Point by point response:

Associate Editor (E)

Authors (A)

Overall comments

E: *The core contribution of the paper – a preliminary investigation into how LROE for a wind farm can be calculated to aid in design, PPA calculations, etc – is very interesting. However, weaknesses in how the method is presented, lack of justification for key analysis decisions, incomplete reporting of the results, and inadequate grounding of the work in prior art mean that major revision is still needed.*

A: Thank you very much for this very detailed and constructive review. Your comments below are very specific and have highlighted main weaknesses of the paper that needed major improvement. We have tried to implement all comments in the revised version of the paper.

E: ***The paper structure needs work.*** *It needs significant improvement in this work builds from and extends the state of the art – i.e. the contribution beyond the past efforts. The methods section jumps right into details without providing a good overview of the approach and most importantly WHY such an approach has been taken and how it differs and improves upon past efforts*

A: The derivation of the model requirements from the state of the art and a broad overview of the selected procedure is now presented at the beginning of Section 2. Originally, Figure 1 was intended to fulfill this purpose. This Figure has been revised and now also contains the connection between the results of the forecast model and the LROE.

E: *The results section provides one results of one type for scenario A and another type for scenario B. This mix and matching tells an incomplete story. Both scenario results need reporting in order to properly build to the conclusions*

A: The results of the respective other scenario are now also listed and analyzed in Section 3. The idea behind the previous version was to present only the most interesting scenario results. However, it is agreed that this has resulted in an incomplete presentation.

E: *Outlook is insufficient in addressing key paper limitations*

A: The overall presentation of the model has been revised throughout the paper to take a more critical look at its limitations and simplifications. The limitations of the presented method are now explicitly mentioned again in the outlook section.

E: *The overall paper needs to be edited for grammar before final publication. At many points it is difficult to interpret the author's intent without re-reading sentences several times. I could not even get through the second page without spotting a large number of syntax and grammar errors. I will not proceed with a thorough review of grammar but will check it prior to final publication*

A: The grammar in the paper was revised. Please excuse the previous mistakes.

Abstract

E: *Line 7 - Consecutively incorrect English grammar – perhaps considerably? Or in the near future?*

E: *Line 8 grammar error*

A: Again, please apologize for the inconvenience. Most grammar mistakes have been due to translation and working in the revision mode of MS Word. The grammar has been revised.

E: *Dynamic field-in profile is odd language – you mean the hourly generation profile?*

A: Because of the slight difference between "generated electricity" and "electricity fed into the grid", the term "feed-in" was originally used throughout the paper. In retrospect, it is agreed that this wording is somewhat strange in English. It has been corrected in the revised document towards "electricity generation".

E: *Are the dismantling of the plants and emissions prices sensitivities you are looking at in the study? Awkward wording*

A: Yes. The wording in the abstract was adapted to make it more understandable.

E: *Remove last sentence of the abstract – it's an overstatement of the contribution and borderline grandiose. The sentence before is fine and speaks more directly to the potential value of the work*

A: The last sentence has been removed. The tone of the entire paper has been adjusted towards a more neutral and less glorifying language to present the overall model results.

Introduction

E: *Need to qualify that you are talking about Germany rather than referring only to the title of the act. I recommend rephrasing to something like "Renewable electricity generation has increased exponentially in Germany over the last few decades due in large part to the Renewable Energy Act of (year)…"*

A: The beginning of the introduction has been adapted accordingly.

E: *Grammar error in sentence 31-32*

A: The introduction has been revised in terms of correct grammar.

E: *Line 42, what state of the art? Lacking a bit in terms of citations… please do not speak generically about other work. Cite a specific work or collection of works*

A: This sentence has been moved to the discussion section and refers now to the state-of-the-art models discussed and cited in Section 1.2.

E: *Line 56 – direct marketing doesn't make sense in English. Since it is key terminology, it is important to update it. Try direct merchant market participation or direct marketing of their electricity to the system, etc…*

A: Like for the term "feed-in" the terminology "direct marketing" has been replaced by "selling electricity directly on the exchange markets" in the entire manuscript to enhance comprehensibility.

E: *PPAs have been the historic status quo in the US for decades. (whereas most of Europe tended towards FITs). There is some missing context here. PPAs are not novel by any means. There are tons of works out there that compare and contrast FITs, PPAs, quotas and other policy support mechanisms. It might be good to provide a bit more of that broader context before jumping to the current debate around PPAs in Germany*

A: The globally different propagation and prior application of PPAs is now described in more detail in Section 1.1 to provide more context.

E: *Pg 115 many proprietary models are commercial. I would not call this a criticism. It's a common feature of commercial software. I also agree with the reviewer that even though PLEXOS is a commercial code, it is used extensively both by industry and the research community and should be mentioned.*

A: Being commercial is less of a critical point rather than not knowing, how calculations are being executed or what data is used. Because PLEXOS seems to be very transparent in terms of underlying data sets and calculation methods and because of its broad applications it is now being mentioned in the state of the art in Section 1.2. It is also used for benchmark in terms of calculation time in Section 2.6.

E: *In addition, it would also be good to mention literature by Hirth and others looking at the value of wind energy. You might check the reference list of this recent paper:* https://www.sciencedirect.com/science/article/abs/pii/S0960148120301531

A: A new Section 1.3 has been added, covering some relevant measurands for assessing the economic efficiency and value of wind energy, also including Hirth's work and the recommended recent paper. The reference list was found to be particularly helpful in finding some more very interesting documents for this research.

Methodology and forecasting model

E: *before diving into the model, the paper is lacking an overview that describes the key structure of the model, highly level i/o, methodology used and perhaps most importantly, the assumptions and limitations of which there are many (as noted by the reviewers) and this should be front and center so the reader has a good idea of what the model is about before diving into the details.*

A: Section 2.1 now contains a high-level method description and the most essential model assumptions. Detailed assumptions are presented in the respective sub-sections together with the corresponding modelling parameters.

E: *Also, how does your modellilng approach compare and contrast to the state of the art?*

A: The modelling approach is now put into perspective by model classifications by Weron* and compared to the models cited in Section 1.2. However, in accordance with Weron*, the comparison of different models' results was found to be difficult due to deviations in the forecast object and granularity of the model structure and calculation method. This is why the backtesting approach has been chosen for validation. A short comparison to PLEXOS in terms of calculation time has been added in Section 2.6. Anyhow, further comparison should be done in future model application. This is now also mentioned in the outlook.
*https://www.researchgate.net/publication/265853980_Electricity_price_forecasting_A_review_of_the_state-of-the-art_with_a_look_into_the_future

E: *What do you mean the model designs adds a more agent-based approach? Are you using an agent-based model? Be careful on terminology*

A: A single object with an individual cost function is derived for each conventional power plant, which can also be individually parameterized and analyzed later. The number of power plants constitutes the number of agents. Because of the underlying a merit-order approach, the decision-making heuristic for every agent and hour is to offer electricity at their own marginal generation cost and to generate and sell electricity if they are below the uniform market clearing price. An interaction topology is given by the competition to the other power plants or agents. The exogenously given electricity demand represents the environmental influence that drives the decision of every agent. Even though this poses a very simple multi-agent approach, it can be classified as such. For future studies, learning rules for agents as well as the introduction of randomness could be very interesting. This argumentation has been added to section 2.3 and the outlook of the manuscript.

E: *The assumption that the weather data and load profile do not need to be synchronized is inadequately motivated. I am not convinced per the reference to the one study. I have seen even phase shifting by a few hours can result in very different correlation statistics… for this study, you may have been limited, but again, the assumptions are what make good fodder for future work. You should be realistic about the limitations of the current work and very explicit wherever possible.*

A: The investigation regarding correlation between temperature and demand has been added to Section 2.4. The limitations that come with the simplification of desynchronized weather data and demand are now part of the discussion section.

E: *Model validation is also inadequate. What statistics can you report? How much do they different in time versus the cumulative effect that is seen in the price duration curve? You must have statistics on the errors overall between the simulated and historical time-series*

A: Designed for a long-term forecast, the model is not suitable for estimating exact hourly price patterns. This is partly due to the neglection of weather effects and the annually recurring fluctuation in demand. Anyhow, overall price trends and distributions can be reconstructed, which was the initial requirement for the research question. Statistics for both comparisons are now stated and discussed in Section 2.6.

Model application, results and case study

E: *Again, see prior recommended paper https://www.sciencedirect.com/science/article/abs/pii/S0960148120301531 . LROE is just one potential metric so it should be discussed in comparison to others… for example, sLCOE is too cumbersome for the current approach, etc. It is a good choice, but it needs further context.*

A: Further metrices are now described and discussed in the new Section 1.3. The decision for LROE is being argued in the revised Section 2.

E: *Line 251 – minimium FIXED or AVERAGE revenue…*

A: Fixed. The addition has been made in the revised version and discussion of LCOE in Section 1.3.

E: *Where does scenario B come from? Did you make it up? If so, how did you choose which plants to dismantle? I agree scenario A is not realistic but it leads me to believe both scenarios are somewhat ad hoc in their creation. Please provide a bit more justification for the development of the scenarios*

A: Additional information on how both scenarios have been developed is now provided and cited in Section 3. The scenarios are based on the renewable expansion path as defined by the Renewable Energy Act and on the scenario framework approved by the German Federal Network Agency in June 2018.

E: *Figure 5 graphic quality needs to be improved*

A: The graphic has been replaced at a better resolution.

E: *There are a huge number of works creating future energy scenarios. Even if this work is too far along to use these, it would be good to refer to these and again explain better the choices made in this study. DNV GL, BP, IRENA, IEA etc… there are tons of organizations out there looking at future energy mix. See IEA Wind Task 25 for a relatively good source of studies, also see ESIG and their work.*

A: Further scenarios developed by the different organizations are now referred to in Section 3 and in the outlook of the revised paper. Thanks again for pointing at the relevant sources.

E: *Variation in CO2 is a sensitivity analysis on carbon price. Would be good to describe it as such. However, there is a problem here as the price of CO2 will have an endogeneous effect on the long term electricity generation mix. ReEDS and other models take this into account. It is important to note this limitation. See works by Trieu Mai and others from NREL with ReEDS or again, see ther various many works by the collective research community of IEA Wind Task 25*

A: The wording for the sensitivity analysis has been adapted. Interdependence between emission price and generation mix can not be considered since the generation capacities need to be pre-defined for each scenario. This, among the other limitations, is now part of the model discussion.

E: *Explain better what you are doing in lines 299-301… fictitious??? Again, decisions in analysis need grounded explanation*

A: Analysis decision and presentation have been revised for Section 3.2. This line was only hypothetical and fictious and has therefore been removed for better comprehensibility.

E: *The PPA approach needs much stronger justification especially if you are going to use it in generalized conclusions based on the results as in lines 307-310*

A: Further PPA considerations have been added to Section 1.1. The formulations in the revised paper have been weakened in a less generalizing way.

E: *Why do you not have a similar figure 8 for scenario A? or put both scenarios side by side on the same plot?*

A: A new Figure 8(a) has been added that addresses the case study results for scenario A.

E: *And why is figure 6 only for scenario A? this is very strange. You don't need to use histograms. You could use lines and plot both scenarios on the same plots. Or alternative use two sets of plots – one for each scenario*

A: Figure 6 has been revised and shows now the results for both scenarios.

Conclusions

E: *What does low data requirements and low computational cost mean? Be specific and compare to alternative approaches. Also, given the myriad of assumptions made I do not think you can claim this at present. Much more work is needed to establish external validity of this claim*

A: Currently, a complete model execution takes about five minutes. Regarding the data requirements, only the annual cumulated installed generation capacity of the power plants and the annual electricity demand for the forecast period are needed for the current calculations of different scenarios. All other dynamic quantities are determined automatically or are obtained from the presented reference data of the TYNDP. Nevertheless, you are right, that because of the many assumptions this claim needed to be relativized and revised.

E: *For conclusions on the effects of renewables, you need both scenarios to be shown and compared and contrasted (see comments above).*

A: The model results have been added and discussed accordingly in Section 3.1.

Discussion and outlook

E: *WIFO needs to be defined (no acronyms should be used).*

A: WIFO is defined now in the outlook. It stands for WInd Farm Optimizer.

