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Cross-border Electricity Transfers in the case of differentiated Renewable Energy Sources: A Simulation Analysis for Germany and Spain

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Cross-border Electricity Transfers in the case of differentiated Renewable Energy Sources: A Simulation Analysis for Germany and Spain†

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Abstract

Renewable electricity plays an increasingly important role in the effort to reduce CO_2 emissions in the electricity sector. One of the major challenges that must be addressed is the fluctuating supply of renewable electricity. We explore the impact of cross-border electricity transfers on both the security of electricity supply and renewable electricity expansion. We focus on Spain and Germany due to the relative abundance of their country-specific renewable electricity sources (solar for Spain and wind for Germany). We develop an electricity market model that allows for cross-border electricity transfers by connecting country-specific electricity markets. We apply six policy scenarios aiming towards securing the electricity supply and renewable electricity expansion. Our simulation results show that cross-border electricity transfers postpone supply shortages in both countries. These shortages occur as a result of an increasing amount of low-marginal-cost renewable electricity, which, in turn, leads to a decrease in the electricity price, so that power plants cannot operate profitably. However, the postponement of these supply shortages is primarily achieved through an excess supply of German conventional power plants that are utilised to meet excess demand in Spain. Although this serves to reduce required government subsidies, it also leads to an increase in CO_2 emissions.

Keywords: Cross-border electricity transfers; Security of electricity supply; Renewable Electricity

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Abbreviations

ED	Excess Demand
ES	Excess Supply
FIT	Fixed Feed-in Tariffs
G	Germany
GWh	Giga-Watt hours
ICT	Information and Communications Technology
LDC	Load Duration Curve
LDCM	Load Duration Curve Model
MOC	Merit Order Curve
MW	Mega-Watt
MWh	Mega-Watt hours
NPV	Net Present Value
PDC	Price Duration Curve
RE	Renewable Electricity
S	Spain
TWh	Tera-Watt hours

1. INTRODUCTION

Renewable electricity (RE) plays an increasingly important role in the ongoing effort to reduce CO_2 emissions in the electricity sector. According to the European Environment Agency (2019), the share of renewable electricity consumed in the EU rose from around 21% in 2010 to more than 30% in 2017. This expansion has been driven by significant decreases in the production costs of RE as a result of technological developments (Kumar et al., 2016). However, the ever-growing amount of RE results in lower electricity prices on the free market due to the low marginal costs of RE (Hirth, 2013). These price reductions weaken the profitability of both RE and conventional power plants to such an extent that many power plants have to be decommissioned on economic grounds. As a consequence, the security of electricity supply cannot be guaranteed in the long term (Coester et al., 2018a). The fluctuating supply of RE constitutes a further challenge that must be addressed in order to maintain sustainable green electricity generation. Notwithstanding demand-side management (e.g., industrial customers receiving some form of remuneration if they reduce their demand during times of peak demand) changes to the electricity market design, which includes, amongst other things, new remuneration schemes for renewable and conventional electricity, electricity storage technologies, infrastructural improvements and expansions of the electricity grids are other key instruments through which to support the ongoing development of RE (Larsen et al., 2017, Coester et al., 2018b and Coester et al., 2020). Expanding the electricity grids is necessary in order to integrate decentralised RE. Moreover, an extended grid would help to balance fluctuations in RE supply, insofar as a temporarily high (excess) RE supply in one region/country could be transmitted through the grid to another region/country where the RE supply is temporarily low, and vice versa. At the same time, grid-technology improvements focused on reducing electricity losses during grid transmissions are a fundamental requirement if we are to fully benefit from the aforementioned expansions (Lumbreras and Ramos, 2016).

