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The Role of Flexibility in the European Electricity Market: Insights from a System Dynamics Perspective

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Abstract

This paper studies the role of flexibility sources in the European electricity market, using a system dynamics model that includes various socio-technical factors, and a novel flexibility scoring concept. The learning rate impact of a new technology (gas-CCS) on the system's flexibility is analyzed. Simulation results show that the flexibility score of the system can reach 102.8 GW and 167.3 GW in 2050, respectively, when 5% and 10% of the development rate of flexible solutions are considered. When socio-technical factors are ignored the flexibility score only reaches 24 GW. The impact of the renewable energy mix on the market's flexibility is studied by focusing on offshore wind. Simulation results show that offshore wind can ensure higher flexibility compared to onshore wind. The scenario which encompasses a higher share of offshore wind in the renewable energy mix has a 16.5 GW higher flexibility score, a difference that decreases to 2.4 GW in 2050 when assuming a 10% learning rate for gas-CCS. Socio-technical parameters increase the difference in the flexibility score between offshore and onshore wind power up to 10 GW. We conclude that the system may actually have more flexibility in an offshore wind-oriented market without governmental support.

Keywords: Flexibility, system dynamics, renewable integration, socio-technical factors
JEL Classification No: Q63, Q47, Q55, Q48

Nomenclature

CCS	Carbon capture and storage	NTC	Net transmission capacity
CGE	Computable general equilibrium	P2H	Power to heat
DSM	Demand side management	R&D	Research and development
DSO	Distribution system operators	SD	System dynamics
NPV	Net present value	VRES	Variable renewable energy sources

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1. Introduction

The integration of an increasing share of variable renewable energy sources (VRES) in the energy system is one of the most indispensable and challenging pathways towards a low-carbon energy system (Denholm and Hand 2011). The European Commission aims at achieving an energy transition characterized by higher sustainability, energy security, and economic competitiveness (Von der Leyen 2019). Moreover, lower dependence from energy imports plays an important role in the increasing share of renewables in the European electricity system (Skea 2012; Martinot 2016). Therefore, since the major part of additional renewables stems from intermittent wind and solar energy, production and consumption of energy in such a system must be well balanced (Georgilakis 2008; Jacobson and Delucchi 2011).

Flexibility is the ability of the aggregated set of power plants to balance the variation and uncertainty in the electricity market. The literature on renewable energy integration with flexibility options is extensive. This includes, as an illustration, the maximum share of VRES (Saarinen et al. 2015) or the operation mode of VRES regarding curtailment and interconnection options (Child et al. 2019). Most of the recent literature corresponding to the analysis of flexibility can be divided into engineering models and system models (Grünewald et al. 2012). The main aim of this study is the analysis of electricity from a system's point of view. Flexibility options for efficient VRES integration are reserved to be carried out on both the supply side and the demand side of the energy system (Kopiske et al. 2017). The economic literature on the analysis of flexibility in the electricity market falls into two categories (Bertsch et al. 2016). In the first group, scholars scrutinize the power market with dispatch models (static models) (Denholm and Hand 2011). Impacts of flexibility requirements on different parameters – such as-the capacity mix, electricity generation, and curtailment of renewable – have been discussed in Lamadrid et al. (2011) and Lorenczik (2017), among others. Kopiske et al. (2017) use a unit commitment model to analyze the value of flexibility in the electricity-only market of Germany. They draw the important conclusion that flexibility has more value than a share of renewables, and this value can be determined by a combination of flexibility requirements and available flexibility. In the second group, many studies analyze power markets by means of dispatch and investment models (dynamic models) (De Jonghe et al. 2011). Nicolosi (2010), as an example, examine the impact of integrating more wind power plants in the electricity system on the system's flexibility.

Many technologies can provide flexibility in the electricity market (Zöphel et al. 2018). Several authors have called the impact of many flexible sources on the performance of system into question, by using optimization models. These flexibility options included hydro power (Huertas-Hernando et al. 2017), power-to-heat (Hedegaard et al. 2012; Kirkerud et al. 2017), demand response (Bertsch et al. 2016), electric vehicles (Schuller et al. 2015), storage (Zhao et al. 2015), carbon capture and storage (CCS) (Cloete and Hirth 2020), or some combination of these (Salpakari et al. 2016; Pudjianto et al. 2013). Pilpola and Lund (2019) analyze the impact of different flexibility sources on the integration of wind power into the national energy mix in Finland. They conclude that power-to-heat and wind power curtailment are the best flexibility options available from a cost efficiency perspective. In our study, we use several of the above-mentioned flexibility options, including gas peaker power plants, CCS power plants, pumped hydro storage technologies, transmission interconnection, and wind curtailment. Although CCS technology involves high costs and critical risks (Ram et al. 2017), it can provide flexibility for the electricity system. Flexible CCS power plants can switch off their capture units in some hours. As a result, they can support the integration of renewables as flexible sources. Since designers of future CCS power plants topically do not consider the possibility of flexible technologies, but rather the level of flexibility of technologies (Litzelman et al. 2021), we focus on flexible CCS technologies instead of inflexible CCS technologies. Analogously to peaker power plants, flexible CCS power plants can detach their CCS unit during peak load hours and/or low renewable feed-in (see subsection 2.2.3 for further details). Moreover, to the best of our knowledge, the impact of learning effects on the diffusion of electricity market flexibility options has not been investigated yet using a system dynamics (SD) model/approach.

The quantitative modeling of energy systems has restrictions with regard to socio-technical parameters in the system (Cherp et al. 2018). Bolwig et al. (2019) discuss how an SD perspective could be implied to incorporate enhanced flexibility into the electricity supply system. Gravelsins et al. (2018) identify flexibility in a power system conceptually by using an SD perspective. We specifically analyze the European electricity market from 2015 up to 2050 using a large-scale electricity market model (see section 2.1) and considering all presented flexibility options on the supply side. The analyzed region comprises 28 European countries, but the implementation is adaptable spatially/regionally (up- or downscaling).

Most of the previous studies analyzed the future of flexibility by means of specific characteristics or indicators, such as the quantity of surplus electricity generated from RES (Papaefthymiou et al. 2018). One of the most significant challenges of the flexibility analysis in the electricity market is exploiting quantitative criteria in an electricity system in order to analyze flexibility in the electricity market. While increasing the share of VRES results in rising flexibility requirements, this alone does not necessarily translate into flexibility having a significant (positive)value. The value of flexibility is rather determined by a combination of required and available flexibility. In this paper, we tackle the market value of flexibility with the novel scoring concept of "flexibility points". Different flexibility points have been assumed for different technologies. Data for these technologies have been adopted from a tool called "Energy Policy Simulator" (Busch and Orvis 2020).

One of the most significant factors in the development of flexibility is the VRES mix. There is a political aim for higher integration of renewables at the European level. As a result, various combinations of renewables can provide different levels of flexibility for the power system. All these factors lead to an increasing uncertainty regarding the optional combination and share of VRES and the future of flexibility needs. Xing et al. (2017) analyze which flexibility sources are more optimal in the electricity market. Huber et al. (2014) state that the future flexibility requirements in the European power system depend on three leading parameters: the share of renewables, the mix of renewables, and the size of the balancing area. Furthermore, Brunner et al. (2020) sparked a discussion about the role of offshore wind on power market flexibility, and showed how an efficient mix of renewable energy can decrease the need for flexibility. The authors conclude that offshore wind requires less flexibility than onshore wind and photovoltaics. In this context we take a new look at the future of the electricity market in two scenarios (offshore wind and onshore wind-oriented market) taking socio-technical factors (e.g. environmental pressure, technological development rate, motivation for development for new solutions) explicitly into account.

The penetration of VRES has both positive and negative impacts on the flexibility of the power system. Höfer and Madlener (2021) consider adverse negative effects of introducing renewables into an inflexible system, showing that all renewable energy sources, except for hydroelectric power plants, can cause RES curtailment in a DSO region. Klie and Madlener (2020 a, b) examined the potential of a hybrid approach (improving profitability and total system costs at the same time) used to enhance the economics of onshore wind power in Germany, concluding that additional system flexibility might improve the profitability of wind power energy. On the one hand, an increasing share of renewables can reduce the stability of the system. On the other hand, since wind curtailment is considered as a source of flexibility it can provide stability to the system. Hirth (2015) finds that renewables and CCS are substitutes rather than complements. Hence, considering the socio-technical impact of the renewables and new flexible solutions can disclose the synergy potential between renewables and CCS technologies.

Most of the portrayed studies analyze the future need for flexibility with optimization models by evaluating parameters such as installed capacities or the generation mix. In contrast, this paper focuses on the development of available power system flexibility in Europe, using a simulation model which is based on system dynamics. Accordingly, three main research questions are of particular interest: (1) How learning of CCS technologies can influence the development of flexibility in a power system considering socio-technical parameters?, (2) Is there any synergy between CCS technology and renewables depending on the renewable energy mix, (3) What is its impact on the flexibility and system performance?

To set the foundation for own analysis, we start in section 2 with a description of the logic of the electricity market model HECTOR, followed by a description of the notion of "flexibility points" and its implementation in a system dynamics model (both dispatch and investment model). This section ends with an introduction of the data basis used in the model. In section 3, results regarding flexibility implementation are analyzed. Section 4 addresses the limitations of the work. Section 5 concludes and provides some policy implications regarding power system flexibility.

2. Methodology

Due of the contribution from all sectors of the electricity system to flexibility, a systematic analysis of different parts of the electricity system is essential. For this purpose, we employ the electricity market model HECTOR. In the following subsection, a detailed description of HECTOR is provided, including the flexibility module of HECTOR, which was added in 2019. In addition, the main sources of flexibility considered in the model and their corresponding implementation are documented. This section ends with an introduction of the data used and some key model assumptions.