E: *Again, strike the last sentence – as with the abstract, it is overly broad*

A: The sentence has been removed.

E: *Outlook insufficiently critical of the current limitations… the outlook section is where you should circle back to what the key limitations of the current approach are. This needs to be done at the beginning of the methodology section and then the different approaches to remedy them should be discussed here.*

A: The discussion and outlook section has been revised more critically, especially in terms of the current model assumptions and limitations as well as necessary model improvements to dissolve simplifications.

Overview of major changes:

- The Paper has been revised for grammar errors and overly exalting language.
- The Introduction (Section 1) has been revised to better derive the papers research question and subsequent model.
- PPAs are now given a more global discussion in Section 1.1 before mentioning the current discussion in Germany.
- A new Section 1.2 has been added, addressing different metrices for evaluating profitability of renewable energy sources.
- The model PLEXOS has been integrated in the regarded state of the art models and subsequent discussion.
- Section 2 has been revised and now contains a broader model description including the most relevant assumptions.
- The argumentation about desynchronized weather data and demand has been extended in Section 2.5.
- Model validation has been revised by additionally discussing further error quantities as well as the temporal course of the prices.
- The chosen scenarios in Section 3 are now derived more thoroughly. Results are now presented and discussed for both scenarios throughout all Sub-Sections.
- The discussion in Section 4 now deals much more critically with model limitations and assumptions as well as future improvement measures.

Marked changes:

Future Economic Perspective and Potential Revenue of Non-Subsidized Wind Turbines in Germany

Lucas Blickwedel[1], Freia Harzendorf[1], Ralf Schelenz[1] and Georg Jacobs[1]

[1] Chair for Wind Power Drives, RWTH-Aachen University, Aachen, Germany

Correspondence to: Lucas Blickwedel (lucas.blickwedel@cwd.rwth-aachen.de)

Abstract. ~~Thanks to~~Fixed feed-in tariffs based on the Renewable Energy Act ~~todays~~grant secure revenues from selling electricity for wind turbine operators in Germany~~ are dealing with low risk on the revenue side. Fixed feed-in compensation ensures planning security and high system utilisation.~~. Anyhow, the level of federal financial support is being reduced consecutively. ~~Tomorrow's~~ Plant operators must trade self-sufficiently ~~on European electricity markets~~in the future, hence generate revenue ~~only~~ by ~~marketing~~selling electricity~~.~~ directly on electricity markets. Therefore, uncertain future market price developments will influence investment considerations and may lead to stagnation in the expansion of renewable energies. ~~It is of interest to estimate~~This study estimates future revenue potentials of ~~those~~ non-subsidized wind turbines in Germany to reduce ~~those risks. This~~this risk. The paper introduces and analyses a forecasting model that generates ~~data specifically~~electricity price time series suited for revenue estimation of wind turbines~~.~~ based on the electricity exchange market. Revenues from the capacity market are neglected. The model is ~~solely~~ based on ~~open access~~openly accessible data and applies a ~~modified~~ merit~~-~~order approach in combination with a simple agent-based approach to forecast long-term day-ahead prices ~~on European electricity markets~~ at an hourly resolution. ~~In doing so, the dynamic feed-in~~The hourly generation profile of wind turbines can be mapped over several years in conjunction with fluctuations in the electricity price. Levelized Revenue of Energy are used to assess both dynamic variables ~~within~~(electricity supply and price). The merit order effect from the ~~same measure. The results show how changes in the German power generation landscape like dismantling~~expansion of ~~coal and nuclear power plants~~renewables as well as ~~different emission prices impact the potential revenue~~the phasing out of ~~wind~~nuclear energy~~.~~ and coal are assessed in a scenario analysis. Based on the assumptions made, the opposing effects could result in a constant average price level for Germany over the next twenty years. The influence of emission prices is considered in a sensitivity analysis and correlates with the share of fossil generation capacities in the generation mix. In a brief case study~~ then highlights~~, it was observed that ~~for the given results most of today's~~current average wind turbines ~~in Germany~~ are not able to yield financial profit over their lifetime without ~~guaranteed~~additional subsidies~~.~~ for the given case. This underlines ~~an urgent~~a need for technical development and new business models~~. Possible business models could be~~ like Power Purchase Agreements~~ for which~~. The model results can be used for setting and negotiating appropriate terms, such as energy price schedule or penalties for those agreements.

~~Overall, the information obtained by the given model contributes to reducing investment risks, deducing development goals and finally supports the expansion of tomorrow's wind turbine technology.~~

1 Introduction

Renewable electricity generation ~~technologies have been heavily subsidised by the German~~ has increased exponentially in Germany over the last few decades due in large part to subsidization by the Renewable Energy Act (~~EEG,~~ Erneuerbare Energien Gesetz~~) in the past~~, EEG). The law was enacted to achieve ~~energy~~the policy ~~goals by~~goal of reducing the energy sectors greenhouse gas emissions. Fixed feed-in tariffs ~~decoupled~~secured revenues from ~~the~~ selling electricity for renewable energy sources and ensured independence from the fluctuating electricity exchange price~~ which made~~. Thus, investments in the renewable energy sector were particularly attractive and led to a strong expansion. ~~In the form of~~By introducing a tendering procedure, an attempt was then made to increase competition and promote the competitiveness of wind energy. ~~However, at the same time more strict requirements alongside lengthy approval and licensing procedures led to stagnation in onshore wind energy expansion in Germany .~~ In the future ~~case of direct marketing revenues will depend solely on the current~~ however, subsidies will probably cease completely. Electricity from renewable energy sources will have to be sold in alternative ways to generate revenue. These are likely to be based on the electricity exchange ~~price and the power fed into the grid.~~

~~The final investment and thus expansion decision usually take place on a local and project-specific basis. Whether a new wind farm is erected is therefore a new consideration for each individual case. In this context, the development of~~ markets. Hence, the electricity exchange price ~~represents a crucial and uncertain external factor for the investment decision. In Germany, relevant decision-makers are often located at municipal level .~~ at the time of electricity generation will become a crucial factor for profitability next to the already widely considered cost of electricity generation (Federal Ministry for Economic Affairs and Energy, 2019a, 2019b, 2019c).

The aim of this research is to address and quantify the barrier of uncertain ~~market~~ revenues of electricity generation from wind turbines (WT) without subsidies in Germany~~ by estimating~~. How can future electricity exchange prices~~. Due to the changing political conditions, it is also advantageous to be able to calculate different future scenarios. For this macroeconomic topic, national and European electricity markets must be considered. However, due to the decentralised nature of renewable energies it is also necessary~~ be estimated and put in perspective to ~~investigate individual expansion projects on a microeconomic, municipal scale. With respect to the dynamic electricity supply from wind turbines, a long-term forecast (over 20 years) with a relatively high (hourly) temporal resolution is carried out. Compared to most state-~~the generated electricity? To answer this question, the markets of~~ the-art~~ Germany and its neighboring countries are considered within the framework of a new forecasting ~~models,~~ model, which will be developed and discussed in this paper.

First, a literature research for three different aspects relevant to this ~~is a rather unusual combination. In this special case, however, this makes sense in order to take the dynamic characteristics into account when calculating revenue.~~

~~By forecasting future prices, it is desired to support and enable municipal decision-makers at planning and designing local expansion more independently.~~

~~In the following~~task is conducted: In Section 1.1 the current market situation and potential revenue sources for WT operators in Germany ~~is summarized. Afterwards in~~are assessed with a focus on long-term Power Purchase Agreements as one possible alternative for selling electricity. Section 1.2 will then address existing approaches for modelling and forecasting ~~and system analysis models~~electricity exchange prices with a similar scope. Afterwards, in Section 1.3 different metrices to evaluate the economic efficiency and perspective of renewable energy sources are being discussed.

Based on ~~these two sections~~the literature research, the elaborated model requirements and forecasting model will be derived and discussed in Section 2. Finally, in Section 3 model results are presented and interpreted along a brief case study and conclusion, followed by a critical discussion of the model and outlook in Section 4.

1.1 ~~Revenue situation~~ Potential revenue sources for wind turbine operators in Germany

~~In~~Since 2017~~, the whole EEG support scheme has been overhauled.~~ the level of subsidization for electricity from WTs in Germany is ~~now being~~ determined through tendering~~. The operator receives an individual market premium~~ with a pay-as-bid system, regulated by the German Renewable Energy Act. After successfully taking part in ~~a~~the tendering procedure~~. In addition, the EEG 2017~~, WT operators receive individual feed-in tariffs per kWh according their bid. The Renewable Energy Act defines a maximum tender volume for each year. Bids that exceed the set limit are not receiving financial support (Deutscher Bundestag, 2020)~~.~~

~~Since 2016 new power plants with an installed capacity of over 100 kW~~. There are ~~bounded~~three main options for plant operators in Germany who do not receive subsidies to ~~direct marketing (§21 EEG 2017, §EEG 2014). For operators of WTs that have been approved before EEG 2014 direct marketing is optional. (EEG 2014, §100, subsection 1, number 6) The first step towards direct marketing is to choose a direct marketer and then conclude a contract, which regulates payment terms, possible compensation payments and the remote controlling. The latter is required for direct marketing. The direct marketer then needs to register the new plants at the distribution grid and include them into his accounting grid to be finally able to enter~~sell their generated electricity: Selling directly on the electricity exchange market, through bilateral contracts or by providing generation capacity on the capacity market. The latter naturally does not pose a significant source of revenue for the volatile electricity generation from wind and solar energy so far and will therefore be disregarded for this paper. In case of selling directly on the electricity exchange market, revenues depend largely on the time courses of the exchange price and local wind conditions. The question of how its course over a longer period of time can be estimated is the core element of this research and the following chapters.

An alternative for selling electricity from renewable sources ~~are long-term~~on the electricity exchange markets are so called Power Purchase Agreements (PPA). ~~These~~PPAs are mostly made between corporate electricity consumers and plant operators. They enable bilateral trading including consultation between contracting parties. Those agreements normally cover a period of up to ten years and are established individually each time by the contract parties. PPAs define the following aspects of power purchase: amount of electricity, price, contract terms and penalties for breach of contract (Javadi et al., 2011; Elwakil and Hegab, 2018 - 2018)~~. A distinction is made between on-site and off-site PPAs with different subcategories. On-site PPAs include a direct physical electricity delivery from the producer to the customer. That is the reason why a geographical proximity~~

is significant for these types of PPAs. The costumers minimize their risks by outsourcing power generation while long-term contracts ensure economic viability and calculability for the operator. .

Off-site PPAs on the other hand deliver the defined electricity amount through the public electricity grid. No direct physical deliveryalready have a significant market share in the sale of electricity between producer and costumer is happening. A network charge needs to be paid for these PPAs, but also geographical flexibility exists. This means that producers can choose their location by site-specific factors, which allows production to be optimized. Plants may enter several PPAs with different customers at the same time . Both, on-site as well as off-site PPAs are possible alternatives for selling electricity from WTs.

So far long-term PPAs are highly controversial. Proponents state that they are a good and necessary tool to support renewable energy. Opponents criticize that the PPA price is currently often set well below the exchange market price and thus makes the economic operation of plants even more difficult. Existing non-subsidized WTs that have exceeded the 20-year limit can either be repowered, deconstructed or further operated . First contracts for PPAs sources in some countries around the world. In particular in the US, the market for PPAs has been growing in recent years. Energy intensive companies such as Google, Microsoft and Facebook have been committed to 100% green electricity. Google has already concluded for old WTs, but also new WTs.PPAs for a total of about 1.8 GW. In Brazil, energy-intensive consumers have been able to conclude PPAs for electricity from conventional or renewable energy sources since 1995 (Coussi and Harada, 2020; Berger et al., 2016). Compared to other European countries the PPA market in Germany is much less developed. In a lot of neighbouringneighboring countries PPAs are already an established procedure (Fischer et al., 2019; Tang and Zhang, 2019). Sweden (33%), Norway (30%) and the UK (16%) are the European countries with the highest share of PPAs (Klinger 2019). However, the majority of renewable energies in Europe, including Germany, were supported through a fixed feed-in tariff financed by public funds (Berger et al., 2016). Since many plants will be excluded from subsidies from 2020 onwards, PPAs are increasingly being considered in Germany.

