Applied Energy 275 (2020) 115364

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Economic analysis of batteries: Impact on security of electricity supply and renewable energy expansion in Germany

Andreas Coester[a,*], Marjan W. Hofkes[b,a], Elissaios Papyrakis[c]

[a] *Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, the Netherlands*
[b] *School of Business and Economics, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, the Netherlands*
[c] *International Institute of Social Studies (ISS), Erasmus University Rotterdam, Kortenaerkade 12, 2518 AX The Hague, the Netherlands*

HIGHLIGHTS

- We study the impact of batteries on electricity supply and renewable energy expansion.
- We simulate optimal capacity of batteries depending on excess electricity demand.
- We develop policy scenarios in which batteries are subsidized by the government.
- We show that electricity market conditions require governmental intervention.
- We show that government subsidies for batteries can be economically feasible.

ARTICLE INFO

Keywords:
Batteries
Electricity market design
Energy security
Renewable energy

ABSTRACT

Increasing amounts of fluctuating renewable energy lead to decreasing electricity prices and impair security of electricity supply. Consequently, sustainable and economically feasible solutions need to be found to ensure both ongoing renewable energy expansion and stable electricity supply. We examine the impact of batteries on security of the electricity supply and achieving renewable energy expansion. For this purpose we develop an electricity market model that enables the simulation of batteries both as an economic-driven investment option and as a government subsidized option. We present six policy scenarios in which batteries are utilized as an option that is subsidized by the government to secure electricity supply and engender renewable energy expansion. Our simulations, based on empirical data, indicate that, in a free market, battery investments are not profitable for private investors. On the other hand, these six policy scenarios show that by subsidizing investments in batteries governments could ensure a secure electricity supply as well as ongoing renewable energy expansion. A comparison to similar policy scenarios that do not adopt batteries indicates that the total sum of government subsidies and external costs is up to 36% lower when utilizing batteries.

1. Introduction

As a result of technological developments, onshore wind energy has become cost competitive with conventional power plants. At the same time, the lower marginal costs of renewable energy (RE) has led to a significant decrease in the price of electricity on the free market. This impacts substantially upon the profitability of both RE and conventional power plants. Recent research (see [1] showed that many power plants must be decommissioned for economic reasons, resulting in insufficient generation capacity within the market to meet peak electricity demand. This imbalance has initiated further research on the range of market instruments that are designed to secure the electricity supply and RE expansion. Key factors commonly cited in extant literature include changes in market design, adaptation of the electricity grid, consistent demand-side management, as well as both short-term and long-term storage [2–7]. Sustainable storage technologies have received increased interest as an economically profitable and environmentally friendly option through which to achieve the objective of a green energy supply [8]. In this regard, especial focus has been paid to utilizing batteries as a safe and stable energy storage system with

Abbreviations: EEX, European Energy Exchange; FIT, Fixed Feed-in tariffs; GWh, Giga-Watt hours; LDC, Load Duration Curve; LDCM, Load Duration Curve Model; MO, Merit Order; MW, Mega-Watt; MWh, Mega-Watt hours; NPV, Net Present Value; PDC, Price Duration Curve; RE, Renewable Energy

* Corresponding author at: Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1111, 1081 HV Amsterdam, the Netherlands.
E-mail address: a.coester@vu.nl (A. Coester).

https://doi.org/10.1016/j.apenergy.2020.115364
Received 15 February 2020; Received in revised form 26 May 2020; Accepted 7 June 2020

sharply decreasing costs [9,10].

This paper explores the impact of large-scale battery systems on the security of the electricity supply and RE expansion. We develop an electricity market model that enables the simulation of batteries as a dynamic, economic-driven investment option. Moreover, we delineate six policy scenarios that utilize batteries as a government subsidized option for securing electricity supply and RE expansion. For each scenario, we simulate, using empirical data from the German electricity market, the amount of RE produced, the charging and discharging volume of batteries (battery energy), total CO_2 emissions, as well as the subsidies and external costs required to ensure security of supply.

We focus on Germany, being among the leading countries in the transition towards renewable electricity supply systems. With its strong expansion of RE and its decision to phase-out both nuclear and coal power plants, Germany is faced with the major challenge of increasingly fluctuating RE leading to decreasing electricity prices and impairing security of electricity supply. As a consequence, Germany has to find sustainable and economically feasible solutions in the short-term on how to realize ongoing RE growth as well as security of electricity supply.

To the best of our knowledge, this is the first paper that develops a theoretical framework incorporating long-term interaction amongst multiple energy and energy storage systems (renewable/conventional energy, battery storage) and accordingly simulating optimal capacity of batteries depending on excess electricity demand. We contribute to the academic literature by developing policy scenarios that utilize batteries and aim to achieve both RE expansion and security of electricity supply. Our scenarios are based on alternative assumptions on market conditions (free market versus subsidized production) for batteries, both for the conventional and the RE energy sector. Our research expands extant literature by comparing the potential costs incurred by subsidizing batteries to policy scenarios not relying on battery use. This paper contributes to the field by producing new insights into the impact of batteries on the future development of RE and the capacity of conventional power plants. Accordingly, our research assists the decision-making process of policy makers by providing a new understanding of future electricity generation and its attendant subsidies and external costs. In Section 2, we review the existing literature on the impact of batteries on the development of RE and conventional power plant capacity. The methodological approach that underpins our analysis is outlined in Section 3. Section 4 presents the results of our simulation, while Section 5 provides concluding remarks.

2. Review of the literature

Several papers model energy storage systems; Zerrahn and Schill [11] provide a comprehensive overview of different approaches in the literature. Hemmati et al. [12] showed that energy storage facilities may lead to a replacement of peak-load fossil-fuel power plants. According to Bento et al. [13] and Zhao et al. [14] the integration of storage facilities can partly compensate for fluctuations of RE with the result that the overall electricity generation becomes more stable and cost-effective. Similar to this finding, Gaete-Morales et al. [15] came to the conclusion that long-term energy storage helps to achieve low electricity costs. Narayanan et al. [16] investigated the feasibility of a 100% RE supply for cities and concluded that storage facilities are crucial for that purpose. Zerrahn et al. [17] showed that electrical storage needs can be reduced if the electricity sector is broadened by including flexible additional demand, e. g. related to heating or mobility.

Timilsina et al. [18] explored the efficiency of photovoltaic power plants during periods of low radiation. They concluded that batteries were indispensable to bridge gaps in the RE supply. In Bangladesh, a power system comprising wind and photovoltaic power plants in combination with batteries has also proven to be an economically profitable and environmentally friendly alternative. The system can supply electricity to an entire remote community at a low cost, whilst, simultaneously, reducing CO_2 emissions and rendering grid expansion unnecessary [19]. Afanasyeva et al. [20] calculated the economic competitiveness of a Moroccan hybrid power plant consisting of a photovoltaic installation, a gas turbine and batteries. They found that there was a tenfold reduction in CO_2 emissions in the hybrid power plant compared to a conventional power plant. Although, based on present fuel costs, the total production costs of the hybrid power plant are 20% higher, due to the utilization of RE and batteries, the hybrid power plant is considerably less vulnerable to any potential increase in fossil resource prices.

A specific option for balancing the differences between electricity supply and demand is using electric vehicles to serve as mobile battery carriers [21]. Kempton and Kubo [22] observed that electric and hybrid vehicles were frequently on stand-by during peak load hours. Instead, their battery capacity could be utilized to bridge the demand peaks in urban metropolitan areas [21]. This would result in a reduction of the necessary peak load capacity, enhance the cost-efficiency of private electric car ownership and reduce CO_2 emissions [23].

More specifically for Germany, Babrowski et al. [24] integrated battery storage facilities into an optimization model in order to determine the optimal amount of storage capacity up to 2040. They found that it is beneficial to commission about 3.2 GW of batteries until 2040 (provided that investment costs of batteries are at a level of 150 €/kWh). Sinn [25] also simulates the electricity storage requirements for Germany. He concludes that in order to achieve a combined share of wind and solar of 89%, electricity storage capacity in excess of 16,300 GWh is necessary. In contrast to this, Schill and Zerrahn [26] found that for a share of RE of 88% in electricity generation, a minimum of 436 GWh of storage would be required in Germany (different to Sinn [25], Schill and Zerrahn [26] combine RE expansion, RE curtailment and electrical storage). Similarly, Pape [27] found that for Germany as well as for Europe as a whole hardly any investments in electricity storage are needed in the short- to medium-term.

Nieto et al. [28] came to the conclusion that battery electricity storage media are essential for stabilizing electric grids and ensuring the security of the electricity supply against the backdrop of RE expansion. However, they also stressed that batteries are simply not economically viable without support from subsidies. Based on a model-based calculation, Locatelli et al. [29] also found that British energy storage plants would not be profitable without subsidies.

In summary, the application of batteries has been shown to have a positive impact on securing the energy supply by balancing the fluctuating supply of RE. Furthermore, batteries can reduce the amount of energy required from fossil fuel power plants that would otherwise be necessary to supplement RE and meet peak load. Consequently, batteries can reduce CO_2 emissions. However, the current costs of batteries are not competitive with conventional generation technologies, and, thus, free market-based investments in batteries are likely to be the exception rather than the rule in the short to medium-term.

Our analysis contributes to this earlier literature by explicitly focusing on the role of government subsidized batteries in the German electricity market. Different to the existing papers, we develop six policy scenarios that simulate government subsidized optimal capacity of batteries depending on excess electricity demand.

3. Methodological approach

In this section we present the methodological approach underpinning our study. In Section 3.1 we explain the Load Duration Curve Model, which forms the basis of our electricity market model. Next, we proceed to present our approach to integrating batteries into the electricity market model, first, as a free market investment (see Section 3.2.1) and, subsequently, as a subsidized investment (see Section 3.2.2).

3.1. Load Duration curve model

In this subsection we delineate the electricity market model that serves as the basis for our integration of batteries (see Section 3.2) and simulation of policy scenarios (see Section 4). The market model, commonly referred to as the Load Duration Curve model (LDCM) in extant literature [30–32] is based on the Load Duration Curve (LDC) and the Merit Order Curve (MO). The LDC shows the electricity demand in MW per hour for a given year, presented in descending order of magnitude. In the MO, the electricity supply of both RE (in the case of RE traded on the free market) and conventional power plants is ranked in ascending order of marginal costs. Linking the LDC and MO in this way allows each hourly electricity demand to be assigned to the corresponding electricity price. Based on this, the so-called Price Duration Curve (PDC) can be identified, which allocates the price of the demanded quantities of electricity to the corresponding duration in hours. The PDC allows for the calculation of the contribution margins of each power plant, so that net present values (NPV) can also be determined (see [1]).

