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Consequential environmental system analysis of expected offshore wind electricity production in Germany

Martin Pehnt[a,*], Michael Oeser[a,1], Derk J. Swider[b]

[a]*IFEU—Institute for Energy and Environmental Research Heidelberg (IFEU), Wilckensstr. 3, D-69120 Heidelberg, Germany*
[b]*Institute of Energy Economics and the Rational Use of Energy, University of Stuttgart, Heßbrühlstraße 49a, D-70565 Stuttgart, Germany*

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Abstract

Taking advantage of offshore wind power appears to be of special significance for the climate protection plans announced by the German Federal Government. For this reason, a comprehensive system analysis of the possible CO_2 reduction including the consideration of all relevant processes has to be performed. This goal can be achieved by linking a life-cycle assessment model of offshore wind utilisation with a stochastic model of the German electricity market. Such an extended life-cycle assessment shows that the CO_2 emissions from the construction and operation of wind farms are low compared with the substitution effects of fossil fuels. Additionally, in the German electricity system, offshore wind energy is the main substitute for medium-load power plants. CO_2 emissions from the modified operation and the expansion of conventional power plants reduce the CO_2 savings, but the substitution effect outweighs these emissions by one order of magnitude. The assumptions of the model, shown here to be above all CO_2 certificate prices, have a considerable influence on the figures shown due to a significant effect on the future energy mix.

Keywords: Life-cycle assessment; Consequential environmental system analysis; Wind; Offshore; Compressed air energy storage

1. Introduction

The generation of electricity from renewable energy sources already provides a major contribution to climate protection today. For example, according to data from the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, approximately 67 million tons of CO_2 was avoided in 2006 by generating electricity through wind and hydropower, biomass and photovoltaics [1]. With a share of 5%, wind power plays the most important role in the generation of electricity from all renewable energies. In the future, the amount of electricity generated by wind power is expected to increase. The Federal Government's goal is to achieve at least 20% of its power generation through renewable sources by the year 2020 [1]. A great part of this vision is to be achieved by expanding the capacity of wind turbines installed. This will not only require erecting new onshore wind parks and installing new technology to existing ones but also opening up offshore farms to harness more wind energy.

A further increase in the share of wind power for the generation of electricity raises questions about the impact caused by the integration of large amounts of wind power into the German electricity grid. Due to the fluctuating and, sometimes inaccurately, forecasted feed-in of wind power, it is only possible to substitute conventional power capacity by wind capacity to a small extent. This is why one frequently hears of the capacity credit of wind power, whose calculation is strongly influenced by the model's assumptions. In particular, it is dependant on the market penetration of wind energy converters (WEC) and the required system reliability. For Germany, a capacity credit of up to 9% in the year 2003 has been calculated, which is reduced to less than 6% in the year 2015 due to higher wind penetrations [2]. Yet, each kWh of wind power still substitutes conventionally generated electricity and thus saves fossil fuels and, in turn, CO_2 emissions. However, the characteristics of wind power feed-in results in additional

*Corresponding author. Fax: +49 6221 4767 19.
E-mail address: martin.pehnt@ifeu.de (M. Pehnt).
[1]Now at Braunschweiger Versorgungs-AG (BS Energy).

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requirements on operating the existing conventional power plants (i.e. increased part-load operation resulting in less full-load hours of operation), a higher demand for reserve power capacity and the expansion of the electricity grid, which in turn leads to a reduction of the potential CO_2 emission savings.

1.1. Integration of renewable energies in other studies

The technical and economic aspects of the integration of large wind power capacities are analysed in a number of studies, for example, the least cost integration of renewable energies into the European electricity grid [3], the economic evaluation of the variability and unpredictability (''integration cost'') [4], the utilisation of wind power for ancillary power services [5] or the significance of storage technologies [6]. In accordance with the integration of wind power, the European power exchange including its technical requirements and the rules of market economy is also of importance [7]. Regulation strategies—for example, the promotion of electric heat pumps or the integration of combined heat and power generation (CHP) and wind energy for system services—are investigated in Ref. [8] based on the Danish situation, a country which not only has great wind power input but also a significant share of decentral CHP. The impacts of wind power expansion on the German electricity system with regard to the long-term energy management planning capacity (including network studies concerning the integration of wind power into the German interconnected network grid while maintaining a reliable supply at optimal cost) are analysed in Refs. [2,9]. Other studies have developed models for time and space-resolved balances of energy quantities and powers [10]. They have also featured models of power plant utilisation for mapping the large-scale technological electricity generation from wind energy and other fluctuating sources to the existing electricity supply grid based on a selected network area [11,12].

However, the environmental consequences of an increased input of fluctuating generators have only been investigated in a few studies. In the discussion concerning power management, considerable reductions of CO_2 savings through wind power due to the altered manner of operation of conventional power plants and the provision of reserve capacities were postulated (see e.g. Refs. [13,14]). In a study of the power plant scheduling in the German power system, the additional CO_2 emissions in conventional power plants caused by wind power are comprehensively analysed for the first time [15]. The simulation applied is based on heuristic methods with regard to variable costs as well as power plant-specific and operational parameters. Thus, in this study, the differences in direct emissions caused by the altered operation of power plants are analysed only. Similar analyses were carried out for other regions worldwide (e.g. Scandinavian countries [16]).

In another comparable study, a short-term production planning model and a long-term optimising electricity system model is coupled [17]. The applied model shows relatively large reductions of net emission savings depending on the share of wind energy in Germany. One of the reasons for this rather pronounced effect is that, according to the model results, with increasing wind shares, wind power also substitutes base-load technologies including nearly CO_2-free nuclear power.

A recent comparison of several studies analysing the CO_2 mitigation in the German electricity system by the integration of renewable energies can be found in Ref. [18]. All studies analysed showed that wind power primarily substitutes medium power plants and to a lesser amount lignite-fired base-load power plants but did not explicitly analyse the integration effects of offshore wind power.

In contrast to the studies cited earlier in the text, this article extends the existing literature by coupling a detailed bottom-up life-cycle assessment (LCA) model—using a cradle-to-grave approach to assess the impacts along the full life cycle—with an electricity market model, which explicitly takes into account the stochastic nature of the future offshore wind electricity feed-in. This approach leads to a consequential environmental system analysis (CESA) of expected offshore wind electricity production in Germany.

