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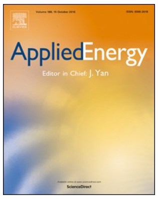

Economics of renewable energy expansion and security of supply: A dynamic simulation of the German electricity market☆

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

[a] *Institute for Environmental Studies, Vrije Universiteit Amsterdam, De Boelelaan 1087, 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*
[d] *School of International Development, University of East Anglia (UEA), NR2 4AG Norwich, UK*

HIGHLIGHTS

- Market model with renewables as an economically-driven investment option.
- Development of policy scenarios for renewable expansion and security of supply.
- New market design with optimal adaption of conventional power to renewables.
- Simulation of renewables that are able to generate base-loadable electricity.
- Cost comparison for governments to reach energy goals.

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ABSTRACT

We explore the impact of renewable energy under free market conditions on the security of energy supply using data for the German electricity market. We design a fundamental electricity market model, where renewable energy capacity is not driven by expansion goals, but is dynamically modeled as an economically-driven investment option. Furthermore, we analyze the economics of five policy scenarios designed to secure both electricity supply and renewable energy expansion. Our analysis demonstrates that renewable energy expansion leads to conventional power plant shut-downs (due to economic losses) and, as a result, to energy shortages. We find that the application of a fixed feed-in tariff mechanism for renewable energy (i.e. a fixed payment for the provided energy) is an appropriate instrument to simultaneously achieve renewable energy expansion and uninterrupted energy supply. However, when internalizing the external costs of electricity generation, the scenario of a free market for renewable energy together with subsidies for conventional power plants becomes the most cost efficient option.

1. Introduction

The political and economic conditions in Germany for renewable energy (RE) have changed over the past years. As a consequence, providers of RE have been participating increasingly in the free electricity market, instead of relying on fixed feed-in tariffs (FITs). In parallel, the increasing use of RE technologies with low marginal costs is causing substantial economic problems for conventional power plants and consequently for the utility corporations that own them. Recent research (see [1]) has shown that the economic losses of conventional power plants results in decommissionings and, as a result, in insufficient generation capacity to meet peak demand. Against this background, the question arises whether the current market mechanisms allow for a profitable operation of RE that ensures meeting the

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Abbreviations: CCGT, combined cycle gas turbines; CM, contribution margin; CPP, full power plant capacity; EEG, erneuerbare energien gesetz (renewable energy sources act); EEX, European energy exchange; FCPP, annualized fixed costs of power plant; FIT, fixed feed-in tariffs; GT, gas turbines; GWh, giga-watt hours; LDC, load duration curve; LDCM, load duration curve model; MCPP, marginal cost curve of power plant; MO, merit order; MW, mega-watt; MWh, mega-watt hours; NPV, net present value; P, price of electricity; PDC, price duration curve; PP, power plant; PV, photovoltaic; RE, renewable energy; RLDC, residual load duration curve; TCM, total contribution margin of power plant

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* Corresponding author.
E-mail address: a.coester@vu.nl (A. Coester).

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German Federal Government's expansion goals of a RE share in total electricity generation between 40% and 45% in 2025 and between 55% and 60% in 2035 [2]. Furthermore, it is crucial to raise awareness of potential energy disruptions and the associated costs of countermeasures. Uyanik [3] has shown that the number of redispatch actions required to ensure grid stability has increased significantly, making it more challenging and costly to maintain the security of energy supply.

Our analysis explores the impacts of RE (on and offshore wind, solar, water, bioenergy and geothermal) under free market conditions on the level of security of supply. By applying a fundamental electricity market model, RE capacity is not driven by expansion goals, but is dynamically modeled as an economically-driven investment option. Furthermore, we analyze the economics of five policy scenarios, designed to secure both electricity supply and RE expansion. The policy scenarios differ in terms of the underlying market designs, subsidies for conventional and RE power plants and the assumptions concerning supplementation investments in case of undercapacity. For each policy scenario, we measure the development of power plant capacity (especially with regard to RE expansion), total CO_2 emissions and the (direct and external) costs that are necessary to maintain security of supply.

To our knowledge, this is the first paper that applies a novel electricity market design, where a complex of conventional power plants is optimally adapted to RE supply. In theory, such a composition of power plants always leads to the highest possible average electricity price and the most cost efficient supply of electricity. Our analytical framework pays particular attention to the development of green energy systems (that maintain security of energy supply and support RE expansion); this is done by dynamically simulating a mixture of different RE power plants that are able to generate base-loadable electricity. Moreover, our analysis contributes to the literature through the development of alternative policy scenarios that give a detailed comparison of the costs government incurs to reach RE expansion goals and simultaneously secure energy supply (hence, providing new insights into the future development of RE and conventional power plants capacity). Based on an economic comparison of the developed policy scenarios, we provide clarity to policy-makers regarding the expected direct and external costs of electricity generation in the future.

Section 2 reviews the existing literature on the expansion of RE and security of electricity supply. Section 3 presents the modeling framework, the data and the policy scenarios. Section 4 studies the simulation results and provides a sensitivity analysis. Finally, Section 5 concludes.

2. A review of the literature

In this section we provide a review of the recent literature on RE expansion and the security of energy supply. Given the complexity of the issue, our literature review draws on studies that largely cut across a range of disciplinary themes (i.e. across the fields of technology development, politics and economics for energy generation, conservation and efficiency). This broad cross-disciplinary focus allows us to generate a synthesis of the numerous drivers and barriers behind a successful energy transition.

2.1. Expansion of RE

In recent years, there has been a massive cost reduction for wind and solar energy both in Germany and worldwide [4–11]. Between 2010 and 2012 alone, prices for photovoltaic (PV) modules fell by 75%, dramatically improving competitiveness of solar power [12]. Further cost reductions for solar electricity are expected by 2020 [13]. The Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety [14] predicts that production costs for PV and offshore wind electricity will decline to €0.1/kWh by 2030, while corresponding costs for onshore wind are expected to fall to €0.6/kWh. While utility-scale biomass, hydropower, geothermal and onshore wind can easily compete with fossil fuel-fired power generation today, the cost of PV electricity is still somewhat higher on average [15]. Pescia and Graichen [9] state that, in Germany, onshore wind power and large-scale solar PV are already cost-competitive with all newly-built conventional energy sources. At the same time, prices for fossil fuels (as well as carbon emission costs) are expected to rise in the future; consequently, this would enhance the competitiveness of RE against fossil-fuel fired plants [16–18]. Lins et al. [19] use the notion of a “virtuous circle” to describe the improvements in competitiveness of RE; this refers to a dynamic process where the rapid expansion of RE (initially encouraged by corresponding support policies) and resulting cost reductions for RE investments mutually reinforce each other.

To achieve carbon-neutral electricity generation, innovations need to be introduced at different levels (i.e. not only regarding advancements in RE technologies, but also in relation to energy infrastructure and overall market conditions). According to Harvey [20], the creation of a stable and reliable market for investors is an important prerequisite to further drive down prices. He also points out that German authorities will have to reinvent power markets, expand the transmission grid and rethink business models for utilities if the energy transition is to succeed. Wirth [21] suggests that new PV capacity installed still lags behind the energy transition goals and claims that the progress of future expansion will depend on corresponding incentive schemes for PV systems. According to Baker et al. [22] and Kabir et al. [23], solar electricity will be of vital importance in a carbon-constrained future. Accurately optimized investments, operations and demand management decisions, together with extensive near-term R&D funding, are crucial prerequisites to minimize the cost of reduced fossil-fuel dependence. Under such optimized conditions, they conclude that the grid integration costs of rising solar penetration can be kept relatively small.

As to remuneration schemes, Narbel [24] focuses on policy tools that support the expansion of RE and claims that customary instruments (such as FITs, feed-in premiums or quota systems), are not apt to foster the most valuable RE technologies (i.e. those which require little financial support and limit the need for capacity payments in order to ensure security of supply) because they ignore the cost of intermittency. In his view, remuneration should not be arranged as a fixed amount but in a way that amplifies the variation in prices appearing in the wholesale electricity market. Ponta et al. [25] investigate the economic effects of a FIT policy aimed to foster investments in renewable energy production capacity. Their results show that the FIT mechanism is effective in promoting the sustainability transition of the energy sector, as well as increasing investments and employment.

2.2. Security of electricity supply

Modeling and forecasting of RE expansion is a demanding exercise that generally involves making assumptions about a large number of associated variables. Predicting the security of electricity supply, environmental impacts and related costs requires sound modeling [26,27]. Obviously, the level of security of supply has remained high so far in spite of an already significant share of RE in the German electricity consumption [28–30]. This is due to a number of directed measures, such as the extension and improvement of the electricity grid or changes in the bahavior of power producers and consumers. According to Huneke et al. [29], the adaption of the electricity grid to meet the demands of more decentralized power production, consistent demand-side management, and both short-term and long-term storage, will play a decisive role in adjusting the system to a further rising share of RE and maintaining security of supply. These key elements are commonly mentioned in the academic literature [31–34]. The Konrad-Adenauer-foundation [35] adds that a market-based, technology-neutral increase in flexibility requires interlinkages across sectors and a level playing field. In the context of diminishing shares of baseload power plants, Jungjohann [36] also highlights the importance of sector coupling, which is apt to reduce the need for costlier options such as curtailment or battery storage. Although the level of security of electricity supply remained high over the past years, the number of redispatch actions required to ensure grid stability has increased significantly, indicating that it has become more challenging and costly to maintain this high level of supply security [3].

Summing up, although most RE is already cost competitive and the level of security of supply is still largely unaffected by the increased shares of intermittent sources, further expansion of RE in the course of the energy transition will intensify integration challenges. These will call for intelligent economic solutions, market reforms, enhanced demand-side management and cross-border interconnections, appropriate business models for utilities, R&D funding to spur technological progress and the building of ample storage capacity to reduce intermittency problems [37].

3. Modeling and simulation results

This section starts by introducing the reference scenario for our policy analysis. In Section 3.1 we first present our general modeling framework. Next, we develop a dataset that we then use for making a projection of the electricity market (representing the status quo). This projection is subsequently used as the reference scenario in our policy analysis. In Sections 3.2–3.6 we develop five policy scenarios that aim at securing sufficient electricity supply and RE expansion. The policy scenarios apply two different electricity market designs, considering the cases of both FIT support as well as free market conditions for RE. Furthermore, the policy scenarios assume both conventional and RE power plants as technologies available for supplementation capacities. We evaluate our policy scenarios on the basis of three main criteria: the development of power plants capacity (especially with regard to RE expansion), CO_2 emissions and the costs that are necessary to maintain security of supply.

3.1. Reference scenario

3.1.1. Fundamental electricity market model

This subsection presents the theoretical underpinnings for our reference scenario (i.e. the status quo). We assume that both conventional electricity and RE are freely traded on the spot market. The economic impacts of this assumption are analyzed by means of an electricity market model, the Load Duration Curve model (LDCM) [38–40]. The LDCM is based on the Load Duration Curve (LDC) and the Merit Order Curve (MO). It allows to determine electricity prices and to calculate the contribution margins of power plants. In the LDC, the hourly electricity demand in MW for the entire 8760 h a year is listed in descending order. In the MO, the electricity supply of RE and conventional power plants is ranked in ascending order of marginal costs.

By linking LDC and MO, it is possible to determine the applicable electricity prices for the hourly amounts of demand in a year. Electricity prices for each MW supplied, as identified from the MO, are assigned to the respective electricity demands in MW from the LDC. On that basis, electricity prices for the demanded quantities are allocated to the corresponding duration in hours. This leads to the so-called Price Duration Curve (PDC). Based on the PDC, the contribution margins (*CM*) of each power plant (PP_i) with marginal costs ($MCPP_i$) in the spot market can be determined by means of integral calculus:

$$CMPP_i = \int_0^{d_i} [PDC(x) - MCPP_i(x)]dx \tag{1}$$

where x = number of yearly production hours, d_i = production hours (for power plant i).