This paper explores the impacts of cross-border electricity transfers between countries upon both the security of electricity supply and RE expansion. In order to allow for electricity transfers between countries, we assume that the electricity grid is of sufficient quality and size and that the level of investment required for this is in place. We focus on electricity transfers between two specific countries: Spain and Germany. These two countries were chosen in order to incorporate country-specific advantages related to RE, that is, we assume that photovoltaic and wind power plants have a higher efficiency rate in Spain and Germany respectively, as a result of the relative abundance of these electricity sources in the two countries (Anemos, 2017 and Handelsblatt, 2008). We develop an electricity market model that allows the national electricity markets of Germany and Spain to be connected. Based on the assumption of a developed electricity grid, the model permits investing in the power plant capacity in Spain in order to meet German demand, and vice versa. Moreover, an excess electricity supply in one country can be utilised to meet excess demand in the other country. We apply six policy scenarios that represent different policies aimed towards securing electricity supply and RE expansion. These policy scenarios encompass a wide range of assumptions pertaining to the market conditions for conventional electricity, RE and batteries, and can be applied in both countries independently. In order to explore which of the scenarios is best equipped to secure the electricity supply, while, simultaneously, leading to the highest amount of RE and lowest level of governmental subsidisation, we model 36 different combinations of these six national policy scenarios for Spain and Germany. Finally, we compare the results of our model that allows for cross-border electricity transfers to the results of separately modelling the electricity markets of Germany and Spain.

To the best of our knowledge, this is the first paper that develops a detailed model that allows for cross-border transfers of electricity in the context of competing investments in renewable and conventional electricity technologies as well as batteries. By so doing, this paper contributes to the field by producing new insights into the effects of different policy scenarios aimed towards both the security of electricity supply and expansion of RE in the context of accommodating for cross-border electricity transfers along with investments in batteries. Our results will assist policy makers' decision-making by providing a better understanding of future electricity generation and its attendant subsidies and external costs.

Section 2 reviews extant literature that examines the effects of expanding and internationally connecting grid capacities. In section 3, we discuss the methodological approach underpinning our analysis. Section 4 presents the results of our simulation, and, finally, section 5 concludes the paper.

2. Review of the literature

Cross-border electricity transfer is one major option to meet the challenge of fluctuating domestic RE generation and to secure electricity supply (Thaler and Hofmann, 2022, Haque et al., 2020, Singh, 2013). In this context, the electricity grid infrastructure is crucial for how this option can be utilized (Lumbreras et al., 2020, Nordensvärd and Urban, 2015). This is because, during periods of high RE supply, grids are overburdened to the extent that part of the produced RE cannot be integrated into the grid. Conversely, during periods of low RE production, grids are insufficiently expanded and connected to be able to supply regions with RE from elsewhere (Becker et al., 2014). The improvement and expansion of the electricity grid takes on even greater importance in light of both the objective to achieve a completely green electricity supply and the increased marketability of electric vehicles (Child et al., 2019, Un-Noor et al., 2017, Putrus et al., 2009, Turton and Moura, 2008).

Against this backdrop, several studies have analysed the suitability of the prevailing Information and Communications Technology (ICT) applications for managing electricity generation, transmission, distribution and demand, so that supply and demand are adequately matched. For instance, Wissner (2011) recommends that the operation of decentralised RE plants should be managed comprehensively by ICT within a smart network. In line with this, Yuan et al. (2010) point out that on-time bidirectional communication with ICT amongst all producing and consuming units can reduce supply-demand gaps. However, Cavillo et al. (2016) emphasise that smart grid technology requires significant investment in both the micro- and macro-grid infrastructure. With regard to Germany's electricity production, Wissner (2011) states that integration into a European network is essential for both extending the buffer range of the grid and utilising demand and supply differences across Europe (Wissner, 2011). In accordance with this, Tagliapietra et. al. (2019), Battaglini et al. (2009), Biberacher (2004) and Czisch (2005) all underscore that SuperSmart Grids, which are able to connect decentralised RE to the grid, can overcome the key challenge of fluctuating RE supply, while, simultaneously, enhancing the security of electricity supply and preserving the environment. Both Steinke et al. (2013) and Ajanovic et al. (2020) also stress the importance of a combined expansion and smart integration of storage and grid capacities, so as to be able to operate all European electricity networks on a 100% RE basis.

