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The impact of renewables on the incidents of negative prices in the energy spot markets

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ABSTRACT

In this paper we analyze the impact of growing renewable energy generation on the instances of negative day-ahead auction prices. We perform a simulation that is based on the real-world day-ahead wholesale supply and demand curves from the German-Luxembourg coupled market to gain insights about which developments in instances of negative market clearing prices could be expected in the short to middle term period with more intermittent energy in the system. This is achieved through transforming the real-world supply curves to include more renewable generation and recalculating the market clearing prices. The results of the spatial analysis suggest that keeping the strong fiscal support for renewables, auction design, and marginal cost bidding in place unchanged would gradually lead to more instances of negative prices in the coming years. Conclusively, we discuss the implications of the observed phenomena on the energy policy.

1. Introduction

Negative prices are a phenomenon that goes against economic intuition behind optimal allocation of goods, especially when they occur at the auctions as according to the auction theory any good should be allocated to wherever it is most valued. Nevertheless, in the real world we do observe instances of negative prices, and this has been an increasingly noticeable phenomenon in the energy sector (Fig. 1). In Germany, negative market prices on the spot power markets have been allowed since 2007 in order to perform a signaling role for promoting a need for flexibility of supply among the generation technologies. During that time, shares of renewable generation were still insignificant at the system level and the negative price instances were rare. However, as the renewable energy generation is gradually becoming an important influencing force in the power markets by approaching high expansion rates with accordance to the EU's long-term decarbonization plans, we can observe more frequent instances of negative power pricing on the spot markets. In 2020, 38% of EU's power generation came from renewable sources. From 2010 to 2020 the share of renewable generation of wind and solar in Germany has increased from 8% to 32.7% (Agora Energiewende and Ember, 2021, p.4). The renewable expansion will continue to increase in the nearest future as the EU alongside with the USA and China have just conducted policy shifts to achieve carbon neutrality earlier - by 2045 instead of 2050 in the specific case of Germany (Prognos, Öko-Institut, Wuppertal Institut, 2021). Yet, to achieve the EU2030 climate targets, the buildup of wind and solar capacity must triple (Agora Energiewende and Ember, 2021, p.4). A major role in achieving that will rely on the nuclear and coal phase-out and a proportional buildup of renewable generation capacity at the same time.

First instances of negative prices were recorded on the German intraday markets back in 2007 (Aust and Horsch, 2020). There were 97 cases of negative prices on the spot markets in 2013, and by 2022 they were expected to become a rule rather than an exception due to high renewable energy generation (Götz et al., 2014). The surge in the renewable energy sources (RES) generation in Q1 2020 has driven spot prices to record lows, slightly stepping into the negative values area. In Q1 2020 alone there were 128 cases of hours with negative prices, thus representing a 50% increase YoY from 2019 (European Commission, 2020), see Fig. 1. According to the EPEX SPOT data, there were 238 h with negative MCPs in 2019 and 298 in 2020 on the day ahead (DA) auctions in Germany alone.[1] One of the factors that has catalyzed the occurrence of this phenomena even further, were the restrictions caused

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[1] The combined events described earlier have resulted in negative prices occurring on the DA markets in countries where they typically do not happen, i.e. with a rising photovoltaic penetration in the grid – such as France, the UK, the Netherlands, and for the first time on record in Sweden and Finland (European Commission, 2020).

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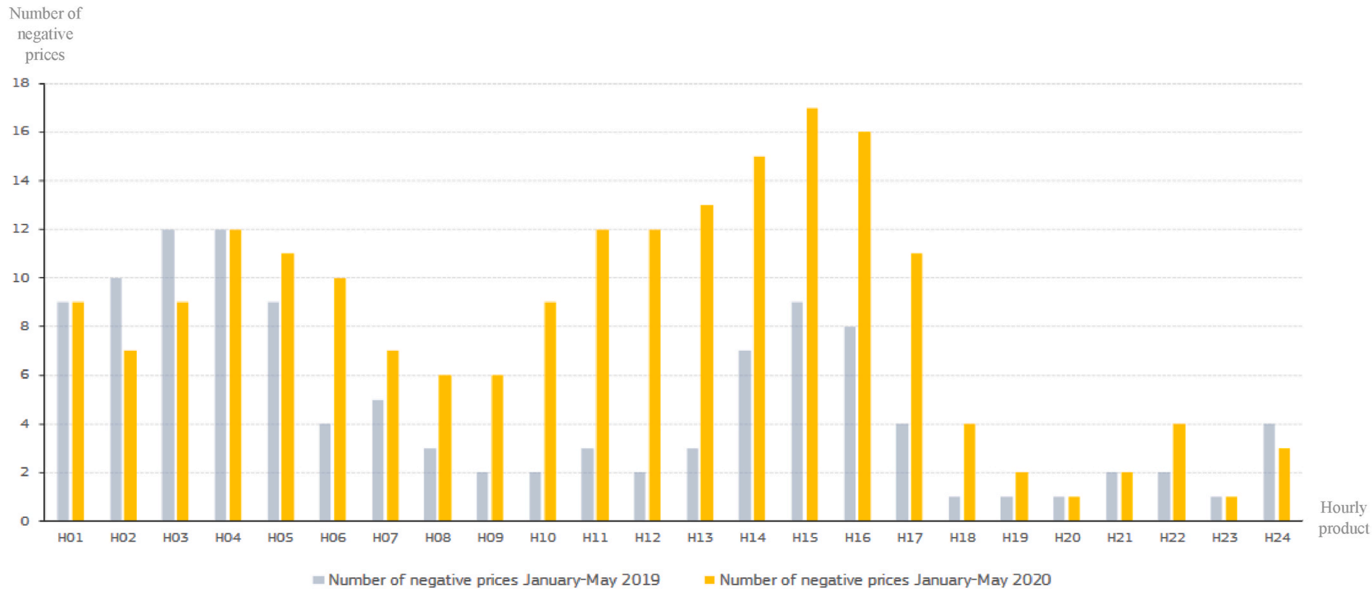

Fig. 1. Occurrence of Negative Hourly Prices in DA market in Germany. Source: (European Commission, 2020).

by the COVID-19 pandemic. This has led to an observable short-term negative demand shift for energy as industries had to curtail production which played a role in amplifying the negative price frequencies in 2020. Since the majority of the renewable generators in Germany is subsidized, lower prices on the day ahead markets lead to an increased need in additional resources to be collected via green levies from the consumers' side to guarantee the revenue levels for the generators. According to the report by the European Commission (2020), this has resulted in a negative account balance of 1.9bn Euro in the Q1 and Q2 of 2020 thus leading to the need for increasing levies in the future to cover the financing gap.

The latest developments in the system prices are extraordinary. Currently high electricity prices are caused by a combination of the production mix metamorphosis and the geopolitical situation in Europe. Increased energy generation costs, increasingly higher taxes, and adjustments in surcharges are reflecting these changes. By phasing out coal and nuclear generation, the system becomes more reliant on the renewables (VRE-dominant in Germany) and gas. Changes coming to the procurement of gas in Germany (switching suppliers) and its still low diversification of the gas imports also results in extremely high marginal generator costs on the DA markets. Our paper shows the future development of the DA auction MCPs in the medium-term perspective assuming the status quo in the regulatory framework. Despite a short decrease in the negative price instances on the DA market in 2021 (139 h priced negatively according to Statista (2022)), current extraordinary events rather contribute to the growing concerns regarding the market design by showing the other side of the medal that can be occurring interchangeably with the high frequencies of the negative MCPs. In the hours with the high levels of intermittent generation, the supply is enough to cover a big share of the short-term demand and thus the prices for electricity converge towards the lower marginal costs of the renewables. In the opposite scenarios, when the weather conditions are unfavorable for the intermittent technology generation, the demand must be covered with more reliable conventional generation that features increasingly higher marginal costs due to rising CO2 fees and fuel prices.[2] One of the cases when negative prices usually arise is in the times of a lower demand level with a simultaneous oversupply of energy. Conventional generators decide on the pricing depending on their flexibility and the costs of shutting down and ramping up as compared to incurring short-term sales at negative prices. If the estimated losses from paying for their energy to be bought are lower than the costs of restarting the generator, then in order to minimize losses the energy will be offered at negative prices. This may also occur as some of the generators have contractual obligations to run during the times with negative prices.