Preliminary results of this article have been published in Ref. [19]. The present Energy paper, however, discusses for the first time the three models applied, the methodology of the model coupling and the interfaces between the models, the embedding of this study in the LCA discussion on CESA, the mathematical formulation of the environmental impacts, the underlying numerical and energy economic assumptions and the wind extension scenarios, as well as a number of details, such as the LCA results of the CAES storage and the substitution mechanisms.

1.2. From life-cycle assessment to consequential environmental system analysis

When evaluating the energy produced by offshore wind, as an example of a new technology, the environmental impacts along the complete life cycle from cradle-to-grave need to be analysed. The most appropriate instrument for this is an LCA, which takes environmental impacts into consideration, starting with the raw material extraction and construction of plants onto the utilisation and disposal or recycling. Conventional LCAs, so-called attributional life-cycle analyses (ALCA), normally cannot take comprehensive system changes into consideration, or only can do so inadequately. An example may illustrate this more clearly.

The LCA of an electric heat pump, for example, normally does not take into consideration that the heat pump increases the electric power consumption and thus will cause a shift in the generation system. Effects that ''influence the budget'' are also not taken into account. The expenses for the purchase and operation of the system may tie up capital; however, no money is spent for other items, which in turn contributes to saving resources. Typically, in an ALCA, average modelling is applied, i.e. all environmental impacts of a subsystem in the product life cycle (for example, the production and the erection of a wind power farm) are divided by the functional output of this subsystem. The majority of ALCAs therefore take a sort of "snapshot" of a situation without taking far-reaching system consequences into consideration.

However, an extensive analysis must take a closer look beyond the system boundaries in order to illustrate the indirect consequences of a development. In our case, the harnessing of offshore wind power involves:

- the substitutive and structural effects of wind power for the supply of power;
- the altered operation of the conventional power plant mix;
- the connection of the wind park to the existing grid;
- when necessary, an additional expansion or reinforcement of the grid; and
- the possible storage of wind power.[2]

There is a similar debate going on in the LCA community involving the key term Consequential Environment System Analysis (CESA) [20]. A CESA is defined as "an attempt to estimate how flows to and from the environment will change as a result of a decision" [21]. To achieve this goal, "it should ideally include all processes, within and outside the life cycle, to the extent that they are expected to be affected by decision or a decision-maker" [22]. These processes can be a direct consequence of changes, or can occur as indirect ones via economic, physical or social interactions. Thus, the CESA links the ecological model of the object investigated with the economic models. Until now, only a few studies have been conducted which explicitly meet the demands of a CESA (e.g. Ref. [22]).

In this article, the results of a study are presented in which the projected expansion of offshore wind power in Germany until the year 2020 has been assessed with the aid of an extensive CESA. Three models and their necessary input parameters for such a life-cycle analysis are presented (Section 2). For the first time, an LCA for an adiabatic compressed air energy storage (CAES) plant has been conducted. The results of the individual submodels are discussed (Section 3). Finally, conclusions are drawn (Section 4).

2. Models and input data

In the following text, the goal and scope of the study are defined (Section 2.1). The principles of model coupling (Section 2.2) and the three submodels (Section 2.3) are discussed. Finally, the parameters defining the inputs of the application to the German case are presented (Section 2.4).

2.1. Goal and scope definition

The goal of the extensive CESA is to determine the environmental impacts U_j that occur as a result of the introduction of extra offshore wind parks in an ongoing process of wind power capacity additions.[3] The environmental impact U_j (j: the environmental impact category, for example, the greenhouse effect or acidification) is made up of the specific emission factors e_i (e.g. CO_2) which are each weighted according to their characterisation factor g_{ij}, which calculates the contribution of substance e_i to impact U_j (e.g. global warming potential of 1 kg CO_2 equivalent per kg CO_2). The impact U_j is calculated as follows:

$$U_j = \gamma_{\text{Store}} \left[\sum_i g_{ij} e_{i,\text{Store,construct}} + \frac{1}{\eta_{\text{Store}}} \sum_i g_{ij} (e_{i,\text{Wind,construct}} + e_{i,\text{Infra}}) \right] + (1 - \gamma_{\text{Store}}) \left[\sum_i g_{ij} (e_{i,\text{Wind,construct}} + e_{i,\text{Infra}}) \right] + \sum_i g_{ij} \left[\sum_x \Delta e_{i,\text{convPP},} r_x (c_x, c_{CO_2}, \ldots) \right] - U_{j,\text{substituted}} + U'_j. \quad (1)$$

The entire environmental impact j from offshore wind is made up of one part (γ_{Store}) that is stored in a CAES plant—and thus is subject to a loss in efficiency—and another part ($1-\gamma_{\text{Store}}$) that directly supplies energy to the grid. The environmental impacts result from the construction of the wind park with specific environmental impacts $e_{i,\text{Wind,construct}}$ and the infrastructure activities $e_{i,\text{Infra}}$ necessary for the supply (e.g. expansion of the electricity network). The environmental impacts, which are to be contributed by conventional power plants with respect to the network integration of the non-refined share of wind power, must also be added (the third-last term in Eq. (1)). These especially refer to the changes in the environmental impacts $\Delta e_{i,\text{convPP}}$ that occur because of different operational modes of conventional power plants. These modified environmental impacts vary depending on the various types of fuel x ($x =$ coal, nuclear power, gas, etc.) and therefore have to be weighted with the share of fuels in the energy mix r_x. The share of fuel r_x is a function of the energy prices of this fuel c_x as well as the CO_2 certificate price c_{CO_2}, as fuels lower in CO_2 are favoured when certificate prices increase. The environmental impacts $U_{j,\text{substituted}}$ are the impacts substituted by wind power (e.g. replaced coal power plants with their associated impacts). U'_j are to be added, which may result from further macro-economic or other contexts, for example,

[2] In this study, storage is not considered as dedicated back-up for wind power—which is currently not needed given the large and usually uncongested grid-based power system considered—but as one future integration measure.

[3] Note that this does not characterise the impacts of the first offshore power plants.