Extant literature has also analysed the effects of grid extensions and sufficient storage capacities upon both conventional power plant capacity and electricity prices. According to Chalvatzis and Hooper (2009), Sensfuß et al. (2008), Schaber et al. (2011), Giebel (2000) and Heide et al. (2010), conventional power plant requirements can be reduced and market prices for RE can be stabilised during peak production hours with little electricity demand. Similarly, Schaber et al. (2011) state that if renewable electricity can be distributed flexibly and adequately to meet demand across Europe, then subsidisation schemes for RE become redundant. Furthermore, if pre-existing international grid transfer capacities are fully utilised, then electricity backup requirements can be reduced by 13% compared to the national stand-alone utilisation of grids (Becker et al., 2014). Similarly, Becker et al. (2014) assume that a doubling of grid capacities would reduce national storage requirements by 26%. In addition to this, Rasmussen et al. (2014) show that in a pan-European grid, differences between electricity supply and demand can be fully balanced using hydrogen storage units and a comprehensive smart distribution system. Finally, Rodriguez et al. (2014) find that a grid spanning 27 European countries would reduce the total required grid capacity for annual electricity consumption from 24% to 15%. Consequently, international connections of grids reduce the overall required amount of grid capacity compared to the isolated national grid infrastructure. The Desertec project (Desertec 2019) also aims to make use of the advantages of cross-border electricity transfers. Amongst its multiple objectives, the project intends to benefit from country-specific electricity sources by generating solar electricity in North-Africa where solar energy is abundant. Through the utilisation of smart grids, this solar electricity could be transferred to European regions. In this way, around 17% of European electricity needs could be covered (Moreno, 2011, Samus, 2012). Weisensee and Ragheb (2012) posit that the additional storage of solar electricity in hydroelectric storage facilities could even enhance the potential of Sahara-electricity grids. However, in order to objectively assess the costs and benefits of the Desertec project, Backhaus et al. (2015), Rothe (2016) and Stegen et al. (2012) advise that one must include country-specific risks in the overall assessment (e.g., political instabilities in North Africa that result in breakdowns of power plants or delays in the building of plants).

In summary, extant literature assesses electricity transfers between countries based on an expanded and improved grid system as a valid option for increasing the amount of RE and securing electricity supply. Our analysis contributes to this literature by explicitly focusing on cross-border electricity transfers. In contradistinction to previous research, we develop an electricity market model that connects two national electricity markets and allows for cross-border electricity transfers based on excess electricity supply and demand within the two countries. Furthermore, we apply 36 combinations of policy scenarios (six for each country) that simulate the impact of various assumptions pertaining to government subsidies for RE, batteries and conventional power plants upon RE expansion and the security of electricity supply.

3. METHODOLOGICAL APPROACH

This section delineates the methodological approach applied in this paper. We utilise the Load Duration Curve Model (LDCM), which is frequently used in the extant literature (Poulin et al., 2008, Turner and Doty, 2007, Geiger, 2010), as the basis for our electricity market model. In our simulations, the NPV for each year is calculated over a ten-year period, both for conventional and RE power plants. Free market-based investments in power plants are implemented in an optimisation model that identifies both the type of power plant investment and the optimal capacity in MW that maximises the NPV. Furthermore, it is assumed that power plants may be removed from the market for two reasons. Firstly, they are removed if they reach the end of their technical lifecycle. Secondly, power plants can be decommissioned on economic grounds in the event that their NPV is negative for five successive years. For more details on the LDCM and our simulation approach, see Coester et al. (2018a) and Coester et al. (2018b).

We also integrate batteries in our LDCM along the lines of Coester et al. (2020). Within a free market, we simulate the profit maximising investment in batteries each year by maximising the NPV. In our policy scenarios (see subsection 4.2), batteries are utilised as a subsidised government investment aimed towards expanding RE and securing the electricity supply.