Being in a phase of increasing momentum of renewable energy transition, the question inevitably arises whether this will fortify the negative prices phenomenon. Continuous reduction of market clearing prices makes covering total costs of conventional energy producers challenging and consequently decreases their supply which on the one hand fits well to the phase-out plans for conventional generation. On the other hand, this reduces stable capacity generation which may expose electricity markets to more uncertainty and volatility, especially in the cases like Germany which achieves RES buildup plans mostly through wind and solar capacity. Moreover, reports suggest (Agora Energiewende and Ember, 2021, p.4) that renewable capacity buildup is still not enough to cover the gap from the nuclear and coal phase-out entirely. Higher degrees of renewable energy require higher flexibility both on the physical grid and on the markets. As stated above, the current high price level is not sustainable from the social welfare perspective, and it only increases the burden for private and commercial consumers who are already carrying the load of the green taxes and charges that are fueling the renewable transition. Indeed, extremely high electricity prices can temporarily move previously infeasible storage technology to the list of the current options or make some conventional generators well profitable. But significant projects like adopting storage technology at scale would take years to be implemented and cannot be decided ad-hoc and solely based on the temporary exogeneous macroeconomic nature of the current high electricity prices. Again, electricity should not be a luxury good – it must be an affordable

[2] Such a case could be observed in Q4 2020 in Central Western Europe where the monthly average price has increased by 9% and 21% (European Commission, 2020) for baseload and peak load correspondently. Hence, higher degrees of renewables induce higher volatility to the markets and also impose bigger challenges to the transmission system operators that are balancing the grid.

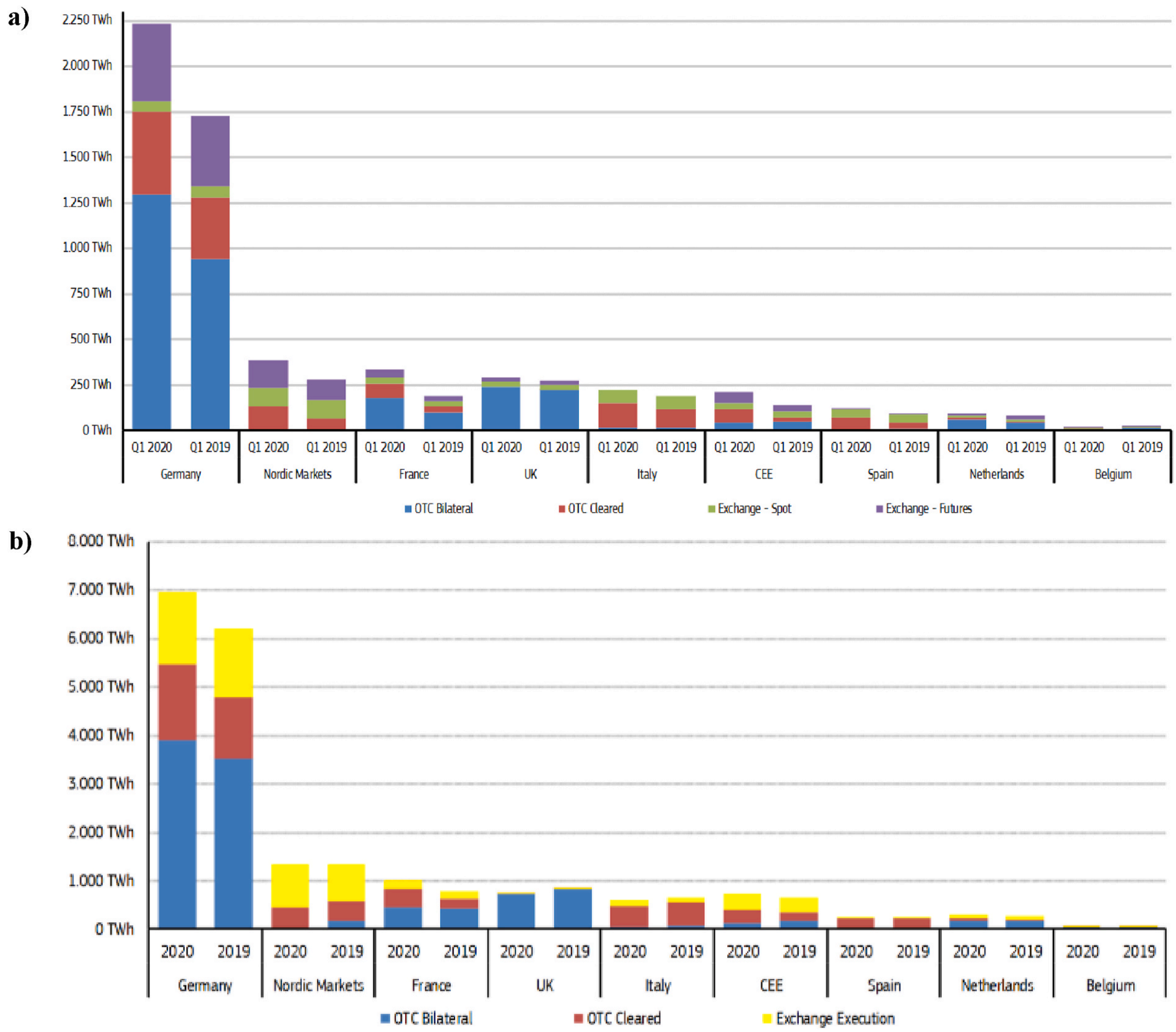

Fig. 2. Changes in traded volumes in the most liquid European electricity markets **a)** Q1 2020 vs Q1 2019, **b)** years 2020 vs 2019. Sources: (European Commission, 2020), (European Commission, 2021a).

commodity. Therefore, there is a need for further investigation of negative prices as this may be one of the early signals for market design inefficiencies and market anomalies.

This paper is organized as follows: section two gives an overview of related literature in the field of day-ahead power market auction prices, bidding behavior, and power market design. Section three introduces the regulatory framework, the data set and the simulation model used to investigate the negative prices' occurrence in the years 2019 and 2020. Section four presents the results of the simulation. Section five concludes with a discussion of the findings and policy implications.

2. Literature review

The latest developments in the research field indicate the growing need for adjustments in the structures of spot power markets. Different options of electricity market design are discussed by Cramton (2017), as well as Tanrisever et al. (2020), Chyong et al. (2019). Cramton (2017) discusses the electricity market design that would satisfy short- and long-term efficiency requirements while promoting investments in renewable capacity. Options to reduce the share of fossils such as the effect of a CO2 tax and the lack of capital investments in renewables are discussed by Chyong et al. (2019) in their literature survey. This is further expanded with the discussion of aspects of price building and the impact of the use of emission licenses. Tanrisever et al. (2020) provide evidence of the lack of empirical proof in market optimization. Aklin (2021) contributes by investigating social acceptance of renewable transition in the hindsight of the heavy fiscal support that is associated with achieving renewable transition goals. The study suggests that fueling the renewable transition through increasingly higher non-VAT taxes on the consumers side may hinder the social acceptance of achieving green energy goals. This consequently questions the political and economic feasibility of the regulatory framework medium. The Fraunhofer IEE and ISE (2021) investigate the adjustments in the current body of regulation that must be made to enable efficient renewable transition. It is argued by Blazquez et al. (2018) that under the current market architecture transition to a completely renewable energy supply is unattainable.

In the domain of auction design, concerns of efficiency of auctions are developed by Deb and Pai (2014) who demonstrate that under circumstances of additional properties and restrictions of the auctions, stemming either from the market environment or from intentions of the players, it may appear impossible to implement an optimal auction. However, despite efficiency concerns, in practice auctions have proven to still be cost-efficient mechanisms for goods allocation, especially in the power markets where multiple homogeneous goods are traded as shown by Klessmann et al. (2015). A general discussion on the auction design and clearing approaches in the context of electricity markets is provided by Zalzar and Bompard (2018) and Csercsik (2020) with Csercsik further covering game theoretical approaches to power auction designs via comparing alternative methods for price determination. He also demonstrates potential welfare gains through auction redesign. Zalzar and Bompard (2018) state that a successful market-clearing model must ensure profitability for participating companies and conclude that mid-term support for conventional energy suppliers will be needed. Hirth (2013) as well as Brownand Reichenberg (2021) discuss the developments in the market value of the VRE as their market share grows. The different ways of overcoming the drops in the market value of VRE are assessed.

Bidding behavior of the market players can distort efficiency of the market design. Deng et al. (2015) discuss the incentives the current market design gives towards negative price bidding. The behaviour of marginal cost bidding in power auctions and associated congestion risks are confirmed by Mills et al. (2020) for the US. Hildmann et al. (2015) investigate market distortions coming from the feed-in tariffs (FiTs) and provide evidence that without the feed-in tariffs and under the true marginal costs bidding the instances of negative prices can be reduced. Tesfatsion (2009) discusses deviations in power market auctions from the assumptions of the Revenue Equivalence Theorem in the context of using different bidding strategies. Additionally, under the conditions of lowering average MCPs, non-subsidized generators strive for finding new ways to remain solvent via deployment of new bidding strategies and arbitrage, which can send misleading signals to the markets.