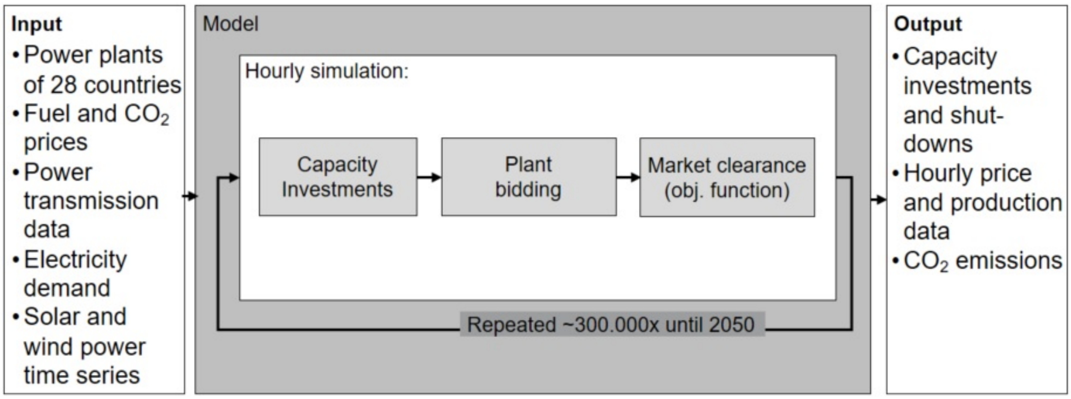

Figure 1: The model summary and main inputs and outputs of the HECTOR model

2.1. *Long-term energy system model*

The Hourly Electricity Carbon capture and storage (CCS) Transmission Optimizer (HECTOR) is a simulation model that simulates generation, auctioning, dispatch, and electricity exchange between regions of the electricity market (Sheykhha and Madlener 2019). The simulation covers the supply side of the electricity market of 28 European countries (see Table A1 for a list of the countries covered). The model is based on a system dynamics setup in which objective functions are solved separately for each hour (time step). This feature helps the model to represent reality more precisely than most other long-term models that can be found in the literature. The objective function of this long-term model, which minimizes total system costs subject to a set of constraints, is solved in the market clearance module. This function matches supply and residual demand considering regional constraints – such as import and export costs and transmission capacities – in order to find the lowest total system cost. As an illustration, for a typical simulation run from 2015 to 2050, each module is executed about 300,000 times (35 years*365 days*24 hours) (see Fig. 1). The main features are the following:

- Full description of the supply side of the energy sector
- Calibrating withing the study region the auction at the national scale by means of an international auction
- Making investment decisions based on the net present value (NPV) approach
- Generating both global and regional details.

The objective function for every hour is the minimum cost, considering the matching of supply and demand in each region and the transmission costs. The linear objective function is specified as:

$$min \sum_{p=1}^{P} \sum_{r=1}^{R} price-bid_{p,r,t}.vol-bid_{p,r,t}.x_{p,r,t} + \sum_{r_1} \sum_{r_2} exports_{r_1,r_2,t}.costs_{r_1,r_2,t} \tag{1}$$

s.t.

$$\sum_{p} vol - bid_{p,r,t}.x_{p,r,t} - \sum_{r_1=1}^{R} exports_{r,r_1,t} + \sum_{r_2=1}^{R} exports_{r,r_1,t} = res - demand_{r,t} \quad \forall r = 1, ..., R \tag{2}$$

$$0 < exports_{r_1,r_2,t} < capacity_{r_1,r_2,t} \quad \forall r_1, r_2 = 1, ..., R \tag{3}$$

$$0 < x_{p,r,t} < 1 \quad \forall r = 1, ..., R, \ p = 1, ..., P \tag{4}$$

Eq. (2) indicates the balance of supply and demand in a given region, whereas eqs. (3) and (4) ensure the interconnections between regions and the dispatch of power plants, respectively.

Since the impact of learning on the market diffusion dynamics of flexibility sources is one of the research questions in this paper, the learning curve module of the model is described briefly next. Technological learning is modeled by using the two-factor learning curve method, which enables to estimate the impact of cost decreases due to learning curve effects separated between R&D funding lead to technological improvement in the form of energy efficiency gains, and subsidizing market diffusion bringing down the per unit costs. As eq. (5) reveals, although the cost of a specific technology decreases due to its deployment, corroborated by cumulative R&D efforts. We can mathematically model the two-factor learning curves as follows:

$$C = C_0 \times Cap^{-\alpha} \times KS^{-\beta} \tag{5}$$

where C, C_0, Cap, and KS represent specific costs of a technology per unit (€/MW), the initial investment costs at $t = 0$, cumulative capacity, and accumulated knowledge, respectively. α is the learning-by-using elasticity and β stands for the learning-by-searching elasticity. Lohwasser and Madlener (2013) developed and implemented this module into the electricity market model HECTOR in 2012.

For the implementation of the model we use Version 6.4 E of Vensim (Ventana System), coupled with a C compiler. The coupling is not only for solving the cost-minimization problem of the model but also for using several external functions that are not supported by SD. The current design of the model evaluates thousands of equations per time step. In order to mitigate the computational time of the model, a representative time period is used in the model (i.e. simulating one week per month). In this mode, the running time of the model is 6 h for a full simulation from 2015 until 2050 (on a personal computer with Intel i7 Quad-core hardware, 4 x 3.7 GHz CPUs and 8 GB RAM), using the Vensim Simulation Software and Microsoft Windows 10.

2.2. Flexibility in electricity markets

Since the electricity production of solar PV and wind power technologies depends on solar irradiation and wind speeds, respectively, they are considered as the main VRES technologies in the model. As a result, integrating these technologies needs technologies that can provide flexibility in the market. Some technologies can provide flexible services to the electricity market, such as storage technologies, gas-peaker technologies, CCS, or Demand Side Management (DSM) technologies, among others. In addition, transmission interconnections can be taken into account as a source of flexibility (see Fig. 2). All these flexibility sources ease the integration of renewables into the system because they can compensate for the drop-off of variable renewable energy technologies in the market. HECTOR includes all sources of flexibility in the system except for DSM, so an abstraction has been used to include flexibility sources as a support for VRES technologies. We introduce the scoring concept of "flexibility points". According to our definition, one flexibility point is the amount of flexibility that any kind of flexible service can provide to the system. As an illustration, 100 MW of pumped hydro storage with X flexibility points can support 100*X MW of solar or wind power in the system. As HECTOR contains both an investment and a dispatch model, the implementation of flexibility is realized in the investment decision module. On the one hand, it restricts the installation of new renewable energy technologies based on the available amount of flexibility in the system. The new renewable power capacity could be installed based on the difference between flexibility points provided and the existing renewable power capacity. On the other hand, renewables might have to be curtailed. To this end, a curtailment module has been developed in the model that can curtail wind onshore, wind offshore, solar PV, and hydropower plants according to the oversupply of renewables. The technology-specific curtailment of renewables is determined by the following equation:

$$Curtailment_t = RES\ Generation_t - Theoretical\ infeed_t \tag{6}$$

where theoretical infeed is calculated as follows:

$$Theoretical\ infeed_t = Installed\ capacity \times Profile\ value. \tag{7}$$

The profile value is a time series of renewable electricity output which is used as an input in the model. The curtailment of renewables, based on transmission constraints, is subject to further research. If more VRES technologies than supported capacity are installed, the model curtails the VRES production accordingly.

Since the investment and dispatch of renewables in HECTOR are implemented endogenously, flexibility points are modeled in an endogenous, and market-driven way. As can be seen in Fig. 3, building new technology is constrained by fuel constraints, maximum yearly capacity, maximum plant scale per investment, the upper capacity of renewables (i.e. calculated considering the renewable energy potential in different countries), and the maximum capacity based on the flexibility of the grid that can be built. Furthermore,

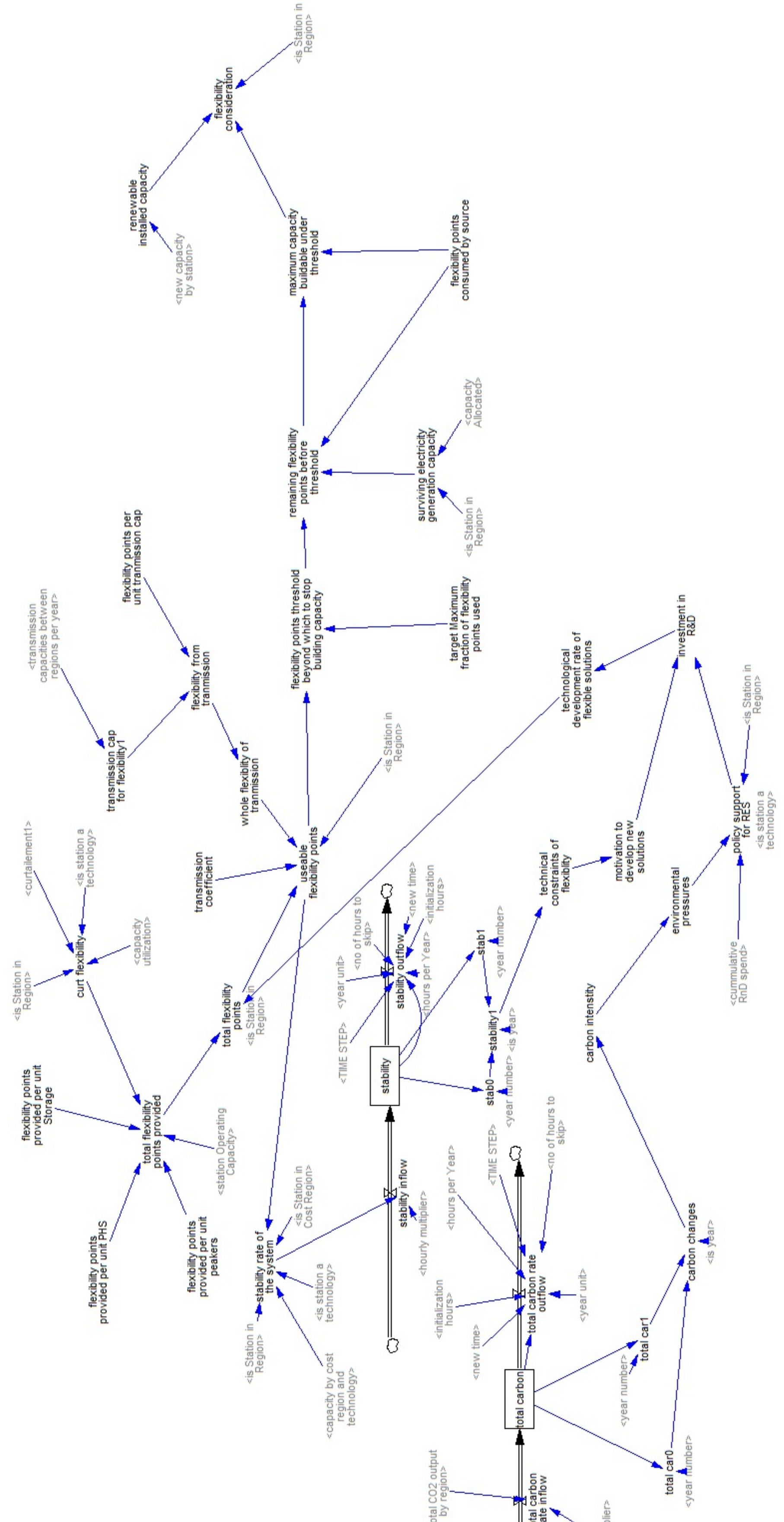

Figure 2: Flexibility points in HECTOR

the scope for building new capacities depends on a percentage of total operational capacities in each region. The reason behind this fact is the need for covering the peak demand in each region. This expands all technologies with a positive NPV and assigns investment shares to them in accordance with the total capacity in each region, the ratio of expected NPV to total investment costs, and user-defined parameters. The user-defined parameters determine the minimum capacity that can be installed for each technology. Hence, having changes on this parameter, we can manipulate the shares of a specific technology in the market. This is one of the unique features of the model which helps to analyze the market when a specific technology is dominant in the market. Having used high investment shares for offshore wind or onshore wind technology, a market with high shares of them can be scrutinized. If any technology satisfies all conditions mentioned the model invests in that technology. In the next section, the general heuristics of the HECTOR model are described.