Taking into account each power plant's full capacity (CPP_i) in MW, the total contribution margin (*TCM*) of each power plant (PP_i) can be defined as follows:

$$TCMPP_i = CPP_i \cdot CMPP_i \tag{2}$$

The net present value (NPV) of a power plant is now given by:

$$NPVPP_i = \sum_{n=1}^{n_{op}} \left(\frac{TCMPP_i^n - FCPP_i^n}{(1+dr)^n}\right) \tag{3}$$

where superscript n refers to the year of production,$FCPP_i^n$ are the annualized fixed costs of a power plant, n_{op} represents the operating lifetime of PP_i and dr represents the discount rate (for more details see [1]).

Through the application of the LDCM, the profitability of conventional and RE power plants is determined for the period under consideration. The NPV of each power plant (for each year) is calculated for a time span of ten years (n_{op}). In addition, an optimization modeling is executed in order to identify the NPV maximizing investment capacity in MW in one of the following power plant technologies: lignite, hard coal, combined cycle gas turbines (CCGT), gas turbines (GT), wind energy onshore, wind energy offshore, PV, hydropower, biomass and geothermal.

During the period under consideration, power plant shut-downs according to their assumed life cycle are taken into account. Apart from power plants that are taken out of the market due to reaching the end of their technical lifecycle, decommissions of power plants on the basis of economic considerations are modeled as well. In this context, it is assumed that a power plant is shut down in case its NPV is negative for five years in a row. Both power plant shut-downs, as well as new investments, are assumed to take effect in the subsequent year, respectively.

3.1.2. Data

This subsection presents the database we developed for our study that covers the period 2016 to 2035. We choose 2016 as our starting year, as our simulation is based on data of actual existing power plants. The forecast of German electricity demand is also based on actual data from the European Energy Exchange [41]. Based on these data for the years 2010 to 2013, we calculate the hourly average electricity demand. These figures form the basis for the projection of electricity demand up to 2035. To account for possible changes in the development of actual demand, we carried out a sensitivity analysis (± 0.50%/year; see Section 4).

The representation of the conventional complex of power plants is based on data from the Federal Network Agency [42]. The Federal Network Agency is a German regulatory authority entrusted to ensure efficient and undistorted competition in the energy market. To account for any unavailability of plants, as well as start-up and shut-down times, the installed capacity of each power plant is reduced by 10%. Economic and technical data of conventional power plants are mainly based on historical data that have been provided by the research department of the Westdeutsche Landesbank German Bank [43]. Based on this dataset and forecasts by the Institute of Energy Economics at the University of Cologne (EWI), the Institute of Economic Structures Research (GWS) and the Prognos Research Centre [44] as well as the Agency for Renewable Energies [45], we calculated the future projection of our model parameters (any missing data of existing power plants are determined by linear interpolation). The installed capacity of RE power plants in 2016 (i.e. the starting year of the simulation) is based on data from the Federal Ministry for Economic Affairs and Energy [46]. Kaltschmitt et al. [47] and Deutsche Windguard GmbH [48] serve as the basis for economic and technical data of RE. Bioenergy and geothermal energy are assigned a customary availability factor of 0.9, while the availability factor of hydroenergy is 0.4 [49]. The availability factors of solar and wind energy are calculated based on time series analysis. For this purpose, we compared the real hourly production of solar and wind energy between 2010 and 2014 with the theoretical maximum production per hour [50].

A key assumption is that conventional electricity is fully traded on the spot market. Furthermore, we assume that there is no transnational trade

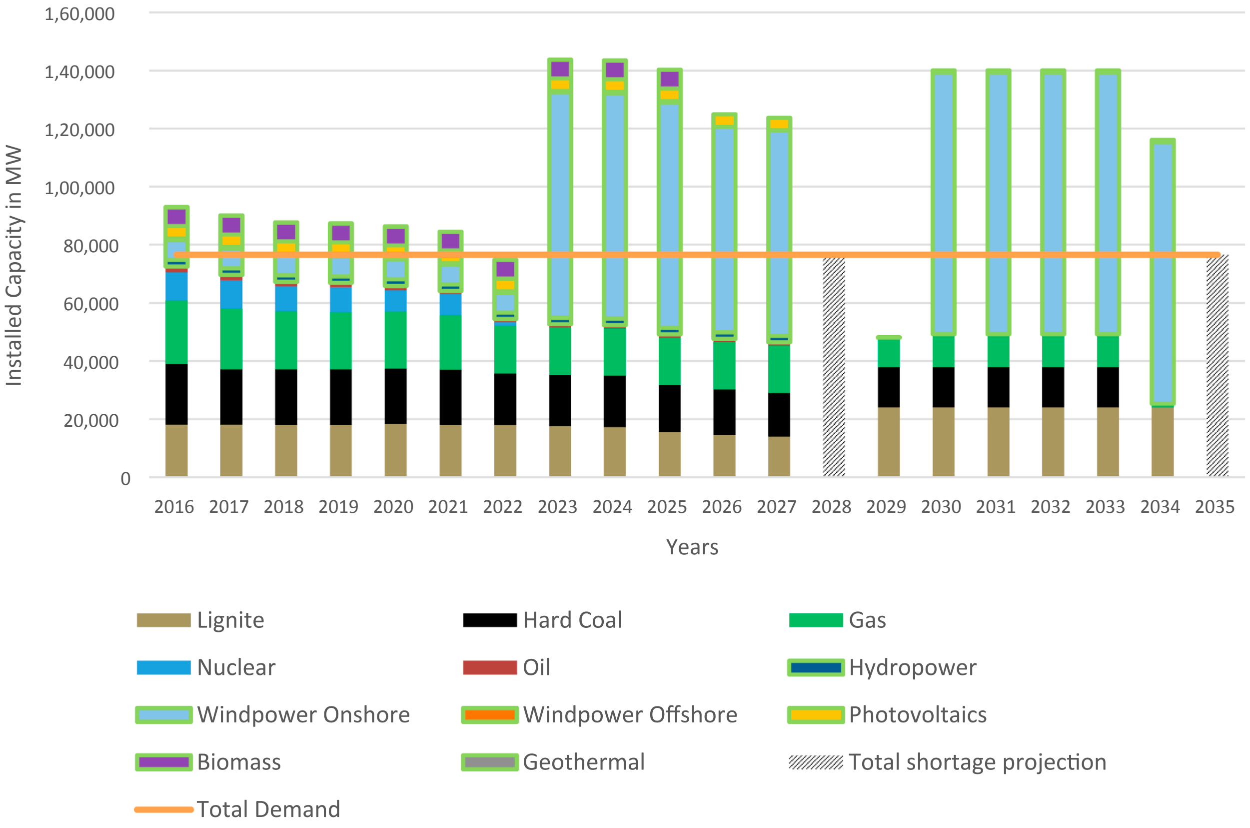

Fig. 1. Installed conventional and RE power plant capacity and total demand curve (reference scenario).

in electricity – i.e. we focus exclusively on the German market. To account for peak load prices, the prices on the spot market are increased by 5%. As a discount rate, we assume a weighted average cost of capital equal to 7.14% [51]. Changes in markup prices, the discount rate, as well as CO_2 prices, are also subject to a sensitivity analysis (see Section 4).

3.1.3. Projection

This subsection presents the projection of the electricity market based on our dataset. This projection is used as our reference scenario in the subsequent policy analysis. Fig. 1 shows the projection of installed capacity. It can be seen that projected conventional and RE power plant capacity exhibit little fluctuation between 2016 and 2022. There are hardly any investments in new capacity and the majority of decommissionings are due to power plants reaching the end of their life cycle. In 2022, the NPV optimization modeling as discussed in Section 3.1.1 leads to a substantial investment in onshore wind energy. This is because the zero marginal costs of wind energy generate large contribution margins, as the electricity prices are set by high-marginal-costs conventional power plants. Through this investment, RE power plants in the market are sufficient to meet total electricity demand. Due to the low marginal costs of RE power plants, all remaining conventional power plants are driven out of the market. However, as a result of this, the price of electricity that is paid to RE power plants in the market also becomes zero (or at least close to zero, accounting for the very low marginal costs of biomass and a peak load price increase of 5%). These impacts are known as the merit order effect of RE (for more details see [1]). As a consequence, both RE and conventional power plants incur substantial losses in each year from 2023 to 2027. By assumption (see Section 3.1.1), after these five consecutive years of negative NPVs, all power plants are decommissioned (i.e. no power plants remain in the market in 2028). Following this, in 2028, investment in mainly conventional power plant technologies takes place according to the NPV maximization modeling. However, the total amount of installed capacity in 2029 is only sufficient to meet around two thirds of demand. In 2029, the same cycle (as the one in 2022) occurs, with substantial investments in wind energy onshore. Again, the resulting merit order effect of RE leads to economic losses for all power plants in the market from 2030 to 2034. As a result, in 2035, after five years of consecutive losses, all power plants are decommissioned, which again leads to an extreme shortage of electricity supply. To sum up, the modeling of RE and conventional power plants under free market conditions shows that the merit order effect of RE rules out a profitable operation of power plants and a stable electricity supply.

With regard to total CO_2 emissions for the reference scenario, Fig. 2 shows a relatively stable quantity of about 250 million tons per year between 2016 and 2022. Through the substantial investments in carbon-free wind energy in 2022 and the resulting replacement of conventional power plants, emissions are reduced to zero from 2023 onwards. Even though conventional power plants are still present, they are not operational anymore and, consequently, do not emit any CO_2. After the decommissionings of all power plants in 2028 (due to economic losses), emissions rise temporarily to more than 200 million tons in the following year as a result of investments in conventional power plants. This market situation again fosters substantial investments in wind energy in 2029, which lead to the merit order effect of RE in the following years; consecutively, conventional power plants are shifted out of the market again and CO_2 emissions drop to zero.

3.2. Standard policy scenario

3.2.1. Description

We design the standard policy scenario to address electricity shortages (based on our reference scenario projections). In cases of insufficient electricity supply, we assume that RE is taken out of the free market and is instead subject to a FIT mechanism for the rest of the period under consideration. The FIT mechanism assists the RE sector to meet the expansion

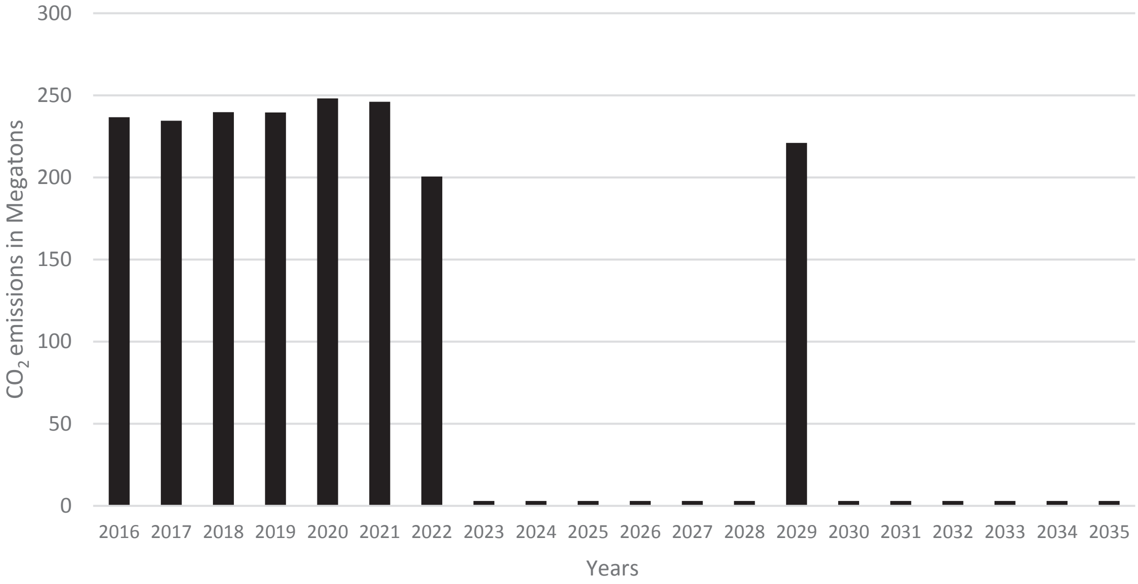

Fig. 2. CO_2 emissions (reference scenario).

goals of the German Federal Government (i.e. an RE share in total electricity generation between 40–45% by 2025 and 55–60% by 2035, [2]. The average annual tariffs for each RE technology (based on actual data between 2000 and 2016) are extrapolated until the end of the period [52]. We assume that conventional power plants are subsidized. If their NPV is negative for five years in a row, they are now not decommissioned, but remain in the market. In this case, the costs of negative NPVs are subsidized, starting from the sixth year. In the event of insufficient capacity in the market, complementary investment in efficient Supplement Gas Turbine (GT) power plants is made. These supplementation power plants also receive subsidies in case of negative NPVs. We call this first scenario "standard", since the energy from conventional power plants is traded based on the common electricity market design, while RE is subject to the classical FIT mechanism that was applied for several years in order to foster RE expansion.

