To reach these ambitious goals, citizens need to be able to understand and engage in the process, also at the local level. One way to increase engagement and understanding is to increase transparency and accessibility of the analytical tools used in the design of the EU's strategy. The need for transparency to achieve societal consensus down to the local level has been recognised by the EC. The Commission therefore fosters transparency with its action plan to turn FAIR data into reality, where FAIR stands for Findable, Accessible, Interoperable, and Reusable [6]. FAIR data is of high relevance for some of the most important energy systems planning tools: models. FAIR data is expected to have a significant impact by facilitating the generation of new insights, as highlighted by Manfren et al. [7]. Manfren et al. conclude that open energy modelling is crucial to an effective science-policy-market interaction in the energy transition [7]. Pfenninger et al. highlight in this regard that open models and open data can improve the quality of research, increase the efficiency of the collaboration across the science-policy boundary, increase the productivity through burden sharing, and that energy models and data have a profound relevance to societal debates [8].

The purpose of models is to quantify and analyse scenarios and policy options [9]. Over the last 70 years a wide range of models have emerged [10]. In the following a selection of models is presented.

A landmark in the field is the PRIMES model developed at the

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National Technical University of Athens [11] and used for several EU Reference Scenarios [12]. The PRIMES model and its submodules are able to provide detailed insights on potential decarbonisation pathways of the European energy system.

The POTEnCIA model was developed at the Joint Research Centre (JRC) of the EC [13]. POTEnCIA combines behavioural decisions and optimization. Especially on the demand side the model provides a high level of detail, considering energy demands at a subsector level [14].

A well established energy planning tool by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) is the TIMES modelling framework [15]. It has been used for numerous national and regional analysis', for example to analyse the interaction between nation renewable support schemes and the EU ETS [16], or as part of an integrated assessment toolbox by Korkmaz et al. [17]. One TIMES model is the JRC-EU-TIMES model developed at JRC. It was first used in 2013 for analysing the long-term role of the energy technologies in the SET plan [18]. The JRC-EU-TIMES model is available under an open source license [19]. So is the TIMES framework [20]. Also using TIMES is the TIMES PanEU model developed and maintained at University of Stuttgart IER. TIMES PanEU covers the entire energy system with sector interlinkages of the EU member states, Iceland, Norway and Switzerland. It covers the time period 2000 to 2050 [21]. A third European power and heating system model built in TIMES is used by Ringkjøb et al. [22]. They analyse the representation and impacts of short-term variability of renewables on the European energy system.

Another effort to build a European long-term energy planning model has been made by Ref. [23] using the Global Energy System Model (GENeSYS-MOD), a modelling framework based on OSeMOSYS [24]. In this model Europe is represented in seventeen regions, i.e. it is aggregating several groups of countries to regions. The model goes in 5-year time-steps and splits the modelled years into 16 time slices.

Furthermore, there are several models of Europe that are fully open-source. One of them is built using Calliope [25]. Calliope is a fully open source framework for energy systems modelling [26]. It provides a great amount of flexibility regarding the temporal and spatial resolution. Calliope models commonly simulate the operation of an energy system for a year under certain boundary conditions, e.g. regarding the shares of different energy carriers; one can start with a greenfield or a brownfield [27,28].

Another open-source model of the European power system has been built using the framework PyPSA [29]. The goal of this work is to provide a highly detailed model at generation and transmission network level. In general, the modelling framework PyPSA is designed to build models to analyse power flows in power systems with large shares of variable renewable energies over multiple periods. However, it cannot model multi-year dynamic investment patterns like OSeMOSYS can [30].

The open energy modeling framework oemof has to the knowledge of the author not been used for building a model of Europe [31]. However, the design of oemof seems to aim for allowing sophisticated and detailed technology modelling, which necessarily results in a more sophisticated framework requiring in depth technological knowledge [32].

Summarizing, it can be noted that there is a large variety of long-term energy planning models for Europe. However, many of these models are not fully accessible. Either the models are completely closed or parts of them are, like for example the modelling language used by the framework, e.g. PRIMES [11], POTEnCIA [14], TIMES [20] or GENeSYS-MOD [24], or in the case of TIMES also the interface [20].

In sum, the above-mentioned models are not fully complying with the FAIR criteria. The existing fully open-source models like Euro-Calliope or PyPSA-Eur have a different scope of analysis.

Therefore, the goal of this work is to present OSeMBE (Open Source electricity Model Base for Europe), a fully open source and low-threshold long-term energy planning model that provides insights on how the transition to a low-carbon power system in Europe could look like. OSeMBE does not aim to be one more large energy system model, but rather to complement the existing ones as an engagement tool, which creates a link between non-modellers and students and the community of energy modelling experts and increases reach and accessibility of the modelling science. This paper documents its creation and structure in detail, as a first step towards accessibility.

OSeMBE is built using OSeMOSYS, a leading energy modelling tool widely used for education, capacity building and stakeholder engagement. OSeMOSYS is a deterministic optimization tool ideal for modelling of long-term energy investment pathways [33]. An alternative modelling approach could have been a simulation model, which provides a high degree of flexibility due to its modularity. Due to this characteristics Lund et al. conclude that simulation models are well-suited for debating the desired future [34]. However, the flexibility can create complexity, as highlighted by Pfenninger et al. [35]. Like all long-term energy investment tools, also OSeMOSYS comes with certain shortcomings. For example, the detailed operation of the system is only represented to a limited extent. This brings up a question related to the trade-offs between operational detail and width of the scope. However, such reflection deserves own elaboration and is outside of the scope of this paper. Chang et al. conclude in their comparison of 54 modelling tools that there is not and cannot be one tool that captures all aspects that could be interesting to analyse [36].

Considering the design of OSeMOSYS with a focus on long-term investment planning and on education and engagement, it was used for this modelling task.

OSeMBE is designed to be useable in higher education and allows continuous development by a community of users. Its structure captures the main dynamics of the EU electricity sector, while keeping simple and incrementally modifiable.

The remaining part of this paper is structured into the following sections. The methodology section (2) presents the structure of the model and the data used. Section three (3) describes the modelled scenarios. In section four (4) the modelling results are presented and discussed. The final section five (5) presents the conclusion and summarises the scientific contribution of this work.

2. Methodology

OSeMBE was developed using OSeMOSYS - the Open Source energy Modelling System. OSeMOSYS is a bottom-up linear optimization tool for long-term energy planning [33]. It is widely used in capacity development activities in developing countries, for example during the summer schools at the International Centre for Theoretical Physics [37–39] or the Energy Modelling Platform for Africa (EMP-A) [40], and has been adopted by governments for the creation of national energy plans [41]. OSeMOSYS provides a fully open source framework with clear structured code and a growing community. This facilitates its usage in education and enables new users to pick up existing models and further develop those.

The GNU MathProg implementation of OSeMOSYS with some minor modifications was used, as available on the OSeMBE GitHub repository [42].

Below, the model is described in terms of its model structure, representation of time, final demands, technology and fuel portfolio, representation of fossil fuels and renewables, trade technologies and emissions. A description of illustrative scenarios used in this paper to demonstrate the insights of the model is presented in section 3.

2.1. Model structure

The model captures the European electricity sector. All 27 EU member states are modelled, as well as Switzerland, Norway, and the United Kingdom. Each country can be seen as one node in the model. The countries are connected by transborder electricity transmission lines. Existing capacities as well as the ones currently under construction are considered [43]. In its first implementation, the model considers for energy storage only pumped hydro storage (PHS) in a simplified manner. A more detailed consideration of storage technologies would have implied a significant increase in Random-Access Memory (RAM) required and currently storage technologies account for approximately 5% of the installed power capacity in the EU28 [44,45]. A detailed explanation of the consideration of storage technologies can be found in section 2.5. Per country one separate final electricity demand is considered. The development of the demand throughout the modelling period follows the expectations indicated in the EU reference scenario 2016 [12]. Only for Norway [46] and Switzerland [47] the demand development had to be taken from other sources since they are not part of the EU reference scenario 2016.

2.2. Time definition

The modelling period covers each year from 2015 to 2050. The time resolution is defined based on the overall electricity load and average capacity factors for wind and solar of all the modelled countries.

Each year is divided into fifteen time slices. The time slices were defined in a three-step approach. In the first step the daily average load and the daily average capacity factor of wind are compared to identify characteristic seasons. The graphical analysis resulted in a division of the year into five seasons. The division is shown in Table 1 and Fig. 1. In Fig. 1, the green line represents the daily average load and the blue line the capacity factor wind, the red line indicates the seasonal average, i.e. every horizontal section of the red line represents one season.

After the definition of the seasons, the average load profile of each weekday in each season was analysed to define the number of day types per season. The main difference identified is between weekdays and weekends, shown in Fig. 2. On the days of the weekend, the load is clearly lower than during the working days. However, the load curve follows the same pattern. Therefore, the compromise was made to have just one type of day per season in order to keep the model as light as possible.

In the third and last step the time slices in each season were defined, using graphs like shown in Fig. 3. The red area in the background of the graph indicates the load on an average day in the season. The dotted line indicates the average solar PV capacity factor. The columns indicate the average load of the defined time slices. In Fig. 3 the first 6 h of a day comprise one time slice, the hours from 7 to 21 a second time slice and the hours from 22 to 24 a third time slice.

The approach chosen for representing variability of supply and demand is rather simple. However, by keeping the consecutive order of the time slices a later addition of storage to the model is possible.

This analysis uses hourly load values from ENTOS-E's transparency platform [43]. The hourly wind and solar capacity factors are the averages for the years 1980–2016 and 1985 to 2016 respectively and were derived from the renewable.ninja platform [48].

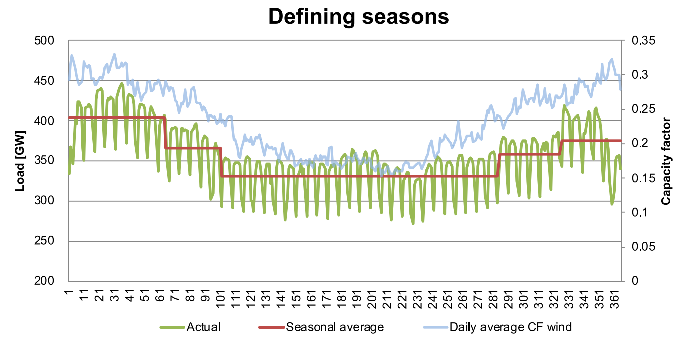

Fig. 1. Definition of the five modelled seasons.

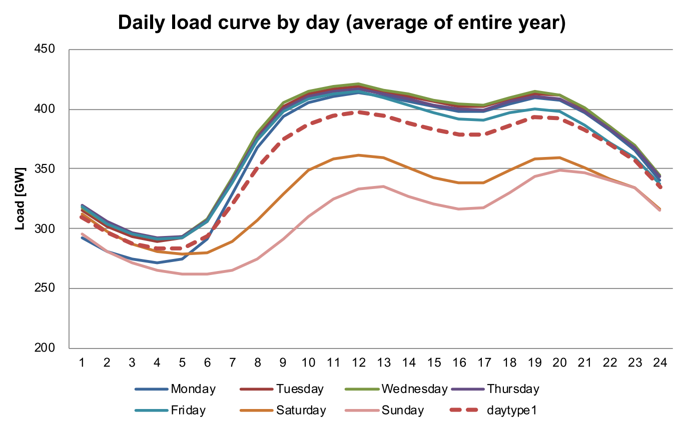

Fig. 2. Defining daytypes

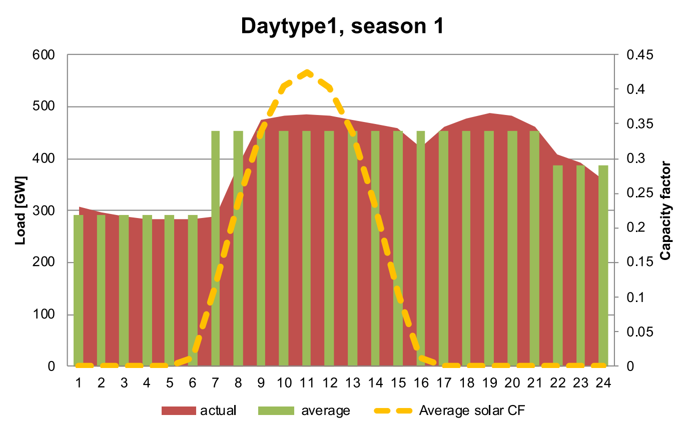

Fig. 3. Defining time slices.

