Reliving the German Transmission Grid with Regulated Wind Power Development

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Abstract

A prerequisite for the further integration of renewable energy sources into the German electricity sector is the expansion of transmission network capacities. In this study, an approach to relieve the German transmission grid by regulating the wind power development is evaluated for the year 2030. Compared to a reference scenario, the development of wind power plants with an annual energy yield of 4 TWh is reallocated from the wind-swept north of Germany to grid-convenient sites in central and southern Germany. Benefits of such a measure and resulting expenses are contrasted with the expected status quo in 2030 and two grid expansion scenarios. Results show 24 % - 53 % higher annual cost for the regulated wind power development scenarios compared to conventional grid expansion with a similar grid relieving impact. But taking into account that grid expansion faces public acceptance problems, regulated wind power development can be considered as a reasonable alternative, up to a certain degree. This insight may trigger a debate about the acceptance for either building transmission lines or additional wind power plants.

1 Motivation

The share of renewable energy sources (RES) of gross electricity consumption in Germany is increasing steadily, towards the set target of 50 % by the year 2030 [1]. To allow for the integration of high shares of RES, upgrading German transmission grid capacities has become a necessity. In this context, the research project *MONA 2030*[1] addresses the comprehensive assessment of various grid optimising measures like Overhead Line Monitoring or Power-to-Heat which are contrasted to conventional grid expansion measures and assessed as alternatives for grid expansion. The analysis is performed by using the simulation model *ISAaR*[2].

Grid simulation results indicate bottlenecks in the transmission grid by the year 2030, when transporting wind energy from northern to southern Germany. As a reaction, conventional grid expansion can be conducted. In this paper, a further approach for relieving the German transmission network is analysed. Bottlenecks in the transmission

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[1] "Merit Order Grid Expansion 2030" (funding code 03ET4015) is co-funded by the German Federal Ministry of Economic Affairs and Energy through the funding initiative "ZukunftsfähigeStromnetze". (www.ffe.de/mona).

[2] Integrated Simulation Model for Planning the Operation and Expansion of Power Plants with Regionalisation. (www.ffe.de/isaar).

grid can be avoided by implementing regulatory measures, aimed at controlling the locations for wind power development in Germany. In such a scenario, new wind power plants are constructed in central and southern Germany and consequently closer to the load centres, instead of the wind-swept north. In general, the expenses for the construction of wind power with the same energy yield are higher if wind power plants are built in central or southern Germany compared to the wind-swept north. However, transmission line relief is achieved and reduced curtailment of renewables as well as lower redispatch volumes can be noted.

The following text is outlined as follows: Chapter 2 describes the optimization model *ISAaR*. In chapter 3, underlying assumptions, provided in scenarios, are explained, and the scenarios for regulated wind power development as well as grid expansion are introduced in detail. Result are discussed in chapter 4 and concluded in chapter 5.

2 Optimisation Model

The FfE energy system model *ISAaR* is a linear optimisation model, which minimises the deployment of power plants to meet the demand for electricity in Europe and for district heating in Germany and Austria. The model allows for the coupling of the electrical and the heating sector, thereby enabling a holistic evaluation of the complete energy system, consisting of power plants, storages, localised demand, renewable energy sources, and heating plants (see **Figure 1**).

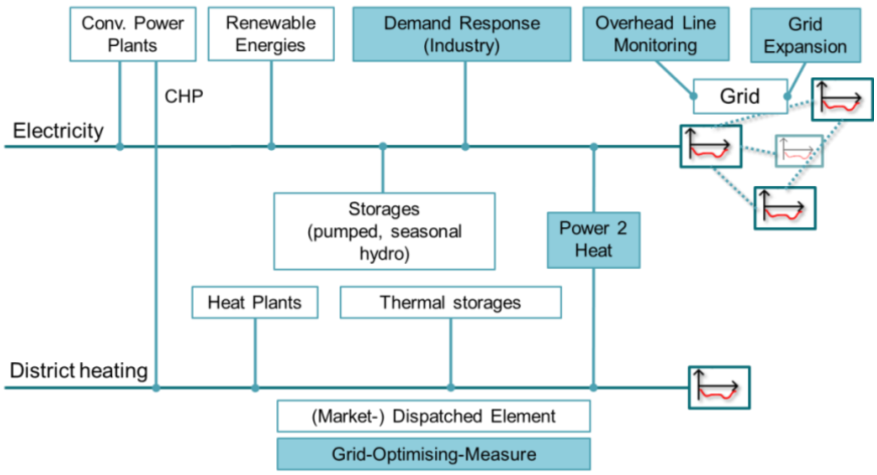

Figure 1: *Overview of the schematic ISAaR-models' structure.*

A detailed conceptual and mathematical description of the optimisation model is provided in [2] and [3]. Information on scenario input data is given in chapter 3.