Although PPAs can be negotiated independently of the electricity exchange price, it is nevertheless common for the contracting parties to base their agreement on the development of the electricity exchange price. PPAs are therefore considered as an alternative selling option in this paper. The future electricity exchange price seems to be the correct forecast object to derive statements about both potential revenue sources.

1.2 Existing forecasting models

Extensive literature is available in the field of modelling and forecasting electricity exchange prices. However, there is no consensus on the approach and methodology of modelling. Most models are designed for a specific market situation or forecasting horizon in which they perform well and deliver robust results. However, many. In an extensive review, Weron has identified five different categories of electricity price forecasting models aim to predict EEX price movements reliably.: Multi-agent, Fundamental, Reduced-form, Statistical and Computational intelligence models. Hybrid combinations of model types do also exist (Weron, 2014). This classification will be used for assessing the state-of-the-art forecasting models as well as the newly developed model in this paper. In the following, some practical examples of forecasting models of electricity exchange prices are presented which are of methodological interest for this work.

In 2010 Jonsson et al. investigate the influence of wind energy forecasts and actual wind volume on the Danish electricity exchange price. They use a non-parametric regression model and ~~the~~a statistical distribution of the spot price for different scenarios and conclude that a high forecast feed-in from wind turbines lowers the ~~exchange~~electricity price. The actual amount of wind energy also influences the price.~~ In both cases the correlations are strongly non-linear.~~ The authors observe growing price volatility and weather-related price patterns (Jónsson et al., 2010). Jonsson et al. focus on the impact of wind energy onto the electricity price, ~~whereas the given paper will reverse this focus and analyse~~but do not consider the impact of the electricity price during different wind conditions onto the economic efficiency of WTs.

In 2013 Jonsson et al. then pursue a two-step approach to model the short-term spot prices in Denmark for the years 2010 and 2011. They forecast grid load and ~~feed-in~~electricity generation from ~~wind turbines~~WTs. Non-linear and transient influences of these two variables are considered in the first step of the model by a non-parametric regression. Subsequently, time series-based models are used to represent remaining autocorrelations and seasonal effects. The authors conclude that models with variable parameter estimation can yield better results over time than those with static parameters (Jonsson et al., 2013). However, robust parameter estimation has the advantage that models are less vulnerable to abrupt parameter changes e.g. due to excessive price peaks.

Fanone et al. can generate both negative and positive price peaks with a ~~forecast~~parameter rich fundamental forecasting model of the German intraday market with hourly resolution. The model parameters are calibrated using historical EPEX intraday data. The hourly spot price is divided into two components, namely a time-dependent adjustable component and a deterministic component containing long-term variations and seasonal effects. When investigating daily spot prices an annual and a half-yearly periodicity can be observed (Fanone et al., 2013)~~. A possible~~. A disadvantage of this approach is that ~~calibration based on historical data against the background of~~ fundamental ~~market~~ changes in generation capacities such as ~~dismantling~~decommissioning of coal powered plants are neglected. This could lead to long-term forecasting errors.

Šumbera and Dlouhý model the German spot market based on the fundamental assumption that the demand for electricity and the system load always equal the generation capacity provided by all power plants. A merit-order approach is used for pricing~~, which is subsequently extended.~~. The power plants are divided into dispatchable and non-dispatchable power plants~~ and others~~. The dispatchable power plants~~ and their~~ schedules are presented in high detail. Non-dispatchable power plants are grouped together in the model according to energy source and defined as "must-runs". Power plants whose generation depends only on their availability are modelled with variable costs of zero (Šumbera and Dlouhý, 2015). A disadvantage of this methodology is that a set of all generation units or at least a representative data set must be available.

~~A general criticism of existing models that are not open access is the lack of transparency and accessibility of the calculation methods and databases. Therefore, only openly accessible data is used for the presented forecasting model, except for the historical exchange market price data of EPEX Spot used for validation. However, these are not necessary for the subsequent use and functionality of the tool.~~

Next to the discussed forecasting models there is also a broad variety of equilibrium models that ~~analyse~~analyze energy systems and consequently may be used for electricity price estimation. The Balmorel model will be discussed as representative for this group. Balmorel is a partial equilibrium model for analyzing the electricity and combined heat and power sectors in a large geographical and international perspective. It has been directed towards the solution of an optimization problem in GAMS to determine entities like generation, consumption, transmission and prices of electricity and heat as well as emission. Especially positive is that the source code of Balmorel is openly available since 2001~~.~~ (Wiese et al., 2018). Due to the wide range of performance and the necessity to solve an optimization problem, the model imposes comparatively high demands on the level of technological detail and data, even if these can be reduced by later model adjustments. ~~It is questionable whether a leaner model might not be sufficient to achieve one of these goals at less computational effort.~~

~~2 Methodology and forecasting model~~

~~To make investment decisions based on the revenue potential~~ Another widely used, commercial tool is the market simulation software PLEXOS (Papadopoulos et al.). Like Balmorel, PLEXOS is able to solve complex optimization problems with an object-oriented approach and delivers market results for the gas, electricity and water system. Thanks to parallel computing, PLEXOS can boast comparatively short calculation times in the range of a few hours up to minutes (Energy Exemplar, 2019). Yet, it is questionable whether a leaner model might not be sufficient to achieve comparative results at lower computational effort.

1.3 Existing metrices for evaluating the economic value of wind turbines

Several different metrices are known by literature to describe the economic efficiency of electricity generation techniques and plants. Generally, the economic efficiency of a WT can be assessed based on three essential quantities: Cost, revenues and electricity yield. A distinction can be made between those metrics that consider the costs of a generation technology and those that consider the revenue situation. Those metrices that are found to be relevant for evaluating potential revenues within this study are listed in Table 1 and further described in the following.

Table 1: Overview of relevant metrices for evaluating the economic value of electricity generation techniques

Metric	Abbreviation	Objective	Formula
Levelized Cost of Energy	LCOE	Cost	$\sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \Big/ \sum_{t=1}^{n} \frac{W_{t,el}}{(1+i)^t}$
System Levelized Cost of Energy	sLCOE	Cost	$\sum_{t=1}^{n} \frac{C_t}{(1+i)^t} \Big/ \sum_{t=1}^{n} \frac{W_{t,el}}{(1+i)^t} + \frac{d}{dW_{t,el}} C_{int}$
Levelized Revenue of Energy	LROE	Revenue	$\sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \Big/ \sum_{t=1}^{n} \frac{W_{t,el}}{(1+i)^t}$
Levelized Avoided Cost of Energy	LACE	Revenue	$\sum_{j=1}^{Y} R_{j,el} * h_j + R_{j,cap} \Big/ \sum_{j=1}^{Y} h_j$
Simplified Levelized Avoided Cost of Energy	LACEs	Revenue	$\sum_{j=1}^{Y} R_{j,el} * h_j \Big/ \sum_{j=1}^{Y} h_j$

C	Cost	W_{el}	Electricity generation	R_{el}	Revenue from electricity sales	h	Dispatched hours
C_{int}	Integration cost	i	Interest rate	R_{cap}	Revenue from capacity market	Y	Time periods

The overall performance of WT (or other generation plants) is often evaluated based on the levelized cost of energy (LCOE). The LCOE are defined as the total lifetime cost over the total lifetime energy production. It is a widely used and simple metric for estimating the value of renewable energy sources projects (Campbell et al., 2009 - 2009; Boubault et al., 2016; Ouyang and Lin, 2014; Parrado et al., 2016). To calculate the LCOE, information on annual costs and annual electricity generation is needed. The annual costs consider investment, O&M and fuel costs. However, the LCOE does not consider the time-varying value of electricity generation, which is already criticized in literature (Hirth and Steckel, 2016; Hirth, 2013; Simpson et al., 2020). Therefore, the LCOE is no holistic indicator for the profitability hence economic value of a plant and potential revenue. Its value can only be interpreted as the minimum fixed revenue required for an economical plant operation.

The System LCOE (sLCOE) metric addresses this problem by adding marginal integration costs. Uckerdt et al. define a method to determine the marginal integration costs from annual electricity demand, generation from renewable sources and system costs with and without renewables (Ueckerdt et al., 2013). This makes the metric interesting for a systemic view, but is not suitable for the centralized planner, since revenues are not considered and complex simulation of integration costs is required. (Joskow, 2011; Lucheroni and Mari, 2018; Reichenberg et al., 2018)

Analogous to the LCOE, the LROE measures the revenues instead of the costs of a plant. With LROE and LCOE the net present value (NPV = LROE - LCOE) can be calculated and thereby provides information on how incentives have to be set to encourage growth of renewable energy. However, timeseries data and revenues from electricity & capacity sales as well as incentives must be considered when calculating revenues (Baker, 2011b, 2011a). The LROE can be regarded as the expectable average revenue in a given market. LROE vary for the same plant in different markets. The additional market information poses an advantage of LROE over LCOE.

Unlike LROE, LACE does not consider revenues from incentives, but from the capacity market. This makes modeling a bit less complicated and it is more interesting for centralized planners than from a systemic point of view. Due to the neglection of the capacity market in this paper, the LACE appears to be less suitable for the subject under consideration. The LACEs further simplify revenues by incorporating capacity sales, which generally represent only a small part of RES revenues. Revenues are calculated on the assumption of a linear relationship between spot market price and residual demands. This simplifies the simulation even more, but still takes into account that the value of electricity generation varies over time (Simpson et al., 2020).

In order to evaluate the revenue potential from wind energy, a measurand must be chosen that considers revenues instead of costs. Against this background, LROE and LACEs seem equally suitable. LACEs require simplification in the price calculation. This paper attempts to provide the price time series needed to calculate the LROE using the forecasting model described below.

2 Methodology and forecasting model

In order to draw conclusions about the economic perspective of wind turbines in Germany, model requirements are derived from the previous chapters. Based on Section 1.1, the forecasting objective of this study should be the day-ahead spot market as it is one of the most relevant markets for trading electricity from wind turbines and furthermore a reference for drafting PPAs. On the day-ahead market electricity is traded for each hour of the following day.

To assess the potential revenue of WTs, the entire life cycle ~~must~~has to be considered~~, which lies usually in the range of at least 20 years~~. Therefore, the long-term development of the electricity exchange price ~~must~~should be estimated. At the same time~~ microscopic market effects like ~~, increased price volatility due to ~~feed-in of renewables~~higher generation from renewable sources should ~~also ~~be considered~~. These effects are represented better~~ by ~~short-term forecast models~~the chosen temporal resolution. In conclusion, a long-term forecast period ~~with ~~of 20 years at a high temporal resolution will be ~~simulated~~modelled to fulfill both requirements. Due to the hourly trading steps of the day-ahead market, the model is designed to calculate prices in hourly resolution to ensure comparability.

To calculate hourly prices it is required, that short term demand characteristics like daily and weekly patterns are modelled. Seasonal demand variations as well as long term developments of the average demand should be possible to include. For this study it is assumed that the hourly demand for the entire forecast period is known in foresight and that the hourly demand equals the grid load at all times.

The available generation capacity from renewable and conventional sources needs to be considered by generation technology. It is also required, that changes in national electricity generation landscapes can be parametrized in the model to account for developments like the decommissioning of coal and nuclear energy in Germany. Electricity from weather dependent renewable sources must be integrated. Finally, neighboring electricity markets should be considered in terms of electricity import and export.