Table 1
Season definition by start and end day.

	Start day	End day
Season 1	1	64
Season 2	65	101
Season 3	102	284
Season 4	285	325
Season 5	326	365

2.3. Demands

The current version of the model considers one overall electricity demand per country, using data from the EU Reference Scenario 2016 [12]. However, the model can be easily modified and additional demands or a more disaggregated representation of the electricity demand can be implemented if data is at hand. This enhancement of the model could also be done only for selected countries, perhaps in context of a country case study.

2.4. Technology portfolio and fuels

The technology and fuel portfolio in OSeMBE aims to cover the key power generation technologies applied in the European power sector. Fig. 4 illustrates exemplarily the Reference Energy System (RES) of Germany. It illustrates the connections of fuels and technologies in the model with the demanded electricity on the right side of the graphic. With small adjustments, the general structure can be applied to all modelled countries. The RES is slightly simplified at the power plant level. To allow readability, the different power plant options per fuel are summarised to Power Plant - PP and Combined Heat and Power plant - CHP. On the left side of the RES the different available fuel options are represented. In the middle column, the centralised power generation options are indicated. The column between secondary and final energy level shows distributed power generation options, as well as transmission and distribution. In the lower areas of the secondary energy level the links to neighbouring countries are indicated in pink.

Table 2 shows a full list of all available power generation technology-fuel combinations that are considered in OSeMBE. The aim is a consistent technology specification methodology, the characteristics of most technologies are retrieved from the Energy Technology Reference Indicator projections for 2010–2050 [49]. All sources are listed in Table 2.

As shown in Table 2, the available fuels in OSeMBE are: Biofuel liquid, Biomass, Coal, Geothermal, Heavy Fuel Oil (HFO), Hydro, Natural gas, Nuclear, Ocean, Solar, Waste, and Wind.

In the model the technologies are named following the naming convention shown in Table 3. The abbreviations used for countries, commodities and technologies in the technology names are listed and explained in appendix A.

In the following three paragraphs light is shed on aspects of the representation of coal, hydro, nuclear and wind power that go beyond the representation of the other technologies.

A phase out of the power generation from coal is considered in the following countries based on information by Europe Beyond Coal [55]: Austria, Belgium, Germany, Denmark, Finland, France, Greece, Hungary, Ireland, Italy, the Netherlands, Portugal, Sweden, Slovakia, and the United Kingdom.

For hydro power the model distinguishes between run-of-river, dam and PHS. The technologies vary in terms of cost and availability.

In OSeMBE nuclear power plants of the second and third generation are considered. The second generation represents the existing nuclear power plants, but the model cannot add new capacity of this type [49]. The third generation is available for the model to be added in countries that either have already nuclear power plants or are in an ongoing discussion on building nuclear power plants like e.g. Poland [56]. In countries that have decided to phase out nuclear power, like Germany and Switzerland, no new nuclear power capacities can be added.

With the goal to picture a potential expansion of nuclear power in a realistic manner only 3 GW of new capacity can be added by the model per year and country.

Table 2 indicates that there are countries where wind power is considered with two onshore technologies and with up to three offshore technologies. The reason for having multiple technologies per type of wind power can be found in two aspects that need to be considered when modelling wind power. Firstly, the geographic variation in wind speeds. And secondly the improving capabilities of wind turbines to deal with different and specifically low wind speeds. OSeMBE currently follows the approach of Staffell and Pfenninger in distinguishing between currently installed capacities, capacities under construction and planning, and long-term capacity additions [57].

The model is only allowed to invest in one onshore and one offshore technology type per country at a time, i.e. for example first in the near-term and later in the long-term offshore wind power.

2.5. Storage

Storage processes were not explicitly modelled in this version of the model. In the current implementation of OSeMOSYS, the representation of storage processes would require high performance computational hardware, defying the purpose of OSeMBE of providing an engagement model. However, the implementation of storage its strength and its limitation were studied on one country, Germany, by extracting it from the entire model. In the Germany model battery storage was implemented. For the batteries different scenarios were implemented regarding the cost development, under different time resolutions, listed in Table 4.

Welsch et al. point out that a time slice approach allows a simplified analysis of storage, but not at the hourly level [58]. The results of the Germany model show that at OSeMBE's current time resolution, storage is not being applied. However, by increasing the time resolution, storage finds its use. With a time-resolution of 144 time slices batteries start being installed from the mid 2030s onwards. Fig. 5 shows power generation patterns in the German model with 144 time slices for the summer season. For both, weekdays and weekend days the results show the use of storage, for both PHS and batteries.

The sensitivity of long-term energy planning models regarding their time resolution is not unusual. Welsch writes in her analysis of storage and flexibility options using the TIMES PanEU model, that for a detailed analysis of storage and flexibility options an increase of the time resolution is required [59].

In OSeMBE only a simplified representation of one storage option was introduced: PHS. PHS is modelled using only the parameter availability factor, while the other hydro power technologies are modelled using the parameters availability factor and capacity factor. The former indicates the availability of a technology in the entire year while the later specifies the availability per time slice. Like this the model can schedule the use of PHS more freely.

The representation of storage presented above for Germany could be implemented in OSeMBE for all countries, if the equations for storage in OSeMOSYS are improved. Niet et al. has compared different sets of storage equations in OSeMOSYS [60]. The possibility to accurately account for storage losses in OSeMOSYS has been improved by Palombelli et al. [61]. The possibility to consider other flexibility options within a smart grids approach has been explored by Welsch et al. [58]. However, a set of storage equations that are computational more efficient is still pending.

2.6. Resources

OSeMBE considers as fossil fuels coal, natural gas and heavy fuel oil (HFO) for power generation. In the case of HFO also unrefined crude oil is considered as a preceding commodity, which can be converted in refineries to HFO.

The domestic production of coal, natural gas and crude oil in the

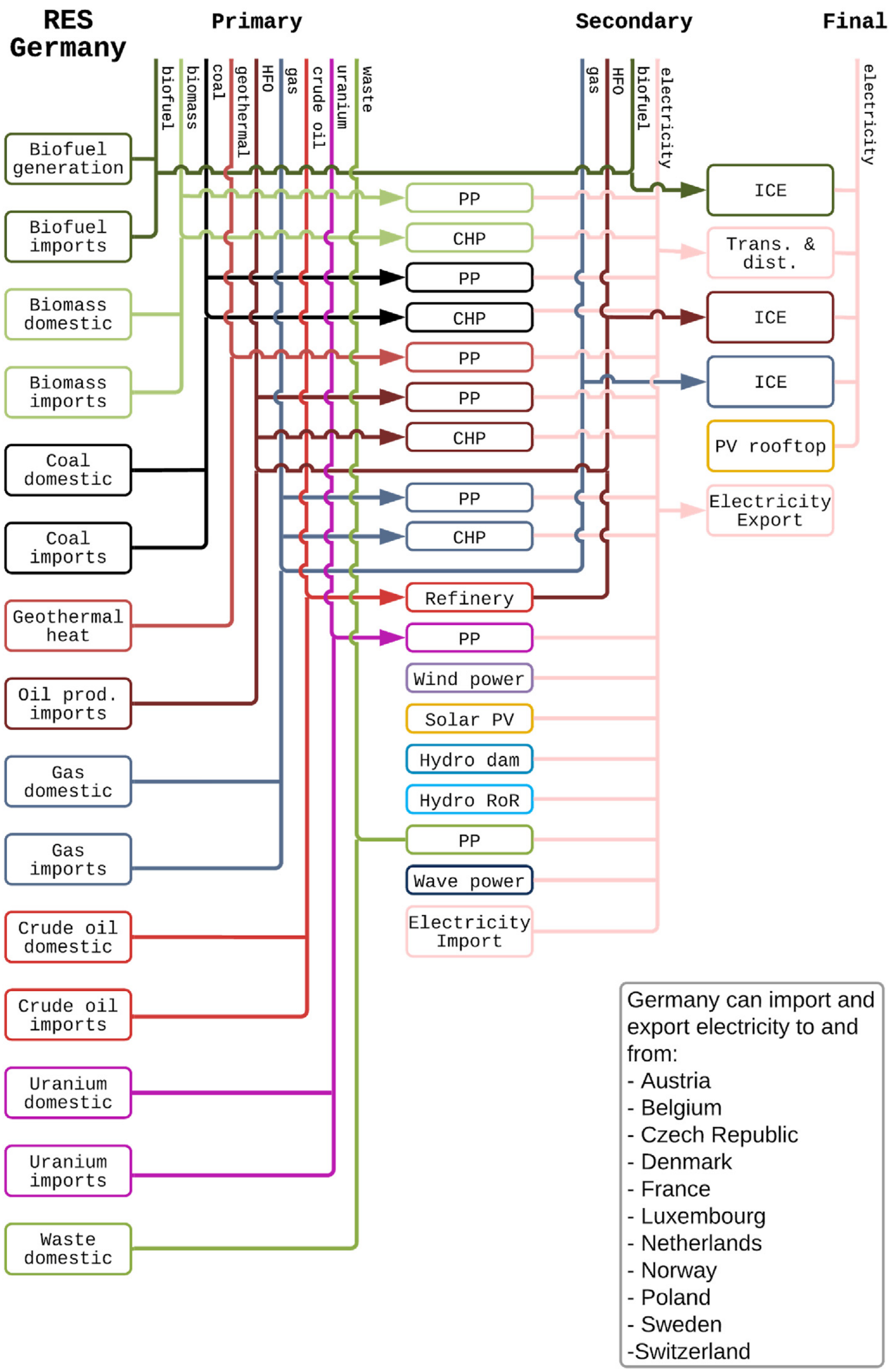

Fig. 4. Reference energy system Germany.

modelled EU member states is limited on an annual base following the EU Reference Scenario 2016 [12]. In Switzerland there is no significant domestic production of coal or natural gas [62,63]. The same was assumed for domestic oil in Switzerland. For Norway it is assumed that no coal mining of significance takes place due to lacking indications in literature. An unlimited extraction of oil and gas is allowed in Norway. This is allowed since oil and gas distribution and trade are not considered in the model. Domestic production can only be used domestically and cannot be exported.

In all countries modelled, coal, natural gas and HFO can be imported not taking into account any limits. Their costs are implemented in M€/PJ and are retrieved from a report by the UK Department of Energy & Climate Change [64].

Most of the resource potentials are derived from the EU Reference Energy Scenario 2016 [12]. The following points highlight particularities of the representation of renewable resources and diverging data sources:

Biomass

- The EU Reference Scenario 2016 indicates biomass and waste used for power production jointly, with a varying ratio [12]. In OSeMBE waste and biomass are considered separately. The

Table 2
Technology fuel combinations.