2.1 Grid Model

The transmission grid is modelled using the DC power flow approach, described in [4]. This linear representation of the grid is a result of the necessary trade-off between accuracy and computational expenditure. Transmission network losses as well as voltage-drops are neglected. Further, only active power flows are represented in the grid model. Nevertheless, this method is accurate within given bounds (see [5]). Above 70 % utilisation, reactive power becomes relevant, leading to notable deviations between the DC power flow and the non-linear power flow calculation [6]. In the *ISAaR* simulations, AC transmission line utilisation rates are forced to stay below 70 %, thereby guaranteeing the "(n-1)-safety criterion" of the grid (see [7] and [8]).

Grid data for Germany and Austria is taken from available data of transmission grid operators ([9], [10], [11], [12], [13]). The data is validated through comparison with the "ENTSO-E grid map" [14]. Faulty or non-existent data is taken from the unpublished "BNETZA Integral" dataset, instead. Current and planned Grid extension projects (AC-lines as well as DC-lines) are taken from the grid development plans NEP 2015, ONEP 2015, and TYNDP 2016 ([15], [16], [17]). Planned grid extension projects are added to the grid model under the assumption to be completed by the year 2030. Grid data for the rest of Europe is taken from the open-source platform *OpenStreetMap,* using the toolkit *Gridkit* [18]. The toolkits *SciGRID* [19] and *osmTGmod* [20] are used for the georeferencing of nodes and lines in the transmission grid. This is a prerequisite for assigning local loads and renewable energy potentials to grid nodes. In some parts of the German-Austrian grid, the underlying distribution network (110 kV) is a relevant support of the transmission grid and is therefore partly considered in the model.

The collected grid data is revised in order to obtain a consistent grid model. Due to the variety of data sources, some lines possess faulty and dissimilar line parameters (especially line reactances). These inconsistencies are rectified in a systematic correction process which is described in [3]. Line parameters for the rest of Europe are gathered by a method, utilising all available line data (e.g. cables and wires) and applying standard values where necessary (see [3]).

The grid topology in regions in a remote distance from the German-Austrian transmission network possesses only little influence on line utilisation in Germany and Austria. Thus, regions like Spain, Greece, or Norway are simplified to reduce computational expenditure. The method is presented in [3]. The resulting transmission grid builds the basis for grid simulations in ISAaR and is depicted in **Figure 2**.

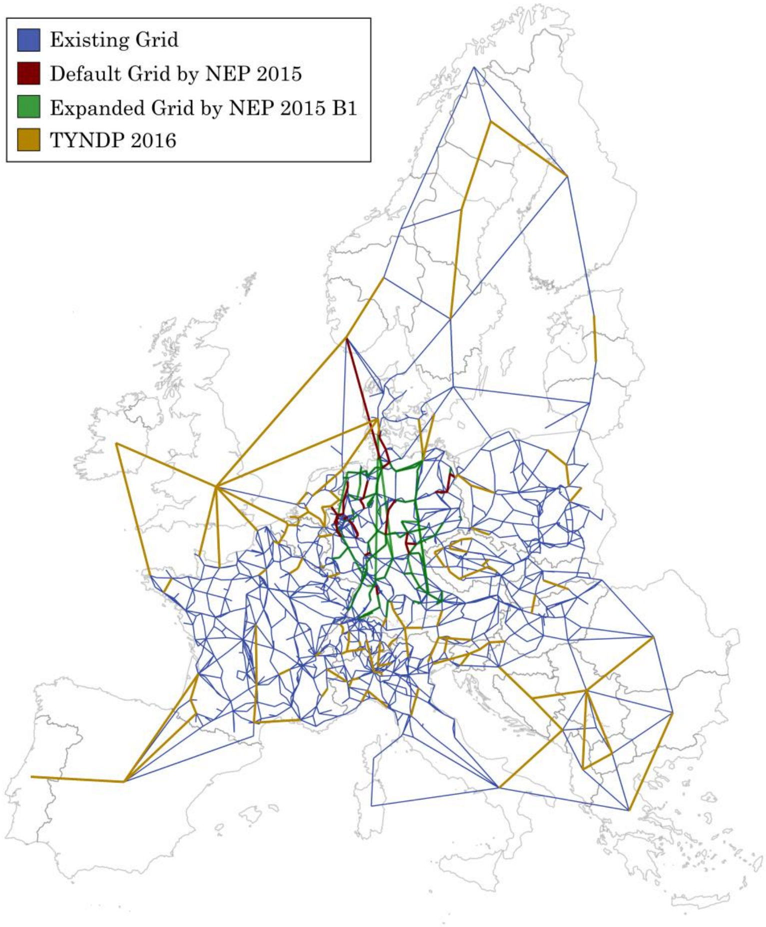

Figure 2: *Applied grid of the year 2030 with simplified grid regions distant from Germany and Austria.*

2.2 Optimisation Sequence

The simulation of a scenario (e.g. conventional grid expansion in the German grid) demands a sequence of different computation runs. This reduces the computational effort, and allows for the analysis of the complete European energy system. The structure of the sequence is given in **Figure 3**: In a first step, the market based dispatch of power and heat plants is calculated for Europe. Existing net transfer capacities between the energy markets are considered. Subsequently, the grid utilisation of the European transmission network is computed. Cross-border capacities are obtained and used as boundary conditions for further simulations of the German-Austrian energy system. Hereby, market-coupling and loop flows are considered in the following isolated simulations of the German-Austrian network.