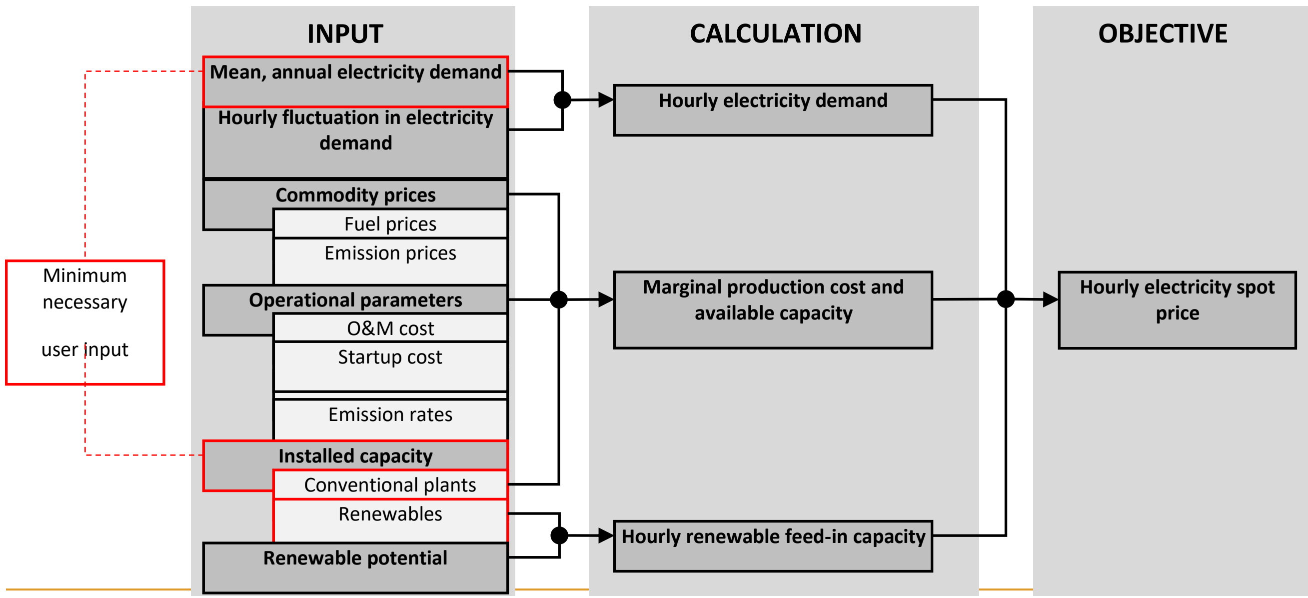
A general criticism of many existing models is the lack of transparency and accessibility of the calculation methods and databases as they are often not openly accessible. Therefore, only openly accessible data shall be used for the forecasting model, except for the historical exchange market price data of EPEX Spot used for validation. However, these are not necessary for the subsequent use and functionality of the tool.

2.1 Forecasting objective

~~**The given model is oriented towards the mechanisms of the existing power exchange. The EEX markets and electricity exchanges represent a highly relevant objective for forecasting, due to their central location and economic influence. One of the most relevant markets for trading electricity from wind turbines is the day-ahead market. On this market, electricity is traded for every hour of the following day. In practice most over the counter (OTC) trades are based on the current level of the (day-ahead) spot market. When drafting PPAs, it is customary to use the course of the electricity exchange price as reference. The forecasting objective of this study is therefore the day-ahead spot price for the next twenty years. This automatically satisfies the initially formulated requirement for a high temporal resolution.**~~**and model classification**

~~Figure 1 shows which input variables and calculations are necessary to describe this objective and how they have been connected within the presented model. In the following, the input data and intermediate steps used are explained in more detail.~~ The ~~elaborated forecasting model~~subject of this study is ~~based on a~~ the hourly German day-ahead spot market price over the next twenty years. The developed forecast model uses a merit-order approach to calculate hourly prices and can therefore basically be ~~categorized~~classified as a fundamental model ~~following~~according to Weron (Weron, 2014). An object-oriented approach has been ~~chosen~~added for the implementation of power plants~~, where individual characteristics and cost~~. Each conventional electricity generation unit functions as a single agent and can be ~~set. This model~~parametrized individually. Due to this design ~~adds a more~~decision, the model can moreover be assigned as an agent-based ~~approach~~model, yielding additional benefits over a solely fundamental procedure. ~~The object-oriented design makes it easy to adapt parameter variations and can be used to check plausibility of results on plant level. The presented~~All in all, according to Weron, the model presented is ~~therefore finally to be~~being classified as a hybrid model~~. The required data and calculation steps are descried in the following subchapters.~~

~~The average annual~~, combining fundamental and agent-based aspects. Figure 1 shows which input variables and calculations are necessary to describe this target and how they have been linked together within the presented model. First, the electricity demand ~~and the annual installed plant capacity are the only data to be provided by the user. Reference values are available~~is calculated for ~~all other~~every hour of the forecasting period based on a mean annual value and an hourly fluctuation factor. Afterwards, marginal generation cost and generation capacities of conventional power plants are derived from different operational parameters and commodity prices. The hourly renewable generation capacity from solar and wind energy is calculated based on installed capacity and an hourly generation potential. The hourly electricity price is derived as the marginal generation cost of the most expensive power plant that is still needed to meet the current electricity demand. The obtained time series data are used in the end to calculate LROE for economic evaluation of wind turbines.



In the following Sections, the input data and intermediate steps of the calculation model are explained in more detail.

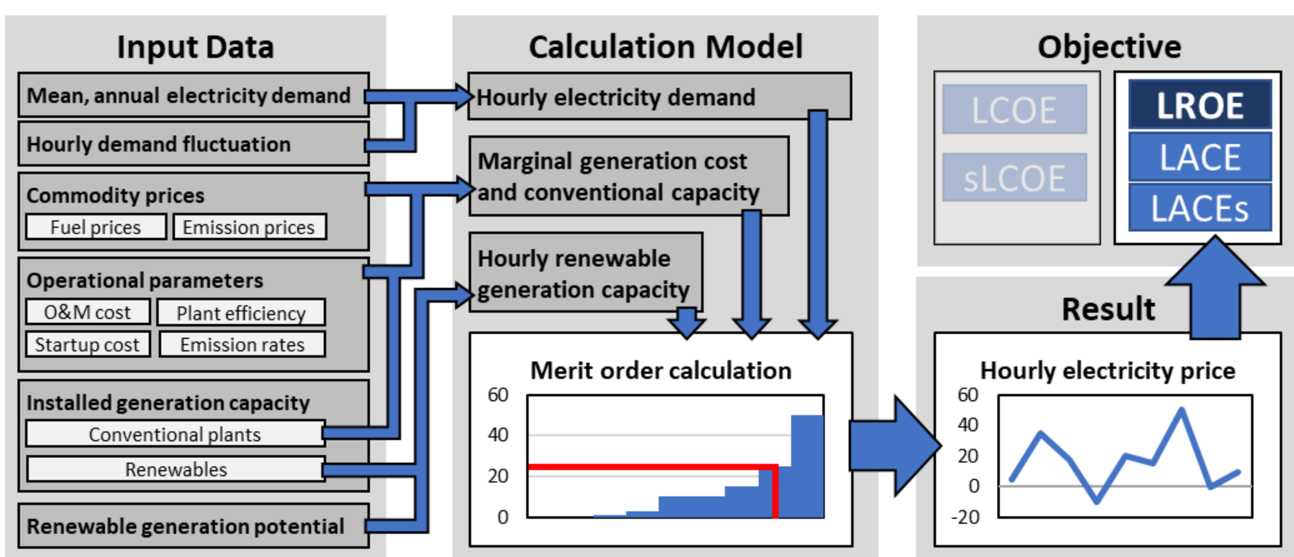


Figure 1: Schematic model structure and input data requirements

2.2 Hourly electricity demand

The hourly electricity demand of a country for each year is composed of an annual mean value D_{mean} and an hourly fluctuation factor f_{var} according to Eq. (1). D_{mean} is derived from the total annual demand required as model input while f_{var} remains the same for any scenario. The time series for f_{var} is derived from data of the Ten Year Network Development Plan (TYNDP18) of the European network of transmission system operators (entso-e, 2018). Figure 2 shows annual ~~(a),~~, weekly ~~(b)~~ and daily ~~(c)~~ sections of f_{var}. It can be observed how f_{var} covers different cyclic characteristics of the actual electricity demand like higher demands during winter as well as peak and off-peak hours. All long-term demand trends must be considered within D_{mean}. The hourly electricity demand is assumed to be equivalent to the load profile used for the merit-order approach.

$$D(t) = D_{\text{mean}} \cdot (1 + f_{\text{var}}(t)) \tag{1}$$

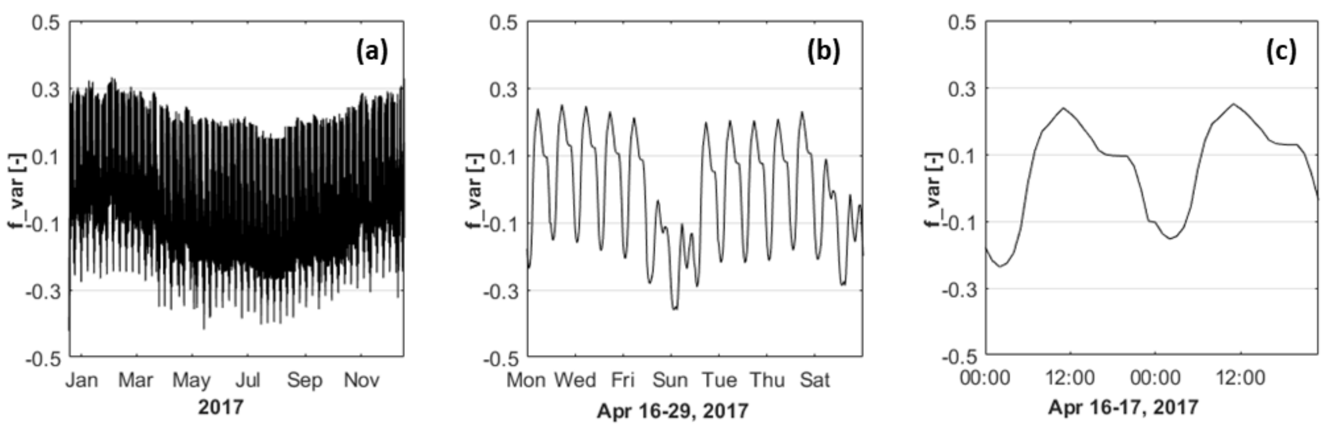


Figure 2: Demand variation factor f_{var} for Germany in 2017 with annual (a), weekly (b) and daily (c) characteristics

2.3 ~~Available~~Marginal generation cost and conventional capacity ~~and marginal cost~~

The national installed ~~capacity and~~ generation ~~plants~~capacities are ~~classified by~~divided into conventional and renewable plants, where gas, hard coal, lignite, oil and nuclear ~~fuelled~~fueled plants are considered as conventional. On the other hand, hydro, solar, wind (onshore and offshore) and others (mainly biomass) are considered as renewable. Based on these categories, a total installed capacity per year is required as user-input. In a next step the model derives individual objects to generate an object-oriented plant fleet based on reference data. ~~Afterwards each object can also be parametrised individually. Marginal generation cost c_{var} is then calculated for every plant following Eq. (2)~~The procedure can be classified as a simple agent-based approach. The number of power plants constitutes the number of agents. Because of the underlying merit-order approach, the decision-making heuristic for every agent and hour is to offer electricity at their own marginal generation cost and to generate and sell electricity if they are below the uniform market clearing price. An interaction topology is given by the competition to the other power plants or agents. The exogenously given electricity demand represents the environmental influence that drives the decision of every agent.

Marginal generation cost c_{var} is calculated for every conventional plant following Eq. (2)

$$c_{\mathrm{var}} = c_{\mathrm{fuel}} + c_{\mathrm{o\&m}} + c_{\mathrm{CO_2}} \quad \text{with} \quad c_{\mathrm{fuel}} = \frac{p_{\mathrm{fuel}}}{\eta} \quad \text{and} \quad c_{\mathrm{co_2}} = \frac{p_{\mathrm{CO_2}}}{\eta} \cdot f_{co_2} \tag{2}$$

where c_{var} is the marginal generation cost of a specific power plant used for the merit-order approach. Commodity prices are split into fuel prices p_{fuel} and emission (CO_2) prices $p_{\mathrm{CO_2}}$ which are both assumed to be constant over time during a simulation run. The resulting cost are then calculated regarding both, efficiency η of plants as well as emission rate $f_{\mathrm{CO_2}}$.

~~During~~For this research, values given in Table 2 have been assumed as reference for commodity prices and efficiencies. The values have ~~also~~ been derived from TYNDP18 data~~.~~ and are assumed to be constant over time (entso-e, 2018). The specific cost terms can be varied for each individual power plant.~~ Also,~~ When adding additional plants, cost values can be set individually. For the plant efficiency it was assumed that over all power plants the efficiency follows a beta-distribution defined by η_{min}, η_{mean} and η_{max} where the oldest plants operate at the lowest efficiency and vice versa. Every plant is also given a date of commission and shutdown date. Outside the resulting time span, the respective power plant is not considered for the price calculation. The given emission factors refer exclusively to emissions occurring during operation.