Fuel	Technology	Country	Source
Biofuel liquid	Heat and Power unit	all	Biomass CHP Small in Ref. [50]:
Bio-mass	Combined Cycle	all	[49]
	Combined Heat and Power		[49]
	Carbon Capture and Storage		[49]
	Steam turbine		Biomass power plant in Ref. [50]:
Coal	CHP	all	[49]
	CCS		[49]
	Steam turbine small		Steam Coal-Subcritical in Ref. [50]:
	Steam turbine large		Steam Coal-Ultrasupercritical in Ref. [50]:
Geo-thermal	Conventional	All except: CZ and MT	[49]
Heavy Fuel Oil (HFO)	Combined cycle	all	[49]
	CHP		[51]
	Gas cycle old		[49]
	Gas cycle new		[49]
	Heat and power unit small		[51]
	Heat and power unit large		[51]
	Steam turbine small		Steam Coal-Supercritical in Ref. [50]:
	Steam turbine large		Steam Coal-Ultrasupercritical in Ref. [50]:
Hydro	Run of river	All except: CY and MT	[49]
	Dam small		[49]
	Dam medium		[49]
	Dam large		[49]
	Pumped storage medium		[49]
	Pumped storage large		[49]
Natural gas	Combined cycle	all	[49]
	CHP old		[49]
	CHP new		[49]
	Fuel cell		[49]
	Gas cycle old		[49]
	Gas cycle new		[49]
	Heat and power unit small		[51]
	Heat and power unit large		[51]
	Steam turbine		Steam Coal-Supercritical in Ref. [50]:
Nuclear	Generation 2	BE, BG, CH, CZ, DE, ES, FI, FR, HU, NL, NO, RO, SE, SI, SK, UK	[52]
	Generation 3	BE, BG, CZ, ES, FI, FR, HU, NL, NO, PL, RO, SE, SI, SK, UK	[52,53]
Ocean	Wave	BE,BG, CY, DE, DK, DE, EE, ES, FI, FR, GR, HR, IE, IT, LT, LV, MT, NL, NO, PL, PT, RO, SE, SI, UK	[49]
Solar	Rooftop PV	all	[49]
	Utility PV		[49]
Waste	CHP	all	[49]
	Steam turbine		[49]
Wind	Offshore current	BE, DE, DK, FI, FR, IE, NL, NO, SE, UK	[49]
	Offshore near-term	BE, DE, DK, FI, FR, IE, IT, NL, NO, SE, UK	[49]
	Offshore long-term	BE, DE, DK, EE, ES, FI, FR, GR, IE, IT, LT, NL, NO, PL, PT, SE, UK	[49]
	Onshore current	all	[49]
	Onshore near-term	AT, BE, DE, ES, FI, FR, IE, IT, LU, NL, NO, PL, RO, SE, UK	[49]

Table 3
Technology naming convention [54].

AA	BB	CC	D	E	F		AABBCCDEF
Country	Commodity	Technology/connected country	Energy level	Age	Size	→	Technology name

Table 4
Time resolutions tested for storage.

Version	Seasons	Day-types	Daily time slices	Tot. Time Slices
1	5	1	3	15
2	6	2	3	36
3	6	2	6	72
4	6	2	12	144

indicated ratio from the EU Reference Scenario was used to calculate the separate potentials.

- The biomass potential for Switzerland has been derived from Steubing at al. who indicate the sustainable potential of biomass [65].
- The Norwegian potentials for biomass and waste are derived from Scarlet et al. [66].

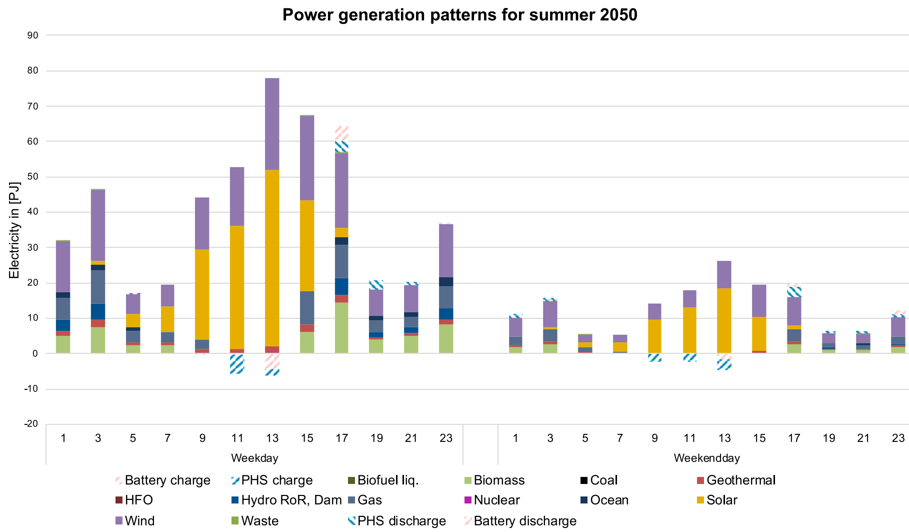

Fig. 5. Power generation on summer weekdays and weekends in Germany in 2050.

Geothermal

- The considered potential of geothermal potential for Switzerland is based on estimates of the Swiss Federal Office of Energy [67].
- For Norway the potential is assumed to be neglectable due to lack of references.

Hydro power

- The hydro power generation potential in OSeMBE is implemented by country, similar to other resource potentials. Since there is only one limit for all hydro power in each country, the limit is implemented via a virtual emission, i.e. in the model each hydro power technology of a country emits one unit of virtual emission per unit of produced electricity. The hydro power potential is then entered as an emission limit.
- The availability of hydropower is modelled via the availability factor and the capacity factor.
- Run-of-river and hydro reservoirs have an availability factor of 0.98 [68]. The parameter capacity factor captures the availability of water based on historic generation data from ENTSO-E [43].
- The national availability factors for pumped hydro storage are determined from historic generation data from ENTSO-E [43]. Using the availability factor only gives the model the flexibility to use the installed capacity when most needed.

Solar PV

- The representation of the solar PV power generation potential follows the same approach as the one for hydropower. There is one production limit for each country. In each country solar PV rooftop and solar PV at utility scale are available. When producing, these technologies also generate a country specific virtual solar emission and the production of this emission is limited with the production potential.
- The solar PV production potential for Switzerland is based on [69].
- In Norway solar PV does not require a limit due to the poor resource potential, captured by the capacity factors.
- The capacity factors for solar PV in OSeMBE are calculated based on country specific data from the platform renewables. ninja [70].

Wind power

- Like for solar the availability of wind power is implemented in the model using the time slice specific OSeMOSYS parameter capacity factor. The capacity factors are calculated using data from renewables. ninja [57].
- The wind power generation potentials for the 27 member states of the EU and the United Kingdom are derived from a study conducted by JRC [71].
- For Switzerland the annual wind potential is based on estimates by Bauer and Hirschberg [69] on generation is implemented due to its vast resource potential.

Uranium

- The uranium needed to run nuclear power plants is assumed to be all imported in the countries covered by the model. Some of the modelled countries have a domestic uranium production, however the domestic production is close to marginal in comparison to the fuel input needed for the nuclear power plants.

2.7. Capacity expansion of variable renewables

In the transition to a low carbon power system, not only the potential annual generation from renewable sources but also the potential annual capacity investments need to be understood. In this work the maximum capacity expansion of wind onshore and solar PV has been estimated in relation to the annual electricity demand of each country. The countries are categorized following the approach in Table 5 using the 2015 electricity demand as a reference. Limiting the capacity expansion based on historical values was considered not suitable since capacity additions have varied significantly based on policy frameworks and changes in those.

Table 5
Annual investment limits for utility PV and wind onshore.

Annual electricity demand	Maximum annual new utility PV/wind onshore capacity
<100 TWh	1 GW
100 to 200 TWh	2 GW
200 to 300 TWh	3 GW
…	…

2.8. Electricity transmission

OSeMBE represents electricity transmission infrastructure in an aggregated way. The RES in Fig. 4 indicates that domestic transmission and distribution of electricity in OSeMBE are represented by one technology. Also the electricity transmission lines that link two countries are aggregated to one technology in the model. This technology can operate in two modes of operation. In mode of operation 1 electricity is transferred from country A to B and in mode of operation 2 electricity is transferred from country B to A. All transmission technologies, i.e. the domestic ones and the cross-border technologies, are modelled in the same way. A loss of 5% of electricity is assumed [72]. In the current version of the model no costs are related to the transmission of electricity. The capacities of the cross-border links are fixed at their existing capacity and new capacities that are planned or under construction are added from the year of their planned start of operation. Therefore, no least-cost optimization of the transmission capacity expansion is allowed. This can be changed, where detailed data on the investments required for new lines is available and where the purpose of the analysis becomes optimization of the interconnections.

2.9. Reserve margin

With the modelling infrastructure that is commonly available today, long-term energy modelling frameworks have limited possibility to assess aspects related to grid reliability [73]. The representation of reserve capacities for example is affected by such limitation, as it normally requires significantly higher computational effort. Like other modelling frameworks [74], OSeMOSYS summarises upwards reserves, including spinning, secondary, tertiary and replacement reserves on the supply side to one reserve margin [75]. Hence, the reserve margin describes the capacity that needs to be available at a given time, beyond the peak demand [76]. OSeMBE uses a reserve margin of 15%. This means that at all times there need to be capacities available that can provide electricity 15% beyond the expected annual peak demand.

The reserve margin is calculated per country. Table 6 lists the assigned capacity credits for technologies in OSeMBE. The capacity credit describes to what extent a technology contributes to the planning reserve margin [77], i.e. a value of 100% in Table 6 indicates that the entire capacity installed of a technology is counted for the reserve margin, while a smaller value indicates that only the indicated fraction is counted.

Table 6
Reserve margin contributions.

Technology type	Contribution to reserve margin
Biofuel	100%
Biomass	100%
Coal	100%
Geothermal	100%
Oil	100%
Hydro power	50%
Gas	100%
Nuclear power	100%
Wind	5% [78]
Waste	100%

2.10. Emissions

OSeMBE covers two types of emissions: carbon dioxide and particulate matter. Carbon dioxide - CO2 is accounted for at the source technologies of fossil fuels, i.e. at technologies that represent import or extraction of coal, gas or oil, for simplicity of representation. This is justified by the fact that CO2 emissions depend scarcely on the process or technology directly emitting them and mostly on the carbon content of the fuel.

The CO2 emissions are limited using the limits of the EU ETS and its trajectory to reduce the CO2 emissions [79]. From 2013 till 2020 the emission limit in the EU ETS was reduced by 1.74% per year. From 2021 onwards the reduction is accelerated to 2.2% [80]. Since the EU ETS covers more than the power sector the limit in OSeMBE is adjusted to the share of emissions by the power sector. The share is estimated based on the power sector emission intensity [81].

Furthermore, the carbon price floor established in the United Kingdom is considered in the model. The carbon price floor sets the minimum cost for CO2 emissions under the EU ETS in the UK to 18£/t of CO2 [82]. To the authors knowledge, the UK is the only country within the EU that has established such a minimum price for GHG emissions in relation to the EU ETS.

OSeMBE accounts for particulate matter smaller than 2.5 μm - PM2.5. The emission factors used are derived from the EMEP/EEA air pollutant emission inventory guidebook 2019 [83]. The used emission factors for PM2.5 are listed in Table 7 below.

3. Scenarios

To demonstrate the insights that can be obtained through the model, three scenarios were implemented. The key policy assumption and modelling constraint is the emission reduction

Table 7
Emission activity ratios for PM2.5 [83].

Technology	Emission Activity Ratio [Mt/PJ]
Biofuel, Internal combustion engine	0.0217
Biomass, Combined cycle power plant	0.0002
Biomass, CHP	0.133
Biomass, Steam cycle power plant	0.133
Coal, CHP	0.0028
Coal, Steam cycle power plant	0.0028
HFO, Combined cycle power plant	0.00195
HFO, CHP	0.0193
HFO, Gas cycle power plant, old	0.00195
HFO, Gas cycle power plant, new	0.0002
HFO, Internal combustion engine	0.0217
HFO, Steam cycle power plant	0.0193
Natural gas, Combined cycle power plant	0.0002
Natural gas, CHP	0.0002
Natural gas, Gas cycle power plant	0.0002
Natural gas, Internal combustion engine	0.002
Natural gas, Steam cycle power plant	0.00089
Waste, Extraction	0.00074

path set by the EU ETS, described above. The first scenario is a reference scenario, in the following referred to as REF. In many aspects, such as demand development, the REF follows the EU Reference Scenario 2016 [12]. In the two other scenarios the effects of changes in available cross-border electricity transmission capacity are tested. The first one allows the model to freely add additional *trans*-border electricity transmission capacity. This scenario is referred to as OBS. The intention of the OBS is to get an impression of which resources an optimization model would use to satisfy electricity demand if there were no bottlenecks in the cross-border flow of electricity. The OBS does not take into account the cost that would come with increases of the *trans*-border transmission capacities.

The second scenario draws the opposite picture in terms of cross-border electricity flow development in Europe in comparison to the OBS. In this scenario the availability of cross-border links is stepwise reduced from 2020 onwards until it is down to 10% in 2027, this scenario is referred to as CBS. The reduction in availability of cross-border transmission lines in the CBS reproduces the pattern of the Danish-German transmission link between the years 2010 and 2016 [84]. In this case the reduction was caused by the procedure to determine the available capacity which took into account the wind power production in Germany. With increasing power production from wind in northern Germany, the availability of the *trans*-border link to Denmark was reduced. The reduction in availability of *trans*-border capacity between Germany and Denmark was ended by the EC.