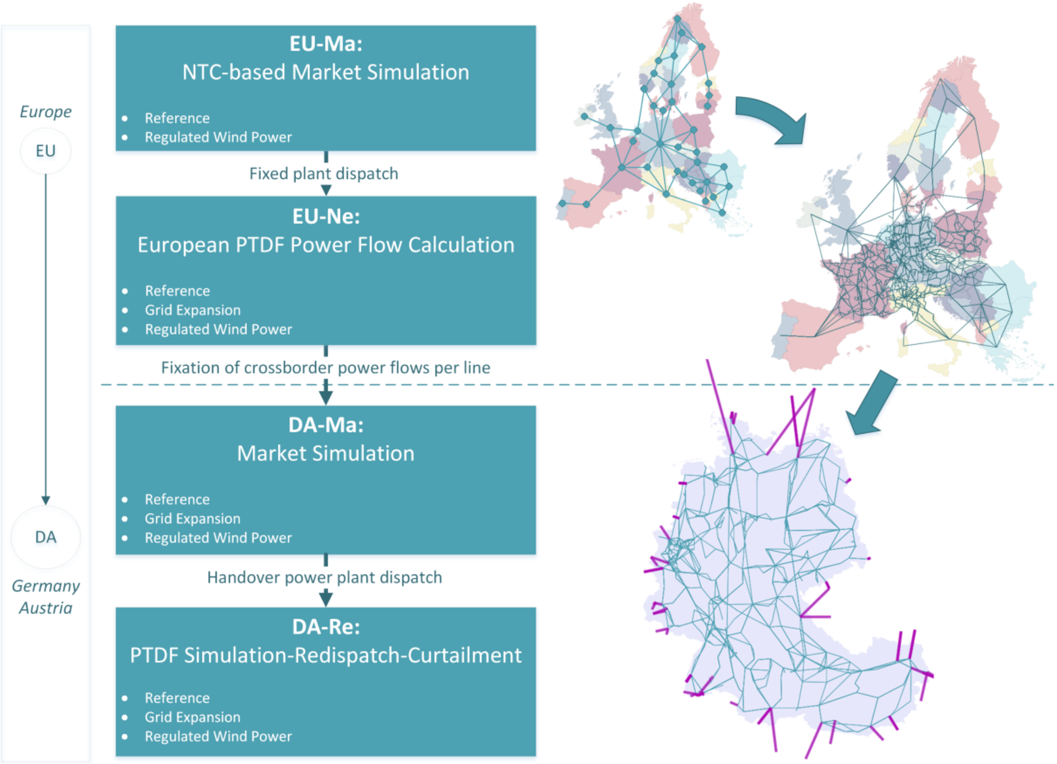

Figure 3: *Schematic overview of the optimisation sequence in ISAaR and the computed runs in each part.*

The first optimisation run of the German-Austrian energy system is a market simulation representing dispatch that results from energy traded on the day-ahead market and energy traded "over the counter". In a second simulation, objective of the power plants commitment is the previously calculated dispatch, but now power flow restrictions in the transmission grid are considered. Arising bottlenecks in the grid lead to deviations from the planned dispatch resulting in redispatch of power plants[3] and curtailment of RES[4].

Using this method, a reference scenario as well as the scenarios "conventional grid expansion" and "regulated wind power development" are computed (cf. Figure 3). Among many other results, the sequences deliver the quantities "redispatch", and "curtailment (of RES)" as output.

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[3] When redispatch is applied, the most expensive power plants causing a bottleneck in the transmission grid are down-regulated. The next-cheapest power plants able to clear the bottleneck are then ramped up to provide the required power. It is to note, this process is an optimal redispatch. There is no condition considering minimum operation hours of redispatched power plants.

[4] Curtailment of renewable energy sources, normally occurring in the distribution grid, is accounted for curtailment in the transmission grid due to the direct linkage of fee-in and loads at high-voltage nodes in the simulation model.

3 Scenarios

The year of assessment for the conducted study is 2030, therefore, various surrounding assumptions are provided in a so called coating-scenario (see [21]). **Table 1** shows a selection of relevant assumptions used in the coating-scenario. The share of renewable energy production of the total electricity consumption is set to 61 % in all presented scenarios.