In the reminder of this section, the main sources of flexibility in the electricity system are described. Four main flexibility options, including energy storage, transmission interconnections, peaker power plants, CCS technologies, and renewable curtailment are considered. DSM is another significant source of flexibility that has not been taken into account in this paper, but should be included in future research.

This paper quantitatively addresses the impact of socio-economic parameters on the development of flexibility in the electricity market. On the one hand, reaching high shares of renewables in the electricity market can jeopardize the stability of the power system. Consequently, the incentive for investments in renewable energy or the adoption rate of renewable energy technologies will be decreased accordingly. On the other hand, decreasing renewable energy shares in the power system can cause a higher carbon intensity. As a result, an increase in carbon emissions can lead to higher environmental pressures and higher policy support for RES. A combination of policy support for RES and a high motivation for the development of new flexible solutions influences investment in renewables. The endogenous impact of investments in Research and Development of new or improved renewable energy technologies can induce the technological development rate in flexible solutions. The latter parameter can impact the development of flexibility with a direct relationship. As we already proposed and designed a generalized concept of flexibility incentivations by flexibility points, the development of flexibility in the power system can be assessed accordingly.

2.2.1. Energy storage

Energy storage technologies are dispatched by taking their expected costs into account. Based on the time horizon of projections, they are divided into two groups: short-term and long-term storage units. In the model, the energy storage technologies are scheduled for the market on two levels. First, depending on their size and market price expectations, bids are offered to the market. Second, their schedule is updated with an hourly update of the price forecast. For pumped hydro storage, changes in the reservoir volume also impact corrections to the price forecast. It is noteworthy, that only pumped hydro storage is modeled in this paper. Furthermore, Bertsch et al. (2016) conclude that storage technologies seem mainly to be built to prevent renewable curtailment, rather than to provide flexibility

Table 1: The flexibility scoring system considered by technology (Busch and Orvis 2020)

Technology	Flexibility points
Pumped hydro storage	3.07
Storage technologies	6
Transmission	1
Peaker power plants	6
CCS technologies	6

2.2.2. Transmission interconnection

Although HECTOR in some cases covers regions instead of countries, all interconnected cross-borders provide flexibility for regions. Net transmission capacity (NTC) investment has been modeled exogenously in the model. Therefore, we use different NTC developments, which is in line with our storylines.

2.2.3. Peaker power plants and CCS technologies

Due to the carbon capturing characteristics of CCS technologies, they may become successful alternatives for conventional power plants in the near future, depending on the CO_2 price and public acceptance. In addition to the significant role of CCS technologies in decarbonization, another valuable feature is flexibility: flexibility (Heuberger et al. 2017). As a result, three kinds of CCS technologies – gas power plant with CCS unit, coal power plant with CCS unit, and biomass power plant with CCS unit – have been taken into account in this paper. As was mentioned, flexible CCS power plants can switch off their capture unit and increase their power output. This can be considered as a provision of short-term flexibility in the system. Nevertheless, their peaker behavior has been taken into account in order to provide flexibility to the system. Although data on the flexibility of commercial CCS technologies is scarce, there are examples of the dynamic operation of CCS technologies at pilot projects in Europe (Tait et al. 2016). Thus, considering the peaker behavior of CCS technologies, we assume the same amount of flexibility points for peaker power plants and CCS technologies. Table 1 shows the flexibility points attributed to various flexibility sources.

2.3. Data basis and model assumptions

The input data in this paper stem from different open-source databases which have been gathered in the Project 4NEMO[1]. The model input is organized on a regional level. The regional split is usually based on real markets, e.g. countries, but further splits reflecting internal bottlenecks are possible. A reasonable model runtime is the boundary condition for the maximum level of detail. The description of input data is as follows:

- Demand and commodity prices: The load curve of every region is included as hourly data. The shape of the curve is kept constant over the entire modeling period, while the maximum demand can be adjusted according to the expected demand growth. In addition, energy carrier prices, CO_2 prices, and CO_2 storage capacity are addressed in this section.

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[1] https://www.4nemo.de/

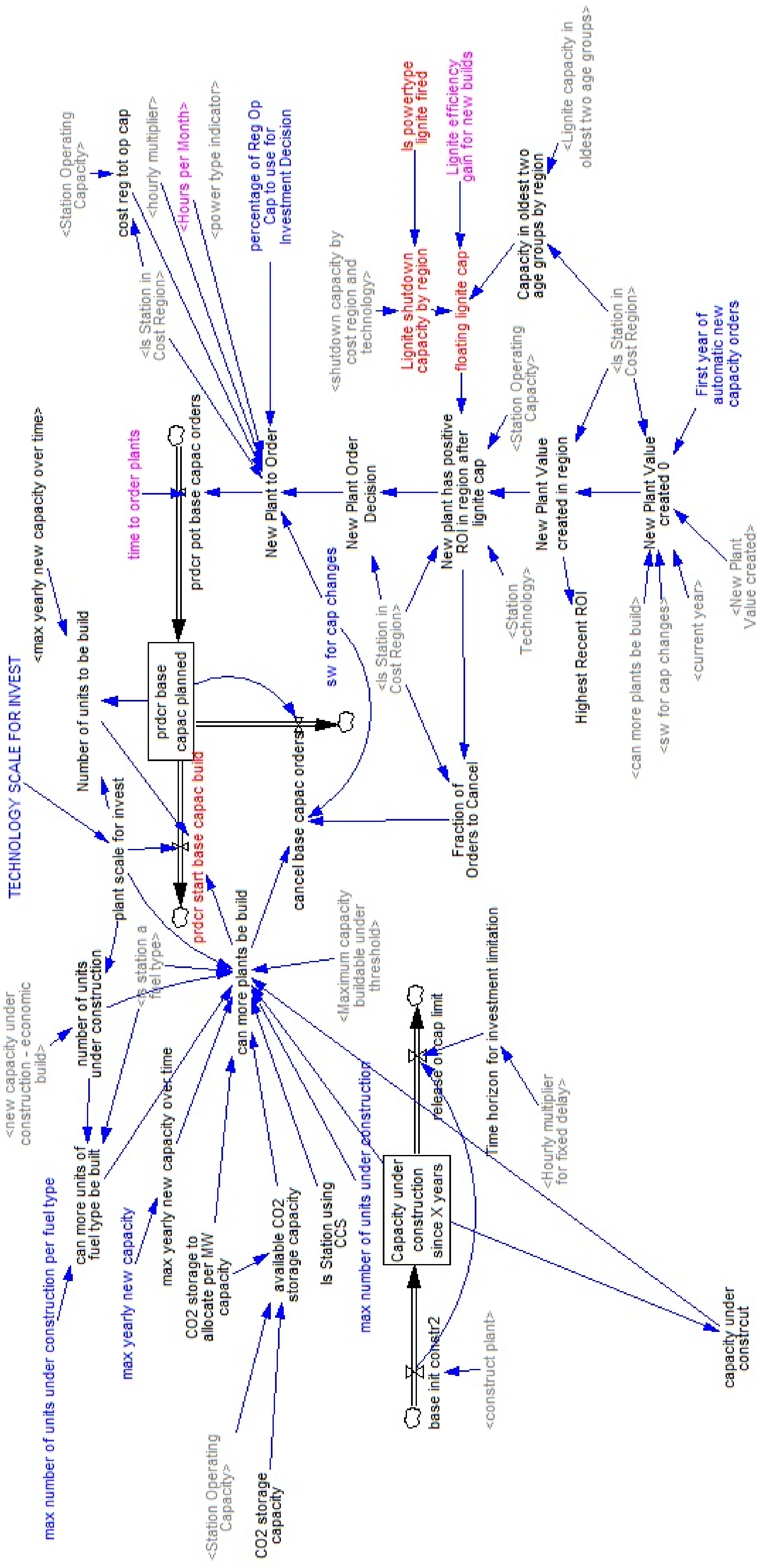


Figure 3: Investment decision module in HECTOR

- Process: Power plants can be modeled at the unit level. A decrease in the model run-time and the lack of detailed information can be reasons to aggregate the power plant units into larger blocks of a certain power plant type. The model uses cost data specific for each plant type to dispatch these blocks. This data includes investment costs (Total investment cost for adding capacity (€-cent/kW)), fixed costs (Operation-independent costs for existing and new capacities per unit of installed capacity (€-cent/kW)), variable costs (Variable costs per energy unit (MWh) produced (€-cent/kWh)), depreciation period, technology lifetime, reliability (Average available capacity due to technical categorization (MW)), and cap-credit (Lowest operating level as a fraction of station capacity (%)).

- Process conversion: Techno-economic data characterizing the power plants, including efficiencies, CO_2 emission factor, and CO_2 capture ratio, are taken into account.

- Transmission: Each interconnection between two regions is included in the input file, with the available capacity and transmission costs. Since the model does not have an endogenous transmission investment decision module, lower transmission capacities for further years have been taken into account.

- Storage: In addition to process data which are considered for all technologies, storage technologies need further data due to their technical characteristics in the model. As a consequence, further data regarding input/output efficiency, discharge rate, and the maximum cycle of the storage technologies considered are needed.

- Capacity factors of renewables: Time series of capacity factors are another significant input that can influence RES development in the long term. Since the location of the RES has a significant impact on the electricity generation from solar PV, onshore and offshore wind, we use a detailed time series dataset with 21 categorizations in all European countries, including onshore/offshore wind speeds in three hub heights (80 m, 100 m, 120 m) and solar irradiation. Each technology is grouped under three high, middle, and low categories – representing the wind or solar potential of regions with high, middle, and low level of full-load hours. As an illustration, Table 2 shows the full-load hours for 2015 in Germany. As is detailed in the table, full-load hours of offshore wind are higher than those for onshore wind and solar PV. As the accurate prediction of the actual meteorological weather conditions is hard to accomplish, we use the same time series for all further years as a simplification.