In order to explore the profitability of both conventional and RE power plants, the NPV for each year was calculated over a ten-year period. Free market-based investments in power plants are executed with an optimization model that identifies the type of power plant investment (e.g. wind or gas) that maximizes the NPV, as well as the optimal capacity in MW. Furthermore, it is assumed that power plants are removed from the market once they reach the end of their technical lifecycle. In those policy scenarios (see Section 4.2) where power plants are decommissioned due to economic inefficiency, the underlying assumption is that there is a negative NPV for five successive years. In the case of closures and new investments in power plants, it is assumed that these materialise in the following year. For more details on the LDCM, see Coester et al. [1].

3.2. Integration of batteries in the model

We used the LDCM as a basis and extended it to integrate the special characteristics of batteries. In Section 3.2.1 we develop a model where batteries are treated as a free market investment, while Section 3.2.2 develops a model where batteries are applied as a government subsidized investment.

3.2.1. Batteries as a free market investment

Fig. 1 presents in schematic form the impact of batteries on electricity demand, based on empirical data from the German electricity market (for more information concerning the data see Section 4.1). The black curve depicts a typical level of electricity demand over the course of a 24-hour period with no batteries in the market. The blue curve presents the corresponding price per hour of electricity. The dotted black segments of the curve indicate the adjusted electricity demand subsequent to the investment in batteries with a capacity of Δ. In a free market, battery capacity will be charged at the lowest possible cost, thus, at the lowest level of electricity demand and the (corresponding) lowest price of electricity. Resultantly, electricity demand increases by Δ during the period of charging the batteries. The increase in demand in turn leads to a corresponding rise in the price of electricity (see the blue dotted segments of the curve). The opposite effect occurs during the discharging of batteries. In order to maximize profitability within a free market, batteries will be discharged during peak demand hours that have the highest level of electricity prices. In so doing, electricity demand decreases by Δ and electricity prices fall accordingly. As a consequence of increased investments in batteries, the demand curve flattens. This reduces the gap between low and high electricity prices, which corresponds to the contribution margins of batteries.

In a free market, the profit maximizing investment in batteries in year t (B_t) can be determined by maximizing the net present value (NPV_{Bt}):

$$\max NPV_{Bt} = \sum_{i=t}^{t+10}\left(\frac{(B_t CMB_i - FCB_i)}{(1+dr)^{i-t}}\right), \tag{1}$$

where t refers to the year of production (t = 2017, … 2036; we chose 2017 as the starting point for our simulations as data was fully available from that year onwards, see also Section 4.1), CMB_i is the contribution margin of B_t in year i, FCB_i are the annualized fixed costs of B_t in year i and dr represents the discount rate.

While the entire period of investigation is 20 years, the NPV maximization modelling for each year considers only a ten year period, due to the fact that market development is too uncertain over a longer period of time. In order to account for the aforementioned interdependency between battery investments and the resulting effects on the demand curve and electricity prices, respectively, it is critically important to link the NPV maximization modeling of B_t to the demand curve. In so doing, the impact of the flattening effect of increasing battery capacity on the demand curve can be reflected in CMB_i.

We assume that charging batteries takes the same time as discharging. Moreover, we assume that batteries cannot be charged and discharged during the same hour and must be charged and discharged over the course of 24 h. To achieve a positive contribution margin, the electricity price during the discharging of batteries must be higher than the price when charging the batteries. We model twelve possible combinations of charging and discharging hours per day. The couple of hours that yield the highest contribution margin reflects the discharging of batteries during the peak price of electricity and the charging of batteries during the minimum price of electricity. Conversely, the couple of hours that yield the lowest contribution margin in turn assumes a period of discharging at the twelfth highest electricity price and a period of charging at the twelfth lowest price (thus, no couple of hours results in negative contribution margins). At this point, the contribution margin for one day is equal to the sum of the contribution margins associated with the twelve couples of hours. Accordingly, the contribution margin for the full year, for a given investment in battery capacity, is equal to the sum of the daily contribution margins for that invested capacity. The optimal investment capacity in batteries in year t is then given by the battery capacity B_t generating yearly contribution margins (in combination with yearly annualized fixed costs) that maximize NPV. For each subsequent year, the demand curves must then be amended according to the battery investments that came into the market, i.e. an increase in demand during the charging of batteries and a decrease in demand during periods when batteries are being discharged. In those cases when a battery investment has a negative NPV five years in a row, it is assumed that these batteries are deinstalled and, subsequently, they are taken out of the market in the sixth year.

3.2.2. Batteries as a subsidized investment

In the policy scenarios developed in Section 4.2, batteries are utilized as a government subsidized investment in order to secure the electricity supply and support RE expansion. Against this backdrop, the optimal capacity of battery investment (B_t^{opt}) is no longer determined by maximizing NPV. As Fig. 2 illustrates, B_t^{opt} now refers to the difference between the electricity demand curve D and the maximum of electricity supply S for those hours where there is excess demand ED. As a next step, the existing excess supply capacity ES of power plants in the market must be defined. ES is given by the difference between S and D for those hours where there is excess supply. If $B_t^{opt} > ES$ then a supplementary investment in power plants (the type of power plant varies depending on the particular policy scenario, see Section 4.2.) is necessary in order to have sufficient generation capacity for the charging of batteries. The capacity of the supplementary power plant investment is thus given by the difference between B_t^{opt} *and* ES.

The necessary battery and supplementary power plant capacities are then integrated into the market model in the same way as under free market conditions (see Section 3.2.1). In the case that the NPV of batteries is negative for five years in a row, then further losses beginning in

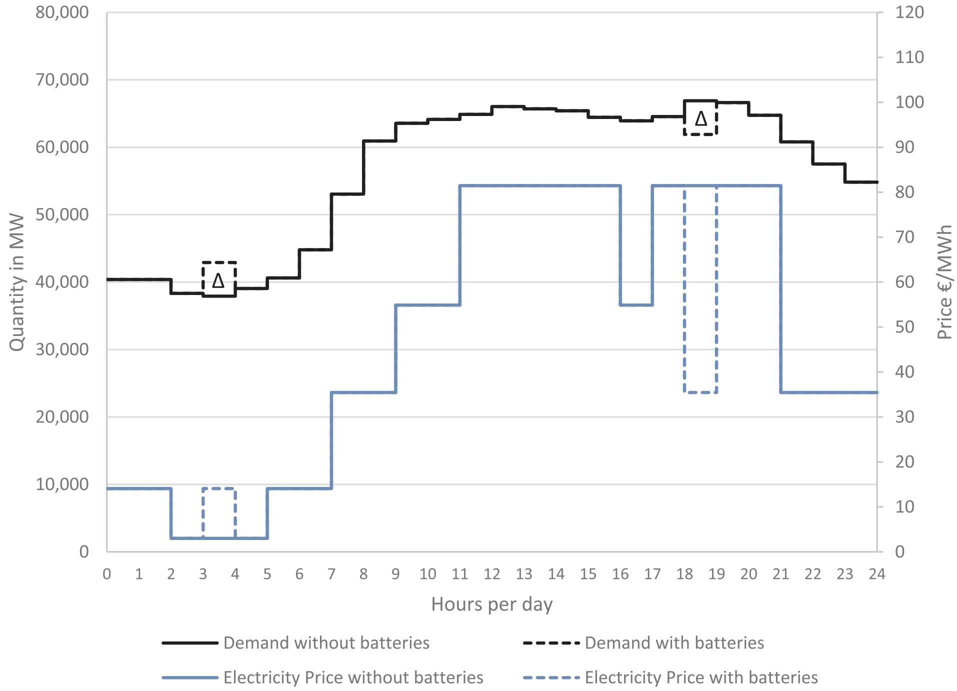

Fig. 1. Schematic impact of batteries on the demand curve.

the sixth year are subsidized by the government, so that these investments can remain in the market.

4. Simulations

This section presents our simulations. After a description of the empirical data in Section 4.1, we describe the six policy scenarios we developed and outline the main simulation results for each scenario (see Section 4.2). In Section 4.3, we analyze further the results of our simulations before proceeding to show the findings of our sensitivity analysis.

4.1. Data

In this subsection we present the empirical data that we utilize in our simulations. We investigate a 20-year period beginning in 2017. We assume that there is no transnational trade in electricity and that conventional electricity is fully traded on the spot market. Peak load prices are assumed to be equivalent to those prices on the spot market, with a mark-up of 5%. We regard this assumption to be valid as the size of the mark-up depends on the ratio of available generation capacity and demand [33]. Furthermore, we assume a discount rate of 7.14% [34]. With regards to the supply side, economic and technical data on actual

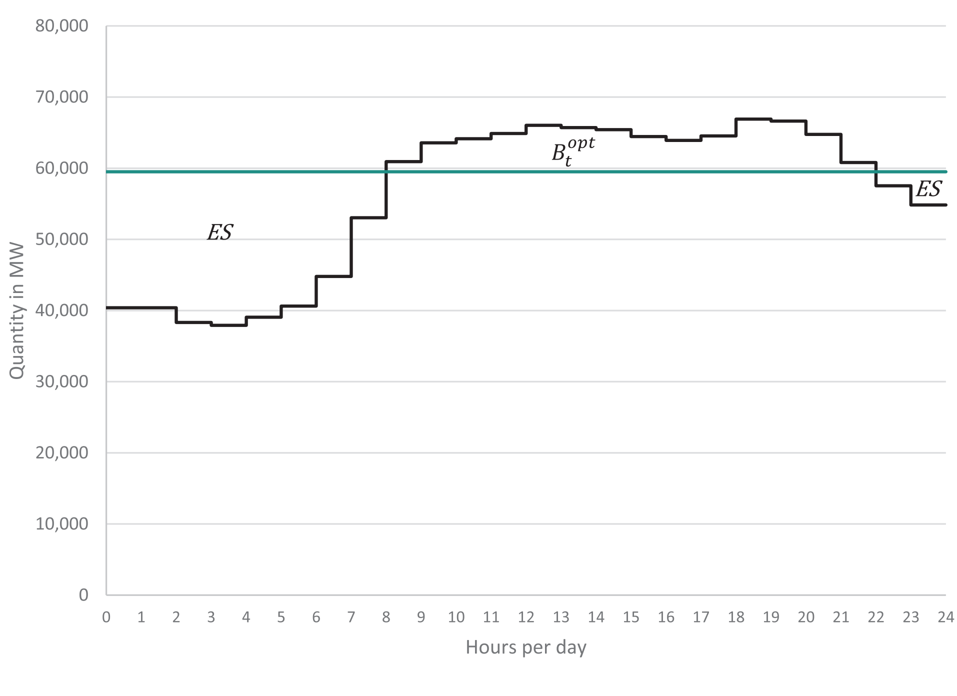

Fig. 2. Schematic depiction of battery capacity under subsidized market conditions.