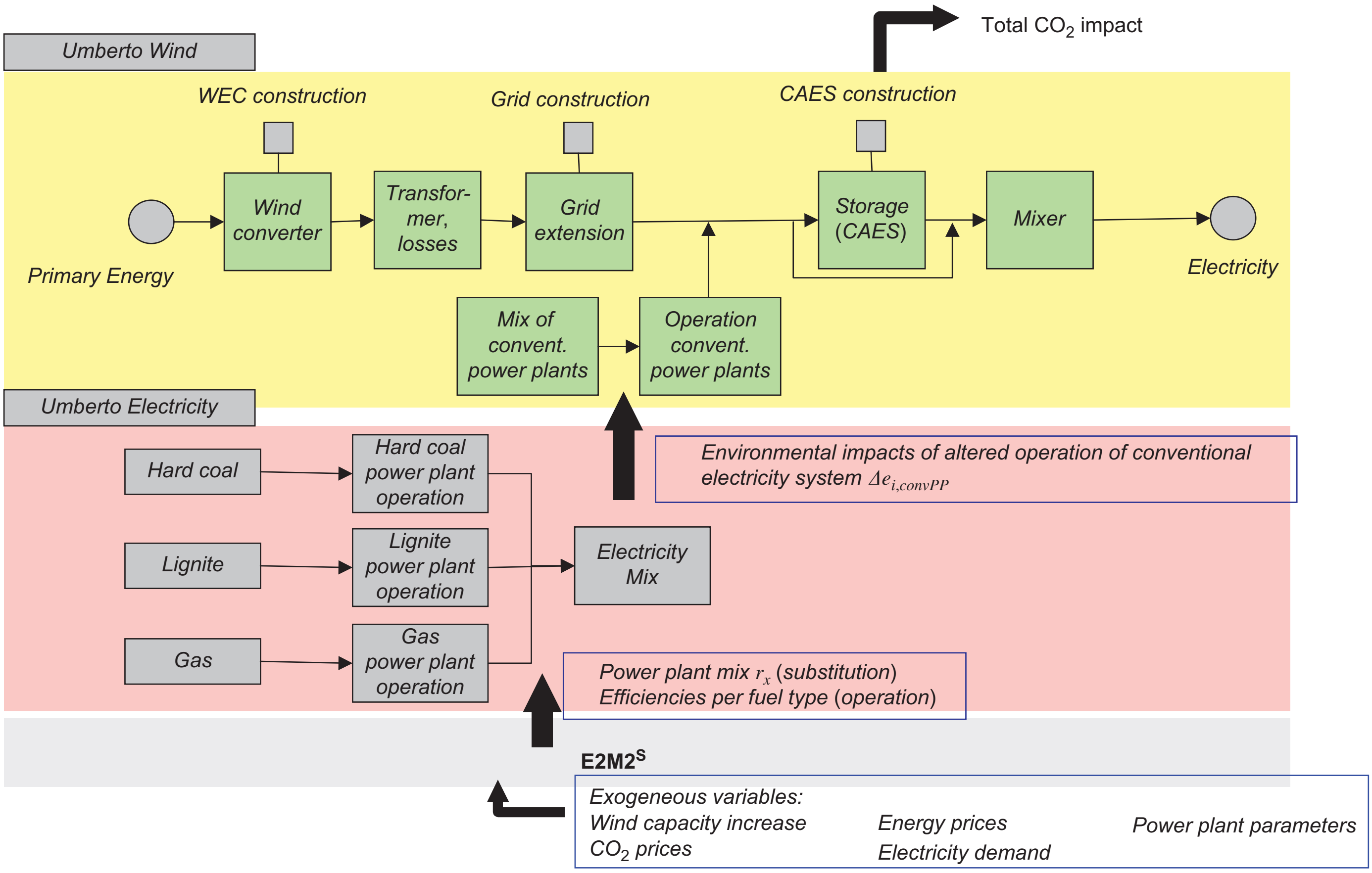

Fig. 1. Model architecture and model interfaces.

mutual influences between the amount of wind power feed-in and the certificate market.

As a functional unit of the LCA, a *kWh of electrical energy generated offshore* is established. The period of observation of the evolving power system structure runs from the year 2005 to 2020.[4] This article only reports the results for CO_2 because the focus of this study is on the methodological aspects of coupling the different models, which can be well illustrated with CO_2 emissions.

2.2. Model coupling

In order to achieve a CESA for offshore wind power generation, three existing models were combined and further developed within the framework of this study. An LCA wind model and an LCA electricity system model were created by using the software Umberto [23] and coupled with a stochastic model of the European electricity market (E2M2s) [24]. After illustrating the coupling of the models, the approaches will briefly be described in the following text.

The calculations were done according to the various steps shown in Fig. 1. The environmental effects of offshore wind power generation were determined by creating a reference scenario using moderate onshore wind expansion, without any offshore development, and comparing it to a scenario with offshore expansion. The first step here was to define a basic set of input data, particularly c_{CO_2} und c_x in Eq. (1). The optimum energy mix (r_x), the mode of operation and the annual efficiency of the respective power plant categories were determined by E2M2s. The latter were subject to boundary conditions with regard to the wind energy supply as well as the model-inherent determination of power plant investments and reserve capacity to be kept available. These results are transferred to the LCA electricity system model. The changes in the CO_2 emissions in the electricity grid resulting from wind-induced structural changes in the power plant portfolio and the changes in the efficiency of thermal power plants were determined by this model. Finally, these emissions as well as the life-cycle impacts for the erection, operation and disposal of an offshore wind power farm and the impacts of the electricity network are integrated into the LCA wind model. For details on this model structure, refer to Ref. [25].

2.3. Submodels

The LCA wind model (Section 2.3.1), the LCA electricity system model (Section 2.3.2) and the stochastic electricity

[4]This does not, however, refer to the lifetime of the infrastructure, which is longer (e.g. the lifetime of an offshore foundation is assumed to be 40 years). This larger lifetime is considered in the LCA.

market model (Section 2.3.3) form the coupled approach applied in this study for the CESA of expected offshore wind electricity production in Germany.

2.3.1. LCA wind model

The life cycle of offshore wind electricity generation is analysed using the LCA wind model. The model is made up of six main modules, so-called transitions, which together simulate the environmentally relevant processes of power generation from offshore wind turbines. The individual transitions are described as follows.