Table 1: *Relevant parameters of the coating scenario for the year 2030 [21].*

Parameter	Unit	Status 2015	Coating Scenario 2030 (61 % RES)
CO_2-Prices	€ / t	7.6	30.0
Fuel Prices	-	-	moderate increase, see [21]
Installed Capacity of Conventional Power Plants			
Overall Power	GW_{el}	87,0	59,0 (without back-up)
Installed Capacity of Renewable Energy Sources			
Wind (onshore)	GW_{el}	41.2	58.5
Average Full-Load Hours (Onshore) Existing / Addition	h / a	1,700 / -	1,700 / 2,650
Wind (Offshore)	GW_{el}	3.4	15.0
Full-Load Hours (Offshore)	h / a	-	3,950
Photovoltaic	GW_{el}	39.3	76.8

Details on the origin and processing of further input data (available power plants, potential of renewable energy sources, …) are given in [3] and [21]. In general, input data for the *ISAaR*-model is handled in the form of scenarios, which are provided by the “FfE regionalised energy system model” (FREM) [22].

3.1 Conventional Grid Expansion

Conventional grid expansion is conducted in various ways. One can add circuits to an existing line, level up the voltage of a circuit, or construct new lines in a current or new path. Grid planners choose which measures are implemented. Amongst other factors, their decision is based primarily on the evaluation of technical, economic as well as regulatory requirements.

Two scenarios with conventional grid expansion are developed for this study. Therefore highly loaded lines are upgraded as follows: First, 220 kV lines are upgraded to 380 kV if there is an existing 380 kV transformer connectable, otherwise two 220 kV circuits are added. Then, 380 kV lines are upgraded with to two additional circuits. All expansion measures are built on the existing path.

In the first grid expansion scenario *GE 1,* five bottlenecks in the reference scenario are upgraded and thereby 166 kilometres of grid expansions are conducted. In scenario *GE 2*, ten more bottlenecks are upgraded. An additional 341 kilometres are added.

The bottlenecks in the reference scenario are located using an algorithm which searches for the most stressed lines throughout the simulation period. On the one hand, the amount of time of a transmission line in full utilisation is incorporated; on the other hand, the algorithm considers the amount of transported energy during high utilisation periods. The latter is the key factor used in determining the priority of a line extension on big lines. The affected lines for the two grid expansion scenarios are shown in **Figure 4**.