Summarizing, the three scenarios compare how the power sectors in the 30 modelled countries could evolve depending on the existence of cross-border electricity transmission lines. The cross-border transmission lines can be seen as an indicator of cooperation towards market integration. Therefore, the OBS with open border represents a scenario where member states and EU agree on the expansion of cross-border transmission links to strengthen the European energy system as a whole, a collaborative scenario. On the other hand, the CBS scenario with less cross-border transmission capacities available than today represents a non-cooperative scenario. OBS and CBS represent cases at the edges of the spectrum of possible futures. However, they aim to provide insights on how the borders of the spectrum of possible futures look like and for what kind of analysis OSeMBE could be used.

4. Results and discussion

In this section the results of the three scenarios are presented and analysed, with the aim to highlight the insights that OSeMBE provides.

The results of Germany and Ireland are taken as examples. The two countries are chosen due to their differences. One is in the centre of Europe, connected with many neighbours, has a lot of industry and rather poor energy resources. The other is at the edge of Europe, is only connected to one neighbour, has little industry, but some good resource potentials.

4.1. Power generation patterns

Fig. 6 and 7 show the development of the power generation mixes in Germany and Ireland, respectively. Above the x-axis power generation and imports are shown, below exports are shown.

For Germany, it shows that the power mix in 2015 is dominated coal. However, as indicated in section 2.4, the German policy is considered and coal phases out by 2038 [85]. Also nuclear power phases out by 2022, as can be seen in the Figure. In the years 2030–2050 is notable that wind power achieves a larger share in the power mix if less imports are available. However, photovoltaics

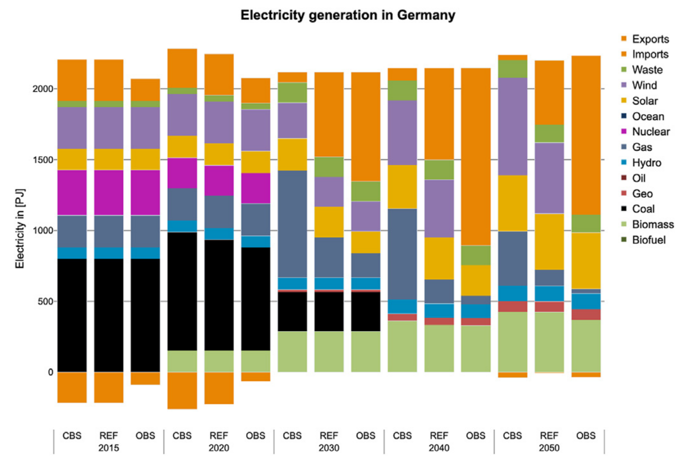

Fig. 6. Electricity generation in Germany across the three scenarios.

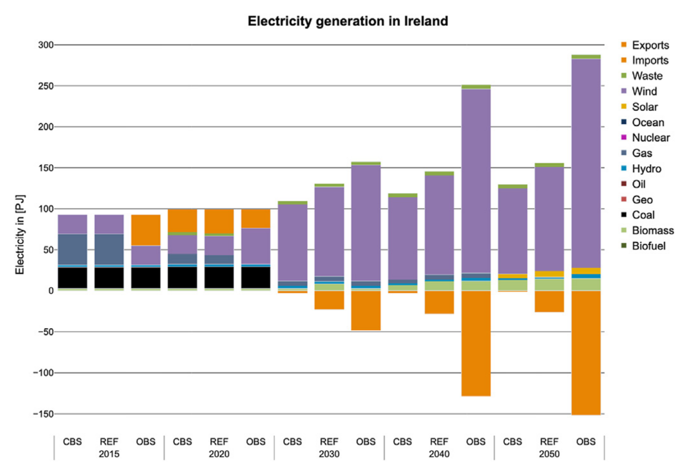

Fig. 7. Electricity generation in Ireland across the three scenarios.

and biomass power are less affected by the availability of cross-border transmission lines.

The increase of imported electricity, as soon as more capacity is available, highlights how important cross-border connections are for Germany to achieve low cost of electricity. The CBS columns in Fig. 6 indicate that when cross-border link availability is reduced natural gas gains importance, which is a GHG emitting technology.

The Irish situation looks very different than the German one. In Fig. 7 one sees that the current Irish power system is dominated by gas, coal and some wind. For the future, the model indicates how renewable resource rich countries like Ireland could benefit from the decreasing cost of renewable energy technologies. In the Irish case the good wind conditions could make the country a net-exporter in the mid-term future.

Fig. 8 and Fig. 9 show the results for the electricity generation more in detail for the REF scenario in 2050 for Germany and Ireland, respectively. The overall picture resembles of course the annual mixes shown in Figs. 6 and 7. However, one can notice the variation of demand, wind and solar variability and their effect on the generation mix. The demand is characterised by low demand during nights, high demand in the daytime, and evenings at an intermediate level. Also, well visible are the seasonality and daily variation of solar power, shown in yellow.

In particular in Germany, it is interesting to notice how the balancing of supply and demand is to a significant extend done by

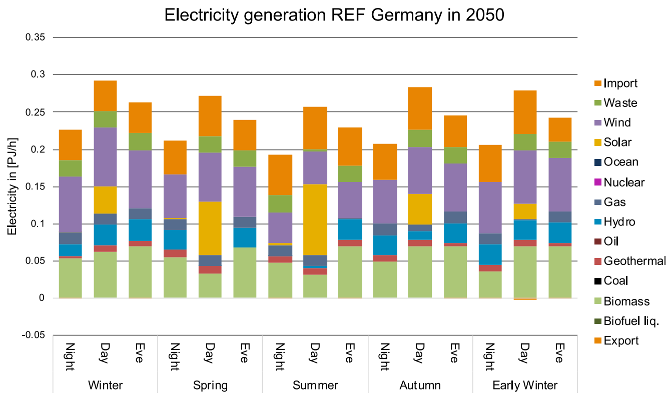

Fig. 8. Electricity generation in Germany in 2050 in REF across Seasons and time slices per hour.

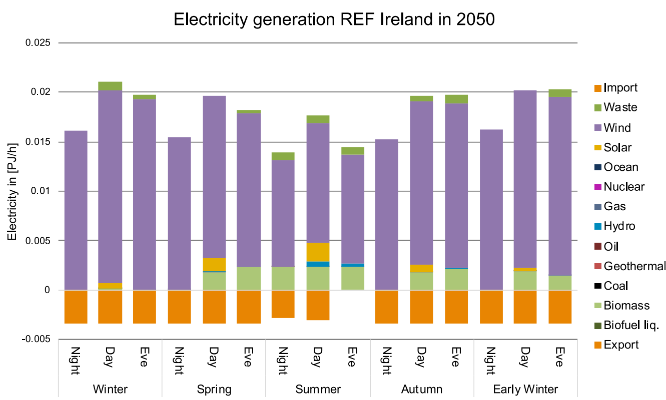

Fig. 9. Electricity generation in Ireland in 2050 in REF across Seasons and time slices per hour.

biomass power plants while imports show a lower variation. In Ireland one can see how biomass, hydro and waste compensate the variability of wind and solar.

4.2. Capacity development/new capacities

This section discusses the capacity development in Germany and Ireland throughout the modelling period. They are shown in Fig. 10 and 11.

The capacity development in Germany across the three modelled scenarios, shown in Fig. 10, illustrates how different the mix of installed capacities could look like depending on the

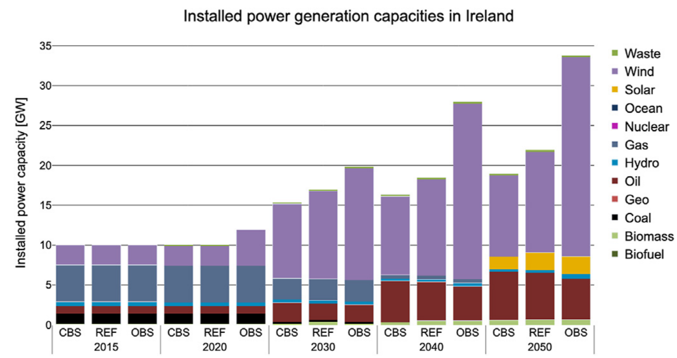

Fig. 11. Power generation capacities in Ireland across the three scenarios.

boundary conditions. Between the OBS and CBS, one sees a difference in overall installed capacity of almost 100 GW. Such differences can be of particular interest when estimating investment needs. However, as indicated in the previous section on power generation patterns, the low capacity in the OBS scenario goes along with reliance on imports from neighbouring countries.

The development of installed power generation capacity in Ireland is inverted in comparison to Germany, i.e. in 2050 the installed capacity is higher in the OBS scenario than in the CBS scenario.

The plots show in brown oil burning capacities. However, in the power generation plots in the previous section oil does not appear. This indicates that the model installs capacities relying on oil to meet the reserve margin requirement. This is the result of a pure optimization, where the model is let free to use any type of thermal capacity for the reserve margin. No policy considering restrictions in that regard is introduced, as the purpose of this analysis is to demonstrate the functioning and cost-competitiveness dynamics in the model, rather than specific pathways.

However, it may be argued that the investment in oil burning capacities in the next decades, even though only for reserve purposes, may be anachronistic. In Fig. 12 a comparison is presented between the previously described REF scenario and a REF scenario with the modification that HFO burning technologies are not considered for the reserve margin, called No-Oil-Reserve-Margin (NORM). It shows that the removal of oil for the reserve margin is almost fully compensated by additional gas burning capacities (dark blue). One might also notice that the installed wind power capacity is slightly lower in the NORM scenario than in the REF scenario. This reflects that the gas capacities that are installed instead of the oil capacities have a higher share in the generation

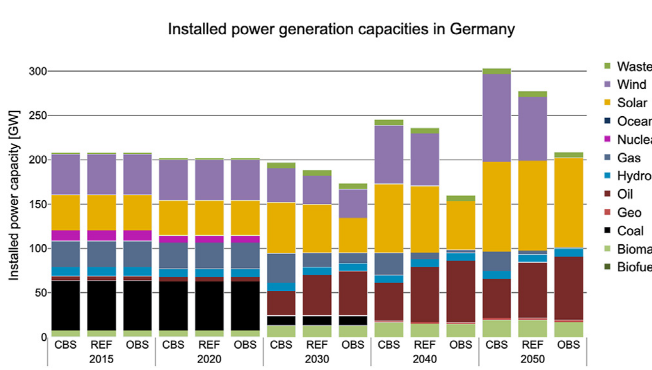

Fig. 10. Power generation capacities in Germany across the three scenarios.

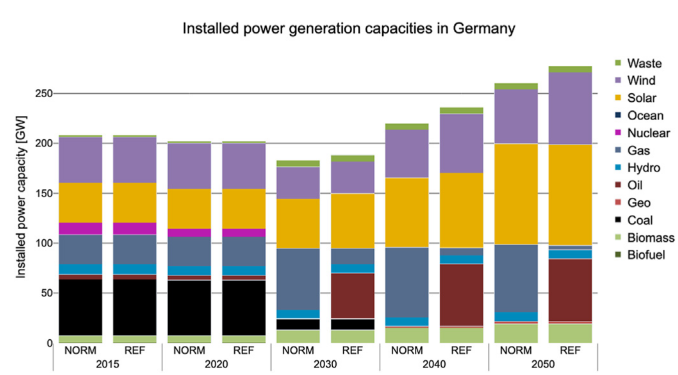

Fig. 12. Comparison of installed capacities in reference scenario and no−HFO−in-RM scenario.

mix than the oil capacities have in the generation mix in the REF scenario, this can be observed in Appendix B, Fig. B1. This comparison shows in short how the least-cost technology mix may change in the light of different policy priorities and how scenario analysis could be carried out with the model.