~~The given emission factors refer exclusively to emissions occurring during operation. Holistic life cycle analysis (LCA) approaches would provide an emission factor greater than zero in the case of nuclear power plants, since greenhouse gases are released during fuel transport and plant construction and dismantling.~~

Table 2: Reference values for commodity prices and plant efficiencies (entso-e, 2018)

Property	**Sign**	**Unit**	Gas	Hard Coal	Lignite	Oil	Nuclear
O&M cost	$c_{o\&m}$	€/MWh	1.46	3.3	3.3	2.57	9
min efficiency	η_{min}	%	25	30	30	25	30
mean efficieny	η_{mean}	%	44	40	40	36	33
max efficiency	η_{max}	%	60	46	46	43	35
fuel price	p_{fuel}	€/MWh	21.96	8.28	3.96	50.76	1.69
emission rate	$f_{\mathrm{CO_2}}$	kg/MWh	205.2	338.4	363.6	280.8	0

~~**2.4 Hourly renewable generation capacity and weather time series data**~~

~~For the implementation of weather-dependent electricity generation technologies such as photovoltaic plants and WT are essential and of fundamental importance. The influences of wind speed and solar radiation are taken into account by referring to previous studies of Staffell and Pfenninger . The authors use weather data~~

~~from global reanalysis models and satellite observations to generate synchronized national time series data for solar and wind generation capacity for the years 1985 to 2016 at an hourly resolution . The capacity factors given by their studies are then scaled with the overall installed generation capacity of WT and solar panels. This data is used for forecasting by shifting it into the future, meaning that the original data for the year 1985 will be used for the first year of the forecasting period. The influence of the ambient temperature on the electricity demand was investigated in a previous study, with the result that for Germany there is no significant influence . Therefore, it is assumed that weather data and load profile do not need to be synchronized. All other weather and climate influences are neglected in the model. In addition, the assumption is made that there are no long-term climate trends within the next twenty years regarding wind and radiation supply and that capacity factors will not change. The latter poses a simplification because an increase in capacity factors may be expected due to technological progress.~~

~~2.5~~2.4 Implementation of cross-border transactions

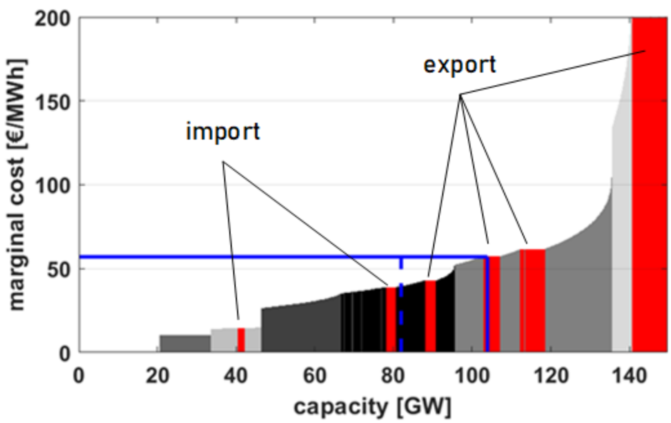
~~The general idea to implement~~When considering the German market, the import and export of electricity is very relevant due to its many neighboring countries and its central location in the increasingly interconnected European power grid. The approach for this paper on integrating cross-border transactions ~~within the given approach is to depict neighbouring~~is to model neighboring countries as single power plants (agents). These agents are assigned individual capacity and dynamic marginal cost so that they can be included into the merit-order plot. The net transfer capacity (NTC) provided by the European network of transmission system operators is assumed to be the technical upper bound for cross-border electricity transfer. Regarding the merit-order plot, this corresponds to the capacity (bar width) of the agent. NTC values for Germany are implemented as given in Table 3. At this state, NTC is assumed to be constant over time for all countries.

Table 3: Cross-border NTC capacities for Germany (entso-e, 2018)

Country	AT	BE	CH	CZ	DK	FR	LU	NL	NO	PL	SE
NTC [MW]	5000	1000	4600	2100	2765	1800	2300	4250	1400	2500	615

In case of the ~~neighbouring~~neighboring countries the NTC can function as both, demand capacity and supply capacity, depending on the current electricity spot price of the country. The spot price is set as the marginal cost (bar height) for ~~neighbouring~~neighboring countries. The bar height ~~of the neighbouring countries~~ determines whether ~~they~~ there is electricity import or export at a certain hour. If the local price of a ~~neighbouring~~neighboring country is lower than the German price, it is assumed that ~~the~~ Germany will import electricity from this country to the extent of available NTC. ~~It~~The neighboring country thereby acts as a supplying power plant. On the other hand, if the local price in a ~~neighbouring~~neighboring country is higher than the German price, it is assumed that Germany will export electricity to the extent of available NTC. In this case the available NTC enlarges the current electricity demand. To estimate ~~local~~hourly prices ~~of~~for the ~~neighbouring~~neighboring markets a simplified pre-simulation for each country ~~must be~~is executed where import and export are neglected. This pre-simulation is based on the current plant portfolio and annual demand of each ~~neighbouring~~neighboring country and thereby also respects its generation mix.

Figure 3(a) illustrates this approach for one hour within the model. The electricity demand on the German market is depicted by the dotted line at 80 GW. Whenever the market price on a ~~neighbouring~~neighboring market is lower than the local price, the ~~neighbouring~~neighboring market is handled as a power plant that supplies electricity for the German market. This applies to the two countries at the left side of the dotted line. When a country exhibits a higher market price than the local price it is assumed to be a potential market for export of electricity. ~~Within the model~~ This means that the actual demand ~~must~~can be extended by the NTC of the according countries. The continuous line at 105 GW shows the resulting total demand that finally defines the price. In this case the German spot price increases due to cross-border transactions, because there are several markets available for export. Figure 3(b) shows an exemplary weekly course of the modelled cross-border transfer. It can be seen that at all times there is import and export at the same time, while in the overall balance there is more export in this particular week.



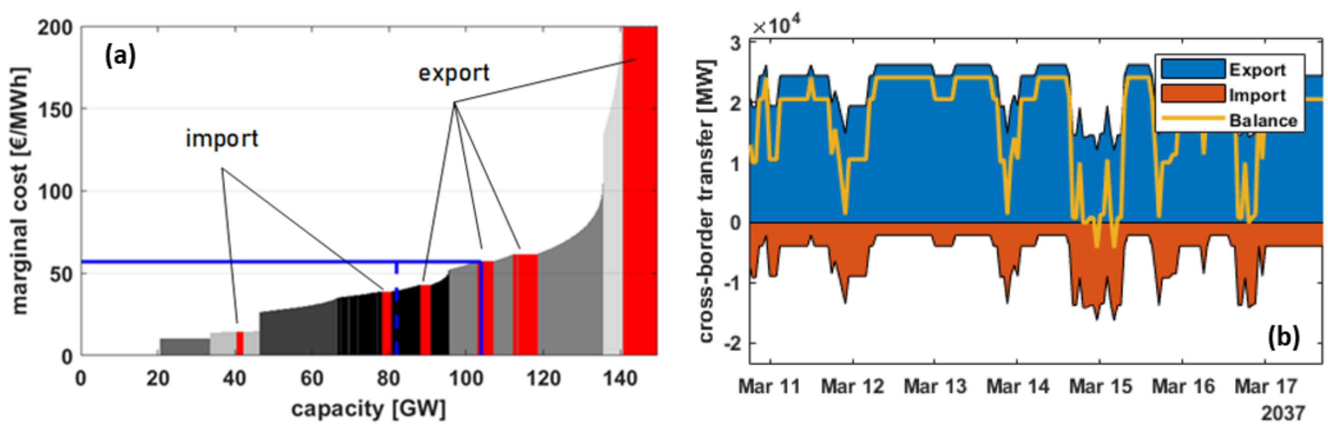


Figure 3: Exemplary merit-order plot from forecasting model with cross-border considerations (a) and exemplary weekly course of modelled cross-border transfer (b)

2.5 Hourly renewable generation capacity and weather time series data

For the implementation of weather-dependent electricity generation technologies such as photovoltaic and WTs, the underlying weather time series data are of fundamental importance. In this paper, the influences of wind speed and solar radiation are assumed according to previous studies of Staffell and Pfenninger (Staffell and Pfenninger, 2016; Pfenninger and Staffell, 2016). The authors use weather data from global reanalysis models and satellite observations to generate synchronized national time series data for solar and wind generation capacity factors for the years 1985 to 2016 at an hourly resolution. This data is also used for commercial application in the dataset PLEXOS World 2015 (Brinkerink and Deane, 2020).

It is assumed that there is no long-term weather trend in terms of wind and solar radiation. To calculate the hourly available electricity generation, the technology specific capacity factors are multiplied with the overall installed generation capacity of solar panels and WTs. In addition, the assumption is made that capacity factors will not change in the future. This poses an underestimation of the available electricity because an increase in capacity factors may be expected due to technological progress.

The influence of the ambient temperature on the electricity demand and spot price was assessed by investigating historic data of the German day-ahead spot price, trading volume and temperature in Germany. Hourly data from 2012 to 2017 has been used and analyzed in terms of correlation (Deutscher Wetterdienst, 2020). Figure 4 shows the results of this analysis in scatter plots with a least square regression line and correlation coefficient r. It can be seen that there is a weak positive correlation (r = 0,1652) between temperature and trading volume and a weak negative correlation between temperature and spot price (r = -0,1270) as well as trading volume and spot price (r = -0,1454). For the given model it is assumed that the electricity demand always corresponds exactly to the trading volume. Under this condition and given the very low correlation coefficients, the assumption is made that weather data and load profile do not need to be synchronized further for the given case. All other weather and climate influences are also neglected within this study.

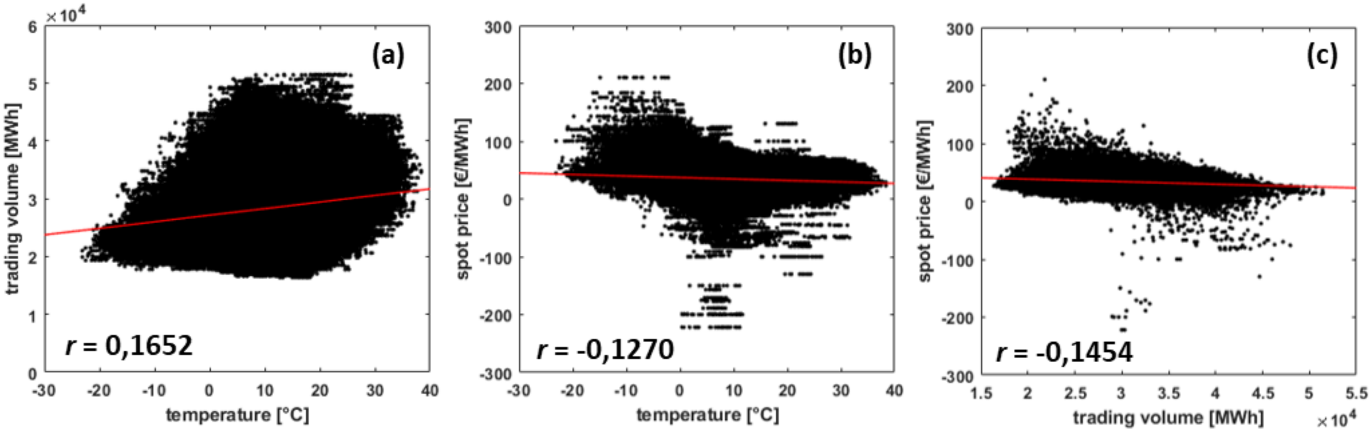
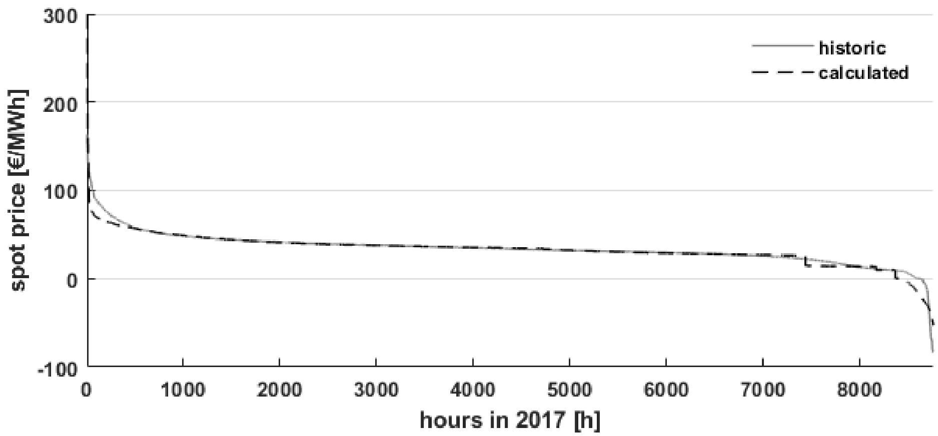