2.3.1.1. Wind energy converter (WEC). As an example of offshore wind power generation, a fictitious multi-megawatt plant (nominal output: 5 MW) of a possible future North Sea wind park in the German Bight was analysed. The LCA is based on Ref. [26]. In addition to the materials required for constructing the plant (tower, nacelle and rotor blades, cabling inside the park itself) and the peripherals (foundations, cabling and substation), the construction measures (expenses for onshore and offshore transports, assembly of the WEC), the disposal (transports back, dismantling) of the WEC and the environmental impacts during operation of the WEC were covered.

2.3.1.2. WEC/transformer losses. The system efficiency was introduced in order to consider the losses during energy transmission (transformers, cabling in the sea) and subtracting a safety margin for unpredictable events (e.g. the wake effect). Following Ref. [27], the system efficiency ratio is assumed to be 95%.

2.3.1.3. Grid expansion. The LCA of the necessary network expansion is based on Ref. [2]. According to this study, a network of 850 km of lines, with an expansion of the network by 392 km of lines at the maximum voltage level by the year 2015, is required at an installed offshore wind capacity of 9.79 GW. To determine a specific network expansion per kWh of offshore wind power, the 850 km was divided by the product of 9.79 GW, WEC lifespan and WEC full-load hours.[5] The material and construction expenses for the expansion of the network were modelled according to Ref. [28].

2.3.1.4. Compressed air energy storage (CAES). One option that was taken into account was the expansion and operation of an adiabatic CAES plant, which is characterised here by a cycle efficiency of 70%. Its construction entails the construction of the actual plant technology, the erection of heat storage, as well as expenses for the cavern (electricity for disposal of salt brine) and for the construction measures and disposal. Figures for the construction of the cavern were taken from Ref. [29]. The CAES plant uses technology from the branches of mechanical, structural and electrical engineering. The material data for the machinery were mainly taken from the LCA of a combined-cycle power plant [30].

2.3.1.5. Energy mix. Only a small share of the total wind energy can be stored in CAES plants, based on the assumption that capacity is limited. This portion (γ_{Store}) is put into the energy mix. First, on the basis of rough estimates, it is assumed that only 1% of the total offshore wind energy will go through the CAES storage cycle.[6]

2.3.1.6. Power plant mix. The environmental effects caused by adapting the structure of all power plants or by changes in the efficiency of thermal power plants due to the offshore wind energy integration are considered as an input from the LCA electricity system model.

2.3.2. LCA electricity system model

In order to determine the CO_2 emissions caused by wind energy, the emissions caused by the generation of electricity must first be calculated. This requires a model of an electricity network that includes all relevant material flows (including the upstream and downstream chains). Using the LCA electricity system model, various regional, national or international electricity grids can be analysed. For this paper, only the electricity grid of the public German power supply system is of significance. The power distribution (including transformer and transmission line losses) as well as the corresponding fuel upstream chains and the power plant processes for the generation of electricity (hard coal, lignite, oil, natural gas, nuclear power, waste incinerators, biomass, hydropower, solar power and WEC) up to the final consumer is covered here based on detailed life-cycle investigations. The model includes the coupled production of district heating. Its proportional generation can be entered for every kind of power plant. The allocation of environmental impacts to the products of electricity and district heating is carried out through allocation based on energy.

2.3.3. Stochastic European electricity market model (E2M2s)

The power plant mix, seasonal efficiencies and full-load hours as needed in the power plant mix transition of the LCA wind model are determined using the linear optimisation model E2M2s. In principle, the approach of such a model is to examine the electricity market by representing the technical and economic aspects of electricity generation, distribution and demand. They are based on the assumption of an efficient electricity spot market, namely an electricity system where the price of electricity is based on the short-run marginal costs of the last power plant in

[5] This is a simplified, but maximum estimate, as the expansion of the electricity network for future power distribution is fully charged to the offshore wind energy and not to other activities on the power market, such as increased electricity trading.

[6] Nevertheless, such additional storage can govern the whole system and may allow to better cope with wind's variability [24].

Table 1
Wind capacity expansion scenarios

Parameter	Time frame	Scenario			
		Reference CO_2 low	Offshore CO_2 low	Reference CO_2 high	Offshore CO_2 high
Installed capacity onshore (MW)	2005	18,428	18,428	18,428	18,428
Expansion capacity onshore (MW)	By 2020	5172	5172	5172	5172
Expansion capacity offshore (MW)	By 2020	0	12,000	0	12,000
Installed total capacity (MW)	2020	23,600	35,600	23,600	35,600
Total power generation (TWh)	2005	29.42	29.42	29.42	29.42
Total power generation (TWh)	By 2020	37.68	70.17	37.68	70.17

the merit-order of all power plants needed to meet electricity demand. The model strives to minimise costs of the electricity system for every year considered.[7] Such models of the electricity market represent the power plant mix of the system to be simulated. The number and type of power plants considered depend on the assumed time frame and the regional definition. Several regions within a country, or between neighbouring countries, can be taken into account for given transmission capacities. Our analysis is restricted to the German power system.

One significant difference from comparable studies is that the analysis—in addition to the coupling of the model approaches—was not done on the basis of a deterministic, but rather a stochastic electricity market model. In deterministic models, an expected wind energy feed-in is subtracted from the electricity demand. The forecast error of the wind energy feed-in is only considered for additional reserve capacity demand. In the stochastic model used here, however, the stochastic of wind energy supply, characterised by strong fluctuation and low predictability, was determined using a recombining tree. Thereby for each considered time segment,[8] three stochastic nodes are distinguished. Each node is characterized by the respective value of the stochastic variable and its probability. Additionally, each node is coupled with all successor nodes with transition probabilities taken into account. Here, the nodes represent different stochastic states, e.g., low, medium and high wind power feed-in [31]. The three cases and the needed probabilities have been derived applying a *k*-means cluster algorithm using historic wind power data for Germany. Thereby a transformation of wind speed to wind power series has been performed based on an approach taking smoothing effects (mainly due to the spatial distribution) into account. This leads to an improved mapping of the influence of the fluctuating wind energy supply on the conventional power plant operation. A model-inherent expansion of new power plants is considered for lignite and hard coal power plants, combined-cycle power plants, gas turbines and adiabatic CAES based on the calculation of long-run marginal costs in the year of investment. The changing reserve power demand with increasing wind power integration is considered applying a probabilistic approach. Start-ups and reduced part-load efficiencies are considered by linear approximations. For a thorough description of the model applied, the reader is referred to Ref. [24].