4.3. Emission pathway

Fig. 13 shows the CO_2 limit implemented in OSeMBE and the total annual CO_2 emissions of the REF scenario. The calculation of the CO_2 limit is explained in the above section on emissions. The results of the other two scenarios are very similar. The black line indicates the emission limit and the grey area the emissions in the REF scenario.

4.4. Trans-boundary electricity exchange

The previous sections illustrate that the availability of cross-border electricity transmission capacity impacts the development of capacity and generation mix in the contemplated countries.

This section compares trade patterns across scenarios for 2030 and 2050.

The scenarios produce cross-border electricity transmission patterns shown in Table 8 for the years 2030 and 2050. Because of the scenario set up, the amount of exchanged electricity varies strongly, as shown in Table 9. In the OBS the total of electricity transmitted across borders is about 24% higher by 2030 and 165% higher by 2050 than in the REF scenario. In the CBS the total of electricity transmitted across borders is between 87% and 82% lower than in the REF scenario.

The connecting bars in the graphs in Table 8 have the colour of the country from which the electricity originates.

Notable in the graphs is that Germany turns to be heavily reliant on imports in most of the shown years and scenarios. One exception is the scenario with reduced availability of cross-border electricity transmission. In that scenario Germany mainly exports electricity in 2050. But also in the REF Germany exports some electricity. The comparison with other major economies in the model is interesting. Also Italy relies strongly on imports in 2050. But in 2030 it exports more than it imports. While across scenarios and years France mostly exports electricity. However, when cross-border capacities are reduced France imports in 2050, the year and scenario where Germany exports. Furthermore, Norway exports large amounts of electricity to connected countries in northern and central Europe.

The variations in the pattern across the scenarios are an indicator that the deployment of renewable energy technologies at locations with their best resource potential in combination with the availability of cross-border electricity transmission lines would on

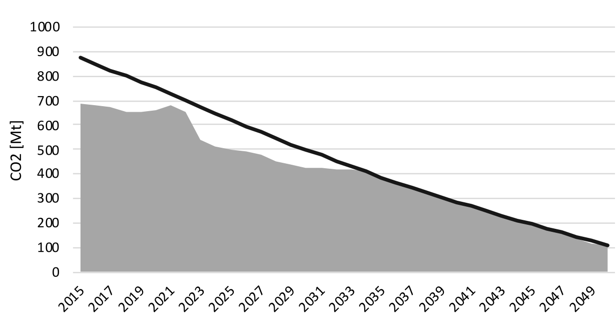

Fig. 13. CO_2 emission limit and CO_2 emission development.

the one hand reduce the overall system cost, but on the other hand massive visual impacts would be a consequence in regions with good resource potentials.

The cost difference across the three scenarios is rather small. The overall system costs in the REF scenario are 2,444,521 M€, this excludes the cost of interconnections. In the OBS they are 1.6% lower, while in the CBS they are 1.3% higher than in the REF. However, this does not consider that national or local cost might be impacted differently, e.g. consumer prices and investment needs.

5. Conclusions

This paper has presented OSeMBE, a low-threshold fully-open model of the electricity system of the EU27+3. OSeMBE captures the key dynamics of the evolution of the EU power sector until 2050 in an essential but realistic way, offering an engagement tool, able to connect non-modellers and students to the European energy modelling community and to offer insights into its work.

To meet such objective, OSeMBE was designed with a simple and modular structure, easily grasped through this scientific paper and the documentation annexed to it. The model is published with an Apache 2.0 open license. The model's dataset is released under a CC-BY-4.0 International License Agreement. Model and dataset are retrievable on GitHub with accompanying scripts [42]. However, model and data-set are also together downloadable in a zip-archive in txt-format from the OSeMOSYS website [86]. The model fulfils the FAIR criteria [87] by being Findable (the data is available on Zenodo and has a DOI), Accessible (downloadable from Zenodo, GitHub and OSeMOSYS webpage), Interoperable (the data is provided in form of a datapackage and can be converted to excel or txt format using open-source software), and Reusable (the data is released under CC-BY-4.0 license) and thereby filling the gap in the literature indicated in the Introduction.

First use of the model as an educational and engagement tool has already been made, at KTH Royal Institute of Technology. It was used in three course rounds at Master level. It was also used in the Horizon 2020 REEEM project to provide more than 100 scenarios for the REEEMgame, a serious game presenting players with decisions regarding the decarbonisation of the EU power sector and grading the results [88].

Before OSeMBE is used for further, more in-depth analysis the following limitations should be addressed. The model covers currently only the electricity sector. This implies that system integration – the interactions with other sectors like transport, industry, heating and cooling – is not captured by the model. Recent literature highlights the importance of system integration under the term smart energy systems approach which taps flexibility options by sector-coupling [93]. System integration provides flexibility options at significantly lower cost since for example thermal energy storage and liquid fuels storages are currently much cheaper than electricity storage technologies [94]. Sectors like cooling could be added by introducing additional demands and technologies to the model. To consider when conducting such addition is that many processes to be represented might require storage capabilities. The challenge of representing storage in OSeMBE is described in section 2.5.

Another limiting aspect of the model is the low detail regarding operational requirements, as indicated in section 2.9.

This paper aims to demonstrate the working principles of the long-term electricity model and the structures underlying the representation of technological options for the decarbonisation of the electricity system. Such demonstration shows future developers the way technology detail could be increased and shows how numerous more energy system decarbonisation pathways could be explored.

Table 8
Trans-boundary electricity transmission in 2030 in the three scenarios in PJ.

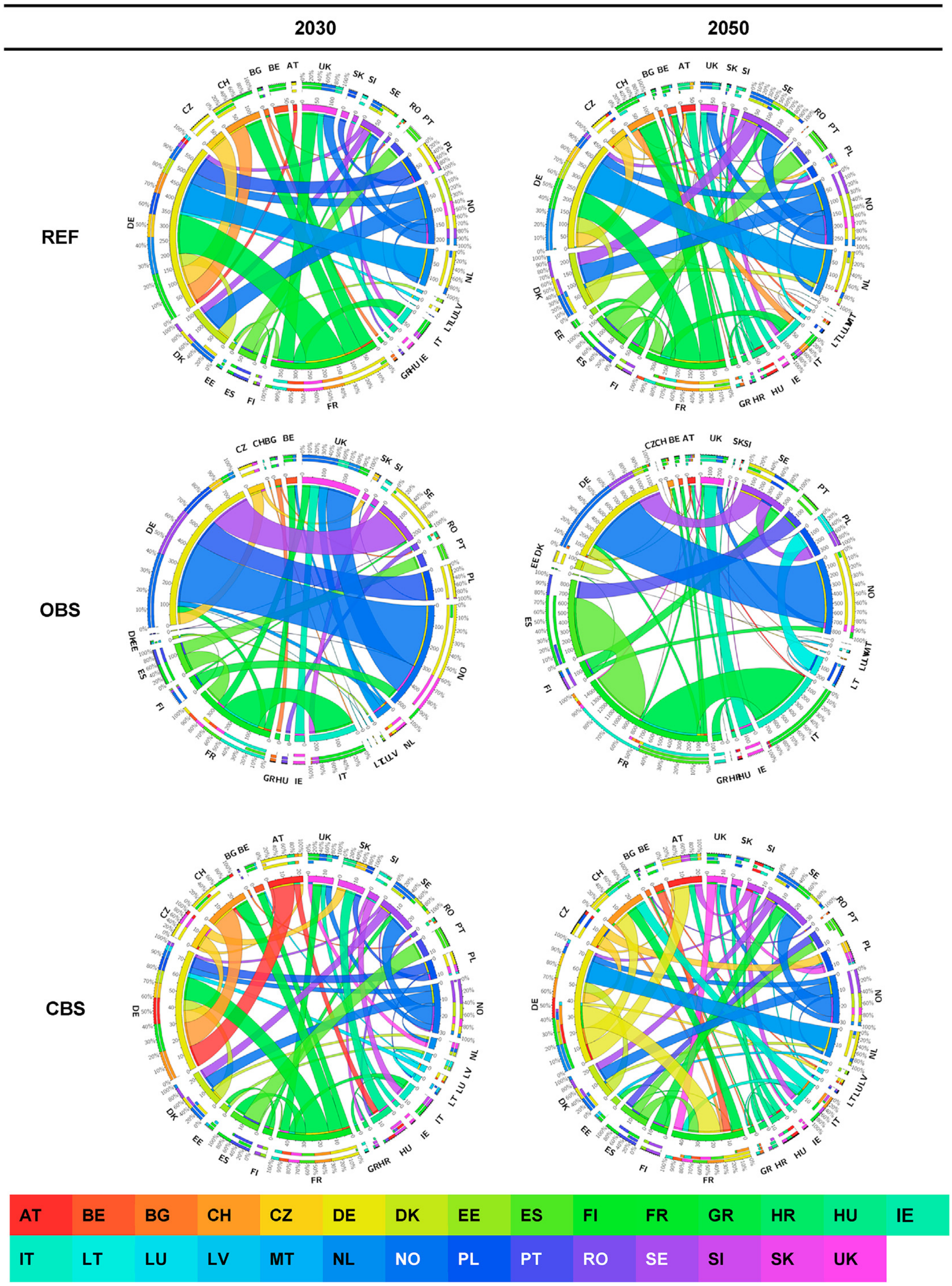

Table 9
Total electricity transmitted through cross-border transmission lines in PJ.

	2015	2020	2030	2040	2050
REF	1313	1358	1247	1675	1461
OBS	1550 (+18%)	1161 (−15%)	1322 (+6%)	2900 (+73%)	3396 (+132%)
CBS	1313 (+-0%)	1405 (+3%)	199 (−84%)	217 (−87%)	171 (−88%)

The open-source license and the retrievability allow further expansion and development of OSeMBE in a collaborative manner. A priority for future work should be to expand the model by adding sectors like heating and cooling to be able to represent the impacts of increasing electrification across sectors and to represent flexibility options to integrate high share of variable renewable energies.

In conclusion this paper presents a model that provides an open and modular base to engage with energy modelling at the EU level, with the potential for further expansions in the future.

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.

Acknowledgments

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Credit author statement

Hauke Henke: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization **Francesco Gardumi**: Methodology, Validation, Writing – review & editing **Mark Howells**: Conceptualization, Validation

Appendix D. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2021.121973.

Appendix A. OSeMBE in brief

Table A1
Fact sheet OSeMBE, adapted from Ref. [54]:

	Item	OSeMBE
1	General Information	
1.01	Model name	The Open-Source energy Model Base for the European Union
1.02	Acronym	OSeMBE
1.03	Institution(s)	KTH
1.04	Author(s) (institution, working field, active time period)	Hauke Henke (KTH, all, 2016 onwards)
1.05	Current contact person	Hauke Henke
1.06	Contact (e-mail)	haukeh@kth.se
1.07	Website	http://www.osemosys.org/osembe.html
1.08	Primary purpose	(Stakeholder) engagement in energy modelling
1.09	Support/Community/Forum	Website: http://www.osemosys.org/osembe.htmlForum: https://groups.google.com/forum/#!forum/osemosys
1.1	Framework	OSeMOSYS
1.11	User Documentation	http://osemosys.readthedocs.io/en/latest/
1.12	Developer/Code Documentation	http://www.osemosys.org/get-started.html
2	**Openness**	
2.01	Open Source	The source code is available at: http://www.osemosys.org/get-started.html
2.02	License	Modelling framework: Apache License 2.0, more information Model data: Creative Commons Attribution 4.0 International, more information
2.03	GitHub	https://github.com/HauHe/OSeMBE
2.04	Data provided	The model data is available at: http://www.osemosys.org/osembe.html
2.05	Number of developers	1
2.06	Number of users	2
3	**Software**	
3.01	Modelling software	GNU MathProg
3.02	External optimizer	GLPK, CPLEX
4	**Coverage**	
4.01	Modelled energy sectors (final energy)	Electricity
4.02	Modelled demand sectors	National electricity
4.03	Modelled energy commodities	Bio fuel (BF), Biomass (BM), Coal (CO), Electricity (EL), Electricity 1 (E1), Electricity 2 (E2), Geothermal (GO), Heavy fuel oil (HF), Hydro (HY), Natural gas (NG), Nuclear (NU), Ocean (OC), Oil (OI), Oil Shale (OS), Sun (SO), Uranium (UR), Waste (WS), and Wind (WI)
4.04	Modelled technology types: components for generation or conversion	Combined cycle (CC), Combined heat and power (CH), Carbon Capture and Storage (CS), Conventional (CV), Distributed PV (DI), Dam (DM), Pumped Storage (DS), Fuel cell (FC), Gas cycle (GC), Generation 2 (G2), Generation 3 (G3), Internal combustion engine with heat recovery (HP), Offshore (OF), Onshore (ON), Steam cycle (ST), Utility PV (UT), Wave power (WV)
4.05	Modelled technologies: components for transfer, infrastructure or grid	Transmission and distribution (TD), *trans*-border electricity transmission, oil refinery (RF)
4.06	Network representation	Net transfer capacities
4.07	Modelled technologies: Components for storage	–
4.08	Changes is efficiency	Defined exogenously, it can change across years
4.09	Geographic resolution	Austria (AT), Belgium (BE), Bulgaria (BG), Switzerland (CH), Cyprus (CY), Czech Republic (CZ), Germany (DE), Denmark (DK), Estonia (EE), Spain (ES), Finland (FI), France (FR), Greece (GR), Croatia (HR), Hungary (HU), Ireland