In the electricity prices domain during the last decade, the condensation of research efforts from the economic perspective of electricity markets has been primarily on the topics of intraday and day-ahead price forecasting with recent approaches covered by Kulakov and Ziel (2021), Aust and Horsch (2020), Ziel and Steinert (2016), and Poplavskaya et al. (2020). In a recent research-synthesis and meta-analysis, Sovacool et al. (2021) address the issue of the integration of energy production externalities into the wholesale energy prices, as they are currently not reflected in the electricity prices and impose increased fiscal pressure. Barbour et al. (2014) have found out that more frequent negative prices allow for a more profitable arbitrage by efficient energy storage. Aust and Horsch (2020) identify correlations between the higher levels of renewables and negative prices frequency on the spot markets (continuous trade), although they report that no potential for market failure is identified. A recent study by Kulakov and Ziel (2021) conclude that errors in renewable energy forecasts have non-linear effects on the intraday prices and additional PV and wind generation changes the intraday price volatility.

As the European power markets are now reaching higher degrees of digitalization, automation and renewable generation and as more novel business models featuring prosumer markets, smart grids, and decentralized generation are emerging, it is a suitable time for introducing adjustments to the existing structures in the spot power markets to enable efficient achievement of the long-term climate goals. It seems like developments in the signals such as negative market prices have not earned the attention they deserve. Therefore, in our analysis we aim to identify the impacts of higher rates of renewable generation on the day ahead auction results in terms of negative prices.

3. Current electricity market framework

According to the Target Model formulated in 2009 and adopted by the European Commission (2017), wholesale electricity procurement in Europe occurs either on the power exchanges or pools (futures and spot markets), or through the over-the counter trade (OTC). Forward markets are linked with prices to the DA and ID spot markets while being supported by the Balancing Services and Capacity markets for ensuring the network stability. Even though most of the energy is traded via the OTC or forwards markets (European Commission, 2021a) (Fig. 2), spot markets play an important reference role for pricing of the energy. The extent of use of the exchanges, OTC, and forward markets are due to local differences of the countries in terms of transaction costs and body of regulation (Danish Energy Agency, 2018, p.19).

As a part of the conducted harmonization process between the national European power markets, electricity is sold on the power exchanges as standardized "products" within each price area. A DA auction for electricity is a sealed-bid multi-object uniform-price auction cleared in a single-joined instance that is carried out daily in Europe. In Germany the DA auction is conducted and cleared by the EPEX SPOT exchange that is currently using the EUPHEMIA clearing algorithm for that (see details in (NEMO, 2020)).[3]

Bidding behavior of the market participants generally depends on their capacity, quality of their forecasts, total and marginal costs of production. Marginal costs are the main basis for bidding energy, it is zero or near-zero for the intermittent sources and is significantly higher in cases of the conventional generation as their variable costs are further inflated by increasing CO2 quotas. The clearing is done by the clearing house that is constructing the merit order curve (supply curve) and the system marginal cost (system lambda) becomes the uniform market clearing price. The merit order is an approach, from the perspective of the market operator, according to which when creating the production schedule, the generators with the lowest marginal costs of production are selected. They are then arranged in an ascending order until the intersection with a usually inelastic demand curve is reached. Originally, the shares of intermittent energy were comparatively low to the conventional generation, hence, despite the zero-price bidding by the wind and solar generators, the MCPs were still high enough to guarantee an inframarginal rent to all the generators except the marginal plant. As the rates of renewable generation are approaching 40% in Germany, in the situations with stable intermittent generation, the average MCPs reduce, except for the cases with unfavorable weather conditions that stall PV and wind generation as it could be seen in the Q4 2020 – Q1 2021. This has evidently led to the adjustment of the bidding strategies among the market players, as stated by Deng et al. (2015), as the generators that are receiving subsidies become more willing to step into the negative price area in their bids to increase chances of being cleared. Moreover, given that generators are usually active on the OTC and futures markets, this allows them to hedge short-term negative price exposure (Redl and Pescia, 2016).

One of the key aspects in harmonization of the European power markets is mutual integration of the national physical grids. A more robust interconnection network has the potential to reduce volatility on the separate domestic markets and reduces the need for investment into the peak generation capacity. As a result of the multi-regional coupling (MRC) initiative, some of the regions have already achieved high degrees of interconnections, such as Germany-Luxembourg being a single power price zone.[4] However, there are still situations in which bottlenecks in the cross-border transmission system capacity pose limitations to the physical transition of the energy and thus lead to curtailing of excess volume ordered.

A cross-border capacity expansion may affect electricity prices in two ways. If countries become a joint bidding zone like Germany and Austria

[3] Registered participants (164 for Germany) must submit their bids in terms of volumes and prices for the 24 hourly products of the next day. The maximum and minimum price boundaries are 3000€/MWh and −500€/MWh accordingly with price and volume ticks of 0.1 MW and 0.1€/MWh. Market participants must submit their bids by 12:00 CET, which will allow the clearing houses of the market operators in the pricing zones to determine the MCPs and pass on the results to the TSOs to validate the DA schedule, based on the grid's available transmission capacity.

[4] Germany is already trading energy with 9 neighbouring countries, predominantly exporting. In 2021, for instance, Germany had a negative net export account (based on the physical flows) with Denmark (3.9 TWh), France (5.6 TWh) and Norway (3.2 TWh) (SMARD, 2022), while a positive one with the rest of the trade partners.

were before 2018, then the shape of the aggregate curves could be transformed according to the fundamentals of each country's power generation and consumption profiles. For example, in Norway the major share of the RES electricity is coming from the hydrogeneration – 93.4% in 2019 (Statistics Norway, 2022), while 75% of the total generation capacity is flexible (Energifaktanorge, 2021). In a hypothetical scenario with unlimited cross-border transmission capacity, matching Norway and Germany would allow for smoothening of the power prices volatility in the latter and increase systems supply side flexibility. This would occur due to a match of highly volatile intermittent generation of Germany and stable and flexible hydrogeneration technologies of Norway.

With recent developments in France regarding the plans to allow modular small nuclear reactors, a theoretical unconstrained cross-border transmission could have a similar stabilizing effect on the German electricity prices as in the example with Norway. There are numerous projects on the national and supernational levels in the EU that aim at improving the cross-border energy infrastructure.[5]

To facilitate achieving of the climate targets, present-day governmental policies promote and even enforce the usage of clean energy through subsidies and surcharges. Since 2000 and with adjustments in 2014 and 2017, the EEG in Germany has been ensuring fairly stable power market conditions through the feed-in tariffs. Additionally, investments in renewable capacity are supported via price guarantees, priority clearing and via renewable capacity auctions that are likely to become the main support scheme as the feed-in-tariffs are to gradually fade out during the coming years. Renewable capacity auctions are conducted as tenders by the local governments, according to the renewable energy capacity buildup plans, where the cheapest bid for project realization wins. In January 2021, the first pioneers of the renewable energy transition have stopped receiving feed-in tariffs, nevertheless, the support and promotion of the renewable investments is far from being over. In order to prevent deconstruction of the installations or from predatory feeding of the electricity from those generators, they will be receiving temporary remuneration for the output until 2027 which will be the difference between the market value and the marketing costs (Appunn, 2021). Since 2017 regulators in Germany have been blending in renewable energy auctions as a support mechanism for investments in renewable generation capacity (BMWi, 2021). As stability is one of the main goals of the state, continuity of financial support for renewable generation is granted, although it will be changing its shape. Hence, as expiration of the feed-in tariffs is going to be gradual, no major changes in the bidding behavior of the market players on the day-ahead auctions are expected in the middle-term. Despite being introduced as a signaling mechanism to pinpoint inflexibilities in supply, latest reactions of the regulation on the negative prices suggest that they are gradually becoming a problem. Countermeasures to prevent negative market prices have been tightened with the recent revision of the EEG 2021. Before, the renewable energy generation installations stopped receiving feed-in tariffs if the prices for energy were negative for six consecutive hours. Now, this threshold has been reduced to 4 h, which intends reducing the predatory bidding that the renewable installations may be tempted with to increase chances of being cleared and avoid curtailment in the periods of high VRE generation.[6] An increased, but still not sufficiently high level of attention on the regulatory level calls for a further exploration of what has to be expected in this regard in the future.