2.4. Input parameters

The assumptions of the model are of key significance for the results to be discussed. The changes in the composition of the energy mix, as well as the changes for the worse in the efficiency of the conventional plants, were determined with the help of E2M2s. The calculations were based on various scenarios which reflect the future expansion of wind energy. Table 1 gives an overview of the four WEC expansion scenarios. In all four scenarios, it was assumed that the onshore WEC capacity of about 18.4 GW that was installed in late 2005 would grow at the same rate until the year 2015. After 2015, there is no further assumed expansion of WECs on land, leading to an onshore WEC capacity of 23.6 GW in the year 2020.

The two offshore scenarios are characterised by an equally sized, moderate expansion of offshore capacity. Offshore WECs are not expected to expand rapidly until after 2015. The figures regarding expansion were all taken from the "probable expansion" scenario developed in a study by Nitsch et al. [32]. This scenario takes the delayed development of originally planned projects (2–3 GW in the year 2010) into account. By the year 2020, an installed offshore capacity of 12 GW is anticipated (following Ref. [32]). Thus, in the offshore cases, a total WEC capacity of 35.6 GW in the year 2020 has been assumed.

To perform the calculations with E2M2s, the projected expansion plans for each scenario were entered in yearly steps until 2020. Then, the electricity generated per power plant category and per simulation year, the additional output generated through expansion and the annual efficiency of the various thermal power plant categories, among other parameters, were calculated. The trading of CO_2 emission certificates practiced since 2005 was also

[7]Thus, the model is myopic with the considered years subsequently modelled.

[8]Any year considered comprised 144 typical hours (6 typical months each with 2 typical days and 12 typical hours).

Table 2
Scenarios of CO_2 certificate prices (€/t CO_2)

Scenario	Year					
	2000	2005	2006	2010	2015	2020
CO_2 low	0	17.89	10.00	10.00	10.00	10.00
CO_2 high	0	17.89	20.00	24.40[a]	31.29[a]	40.00

[a]Values interpolated; annual price increase of 5.1%.

Table 3
Fuel costs including transport to power plant (€/MWh_{th})

Fuel	Year				
	2000	2005	2010	2015	2020
Hard coal	5.95	8.78	8.96[a]	9.14[a]	9.39
Lignite	3.55	3.69	3.76[a]	3.84[a]	3.95
Uranium	6.14	6.14	6.14	6.14	6.14
Natural gas	13.46	17.76	18.76[b]	19.81[b]	20.86

[a]Values interpolated; annual price increase of 0.4%.
[b]Values interpolated; annual price increase of 1.1%.

taken into consideration. The two wind cases were combined with two CO_2 price scenarios, which were designed to cover the possible future range of development (Table 2), resulting in four scenarios to be analysed.

Since the German Federal Government is striving to phase out nuclear power, any new construction of nuclear power plants was excluded. The cost of producing electricity mainly depends on the cost of fuel (Table 3), the efficiency of a power plant and the assumed CO_2 certificate prices. It is assumed that fuel prices will be subject to a slight linear increase until the year 2020 (according to Refs. [24,31]). A higher increase in price is anticipated for natural gas. The price of uranium is set as being constant over time.[9]

3. Model results

In the following text, the life-cycle costs of construction and operation of offshore WECs and adiabatic CAES plants (Section 3.1), the impacts on the conventional power plant fleet (Section 3.2), the results of the complete CESA (Section 3.3) and the calculation of mitigation costs (Section 3.4) are discussed.

3.1. Life-cycle emissions of offshore WEC and CAES

With the LCA wind model, the following events were examined: the construction and operation of an offshore WEC, the necessary network expansion and the construction and operation of an adiabatic CAES plant. The major result is that the construction and operation of an offshore WEC yields to 22 g of CO_2 for the production of 1 kWh of offshore wind power. Nearly all CO_2 emissions (99.7%) originate from the construction of the WEC, of which 70% stem from materials for the balance of the plant (e.g. steel and concrete), 26% for the plant itself and only 4% for disposal and construction work. Approximately 0.1 g CO_2 per kWh_{el} is attributable to the operation, the network expansion and the intermediate storage, respectively.

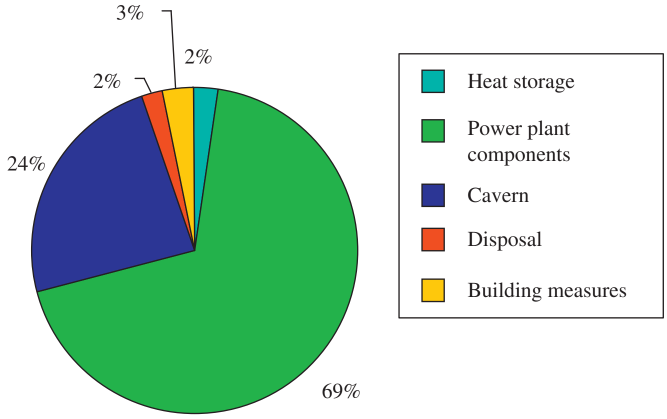

Fig. 2. Breakdown of the CO_2 emissions from the construction and disposal of a CAES plant.

For those amounts of wind power that are stored in a CAES, the impacts of the actual storage process are calculated.[10] For the storage, a CAES cycle efficiency η_{Store} of 70% and a share γ_{Store} of wind power temporarily stored in a CAES facility of 1% were assumed. As depicted in Fig. 2, the major share of CO_2 emissions emitted during construction is due to the power plant components (i.e. compressors, turbine set). Furthermore, an essential share of the CO_2 emissions comes from the power needed for the desaltification of the salt caverns. In contrast, the production of the heat storage, as well as the disposal and construction measures, only plays a minor role.

3.2. Impacts on the power plant mix

The impacts caused by the increasing production of wind energy from the offshore expansion on the remaining power plant mix are quantified with the aid of calculations in E2M2s. There are two effects that must be distinguished here: the structural changes to the power plant mix and the adjustments in the manner of operation of the thermal power stations.

The model was applied to every year between 2005 and 2020. The results for the year 2020 are presented, and, for comparison, the values for the year 2005 (Ref 2005), which are modelling results based on a power station database for

[9]Here, total fuel-cycle costs of uranium are considered. In such a calculation, about a third of the costs are uranium costs.