3.2.2. Simulation results

According to the reference scenario (see Section 3.1.3), insufficient supply is caused by large investments in wind energy in 2022 and later on in 2029. For this reason, within the standard policy scenario, RE is taken out of the free market in 2022. From 2022 onwards, REs are subject to a FIT mechanism and develop according to the expansion goals of the German Federal Government. As Fig. 3 demonstrates, the standard policy scenario prevents the merit order effect of RE and ensures sufficient electricity supply in each year of the period under consideration. Moreover, it allows for a continuously increasing expansion of RE.

Fig. 4 shows the annual total CO_2 emissions resulting from the standard policy scenario. Until 2022 emissions increase due to the phasing out of nuclear power plants (which generate electricity with minimal emissions). After 2022 the increasing amount of RE leads to decreasing CO_2 emissions. However, even though RE continuously increases, total annual emissions do not decrease to the same extent. This is because market conditions trigger investments in lignite power plants, which have higher CO_2 emissions compared to other conventional power plant technologies (e.g. hard coal or gas).

Fig. 5 displays the monetary costs associated with the standard policy scenario. Between 2023 and 2027, these costs relate to subsidies given as part of the FIT mechanism. However, starting from 2028 onwards, costs increase considerably as a result of financial support provided to unprofitable conventional power plants (subsidies in the range of €0.5 and 1.0 billion per year are needed to ensure that these power plants remain in the market). Part of these subsidies are also directed to the Supplement GT power plants, which were installed in order to fill the electricity gap. Overall, in order to ensure security of supply and RE expansion, subsidies amounting to around €8.5 billion need to be granted according to the standard policy scenario.

3.3. Free market green policy scenario

3.3.1. Description

For the free market green policy scenario, we assume that RE is traded on the free market over the entire period under consideration. This implies that RE power plants are decommissioned in case their NPV is negative for five years in a row. Conventional power plants are treated in the same way as in the standard policy scenario described in Section 3.2.

3.3.2. Simulation results

Fig. 6 shows that power plant capacity in the free market green policy scenario looks similar to the reference scenario projection between 2016 and 2027. There are large investments in wind energy in 2022, which lead to the merit order effect taking place between 2023 and 2027. In contrast to the reference scenario, there is no lack of electricity supply in 2028 as power plants remain in the market even when running economic losses. In the event of insufficient capacity, an equivalent investment in a mixture of different RE power plants is made by the government. This mixture is based on the distribution of RE power plant technologies according to the expansion goals of the German Federal Government [14].

By assumption, unprofitable conventional power plants are not shut down and any capacity gap in the market is filled up with an investment in Supplement GT power plants. However, the high marginal-cost power plants (e.g. gas, hard coal) in the market again lead to substantial wind energy investments in 2028. Between 2029 and 2034 the same cycle (to the one six years earlier) repeats itself (and starts once again in 2035).

As the development of power plant capacity is similar to the reference scenario, the time path of total CO_2 emissions is also comparable (Fig. 7). The main differences occur in 2028 and 2034, when CO_2 emissions rise to more than 200 and 150 Megatons respectively. This is because of the provided subsidies for conventional power plants that allow facilities to remain in the market despite running losses. Furthermore, the undercapacities in these years are compensated with investment in Supplement GT power plants, which generate additional CO_2 emissions. In the periods

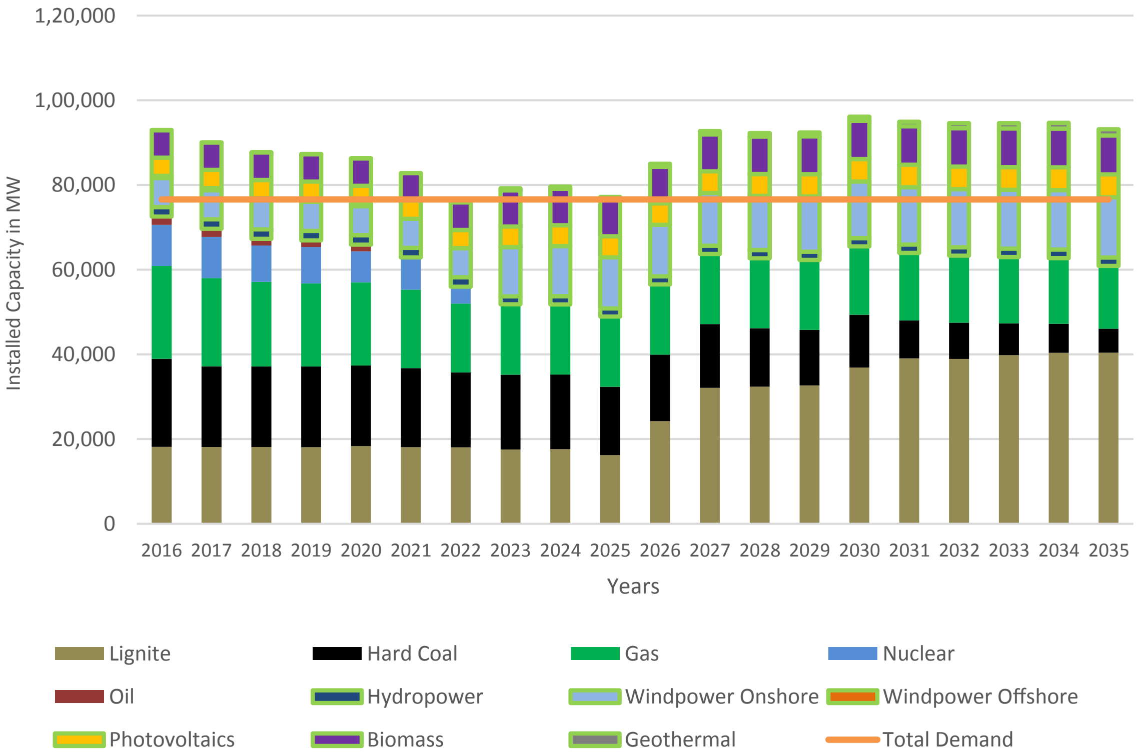

Fig. 3. Installed conventional and RE power plant capacity and total demand curve (standard policy scenario).

between 2023 to 2027 and 2029 to 2033 emissions become negligible, since only RE power plants operate in the market.

Fig. 8 shows the monetary costs associated with the free market green policy scenario. As a consequence of the merit order effect, conventional power plants need to be subsidized starting from 2021. The production of additional electricity by Supplement GT power plants also needs to be subsidized from 2033 onwards. In 2028, in particular, and, to a smaller extent in 2034, the subsidies for conventional power plants are lower, as there is no RE in the market, which leads to relatively high electricity prices. Total subsidies in the period between 2016 and 2035 account for around €25 billion. There are no subsidies directed to RE and RE power plants become decommissioned when facing sustained economic losses.

3.4. *Green support policy scenario*

3.4.1. *Description*

In the green support policy scenario, conventional power plants are treated as in the reference scenario (see Section 3.1). They are taken out of the market either because they have reached the end of their technical lifecycle or for economic reasons (i.e. in case of a negative NPV for five years in a row). On the other hand, RE receives subsidies, which allows RE power plants to remain in the market even when running economic losses. In the event of insufficient capacity, an equivalent

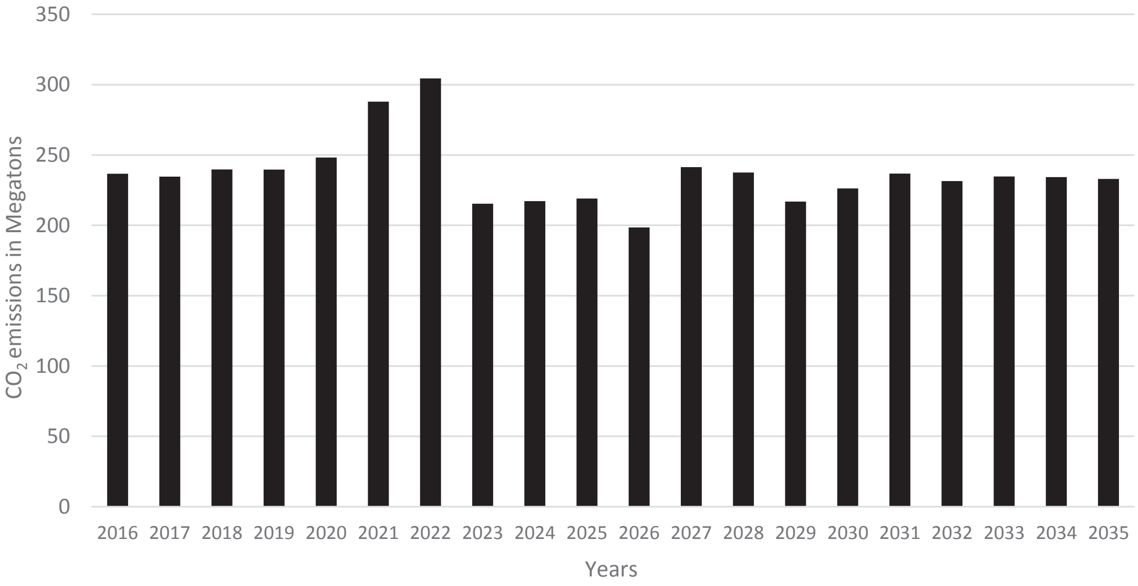

Fig. 4. CO_2 emissions (standard policy scenario).