(*continued on next page*)

Table A1 (*continued*)

	Item	OSeMBE
		(IE), Italy (IT), Lithuania (LT), Luxembourg (LU), Latvia (LV), Malta (MT), Netherlands (NL), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Sweden (SE), Slovenia (SI), Slovakia (SK), United Kingdom (UK)
4.1	Time resolution	5 seasons; one typical day per season; Night, Day, and Peak
4.11	Observation period	2015 to 2050
5	**Mathematical properties**	
5.01	Model class	Mono-objective LP
5.02	Mathematical objective	Net present cost minimisation over the whole space and time domain
5.03	Typical computation time	30 h
5.04	Typical computation hardware	RAM and CPU (256 GB, 3.5 GHz and 4 cores)
6	**Model integration and general data information**	
6.02	Model file format	.txt file
6.03	Integration with other models	No
6.04	Input/output data file format	Input data on a separate.txt file in form of matrices and called by the solver along with model file; all outputs of the model on another.txt and selected outputs on a csv file
6.05	Data input	Annual electricity demand by country, demand profile by timeslice, technology performance and cost data, generation constraints, emission constraints and costs
6.06	Model specific properties	Model simple to understand and accessible to all kinds of users, long pre-processing time to build the matrix of the LP, simplified system structure
6.07	Primary outputs	Global net present cost of the system, capacity and generation mix in every country, year, and time slice, primary fuels consumption
7	**References**	
7.01	Validation	Done based on IEA statistics for electricity generation by country for the years 2015 and 2016.
7.02	Literature and data sources	(EC 2014; Andersson, Boulouchos, and Bretschger 2011; EPA 2015; IEA 2014; EC 2016; IEA ETSAP 2010; IRENA 2015c, 2015b; S&P Global Platts 2015; EWEA 2016; IRENA 2017a, 2015a; IEA-ETSAP and IRENA 2013; DECC 2015; World Nuclear Association 2016; ENTSO-E 2018; Staffell and Pfenninger 2016; Pfenninger and Staffell 2016b; Bosch, Staffell, and Hawkes 2017; Pfenninger and Staffell 2016a; EEA 2018; Eurostat 2018; EEA 2016; CenSES and FME 2015; CenSES and IFE 2015; SFOE 2018, 2015; Geothermie-Schweiz n.d.; Schweizerischer Wasserwirtschaftsverband 2016; OECD 2015; Norwegian Ministry of Petroleum and Energy 2015; Tuuleenergia.ee 2015; VTT 2015; Siyal et al., 2015; Open Power System Data 2019; Statistics Estonia 2018; World Nuclear Association 2019, 2017; IEA 2018)
7.03	Publications	1. Henke, H., Howells, M., Shivakumar, A., (2018) "The Base for a European Engagement Model — An Open Source Electricity Model of seven Countries around the Baltic Sea", CYSENI2018, ISSN 1822—7554, May 2018, Pages 226—247, link 2. Henke, H., (2018) "An indicative study on the opportunities of Pan-European electricity exchange in context of a decarbonised economy", IEW2018, presentation, link