In order to study the impact of cross-border electricity transfers upon both RE expansion and the security of electricity supply, we include the Spanish and German electricity markets within our LDCM. We assume that each country has its own market, that is, both its own demand and supply curves and its own equilibrium price. Furthermore, we assume that electricity transfers between the two countries are based on the excess electricity supply and demand within each country. For this purpose, we compare the annual peak electricity demand in each country with its corresponding supply. If the electricity supply is sufficient to meet the maximum annual demand in both countries, then we assume that no electricity is transferred between Spain and Germany. In the event that one country has excess demand while the other country has excess supply, then we assume that electricity is transferred. Figure 1 shows in schematic form a scenario in which Spain has excess demand (ED_{Spain}) one year, while Germany has excess supply ($ES_{Germany}$). Without the possibility of electricity transfers, $ES_{Germany}$ would not be utilised, that is, the amount of electricity $ES_{Germany}$ would not be produced, but the fixed costs of power plants would be incurred. We assume that (part of) $ES_{Germany}$ is transferred in ascending order of marginal costs, that is, above the domestic equilibrium price.

In Figure 2, the required amount of $ES_{Germany}$ to meet ED_{Spain} is being transferred to the Spanish market (denoted by '$ES_{Germany}$ *for* ED_{Spain}'). Here, we assume that the electricity being transferred to Spain becomes part of the Spanish supply curve. Accordingly, this electricity transfer augments the supply curve for Spain (see *Supply Curve*$_{new}$ for the Spanish market in Figure 2) and, hence, influences both the formation of electricity prices and future power plant investment in Spain. On the other hand, the new supply curve for Germany (see *Supply Curve*$_{new}$ for the German market in Figure 2) is reduced by the same amount (i.e., by '$ES_{Germany}$ *for* ED_{Spain}'). The remaining amount of German excess supply stays in the German market ($ES_{Germany\ new}$).

If the situation of excess supply and excess demand between Spain and Germany is reversed in subsequent periods, then any earlier transferred electricity to Spain can be transferred back to Germany (depending on both the position in the MOC and the amounts of excess supply and excess demand). In the event that the electricity is not transferred back, then the power plants producing this electricity remain in the Spanish market until they are shut-down, either on economic grounds or because they have reached the end of their lifecycle.

As the marginal costs of '$ES_{Germany}$ *for* ED_{Spain}' are lower than the marginal costs of the existing peak load power plants in Spain, the cross-border electricity transfers do not lead to an increase in the equilibrium price in our schematic example shown in Figure 2. The CO_2 emissions, external costs and (if necessary) governmental subsidies for the electricity transferred are also attributed to the country to which the electricity is transferred. We make this assumption, because we aim to investigate the long-term effects of cross-border balancing of excess electricity supply and demand on the development of power plant capacity and the security of electricity supply. For this reason, we do not consider the option of short-term trade based on prices in our research. Given that we allow for free market investment in RE, conventional power plants and batteries (as well as the possible closure of the corresponding production facilities when they become unprofitable), a country that previously had excess demand may end up experiencing excess supply in subsequent years, and vice versa. In the event that both countries have excess demand at the end of the same year, then our policy scenarios become relevant for both countries, that is, scenarios for governmental intervention (see subsection 4.2) related to securing the electricity supply and RE expansion. In situations in which the excess supply of one country is smaller than the excess demand of the other country, then the excess supply of that particular country will be transferred and our policy scenarios will become relevant for the country with excess demand for the remaining gap.