Further information regarding the data basis of the model can be found in the HECTOR manual (Sheykhha and Madlener 2019).

2.3.1. Scenario

As a base scenario, we use the scenario “Restauration of the EU” from the 4NEMO project. The scenario describes a future where European states collaborate to reach ambitious climate targets. For developing consistent scenarios, information was retrieved from expert interviews using the cross-impact balance

Table 2: Full-load hours per year for different renewable energy sources in Germany for 2015 and beyond

Technology	Full-load hours [h p.a.]	Technology	Full-load hours [h p.a.]
Onshore wind 80 m high	1957	Offshore wind 80 m high	3136
" 100 m high	2403	" 100 m high	3266
" 120 m high	3003	" 120 m high	3661
" 80 m middle	1725	" 80 m middle	2913
" 100 m middle	2105	" 100 m middle	3190
" 120 m middle	2976	" 120 m middle	2573
" 80 m low	1519	" 80 m low	1512
" 100 m low	1757	" 100 m low	2617
" 120 m low	2892	" 120 m low	2836
Solar PV high	1055		
" middle	1051		
" low	932		

method (Weimer-Jehle 2006). Market outcomes beyond the power sector (e.g., fuel or carbon prices) were quantified using the computable general equilibrium (CGE) model PACE (Böhringer et al. 2009).

3. Results and discussion

The results are reported in two sections. First, the impact of the assumed learning rate from considering socio-technical dimensions on the development of flexibility is analyzed. Second, the impact of the renewable energy mix on the development of flexibility is studied. In addition, the synergy of CCS technologies and renewables and their effect on flexibility is scrutinized.

3.1. Development of flexibility; sensitivity to variation of CCS technology

To understand the relevance of the learning rate and the development of the flexibility, we develop a flexibility module in HECTOR for the years 2015-2050 for the European electricity market. All types of CCS technologies, including bio-CCS, coal-CCS, and gas-CCS, are included, but since the base run of the model envisages a prominent potential for gas-CCS we focus on this technology in the following. All technologies including renewables and non-renewables are modeled endogenously in the model. The model uses a continuous NPV calculation to construct new power plants in every 5 years. A 7% WACC (Weighted average cost of capital) is taken into account.

In order to investigate the impact of the learning rate regarding gas-CCS power plants on the flexibility of the electricity system, the technological learning module of the model is developed with the interaction of socio-technical factors. As was stated in the methodology section, Lohwasser and Madlener (2013) developed a CCS module for HECTOR in 2012, and to our knowledge they were the first researchers who used two-factor learning curve for the diffusion of CCS technologies. Note that two-factor learning is only accounted for in the case of CCS technology because the focus of this paper is on CCS technologies. However, the decreasing trend of investment costs of other technologies reflect learning effects indirectly. As investment costs of CCS have a far greater impact on the CCS diffusion, contrary to energy efficiency, we focus on this factor, whereas efficiency enhancement is modeled exogenously. Looking into R&D policy

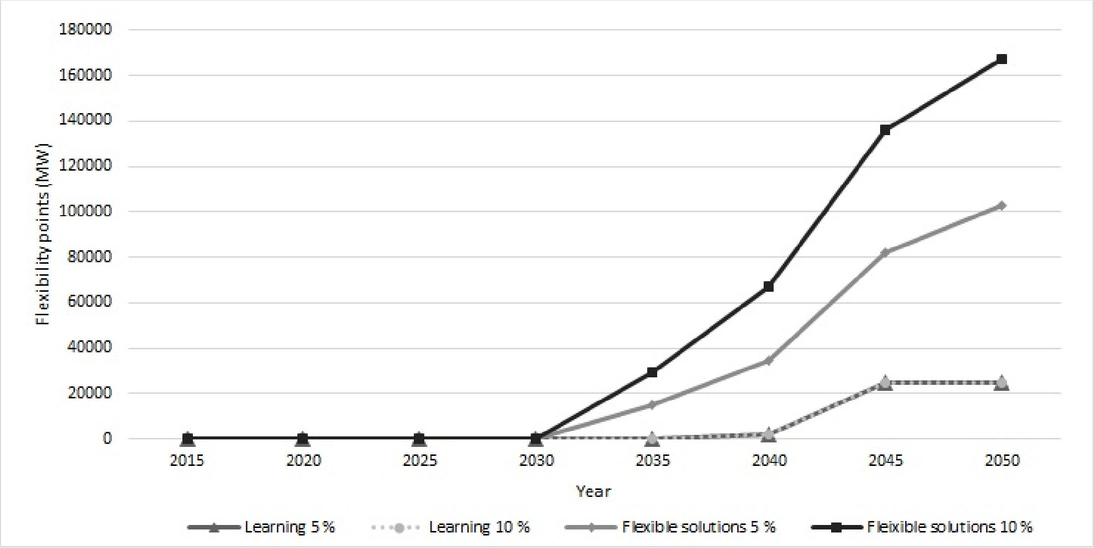


Figure 4: Difference of flexibility points in Europe in the three different scenarios, 2015-2050

we consider a budget of €100 million for R&D investment p.a. Since we are using two-factor learning curves (Junginger et al. 2010), we consider learning rates of 10% for both learning by doing and learning by searching. We adopt these learning rates from Louwen et al. (2018).

The overall diffusion of gas-CCS with different learning rates (5% and 10%) are akin to each other. The sensitivity analysis illustrates that the impact of the learning rate is rather minor. It is apparent from Fig. 4 that taking a reasonable learning rate into account can lead to 24 GW higher flexibility points compared to the base run. Although implementing the learning rate can slightly increase the flexibility points of the system, it can be concluded that in line with Lohwasser and Madlener (2013), the learning rate does not speed up the installed capacity of CCS in the electricity market substantially.

In order to evaluate the impact of the development rate of new flexible technologies on the market, this relationship has been modeled with a 5% and 10% development rate of flexible solutions. This sensitivity analysis reveals that using socio-technical factors in the model can lead to higher flexibility points in the market. Fig. 4 highlights that, contrary to quantitative modeling, the flexibility points reach the equivalant of 102.8 GW and 167.3 GW in 2050 when assuming a 5% and 10% development rate of flexible solutions, respectively. This finding accentuates the importance of the integration of socio-technical factors in dynamic energy system models. In addition, it can be seen that a higher increase will take place when the socio-technical impact of the flexibility constraints are included. In other words, since a linear relationship for increasing flexibility solutions is taken into account, the available flexibility of the power system is higher than the situation when this correlation is not modeled. Hence, the amount of flexibility is varied based on the learning rate and flexibility constraints. It means that both increases in the instability of the market and environmental pressure can induce higher investment in R&D and increasing flexible solutions accordingly.

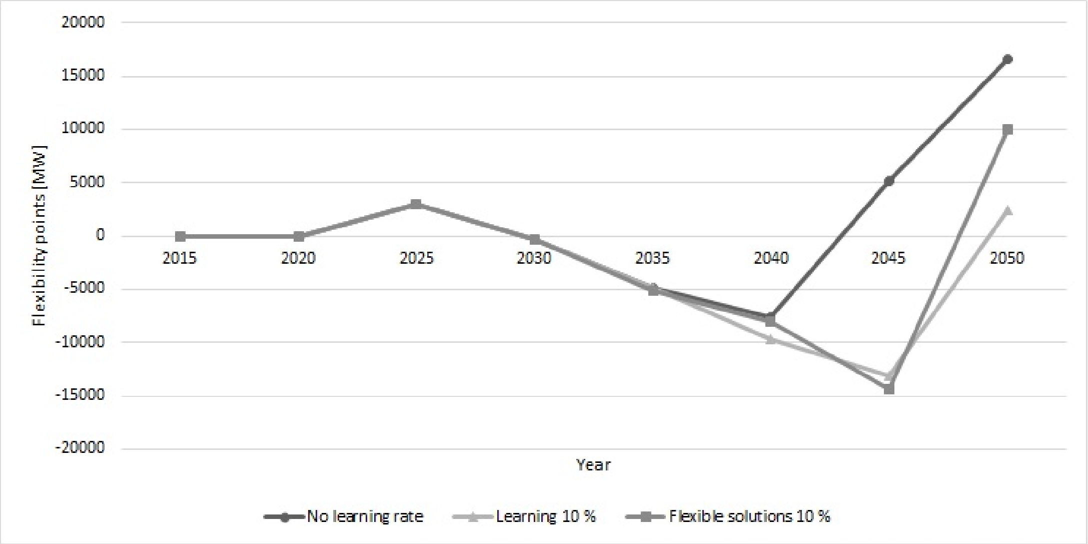


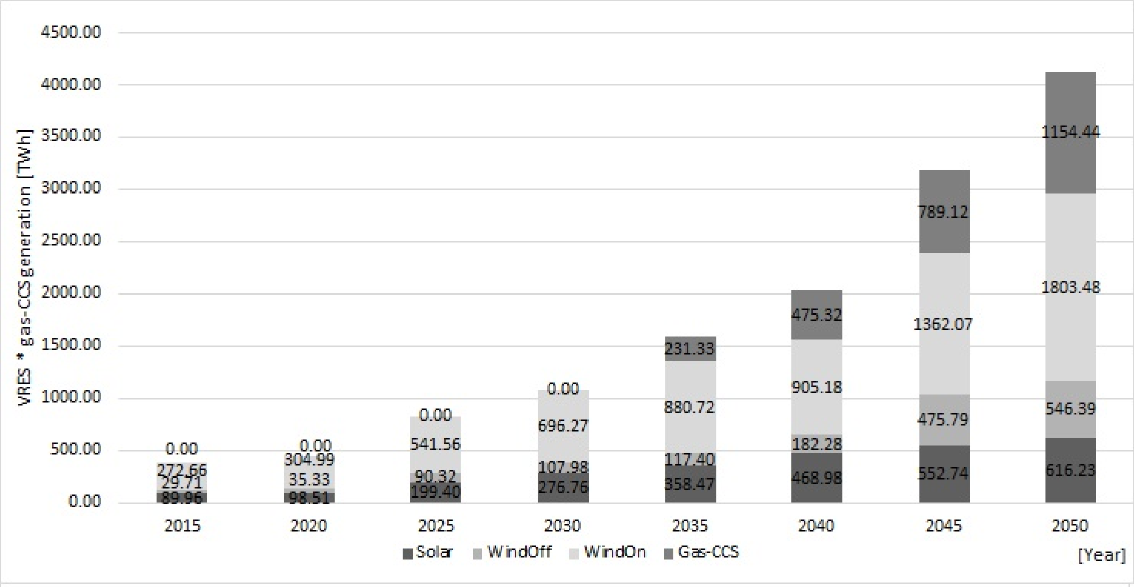
Figure 5: The difference of flexibility points in offshore and onshore scenarios [MW], with and without CCS learning, 2015-2050