conventional power plants operating within the German electricity market are based on information from the Federal Network Agency [35] and Western German state Bank [36]. The Agency for Renewable Energies [37], the Institute of Energy Economics (EWI), the Institute of Economic Structures Research (GWS) and Prognos [38] provide the basis for the future development of the main parameters of our simulations. In order to account for the potential unavailability of plants or start-up and shut-down times, we assume a reduction in the installed capacity of each power plant by 10% [34,39]. Our RE dataset is based on information from the Federal Ministry for Economic Affairs and Energy [40], Kaltschmitt et al. [41] and Deutsche Windguard GmbH [42]. We calculated the availability factors of photovoltaic and wind energy through conducting a time series analysis based on data from EEX [43]. For biomass, geothermal and hydro energy, we utilized customary availability factors based on Möst et al. [44]. With respect to the demand side, our data set is based on historical real data of the hourly electricity demand in Germany [45]. In our reference projection, we assume that this demand is constant for the period under investigation up until 2036. We account for possible changes in the future development of demand by conducting a sensitivity analysis (± 0.50%/year; see Section 4.3.7). Economic and technical data on batteries comes from Zapf [46], Mahnke et al. [47], Pape [27] and Sterner and Stadler [48]. We assume investment costs of M€ 0.36 per MW in 2017 and further annual costs of 2% of total investment costs. In addition to this, we assume a linear decrease in investment costs to M€ 0.22 per MW in 2030. For the remaining years, 2031 to 2036, we assume a further linear decrease in annualized costs. The sensitivity analysis (see Section 4.3.7) considers the effects of annualized costs of batteries that are 10% below our reference projection. The external costs of electricity generation are also considered. These costs refer to the environmental and health damages associated with the respective electricity generation technology, which are borne by third parties. We calculate the average external costs per MWh based on data from Krewitt and Schlomann [49], Hohmeyer [50] Enquete-Kommission [51], Enquete-Kommission [52], Friedrich [53] and Braun [54]. Table 1 provides an overview of the external costs that we assumed for our simulations.

4.2. Description and simulation results of reference scenario and policy scenarios

For our simulation, we developed a reference scenario along with six policy scenarios. The reference scenario serves as a benchmark, reflecting the situation under free market conditions. The policy scenarios are composed of several policy measures, many of them based on measures, such as Fixed Feed-in tariff (FIT) mechanisms for RE and subsidies for batteries, that have already been adopted in practice in Germany as well as several other countries. Moreover, we employ a newly developed market design, the RE adaptation market design for conventional power plants [1]. All six policy scenarios were developed with the objective of simultaneously guaranteeing security of electricity supply and ongoing RE expansion. Each policy scenario comes into operation as soon as total electricity supply falls below the level of demand in the reference scenario.

In practise, policy makers typically focus on subsidizing investments in batteries production plants. As our policy scenarios aim at securing electricity supply, we included policy measures targeted at subsidizing ongoing operation of batteries production plants. We assumed in our scenarios that the subsidization of batteries becomes effective in instances in which their NPV is negative for five successive years. Starting from the sixth year onwards, governments compensate for any additional negative NPVs. Along the same lines we assume in our scenarios that government subsidies pay for necessary supplement power plants (the actual type of supplement power plant is dependent on the assumptions of the specific policy scenario). Finally, we assume that government subsidies pay for RE FITs.

4.2.1. Reference scenario

4.2.1.1. Description. The reference scenario refers to a free market environment. We assume that investments in RE, conventional power plants and batteries are made by private investors.

4.2.1.2. Simulation results. In the reference scenario, the low marginal costs of RE production generate high contribution margins, as electricity prices are (initially) set by conventional power plants operating with high marginal costs. This leads to strong investments in RE, particularly wind energy, which, in turn, results in the highest RE production of all the scenarios. However, the high level of RE production with marginal costs close to zero leads to a corresponding decrease in the price of electricity. Consequently, both conventional and RE power plants are decommissioned after five years of unprofitable operation, which results in the security of electricity supply not being guaranteed in this scenario.

4.2.2. Standard policy scenario - batteries subsidized

4.2.2.1. Description. This first scenario is classified as “standard”, because conventional electricity is traded on the basis of a common electricity market design. In case of insufficient electricity supply, RE is taken out of the free market in this scenario and is instead subject to a FIT mechanism for the rest of the period under consideration. The FIT mechanism applied is the classical FIT mechanism that was applied for several years in Germany in an attempt to engender an RE expansion. The average annual tariffs for each RE technology are extrapolated until the end of the period under consideration [55]. Furthermore, we assume that conventional power plants remain in the free market and are shut down either due to economic inefficiency, or because they reach the end of their economic lifecycle. Existing undercapacities in the market are topped up with an optimal mix of batteries and efficient gas power plants. For these complementary investments, the costs of negative NPVs are subsidized, beginning from the sixth year onwards.

4.2.2.2. Simulation results. The standard policy scenario results in the lowest subsidies being paid by the government in order to guarantee security of supply and RE expansion. This is because RE is subject to a FIT mechanism in this scenario. As a result of this, RE production develops slower but more steadily, so that electricity prices remain at a higher level and the remaining power plants are capable of operating without subsidies. However, for the same reason, the standard policy scenario also produces the highest CO_2 emissions of all scenarios.

4.2.3. Free market green policy scenario – Batteries subsidized

4.2.3.1. Description. In this scenario, both conventional power plants and batteries are treated in the same way as in the standard policy scenario. In contrast to the standard policy scenario, RE remains in the free market. As a consequence of this, RE power plants are not subsidized through a FIT mechanism but are decommissioned in the event that their NPV is negative five years in a row.

Table 1
Assumed External Costs in € Cent per MWh.

Lignite	Hard Coal	Oil	Gas	Nuclear	Hydropower	Geothermal	Biomass	Wind	Photovoltaics
11.07	8.97	14.54	4.79	54.73	0.32	0.80	1.32	0.13	0.86

4.2.3.2. Simulation results. The 'free market green policy scenario' produces the lowest sum of subsidies and external costs of all the policy scenarios. The principal reason for this is that RE remains in the free market in this scenario, so that no subsidies are required for RE production and low external costs arise. However, the free market conditions also lead to extremely cyclical RE production; i.e. after five years of very high RE production, power plants are decommissioned due to unprofitable operating. Our assumption in this scenario is that a mixture of batteries and gas power plants then must be installed to secure the electricity supply. The high marginal costs of these gas power plants, once again, leads to a high level of investment in RE, so that the same cycle with five years of high RE production begins again.

4.2.4. Green support policy scenario - batteries subsidized

4.2.4.1. Description. The key feature of the green support policy scenario is that shortages in supply are topped up with an optimal mixture of batteries and green power plants. These supplementary green power plants comprise a combination of onshore and offshore wind energy, photovoltaic, hydro, geothermal and biomass power plants. This combination is based on the distribution of RE power plant technologies as per the expansion goals of the German Federal Government [56]. The supplementary RE power plants together with batteries receive subsidies, which, in turn, allow them to remain in the market even when running at an economic loss. Further assumptions pertaining to the remaining RE and conventional power plants are similar to those in the free market green policy scenario.

4.2.4.2. Simulation results. This scenario results in the highest RE production and the lowest level of CO_2 emissions of all scenarios that guarantee security of electricity supply. However, it also leads to the highest amount of government subsidies by far. This is because all investments in this scenario that are necessary for securing electricity supply are made in a mixture of green power plants. Consequently, all conventional power plants are driven out of the market, and the price of electricity becomes close to zero. This, in turn, prevents additional free market investments in RE, and thus substantial government subsidies are required to maintain security of supply.

4.2.5. Green FIT policy scenario - batteries subsidized

4.2.5.1. Description. The Green FIT policy scenario differs from the previous one due to the way RE is treated. In the Green support policy scenario, both RE generally and the supplementary green power plants were traded under free market conditions. In contradistinction to this, in the Green FIT policy scenario all types of RE are subsidized through a FIT mechanism in case of insufficient electricity supply. The difference between this and the standard policy is that here shortages in electricity supply are topped up with an optimal mixture of batteries and green power plants, whereas, in the standard policy scenario, supply gaps were resolved by an optimal mixture of batteries and gas power plants.

4.2.5.2. Simulation results. This scenario corresponds to the second lowest level of subsidies and external costs. Given that a FIT mechanism is applied in this scenario, the RE expansion is slower, but more constant. This means that the electricity price remains at such a level that conventional power plants can remain in the market and help to secure the electricity supply without the need for high subsidies. Due to the fact that additional investments necessary for meeting electricity demand are made in a mixture of green power plants, this scenario also guarantees the constant expansion of RE. The combination of retaining electricity prices at a relatively high level, so that conventional power plants can operate until they reach the end of their lifecycle, allied with RE constantly expanding without the need for high subsidies renders this energy policy appealing to policymakers.

4.2.6. Regulated RE adaptation policy scenario - batteries subsidized

4.2.6.1. Description. In this policy scenario, the RE adaptation market design, which is a new market design for conventional power plants, is applied. This new market design is based on the work of Coester et al. [1], who developed a market design with the objective of guaranteeing security of electricity supply and fostering RE expansion. The principal assumption of this novel market design is that electricity prices and the profitability of conventional power plants are significantly dependent on the ability of the complex of conventional power plants to optimally react to changes in residual load, i.e. electricity demand minus RE supply. In theory, it is possible to simulate a complex of conventional power plants that can optimally adapt to residual load. To achieve this, the total annual cost per MW for each conventional power plant must be calculated as a function of their periods of use. On that basis, the most cost-effective complex of conventional power plants can be selected for each quantity of residual load for each of the 8760 h per year. This selection of conventional power plants results in an efficiency cost curve. Based on the optimal order and quantities of conventional power plants as per the efficiency cost curve, the actual power plants that exist in the market are able to offer electricity capacities. The profitability of power plants is then once again modelled through the application of the LDCM with the same underlying assumptions (see Section 3.1). In the event of shortages in the electricity supply, we assume in this novel market design that subsidized investment in an optimal mixture of batteries and conventional power plants is carried out. The type of supplementary conventional power plant corresponds to the optimal adapted power plant as per the efficiency cost curve. Furthermore, in this policy scenario, we assume that RE is taken out of the free market and subsequently subjected to a FIT mechanism.

4.2.6.2. Simulation results. The analysis conducted by Coester et al. [1] showed that, in theory at least, such an optimal adapted complex of conventional power plants invariably leads to the highest possible average electricity price and the most cost-efficient supply of electricity. However, their analysis also reveals that the mere orientation of existing power plants to an optimally adapted solution is in itself not sufficient for achieving an improved market environment and ensuring an uninterrupted power supply in the real world. The main reason for this is that, in theory, the optimal complex of conventional power plants can dynamically change depending on changes in the demand for electricity and the production volumes of RE. However, the requirement for dynamic changes in the complex of conventional power plants cannot be met in reality, as the lifecycle of power plants typically amounts to 40 to 50 years.

The application of this new market design as a policy scenario along with batteries also indicates that it is not a cost competitive option for guaranteeing the security of the electricity supply and achieving RE expansion. Most notably, the external costs were the highest of all the policy scenarios. This is because of the application of nuclear power plants with extremely high external costs.