Figure 1. Schematic supply and demand curves for Spain and Germany

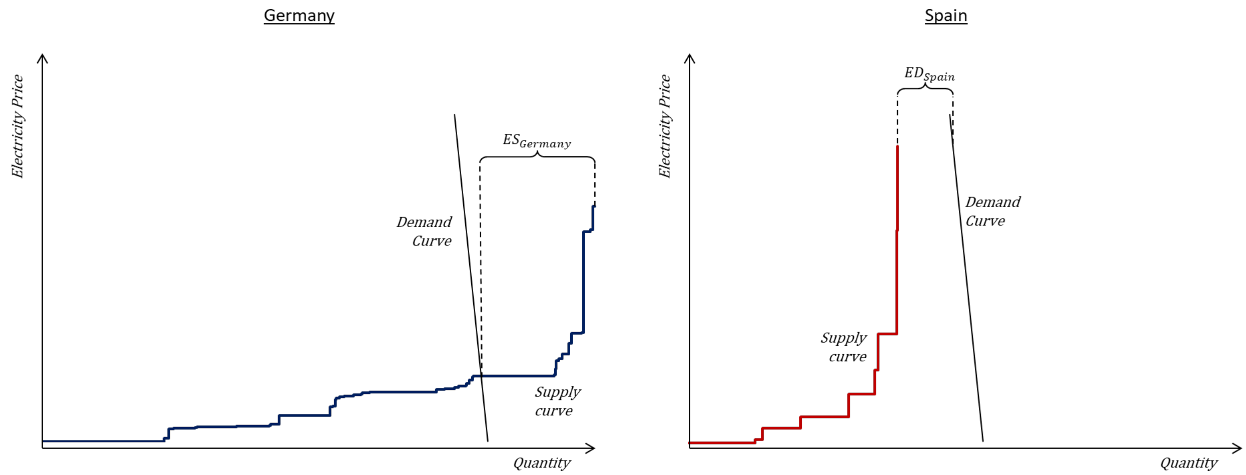
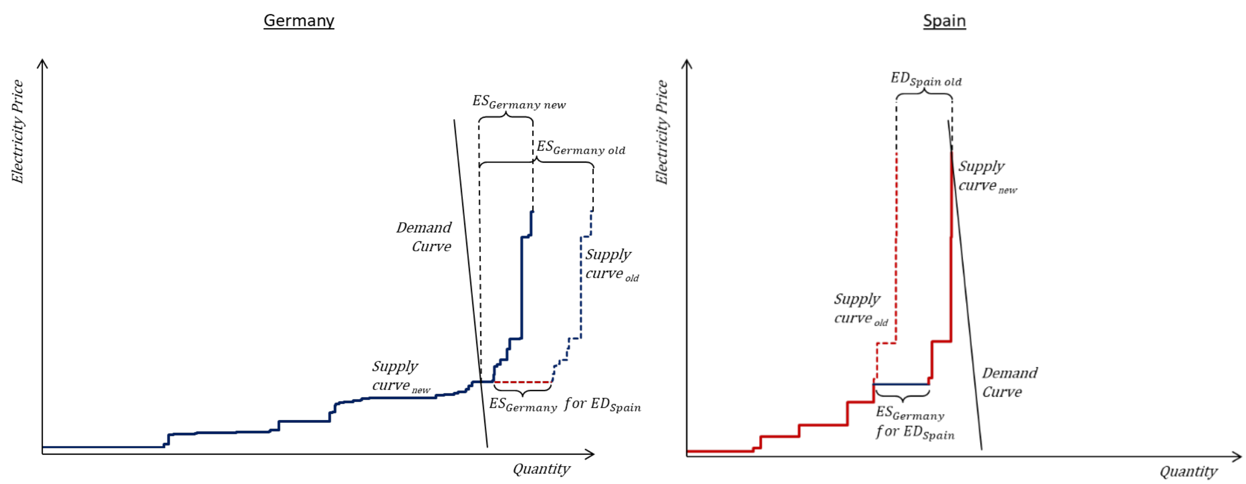


Figure 2. Schematic depiction of electricity transfers between Spain and Germany



4. SIMULATIONS

This section presents our simulations. More specifically, we describe our empirical data in subsection 4.1. Subsection 4.2 delineates the reference scenario and the six policy scenarios as well as outlining the main simulation results for each scenario. In subsection 4.3, we further analyse the results of our simulations, and finally, in subsection 4.4, we present the findings of our sensitivity analysis.