3.2. *Development of flexibility: Impact of RES mix on the flexibility*

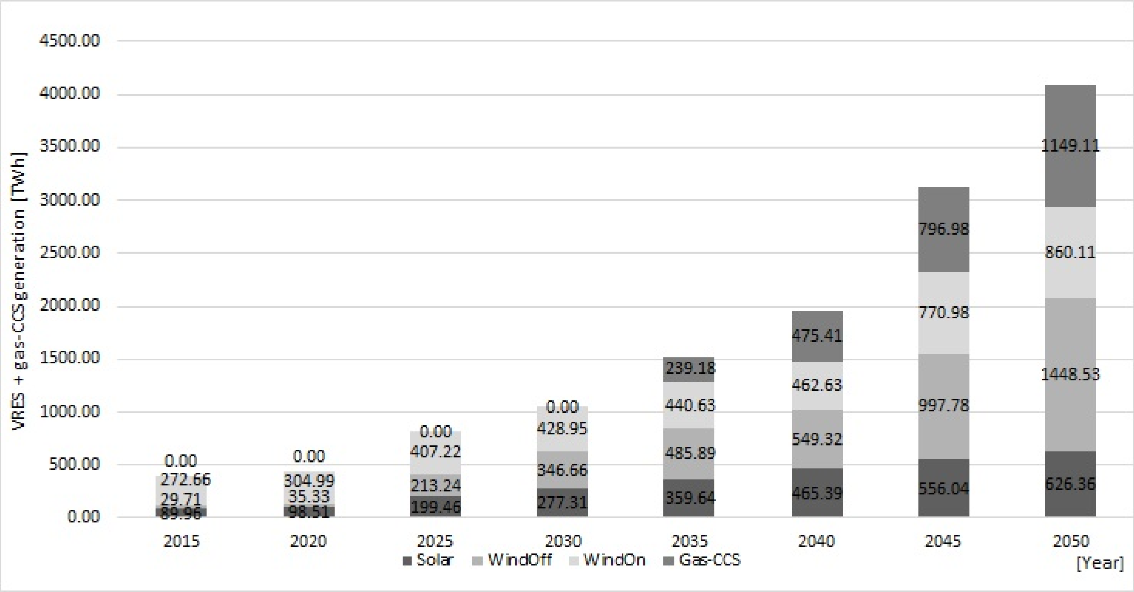
Although onshore wind is a vital element in most scenarios concerning the future of the power system, Brunner et al. (2020) found a cost trade-off between the scenario with the lowest RES generation and the scenario with the lowest need for flexibility. In this section, this relation is analyzed considering the synergy between CCS thechnology and the RES mix. To do so, we compare the flexibility of the system with the novel method, focusing on the new renewable energy mix.

Contrary to the optimization investment decision module, in the simulation model, the investment decision module is exploited to simulate the impact of user-specified policies and decisions on system performance. Since the investment decision module of HECTOR is based on a simulation perspective, we change the investment shares for two scenarios in this section; an onshore wind-oriented market and an offshore wind-oriented market. In other words, as in the simulation model, the future decision is made in accordance with the specific shares of technologies, and we manipulate the shares of offshore wind and onshore wind technologies to determine how the energy system will evolve in the presence of a lock-in of a technology. In the first and second scenarios, a lock-in for onshore and offshore wind, respectively, is considered.

As can be seen in Fig. 5, the flexibility of the market with an offshore wind-oriented perspective is different from the market with an onshore wind-oriented perspective. This difference is negligible (<8 GW) for all scenarios from 2020 to 2040. However, the amount of flexibility points in 2045 and 2050 increases substantially. The drastic CO_2 price increase could account for the rise in flexibility from 2040 onwards (see Table A3). Interestingly, Fig. 5 highlights that the flexibility points of the electricity system reach a higher level when learning is excluded/ignored. Simulation results reveal that although flexibility points of the system reach the equivalent of around 16.5 GW in 2050 (base run), they reach 2.4 GW when taking a 10% learning rate for CCS technology into account. However, it reaches 10 GW when socio-technical factors are accounted for as well. All in all, it can be concluded that when there is a lock-in for offshore wind, the flexibility of the system increases in the long term accordingly, even in the absence of any governmental



(a) Onshore wind-oriented market



(b) Offshore wind-oriented market

Figure 6: Renewable power generation mix and gas-CCS [TWh], onshore and offshore wind-oriented market, 2015-2050

supports related to R&D of CCS technologies. It is noteworthy, that the impact of support scheme of renewable energies such as offshore wind support scheme is beyond the scope of this paper.

However, since the flexibility concept addresses the flexibility of the market with a focus on capacity rather than generation, analyzing the generation mix can complement the assessment of the impact of offshore wind on the market. As a result, other indicators in the market, such as the generation mix and CO_2 emissions, should be explored as well. Looking at the generation mix of two scenarios shows that although flexibility points are higher in an offshore wind-oriented market, generation from renewables is 3.43 TWh lower than in the onshore wind-oriented scenario. Analogously, 5.32 TWh less is generated from gas-CCS technologies (see Fig. 6). As anticipated, the offshore wind-oriented market produces 16.2 Giga tons of CO_2 emissions more than the onshore wind-oriented market (see Fig. 7). Hence, although the offshore wind energy market has a slightly higher flexibility than the onshore wind market, it does not have superiority

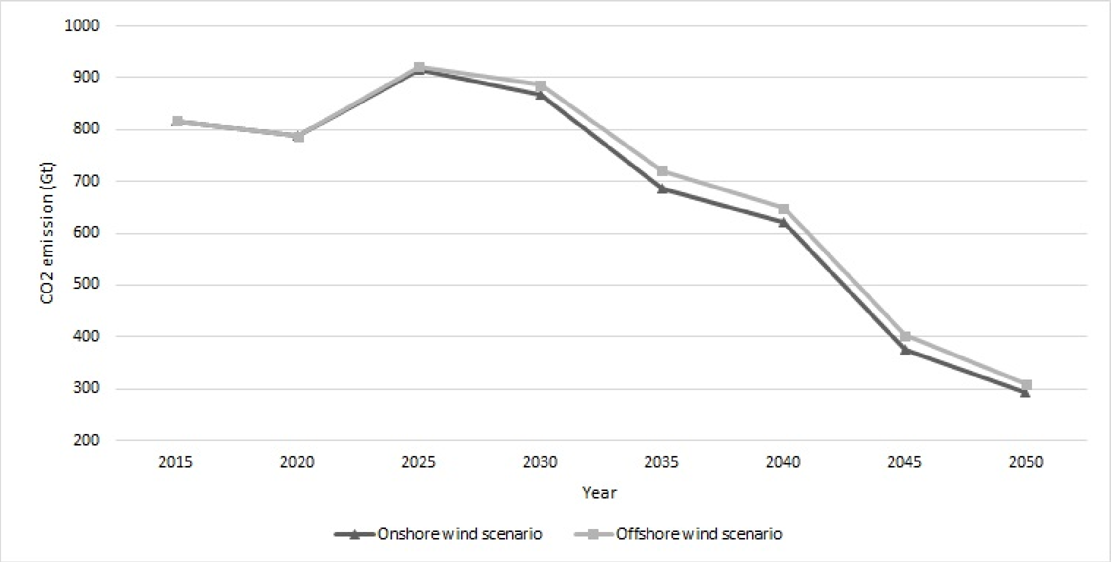


Figure 7: European CO_2 emissions from power plants for two scenarios, onshore and offshore wind scenarios, 2015-2050

over the market with onshore wind lock-in from a renewable energy share and a CO_2 emission point of view. Fig. 6 shows that a higher share of CCS does not only weaken renewable energy integration but also enhances the share of renewables and flexibility of the market. Hence, we can conclude that even traditional CCS technologies may lead to higher flexibility in the market. One reason behind this interesting fact is that offshore wind is not available in all regions. Therefore, this policy should be analyzed separately for each country/region. Further information regarding the development of electricity generation for each technology can be found in Table B2 and Table B1 in the Appendix. Analysis of total system costs reveals that the total costs in both scenarios gradually increase each year. The comparison between Table B3 and Table B4 highlights that the offshore wind-oriented market has higher total costs and it reaches to €299 billion in 2050, which is €50 billion higher than the onshore wind-oriented market.

Table 3 and Table 4 illustrate the flexibility points across different regions in the onshore and offshore wind-oriented market, respectively. The comparison between the two tables shows that flexibility points tend to be higher in the offshore wind-oriented market in all regions except for countries like Germany and some Eastern European countries (i.e. Czech Republic, Poland, and Slovakia), the Alpine region (i.e. Austria and Switzerland), and the Baltic (i.e. Estonia, Latvia, Lithuania). This can be attributed to the lack of CCS storage capacity, fewer of peaker power plants installations, or curtailment. Therefore, as already mentioned, in order to draw some conclusions for each region/country, other indicators, such as the level of electricity generation should be scrutinized separately in each country. Having investigated electricity generation over the period 2015-2050, the promotion of wind power in Germany shows different patterns in the onshore and offshore wind-oriented market. A reasonable explanation could be the sizable offshore wind potential available in Germany. Simulation results show that the total wind power generation in the offshore wind-oriented market is 5.52 GWh higher than in the onshore wind-oriented market. Furthermore, conventional power plants (e.g. gas-fired ones) generate 4 GWh less electricity in the offshore wind-oriented market. Regarding flexibility points, simulation results show a flexibility score of 6000 points more in the

Table 3: Flexibility points onshore wind-oriented market across the regions covered

	2015	2020	2025	2030	2035	2040	2045	2050
Benelux	116518.9	99804.9	79828.9	83741.3	89356.2	125328.6	162684.7	208044.7
Germany	86477.2	74429.2	70239.2	90585.1	132233.3	197938.3	247896.9	328557.5
Czech Republic	21003.4	21282.7	14343.1	18948.3	32388.5	35472.4	21597.7	22279.5
France	55567.4	57305.3	57011.3	84995.3	106721.3	163421.3	238902.0	322622.1
Eastern Europe-SE	47290.9	45244.9	34707.5	50285.1	68775.1	110764.5	104411.8	105377.7
Eastern Europe-SW	15725.3	16067.3	16585.7	24301.7	30443.0	27885.4	25281.7	25358.6
Italy	241731.5	194774.5	129504.3	141280.5	204357.6	293529.8	319824.6	319279.2
Iberia	210910.3	203445.3	156278.3	109490.4	176197.0	262832.6	319159.0	323171.9
Scandinavia	24383.9	22011.9	19168.9	50980.9	86170.9	138730.9	205862.0	282719.9
British Isles	167670.8	106722.8	80570.8	86138.8	96068.8	144370.8	184361.6	230420.8
Alpine	51109.8	52283.1	53105.2	44258.9	40289.5	40245.3	16272.6	16520.0
Baltic	11894.2	12794.2	12758.9	10280.4	16793.0	27263.0	24553.3	42963.4
Sum	1050283.4	906166.0	724102.0	795286.8	1079794.1	1567782.8	1870807.9	2227315.3