4.2.7. Free market RE adaptation policy scenario - batteries subsidized

4.2.7.1. Description. In the Free market RE adaptation policy scenario, we generally apply the same approach as in the previous scenario. When electricity supply falls below the demand level, then subsidized investments in an optimal mixture of batteries and conventional power plants are made. The only difference concerns the way that RE is treated. In this scenario, RE entirely competes in the free market.

4.2.7.2. Simulation results. This policy scenario also necessitates high external costs, as nuclear energy will not be phased out. Given that RE remains in the free market in this scenario, there are large investments in RE. For this reason, the price of electricity significantly decreases and a significant amount of power plants have to be decommissioned as a result. The new electricity market design is capable of substituting for the reduced electricity supply and, thus, the security of the electricity supply can also be guaranteed in this policy scenario.

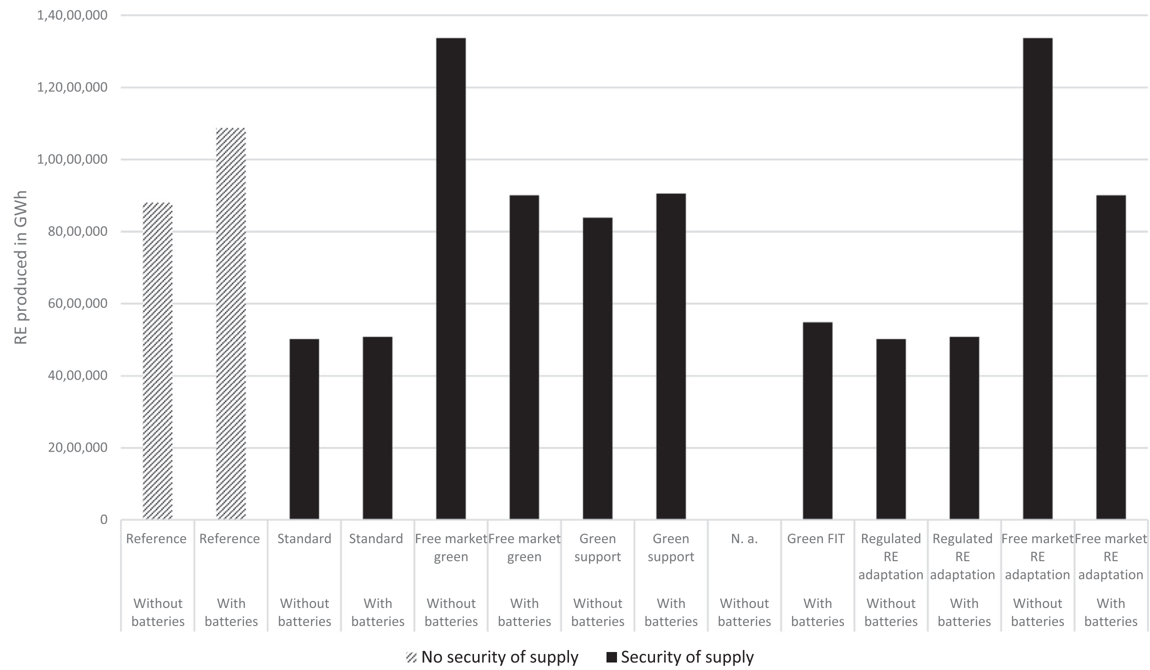

Fig. 3. RE produced (cumulative over the simulation period) [The scenarios without batteries are based on Coester et al. [2]].

4.3. Discussion of results

In this subsection, we further analyze the results of our simulations concerning the security of the electricity supply, RE produced, electricity supply from batteries, CO_2 emissions, subsidies and external costs (Sections 4.3.1-4.3.5; Figs. 3–6). For an overview of the development of installed capacity for conventional power plants, RE and batteries over time under the different scenarios the reader is referred to Figs. A1–A7 in the appendix. Section 4.3.6 compares the results with similar policy scenarios without batteries as per the discussion in Coester et al. [2]. Table 2 provides an overview of the results of all scenarios, both with and without batteries. Finally, Section 4.3.7 analyses the sensitivity of results with regards to changes in electricity demand and the costs of batteries.

4.3.1. Security of electricity supply

The simulation results show that, under completely free market conditions in the reference policy scenario, electricity supply falls below demand, which means that there is no security of electricity supply. This is because of large investments in RE power plants, particularly wind energy. Their low marginal costs lead to a significant reduction in the price of electricity, with the consequence being that both conventional and RE power, as well as batteries, are not able to operate profitably. With regards to the six policy scenarios outlined here, all policy scenarios are capable of guaranteeing the security of the electricity supply. In Figs. 3–6 below the reference scenario, which is incapable of securing the electricity supply, is depicted with dashed bars. Note that Figs. 3, 5 and 6 also include results for scenarios without batteries which will be discussed in Section 4.3.7.

4.3.2. Renewable energy produced

Fig. 3 depicts that most RE is produced in those scenarios (with batteries) where RE is traded on the free market. The three scenarios in which RE operates in the free market result in a total RE production of more than 9 million GWh over the 20 years simulation period.

However, it is important to mention here that the development of RE power plant capacity in these scenarios is extremely cyclical. Under free market conditions, electricity prices are (initially) set by

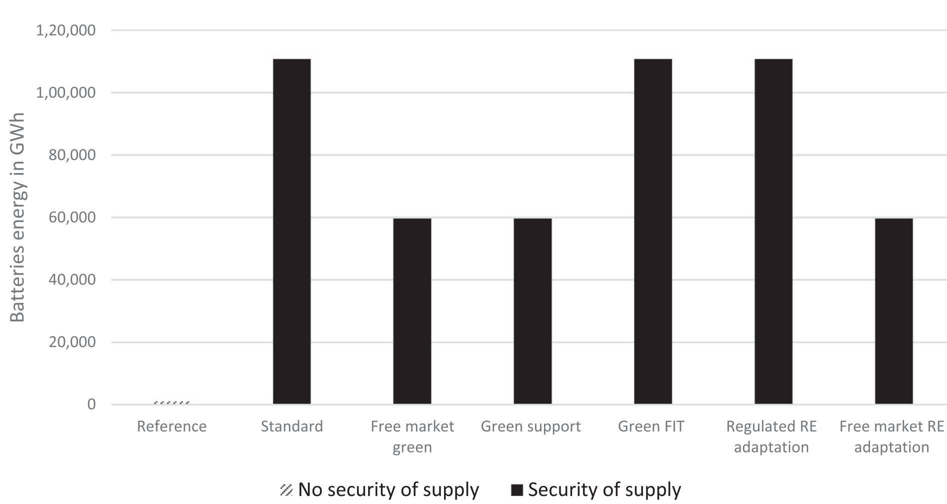

Fig. 4. Electricity supply from batteries (cumulative over the simulation period).

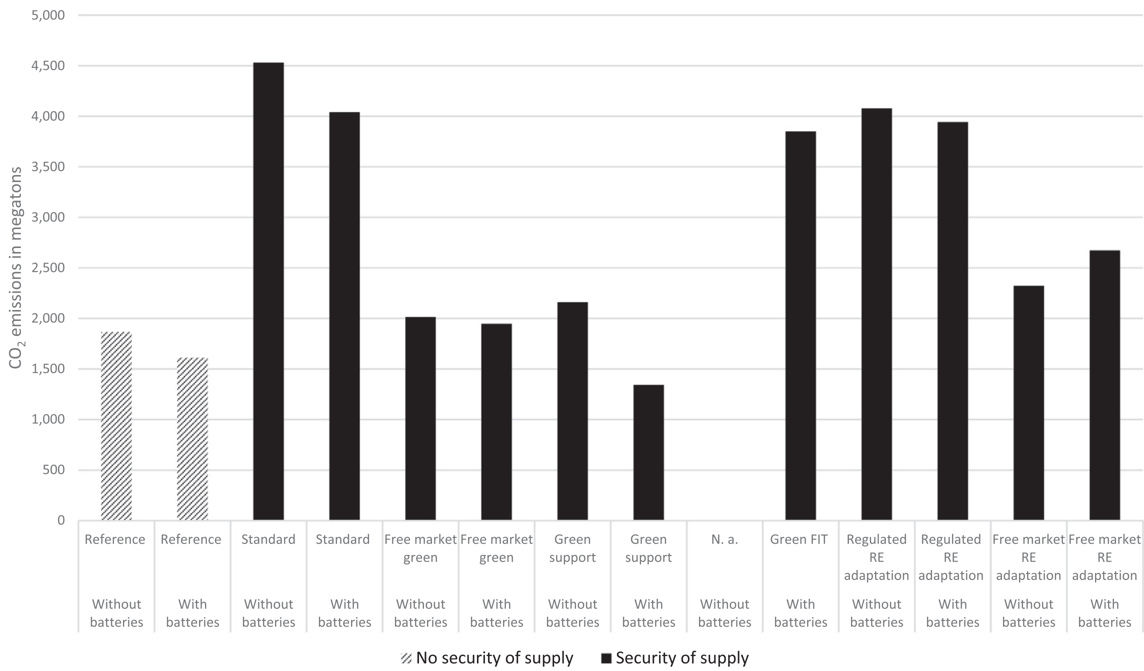

Fig. 5. CO_2 emissions (cumulative over the simulation period) [The scenarios without batteries are based on Coester et al. [2]].

conventional power plants operating with high marginal costs, resulting in huge investments in RE. Following this, the low marginal cost RE production pushes conventional power plants out of the market and results in an electricity price close to zero. In response to this, both RE and conventional power plants are decommissioned after five consecutive years of unprofitable operation. This results in a shortage of energy supply, which, in turn, leads to subsidized investments in an optimal mixture of batteries and efficient gas power plants ('Free market green – batteries subsidized'), subsidized investments in a mixture of batteries and green power plants('Green support – batteries subsidized') and subsidized investment in a mixture of batteries and conventional power plants ('Free market RE adaptation – batteries subsidized'). These subsidized batteries and power plants trigger new, substantial investments in RE power plants so that the same cycle of investment and subsequent disinvestment begins all over again.

In comparison to RE on the free market, those policy scenarios that apply a FIT mechanism lead to a lower RE production of around 5 million GWh. On the other hand, RE expansion in these scenarios is altogether more stable, with the consequence being that prices and the profitability of RE and conventional power plants are less affected than in the free market scenario.