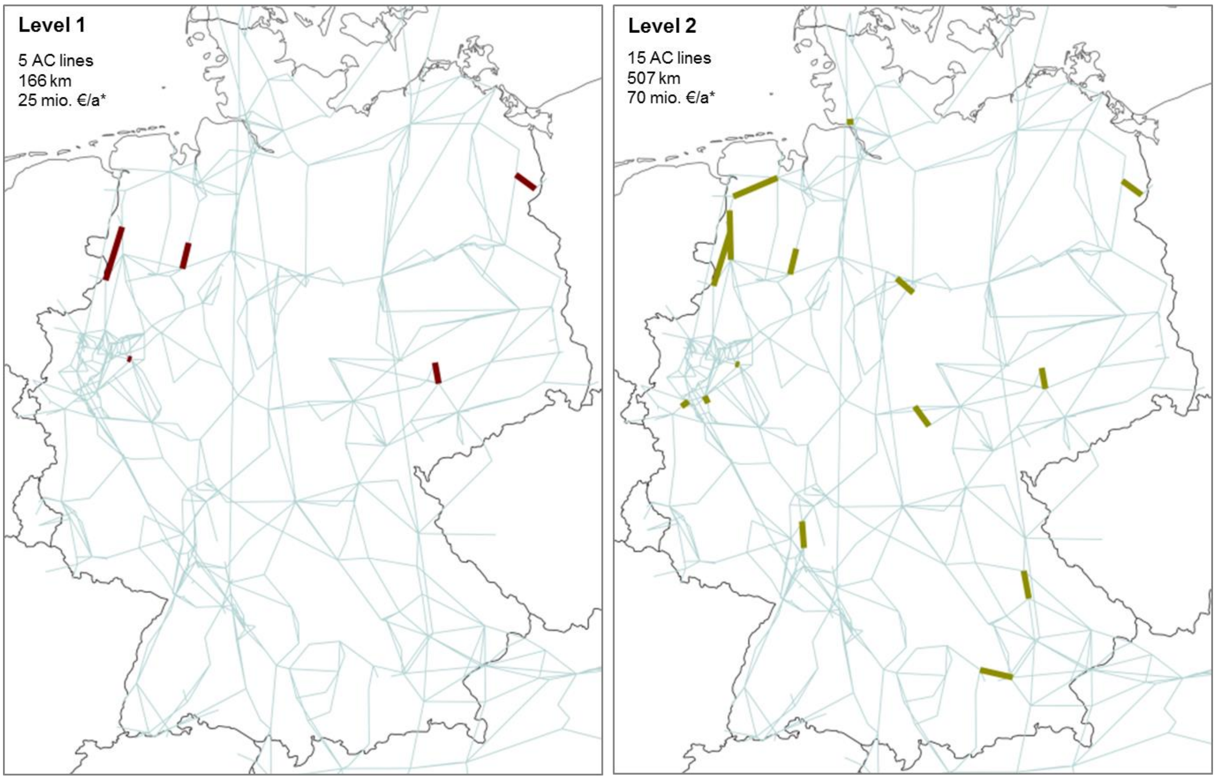

Figure 4: *Upgraded lines in the two different grid expansion scenarios. (*): Cost estimations are based on the NEP 15 [15], the lifetime is set to 40 years, the interest rate to 6 %.*

3.2 Regulated Wind Power Development

In the following scenarios, the expected wind power development, which is set in the reference scenario, is altered. It is assumed that the implementation of regulatory measures, such as laws or incentives, lead to an increased construction of wind power plants at economically less favourable locations in central/southern Germany, when compared to wind sites in the north (see [23]). However, the same amount of energy is to be produced throughout the year, compared to the reference scenario. The consequence is the construction of either additional or more productive wind power plants in central/southern Germany, resulting in higher cost. A relief of the load in the German transmission network is expected, shown within this study.

In two "regulated wind power development"-scenarios, the reallocation of 4 TWh annual wind power energy production is conducted using the following algorithm: In a first step, specific curtailment[5] is computed for every node in the north of Germany for the reference scenario. Wind power plants are then partially removed from nodes with high specific curtailment. This is performed until the annual energy production is reduced by 4 TWh. This value equals 70 % of the curtailment in the reference case. Then, wind power turbines with the same annual energy production are relocated to central and southern Germany. There, wind turbines are reallocated to grid nodes with low specific curtailment plus high wind yield in the reference simulation.

In scenario *On WPD*, only onshore strong-wind wind power turbines are reallocated. To generate a conservative scenario, the turbine type is not altered when shifting to more southern locations. This results in large additional onshore capacities (See right map in **Figure 5**).

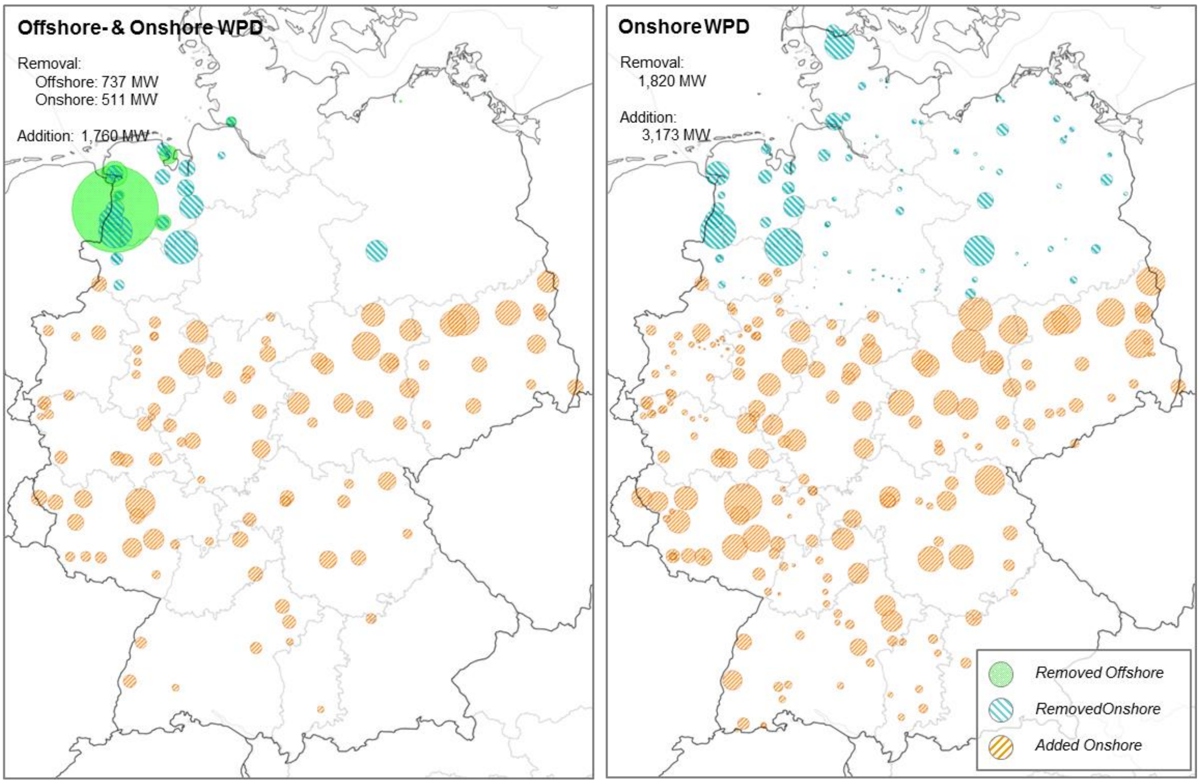

Figure 5: *Deviation in the wind power development scenarios compared to the reference scenario.*