Table 4: Flexibility points offshore wind-oriented market across the regions covered

	2015	2020	2025	2030	2035	2040	2045	2050
Benelux	116518.9	99804.9	79828.9	86681.3	95866.7	136248.0	175915.9	228236.3
Germany	86477.2	74429.2	70243.5	90595.7	130153.2	193758.4	241796.7	322815.4
Czech Republic	21003.4	21282.7	17580.7	18888.7	32376.7	35538.7	21442.6	21418.4
France	55567.4	57305.3	57011.3	88775.3	114491.3	179171.3	264102.0	354157.6
Eastern Europe-SE	47290.9	45244.9	34707.3	50705.7	69944.6	113827.6	107338.4	126372.6
Eastern Europe-SW	15725.3	16067.3	16585.7	25351.7	32129.2	29568.9	25293.8	25388.5
Italy	241731.5	194774.5	129502.9	148006.3	220148.7	319835.8	351563.2	351342.5
Iberia	210910.3	203445.5	156275.5	114810.8	188538.4	286135.5	351295.2	352717.9
Scandinavia	24383.9	22011.9	19168.9	54340.9	93520.9	151330.9	225811.2	310466.1
British Isles	167670.8	106722.8	80570.8	88868.8	102368.8	155500.7	210048.3	284173.6
Alpine	51109.8	52301.3	53100.7	43992.5	39170.4	39171.5	14416.7	13576.9
Baltic	11894.2	12794.2	12759.3	10711.1	17882.0	29394.9	26774.2	40825.3
Sum	1050283.4	906184.4	727335.6	821728.8	1136591.0	1669482.2	2015798.1	2431491.1

onshore wind-oriented market. Hence, it can be deduced that supporting offshore wind cannot lead to higher flexibility in Germany, where significant amounts of offshore wind power are available.

4. Discussion

One of the most significant differences of system dynamics modeling compared to other traditional modeling tools is its ability to consider socio-technical factors and feedback loops that are changing endogenously in the system (Ford 1997). As the relationship between R&D investment and flexible solutions has not been addressed in the literature yet, taking different functions for this relationship can be quite influential on the results. Besides, integrating the concept of delay in the system dynamics can increase the validity noticeably. In this paper, we considered a linear relationship between R&D investment and flexible solutions. Sensitivity analysis regarding the delay can also enrich the accuracy of results.

This paper has used a novel system dynamics approach focusing on the flexibility of the market with the concept of flexibility scoring. As introduced in section 3 and following (Busch and Orvis 2020), every flexible technology has specific flexibility points, which means that how many VRES technologies can be supported by 1 MW of the respective technology. Therefore, performing a sensitivity analysis on flexibility points can enhance the accuracy of the results. Furthermore, using different flexibility points for different countries can increase the robustness of the results.

One limitation of the model is the number of flexibility sources. There are other sources of flexibility such as demand-side management (DSM), power to heat (P2H), and various hydrogen-based technologies, which have not been taken into account in this study. Although including these sources can complement the analysis, they expectedly do not highly change the obtained results.

One of the key differences between simulation and optimization models is their investment decision module which is based on a pre-defined set of policies (simulation model) and optimal strategy (optimization model), respectively. HECTOR as a simulation model with a simulation investment decision module. As a result, it uses investment shares in which the installation of new technologies is based on whether or not the NPV of every technology is positive. Hence, since the model does not look for an optimal strategy in the investment decision module, doing iterative loops for calibrating the investment decision can decrease the difference in the investment decision compared with an optimization model.

Although wind and solar variability happen continuously, we are using a concept that takes a long-term perspective of flexibility into account. As flexibility points are based on capacity (MW) rather than electricity generation (MWh) it aims at addressing large, relatively sudden power needs. This relevant factor is not the portion of the year during which flexibility providers will be called upon to deliver these services. Therefore, the different capacity factors of different plant types or quality tiers do not influence their flexibility point requirements (as these affect generation but not capacity). Although most of the papers in the literature look at the concept of flexibility from a short-term perspective, this method can be used for various applications in which data and computational issues are vital.

5. Conclusions

Achieving a sustainable energy transition in the European electricity market towards high shares of renewables is challenging but seems doable. The European Union set itself the target of a 32% share of renewables across Europe by 2030. Having balanced fluctuations in the electricity system that stem from variable sources, such as wind and solar energy, the system needs more flexibility to overcome this volatility. In this paper, we presented a large-scale electricity model (dispatch and investment decision model) that is based on system dynamics and that enables to integrate the socio-technical dimensions of the energy systems. The impact of socio-technical factors is modeled quantitatively by using feedback loops. The study aims at determining the value of flexibility in Europe from 2015 to 2050 by using a new scoring concept referred to as flexibility points. We use this approach to assess the impact of the learning rate related to specific flexibility sources on the development of flexibility in the European electricity market. Investigating the power system in 2050 reveals that the learning rate does not increase the flexibility of the system markedly. However, considering socio-technical parameters can lead to higher flexibility in Europe (167 MW more than in the base case). The simulation results reveal further that the system shows the equivalent of 16.5 GW in terms of flexibility points without consideration of learning curve effects assumed for CCS technology. Hence, the flexibility of the market can be ensured without any additional governmental support. This should be kept in mind when any new VRES or CCS support policy is going to be designed. The concept of flexibility points could open a discussion regarding a better indicator for the analysis of flexibility in the energy system. Moreover, as many fundamental indicators in the system, such as the renewable electricity mix and the transmission capacities, can cause uncertainty about the flexibility in the system, it is recommended to analyze it separately for each region/country. As an illustration, for the case of Germany, where a considerable amount of offshore wind potential is still unexploited, the offshore wind-oriented market does not show any higher flexibility.

Furthermore, since the renewable power mix is one of the most decisive factors in the development of flexibility of the electricity market, the impact of a combination of offshore and onshore wind in the renewable electricity mix (offshore wind-oriented and onshore wind-oriented market) was analyzed. Although onshore wind is a leading element in most scenario analyses because of its rather low levelized cost of electricity and its technology maturity, the results of this paper suggest that offshore wind energy sources can provide more flexibility for the energy system in the longer term. However, the offshore wind-oriented market produces 16.9 Gt of CO_2 emissions more than the onshore wind-oriented market.

This paper opens up a new avenue for further research. Having added further sources of flexibility, such as DSM, power-to-heat, and others, can enhance the robustness of the results. Concepts from the sustainable transition literature such as technology, market, and social domains can identify significant mechanisms and relationships of variables in the model. Having included more social and behavioral variables in the long-term run, such as prosumage, can help to achieve a more realistic understanding of the future of flexibility in energy systems. Moreover, disruptive innovations, major changes in energy policies, and unexpected phenomena (e.g. a pandemic, or blackouts) may alter the future demand for flexibility in the European electricity market. Integrating the impact of spontaneous changes in the flexibility score model can improve the accuracy of the model.

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References

Bertsch, Joachim, Christian Growitsch, Stefan Lorenczik, and Stephan Nagl (2016). “Flexibility in Europe’s power sector—An additional requirement or an automatic complement?” In: *Energy Economics* 53, pp. 118–131.

Böhringer, Christoph, Andreas Löschel, and Thomas F. Rutherford (2009). “Policy Analysis Based on Computable Equilibrium (PACE)”. In: *Modelling Sustainable Development*. Ed. by Valentina Bosetti, Reyer Gerlagh, and Stefan P. Schleicher. Chapters. Edward Elgar Publishing. Chap. 14. URL: `https://ideas.repec.org/h/elg/eechap/13132_14.html`.

Bolwig, Simon, Gatis Bazbauers, Antje Klitkou, Peter D Lund, Andra Blumberga, Armands Gravelsins, and Dagnija Blumberga (2019). “Review of modelling energy transitions pathways with application to energy system flexibility”. In: *Renewable and Sustainable Energy Reviews* 101, pp. 440–452.

Brunner, Christoph, Gerda Deac, Sebastian Braun, and Christoph Zöphel (2020). “The future need for flexibility and the impact of fluctuating renewable power generation”. In: *Renewable Energy* 149, pp. 1314–1324.

Busch, Chris and Robbie Orvis (2020). *On the state’s current greenhouse gas emission trajectory and six policy opportunities for deepening emission reductions*. URL: `https://energyinnovation.org/wp-content/uploads/2020/05/Insights-from-the-California-Energy-Policy-Simulator_5.1.20.pdf`.

Cherp, Aleh, Vadim Vinichenko, Jessica Jewell, Elina Brutschin, and Benjamin Sovacool (2018). “Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework”. In: *Energy Research & Social Science* 37, pp. 175–190.

Child, Michael, Claudia Kemfert, Dmitrii Bogdanov, and Christian Breyer (2019). “Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe”. In: *Renewable Energy* 139, pp. 80–101.

Cloete, Schalk and Lion Hirth (2020). “Flexible power and hydrogen production: Finding synergy between CCS and variable renewables”. In: *Energy* 192, 116671.

De Jonghe, Cedric, Erik Delarue, Ronnie Belmans, and William D’haeseleer (2011). “Determining optimal electricity technology mix with high level of wind power penetration”. In: *Applied Energy* 88.6, pp. 2231–2238.

Denholm, Paul and Maureen Hand (2011). “Grid flexibility and storage required to achieve very high penetration of variable renewable electricity”. In: *Energy Policy* 39 (3), pp. 1817–1830.

Ford, Andrew (1997). “System dynamics and the electric power industry”. In: *System Dynamics Review: The Journal of the System Dynamics Society* 13.(1), pp. 57–85.

Georgilakis, Pavlos S (2008). “Technical challenges associated with the integration of wind power into power systems”. In: *Renewable and Sustainable Energy Reviews* 12.(3), pp. 852–863.

Gravelsins, Armands, Gatis Bazbauers, Andra Blumberga, Dagnija Blumberga, Simon Bolwig, Antje Klitkou, and Peter D Lund (2018). “Modelling energy production flexibility: system dynamics approach”. In: *Energy Procedia* 147, pp. 503–509.