Figure 4: Scatter plots, least square regression line and correlation coefficient *r* for temperature and trading volume (a) temperature and spot price (b) and trading volume and spot price(c) for the German day-ahead market from 2012 to 2017 at hourly resolution

2.6 Model validation

To validate the model, calculated prices ~~for a past year~~ have been compared to actual prices on the EPEX Spot day-ahead market ~~. Since in~~for the ~~past~~year 2017. As Germany and Austria have been a coupled market~~, back testing~~ until 2018, the test has ~~also~~ been ~~done~~executed for both countries together. Figure ~~4~~ 5(a) shows the ordered annual price duration curve for Germany and Austria as well as the prices calculated by the presented forecasting model ~~for the year 2017. The year 2017 has been chosen, because in 2018 the two countries markets have been separated.~~

. It can be stated that the model provides satisfactory results in reconstructing the average price level and price distribution at a mean absolute error of 2.38 €/MWh and root mean square error of 5,8 €/MWh over the course of a year.



The mean spot price varies by 1,87% between historic data (34,2 €/MWh) and model result (34,84 €/MWh). Anyhow, it can also be seen in Figure ~~4~~ 5(b) that the model is not able to fit the actual temporal order of spot prices. Especially the number of negative price peaks during summer is overestimated, leading to an overall RMSE of 20,26 €/MWh between historic and calculated values. Figure 5(c) underlines, that this is the case all over the year. The daily RMSE is in the range of 10 – 20 €/MWh most of the time. In conclusion, the given model results are sufficient when regarding the overall price structure over a year but must not be used for the forecast of exact hourly values.

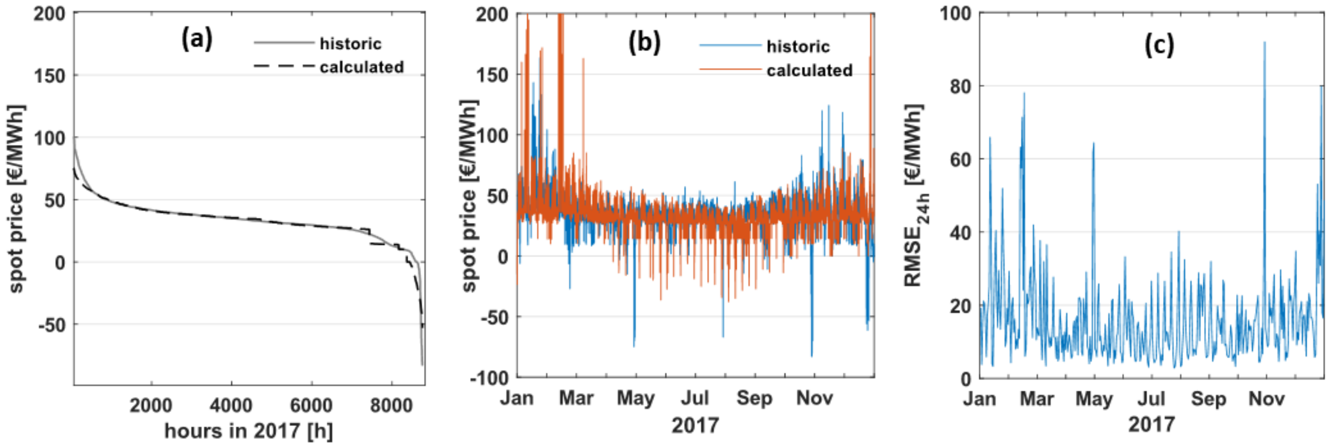


Figure 5: Validation results, comparison of model results against historic values from EPEX Spot for Germany in 2017

The average calculation time for a forecast period of 22 years at an hourly resolution lies at 00:05:11 on a regular home computer without parallelization. In comparison, PLEXOS calculates optimization results for comparable time periods and resolution in several hours, even with parallel computing (Energy Exemplar, 2019).

3 Model application, results and case study

In the following section the forecast market results are being analysed and put in perspective in a brief case study. For this purpose, a measurand for evaluation of model results based on the levelized revenue of energy (LROE) is introduced. In most cases the overall performance of wind turbines (or other generation plants) is evaluated based on the levelized cost of energy (LCOE). The LCOE are defined as the total lifetime cost over the total lifetime energy production .

Since the scope of this paper does not include specific cost but deliberately only market revenue, the commonly used LCOE is no appropriate measure to interpret model results. Instead the levelized revenue of energy based on their discussion by Thomas Baker in 2011 will be introduced . The LROE are understood as the total lifetime revenue over total lifetime energy yield following (Eq. 5) where $W_{t,el}$ describes the quantity of electricity produced in the respective year t and i the calculatory interest rate.

$$LROE = \frac{\sum_{t=1}^{n} \frac{Revenue_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{W_{t,el}}{(1+i)^t}} \quad (5)$$

By using LROE instead of LCOE model results can be evaluated independently from plant specific cost and thereby have a more general character and global applicability. To differentiate between LCOE and LROE, one can assume that the economic efficiency of a WT can be assessed based on three essential quantities: Cost, market revenues and electricity yield. LCOE then considers the cost and electricity yield for a specific case or a specific plant. The LCOE value can be interpreted as the minimum revenue required for an economical plant operation. LROE on the other hand provides information about the market revenue potential as well as given site conditions and electricity yield. The value is therefore not just a plant information, but it also considers the market in which the plant is operating in. The main advantage and difference to the LCOE concept lies in the additional market information. Furthermore, plant costs and associated uncertainties are not included in the measured variable. The latter also leads to a good transferability to different plant concepts. The following must apply for the economic operation of a plant in a given market:

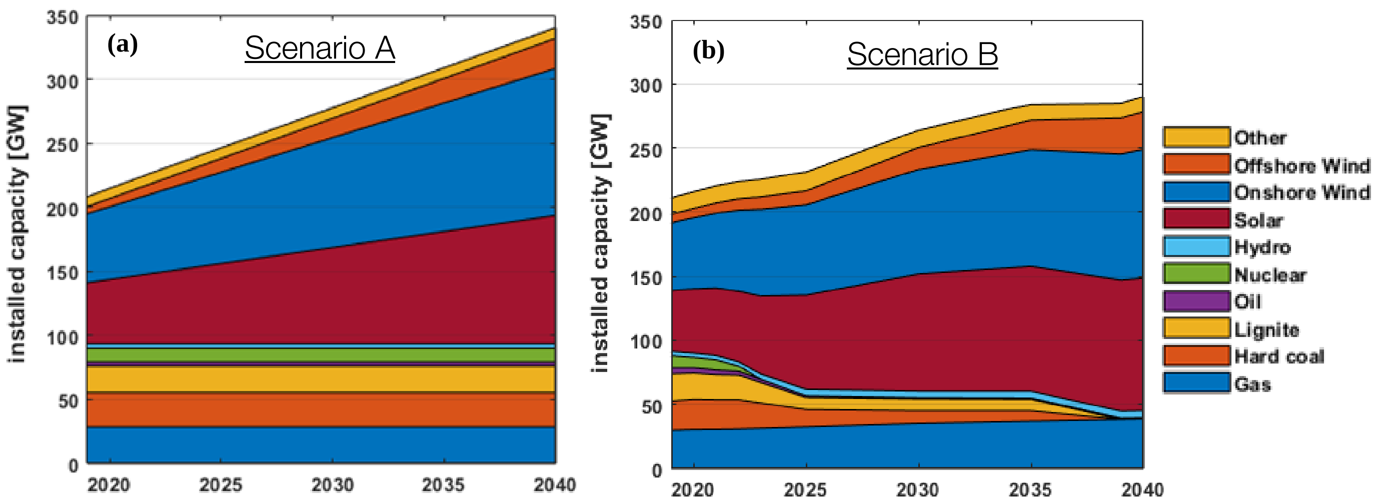
$$LROE \geq LCOE \quad (6)$$

According to this equation, the LROE can be regarded as the expectable constant revenue in a given market to cover the costs of a plant. LROE vary for the same plant in different markets.

3.1 Market results and analysis

An important question which can be answered with this model approach is, how do future energy supply scenarios influence the revenues of wind projects. For this study, two different expansion scenarios are being evaluated for the years 2019 to 2040 (22 years in total). In Figure 5An important question which this research tries to address is, how do different future expansion scenarios influence revenues of WTs. Therefore, the forecasting model described in Section 2 is now used to calculate hourly electricity prices for the German market over the course of the next twenty years. Calculation results will be analyzed in Section 3.1 and finally put into perspective in a brief case study in Section 3.2. For this study, two different renewable expansion scenarios based on German legislation and policy goals are being evaluated for the years 2019 to 2040. Both scenarios are based on the requirements of the Renewable Energy Act and assume that the medium and long-term energy policy objectives of the German government will largely be met. Scenario A represents the increase in the share of electricity generated from renewable energies in gross electricity consumption to 65 % by 2030 as stipulated in the coalition agreement of March 12, 2018 (CDU et al., 2018). Conventional generation capacities are assumed to remain constant in this scenario. Scenario B is derived from the scenario framework approved by the German Federal Network Agency in June 2018 (Bundesnetzagentur, 2018). In addition to scenario A, it includes in particular the phasing out of nuclear power by 2022 and of coal powered plants until 2038 decided by the German Coal Commission in 2019. The forecast lignite and hard coal-fired power plant capacities are based on standardized assumptions on the technical and economic lifetime of power plants. The chosen scenario B follows the basic idea of a moderate sector coupling and a mix of centralized and decentralized structures. It forecasts the development up to 2035. Thereafter, the forecast for gas powered plants and renewable sources is linearly extrapolated for the following five years.

In Figure 6 the overall installed capacity for Germany is shown for Scenario A (renewable energy expansion pursuant to the statutory expansion path of EEG 2017) and Scenario B (additional dismantling of coal and nuclear plants). Mean annual demand is assumed to be constant for both scenarios.