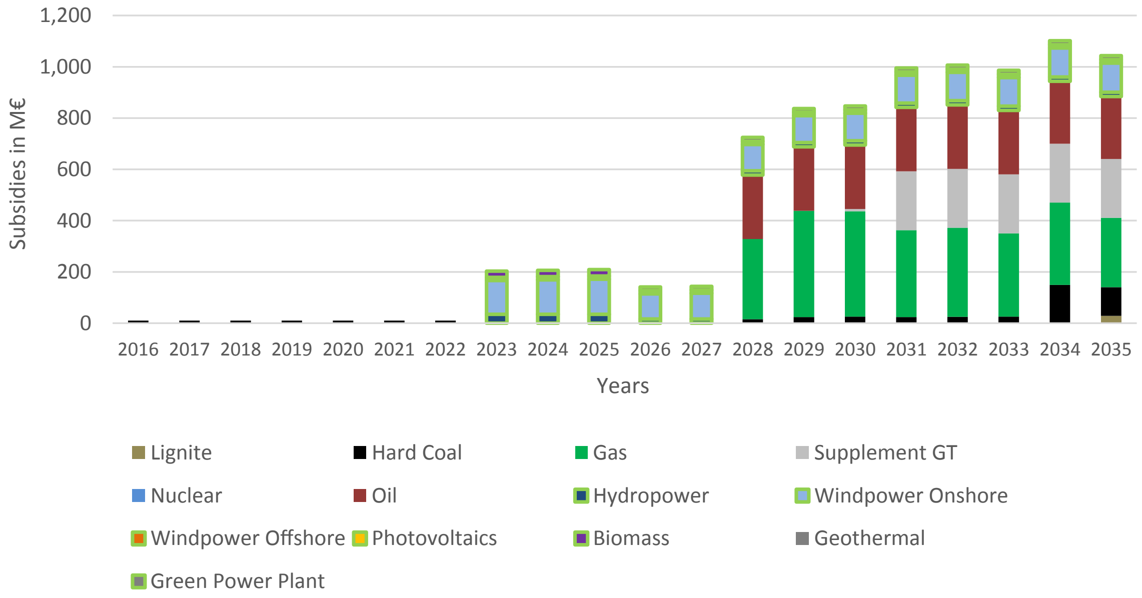

Fig. 5. Subsidies (standard policy scenario).

investment in a mixture of different RE power plants is made by the government. This mixture is based on the distribution of RE power plant technologies according to the expansion goals of the German Federal Government [14].

3.4.2. Simulation results

Fig. 9 shows that power plant capacity develops similarly to the reference scenario during the first years of our analysis. Starting from 2025 onwards, substantial investments in wind power lead to the merit order effect of RE. All conventional power plants are driven out of the market (as a result of the low marginal costs of RE and expected drastic drop in electricity prices). As a consequence, all conventional power plants are decommissioned for economic reasons in 2030. On the other hand, RE power plants remain in the market as a result of being subsidized. Additional investment in a mixture of RE power plants ensures that the security of supply is always maintained (see Section 3.4.1).

During the first nine years, CO_2 emissions amount to around 250 Megatons per year. From 2025 onwards, the merit order effect of RE (and the resulting displacement of conventional power plants) lead to an almost complete elimination of carbon emissions (see Fig. 10).

The costs attributed to financial support for RE are shown in Fig. 11. Between 2021 and 2029, many PV power plants are unable to operate profitably and need support until they reach the end of their economic lifecycle. From 2030 onwards, all RE power plants need to be

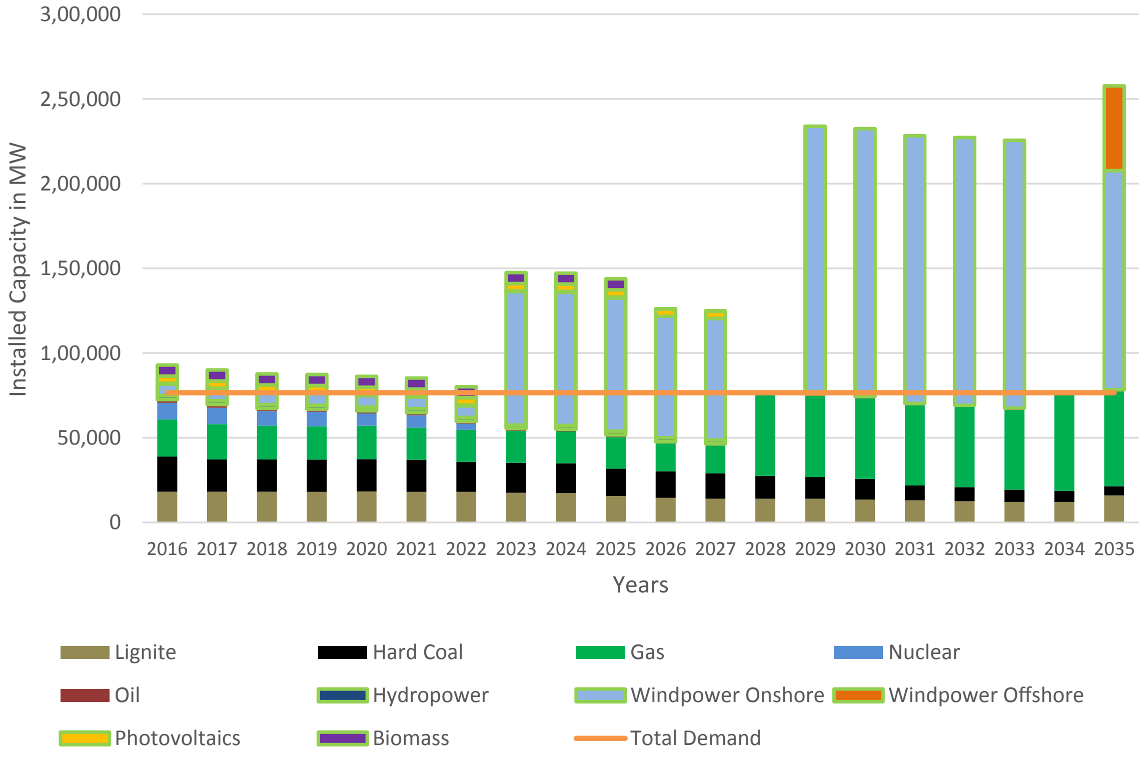

Fig. 6. Installed conventional and RE power plant capacity and total demand curve (Free Market Green Policy Scenario).

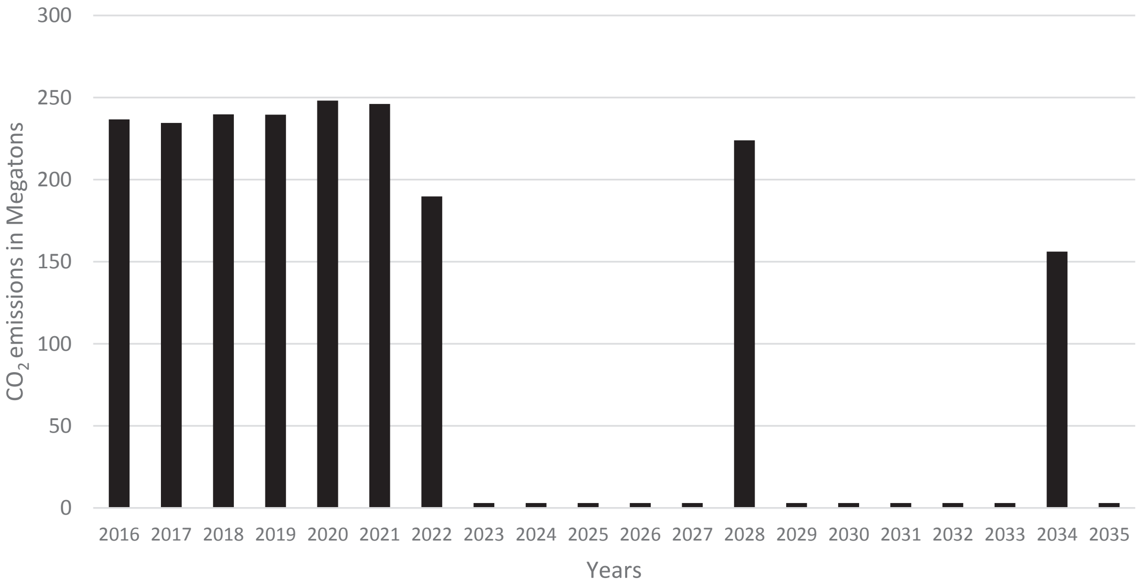

Fig. 7. CO$_2$ emissions (Free Market Green Policy Scenario).

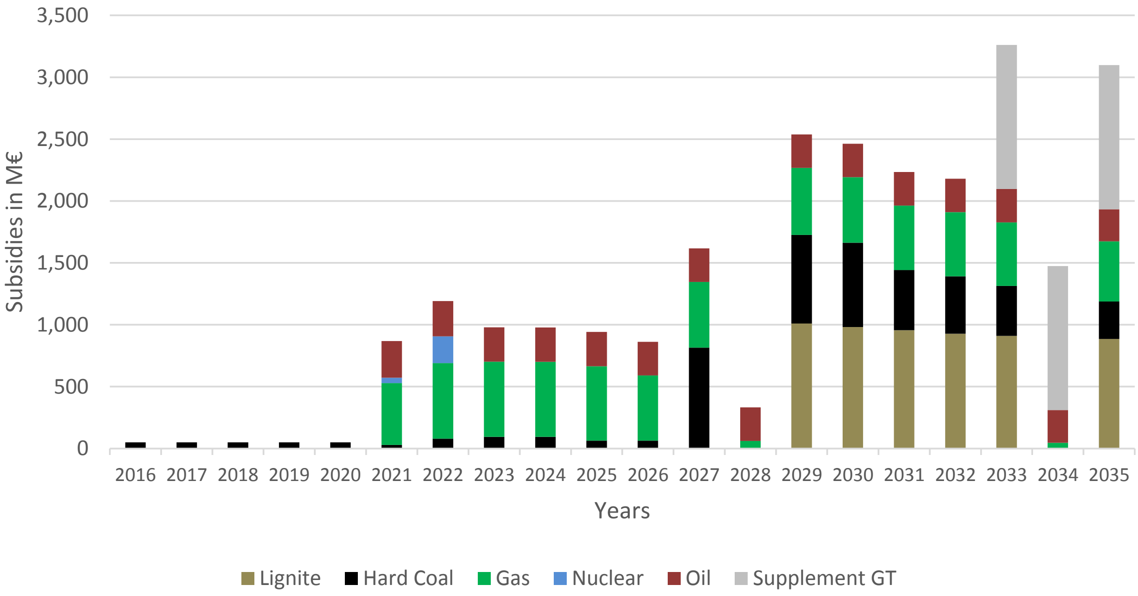

Fig. 8. Subsidies (Free Market Green Policy Scenario).

subsidized as a result of the merit order effect of RE. Additional financial support is provided in the form of investment in a mixture of green power plants in order to eliminate any electricity shortages. In total, subsidies add up to around €549 billion.

3.5. *Regulated RE adaptation policy scenario*

3.5.1. *Description*

This scenario relies on Coester et al. [1], who develop a novel electricity market design that simultaneously ensures stable electricity supply and RE expansion.[1] It assumes that the electricity price and profitability of conventional power plants are significantly dependent on the level of adaptation of conventional power plants to RE supply. Against this background, we utilize a methodology that allows us to model the most cost-effective composition of power plants.

We apply this policy scenario to address concerns of electricity shortages (as identified in the reference scenario). In the current scenario, we assume furthermore, that RE is taken out of the free market and becomes subject to a FIT mechanism. The remaining complex of conventional power plants is modeled to be optimally adapted to the residual load (RLDC) for each consecutive year. This RLDC represents total electricity demand reduced by electricity production from RE. As a next step, for each of the 8760 h a year, the most cost-effective power plant technology is selected, allowing us to derive the efficiency cost curve. This corresponds to a complex of power plants that is optimally adapted to RE supply. As this optimally adapted complex of power plants does not take account of power plant breakdowns or temporary shut-downs due to maintenance, the optimal capacity is increased by 5% per power plant technology. On this basis, the optimally adapted complex of power plants is compared to existing real conventional

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[1] This is equivalent to the ‘new market design’ described in Coester et al. [10].