3.1. Data and approach

There are different approaches existing in performing simulations of the spot markets. As pointed out by Ziel and Steinert (2016), there are generally five types of models commonly used for price modelling on the spot markets – multi-agent, fundamental (also referred to as structural), reduced-form, statistical, and computational intelligence models (Weron, 2014). As the installed capacity is set to be increased, the proportion of the energy allocated via the spot markets and in particular through the DA auctions will proportionally increase as well. To analyze to which market outcomes more renewable energy supply can lead on the DA auctions ex-post we use a structural model taking the empirical Aggregate Demand and Aggregate Supply from the German-Luxembourg DA auctions of 2019 and 2020 sourced from EPEX SPOT as a time series input. The analysis is performed to identify potential issues that could occur from keeping the current market setup in the short- and medium-term perspective. The coal phaseout is planned to be conducted by 2035 in Germany (BMUV, 2021), which is 13 more years to go from now. Indeed, nuclear phaseout that has to take place by the end of 2022 will reduce the width of the merit order in both negative bidding area and positive price bidding area, however, nuclear generation accounts for slightly more than 10% of the total consumption now (Statista, 2021a,b), and given the current situation with energy prices and the geopolitical situation, it is likely that the buildup of the new installed generation capacity might not be able to keep up at a necessary pace to cover the lack (Agora Energiewende and Ember, 2021, p.4). This puts coal and gas into the list of possible solutions to enhance system stability in the short term. Therefore, in the context of the presented study the use of the real aggregated curves from 2019 to 2020 is justified as we show ceteris paribus, that keeping status quo in the market setup will lead to problems in the medium term, even before the complete phase-out of the fossil generation. We identify the VRE volume part of the AS, extend it by the multipliers reflecting the simulated VRE penetration scenarios and recreate the AS curves in a geometrical reconstruction using Python. By that, the new market equilibria are determined through a spatial analysis of the aggregated curves' intersections, the generated output data is recorded for each hour and year in a table and finally analyzed. The conduction of this procedure is explained in more detail in the following.

In the simulation performed other factors than the supply volumes are kept constant to isolate the effects of the renewable generation expansion on the instances of the negative DA auction prices.[7]

Germany was selected as the basis for this simulation due to the consistent achieving of the climate and clean energy goals set by the national government and the EU. Additionally, Germany is the biggest

[5] In January 2022, EU member countries agreed to invest over €1bn. into 5 cross-border infrastructure projects as a part of the Connecting Europe Facility (CEF) initiative (European Commission, 2022). Although cross-border transportation capacity has the potential for stabilizing and improving national power markets, it is not uncommon that such Projects of Common Interest (PCIs) suffer from delays. According to ACER (2021), 25% of electricity and gas projects incur delays, with 44% in NSOG, 42% in NSI-West, 44% in NSI-East, and 3% in BEIMP priority corridors.

[6] This is relevant for continuous markets where exchange participants can deploy automated trading techniques for arbitrage and where speculation is possible to a certain extent. Lowering the tariff cutoff threshold to 4 h could lead to the attempts of clearing more energy on the DA auctions, which is confirmed by the report by the European Commission (European Commission, 2021b, p.19) stating a 5% YoY increase in trading activity at exchanges in 2020 in Germany.

[7] Current expansionary trends in electric vehicles (EVs) and the global production volumes will lead to an increased demand for electricity in the long-term perspective. In this study, for simplification purposes, demand is kept constant as it is inelastic short-term to isolate the effects that the current market setup might lead to without appropriate changes.

Table 1
The table represents the values for the average market clearing price (MCP) for the selected time periods (peak/off-peak) for the four selected scenarios – reference (real world unmanipulated data), and 3 key scenarios with x2, x3, and x4 more VRE volume (calculated using the base volume – see Ch.3 for details) in the system. Source: own analysis.

Comparison of the Results of the Selected Simulation Scenarios				
	Average MCP, 2019		Average MCP, 2020	
Scenario	**Night off-peak (2-6am)**	**Noon off-peak (13-17pm)**	**Night off-peak (2-6am)**	**Noon off-peak (13-17pm)**
Reference	28.64€/MWh	35.49€/MWh	22.30€/MWh	27.20€/MWh
x2 VRE Volume	23.77€/MWh	31.35€/MWh	16.80€/MWh	22.54€/MWh
x3 VRE Volume	21.41€/MWh	29.68€/MWh	14.47€/MWh	20.65€/MWh
x4 VRE Volume	18.96€/MWh (-33,8%)	28.09€/MWh (-20,85%)	12.18€/MWh (-45,38%)	18.79€/MWh (-30,92%)
Scenario	**Morning peak (7am-12pm)**	**Evening peak (18-22pm)**	**Morning peak (7am-12pm)**	**Evening peak (18-22pm)**
Reference	41.07€/MWh	44.93€/MWh	33.21€/MWh	38.16€/MWh
x2 VRE Volume	36.29€/MWh	40.26€/MWh	28.25€/MWh	32.99€/MWh
x3 VRE Volume	34.23€/MWh	38.16€/MWh	26.29€/MWh	30.76€/MWh
x4 VRE Volume	32.32€/MWh (-21,3%)	36.16€/MWh (-19,52%)	24.54€/MWh (-26,11%)	28.66€/MWh (-24,9%)

power market in Europe with wind and solar constituting the dominant share in the renewable generation capacity, with the most liquid and advanced market in terms of design and use of technology (European Commission, 2021a). Therefore, it is reasonable to suppose that the results of the simulation applied to the current setting of the auctions in Germany could be a relevant basis for referencing. An approach of MCP identification through determination of supply and demand intersection has been proven to yield sufficiently precise results to the real-world reference prices. As shown by Ziel and Steinert (2016), in 64% of cases the MCP derived from the intersection of the SCs and DCs was identical to the reported ones, in 89% of cases the results deviated with less than 10 euro cents, and in 99.8% of cases the error was less than 1 Euro.

The main differences between the current market algorithm EUPHEMIA and the one used in this paper were due to the several simplifications. In the latter one the demand elasticity, innovations in the generation technology, grid congestion, effects of the CAPEX rationing and support schemes on the VRE capacity buildup are not modelled. This is likely to have amplified the frequencies at which the negative prices were observed. The simulation model used in the paper starts at the stage of the post-bid clearing and thereby although does not simulate the bid selection process explicitly, it is based on the AD and AS curves that resulted from the EUPHEMIA algorithm run. Therefore, the complex orders are implicitly reflected in the model and are a part of the base assumptions about the bidding behaviour by the VRE generators. The offset modifications of the AS curves are regarded as if they were extensions of the simple block bids within a specific price range. They are used for validating the bidding behavior of the generators to identify the price range in the AS curves that could be attributed to the renewable generators as well as to validate the increasing instances of negative bidding by the market participants. The aggregated curves from the perspective of this model have all the necessary market information embedded in them, including bidding behavior, pricing, clearing approach, and regulation in place, and thus represent a valid basis for the analysis of alternative scenarios.

The developed algorithm is built as an iterative function that utilizes Pandas, NumPy, Shapely and SciPy Python libraries to perform data manipulations. The input data are the raw aggregated curves from the EPEX SPOT data archive which are rearranged as matrices used for unique identification for each hour in a year. For a given single hourly product, in order to simulate scenario offsets of the AS curves, first the base volume has to be identified. That is the portion (energy volume in MWh) of the aggregated supply curve that can be attributed to the intermittent energy based on the typical pricing range that represents the VRE generation, based on the marginal cost bidding convention. Based on the fact that the wind and solar installed capacity constitute the dominating share of the overall installed renewable capacity in Germany (82% based on the data for 2020 (ENTSO-E, 2020), it appeared to be reasonable to assume for the modelling purposes that the injected offset energy volume should be priced within the specified range to mimic the marginal cost bidding by the intermittent generators. Merit order curves enable that as the clearing houses organize the aggregated supply curve in the ascending marginal costs order. This allows to reverse-engineer the proportion of the supply to be attributed to the VRE generation based on the selected price boundaries to identify the proportion of the supply to be attributed to the VRE generation. The price boundary criteria for selecting the base (VRE) volume are set considering behavioural bidding trends discussed in the literature review i.e., the tendency of the renewable generators to bid below zero. Increasing volumes of renewable energy supply offered at near-zero marginal costs gradually motivate the generators to step into the negative price area to secure their participation with the market especially with an abundant VRE generation. The base volume is calculated via the difference between the borderline volume values using the price range criterion. The scenario approach as described is then applied to these base volumes for each hour in a year.