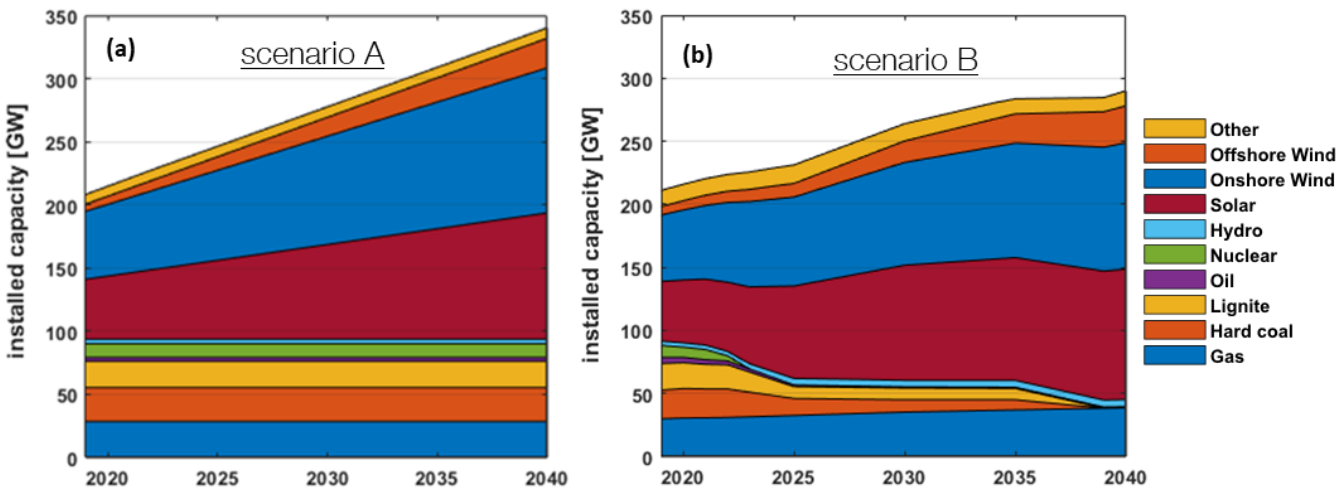


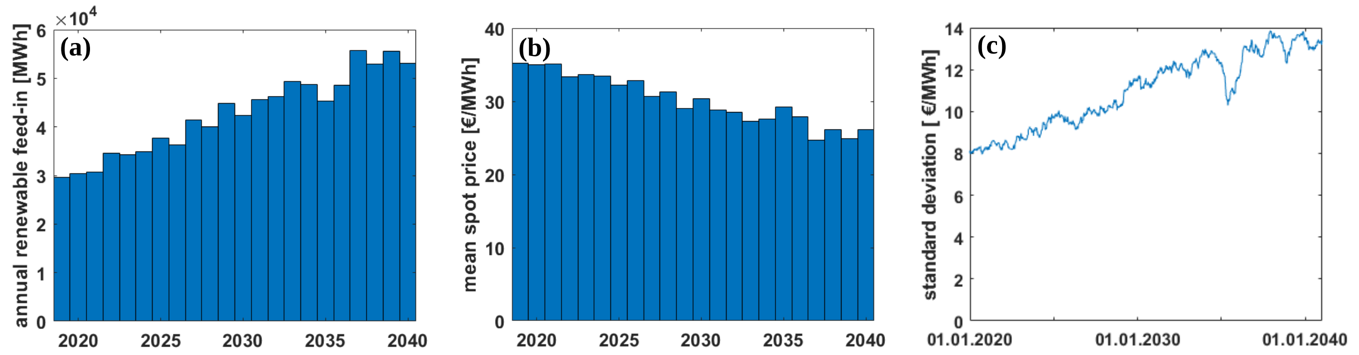
Figure ~~5:~~6: Development of installed capacity in Germany pursuant to statutory expansion (a) and additional dismantling of conventional plants (b)

It should be ~~emphasised~~emphasized that Scenario A with the pure addition of renewables is ~~not~~ a ~~realistic~~highly improbable scenario. ~~Still~~For this study it ~~can be~~is used as a basis for scenario B and to indicate the isolated influence of the renewable energy expansion on the German spot market price. ~~Figure 6 shows~~

3.1 Scenario results and analysis

Figures 7(a)-(c) show the impact of ~~the additional feed~~increasing electricity generation from renewables on the average spot price and price volatility ~~while holding all remaining parameters at a constant level. Comparing Figure 6(a) and 6(b), it is visible that a higher renewable feed-in causes a decrease of the spot market price. As expected, almost constantly falling prices can be observed. The annual fluctuations are merely due to different weather conditions in the individual years. From the wind energy perspective this effect is further amplified at the hourly resolution as low prices occur especially during hours of high wind potential.~~for the given scenarios A and B. Price volatility is represented in Figure ~~6~~7(c) by the floating standard deviation of spot prices at a window size of 365 days. ~~It is clearly observable how additional feed~~

Both scenarios use the same time series data for annual generation from renewables ~~leads to an increasing fluctuation.~~



~~Figure 6: Influence of rising feed from renewables (a) on annual mean spot price (b) and price standard deviation (c) at otherwise constant conditions for scenario A~~

~~In contrast to the hypothetical scenario A, scenario B represents a more realistic future development. Figure 7(a) shows the model results for the average annual spot price for this scenario. In comparison to the previous, hypothetical scenario~~as shown in Figure 7(a). Comparing Figure 7(a) and (b), it is visible for scenario A that the increasing generation from renewables causes a constant decrease of the spot market price. This is referred to as the merit-order effect (Sensfuß et al., 2008). At the same time an increasing price volatility can be observed in Figure 7(c). For scenario B it can be seen in Figure 7(b) how the decommissioning of conventional power plants counteracts the merit-order effect seen for scenario A. Rising prices can be observed for the next five years due to the phase-out of nuclear energy. Prices ~~will~~ then fall until 2035 along the renewable energy expansion and finally rise again with the complete ~~dismantling~~decommissioning of coal energy. In this case the average price level ~~unexpectedly~~ remains ~~roughly~~more or less at a constant level. On the ~~same.~~ other hand, a more strongly increasing price volatility for scenario B can be observed in Figure 7(c). On the example of the year 2035, it is clear to see how reduced generation from renewable sources leads to an increase in price and decreasing price volatility. In reality, this could be the case e.g. in a weak wind year.

~~In addition to considering the two expansion scenarios,~~

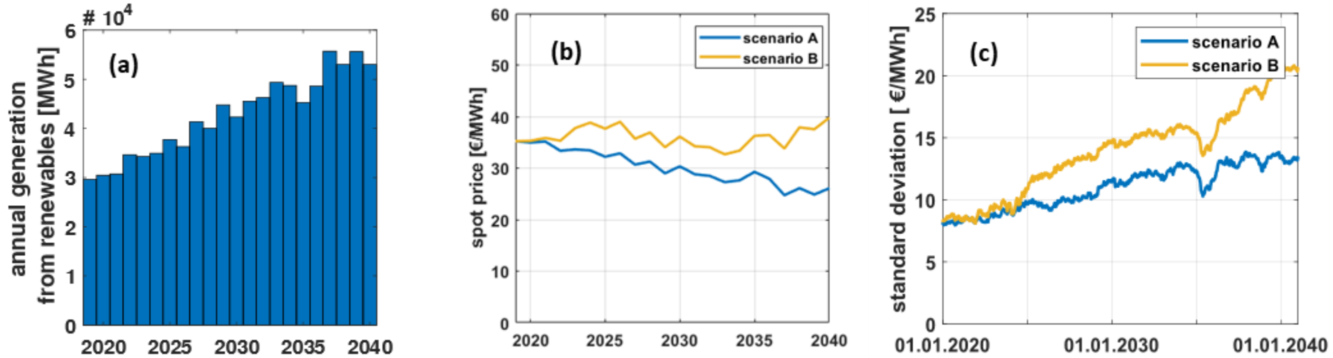
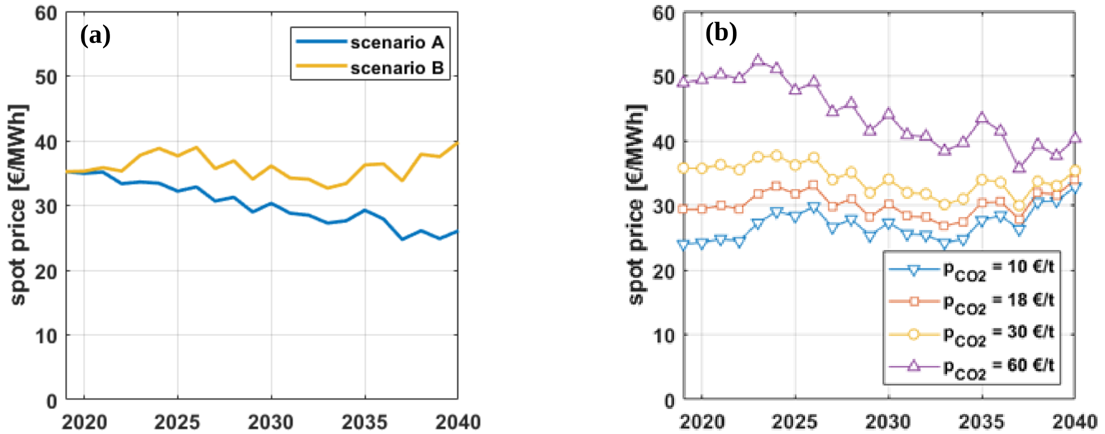


Figure 7: Influence of rising feed from renewables (a ~~variation in~~) on annual mean spot price (b) and price standard deviation (c) at otherwise constant conditions

A sensitivity analysis for the CO_2 price ~~for Scenario B~~ is ~~also~~ investigated~~.~~ on top of both scenarios A and B. Four different specific prices are ~~respected~~analyzed, namely 10, 18, 30 and 60 €/t. Figure ~~7~~8(a) and (b) ~~shows~~show the corresponding results and sensitivity of spot prices against the CO_2 price. It can be observed how an increased emission price leads to higher mean spot prices. This influence becomes stronger the more conventional plants ~~operate within~~are active on the market. The converging lines in Figure ~~7~~8(b) along the expansion shown in Figure ~~5~~6(b) ~~emphasizes~~emphasize this relation. ~~For Scenario~~ A~~, a constant CO_2 price~~ minimal taper of the curves is ~~assumed at 18 €/t~~also shown in Figure 8(a). This is due to the fact that even without the decommissioning scheme, renewable energies are pushing conventional power plants out of the market.



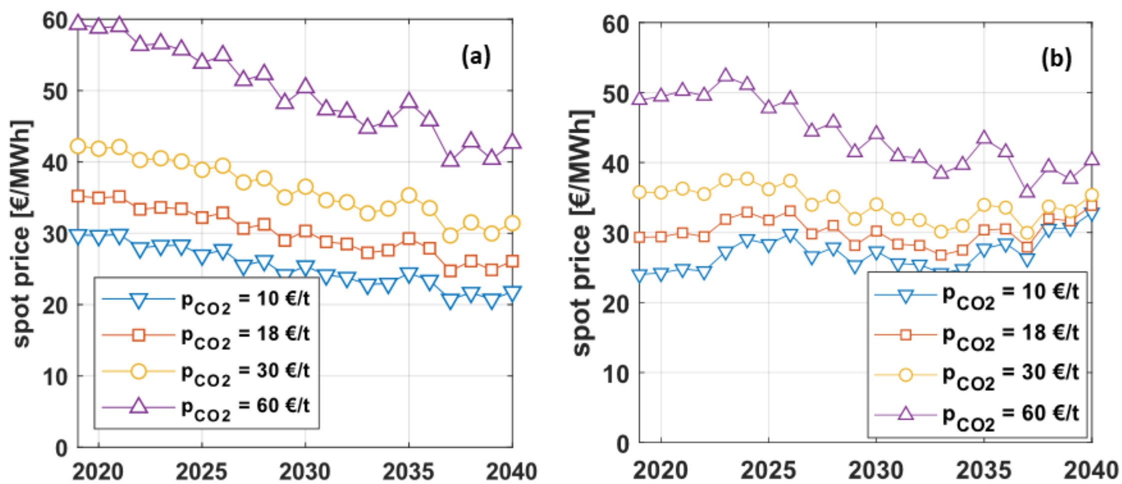
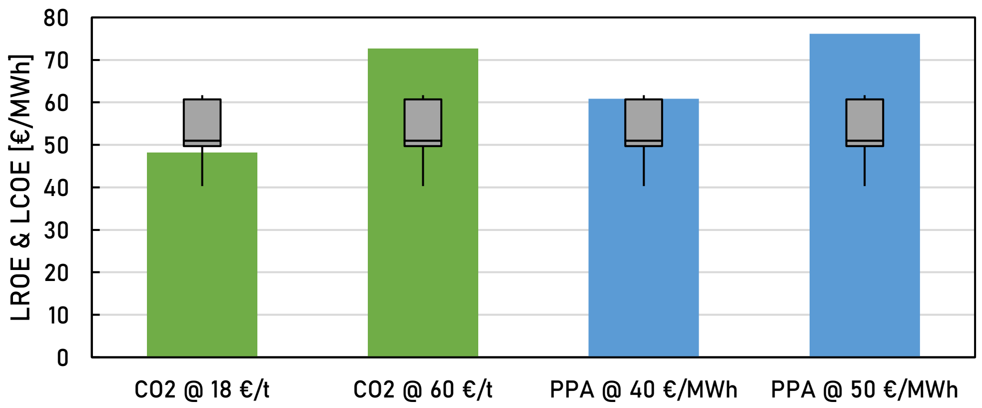


Figure ~~7: (a) Mean annual German spot price for the evaluated scenarios at 18€/t emission price; (b) Calculated~~ 8: Mean annual spot price in Germany for scenario A and B at different CO_2 prices

3.2 Case study observing a small onshore wind park in Germany

The applicability of The model results for wind energy related investment considerations shall be demonstratedare used to evaluate the potential revenue of WTs in a brief case study. Therefore, hourly SCADA data of a German wind park with 5 turbines of the 3 MW class with average full load hours of 1920 h/a has beenwas used. Potential market Following Section 1.3, the commonly used LCOE is no holistic measure to assess revenue has beenpotential and overall profitability of WTs. Instead the LROE as introduced by Baker in 2011 will be used. The modelled hourly prices from the merit order approach are used to determine the time course of the revenues needed to calculate the LROE.