In scenario *Off&On WPD*, wind power plants with an onshore capacity of 0.73 GW and an offshore capacity of 0.51 GW are removed from strong-wind-sites with a high specific curtailment in the north of Germany. For additionally built wind power plants in more southern locations, advantageous turbine types are selected for each wind site. This

[5] The specific curtailment at a node means the curtailment of renewable energy sources per produced energy at the same node.

results in an optimistic scenario, with small additional capacities but large hub heights and wide rotor diameters. The reordering results in this scenario are visualised on the left map in Figure 5.

4 Results

Both, the conventional grid expansion scenario and the regulated wind power development scenario, demand cost for investment. In the following, a cost estimate is performed and put into context to the grid relieving impact of both measures. Due to high uncertainties in determining the cost for grid expansion as well as wind turbine construction, this analysis only serves as approximation cost indication.

Cost for grid expansion
The annual cost for the two grid expansion scenarios are shown in Figure 4. Costs for the chosen measures for line upgrading are based on the NEP 15 [15]. The lifetime is set to 40 years; the interest rate is set to 6 %.

Cost for regulated wind power development
Economic cost for the regulated wind power scenarios are estimated using the "Reference Yield Model" in the "Renewable Energy Sources Act" (EEG) 2017 [24]. It is assumed, the difference in feed-in revenues reflects the economic cost of shifting locations from north to south. First, the average location quality drop of the shifted wind power plants is obtained from the weighted average of the quality factors of the removed and of the added wind turbines. The average quality factors are weighting with the removed/added capacities. The calculation of quality factors is based on the explanations in [24]. In both scenarios, the average location quality of the shifted energy drops from about 100 % to about 72 %. The link between the placement of wind power turbines and their feed-in revenue is then obtained from the correction factor in the "Reference Yield Model" (see **Figure 6**). In both scenarios, shifting onshore wind energy to more central locations in Germany leads to a cost increases of approximately 25 %.

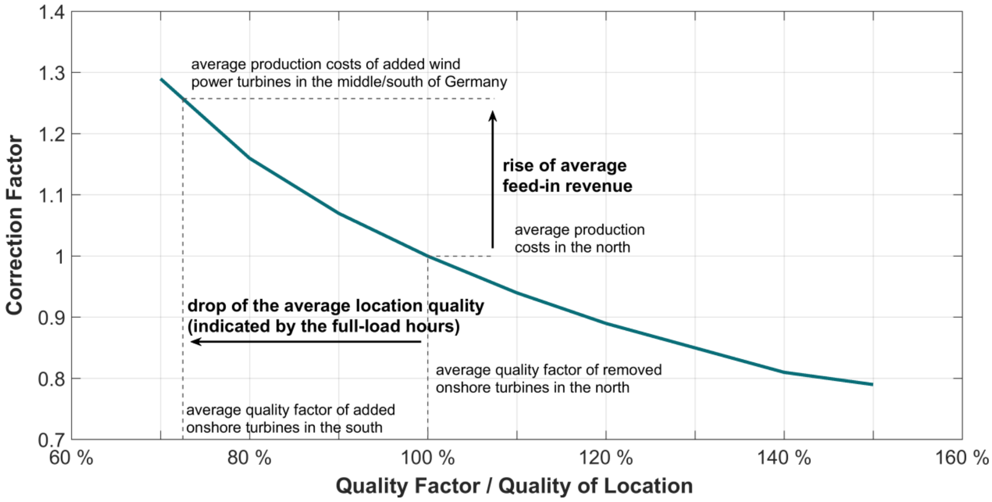

Figure 6: *Correction factors of the "Reference Yield Model" for the revenue of wind energy feed-in dependent on the "Location Quality" from the "Renewable Energy Sources Act" (EEG) 2017. [24].*