Appendix B. Power generation

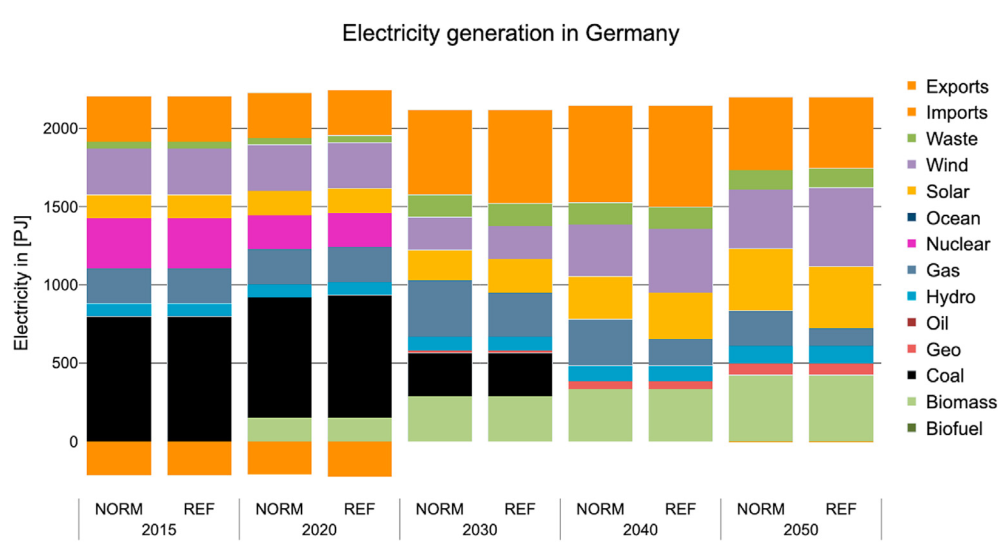

Fig. B1. Electricity generation in Germany, comparison NORM and REF scenario

Appendix C. Cross-border electricity trade

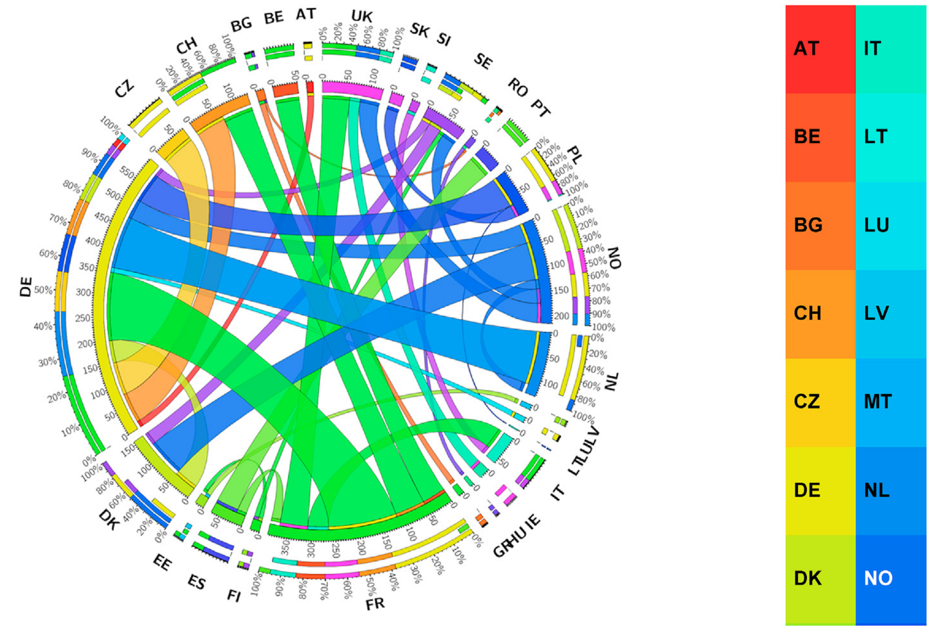

Fig. C.1. Cross-border electricity transmission REF scenario 2030 in PJ

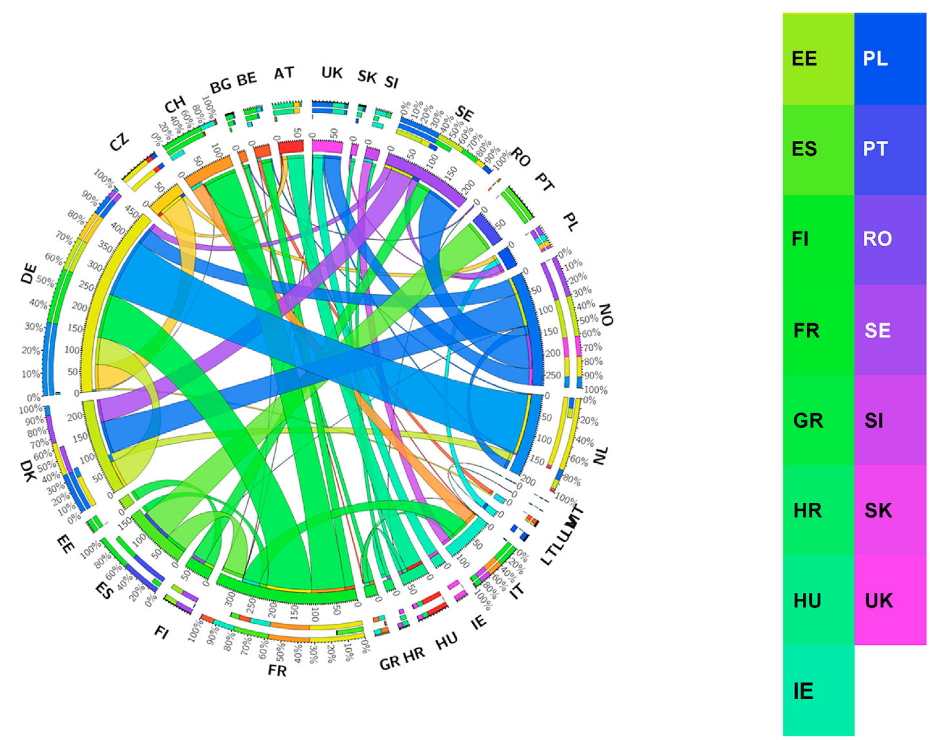

Fig. C.2. Cross-border electricity transmission REF scenario 2050 in PJ

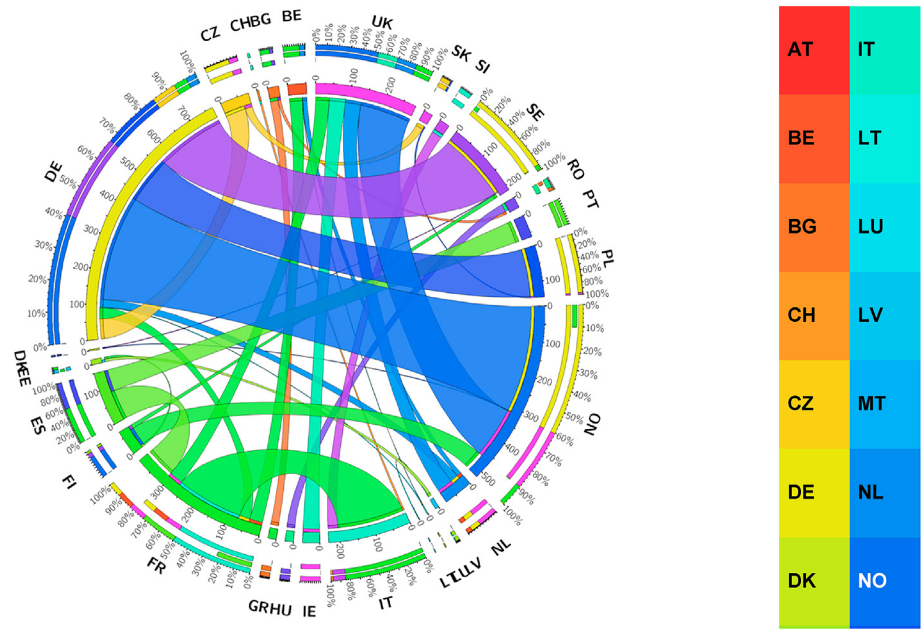

Fig. C.3. Cross-border electricity transmission OBS scenario 2030 in PJ

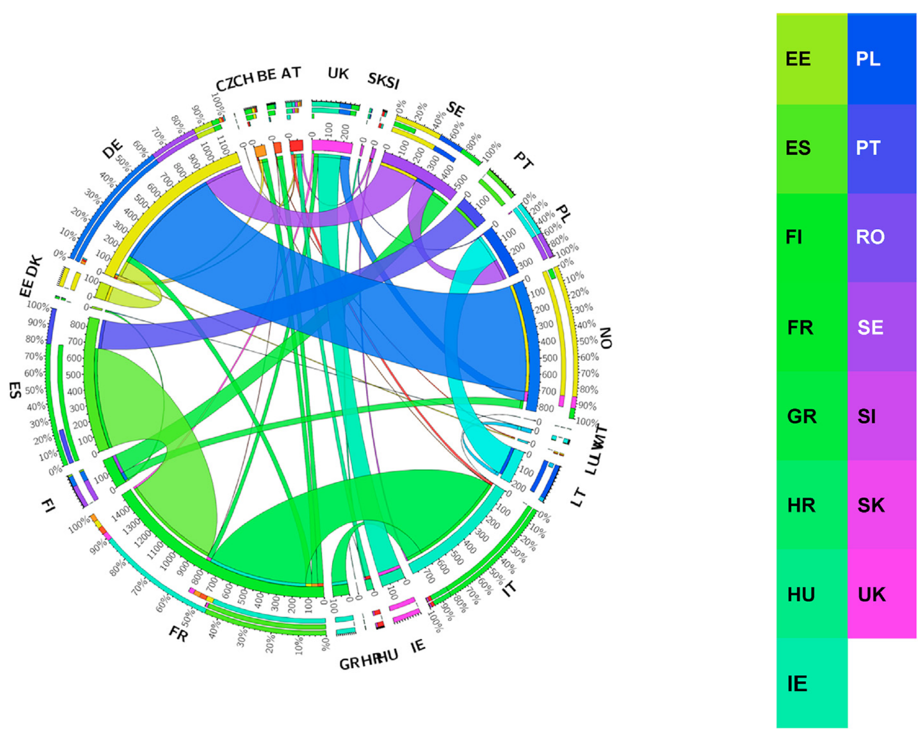

Fig. C.4. Cross-border electricity transmission OBS scenario 2050 in PJ

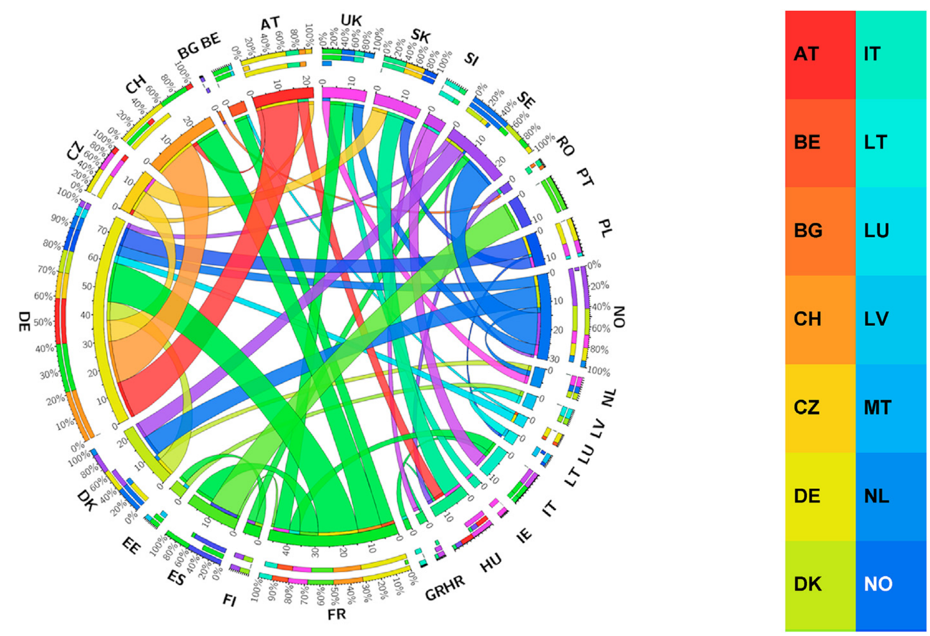

Fig. C.5. Cross-border electricity transmission CBS scenario 2030 in PJ

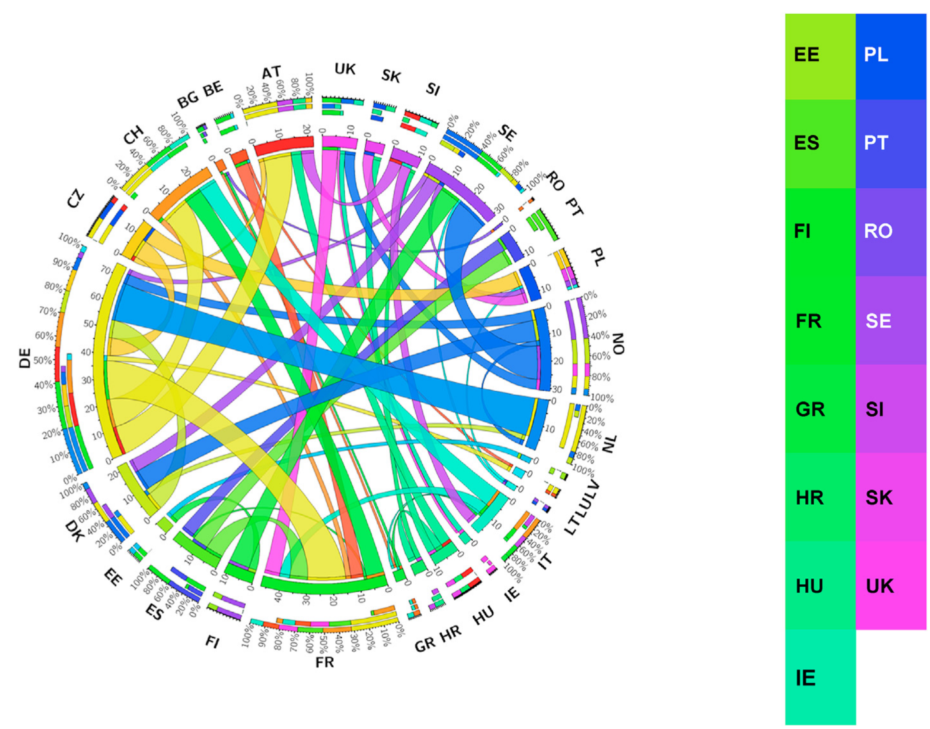

Fig. C.6. Cross-border electricity transmission CBS scenario 2050 in PJ

References

[1] EC. The European green deal - communication from the commission. Brussels, Belgium: European Commission (EC); 2019.
[2] IEA. European Union. 2020 energy policy review. Paris, France: International Energy Agency (IEA); 2020.
[3] EEA. CO2 intensity of electricity generation. European Environment Agency (EEA); 2020.
[4] IEA. Final consumption – key world energy statistics 2020 – analysis. IEA; 2021. https://www.iea.org/reports/key-world-energy-statistics-2020/final-consumption. [Accessed 24 February 2021].
[5] EC. Communication from the commission to the EUROPEAN parliament, the council, the EUROPEAN economic and social committee and the committee OF the regions - an EU strategy on heating and cooling. Brussels, Belgium: European Commission (EC); 2016.
[6] EC. Turning FAIR into reality 2018;78. https://doi.org/10.2777/1524.
[7] Manfren M, Nastasi B, Groppi D, Astiaso Garcia D. Open data and energy analytics - an analysis of essential information for energy system planning, design and operation. Energy 2020;213:118803. https://doi.org/10.1016/j.energy.2020.118803.
[8] Pfenninger S, DeCarolis J, Hirth L, Quoilin S, Staffell I. The importance of open data and software: is energy research lagging behind? Energy Pol 2017;101: 211–5. https://doi.org/10.1016/j.enpol.2016.11.046.
[9] EC. Modelling tools for EU analysis. Eur Comm EC 2016. https://ec.europa.eu/clima/policies/strategies/analysis/models_en. [Accessed 6 August 2020].