[10]Even if the costs of the compressed air energy storage facility are not decisive in the complete analysis—due to the low share of power stored—it is still instructive to analyse the environmental impacts of the construction of a CAES, since no such analysis has been performed to present.

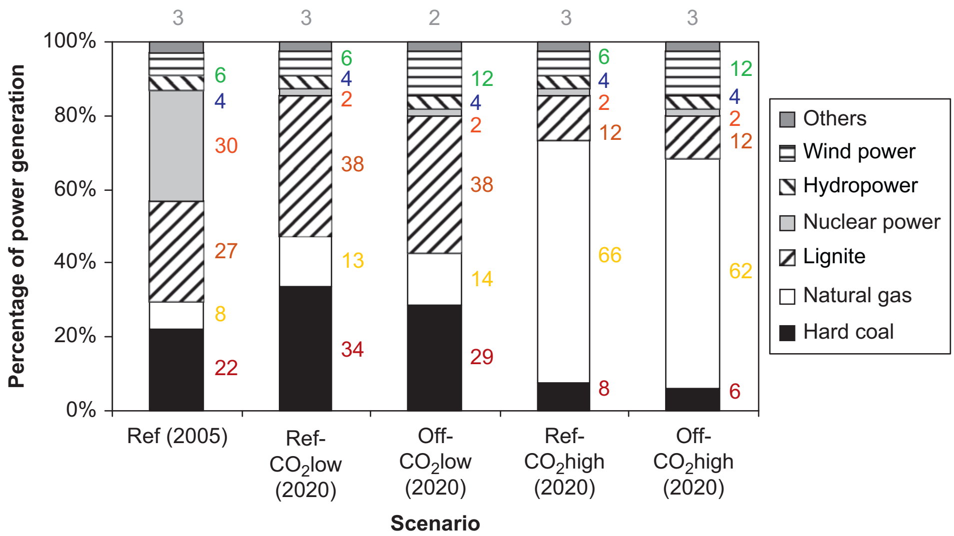

Fig. 3. Gross power generation according to fuel sources.

Germany from the year 2000.[11] When interpreting the energy generation mix, the annual linear increase of the consumer load of 1.1%/a until 2010 and 0.8%/a afterwards assumed in E2M2s and leading to about 593 TWh in the year 2020 should be noted.[12]

3.2.1. *Structural changes to the energy mix and substitution effect*

To determine the efficiency of the introduction of offshore wind power from an environmental point of view, its substitution effect must be examined. In order to do so, the mix of fuel sources for electricity production in the respective reference and offshore scenarios at low and high CO_2 certificate prices were established, cf. Fig. 3. The difference of the reference and offshore scenarios is solely due to the substitution of fuels by the additional offshore wind power. The "substituted fuel mix" shows which of the fuels are primarily replaced by the additionally introduced offshore wind power production, cf. Fig. 4.

Figs. 3 and 4 illustrate the considerable influence of the CO_2 certificate price scenarios on the future model-inherently determined energy mix. In the scenario with the low CO_2 certificate price, offshore wind primarily replaces electrical energy derived from hard coal and, to a lesser extent, from lignite. In addition, a small increase in power generation from natural gas can be determined. This is mainly based on the increased use of gas turbines to compensate for wind fluctuations [33]. In the scenario with the higher CO_2 certificate price, offshore wind power mainly substitutes for electrical energy from natural gas and dramatically less from hard coal, as well as a minor part from lignite. In the scenario with the high CO_2 certificate price, natural gas made up for almost two-thirds of the power generation. Note that the predominance of one single fuel cannot be seen as realistic for the German electricity system of the future, simply because of (1) the close interrelationship between the price and demand of gas[13] and (2) risk aversion of independent investors and, thus, diversification. However, the scenarios show the general tendencies of substitution processes.

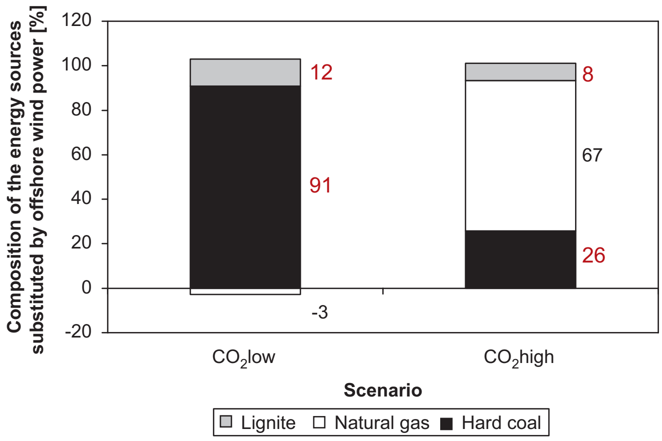

Fig. 4. Substitution by wind: mix of fuels/energy sources in the year 2020.

In the electricity management context examined, the fuels that make up the greatest share of the medium load were substituted by wind power in each scenario due to the variability and limited predictability of wind power generation considered. The displacement becomes especially apparent through a higher rate of part-load operation of these technologies. It may additionally be noted that in the

[11]For this reason, there are slight deviations of the model results compared to the historic data for 2005. In the models, natural gas (8% in 2005) has a slightly lower share, as no must-run CHP plants were taken into account in E2M2s.

[12]In the model, the national electricity consumption is used, i.e. the net electricity consumption including the network losses without consumption for pumped storage as the latter is endogenously considered.

[13]This cannot adequately be taken into account with such kind of market models.

Table 4
Annual efficiency of selected fossil power plants

Annual efficiency[a] (%)	Scenario				
	Reference	Reference CO_2 low	Offshore CO_2 low	Reference CO_2 high	Offshore CO_2 high
Time frame	2005	2020	2020	2020	2020
Hard coal	38.81	43.23	42.70	42.19	41.74
Natural gas	55.08	56.43	56.11	57.60	57.45
Lignite	35.84	41.26	41.24	40.82	40.90

[a]Annual electrical efficiency as an average value of all power plant categories (weighted according to proportion/share of generation).

considered scenarios wind power does not substitute nearly CO_2 emission free nuclear power.

To better assess the results of the model, a comparison with the current projected investment in conventional power stations up until the year 2016 can be made [34]. The main focus is on the construction of coal-fired power plants (13 GW) and gas-fired power plants (8 GW), whereas relatively few new lignite power stations (3 GW) are planned in Germany. For this reason, the composition of the future power plant mix will probably lie between the extreme scenarios driven by the assumed low and high CO_2 certificate prices.