Grünewald, Philipp H, Timothy T Cockerill, Marcello Contestabile, and Peter JG Pearson (2012). “The socio-technical transition of distributed electricity storage into future networks—System value and stakeholder views”. In: *Energy Policy* 50, pp. 449–457.

Hedegaard, Karsten, Brian Vad Mathiesen, Henrik Lund, and Per Heiselberg (2012). “Wind power integration using individual heat pumps–analysis of different heat storage options”. In: *Energy* 47 (1), pp. 284–293.

Heuberger, Clara, Lain Staffell, Nilay Shah, and Niall Mac Dowell (2017). “Valuing Flexibility in CCS Power Plants (IEAGHG Technical Report, 2017)”. In: URL: `https://tinyurl.%20com/yatnzrxc`.

Hirth, Lion (2015). “The optimal share of variable renewables: How the variability of wind and solar power affects their welfare-optimal deployment”. In: *The Energy Journal* 36.(1), pp. 149–184.

Höfer, Tim and Reinhard Madlener (2021). “Locational (In) Efficiency of Renewable Energy Feed-In Into the Electricity Grid: A Spatial Regression Analysis”. In: *The Energy Journal* 42, pp. 133–157.

Huber, Matthias, Desislava Dimkova, and Thomas Hamacher (2014). “Integration of wind and solar power in Europe: Assessment of flexibility requirements”. In: *Energy* 69, pp. 236–246.

Huertas-Hernando, Daniel, Hossein Farahmand, Hannele Holttinen, Juha Kiviluoma, Erkka Rinne, Lennart Söder, Michael Milligan, Eduardo Ibanez, Sergio Martın Martınez, Emilio Gomez-Lazaro, et al. (2017). “Hydro power flexibility for power systems with variable renewable energy sources: an IEA Task 25 collaboration”. In: *Wiley Interdisciplinary Reviews: Energy and Environment* 6 (1), 220.(1), 220.

Jacobson, Mark Z and Mark A Delucchi (2011). “Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials”. In: *Energy Policy* 39 (3), pp. 1154–1169.

Junginger, Martin, Wilfried Van Sark, and André Faaij (2010). *Technological learning in the energy sector: lessons for policy, industry and science*. Edward Elgar Publishing.

Kirkerud, Jon Gustav, Torjus Folsland Bolkesjø, and Erik Trømborg (2017). “Power-to-heat as a flexibility measure for integration of renewable energy”. In: *Energy* 128, pp. 776–784.

Klie, Leo and Reinhard Madlener (Jan. 2020 a, b). *Optimal Configuration and Diversification of Wind Turbines: A Hybrid Approach to Improve the Penetration of Wind Power, FCN Working Paper No. 1/2020. Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, January*. URL: `https://www.fcn.eonerc.rwth-aachen.de/cms/E-ON-ERC-FCN/Forschung/~emvl/Arbeitspapiere/lidx/1/`.

Kopiske, Jakob, Sebastian Spieker, and George Tsatsaronis (2017). “Value of power plant flexibility in power systems with high shares of variable renewables: A scenario outlook for Germany 2035”. In: *Energy* 137, pp. 823–833.

Lamadrid, A, T Mount, and R Thomas (2011). “Geographical averaging and ancillary services for stochasticpower generation”. In: *International Journal of Innovations in Energy Systems and Power* 6 (1), pp. 13–21.

Litzelman, Scott, Max Tuttman, Maruthi Devarakonda, Maxim Lyubovsky, and Ray Duthu (2021). “Flexible CCS Technologies To Reduce the Cost of Net-Zero Carbon Electricity Systems”. In: *SSRN 3821032*. URL: `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3821032`.

Lohwasser, Richard and Reinhard Madlener (2013). “Relating R&D and investment policies to CCS market diffusion through two-factor learning”. In: *Energy Policy* 52, pp. 439–452.

Lorenczik, Stefan (Aug. 2017). “Essays on market design and strategic behaviour in energy markets”. PhD thesis. Universität zu Köln. URL: `https://kups.ub.uni-koeln.de/7896/`.

Louwen, A, M Junginger, and S Krishnan (2018). “Technological learning in energy modelling: experience curves”. In: *Policy Brief for REFLEX Project.* URL: `http://reflex-project.eu/wp-content/uploads/2018/12/REFLEX_policy_brief_Experience_curves_12_2018.pdf`.

Martinot, Eric (2016). “Grid integration of renewable energy: flexibility, innovation, and experience”. In: *Annual Review of Environment and Resources* 41, pp. 223–251.

Nicolosi, Marco (2010). “Wind power integration and power system flexibility–An empirical analysis of extreme events in Germany under the new negative price regime”. In: *Energy Policy* 38 (11), pp. 7257–7268.

Papaefthymiou, Georgios, Edwin Haesen, and Thobias Sach (2018). “Power System Flexibility Tracker: Indicators to track flexibility progress towards high-RES systems”. In: *Renewable Energy* 127, pp. 1026–1035.

Pilpola, Sannamari and Peter D Lund (2019). “Different flexibility options for better system integration of wind power”. In: *Energy Strategy Reviews* 26, 100368.

Pudjianto, Danny, Marko Aunedi, Predrag Djapic, and Goran Strbac (2013). “Whole-systems assessment of the value of energy storage in low-carbon electricity systems”. In: *IEEE Transactions on Smart Grid* 5.(2), pp. 1098–1109.

Ram, Manish, Michael Child, Arman Aghahosseini, Dmitrii Bogdanov, Alena Poleva, and Christian Breyer (2017). *Comparing electricity production costs of renewables to fossil and nuclear power plants in G20 countries*. Tech. rep. Lappeenranta University of Technology (LUT), pp. 1–84.

Saarinen, Linn, Niklas Dahlbäck, and Urban Lundin (2015). “Power system flexibility need induced by wind and solar power intermittency on time scales of 1–14 days”. In: *Renewable Energy* 83, pp. 339–344.

Salpakari, Jyri, Jani Mikkola, and Peter D Lund (2016). “Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion”. In: *Energy Conversion and Management* 126, pp. 649–661.

Schuller, Alexander, Christoph M Flath, and Sebastian Gottwalt (2015). “Quantifying load flexibility of electric vehicles for renewable energy integration”. In: *Applied Energy* 151, pp. 335–344.

Sheykhha, Siamak and Reinhard Madlener (2019). *HECTOR – A Dynamic Dispatch and Investment Model for Electricity Markets in* EUROPE*, FCN Working Paper No. 23/2019. Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University.* URL: `https://www.fcn.eonerc.rwth-aachen.de/cms/E-ON-ERC-FCN/Forschung/~emvl/Arbeitspapiere/lidx/1/`.

Siala, Kais, Mathias Mier, Lukas Schmidt, Laura Torralba-Díaz, Siamak Sheykhha, and Georg Savvidis (2020). *Supplementary materials for manuscript "Which model features matter? An experimental ap-*

proach to evaluate power market modeling choices". DOI: `10.5281/ZENODO.4120577`. URL: `https://zenodo.org/record/4120577`.

Skea, Jim (2012). *Roadmap 2050: A Practical Guide to a Prosperous, Low-Carbon Europe, European Climate Foundation (2010), pp. 67-68*.

Tait, Paul, Bill Buschle, Ilja Ausner, Prashant Valluri, Marc Wehrli, and Mathieu Lucquiaud (2016). "A pilot-scale study of dynamic response scenarios for the flexible operation of post-combustion CO_2 capture". In: *International Journal of Greenhouse Gas Control* 48, pp. 216–233.

Von der Leyen, Ursula (2019). *My Agenda for Europe. Political Guidelines for the Next European Commission 2019-2024*. European Union, Brussels. URL: `https://ec.europa.eu/info/sites/info/files/political-guidelines-next-commission_en_0.pdf`.

Weimer-Jehle, Wolfgang (2006). "Cross-impact balances: A system-theoretical approach to cross-impact analysis". In: *Technological Forecasting and Social Change* 73.(4), pp. 334–361.

Xing, Tian, Qi Caijuan, Zhao Liang, Ge Pengjiang, Gong Jianfeng, and Jin Panlong (2017). "A comprehensive flexibility optimization strategy on power system with high-percentage renewable energy". In: *2017 2nd International Conference on Power and Renewable Energy (ICPRE)*. IEEE, pp. 553–558.

Zhao, Haoran, Qiuwei Wu, Shuju Hu, Honghua Xu, and Claus Nygaard Rasmussen (2015). "Review of energy storage system for wind power integration support". In: *Applied Energy* 137, pp. 545–553.

Zöphel, Christoph, Steffi Schreiber, Theresa Müller, and Dominik Möst (2018). "Which Flexibility Options Facilitate the Integration of Intermittent Renewable Energy Sources in Electricity Systems?" In: *Current Sustainable/Renewable Energy Reports* 5.(1), pp. 37–44.

Appendix A. Model assumptions

Table A1: Regions covered

Region	Countries
Benelux	Belgium (BE), Luxembourg (LU), The Netherlands (NL)
Eastern Europe	Czech Republic (CZ) , Slovakia (SK) , Poland (PL)
Germany	Germany (DE)
British Isles	UK (UK), Ireland (IE)
France	France (FR)
Scandinavia	Denmark (DK), Finland (FI), Norway (NO), Sweden (SE)
Alpine	Austria (AT), Switzerland (CH)
Iberia	Portugal (PT), Spain (ES)
Italy	Italy (IT)
Baltic	Estonia (IE), Latvia (LV), Lithuania (LT)
Eastern Europe-SW	Croatia (HR), Hungry (HU), Slovenia (SI)
Eastern Europe-SE	Bulgaria (BG), Greece (EL), Romania (RO)

Table A2: Nominal fuel price assumptions 2015-2050 [€-ct/kWh] (Siala et al. 2020)

Fuel	2015	2020	2025	2030	2035	2040	2045	2050
Coal	8.35	8.29	8.14	7.96	7.78	7.66	7.58	7.48
Gas	20.65	20.55	20.29	19.91	19.65	19.39	19.12	18.89
Bio	12	12	12	12	12	12	12	12
Nuclear	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33
Lignite	7	7	7	7	7	7	7	7
Oil	40.26	40.84	40.97	41.15	41.43	41.76	42.27	42.65

Table A3: CO_2 prices assumptions 2015-2050 [€/MWh] (Siala et al. 2020)

	2015	2020	2025	2030	2035	2040	2045	2050
CO2 price	7.75	15	22	27	56	68	102	132

Table A4: Techno-economic characteristics of the power generation technologies considered (Siala et al. 2020)