[10] Dantzig G. Linear programming and extensions. Princeton: Princeton University Press; 1963. https://doi.org/10.1515/9781400884179.
[11] Capros P, Kannavou M, Evangelopoulou S, Petropoulos A, Siskos P, Tasios N, et al. Outlook of the EU energy system up to 2050: the case of scenarios prepared for European Commission's "clean energy for all Europeans" package using the PRIMES model. Energy Strategy Rev 2018;22:255–63. https://doi.org/10.1016/j.esr.2018.06.009.
[12] EC. EU reference scenario 2016: energy, transport and GHG emissions: trends to 2050. Luxembourg: European Commission (EC); 2016.
[13] EC. POTEnCIA model description - version 0.9. JRC Tech Rep 2016:150. https://doi.org/10.2791/416465.
[14] Mantzos L, Anca Matei N, Rózsai M, Russ P, Soria Ramirez A. POTEnCIA A new EU-wide energy sector model. IEEE 2017;5. https://doi.org/10.1109/EEM.2017.7982028.
[15] Loulou R, Remme U, Kanudia A, Lehtilä A, Goldstein G. Documentation for the TIMES model - PART I. Energy technology systems analysis Programme. IEA-ETSAP; 2005.
[16] Fais B, Blesl M, Fahl U, Voß A. Analysing the interaction between emission trading and renewable electricity support in TIMES. Clim Pol 2015;15: 355–73. https://doi.org/10.1080/14693062.2014.927749.
[17] Korkmaz P, Cunha Montenegro R, Schmid D, Blesl M, Fahl U. On the way to a sustainable European energy system: setting up an integrated assessment toolbox with TIMES PanEU as the key component. Energies 2020;13:707. https://doi.org/10.3390/en13030707.
[18] EC. The JRC-EU-TIMES model - assessing the long-term role of the SET Plan Energy technologies. Brussels, Belgium: European Commission (EC); 2013.
[19] Nijs W. JRC-EU-TIMES - JRC TIMES energy system model for the EU. Zenodo. 2019. https://doi.org/10.5281/zenodo.3544900. Data set.
[20] IEA ETSAP. Acquiring ETSAP tools. 2020. https://iea-etsap.org/index.php/etsap-tools/acquiring-etsap-tools. [Accessed 17 April 2020].
[21] Blesl M, Kober T, Bruchof D, Kuder R. Beitrag von technologischen und strukturellen Veränderungen im Energiesystem der EU-27 zur Erreichung ambitionierter Klimaschutzziele. Z Energiewirtschaft 2008;32:219–29. https://doi.org/10.1007/s12398-008-0028-z.
[22] Ringkjøb H-K, Haugan PM, Seljom P, Lind A, Wagner F, Mesfun S. Short-term solar and wind variability in long-term energy system models - a European case study. Energy 2020;209:118377. https://doi.org/10.1016/j.energy.2020.118377.
[23] Hainsch K, Burandt T, Kemfert C, Löffler K, Oei P-Y, von Hirschhausen C. Emission pathways towards a low-carbon energy system for Europe - a model-based analysis of decarbonization scenarios, vol. 37; 2018.
[24] Löffler K, Hainsch K, Burandt T, Oei P-Y, Kemfert C, von Hirschhausen C. Designing a global energy system based on 100% renewables for 2050 - GENeSYS-MOD: an application of the open-source energy modelling system (OSeMOSYS). SSRN; 2017. p. 44.
[25] Tröndle T. Euro-calliope. 2020.
[26] Pfenninger S, Pickering B. Calliope: a multi-scale energy systems modelling framework. J Open Source Softw 2018;3:825. https://doi.org/10.21105/joss.00825.
[27] Díaz P, van Vliet O, Patt A. Do we need gas as a bridging fuel? A case study of the electricity system of Switzerland. Energies 2017;10:861. https://doi.org/10.3390/en10070861.
[28] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Appl Energy 2015;152:83–93. https://doi.org/10.1016/j.apenergy.2015.04.102.
[29] Hörsch J, Hofmann F, Schlachtberger D, Brown T. PyPSA-Eur: an open optimisation model of the European transmission system. Energy Strategy Rev 2018;22:207–15. https://doi.org/10.1016/j.esr.2018.08.012.
[30] Brown T, Hörsch J, Schlachtberger D. PyPSA: Python for power system Analysis. J Open Res Software 2018;6. https://doi.org/10.5334/jors.188.
[31] oemof. Oemof - Publications. 2020. https://oemof.org/publications/. [Accessed 5 October 2020].
[32] Hilpert S, Kaldemeyer C, Krien U, Günther S, Wingenbach C, Plessmann G. The Open Energy Modelling Framework (oemof) - a new approach to facilitate open science in energy system modelling. Energy Strategy Rev 2018;22: 16–25. https://doi.org/10.1016/j.esr.2018.07.001.
[33] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. OSeMOSYS: the open source energy modeling system. Energy Pol 2011;39: 5850–70. https://doi.org/10.1016/j.enpol.2011.06.033.
[34] Lund H, Arler F, Østergaard P, Hvelplund F, Connolly D, Mathiesen B, et al. Simulation versus optimisation: theoretical positions in energy system modelling. Energies 2017;10:840. https://doi.org/10.3390/en10070840.
[35] Pfenninger S, Hawkes A, Keirstead J. Energy systems modeling for twenty-first century energy challenges. Renew Sustain Energy Rev 2014;33:74–86. https://doi.org/10.1016/j.rser.2014.02.003.
[36] Chang M, Thellufsen JZ, Zakeri B, Pickering B, Pfenninger S, Lund H, et al. Trends in tools and approaches for modelling the energy transition. Appl Energy 2021;290:116731. https://doi.org/10.1016/j.apenergy.2021.116731.
[37] ICTP. Joint. Summer school on modelling tools for sustainable development - OpTIMUS | (smr 3299) (10-28 june 2019). ICTP - Int Cent Theor Phys 2019. http://indico.ictp.it/event/8751/. [Accessed 9 April 2020].
[38] ICTP. The summer school on modelling tools for sustainable development - OpTIMUS | (smr 3210) (04-29 june 2018). ICTP - Int Cent Theor Phys 2018. http://indico.ictp.it/event/8315/. [Accessed 9 April 2020].
[39] ICTP. CLEWS summer school | (smr 3168) (12-30 june 2017). ICTP - Int Cent Theor Phys 2017. http://indico.ictp.it/event/8008/. [Accessed 9 April 2020].
[40] OpTIMUS. Energy modelling platform for Africa. EMP; 2019. http://www.energymodellingplatform.org/africa.html. [Accessed 9 April 2020].
[41] Republic of Cyprus. Cyprus' Draft Integrated national energy and climate plan for the period 2021-2030. Nicosia, Cyprus. Republic of Cyprus; 2019.
[42] Henke H. OSeMBE repository. Zenodo; 2021. https://doi.org/10.5281/ZENODO.5032445.
[43] ENTSO-E. ENTSO-E transparency platform. 2021. https://transparency.entsoe.eu/. [Accessed 10 July 2018].
[44] Directorate-General For Energy. Database of the European energy storage technologies and facilities. 2020. https://doi.org/10.2906/101110101114/1.
[45] Eurostat. Electricity production capacities by main fuel groups and operator. Eurostat Data Brows; 2020. https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epc/default/table?lang=en. [Accessed 12 October 2020].
[46] CenSES, FME. CenSES energy demand projections towards 2050 - reference path. Trondheim, Norway: centre for sustainable energy studies (CenSES - NTNU), forskningssenter for miljøvennlig energi (FME). Institute for Energy Technology (IFE), UIO Centre for Technology, Innovation and Culture - University of Oslo, Høgskulen i Sogn og Fjordane; 2015.
[47] Andersson G, Boulouchos K, Bretschger L. Energiezukunft schweiz. ETH Zürich; 2011.
[48] Pfenninger S, Staffell I. Renew Ninja 2016.
[49] EC. Energy technology reference indicator (ETRI) projections for 2010-2050. Luxembourg: European Commission (EC); 2014.
[50] IEA. World. Energy outlook 2014 - power generation investment assumptions. 2014.
[51] EPA. Catalog of CHP Technologies. U.S. Environmental Protection Agency (EPA). Combined heat and power partnership. 2015.
[52] IEA ETSAP. IEA ETSAP - technology brief E03. 2010.
[53] IEA. Power generation assumptions in the new policies and SDS scenarios in the world energy outlook 2018. Paris, France: International Energy Agency (IEA); 2019.
[54] Henke H. REEEM-D7.3_OSeMBE - an open-source engagement model, vol. 26; 2019. https://doi.org/10.5281/zenodo.3368574.
[55] Climate Action Network Europe. Coal exit tracker. Eur coal n.d. https://beyond-coal.eu/coal-exit-tracker/. [Accessed 27 February 2021].
[56] World Nuclear Association. Nuclear power in Poland. Nucl Power Pol; 2019. https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/poland.aspx. [Accessed 10 July 2019].
[57] Staffell I, Pfenninger S. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 2016;114:1224–39. https://doi.org/10.1016/j.energy.2016.08.068.
[58] Welsch M, Howells M, Bazilian M, DeCarolis JF, Hermann S, Rogner HH. Modelling elements of smart grids – enhancing the OSeMOSYS (open source energy modelling system) code. Energy 2012;46:337–50. https://doi.org/10.1016/j.energy.2012.08.017.
[59] Welsch J. Modellierung von Energiespeichern und Power-to-X im deutschen und europäischen Energiesystem. 2018. https://doi.org/10.18419/OPUS-10334.
[60] Niet T. Storage end effects: an evaluation of common storage modelling assumptions. J Energy Storage 2020;27:101050. https://doi.org/10.1016/j.est.2019.101050.
[61] Palombelli A, Gardumi F, Rocco M, Howells M, Colombo E. Development of functionalities for improved storage modelling in OSeMOSYS. Energy 2020;195:117025. https://doi.org/10.1016/j.energy.2020.117025.
[62] Bfe B für E. Kohle 2015. https://www.bfe.admin.ch/bfe/de/home/versorgung/fossile-energien/kohle.html. [Accessed 2 June 2020].
[63] Bfe B für E. Erdgas 2016. https://www.bfe.admin.ch/bfe/de/home/versorgung/fossile-energien/erdgas.html. [Accessed 2 June 2020].
[64] DECC. DECC 2015 fossil fuel price assumptions. Department of Energy & Climate Change (DECC); 2015.
[65] Steubing B, Zah R, Waeger P, Ludwig C. Bioenergy in Switzerland: assessing the domestic sustainable biomass potential. Renew Sustain Energy Rev 2010;14:2256–65. https://doi.org/10.1016/j.rser.2010.03.036.
[66] Scarlat N, Dallemand J-F, Skjelhaugen OJ, Asplund D, Nesheim L. An overview of the biomass resource potential of Norway for bioenergy use. Renew Sustain Energy Rev 2011;15:3388–98. https://doi.org/10.1016/j.rser.2011.04.028.
[67] SFOE. Geothermal energy Switzerland. Swiss Fed Off Energy SFOE; 2015. http://www.bfe.admin.ch/themen/00490/00501/index.html?lang=en. [Accessed 16 April 2018]. accessed.
[68] IEA ETSAP. Technology brief E06. 2010.
[69] Bauer C, Hirschberg S. Potenziale, Kosten und Umweltauswirkungen von Stromproduktionsanlagen - synthese. Bern. Switzerland: Paul Scherer Institut (PSI), Bundesamt für Energie (BFE); 2017.
[70] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114: 1251–65. https://doi.org/10.1016/j.energy.2016.08.060.
[71] Dalla Longa F, Kober T, Badger J, Volker P, Hoyer-Klick C, Hidalgo Gonzalez I, et al. Wind potentials for EU and neighbouring countries Input datasets fpr the JRC-EU-TIMES. Model 2018;JRC109698:65. https://doi.org/10.2760/041705.
[72] EIA. How much electricity is lost in transmission and distribution in the United States? - FAQ - U.S. Energy Information Administration (EIA). US Energy Inf Adm; 2018. https://www.eia.gov/tools/faqs/faq.php?id=105&t=3.

[Accessed 13 April 2018].
[73] Welsch M. Enhancing the treatment of systems integration in long-term energy models. Stockholm: industrial Engineering and Management. KTH Royal Institute of Technology; 2013.
[74] Short W, Sullivan P, Mai T, Mowers M, Uriarte C, Blair N, et al. Regional energy deployment system (ReEDS). Golden, CO, United States: National Renewable Energy Laboratory (NREL); 2011.
[75] Welsch M, Deane P, Howells M, Ó Gallachóir B, Rogan F, Bazilian M, et al. Incorporating flexibility requirements into long-term energy system models – a case study on high levels of renewable electricity penetration in Ireland. Appl Energy 2014;135:600–15. https://doi.org/10.1016/j.apenergy.2014.08.072.
[76] IRENA. Planning for the renewable future: long-term modelling and tools to expand variable renewable power in emerging economies. Abu Dhabi, UAE: International Renewable Energy Agency (IRENA); 2017.
[77] Madaeni SH, Sioshansi R, Denholm P. Comparison of capacity value methods for photovoltaics in the western United States. Golden, CO, United States: National Renewable Energy Laboratory (NREL); 2012. https://doi.org/10.2172/1046871.
[78] Holttinen H, Kiviluoma J, Robitaille A, Cutululis NA, Orths A, van Hulle F, et al. Design and operation of power systems with large amounts of wind power: final summary report. IEA WIND Task 25. Espoo, Finland: VTT Technical Research Centre of Finland; 2012.
[79] EEA. EU. Emissions trading system (ETS) data viewer. Eur Environ Agency; 2018. https://www.eea.europa.eu/data-and-maps/dashboards/emissions-trading-viewer-1. [Accessed 10 July 2018].
[80] EC. EU emissions trading system (EU ETS). Eur Comm EC 2016. https://ec.europa.eu/clima/policies/ets_en. [Accessed 10 August 2020].
[81] EEA. CO2 emission intensity. Eur Environ Agency; 2016. https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-3. [Accessed 10 July 2018].
[82] Hirst D. Carbon Price Floor (CPF) and the price support mechanism. 2018.
[83] EEA. EMEP/EEA air pollutant emission inventory. Eur Environ Agency EEA 2019. http://efdb.apps.eea.europa.eu/?source=%7B%22query%22%3A%7B%22bool%22%3A%7B%22must%22%3A%5B%7B%22term%22%3A%7B%22code%22%3A%221.A.1.a%20Public%20electricity%20and%20heat%20production%22%7D%7D%2C%7B%22term%22%3A%7B%22Pollutant%22%3A%22PM2.5%22%7D%7D%5D%7D%7D%2C%22display_type%22%3A%22tabular%22%7D. [Accessed 10 August 2020].
[84] EC. CASE AT.40461 - DE/DK interconnector. Brussels, Belgium: European Commission (EC); 2018.
[85] Bundesregierung. Entwurf eines Gesetzes zur Reduzierung und zur Beendigung der Koh-leverstromung und zur Änderung weiterer Gesetze. Berlin, Germany: Kohleausstiegsge-setz; 2020.
[86] KTH division of Energy Systems. OSeMBE. OSeMOSYS n.d. http://www.osemosys.org/osembe.html. [Accessed 8 October 2020].
[87] Wilkinson MD, Dumontier M, Aalbersberg IjJ, Appleton G, Axton M, Baak A, et al. The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 2016;3. https://doi.org/10.1038/sdata.2016.18.
[88] Foldbo Holm M, Lærke Hansen B, Egholm H, Leo E, Ellefsen O. Online Energy Systems Learning Simulation 2019;D7:4–5. https://doi.org/10.5281/zenodo.3368575.
[93] Lund H. Renewable energy systems. Elsevier; 2014. https://doi.org/10.1016/C2012-0-07273-0.
[94] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016:3–14. https://doi.org/10.5278/IJSEPM.2016.11.2.