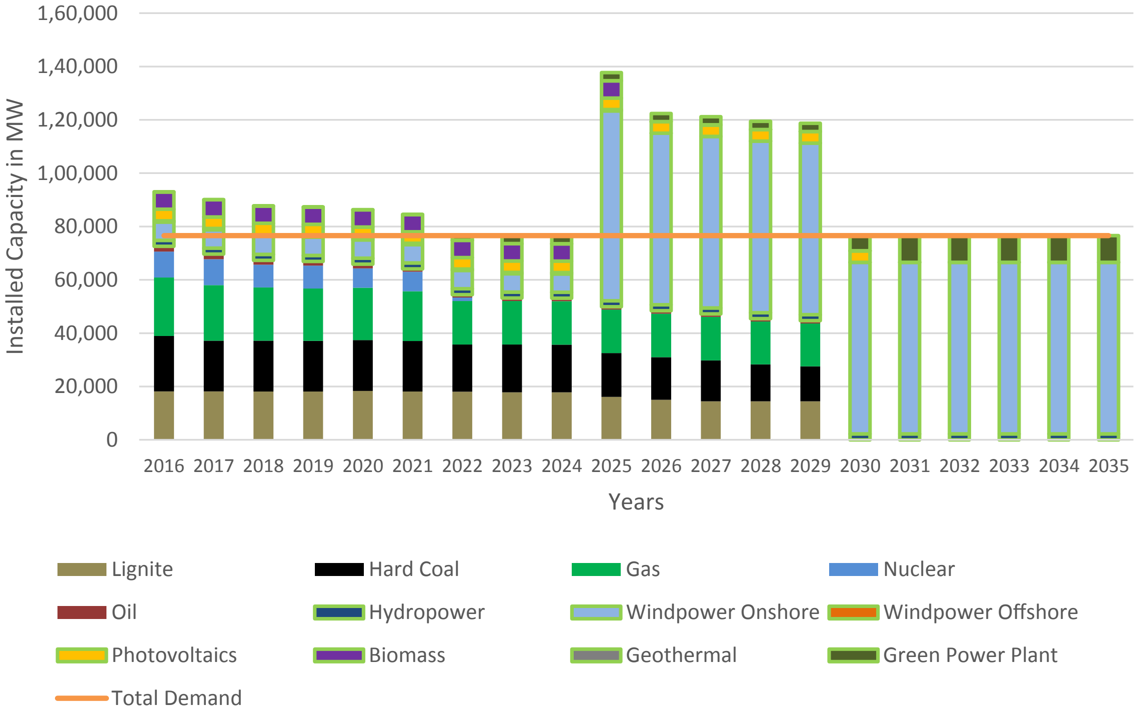

Fig. 9. Installed conventional and re power plant capacity and total demand curve (Green Support Policy Scenario).

power plant capacities. The capacities of existing power plants in the market are allocated on the basis of optimal adaptation guidelines. In case there is need for additional capacity of a particular power plant technology, any identified gaps are filled up by the excess capacity of remaining technologies.

In case that excess capacities still fail to meet the entire demanded quantity, an investment (in additional conventional capacity) is made to optimally fill the gap. This assumes that necessary investments materialize in the next year. If, on the contrary, the existing power plant capacity exceeds demand, redundant power plants are not allowed to offer their capacities on the market. Based on this allocation of production capacities, the profitability of power plants is again modeled by utilizing the LDCM (see Section 3.1.1). By assumption, conventional power plants are subsidized (and are not decommissioned due to losses).

3.5.2. Simulation results

Fig. 12 demonstrates how the development of conventional power plant capacity in the regulated RE adaptation policy scenario differs from the regular market designs applied in the previous scenarios. There are now considerably more gas and oil power plants in the market. Compared to other conventional power plant technologies (such as lignite or hard coal), these power plants have the advantage of reacting more flexibly to changes in (the rather volatile) RE supply. Consequently, the utilization of these power plants is more cost-effective. The expansion of RE is continuous thanks to the support of the FIT

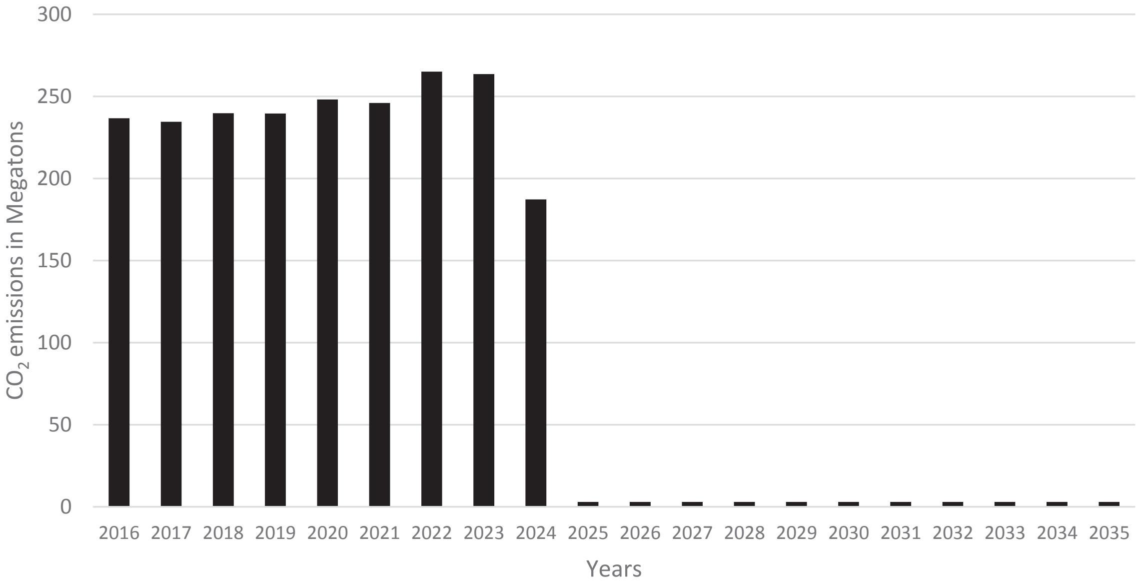

Fig. 10. CO_2 emissions (Green Support Policy Scenario).

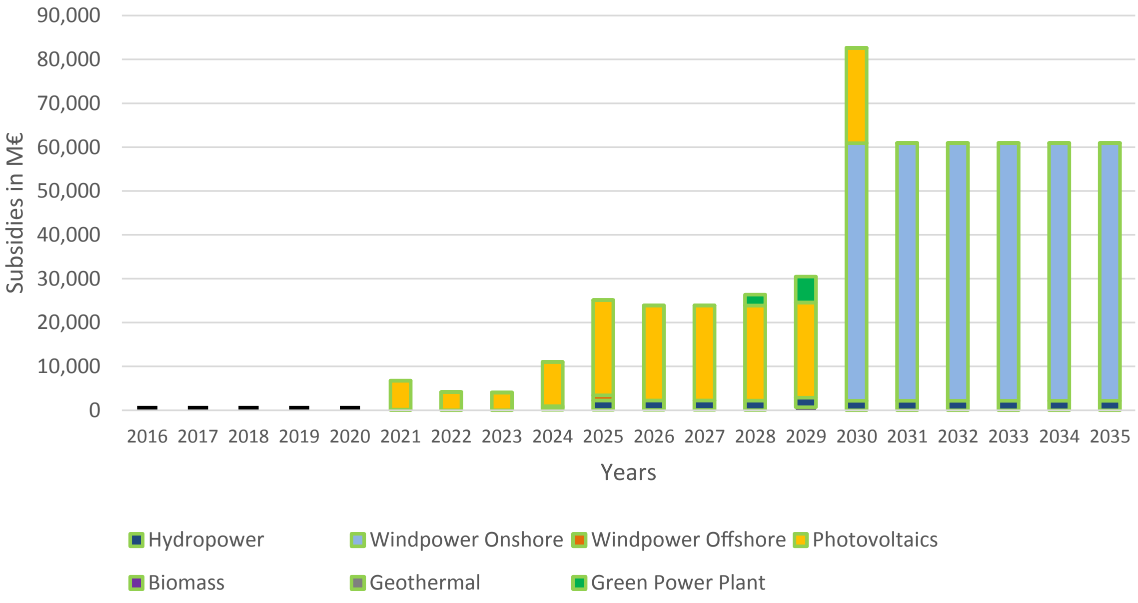

Fig. 11. Subsidies (Green Support Policy Scenario).

mechanism. Over the entire period under consideration, there is always sufficient supply to meet demand.

Through the planned phasing out of nuclear energy, carbon emissions rise until 2022 (see Fig. 13). After that, emissions decline and lie between approximately 125 and 210 million tons per year (originating primarily from the operation of CO_2-intensive lignite power plants in the market). The observed decrease of emissions during the last years of our investigation (between 2031 and 2035) is attributed to an increase in RE supply and additional investment in nuclear power plants (which emit little CO_2). While the German Federal Government [53] has decided on phasing out nuclear energy (and this has been incorporated in the simulation), this policy scenario allows for the possibility of investments in new nuclear energy in the future in case of demand shortages (as those depicted in the reference scenario, see Section 3.1.3).

Fig. 14 shows the monetary costs associated with this scenario; from 2023 onwards, subsidies support RE through the FIT mechanism, and later on (after 2027) also base load power plants (e.g. lignite and hard coal) that run losses. This is because the RE adaptation design gives preference to medium or peak load power plants, which are better able to adapt to fluctuating RE supply. Later on, oil power plants also need to be subsidized to remain in the market. These oil power plants only operate during times of extreme peak load (being, hence, unable to receive sufficient gross margins). The total costs for securing electricity

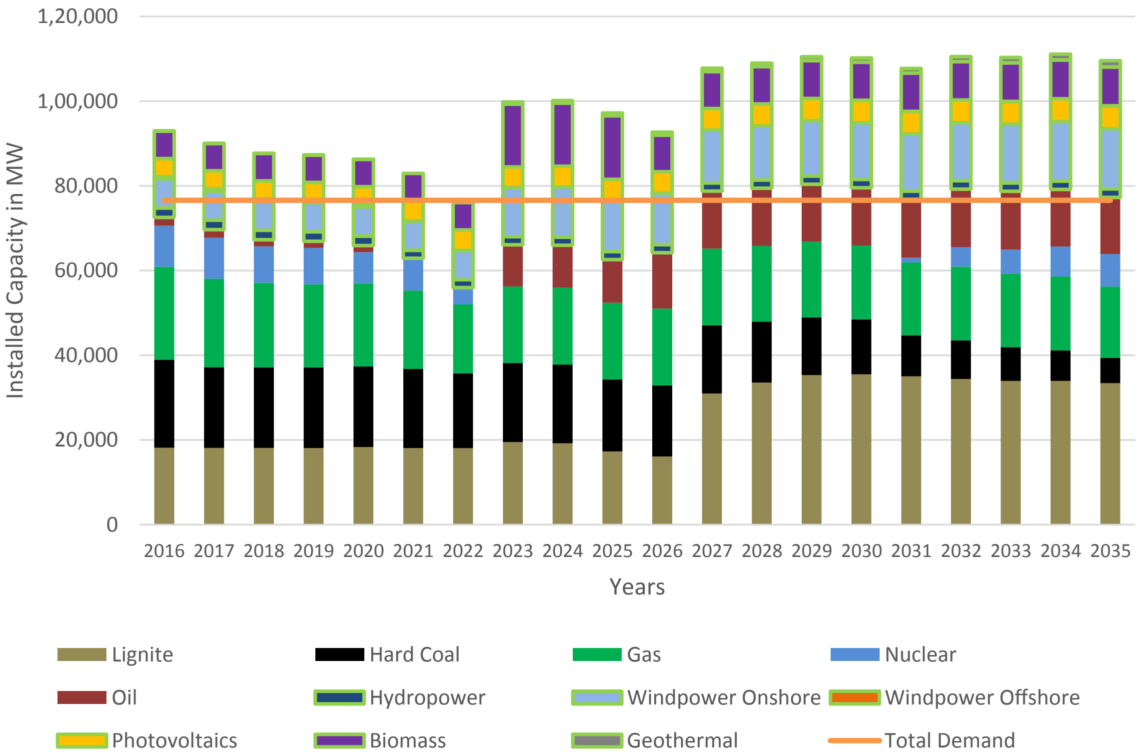

Fig. 12. Installed conventional and RE power plant capacity and total demand curve (Regulated RE Adaptation Policy Scenario).