	Availability [%]	Efficiency [%]	FOM cost [€/kW]	Lifetime [a]	VOM costs [€/kWh]
Nuclear	94	40	264	60	4.4
Coal	90	45	60	40	1.8
Lignite	91	35	65.6	40	2.4
Bio	90	20	211.78	30	2.25
CCGT	96	55	34	30	2
Gas ST	96	42	34	30	1.1
OCGT	94.8	32	17.49	30	2
Onshore Wind 100 m	97.5	100	0	25	0
" 120 m	97.5	100	0	25	0
Offshore Wind 100 m	94	100	130.91	25	0
" 120 m	94	100	130.91	25	0
PV (high, middle, low)	100	100	15	25	0
CCS gas	96	59	32.43	30	12.97
CCS coal	90	45	108.9	30	1.8
CCS bio	90	20	129.71	30	15.14
Hydro	90	100	0	45	0
PHS	98	100	5.3	45	0.01
Storage short-time	98	95	36.1	20	0
Storage long-time	95	60	30.4	20	0
Geothermal	95	9	494.55	30	2.4
Oil	94.8	31	34	30	1.1

Table A5: Specific investment costs assumed, 2015-2050 [€/kW] (Siala et al. 2020)

	2015	2020	2025	2030	2035	2040	2045	2050
Nuclear	6600	6006	5346	5082	4818	4488	4488	4356
Bio	4322	4235	4149	4149	4105	4062	4062	4019
CCGT	850	850	850	850	850	850	850	850
OCGT	437	437	437	437	437	437	437	437
Onshore Wind 100 m	-	1396	1368	1339	1324	-	-	-
" 120 m	-	-	-	-	-	1310	1310	1296
Offshore Wind 100 m	-	3024	2700	2520	2376	-	-	-
" 120 m	-	-	-	-	-	2268	2160	2088
PV (high, middle, low)	1300	1027	936	858	819	780	741	715
CCS gas	1494	1494	1494	1494	1494	1494	1494	1494
CCS coal	3414	3414	3278	3210	3175	3141	3141	3107
CCS bio	4450	4361	4272	4272	4227	4183	4183	4183
Hydro	0	0	0	0	0	0	0	0
PHS	0	0	0	0	0	0	0	0
Storage short-time	2020	2025	2030	2035	2040	2045	2050	
Storage long-time	2020	2025	2030	2035	2040	2045	2050	
Geothermal	12363	11992	11621	11498	11250	11127	11003	11003
Oil	821	821	821	821	821	821	821	821

Table A6: Development of electricity demand 2015-2050, by country [TWh] (Siala et al. 2020)

Country	2015	2020	2025	2030	2035	2040	2045	2050
AT	63.5	64.3	78.3	91.1	137.1	146.9	155.5	163.0
BE	83.1	82.2	96.6	107.3	131.5	158.0	181.6	196.2
BG	29.6	30.1	34.7	36.0	37.3	40.4	42.7	44.4
CH	58.2	60.8	67.2	70.5	116.3	126.0	136.3	147.5
CZ	58.7	62.6	116.8	122.9	126.8	135.2	144.8	153.7
DE	528.1	533.9	832.3	842.8	844.9	874.3	908.5	946.0
DK	31.8	31.8	36.6	35.1	39.3	46.8	52.1	55.4
EE	7.4	7.6	9.3	11.4	11.6	12.2	12.7	13.3
EL	52.4	52.8	58.0	54.9	58.8	64.2	69.6	73.4
ES	238.6	247.5	312.7	367.0	493.1	522.4	542.2	566.9
FI	79.7	72.6	82.9	79.2	80.0	82.1	87.3	90.9
FR	447.7	449.9	759.0	766.8	811.5	864.3	922.3	980.0
HR	15.7	15.7	17.4	17.6	18.2	20.4	23.0	25.4
HU	38.1	36.7	44.2	52.9	67.5	71.4	75.4	82.0
IE	25.7	26.1	30.6	32.6	39.3	42.5	45.1	49.1
IT	297.2	318.7	421.4	564.1	599.8	648.7	694.2	739.9
LT	10.2	12.1	18.4	18.1	17.2	17.8	18.9	19.8
LU	6.2	6.5	7.4	8.2	11.6	14.2	15.5	17.3
LV	6.5	6.6	7.7	8.6	10.0	11.8	12.4	12.9
NL	109.4	113.3	148.9	186.9	191.9	202.3	213.5	230.1
NO	119.3	124.0	130.3	124.9	157.0	166.8	176.8	187.6
PL	138.9	143.3	164.3	180.2	231.1	269.1	281.6	293.7
PT	46.9	51.8	60.9	62.1	66.2	70.2	73.5	76.2
RO	46.9	47.0	54.2	57.6	59.9	66.3	73.6	79.3
SE	127.8	132.8	158.5	161.1	232.7	250.4	268.6	287.8
SI	12.9	13.1	15.3	16.6	19.4	21.5	22.8	24.1
SK	25.4	26.7	33.5	39.1	48.1	56.7	58.7	61.0
UK	311.2	317.1	358.1	388.1	433.5	484.7	527.9	588.7

Appendix B. Output of model

Table B1: Development of electricity generation 2015-2050 in the onshore wind-oriented market [TWh]

	2015	2020	2025	2030	2035	2040	2045	2050
Bioenergy	0.03	0.27	65.57	78.56	180.61	194.22	192.02	180.58
Coal	497.47	474.03	369.25	302.79	148.03	88.81	27.17	14.20
Gas-CCGT	265.05	280.76	817.76	968.57	1095.13	1102.83	619.80	314.61
Gas-OCGT	5.32	6.68	28.22	51.68	57.97	40.30	22.99	16.15
Gas-ST	4.15	3.68	22.26	24.93	24.58	20.50	10.68	3.67
Geothermal	6.80	6.80	6.80	6.80	6.80	6.80	6.78	6.72
Hydro	538.83	533.90	533.90	538.76	537.24	534.86	522.73	510.79
Lignite	229.02	224.16	541.56	174.41	63.40	37.81	9.03	4.82
Nuclear	945.09	972.46	1046.68	1113.90	1169.25	1151.24	937.76	665.66
Oil/Other	0.00	0.00	5.07	2.52	1.65	1.19	0.36	0.78
Solar	89.96	98.51	199.40	276.76	358.47	468.98	552.74	616.23
Wind-Offshore	29.71	35.33	90.32	107.98	117.40	182.28	475.79	546.39
Wind-Onshore	272.66	304.99	541.56	696.27	880.72	905.18	1362.07	1803.48
Bio-CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal-CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas-CCS	0.00	0.00	0.00	0.00	231.33	475.32	789.12	1154.44

Table B2: Development of electricity generation 2015-2050 in the offshore wind-oriented market [TWh]

	2015	2020	2025	2030	2035	2040	2045	2050
Bioenergy	0.03	0.27	67.25	77.28	181.75	193.62	188.85	176.17
Coal	497.47	474.03	369.15	331.80	178.20	106.96	35.65	20.66
Gas-CCGT	265.05	280.76	819.25	972.20	1124.48	1134.19	643.20	313.53
Gas-OCGT	5.32	6.68	28.33	52.35	62.29	49.78	34.73	27.28
Gas-ST	4.15	3.68	22.73	24.39	25.42	19.70	10.46	4.33
Geothermal	6.80	6.80	6.80	6.80	6.80	6.80	6.75	6.73
Hydro	538.83	533.90	533.90	544.98	543.36	541.11	530.36	523.48
Lignite	229.02	224.16	407.22	167.60	55.27	32.16	10.48	6.55
Nuclear	945.09	972.46	1043.77	1114.43	1174.88	1180.00	952.10	671.39
Oil/Other	0.00	0.00	5.21	2.45	1.69	1.14	0.35	0.86
Solar	89.96	98.51	199.46	277.31	359.64	465.39	556.04	626.36
Wind-Offshore	29.71	35.33	213.24	346.66	485.89	549.32	997.78	1448.53
Wind-Onshore	272.66	304.99	407.22	428.95	440.63	462.63	770.98	860.11
Bio-CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Coal-CCS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Gas-CCS	0.00	0.00	0.00	0.00	239.18	475.41	796.98	1149.11

Table B3: Total costs onshore wind-oriented market across different regions covered [bn €]

	2015	2020	2025	2030	2035	2040	2045	2050
Benelux	9.78	9.40	14.68	16.86	22.65	27.30	25.53	21.82
Germany	27.49	25.64	29.19	28.92	30.19	29.97	31.56	29.66
Eastern Europe	10.68	10.73	7.73	8.13	7.85	7.92	6.70	6.75
France	40.16	40.31	43.13	43.14	45.01	46.34	49.11	48.68
Eastern Europe-SE	7.10	6.90	7.32	6.78	6.90	7.42	7.42	5.82
Eastern Europe-SW	3.13	3.04	3.93	4.64	6.08	5.53	6.23	7.61
Italy	12.33	11.78	19.73	27.80	38.45	40.77	41.16	38.91
Iberia	12.78	12.85	16.33	20.67	27.23	31.17	29.61	21.82
Scandinavia	12.62	12.37	14.98	17.00	24.59	28.02	27.24	26.43
British Isles	18.67	18.10	22.97	27.41	32.14	36.63	36.36	30.31
Alpine	3.86	3.80	5.06	7.37	10.23	10.50	9.16	7.05
Baltic	0.69	0.63	1.46	1.87	2.80	2.62	3.52	3.29
Sum	159.29	155.55	186.53	210.58	254.12	274.19	273.60	248.14

Table B4: Total costs offshore wind-oriented market across different regions covered [bn €]

	2015	2020	2025	2030	2035	2040	2045	2050
Benelux	9.78	9.40	16.05	19.60	26.71	27.06	25.18	22.40
Germany	27.49	25.64	33.10	33.22	35.24	29.83	33.14	35.31
Eastern Europe	10.68	10.73	8.36	9.92	9.28	7.65	7.47	7.61
France	40.16	40.31	42.77	42.80	44.80	46.46	49.14	55.54
Eastern Europe-SE	7.10	6.90	8.39	9.32	11.44	8.29	10.28	9.79
Eastern Europe-SW	3.13	3.04	4.03	5.48	7.01	5.41	6.22	7.87
Italy	12.33	11.78	22.50	34.76	51.15	41.23	47.18	48.44
Iberia	12.78	12.85	19.15	27.91	39.26	31.83	34.00	32.30
Scandinavia	12.62	12.37	14.64	16.50	24.09	28.11	29.93	31.89
British Isles	18.67	18.10	22.98	27.39	32.27	36.51	36.87	34.11
Alpine	3.86	3.80	5.06	7.51	10.98	14.05	13.47	10.69
Baltic	0.69	0.63	1.45	1.77	2.81	2.54	3.42	3.23
Sum	159.29	155.55	198.47	236.17	295.05	278.95	296.30	299.18

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