Revenues from selling electricity are calculated based on the extrapolated SCADA data and the modelled spot price forecast over the course of the next twenty years. Figure 89 shows the LROE of the wind farm investigated for direct marketing and expansion scenario B withwind farm at two different emission prices (orange bars). Finally, the18 and 60 €/MWh) for both scenarios. These results are compared by LROE to market revenuepotential revenues based on hypothetic PPAs with different base prices. The LROE for marketing usingMendicino et al. propose that feed-in tariffs of corporate PPAs with different purchase prices are also shown by Figure 8 (blue bars). The two prices quotedover 7 to 10 years should be in the range between 75 €/MWh and 100 €/MWh (Mendicino et al., 2019). For this study are fictitious. They can be understood as if e.g. the WT operator prepares possiblea lower range of base feed-in tariffs is assumed because of the longer time span (40 €/MWh – 50 €/MWh). In the constructed case, electricity sold during times of spot prices below the base price concepts prior to will be remunerated with the respective base PPA price negotiations and compares these with various exchange price scenarios for valuation purposes.. In order to assess the profitability, the results are then compared to current estimates of the LCOE of onshore wind turbines in Germany (Kost et al., 2018; IWR Online, 2019; Wallasch et al., 2019). These are shown in Figure 89 as green box plots.



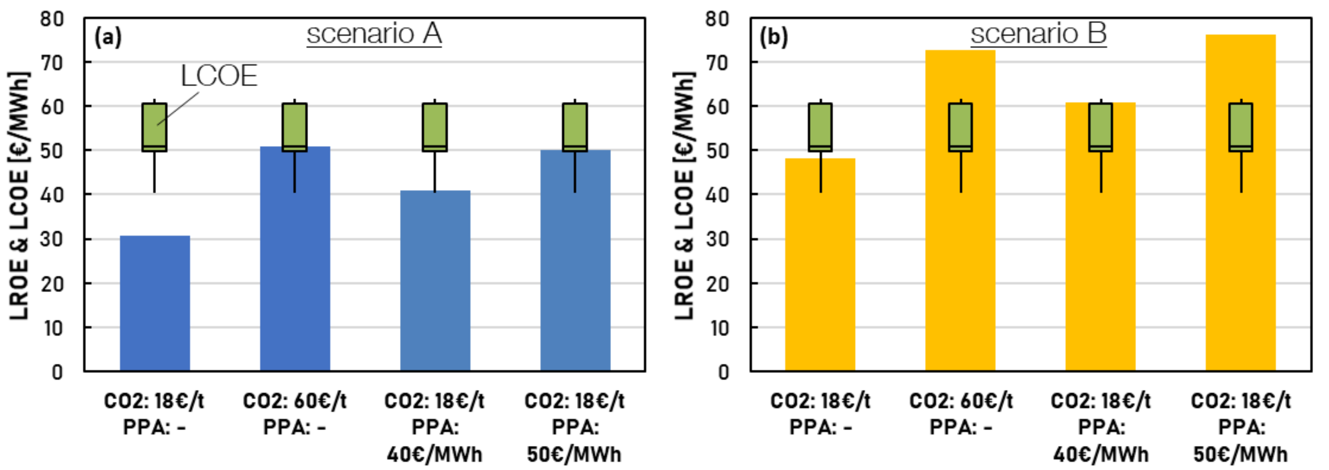


Figure ~~8~~9: LROE of the observed wind park over 22 years at different emission prices ~~for expansion scenario B (orange bars)~~ and different PPAs ~~(blue bars)~~ compared to currently estimated LCOE of onshore WT in Germany (green box plots) for expansion scenario A (a) scenario B (b)

On the one hand, it can be ~~stated~~seen that in the event of higher electricity exchange prices, higher revenues can be expected ~~from direct marketing (orange bars).~~for all cases. Furthermore, it can be observed that for this particular case, the chosen PPAs do not necessarily ~~lead to higher~~guarantee profitability. However, the lower revenues ~~than direct marketing on the electricity exchange.~~ from PPAs should always be evaluated against the background of the ~~great uncertainty at the electricity market this should be evaluated critically~~equally lower risk.

~~In accordance with Eq. (6) it is visible that most~~For the results as shown in Figure 9, many turbines will not be profitable without subsidies for ~~the current case of~~ all cases in scenario A and for scenario B at emission prices ~~at~~of 18 €/t ~~because~~without PPA. For these cases the range of LCOE lies mostly above the LROE. For the other three situations most or all turbines would be economically ~~efficient~~profitable.

3.3 Conclusion

~~Different conclusions can be drawn from the above chapters. First, it can be shown based on~~ The model ~~presented in Sections 2.1 to 2.5~~application and ~~its validation in Section 2.6 that forecasting~~ corresponding results show that it is possible to forecast electricity exchange prices ~~, which are suitable for investment considerations in WTGs, is possible~~ with the presented model at comparatively low data requirements and ~~low~~ computational costs. ~~Furthermore,~~The model results can be used for the derivation of development goals in terms of LCOE and deliver the necessary values for break-even consideration in terms of cost reduction or annual energy production.

Influences of renewable energy expansion and the decommissioning of conventional power plants on the mean spot price can be shown in two calculation scenarios in Section 3.1. The model results in Figure ~~6a~~ 7(a)-(c) show that for scenario A, a pure expansion of renewables ~~would~~could lower the electricity price in Germany by 10,98 €/MWh (-31,2 % compared to 2019) and increase its standard deviation hence volatility~~.~~ by 5,36 €/MWh (+67 % compared to 2019). In addition, ~~Figure 7a shows~~results for scenario B show that the ~~forecast~~forecasted expansion of renewables in Germany, in conjunction with the coal and nuclear power phase-out, ~~could on average~~can lead to roughly constant exchange market prices ~~with~~and increasing volatility~~. Figure 7b also shows~~ by up to 12,37 €/MWh (+151 % compared to 2019). Figure 8(a) and (b) show that the pricing of emissions in the coming years will have a strong influence on the exchange price~~, as long as many conventional power plants are still on the grid.~~. This effect will decrease as ~~fossil power~~more and more conventional plants are ~~increasingly dismantled~~being decommissioned. Overall, the level of ~~a CO_2 price~~emission prices in the next 20 years has a very strong influence on both the exchange price and the profitability of non-~~subsidised~~subsidized WTs. Figure ~~8~~9 shows that at a CO_2 price of 18€/t most of the onshore wind turbines in Germany could not be operated without additional funding. Regarding the evaluation of revenue potential, LROE, as presented in Section 3, has ~~proven~~shown to be an ~~interesting~~appropriate benchmark for evaluating market developments. By using LROE instead of LCOE model results can be evaluated independently from plant specific cost and thereby have a more general character and applicability. Just like LCOE, LROE can be used to define and evaluate technical and financial development goals for engineering. Moreover, ~~they allow~~it allows a consideration detached from plant costs and can be used both in the negotiation of ~~alternative sales models such as~~ PPAs or as a benchmark for policymaking, for example in determining a suitable CO_2 price~~, as shown in Figure 8. The~~. Today, subsidies in the form of the tendering procedure generally follow the LCOE. ~~Accordingly,~~ A funding which considers the LROE for different technologies ~~would~~could be a more holistic approach and a more indirect technology support.

4 Discussion and outlook

In ~~the present~~this study a new forecasting model has been presented that estimates future electricity exchange prices for Germany in order to conclude on potential ~~revenue~~revenues of non-subsidized ~~wind turbines. The~~ WTs. Prices are calculated at an hourly resolution over 22 years. Historically, this used to be a rather unusual combination. However, the necessity to consider the dynamic electricity ~~spot price is calculated~~ generation characteristics of wind and solar energy has become more common in recent years and state-of-the-art models as described in Section 1.2. The given model is using a ~~modified~~ merit-order ~~concept by extension~~approach in combination with a simple multi-agent approach for ~~every hour of the time period under consideration.~~

conventional power plants. The latter allows to integrate neighboring countries and cross-border electricity trading. The developed model is constructed ~~deliberately~~comparatively simple with many assumptions being made. This leads to low data requirements~~, mainly~~ based on open source data ~~to allow unproblematic~~and allows easy adaptation ~~and modification, which is often described as a disadvantage of~~ on the one hand. Compared to modern complex optimization models~~. Despite the model's simplistic design, very satisfactory solutions can be obtained in terms of model evaluation and back testing for Germany. Due to the high resolution of hourly prices, a detailed analysis of daily price developments is possible~~ this may be advantageous. On the other hand, the model assumptions also cause less accurate results and narrow the possible field of application.

~~The model results are suited for revenue estimation of~~ To validate the model results, historic prices of the German day-ahead market of 2017 have been compared to model results for the same year. The annual ordered price duration curve was reconstructed at a mean absolute error of 2.38 €/MWh. Anyhow, because of the simplifying assumptions regarding electricity demand and weather data synchronization it is not possible to forecast the exact temporal course of prices by the hour. For future work it is planned to benchmark the given model results in terms of accuracy against state-of-the-art models like PLEXOS or Balmorel. Even if the model results lag behind proprietary solvers in terms of result quality, the results can at least serve as a first estimation and comparison value that can be generated within a few minutes.

The two scenarios discussed in this study are solely developed from current German policy goals. Especially scenario A is very unlikely to actually happen. Further, more sophisticated expansion scenarios for Germany and other European countries that also consider long-term electricity demand trends should be simulated. The scenarios from the IEA World Energy Outlook and the Ten Year Network Development Plan 2020 by ENTSO-E are currently being considered for this purpose.

A major limitation of the model lies in the neglect of national grid capacities. Grid bottlenecks are already posing major challenges for the expansion of renewable energies today, for example when considering the integration of offshore wind ~~turbine marketing models that orient by electricity exchange markets like EEX/EPEX.~~energy. This strong simplification should be improved in subsequent model extensions. The given model also needs further improvement to overcome current limitations. During future studies, the model shall be extended by implementing dynamic time series for the currently constant parameters like emission and fuel prices as well as cross-border capacity and average electricity demand. Also~~, it enables comparison of new business models like PPA against direct marketing. Therefore, the results can be e.g. used during negotiation of contract conditions and thereby strengthen the position of wind farm operators.~~

~~On the other hand, the model results can be~~ finding rules for synchronizing the weather data used ~~as reference at derivation of development goals and LCOE. In this context the model delivers the corresponding break-even values at considerations like cost reduction, increase in reliability or annual energy production.~~

~~The presented model could be particularly useful in conjunction with energy~~and the electricity demand time series might yield ~~prognosis models. During the planning phase, it could be used~~further improvement of the model results. Finally, the agent-based approach could be further developed by introducing randomness as well as learning rules for agent decision making. Further model application is also planned in combination with planning and optimization tools such as the wind farm optimizer WIFO to generate a more reliable economic yield prognosis in addition to the energy yield prognosis.

~~During further studies, the model shall be further extended, e.g. by implementing dynamic time series for economic parameters like emission and fuel prices. Also, additional expansion scenarios for Germany or other European countries could be simulated.~~

~~Finally, the above leads to overall reduced investment risks and therefore supports wind energy and its expansion. This in the end is a supportive step towards an ecologic electricity supply~~WIFO is an optimization tool that calculates wind farm layouts based on LCOE minimization and maximization of annual energy production (Roscher et al., 2018; Roscher, 2020).

Acknowledgements

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