The base price for onshore-wind feed-in is 5.71 €/MWh[6], revenues for offshore-wind feed-in are set to a range of 5 to 6 €/MWh[7]. It is furthermore assumed that offshore and onshore bids reflect the investment the bidder has to face in the case of project realisation. Hence, bidder margins or markdowns, which can be realised through cross-financing activities, are not considered. Based on these assumptions, the additional costs of the *WPD* scenarios can be compared to the reference case. Following expression shows the derivation of costs resulting from reallocation with the revenue difference of shifted wind turbine revenues:

$$Cost = Rev_{added,onshore} - \left(Rev_{removed,onshore} + Rev_{removed,offshore}\right) \quad \text{with}$$

$$Rev_x = Price_{base,x} \cdot cf_x \cdot E_x$$

$Cost$:	Additional investment cost of a *WPD* scenario compared to the reference case
Rev:	Revenue of the feed-in from added/removed onshore/offshore wind power plants
$Price_{base}$:	Base price of onshore/offshore wind feed-in
cf:	Correction factor gathered from the Reference Yield Model
E:	Produced wind energy of added/removed onshore/offshore wind power plants

In case of scenario *On WPD*, the cost of wind energy production shifted to southern regions account for € 61 million per annum. In scenario *Off&On WPD*, annual costs are in the range of € 49 million to € 78 million, depending on the assumed feed-in price for offshore wind.

[6] The applied base price is the weighted average price from German tender results 2017 [25].

[7] For the determination of the offshore base price, only non-zero bids in the German offshore tender results are considered, leading to a price of 6 €/MWh. We conduct a sensitivity analysis by setting a range from 5 to 6 €/MWh.

Grid relieving effects

In **Figure 7**, these costs are depicted and linked to the corresponding grid relieving impact. The latter is indicated by the reduction of RES curtailment and of redispatch. The highest reduction rates are achieved in scenario *GE 2*. The *Off&On WPD* scenario performs slightly better than *GE 1* and *On WPD*. The greater grid relieving effects of scenario *On&Off WPD* compared to the *On WPD* scenario can be explained by the illustration of the wind turbine removal in Figure 5. In the *On&Off WPD* scenario, capacities from a concentrated wind energy production area in the north-west of Germany are removed, leading to a local reduction of line utilisations and thus a decrease of curtailment. In scenario *On WPD* however, wind power capacities are removed from a wider area, which do not relieve the known bottlenecks in the north-west.

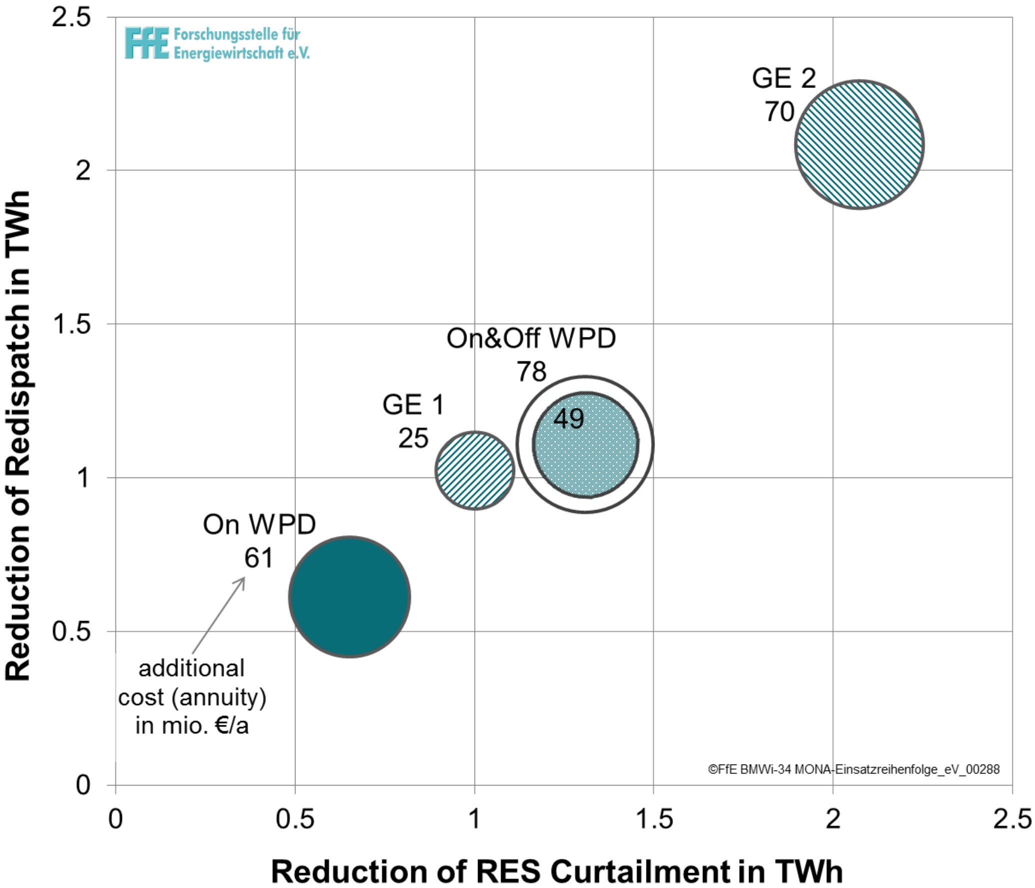

Figure 7: *Reduction of redispatch and of RES curtailment with additional investment for the scenarios grid expansion (GE 1/GE 2) and regulated wind power development (On&Off WPD/On WPD) compared to the reference case.*

Furthermore, the depiction in Figure 7 reveals the fact that in the *On&Off WPD* scenario, bottlenecks are more often solved with redispatch instead of RES curtailment. The use of redispatch causes in general fewer emissions than curtailment and is economically advantageous.