The Federal Government of Germany is aiming to increase the solar generation capacity by 38 GW (from current 62 GW (Statista, 2021a,b) up to 100 GW), onshore wind by 16.6 GW (from current 54.4 GW (Statista, 2021a,b) up to 71 GW) and offshore wind by 12.2 GW (from current 7.8 GW (Statista, 2021a,b) up to 20 GW) by 2030 according to the updated EEG 2021. This base volume is then amplified for each scenario using the array of multipliers which can be represented as the range [1.1; 4.1] where each marginal step represents an increment in the base volume with a step of 10%. Furthermore, it is reasonable to assume that with projected quadrupled volumes of the installed capacity, the allocation of energy via DA auction clearing would proportionally increase, similar to the volumes on the OTC and exchanges clearing.

$$Q_j^{date,h} = \left(q_{date,h}^{max} - q_{date,h}^{min}\right) * \beta_j$$

$Q_j^{date,h}$ is the quantity in MWh which represents the base volume with a corresponding offset for the VRE volume increment β_j, for a specific date and hour in that day in each year, based on the temporal multilayer index from the source tables from EPEX. $q_{date,h}^{max}$ and $q_{date,h}^{min}$ are the threshold VRE-attributable volume values that are identified using the

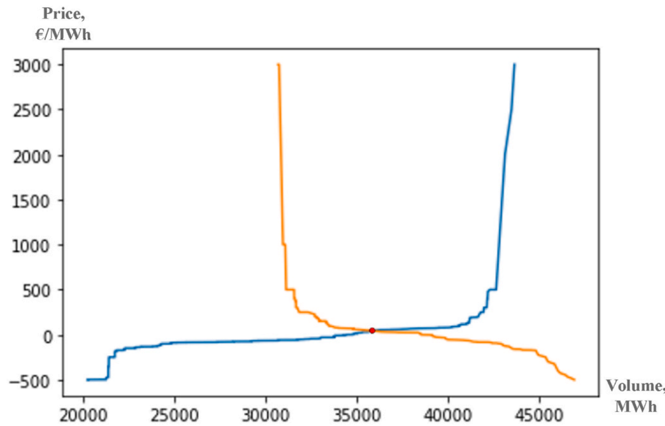

Fig. 3. Identification of the new (MCP, MCQ) couple for a given scenario using the Shapely library; graphical render of the corresponding algorithm stage; the values at the intersection point (marked red) are recorded into the list of tuples and then used in the final analysis. Source: own creation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

original table of values for the AS, based on which a modified supply curve is replotted to contain an extended quantity of the renewable energy for each factor. To achieve that, the LineString class of the Shapely Python library is used to geometrically reconstruct an AS curve based on the adjusted table data. Next, using the same spatial analysis module, an intersection point between the new AS curve and an unmodified real AD curve for this hour is geometrically identified to determine the market clearing price – market clearing quantity couple for a specific hour and multiplier factor combination.

Being based on the real profiles of the demand and supply from the years 2019 and 2020, the results of the simulation with offset scenarios form a valid basis for the projections of the price developments for the upcoming years short-to middle-term. We discuss the processed results fit into the tables, 2D and 3D charts in the next section.

4. The impacts of an increasing share of renewable energy on the auction prices

This chapter presents the simulation results using the following rationale: the changes in average MCPs for selected peak and off-peak periods give a first clear intuition. We then present the 3D surfaces showing the effect of the simulated scenarios on the daily price pattern

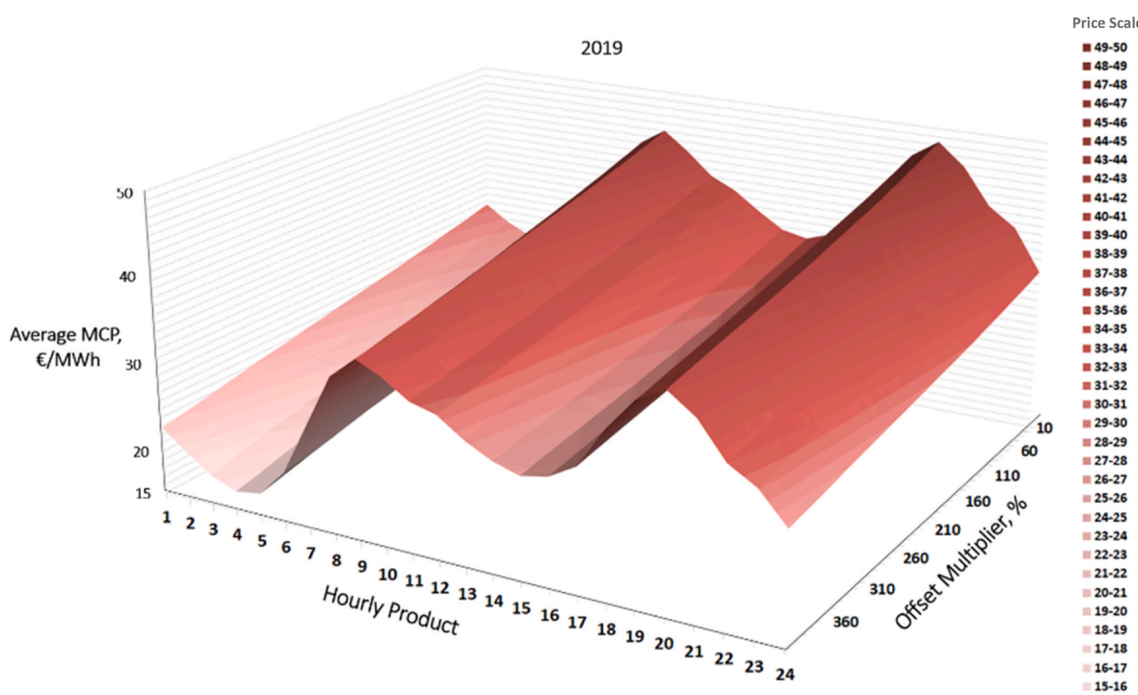

Fig. 4. 3D Visualization of the simulation output using the Germany-Luxembourg DA auction data for the year 2019; x-axis represents the 24 hourly products that are cleared on the DA auction, y-axis represents the average MCP in a year for a specific hourly product and offset factor combination. Source: own creation.

price range criterion[8] as described before.[9] This is in line with the reported expansion necessary to reach at least the EU2030 climate targets – the buildup of wind and solar capacity must triple (Agora Energiewende and Ember, 2021, p.4). In the next step, for each iteration of a scenario offset, the manipulated base volume is then inserted back to the development. Next, we discuss the most significant instances of price drops observed in the simulation. Finally, we explore which part of the price drops has resulted in negative MCPs.

According to the results of the performed simulation, in the scenario with the biggest injection of the VRE volume, the average system price falls by 23.49% (from 37.67€/MWh to 28.82€/MWh) in 2019 and by 30.98% (from 30.47€/MWh to 21.03€/MWh) in 2020. The change in the average price in both peak and off-peak daily periods was more drastic in the simulation for the year 2020 than in 2019, as can be seen in Table 1. The general profile of energy generation and consumption in 2020 was affected by the Covid-19 pandemic. In 2020, more renewable energy was produced (+4.2% gross VRE generation YoY (Destatis, 2022)). At the same time, a negative shift in the power demand in the industrial sector and on the private level has amplified the effects of the

[8] Price criterion for identifying the relevant VRE-attributable ranges is $p \in [-10€/\text{MWh}; 5€/\text{MWh}]$; the range of the values for the offset multiplier was selected as $\beta_j \in [1.1; 4.1]$ to mimic the VRE penetration as described in the Ch.3.1.

[9] More precisely, taking an example of the 29th of September 2020 and the product h = 22, the base attributable VRE volume was identified as 1162,4 MWh, based on the pricing thresholds. With the x2 scenario the VRE volume then was recalculated to constitute 2324,8 MWh, and x4 is 4649,6 MWh.