3.2.2. *Poorer efficiency levels of thermal power plants*

The changes induced by wind power in the mode of operation of thermal power plants can have a negative influence on their annual efficiency. The annual efficiency levels of the most important fossil power plants determined for individual scenarios are listed in Table 4. The changes in the level of efficiency shown in the model context are due to modernisation and mode of operation.

3.2.2.1. Modernisation. In a comparison of the values for the years 2005 and 2020, a dramatic increase in efficiency can be seen, on average, for all power stations. The reason for this is the development of technological improvements expected during this period. The annual efficiency development shows that in the E2M2s model, an increasing number of inefficient power plants will be replaced by modern plants with high efficiency levels.

3.2.2.2. Mode of operation. Conclusions on the influence of offshore wind energy on the efficiency of power plants can be made by comparing data for the reference and offshore scenarios with the same CO_2 certificate price. It can be determined that hard coal-fired power stations exhibit the highest wind power-induced negative effects on efficiency of nearly 0.5% points. The main reason for this is the increased share of part-load operation with concomitant reduced efficiency. For natural gas power stations, there is only a slight reduction in the annual efficiency, as they can be controlled more flexibly than lignite or coal-fired power plants with higher part-load efficiencies. This flexibility, with regard to the operation mode, allows an adaptation to the fluctuating wind power feed-in with lower losses.

3.3. *Results for Germany*

The calculated—reduced—efficiency of the electricity generating technologies resulting from the E2M2s calculations was transferred to the LCA electricity system model, which in turn considered the results of the LCA wind model and calculated the life-cycle CO_2 emissions. This makes it possible to include all relevant upstream and downstream processes resulting to the CESA of expected offshore wind electricity production.

The overall results for the two different CO_2 certificate price scenarios with offshore wind expansion are shown as specific CO2 emissions in Figs. 5 and 6. The CO_2 emissions in both figures are shown as columns for each of the previously described processes (construction, operation and disposal of the wind energy park; wind-influenced network expansion; CO_2 reductions without altered power plant operation; loss of efficiency). They are added from the left to the right.

The result shows that the CO_2 minimising effect is higher for the low CO_2 certificate price scenario than for the high-price scenario. Without taking the loss of efficiency of conventional power plants into account, the specific CO_2 reductions per kWh offshore electricity in the year 2020 amount to 914 and 646 g of CO_2, respectively.[14] In principle, a high CO_2 certificate price leads to increased investments in gas-fired power stations, so that even without an explicit account of additional wind capacities, high CO_2 savings are achieved and the reduction attributed to offshore wind power expansion are proportionately lower.

Poorer efficiency of the conventional power plant fleet (mainly due to a higher fraction of part-load operation), however, leads to additional CO_2 emissions, which are solely attributed to offshore wind energy. The additional

[14]These numbers represent the result of cradle-to-grave modelling. The value for the specific CO_2 reductions by offshore wind power of 914 g CO_2/kWh in 2020, for instance, is distinctively higher than would be expected by the mere generation-related CO_2 emissions, given the fact that around 90% of the replaced electricity is from hard coal. This is due to the upstream emissions of coal supply and, to a much lesser extent, the construction and maintenance of the required power plant infrastructure.

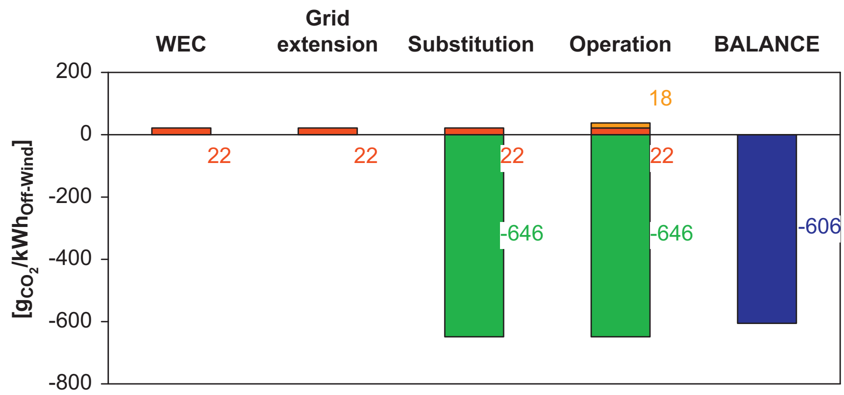

Fig. 5. Specific CO_2 emissions of offshore wind power (CO_2 high) (2020). WEC: wind energy converter; substitution: substitution of fossil fuels by offshore wind energy; operation: altered mode of operation of conventional power plants due to additional offshore wind energy.

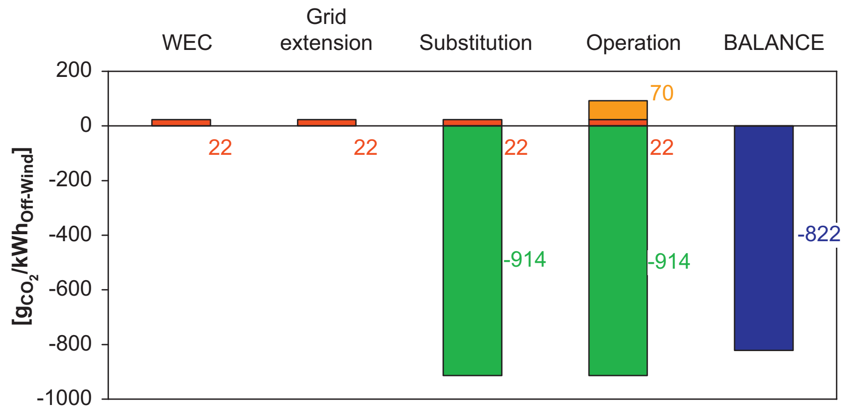

Fig. 6. Specific CO_2 emissions of offshore wind power (CO_2 low) (2020). WEC: wind energy converter; substitution: substitution of fossil fuels by offshore wind energy; operation: altered mode of operation of conventional power plants due to additional offshore wind energy.