4.3.3. Electricity supply from batteries

In the reference policy scenario, batteries are assumed to be a dynamic investment option in a free electricity market model. As Fig. 4 shows, this assumption results in no battery investment. Even though

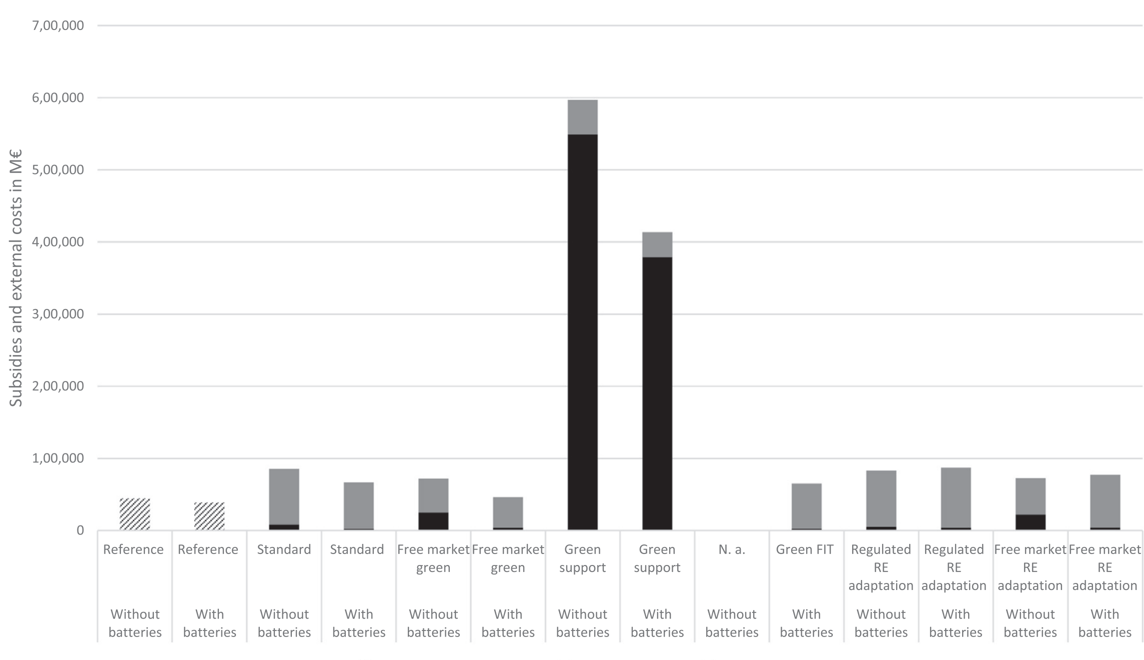

Fig. 6. Subsidies and external costs (cumulative over the simulation period) [The scenarios without batteries are based on Coester et al. [2]].

Table 2
Comparison of Policy Scenarios (cumulative over the simulation period).

Reference scenario and policy scenarios	Battery utilization	Assumption RE	Assumption Conventional energy	Assumption batteries	Security of Supply	RE produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megatons	Subsidies in M€	External costs in M€	Σ Subsidies and external costs in M €
Reference	Yes	Free market	Free market	Free Market	No	10,873,143	0	1,613	0	39,026	39,026
	No	Free market	Free market	n. a.	No	8,799,807	n. a.	1,867	0	44,604	44,604
Standard	Yes	FIT	Subsidization gas power pl.	Subsidization	Yes	5,078,644	110,839	4,041	2,327	64,314	66,641
	No	FIT	Subsidization	n. a.	Yes	5,013,884	n. a.	4,533	8,473	77,040	85,513
Free market green	Yes	Free market	Subsidization gas power pl.	Subsidization	Yes	9,009,828	59,712	1,946	3,842	42,385	46,227
	No	Free market	Subsidization	n. a.	Yes	13,370,005	n. a.	2,015	25,019	46,912	71,932
Green support	Yes	Subsidization green power pl.	Free market	Subsidization	Yes	9,055,392	59,712	1,343	378,939	34,769	413,708
	No	Subsidization	Free market	n. a.	Yes	8,389,771	n. a.	2,161	549,430	47,394	596,824
Green FIT	Yes	FIT	Free Market	Subsidization	Yes	5,483,277	110,839	3,849	2,575	62,546	65,121
	No	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.	n. a.
Regulated RE adaptation	Yes	FIT	Optimal adaptation/	Subsidization	Yes	5,078,644	110,839	3,942	3,741	83,427	85,791
	No	FIT	Subsidization	n. a.	Yes	5,013,884	n. a.	4,078	5,419	77,914	83,334
Free market RE adaptation	Yes	Free market	Optimal adaptation/	Subsidization	Yes	9,009,828	59,712	2,673	3,970	73,317	77,287
	No	Free market	Subsidization	n. a.	Yes	13,370,005	n. a.	2,322	22,321	50,393	72,714

the investment costs in batteries are assumed to decrease over the period under consideration, they are still too high to engender profitable investments. On those days in which the spread between the maximum and the minimum electricity price is high, the contribution margins are sufficient to compensate for high (daily) battery costs. However, the overall NPV maximization modelling over the entire year results in no battery investment. Within those policy scenarios where battery investments are applied as government subsidies to guarantee the security of supply and achieve RE expansion, the cumulative electricity supply from batteries varies between 59,712 GWh and 110,839 GWh. In those scenarios where RE is traded on the free market, the large RE investments result in a relatively small electricity supply gap. Consequently, the optimal amount of electricity supply from batteries is lower at 59,712 GWh. When RE is assumed to be supported by a FIT mechanism, the slower but more constant development of RE requires nearly twice the electricity supply from government subsidized batteries.

4.3.4. CO_2 emissions

With regards to CO_2 emissions, Fig. 5 illustrates that the policy scenarios (with batteries) in which RE is traded on the free market culminate in the lowest amount of total emissions over the period of investigation of 20 years. In particular, the ‘Green support policy scenario’ leads to the lowest CO_2 emissions of all the policy scenarios with only 1343 megatons. On the one hand, this is because RE is traded on the free market in this scenario, which results in high RE investments (see Fig. 3). In addition to this, the subsidized investments in batteries are supplemented by an optimal mixture of RE power plants in this scenario. This further reduces the amount of emissions compared to supplementation via gas power plants that occurred in the ‘Free market green policy scenario’, corresponding to the second lowest total emissions of around 1900 megatons.

Policy scenarios in which RE are subject to a FIT mechanism result in higher CO_2 emissions of around 4000 megatons. As noted in the previous subsections, this is because RE expands more slowly under FITs, with the effect being that more CO_2 emitting conventional power plants operate in the market.

4.3.5. Subsidies and external costs

Fig. 6 shows that the ‘green support policy scenario’ (with batteries) requires the highest amount of government subsidies by far at € 379 billion. As aforesaid, in this scenario RE is traded on the free market, while all necessary investments for guaranteeing the security of the supply are made via an optimal mixture of batteries and green power plants. For this reason, all conventional power plants are driven out of the market, which results in an electricity price close to zero and, hence, extremely high subsidies. At the same time, due to the high level of RE production this scenario produces the lowest external costs. However, the total sum of the subsidies and external costs associated with the ‘green support policy scenario’ significantly exceeds those of the remaining policy scenarios (with batteries). The policy scenario that requires the lowest government subsidies is the ‘standard policy scenario’, totaling around € 2.3 billion. These subsidies account for the FIT mechanism that is applied in this scenario. Because this mechanism leads to a slower expansion of RE compared to free market conditions, the electricity prices in the market are at a higher level, which means that no further subsidies for batteries or supplementary gas power plants are required.

The ‘green FIT policy scenario’ only slightly results in higher subsidies (€ 2.6 billion), but corresponds to lower external costs (as necessary supplementations to battery investments are not made in efficient gas power plants, but rather in a mixture of RE power plants). Overall, the total sum of subsidies and external costs amounts to approximately € 65 billion. The ‘free market green policy scenario’ corresponds to the lowest sum of subsidies and externalities, totaling around € 46 billion. In comparison to the ‘green FIT policy scenario’,

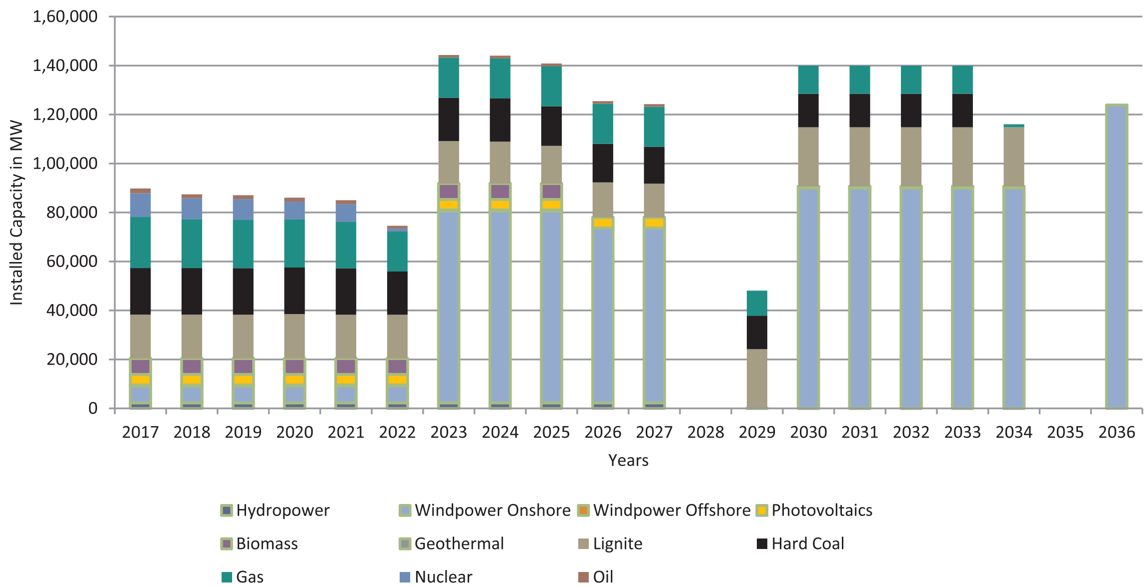

Fig. A1. Reference scenario, installed capacity for conventional power plants and RE.

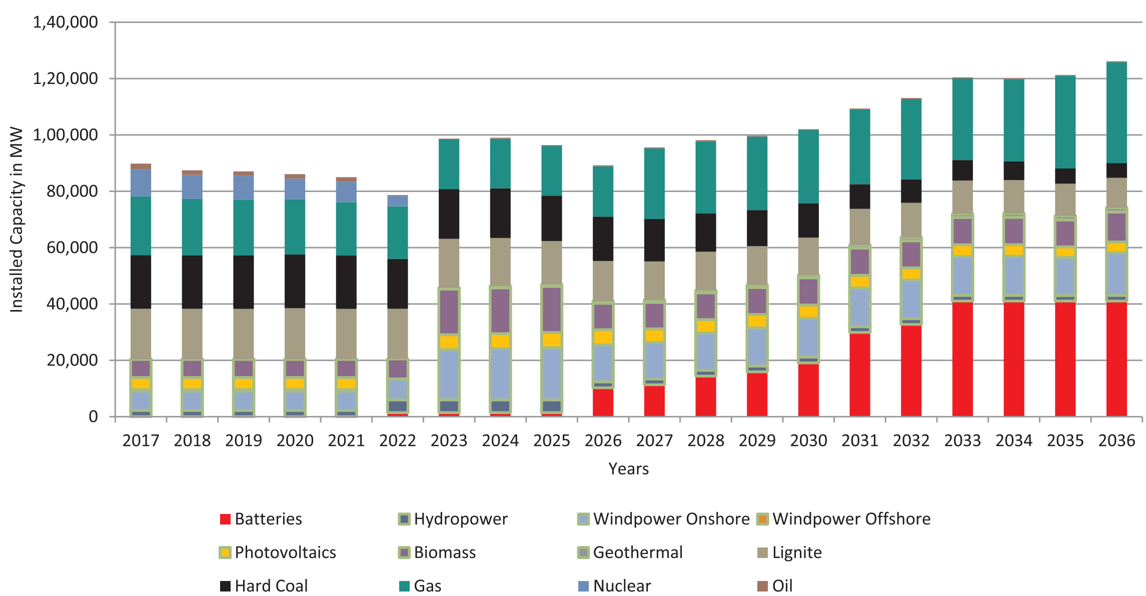

Fig. A2. Standard policy scenario – batteries subsidized, installed capacity for conventional power plants, RE and batteries.

subsidies are higher, but external costs are considerably lower due to the higher amount of RE produced.