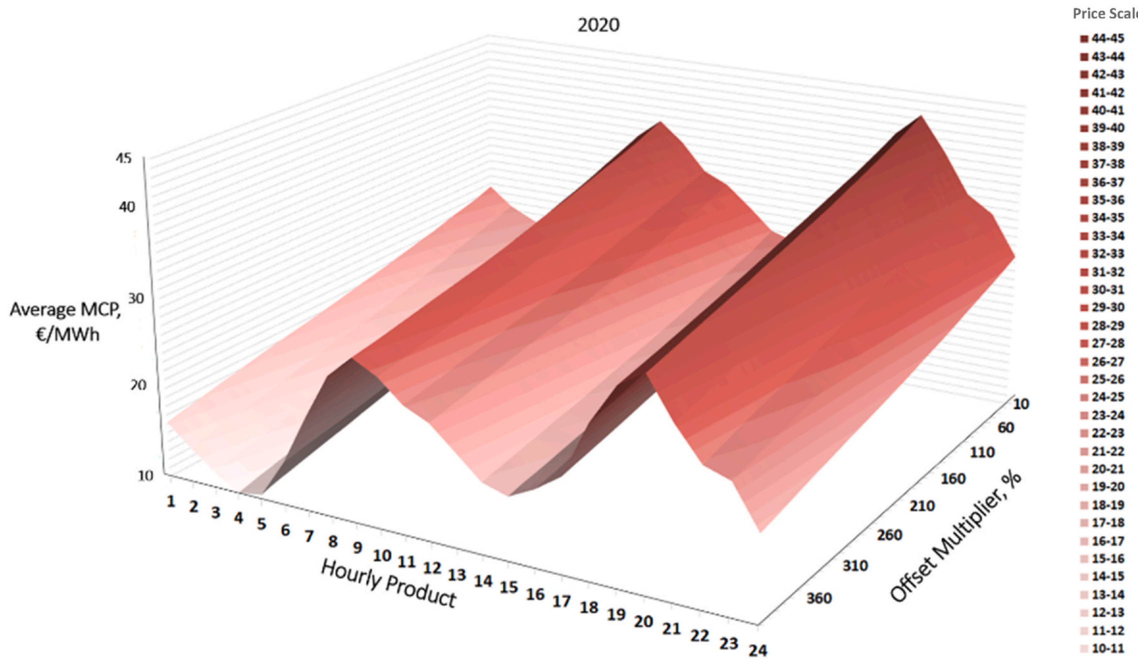

Fig. 5. 3D Visualization of the simulation output using Germany-Luxembourg DA auction data for the year 2020; x-axis represents the 24 hourly products that are cleared on the DA auction, y-axis represents the average MCP in a year for a specific hourly product and offset factor combination. Source: own creation.

Table 2
Numbers of hours in both years for the x2 and x4 simulation scenarios, with price drops in MCPs (at least) below the arbitrarily chosen threshold values 1/3 and 2/3 of an average MCP (30€/MWh). For example, there were 232 h in 2020 with the x2 scenario where the hourly MCP have dropped greater than by 20€/MWh from the reference (real world) price. Source: own simulation.

		Annual Frequency (number of hours)	
Scenario (Offset Factor)	MCP Reduction Value Threshold (ΔMCP)	Year 2019	Year 2020
X2 VRE Base Volume	>20€/MWh	172	232
	>9.5€/MWh	891	1086
X4 VRE Base Volume	>20€/MWh	749	1516
	>9.5€/MWh	2542	3163

renewable energy penetration on the system prices. In 2020, the primary energy consumption in Germany has dropped by 7% YoY (AGEB, 2021). Consequently, VRE generation has covered a bigger share of the primary consumption in 2020 as compared to 2019 (+4% wind and +9.1% PV (AGEB, 2021)). A decreased demand for energy in 2020 due to the Covid-19 pandemics has boosted the occurrence of negative prices as the renewable energy in the system increases.

The total effect on the DA auction MCPs can be more vividly seen on Figs. 3 and 4 for the years 2019 and 2020 respectively. The surface represents the results of the simulation in a single graphic, with the x-axis representing 24 hourly products of the DA auction, the y-axis showing the average annual market clearing prices for the corresponding products, and the z-axis depicting the range of the offset factors (β_j) at which additional renewable energy volumes were simulated. The surface for the year 2020 output (Fig. 5) has steeper peaks and lower minima as compared to 2019, which represents an increased volatility of

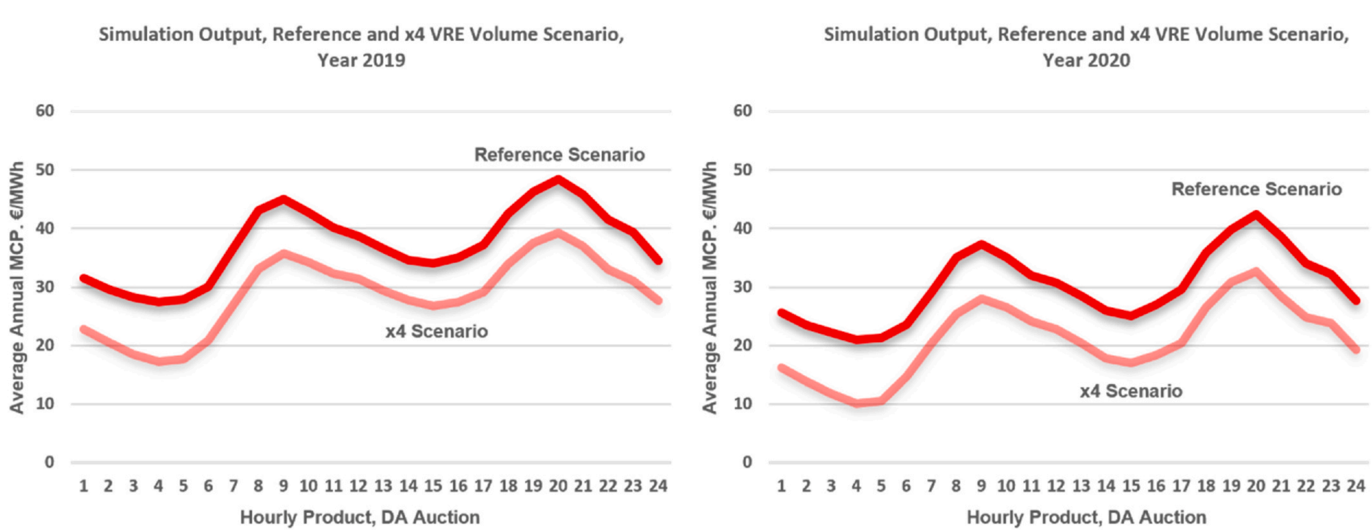

Fig. 6. The figure represents 2D slices of the 3D visualizations on Fig. 4 and 5 at the front and back edges of the 3D surfaces – representing the reference (upper curves here) and x4 offset (lower curves here) scenarios for the years 2019 (left), 2020 (right); source: own simulation.

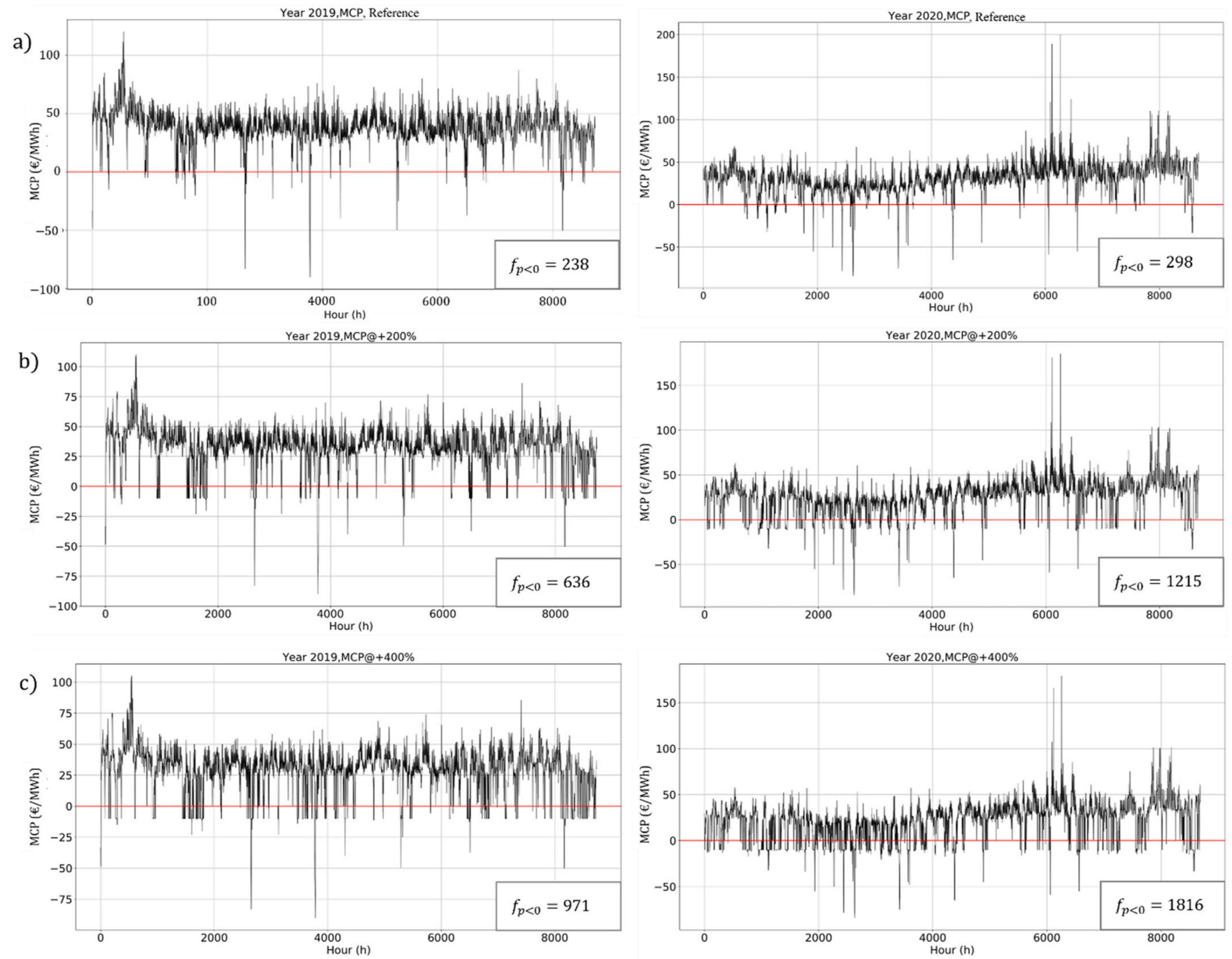

Fig. 7. MCPs and hour combinations, plotted for each hourly product in 2019 and 2020 years for the a) reference cases of 2019 and 2020 DA auctions in Germany-Luxembourg, b) for the x2 intermittent volume scenarios, c) for the radical x4 offset scenario.