CO_2 emissions for the power generated from offshore wind energy in the year 2020 for the CO_2 certificate price scenarios considered here amount to 70 and 18 g CO_2/kWh$_{el}$, respectively. The emissions of so-called "shadow power plant capacities", which are applied to stabilise fluctuating amounts of electricity, strongly depend on the structure of the power plant mix. Accordingly, a power plant mix that relies on gas-firing, which is quicker and easier to control and has fewer losses, would lead to dramatically lower CO_2 emissions than a power plant mix using more coal-firing.[15]

In comparison to the CO_2 savings achieved by avoiding fossil fuels, the CO_2 emissions from the construction and operation of offshore wind parks (2% and 3% of the CO_2 savings) and through altered operation of a power plant (8% and 3% of the CO_2 savings)—each with respect to the two CO_2 certificate price scenarios investigated—are comparatively low, but not negligible. Taking these CO_2 emissions into account, the total CO_2 savings attributed to each kWh of offshore wind electricity in the year 2020 for the low CO_2 certificate price scenario are calculated at 822 g CO_2/kWh and at 606 g CO_2/kWh for the high CO_2 certificate price scenario.[16]

3.4. CO_2 mitigation costs

It is possible to calculate the CO_2 mitigation costs through offshore wind power on the basis of these results. The calculations using E2M2s show that when offshore

[15]The additional CO_2 emissions in conventional power plants caused by wind power as determined in Ref. [15] vary between 35 and 75 g CO_2/kWh depending on the underlying scenario and the assumed wind prediction error. The latter emissions are in line with the 70 g CO_2/kWh in this paper. The former emissions are significantly higher than the 18 g CO_2/kWh here as a result of the higher CO_2 certificate price assumption of 40 €/t CO_2. The comparability of the results of both studies is further limited due to the fact that in Ref. [15] neither the life cycle of CO_2 emissions nor a stochastic modelling of wind power generation is considered.

[16]These results are within the bandwidth of other study results where, depending on the specific model assumptions (both, data inputs and methodologies), CO_2 emission savings of 500–1000 g/kWh wind power have been determined [15,17,19]. However, all these studies do not explicitly focus on offshore wind power. In addition, here—and in difference to the studies cited earlier in the text—the complete life cycle of WEC construction and operation as well as grid extension has been considered. Furthermore, a stochastic electricity market model has been applied. Both lead to a contradiction of the intuitive result and reduce the CO_2 emission saving effect. The CESA in this article may be seen to lead to more robust results as—for the first time—all relevant effects on the CO_2 mitigation achievable by the integration of expected offshore wind electricity production in Germany have been taken into account.

wind is harnessed, a reduction of the costs of the modelled system can be expected (excluding any model exogenous investment costs for wind turbines). For one, this takes into account the costs saved for electricity that would have been generated elsewhere. It also includes the additional costs of a changing conventional power plant mix. This is caused by a higher flexibility of power plants through increased investments in gas-fired power plants to compensate for fluctuating wind energy generation and to cover the increasing basic capacity demand. Furthermore, it includes its altered mode of operation. This means increased part-load operation, which is not optimal regarding energy management, and frequent start-ups and shut-downs of the power stations.

The reduction of the modelled system costs in the year 2020 for each kWh of offshore wind power at the low CO_2 certificate price scenario amounts to 3.6 €ct/kWh and to 5.1 €ct/kWh for the high-price scenario. It should be noted that the additional costs of a changing power plant mix only have a significant order of magnitude of nearly one-third in the low CO_2 certificate price scenario. Consequently, the investments required to reduce CO_2 under the high CO_2 certificate price scenario, especially for gas-fired power stations, are sufficient to provide the power plant mix with the flexibility needed to handle a higher share of variable wind energy generation.

This is contrasted by the expenses for network improvements and network expansion, which are estimated at 0.2 €ct/kWh for offshore wind power [35], as well as the average compensation paid on the basis of the Renewable Energy Law [36], which according to the wind power deployment assumptions of this study amount to 7.6 €ct/kWh of offshore wind power.[17] Regarding compensation, it is assumed that the higher initial tariffs for offshore electricity feed-in will be continued [37]. Corresponding to the latest developments, additional network connection costs are to be covered by the operators of the transmission network [38]. These are to be assumed at 18% of the average compensation. This assumption presents an average value of the analysis in Ref. [39] and tends to be on the lower end of the scale estimated for Germany. In Ref. [38], as much as 30% of the current project costs is assumed, and additional financial aid is even demanded. The values we assume lead to additional expenditures of 1.4 €ct/kWh for every kWh of offshore wind power.

Finally, it is assumed that the expenses presented so far would cover all costs actually incurred for investments in offshore wind energy parks. Under these circumstances, the costs of reducing CO_2 would amount to approximately 67 €/t CO_2 in the year 2020 for both CO_2 certificate price scenarios.

[17] At the time of writing, the compensation was under review, and significantly larger compensation between 11 and 14 Ct/kWh was expected. This would significantly increase the CO_2 mitigation cost.

4. Conclusions

The results discussed here show that by combining a LCA for offshore wind utilisation with a stochastic model of the German electricity market, a comprehensive analysis of the possible CO_2 reductions can be achieved. The most significant results of the investigation are as follows:

- The CO_2 emissions from the construction and operation of offshore wind parks are low in comparison to the substitutions in the power plant mix.
- The use of offshore wind power substitutes mainly for medium-load and for nearly no full-load technologies.[18]
- The CO_2 emissions from the altered operation and expansion of conventional power plants reduce the CO_2 savings effect, but the substitution effect is one magnitude higher.
- The resulting net CO_2 reductions are around 600 and 800 g CO_2 per kWh of offshore wind power, depending on assumed certificate prices.
- The model assumptions, in this case most significantly the CO_2 certificate prices, have a considerable influence on the figures provided.

There are additional interactions between offshore wind production and the electricity market that could not be investigated using the three available models. These include, for instance, effects of wind electricity feed-in on the end-consumer price and thus on the demand of the German power system, and additionally the effect of wind electricity on the CO_2 certificate price, which is an exogenous variable in the applied electricity market model.[19]

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[18] Like, for example, power generated from nearly CO_2 emissions free nuclear energy.

[19] The latter effect depends strongly on the way renewable electricity is considered in the National Allocation Plan of CO_2 emission certificates and whether an over- or undershooting of the expected wind contribution takes place.

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