The 'regulated RE adaptation battery scenario' is not a cost-competitive option. In addition to the subsidies that are necessary for RE in the FIT mechanism, the newly developed market design does not allow for a profitable operation of batteries, which means that further subsidies must be spent. External costs in this scenario are the highest of all policy scenarios at € 83.4 billion. This is primarily because nuclear power plants, which have the highest external costs per MWh produced of all power plants, are not phased-out and remain in operation. In comparison, the 'free market RE adaptation scenario' results in slightly lower total costs, since RE remains on the free market which leads to lower external costs.

In summary, higher amounts of RE production, in the policy scenarios where RE is traded on the free market, lead to market conditions that require subsidies for both batteries and the respective supplementary investments. On the other hand, high RE production volumes result in considerably lower external costs across these specific policy scenarios. However, as aforesaid in Section 4.3.1, RE production can be profoundly cyclical (and, hence, of less appeal to policymakers). In contrast, the 'green FIT policy scenario' (which has the second lowest level of subsidies and external costs) displays a more stable expansion of RE and leads to lower subsidies. Conventional power plants can be successively phased-out in this scenario, i.e. decommissioned when they reach the end of their economic lifecycle.

4.3.6. Summary and comparison with policy scenarios that do not apply batteries

Table 2 gives an overview of our simulation results (with the utilization of batteries) and the results of corresponding policy scenarios that do not apply batteries (for a detailed description and analysis of the scenarios without batteries, see [2]. With regards to securing a stable electricity supply, those policy scenarios that include use of batteries show similar results to the corresponding ones without batteries. In the reference scenario, the electricity supply is insufficient for the demand. The alternative policy scenarios are capable of guaranteeing the security of the supply. Concerning the expansion of RE, policy scenarios with and without batteries also show relatively similar results.

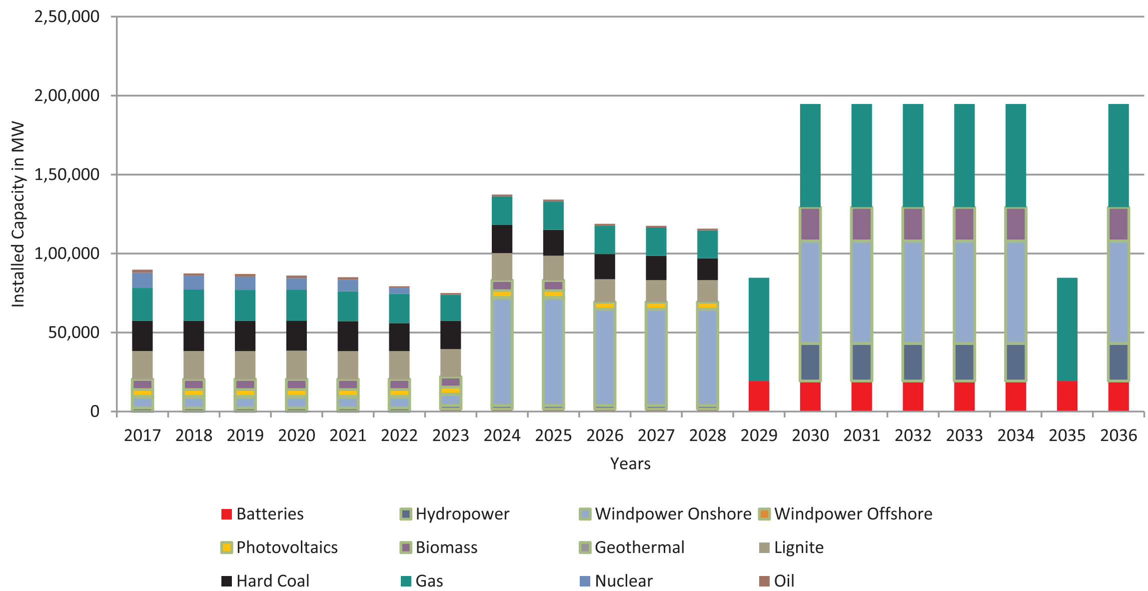

Fig. A3. Free market green policy scenario – batteries subsidized, installed capacity for conventional power plants, RE and batteries.

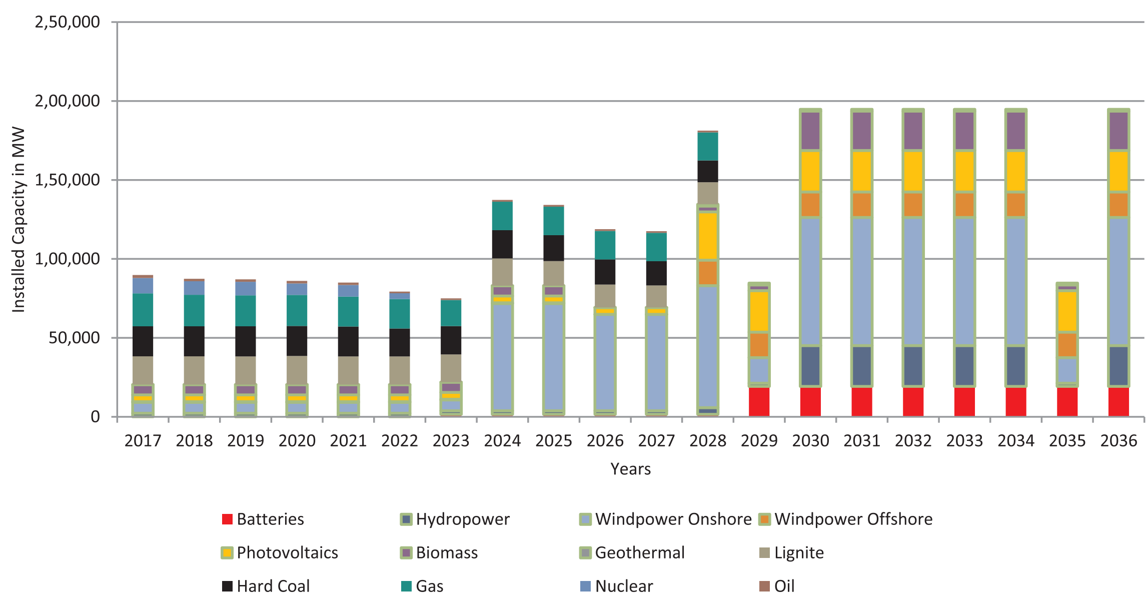

Fig. A4. Green support policy scenario – batteries subsidized, installed capacity for conventional power plants, RE and batteries.

However, in these scenarios where RE remains on the free market, the application of batteries results in a lower expansion of RE. This is because the utilization of batteries reduces peak load prices (see Section 3.2.1), so that investments become less attractive to private investors. The comparison of CO_2 emissions makes clear that the application of batteries leads to reduced emissions. More specifically, the simulations show that this is because batteries store excess RE supply and discharge it during times of high demand, so that less conventional power plants are required. Fig. 6 compares the subsidies and external costs of the developed policy scenarios with the corresponding costs of those scenarios that do not adopt the use of batteries. The results clearly demonstrate that, with the exception of the 'regulated RE adaptation policy scenario' and the 'free market RE adaptation policy scenario', all policy scenarios that adopt batteries result in both lower external costs and lower subsidies. The total costs of the 'free market green policy scenario', which has the lowest total costs among those policy scenarios including batteries, are around € 26 billion (36%) below the costs of the comparable scenario without batteries.

Regarding the decrease in CO_2 emissions, the significant reduction in external costs compared to the comparable scenarios without batteries can be explained by the replacement of conventional power plants by battery storage of excess RE. Batteries are able to store excess electricity that is produced in times of low demand, particularly during the night. This excess electricity comprises to a large extent of wind energy, which has very low external costs. Furthermore, batteries can release electricity during the hours of high demand. As a result, the need for flexibly available power plants, which are typically CO_2 intensive conventional power plants, is reduced. For the same reasons, government subsidies also decrease here in comparison to policy scenarios that do not apply batteries. The charging of batteries in times of low demand leads to a higher utilization of power plants, which, in turn, improves their profitability, so that less subsidies need to be spent. The discharging of batteries when demand is high reduces the need for peak load power plants, which are often highly dependent on subsidies due to low operating hours and small contribution margins stemming from their high marginal costs.

In conclusion, then, many of our simulations are in line with the findings in the existing academic literature. Our simulations indicate

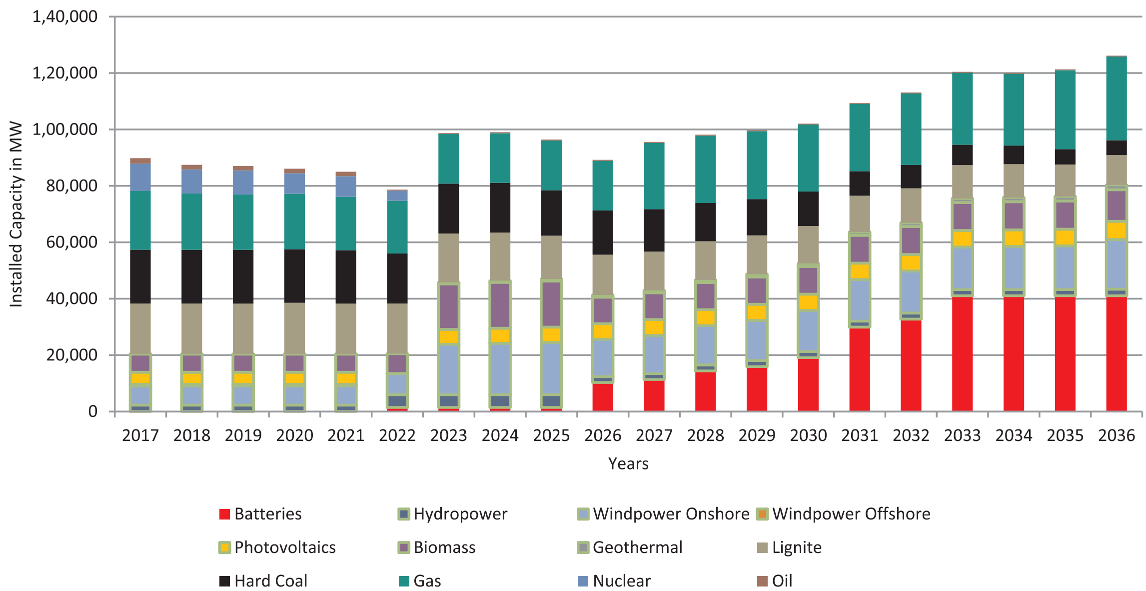

Fig. A5. Green FIT policy scenario – batteries subsidized, installed capacity for conventional power plants, RE and batteries.