prices. For the year 2020, as the VRE volume offset factor (β_j) exceeds the value of 2 (z-axis value of 200%+ on Figs. 3 and 4), in the periods with high wind and solar output the average prices were more frequently pushed below 20€/MWh. In situations with unfavorable weather conditions, hourly prices were higher than in the similar periods a year before. Table 2 counts the most significant price drops occurring in the observed period, categorized into drops sharper than 1/3 and 2/3 of the average normal market price of approximately 30€/MWh. Not all instances of price drops imply negative prices which will be sorted out in more detail in the following.

According to the simulation results, the biggest reduction in 2019 MCPs at the x2 offset factor and a corresponding extra 2560 MWh of intermittent energy occurs on the August 10, 2019 for the hourly product h = 8 (a drop of −29.87€/MWh) with an increase in market clearing quantity of 717 MWh. The 2nd and 3rd biggest reductions in MCPs occurred for the products h = 20 (a drop of −29.82€/MWh), and h = 7 (a drop of −29.75€/MWh) of the same day, with the corresponding offset values of 2651 MWh and 1676 MWh and increases in the market clearing volumes of 553 MWh and 425 MWh respectively. For the offset factor of x4 and the corresponding extra 5361 MWh, 3167 MWh, and 5233 MWh of the VRE supply, the biggest reductions of-38.99€/MWh, −38,74€/MWh, and −38,6€/MWh were observed on the 13 th of January 2019 h = 12, June 21, 2019 h = 13, and August 10, 2019 h = 24 respectively, with 2.6 GWh, 1.1 GWh, and 0.99 GWh of additional volume being cleared at the new prices.

Such frequent cases of price drops reflect a market anomaly, as a reduction of 9.5€/MWh constitutes already a 27,97% drop from the average 33,97€/MWh price (EPEX SPOT, 2021) at the DA auction in Germany-Luxembourg in 2020. A drop of 20€/MWh constitutes already a 58,87% price drop from the average DA auction MCP in 2020. Thus, in the rather soft scenario of the x2 offset in the DA auctions in 2020, 12.4% of all 8784 hourly prices in the year would have reduced by at least 27.97% from the average. In a more extreme case of x4 offset scenario of the intermittent energy volume, 36% of the hourly clearing prices would have reduced by 27.97% from average. The biggest reduction in 2020 MCPs has occurred on the 15th of September at h = 21 and constituted the stunning −101,43€/MWh and −88.06€/MWh cuts for the x2 (+2507 MWh) and x4 (+5002 MWh) factor scenarios and resulted in corresponding increases in the market clearing quantities of 1166.3 MWh and 3471.9 MWh.

Fig. 6 shows a 2D representation of the previous 3D visualizations of the simulation outputs. The 2D curves demonstrate the front and back view (slice) of the 3D surfaces, which belong to the reference (real world 2019 & 2020 market data) and the maximum offset scenarios.

The findings constitute an empirical confirmation that the merit order effect not only perseveres, but also may gradually lead to more

Table 3
The values represent counts of negative MCPs at the selected offset factor scenarios (columns) in the respective years (rows), according to the results of the performed simulation; The extra VRE volume is calculated using the base VRE volume as described in Ch.3.1; source: own simulation.

Number of Negative Prices Observed at Selected Simulation Scenarios									
	Scenario (Extra VRE Volume)								
	Reference	+50%	+100%	+150%	+200%	+250%	+300%	+350%	+400%
Year 2019	238	304	429	544	636	710	792	885	971
Year 2020	298	537	820	1028	1215	1365	1509	1648	1816

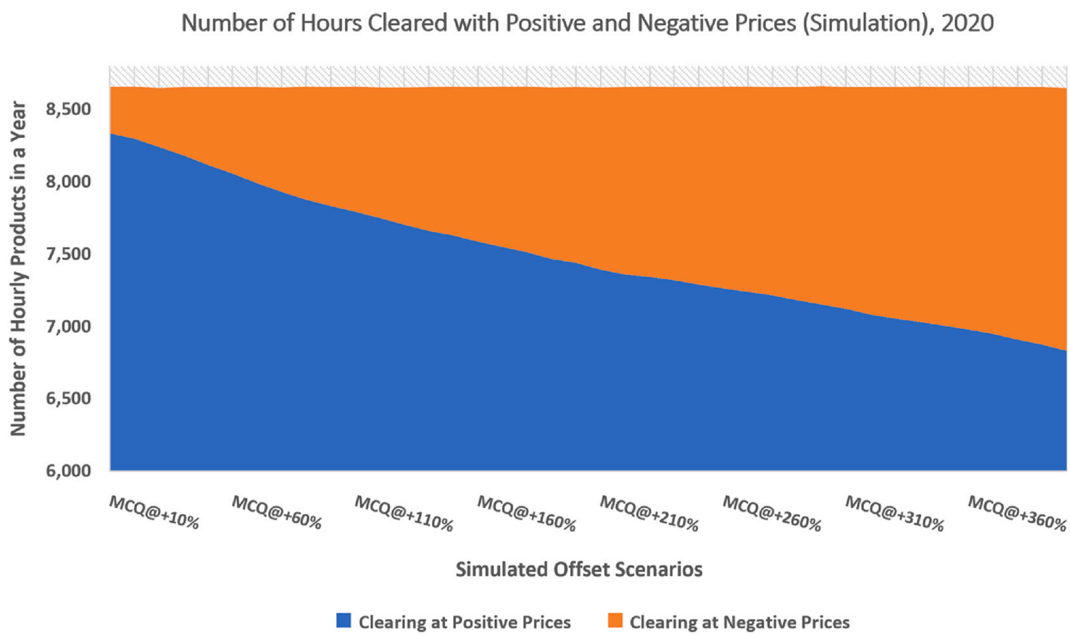

Fig. 8. Shares of hourly products at the German-Luxembourg DA Auction that would be cleared at positive/negative prices in all simulated scenarios using the 2020 market data; MCQ stands for the Market Clearing Quantity at a respective offset factor; please note that the x-axis span starts not at a 0 value for a better visibility of presented information; source: own simulation.

radical profiles of the volatility of market prices, stepping more frequently into the negative price area. The results of the performed simulation suggest that as the proportion of the intermittent generation being cleared through the auctions increases, more instances of negative market clearing prices should be expected. The plots shown in Fig. 7 feature the series of market clearing prices for each hour in the years 2020 and 2019, that have been calculated for each offset factor.[10] The negative price instances can be seen on the charts in the areas below the red line marking the 0€/MWh MCP level. The frequencies of the negative prices for each scenario are shown in the boxes in the right bottom corners of the graphs. In the reference cases there were 238 h with negative MCPs in 2019, and 298 h in 2020. The frequencies of occurrences of the negative prices per offset factor can be seen increasing proportionally to the extra infeed of renewables, under the assumptions of the bidding setup and fiscal support currently present. Key frequencies for selected factor scenarios can be seen in Table 3 below.

Besides the drastically increased frequencies, the level of observed negative prices is not radically negative. For the x2 offset scenario using the 2019 data, the results show only 21 instances of the MCPs being below −50€/MWh, while 584 instances (91.8% of all negative ones for that case) being concentrated in the range of [−0.01€/MWh; −20€/MWh]. For the year 2020, 27 instances of the MCPs are below −50€/MWh for the x2 offset scenario, and 1137 are moderately negative in the range of [−0.01€/MWh; −20€/MWh].