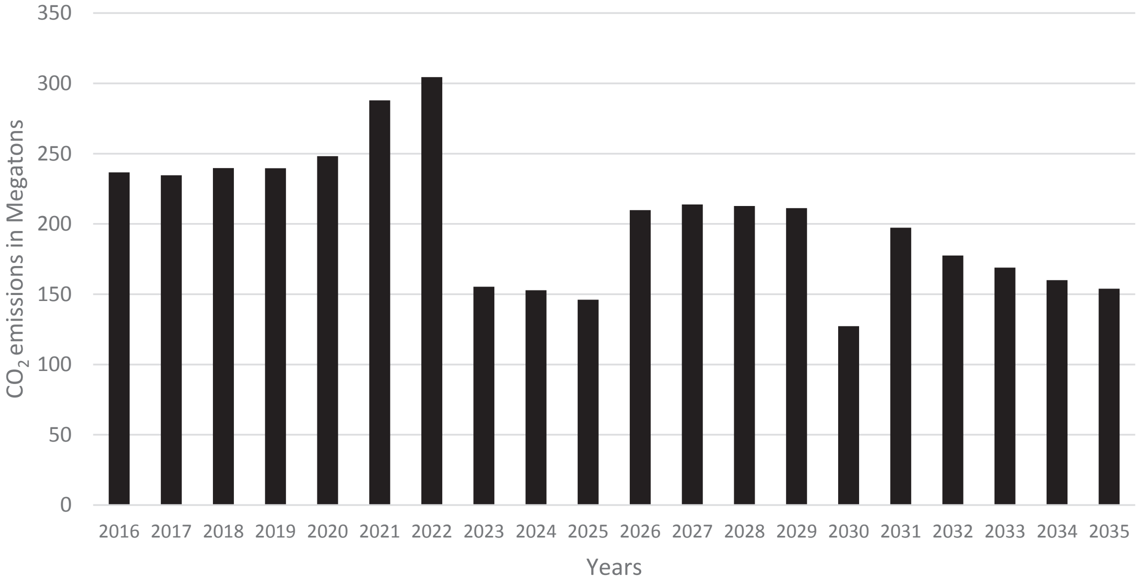

Fig. 13. CO_2 emissions (Regulated RE Adaptation Policy Scenario).

supply and RE expansion amount to around €5 billion.

3.6. *Free market RE adaptation policy scenario*

3.6.1. *Description*

The Free market RE adaptation policy scenario only differs from the regulated RE adaptation scenario by assuming that RE is not subject to a FIT mechanism but instead competes in the free market. All earlier assumptions regarding the treatment of conventional power plants (as in the regulated RE adaptation policy scenario) still hold.

3.6.2. *Simulation results*

From 2016 to 2022, the development of power plant capacity in the freemarket RE adaptation policy scenario is similar to the regulated RE adaptation scenario (Fig. 15). However, due to the assumption that RE competes in the free market, the NPV optimization results in large investments in wind energy in 2023. This additional wind energy leads to the merit order effect, by which the electricity price drops to almost zero; as a result of this, and after five years of operation and consecutive losses, wind power plants shut down. As conventional power plants are subsidized, they remain in the market (and help meet more than two thirds of the electricity demand in 2028). However, this market environment (of comparably high electricity prices, as these are now set by high-marginal-costs conventional power plants) again fosters substantial investments in wind energy. This will again lead to a repetition of the merid order effect and closure of wind energy plans (while the same cycle of reinvestment in RE will repeat itself for a third time in 2035).

With conventional power plants dominating energy production between 2016 and 2022, annual CO_2 emissions lie between approximately 200 and 250 million tons (Fig. 16). The high wind energy investments in the following years lead to the displacement of conventional power plants, with CO_2 emissions dropping close to zero. In 2028 and 2034, all RE power plants are decommissioned for economic reasons, which gives rise to a temporary increase in carbon emissions (from conventional power plants).

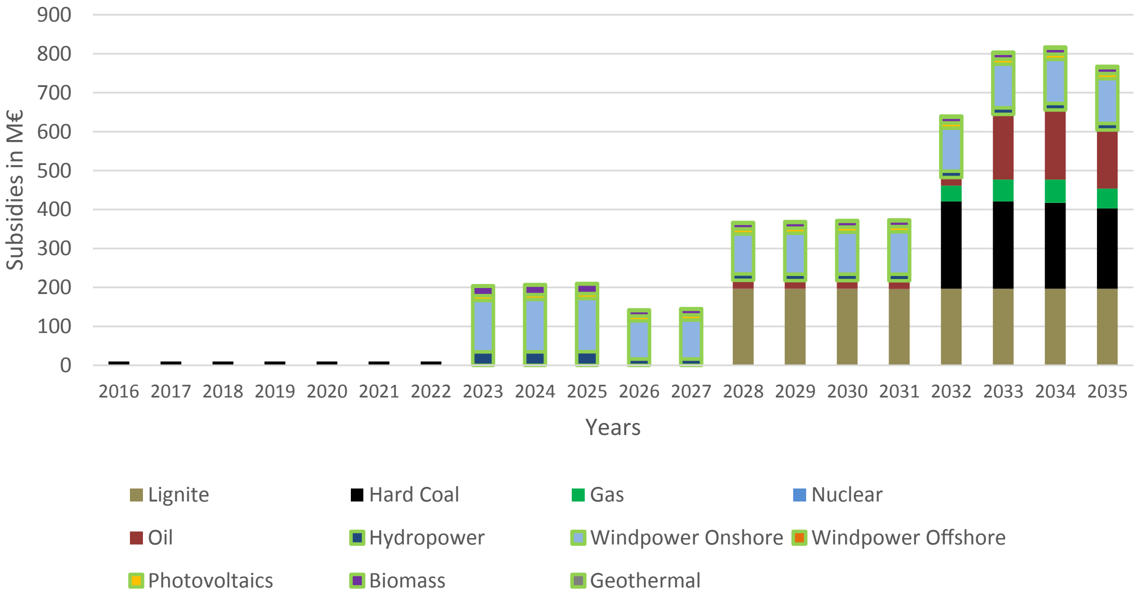

Fig. 14. Subsidies (Regulated RE Adaptation Policy Scenario).

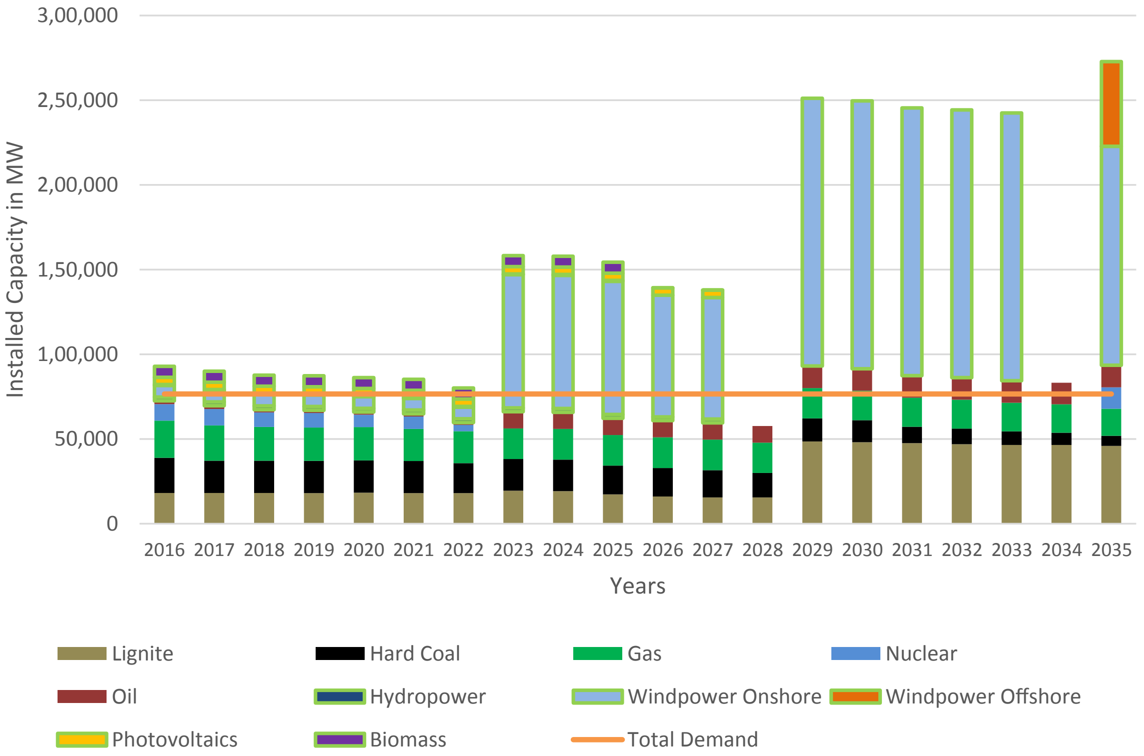

Fig. 15. Installed conventional and RE power plant capacity and total demand curve (Free Market RE Adaptation Policy Scenario).

In the free market RE adaptation policy scenario, we assume that RE power plants participate in the free market and become decommissioned when running sustained losses for a period of 5 consecutive years. For this reason, there are no subsidies directed to RE. As Fig. 17 demonstrates, conventional power plants, however, need substantial subsidies from 2029 onwards. This is due to all conventional power plants sustaining economic losses due to the merit order effect of RE. While this effect consecutively leads to decommissionings of wind power plants in 2028, conventional power plants remain in the market per assumption. Through the absence of RE in 2028, conventional power plants do not need any further subsidies for this particular year. However, this market situation of comparably high electricity prices again fosters substantial wind energy investments in subsequent years. These investments lead to a decrease of the electricity price and a displacement of conventional power plants. Consequently, conventional power plants need high subsidies from 2029 on. After five years, the same disinvestment and investment cycle as before starts in 2034 (with the associated increase in subsidies for conventional power plants). Total costs for subsidies amount to around €18 billion.