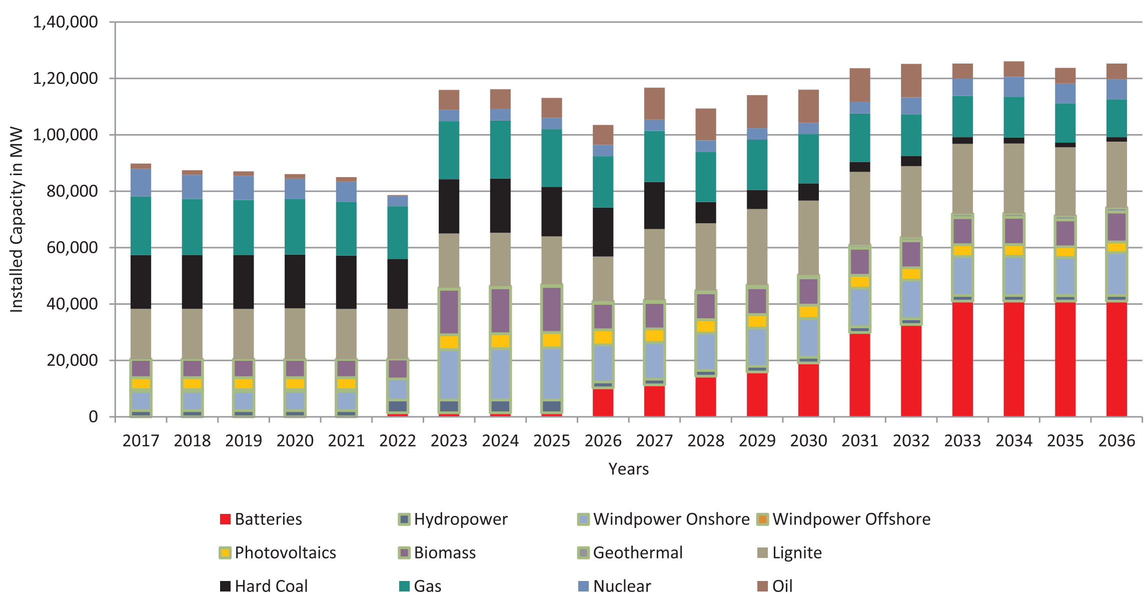

Fig. A6. Regulated RE adaptation policy scenario – batteries subsidized, installed capacity for conventional power plants, RE and batteries.

that batteries could be very suitable as a supplementation to the fluctuating supply of RE, due to their ability to store excess RE supply and discharge it during times of high demand. Furthermore, similar to earlier results in the literature (e. g. [12], our findings indicate that the utilization of batteries reduces the amount of conventional power plants and hence leads to a decrease in CO_2 emissions. Our simulations also show that free market-based investments in batteries are not competitive compared to RE or conventional energy technologies (similar to the findings of e. g. [28]. Finally, our simulations indicate that for most of the policy scenarios we developed, the required amount of government subsidies is considerably lower as compared to required subsidies in corresponding policy scenarios that do not apply batteries. Consequently, governments should consider the application of batteries as an important technology for achieving ongoing RE expansion and security over the electricity supply.

4.3.7. Sensitivity analysis

We carried out a sensitivity analysis to identify changes in the demand for electricity, as well as changes to the costs of batteries (detailed results are available from the authors upon request). Our results show that modest variations in electricity demand (± 0.50%/year) do not have a significant effect on our key findings pertaining to energy security, RE expansion and the amount of installed battery capacity. Within a free market environment, a 10 percent reduction in the cost of batteries does not lead to increased battery investment. In the other proposed policy scenarios, a decrease in the costs of batteries leads to a reduction of subsidies that provide necessary compensation for years of unprofitable battery operations (not applicable for the standard policy scenario and green FIT policy scenario, which do not require any battery subsidization at all).

5. Conclusions

As a result of the ongoing expansion of renewable energy with low marginal costs, electricity prices have decreased. Consequently, many renewable energy and conventional power plants are no longer able to operate profitably and ultimately shut down. Based on empirical data, our research shows that, under free market conditions, this results in an

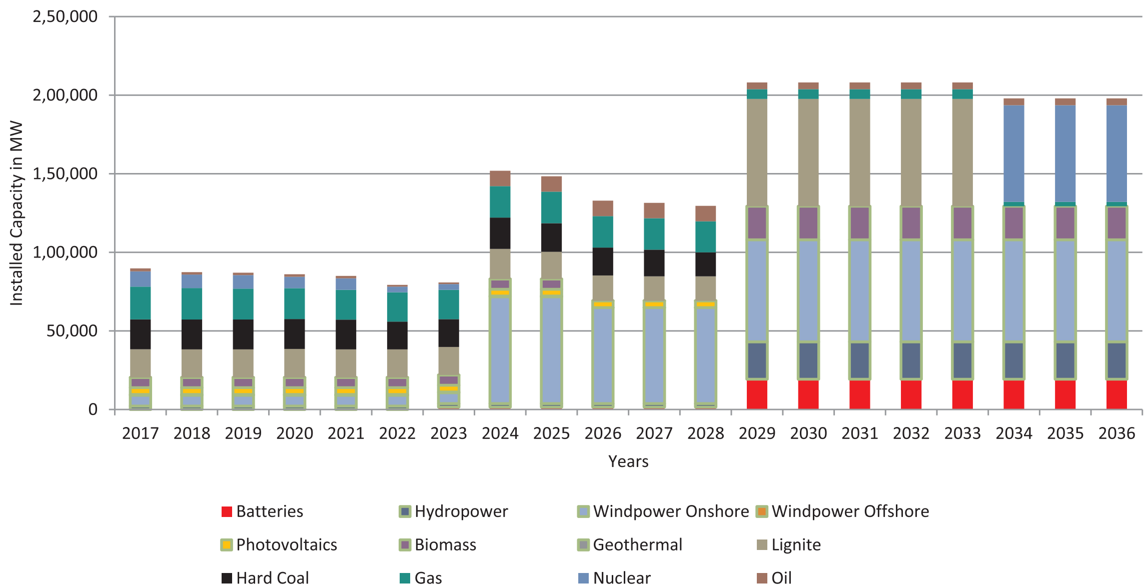

Fig. A7. Free market RE adaptation policy scenario – batteries subsidized, installed capacity for conventional power plants, RE and batteries.

insufficient electricity supply to meet demand. In this context, we analyzed the impact of batteries on renewable energy expansion and the security of the electricity supply. Despite substantial cost reductions in batteries due to technological innovation in recent years, our reference policy scenario shows that, in a free market environment, battery investment is not profitable for private investors. On the other hand, through developing six policy scenarios we showed that by subsidizing investments in batteries governments could ensure a secure electricity supply as well as ongoing renewable energy expansion. Comparisons to comparable policy scenarios that do not adopt batteries indicated that the total sum of government subsidies and external costs was up to 36% lower as a consequence of utilizing batteries. Our analysis showed that batteries are capable of storing excess electricity production, particularly from renewable energy, resulting in a higher utilization of power plants and the replacement of high CO_2-emitting conventional power plants. Policymakers should be aware that the merit order effect of renewable energies (which leads to reduced electricity prices) is a significant risk with respect to securing the electricity supply and achieving renewable energy expansion, and, as such, requires some form of governmental intervention. Our analysis underscores that batteries are a very useful technology through which to simultaneously guarantee ongoing renewable energy expansion and an uninterrupted electricity supply. Furthermore, we underlined that policymakers should always take into consideration the external costs of energy generation when deciding on sustainable policy scenarios.

In general, our results for the German market could be relevant for other countries that aim to increase renewable energy production. Independent of the policy scenario that a country chooses for renewable energy, increasing amounts of renewable energy production will always lead to the challenge of securing a stable electricity supply under fluctuating renewable energy levels. Government subsidies for batteries might be an economically efficient policy scenario for countries to simultaneously guarantee ongoing renewable energy expansion and an uninterrupted electricity supply. Developing economies that often have a huge potential for renewable energy expansion, but at the same time often lack technological expertise and capital to invest in renewable energy technologies, could also apply the recommended subsidization mechanism. The subsidization could be funded by a surcharge on all electricity consumers of the particular economy with electricity-intensive manufacturers being (almost) excluded in order to maintain their international competitiveness. This would allow for profitable investment conditions and consequently international investors and manufacturers could be attracted to invest and transfer their state-of-the art technologies in the developing economies. In order to minimize the surcharge that has to be paid by electricity consumers, governments could additionally grant tax reductions to renewable energy or battery companies. Foreign aid could further facilitate the transition to sustainable energies in developing economies.

Lastly, it is important to acknowledge and reflect on the limitations of our methodological approach; these largely relate to the assumptions adopted for the simulation analysis. In our electricity market model, we utilized average availability factors for renewable energy. This assumption does not allow to investigate the impact of actual fluctuations of renewable energy in detail. Future research could expand our analytical framework with hourly simulations of renewable energy availabilities. This would give a more detailed overview of the economic impacts of both actual excess demand and excess supply in times of very low and very high renewable energy production respectively. Furthermore, our analysis was confined to a limited number of economic and environmental indicators. Future research should broaden the focus and discuss impacts on additional (macro)economic variables (e.g. financial indicators, effects on employment, etcetera) as well as additional environmental indicators (e.g. SO2, PM, NOx, toxic and hazardous materials of batteries, resource use, water use and land reclamation). Moreover, we did not consider the possibility of an increasing utilization of additional storage options, such as electric vehicles and power-to-gas. As these technologies increasingly lead to a rise in electricity demand and serve as storage capacities, it would be an interesting extension of our research to include such options. Finally, future research could expand upon our analytical framework by including the effects of cross-border electricity trade and exploring new remuneration mechanisms for renewable energy.

CRediT authorship contribution statement

Andreas Coester: Conceptualization, Methodology, Formal analysis, Writing - review & editing, Visualization. **Marjan W. Hofkes:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Visualization. **Elissaios Papyrakis:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Visualization.

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.