According to the results of the x2 and x4 offset factor simulations, respectively 7% and 11% of all hourly products are priced negatively in 2019, while 13,8% and 20,7% in 2020. In the x4 VRE scenario for 2020, having 21% of hours priced negatively translates into €561,82mil worth of sales volume that would have to be covered by the suppliers for the energy they sell. This value represents 10.2% of the total sales volume cleared in the DA Auctions at the x4 factor scenario in 2020. Fig. 8 demonstrates the shares of hourly products at the German-Luxembourg DA Auction that are priced positively or negatively, according to the simulated scenarios. The share of negative prices can be seen persistently growing. An explanation for this linear increment is that the model does not directly reflect the investment costs for renewable generation capacity as the simulated VRE volume increases. Depending on the success of the policy measures deployed to promote investments in renewable generation (e.g., capacity auctions, FiTs), the pattern of the increment buildup may not be linear. The growth of the VRE generation capacity is assumed to be stable and linear in our model and constitutes multiples of the volumes that were offered to the DE-LUX market in 2019 and 2020.

As the CAPEX for the VRE generators has been falling significantly over the last decade, so have been the feed-in tariffs (OECD, 2022),

[10] The hourly market clearing prices were fit into the chart with all the 8760 hourly products from 2019 to 8784 from 2020. The hourly products for each year are represented on the x-axes. The corresponding auction clearing prices are represented on the y-axes for the year 2019 on the left side charts and 2020 on the right-side charts of Fig. 7. The two plots at the top of Fig. 7 show the reference case with actual MCPs for the selected years. Plots in the central row represent the auction results with x2 offset scenario, while plots at the bottom show the x4 offset scenario.

being until recent the main tool to promote investments in renewables. Additionally, results in the literature ((Hirth, 2013), (Brown and Reichenberg, 2021)) suggest that the market value of the VRE keeps decreasing, as the market penetration of the VREs grows due to the cannibalization effect which is an inherent phenomenon observed in VRE-abundant markets such as Germany.

The overall impression gained from the simulation is that a remarkable increase in incidences of negative prices in spot markets in the context of an increased share of renewables is to be expected in the future. In fact, the higher frequencies of negative prices comprise an increasingly significant market distortion that is caused by the combination of the market setup factors, heavy fiscal support and the growing share of subsidized renewables altogether and hinder a proper market functioning. We come to a similar assessment to the one presented in a comprehensive analysis by Hildmann et al. (2015) in this regard. Additionally, expectations of the upcoming increased frequencies of the negative electricity prices that have been projected in the current study are also supported by the findings of a recent paper by Fraunhofer IEE and ISE (2021). According to the mentioned study, it is expected that the negative electricity prices will not only remain until the year 2050, but also that the number of hours with negative prices will be gradually increasing up to more than 400 instances in the year 2040. Of course, the deviations between the projected values in the studies are due to the differences in the modelling approach. The Fraunhofer IEE and ISE (Böttger et al., 2021) simulation model considers an expanded set of conditions, such as available projected flexible generation, congestion, and transmission capacities. Moreover, the starting point of that simulation is the supply and demand bidding which is one step prior to the post-clearing AD and AS used in the current paper.

Based on our results, it is hard to neglect that the growing integration of the renewable generation to the mix, although bringing short-term positive effects and contributing to the achieving of the sustainable environment future plans, has also not-so-obvious from the first glance negative implications. As can be seen from our findings, an increasing tendency towards negative bidding has the potential of amplifying the negative effects of a lack of flexibility in the system. This does not necessarily mean that the current plan of the renewable generation penetration is flawed in general, rather it calls for new efforts in transforming the existing systems. Adjustments may be introduced on different levels such as DA auction design, electricity market design, adjustments to the Target Model, improving cross-border capacity and by that developing flexibility in the system, that altogether can minimize the long-term negative effects of keeping the current approach to the renewable transition.

5. Conclusions and policy implications

Analysis shows that more VRE volumes will lead to lower market clearing prices on the DA auctions. With greater shares of renewable penetration in Germany, and without extraordinary exogeneous geopolitical factors in place, bigger reductions in market prices will be observed (>30%, >60% cuts, see Ch.4). The reasons for this phenomenon are a lack of flexible technology in the system, and the current market regulation (marginal cost bidding, uniform pricing). With higher levels of feed-in-tariffs in the past, renewable generators had a secure cash in-flow and a guaranteed profit which is gradually changing with the expiration of the feed-in-tariffs and their quantitative reduction. The energy transition law EEG 2021 has been seeing constant changes during the last year, and there are new market support mechanisms such as capacity auctions emerging to replace feed-in-tariffs in promoting investments in renewables. However, the efficiency of such replacement support mechanisms in promoting a sufficient renewable capacity buildup must be further assessed using empirical data. As of now, with zero marginal costs, and an obligation to bid at the marginal cost levels, the VRE generators are tempted to step further into the negative bidding price area to secure market participation (Deng et al., 2015). This shift in the bidding behaviour was accounted for in the simulation presented in this paper and turns out to be an additional factor that drives increments in the negative price occurrence frequencies on the DA Auctions in Germany-Luxembourg coupled market. Moreover, the demonstrated growing price variability, considered together with the recent real-world spikes in the electricity prices in Germany that can be observed throughout the Q3-Q4 of 2021 constitute an issue that the policy makers must resolve in the nearest future. Currently high price level is not sustainable from the social welfare perspective, and it only increases the burden for private and commercial consumers. Policymakers should not be tempted to regard the latest price surge as a basis for premature at scale integration of previously infeasible storage solutions as it is unclear how long will the current situation last. Electricity should not be a luxury good for the end consumers, however, the current market design if remained unchanged would inevitably lead to distortions on the electricity markets through frequent negative and occasional extremely high prices.

The purpose of the power exchanges is mainly to allow for a transparent discovery of the market reference prices for electricity (Barbour et al., 2014). Our findings raise concerns about how efficiently the auction prices perform the signaling function for the spot, futures, and OTC markets, as they are reportedly failing to account for externalities and true marginal costs of intermittent generation. In addition to the observed intrinsic market trends, the planned phasing out of the nuclear and coal generation has to match with an appropriate buildup of renewable generation capacity, which has to triple to reach the necessary level for covering the gap by 2030. Therefore, persistent fiscal support of the investments in renewable capacity would on the one hand help achieving climate goals faster. On the other hand, it further increases an already significant tax burden for the end consumer side. From the long-term perspective, there is still a divergence in the high-end electricity prices for the end consumers and the lowering wholesale prices consumers actually do not benefit from.

Based on the conducted research, we believe that an intervention to the current policy is required to prevent detrimental effects of keeping the current market design in a newly evolving renewable-dominant environment. There is a strong need in expansion of the system flexibilities. This can be achieved through either infrastructural development of the cross-border integration or through the development of a flexibility technology (storage, hydrogeneration, new technology). Reconsidering the current nuclear phase-out plans and assessment of the repercussions of the increasingly significant role of gas generation technology could be alternative ways to achieve more stable spot markets in the short-term. Consolidation of reliance on the gas generation coupled with low diversification of procurement in Germany can lead to detrimental effects on social welfare. The deviating generation pattern of PV and wind generation sets up another possible solution – balancing the ratios of these technologies as more installed PV can reduce instances of negative prices in the night periods. At the same time, changes must be introduced to the auction design that would allow for a better price discovery and would alleviate the forming pressure towards negative bidding among the renewable generators. The pressure at the taxpayers arising from the fiscal support schemes for renewables must be well-balanced but should not lead to the removal of the support mechanisms in the short- and middle-term to achieve a financially self-sustainable electricity market model. Changes in the pricing and bidding conventions on the spot markets could become an efficient tool in the short-term transformation of the electricity markets.

To allow for a smooth transition to the carbon-free generation it is vital to better understand the functioning of the modern markets with higher shares of intermittent renewable energy sources. The findings of our study may be used as an input for the further dual market design related studies ((Keay and Robinson, 2017), (Peng and Poudineh, 2017), (IRENA, 2020)) that aim introducing changes to the market design fundamentally and have the potential of overcoming current distortions on the markets. To build upon the findings and to further improve our model, an additional demand-side analysis should be performed to identify the mutual effects of the changes in the demand and supply side fundamentals. In order to assess the future trends in the investment attitude towards renewable capacity projects, an additional technology-specific profitability analysis could be performed that would use the setup and findings of this paper and expand further by integrating trends in the LCOE, CAPEX and subsidies of the renewable's factors.

CRediT authorship contribution statement

Oleksandr Prokhorov: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Dina Dreisbach:** Conceptualization, Resources, Validation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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