4. Discussion and sensitivity analysis

In this section, we further analyze our simulation results by mutually comparing the different policy scenarios. Our comparison

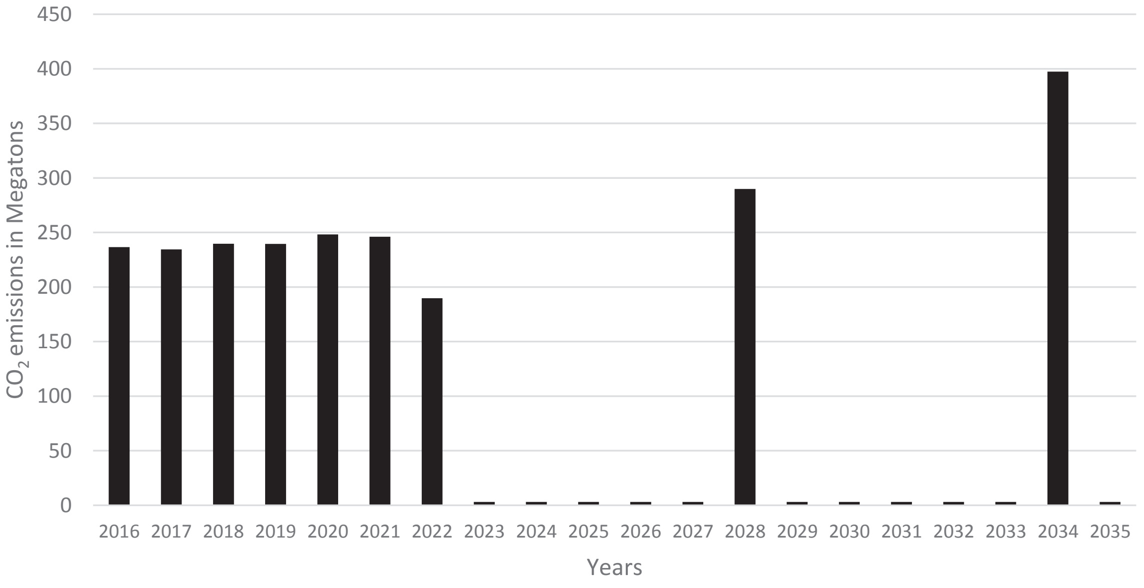

Fig. 16. CO_2 emissions (Free Market RE Adaptation Policy Scenario).

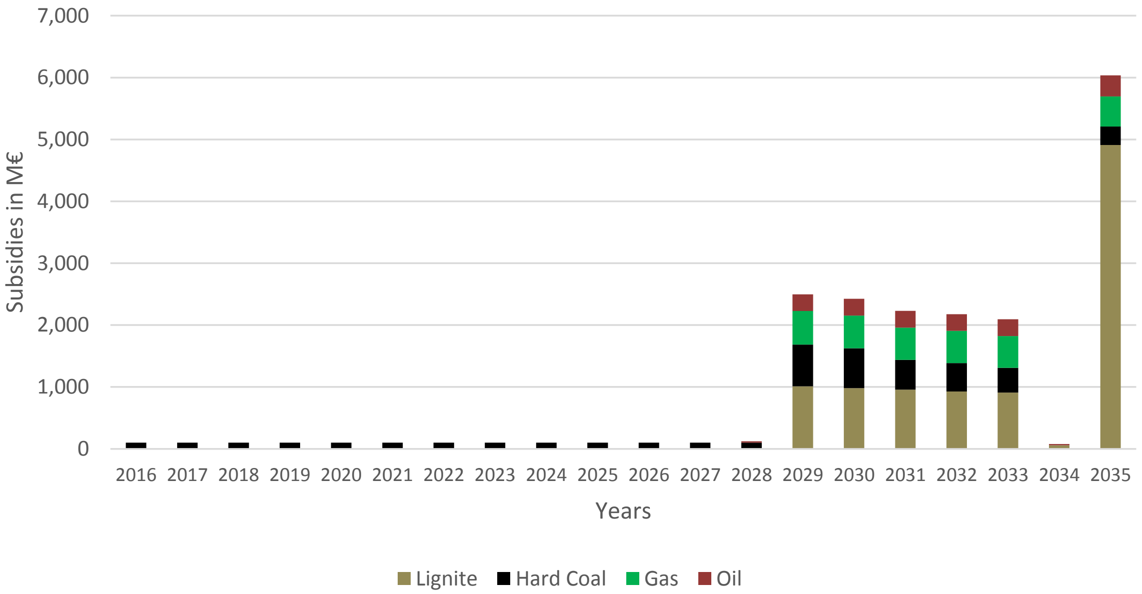

Fig. 17. Subsidies (Free Market RE Adaptation Policy Scenario).

includes security of supply, amount of RE produced, CO_2 emissions, subsidies needed and external costs relating to environmental and health damages caused by electricity generation. We make recommendations for the most suitable countermeasure. Finally, we present the results of a sensitivity analysis on some key assumptions.

4.1. Security of supply, RE expansion and CO_2 emissions

The reference scenario demonstrated how current market conditions lead to insufficient capacity to meet electricity demand (see Section 3.1.3). Table 1 shows that until 2035 around 8.8 million GWh of RE is produced in the reference scenario. Apart from the freemarket RE adaptation policy scenario, all other policy scenarios are able to guarantee the security of supply. With around 13.4 million GWh, the highest amount of RE is produced within the free market green and the freemarket RE adaptation policy scenarios. Both scenarios assume that RE is traded entirely on the free electricity market. In the green support policy scenario, less RE is produced (around 8.4 million GWh). This is because we assume that conventional power plants are not subsidized and become decommissioned when running sustained losses. As a consequence, the electricity price decreases, which in turn reduces the profitability of RE investments. Overall, CO_2 emissions are comparatively low with a total of around 2 billion tons in each of the three policy scenarios where RE is traded on the free market. In the standard and regulated RE adaptation policy scenarios, the lowest amounts of RE are produced (5.0 million GWh). In line with this, CO_2 emissions in both scenarios are higher with a total of approximately 4 and 4.5 billion tons respectively (see Table 1).

4.2. Subsidies

Fig. 18 depicts the total subsidies corresponding to the five policy scenarios. The green support policy scenario requires by far the most subsidies. With around €549 billion (see Table 1), subsidies in this scenario are approximately a hundred times larger compared to the regulated RE adaptation policy scenario (which requires the lowest amount of subsidies close to €5 billion). The large subsidies in the green support policy scenario relate to its underlying assumption of conventional power plants being decommissioned when unprofitable, while RE is subsidized. This leads to the merit order effect of RE, which reduces electricity prices to almost zero and renders RE power plants unable to operate profitably. Total subsidies for the remaining policy scenarios lie between around €8 and 25 billion. In the regulated RE adaptation policy scenario (with the lowest amount of subsidies), the costs refer to financial support provided to RE (as part of the FIT mechanism) and to conventional power plants that do not operate profitably. This result shows that a more consistent expansion of RE leads to a higher profitability of power plants and, thus, less need of subsidies to maintain security of supply. Furthermore, the results demonstrate that the regulated RE adaptation scenario [1] gives rise to an efficient and profitable operation of conventional power plants. However, the standard policy scenario, which also applies a FIT mechanism for RE but instead utilizes the current market design for conventional power plants, leads to only slightly higher subsidies of around €8 billion. To sum up, the results point out that the merit order effect of RE has a significant impact on the profitability of power plants. This leads to shut-downs and, as a consequence, the expansion of RE and security of supply are both in danger. Of the analysed policy scenarios, the most

Table 1
Comparison of policy scenarios.

Reference scenario and policy scenarios	Assumption RE	Assumption Conventional energy	Security of Supply	RE produced in GWh	CO_2 emissions in Megatons	Subsidies in M€	External costs in M€	Σ Subsidies and external costs in M€
Reference scenario	Free market	Free market	No	8,799,807	1867	0	44,604	44,604
Standard	FIT	Subsidization	Yes	5,013,884	4533	8,473	77,040	85,513
Free market green	Free market	Subsidization	Yes	13,370,005	2015	25,019	46,912	71,932
Green support	Subsidization	Free market	Yes	8,389,771	2161	549,430	47,394	596,824
Regulated RE adaptation	FIT	Optimal adaptation/ subsidization	Yes	5,013,884	4078	5,419	77,914	83,334
Free market RE adaptation	Free market	Optimal adaptation/ subsidization	No	13,370,005	2322	17,560	50,393	67,953

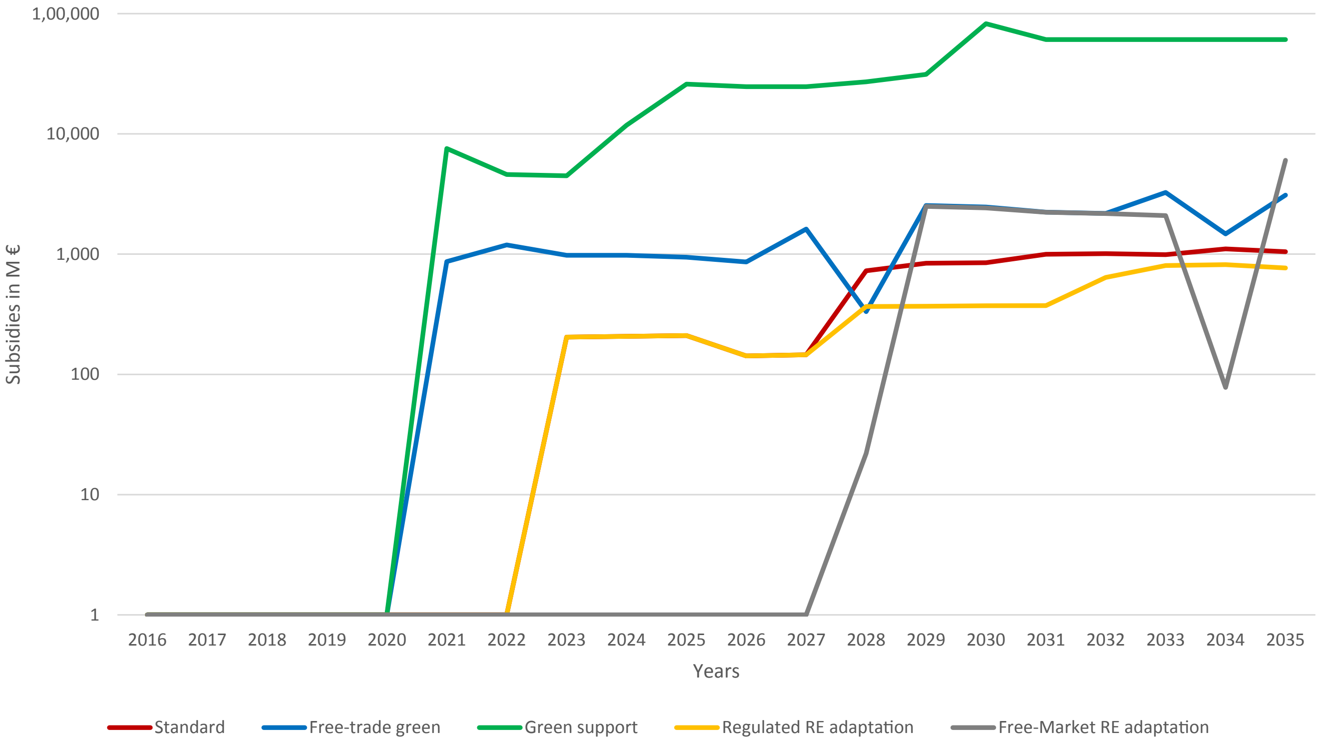

Fig. 18. Comparison of subsidies across policy scenarios.

cost efficient instrument to counteract these developments is to utilize a FIT mechanism for RE and to keep conventional power plants either in the existing market design or to apply the new developed market mechanism. However, up until now, we have avoided discussing the external costs relating to environmental and health damage caused by electricity generation. In the next subsection we investigate how the inclusion of external costs impacts our results.

4.3. Inclusion of external costs of electricity generation

In order to draw a more accurate comparison between our reference scenario and the five policy scenarios, we include the external costs of electricity generation in our calculations. It is generally claimed that environmental and health damages caused by the respective energy generation technologies are not sufficiently reflected in the market prices of electricity [54,55]. These damages (the costs of which are often borne by third parties and future generations rather than the direct buyers and sellers of electricity) are referred to as “externalities” in the economics literature [56]. When determining the external costs of energy generation, calculations need to include the environmental and health impacts of all activities required for electricity production (e.g. damages associated with the construction and installation of equipment, transportation, operational activities or the restoration of a site after its closure, see [57].

For this purpose, we calculated the average external costs per MWh produced for each generation technology based on data from Krewitt and Schlomann [58], Hohmeyer [59] Enquete Kommission [60], Enquete Kommission [61], Friedrich [62] and Braun [63]. These external costs are then multiplied by the production volumes of the corresponding power plant technologies in each policy scenario. Table 2 provides an overview of the external costs that we assumed for our simulations.