Figure 8 differentiates the commitment of redispatch into its positive and negative amount for all scenarios. Furthermore, the curtailment presented in Figure 7 as well as market-based curtailment of RES is depicted. Hereby, market-based curtailment of RES is a theoretical quantity depicting the overproduction of RES in case of no grid restrictions (dispatch on a "copper plate").

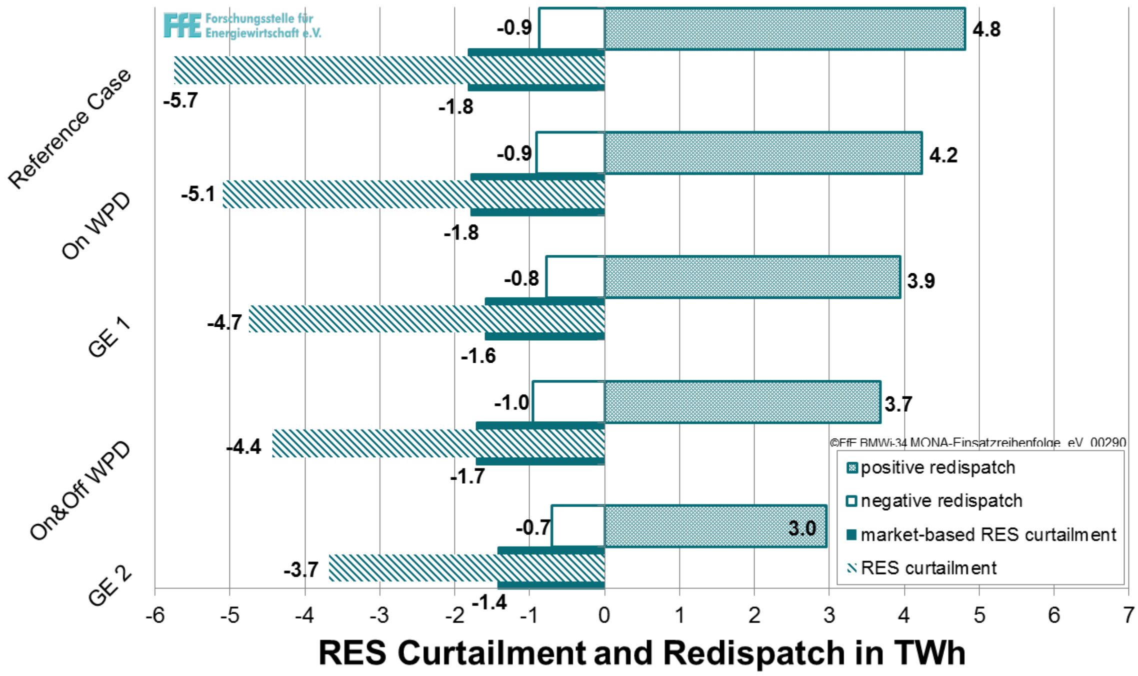

Figure 8: *Redispatch and curtailment of RES in the market region Germany and Austria for all scenarios under analysis.*

Figure 8 shows a reduction in market-based curtailment of RES. This results from increased exports to neighbouring markets. This can be explained through a better utilisation of cross-border lines due to a stronger transmission grid or, in case of *On&Off WPD*, due to a less locally concentrated wind energy production with fewer bottlenecks.

5 Conclusion

In this study, two scenarios of regulated wind power development in the German energy system in the year 2030 are developed and assessed with respect to the bottlenecks in the transmission network. The outcomes are compared and contrasted with the expected status-quo and two scenarios with further conventional grid expansion. In all scenarios, a grid relieving impact can be noted, whereby conventional grid expansion is a more effective and less cost-intensive grid optimising measure compared to regulated wind power development.

Smart regulation of further wind power development bears the potential of reducing system services and therefore relieving bottlenecks in the German transmission grid. But, when considering the large capacities of additionally installed wind power at low-wind speed locations and thus higher cost, grid expansion seems to be a preferable choice under current conditions. This however does not take into account that grid expansion lacks public acceptance and therefore comes at a societal cost [26]. Regulated wind power development can be considered a reasonable alternative to a certain degree. This insight should trigger a debate about the acceptance for building either transmission lines or constructing additional wind power plants.

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