Appendix

See Figs. A1–A7.

References

[1] Coester A, Hofkes MW, Papyrakis E. An optimal mix of conventional power systems in the presence of renewable energy: A new design for the German electricity market. Energy Policy 2018;116:312–22.
[2] Coester A, Hofkes MW, Papyrakis E. Economics of renewable energy expansion and security of supply: A dynamic simulation of the German electricity market. Appl Energy 2018;231:1268–84.
[3] Huneke F, Lizzi P, Lenck T. The Consequences so far of Germany's Nuclear Phaseout on the Security of Energy Supply. KG, Berlin: Energy Brainpool GmbH & Co; 2016.
[4] Zakeri B, Syri S. Electrical Energy Storage Systems: A Comparative Life Cost Analysis. Renew Sustain Energy Rev 2015;42:569–96.
[5] Bräutigam A, Rothacher T, Staubitz H, Trost R. The Energy Storage Market in Germany. Berlin: Germany Trade & Invest Fact Sheet; 2016.
[6] IEA and IRENA. Perspectives for the Energy Transition – Investment Needs for a Low-Carbon Energy System. International Energy Agency and International Renewable Energy Agency, https://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf (accessed on 20 June 2017). 2017.
[7] Hydrogen Council. How Hydrogen Empowers the Energy Transition, http://hydrogeneurope.eu/wp-content/uploads/2017/01/20170109-HYDROGEN-COUNCIL-Vision-document-FINAL-HR.pdf (accessed on 20 June 2017). 2017.
[8] Larcher D, Tarascon JM. Towards greener and more sustainable batteries for electrical energy storage. Nat Chem 2015;7:19–29.
[9] Janek J, Zeier W. A solid future for battery development. Nat Energy 2016;1. Article number 16141.
[10] Naumann M, Kar RC, Truong CN, Jossen A, Hesse HC. Lithium-ion Battery Cost Analysis in PV-household Application. Energy Procedia 2015;73:37–47.
[11] Zerrahn A, Schill WP. Long-run power storage requirements for high shares of renewables: review and a new model. Renew Sustain Energy Rev 2017;79:1518–34.
[12] Hemmati R, Saboori H, Jirdehi M. Multistage generation expansion planning incorporating large scale energy storage systems and environmental pollution. Renew Energy 2016;97:636–45.
[13] Bento P, Nunes H, Pombo J, do Rosário Calado M, Mariano S. Daily Operation Optimization of a Hybrid Energy System Considering a Short-Term Electricity Price Forecast Scheme. Energies 2019;12(5).
[14] Zhao H, Wu Q, Hu S, Xu H, Rasmussen CN. Review of energy storage system for wind power integration support. Appl Energy 2015;137:545–53.
[15] Gaete-Morales C, Gallego-Schmid A, Stamford L, Azapagic A. A novel framework for development and optimization of future electricity scenarios with high penetration of renewables and storage. Appl Energy 2019;250:1657–72.
[16] Narayanan A, Mets K, Strobbe M, Develder C. Feasibility of 100% renewable energy-based electricity production for cities with storage and flexibility. Renew Energy 2019;134:698–709.
[17] Zerrahn A, Schill WP, Kemfert C. On the economics of electrical storage for variable renewable energy sources. Eur Econ Rev 2018;108:259–79.
[18] Timilsina GR, Kurdgelashvili L, Narbel PA. Solar energy: Markets, economics and policies. Renew Sustain Energy Rev 2012;16(1):449–65.
[19] Nandi SK, Ghosh HR. Prospect of wind–PV-battery hybrid power system as an alternative to grid extension in Bangladesh. Energy 2010;35(7):3040–7.
[20] Afanasyeva S, Breyer C, Engelhard M. Impact of battery cost on the economics of hybrid photovoltaic power plants. Energy Procedia 2016;99:157–73.
[21] Kempton W, Tomić J. Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy. J Power Sources 2005;144(1):280–94.
[22] Kempton W, Kubo T. Electric-drive vehicles for peak power in Japan. Energy Policy 2000;28(1):9–18.
[23] Scott MJ, Kintner-Meyer M, Elliott DB, Warwick WM. Impacts assessment of plug-in hybrid vehicles on electric utilities and regional US power grids: Part 2: economic assessment. Pacific: Northwest National Laboratory; 2007.
[24] Babrowski S, Jochem P, Fichtner W. Electricity storage systems in the future German energy sector: an optimization of the German electricity generation system until 2040 considering grid restrictions. Comput Oper Res 2016;66:228–40.
[25] Sinn HW. Buffering volatility: A study on the limits of Germany's energy revolution. Eur Econ Rev 2017;99:130–50.
[26] Schill WP, Zerrahn A. Long-run power storage requirements for high shares of renewables: results and sensitivities. Renew Sustain Energy Rev 2018;83:156–71.
[27] Pape C. Roadmap Speicher: Speicherbedarf für erneuerbare Energien – Speicheralternativen – Speicheranreiz – Überwindung rechtlicher Hemmnisse, http://www.fvee.de/fileadmin/publikationen/Politische_Papiere_FVEE/14.IWES_Roadmap-Speicher/14_IWES-etal_Roadmap_Speicher_Langfassung.pdf (accessed on 05 January 2018). 2014.
[28] Nieto A, Vita V, Ekonomou L, Mastorakis NE. Economic analysis of energy storage system integration with a grid connected intermittent power plant, for power quality purposes. WSEAS Trans Power Syst 2016;2:5.
[29] Locatelli G, Palerma E, Mancini M. Assessing the economics of large Energy Storage Plants with an optimisation methodology. Energy 2015;83:15–28.
[30] Poulin A, Dostie M, Fournier M, Sansregret S. Load duration curve: A tool for technico-economic analysis of energy solutions. Energy Build 2008;40(1):29–35.
[31] Turner WC, Doty S. Energy Management Handbook. 6th ed. Lilburn: The Fairmont Press Inc.; 2007.
[32] Geiger A. Strategic Power Plant Investment Planning under Fuel and Carbon Price Uncertainty. Karlsruhe: Karlsruher Institut für Energie; 2010.
[33] Sensfuß F, Ragwitz M, Genoese M. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy 2008;36(8):3086–94.
[34] Enervie, 2014. Personal interview with the head of electricity generation.
[35] Federal Network Agency. Kraftwerksliste, http://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/kraftwerksliste-node.html (accessed on 13 March 2018), 2015.
[36] WestLB. Empirical data collection. Research department, Westdeutsche Landesbank German Bank. 2009.
[37] Agency for Renewable Energies, 2012. Studienvergleich: Entwicklung der Investitionskosten neuer Kraftwerke, http://www.forschungsradar.de/uploads/media/AEE_Dossier_Studienvergleich_Investitionskosten_nov12.pdf (accessed on 20 June 2017).
[38] EWI, GWS, Prognos. Energieszenarien für ein Energiekonzept der Bundesregierung, Projekt Nr. 12/10 des Bundesministeriums für Wirtschaft und Technologie, Basel, Köln und Osnabrück. 2010.
[39] Koepp M, Peter F. Ohne Kohle und Gas geht es nicht, https://www.prognos.com/fileadmin/pdf/publikationen/trendletter/trendletter_2008_1_Energie_Seite_10.pdf (accessed on 15 September 2012). 2008.
[40] Federal Ministry for Economic Affairs and Energy. Energy Data: Complete Edition, https://www.bmwi.de/Redaktion/EN/Artikel/Energy/energiedaten.html (accessed on 26 December 2017), 2016a.
[41] Kaltschmitt M, Streicher W, Wiese A. Erneuerbare Energie – Systemtechnik, Wirtschaftlichkeit, Umweltaspekte. Berlin: Springer; 2014.
[42] Deutsche Windguard GmbH. Kostensituation der Windenergie an Land in Deutschland, file://eu.degussanet.com/dfs-027/USRH22/A27186/data/profile%20redirected%20folders/downloads/Kostensituation%20der%20Windenergie%20an%20Land%20in%20Deutschland.pdf (accessed on 10 October 2017), 2013.
[43] EEX (European Energy Exchange). Solar & Wind Power Production. https://www.eex-transparency.com/homepage/power/germany/production/usage/solarwind-power-production/solar-wind-power-production-chart/ (accessed on 3 October 2016), 2010-2014.
[44] Möst D, Müller T, Schubert D. Herausforderungen und Entwicklungen in der deutschen Energiewirtschaft – Auswirkungen des steigenden Anteils an erneuerbarer Energien auf die EEG-Umlagekosten und die Versorgungssicherheit, Electricity Markets Working Papers, Vol. 52. 2012.
[45] EEX (European Energy Exchange). Actual Consumption. https://www.eex-transparency.com/homepage/power/germany/consumption/usage/actual-consumption (accessed on 26 December 2017), 2010-2013.
[46] Zapf M. Stromspeicher und Power-to-Gas im deutschen Energiesystem: Rahmenbedingungen. Bedarf und Einsatzmöglichkeiten. Springer Vieweg; 2017.
[47] Mahnke E, Mühlenhoff J, Lieblang L. Strom Speichern. Renews Spezial, Nr. 2014:75.
[48] Sterner M, Stadler I. Energiespeicher – Bedarf, Technologien, Integration. Springer Vieweg; 2014.
[49] Krewitt W, Schlomann B. Externe Kosten der Stromerzeugung aus erneuerbaren Energien im Vergleich zur Stromerzeugung aus fossilen Energieträgern, http://www.bmu.de/files/erneuerbare_energien/downloads/application/pdf/ee_kosten_stromerzeugung.pdf (accessed on 20 September 2017). 2006.
[50] Hohmeyer O. Vergleich externer Kosten der Stromerzeugung in Bezug auf das Erneuerbare Energien Gesetz, http://www.loy-energie.de/download/hohmeyer%20externe%20kosten.pdf (accessed on 20 June 2017). 2002.
[51] Enquete-Kommission. Schutz der Erdatmosphäre - Mehr Zukunft für die Erde – Nachhaltige Energiepolitik für dauerhaften Klimaschutz, Bonn, 1995.
[52] Enquete-Kommission. Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung, Amtl. Drucksache Nr. 14/9400, 2002.
[53] Friedrich R. ExternE: Methodology and Results, http://www.externe.info/brussels/br0900.pdf (accessed on 20 June 2017). 2005.
[54] Braun M. Environmental External Costs from Power Generation by Renewable Energies. Institut für Energiewirtschaft und Rationelle Energieanwendung; 2004.
[55] Federal Ministry for Economic Affairs and Energy. EEG in Zahlen: Vergütungen, Differenzkosten und EEG-Umlage 2000-2007, www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/eeg-in-zahlen-pdf.pdf?__blob = publicationFil (accessed on 20 June 2017), 2016b.
[56] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety. Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global, http://www.dlr.de/dlr/Portaldata/1/Resources/documents/BMU_Leitszenario2009_Langfassung.pdf (accessed on 15 August 2017), 2012.