Fig. 19 and Table 1 show that the total external costs of the five policy scenarios are in the range between approximately €46 and 78 billion. The market conditions for RE are a defining factor behind these differences. Both in the standard and in the regulated RE adaptation policy scenario, where RE is subject to an FIT mechanism, the costs of externalities amount to approximately €78 billion. On the other hand, the other policy scenarios, which assume a free market for RE, show lower external costs between €47 and 50 billion. In the presence of a FIT mechanism, RE expands steadily but not as rapidly as under free market conditions. In contrast, the free market environment (with comparably higher electricity prices) fosters additional RE investments, hence reducing the need for conventional power plants and lowering the corresponding external costs.

Fig. 20 (see also Table 1) provides the sum of subsidies and external costs per policy scenario; the green support scenario remains the least cost efficient option. As mentioned in Section 4.1, the freemarket RE adaptation scenario (despite its lower total costs) is not a viable alternative, since it fails to guarantee the supply of security. The remaining three policy scenarios are all characterized by similar total costs ranging between approximately €72 and 86 billion. The free market green policy scenario is now more cost-efficient in comparison to the standard and the regulated RE adaptation policy scenarios (while the opposite held when only

Table 2
Assumed external costs in € cent per MWh.

Lignite	Hard Coal	Oil	Gas	Nuclear	Hydro-power	Geo-thermal	Biomass	Wind	Photo-voltaics
11.07	8.97	14.54	4.79	54.73	0.32	0.80	1.32	0.13	0.86

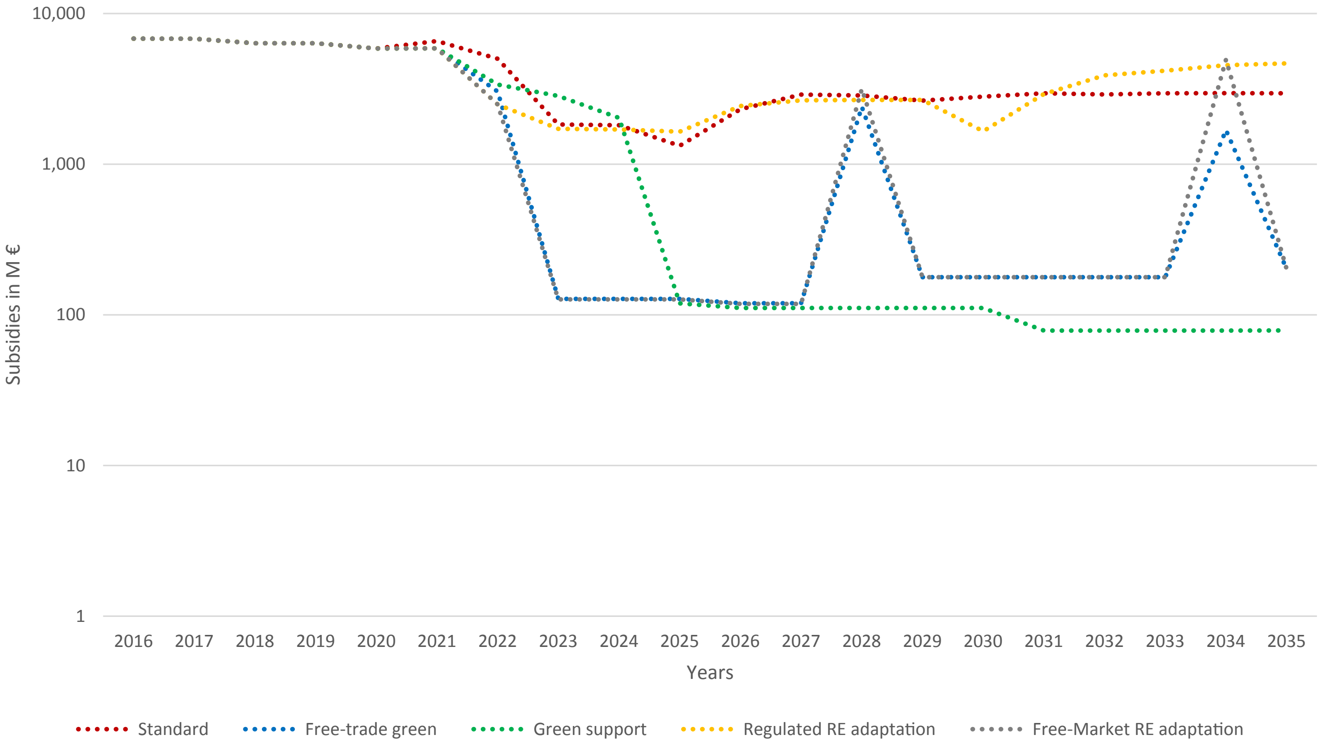

Fig. 19. Comparison of external costs across policy scenarios.

subsidies were considered, see Section 4.2). This is because the free market green policy scenario is associated with the lowest CO_2 emissions across all scenarios that ensure security of energy supply. This result shows that free market conditions for RE are a competitive viable option in case external costs are taken into consideration and conventional power plants are subject to a subsidy mechanism.

4.4. Sensitivity analysis

Finally, we carry out a sensitivity analysis by relaxing some of our key assumptions (results available from the authors upon request). Overall, the results show that increased CO_2 emission costs do not reduce the profitability of power plants, as these costs can be transferred

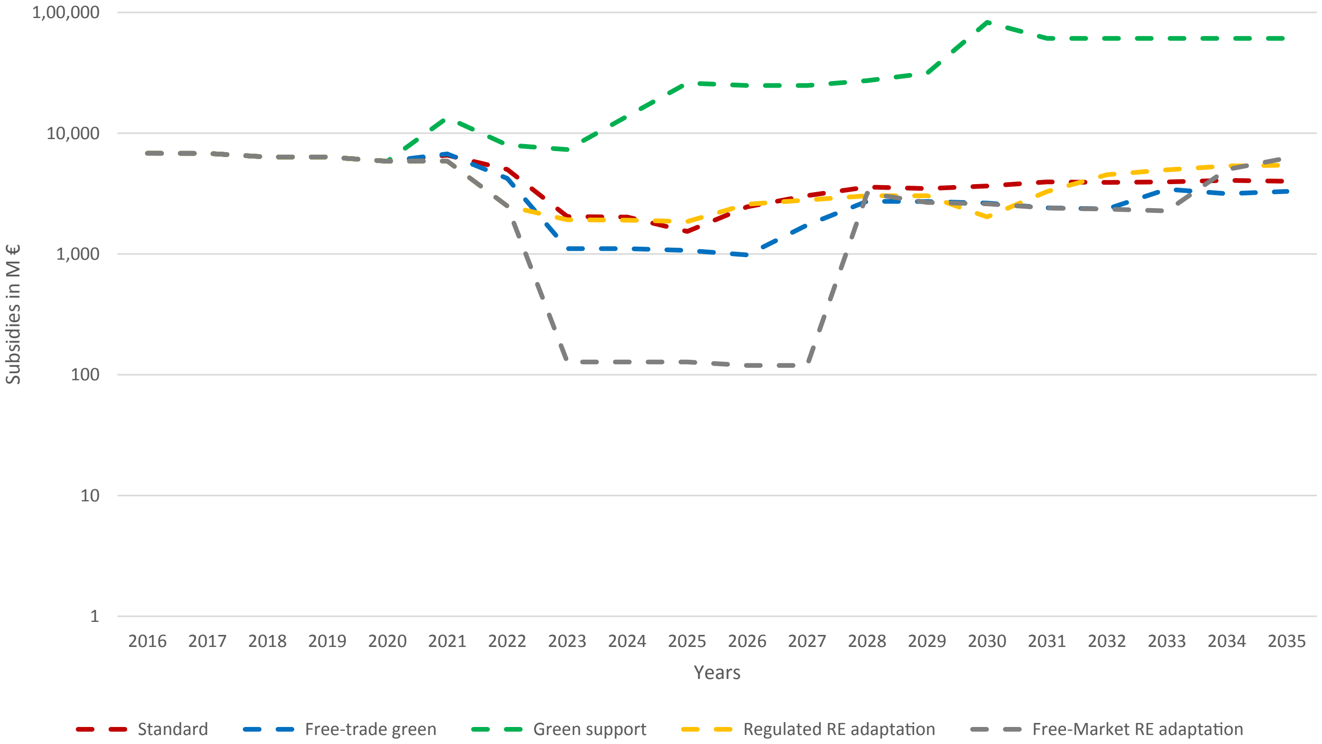

Fig. 20. Comparison of the sum of subsidies and external costs across policy scenarios.

to electricity prices. Modest variations in electricity demand also do not have a substantial effect on the installed power plant capacity. We also consider alternative scenarios corresponding to a halving of the discount rate as well as a doubling of markup prices. These alternative scenarios improve the profitability of power plants and, thus, increase installed capacity substantially; at the same time, our key findings regarding energy security and the cost efficiency of alternative policy scenarios still hold.

5. Conclusions

Over the past years, technological improvements have resulted in substantial cost reductions for renewable energy. At present, many renewable energy technologies are cost-competitive compared to conventional power plants. Due to their marginal costs being close to zero, the expansion of renewable energy leads to a displacement of conventional power plants in the market and to a reduction of the electricity price (i.e. the merit order effect of renewable energy materializes). For this reason, many conventional power plants are unable to operate profitably and, consequently, have to shut down. In this context, we studied the impacts of renewable energy under free market conditions on the security of electricity supply, based on empirical data. Our reference scenario showed that such a market environment leads to decommissionings of conventional power plants and, as a consequence, to energy supply falling short of demand.

We developed five policy scenarios with the aim of securing electricity supply as well as renewable energy expansion. Our results show that the green support policy scenario (where renewable energy receives subsidies, while conventional energy is traded on the free market) leads to a decrease of the electricity price close to zero, which in turn necessitates very large subsidies to compensate for the losses of power plants. On the other hand, our analysis reveals that the regulated renewable energy adaptation policy scenario (with a fixed feed-in tariff mechanism for renewable energy and optimally-adapted conventional power plants) results in the lowest subsidies necessary to maintain security of supply. However, the free market green policy scenario (where renewable energy is traded on the free market, while conventional power plants are subsidized) appears to be the most cost efficient option, once we take into account the external costs of electricity generation. This is because the free market green policy scenario leads to the lowest CO_2 emissions (out of all policy scenarios that ensure security of energy supply).

Policy-makers need to realize that the merit order effect of renewable energy leads to significant economic problems not only for conventional power plants but also for renewable energy units (which, as a consequence, threatens both further renewable energy expansion, as well as the security of electricity supply). In addition, and to obtain a transparent overview of the real costs of energy generation, policy-makers should take into consideration the external costs of energy generation.

Our analysis emphasizes the need for some form of governmental intervention in order to maintain an uninterrupted security of supply together with further renewable energy expansion. Each form of governmental intervention requires a certain amount of administrative effort. For the adoption of the renewable energy adaptation market design, in particular, there would be a need for changes in fundamental market conditions but also continuous regulation. Furthermore, even though the application of the free market green policy secures energy supply and renewable energy expansion at the lowest total costs, this scenario can only be utilized for a limited period of time as conventional power plants gradually reach the end of their lifecycles. In order to reach an ongoing expansion of renewable energy without new investments in conventional power plants, this scenario would also have to be amended in the long term.

Against this background, further research should build on and expand our current analytical framework by considering the effects of international trade in electricity, growing energy storage options and by investigating new forms of remunerating renewable energy in a market environment with a decreasing number of conventional power plants.

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