4.1 Data

Our simulations are based on empirical data. We consider a 20-year period of investigation that starts in 2018. With regards to the supply side, our data on actual conventional power plants operating within the German and Spanish electricity markets are based on information from the Federal Network Agency (2015) and Entsoe (2019a), respectively. Further economic and technical data pertaining to conventional power plants are based on information from the Western German State Bank (WestLB, 2009). While these data refer specifically to conventional German power plants, we assume the same economic and technical data for conventional Spanish power plants (an assumption that can be justified by the fact that both capital and operating expenditures, not to mention technical data for conventional power plants, are likely to be very similar in two industrialised countries within the European Union, Ram et al., 2017. The Federal Ministry for Economic Affairs and Electricity (2016b), Kaltschmitt et al. (2014), Deutsche Windguard GmbH (2013) and Entsoe (2019a) serve as the basis for our data on RE. In comparison to Germany, we assume that wind resources in Spain are 10% lower (Anemos, 2017), while there are 1,400 more hours of sunshine per year in Spain (Handelsblatt, 2008). The economic and technical data for batteries come from Zapf (2017), Mahnke et al. (2014), Pape et al. (2014) and Sterner and Stadler (2014). Our data for the demand side is based on historical real data of the hourly electricity demand in Germany (EEX, 2010-2013) and Spain (Entsoe 2019b).

We base our cost estimations for expanding and improving the electricity grid on data from the Desertec project that we also referred to in section 2 (TREC - Trans-Mediterranean Renewable Electricity Cooperation, 2007). These estimate the total investment costs for an improved grid infrastructure across Europe, the Middle East and North Africa to amount to €101,000 million. Given that these data are based on earlier estimates, subsequent technological developments may have resulted in a decrease in the actual costs. However, for the purpose of our research focus, we continue to make use of the estimated values by TREC to avoid underestimating the costs of expanding and improving the grid infrastructure. We assume that the distribution of these costs between the participating countries is determined by each country's electricity consumption, which we base on Entsoe (2019b) and World Data (2019). On this basis, we calculate the total investment costs needed to expand and improve the electricity grid to be €13,239 million and €6,486 million for Germany and Spain, respectively. We assume that these investment costs, which are the basic requirement for cross-border electricity transfers, are one-time set-up investment costs that are paid by the German and Spanish governments. Compared to these investment costs, the variable costs of operating national and international grids are relatively low. For this reason, we do not consider them in our analysis. Neither are the basic costs for grids (independent of expansion and improvement) considered, for the simple reason that we regard these costs to be a fundamental basis for national electricity supply. Against this backdrop, the additional costs of expanding and improving electricity grids are only of relevance when comparing the results of policy scenarios with electricity transfers to the results for separate markets (see subsection 4.3.7). The external costs of electricity generation are also taken into account (for further details see Coester et al., 2020).

4.2 Description of reference and policy scenarios

For our simulations, we developed a reference scenario along with six policy scenarios (see also Coester et al., 2020). The reference scenario serves as a benchmark, insofar as it reflects the situation under free market conditions. The policy scenarios are composed of several policy measures, many of which are 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 several countries, including in Germany and Spain. All policy scenarios aim at simultaneously guaranteeing the security of electricity supply and ongoing RE expansion and can be applied in both countries independent of the policy scenario employed in the other country. We included policy measures targeted at subsidising the ongoing operation of battery production plants. We assume in all our scenarios that the subsidisation 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. In a similar vein, we assume in our scenarios that governmental subsidies pay for any necessary supplemental power plants (the actual type of supplement power plant is dependent on the assumptions of the specific policy scenario). Finally, we assume that governmental subsidies pay for RE FITs.

By assuming that each country chooses its policy scenario independently, we can abstract from strategic behaviour by the countries. Consequently, we simulate all possible 36 combinations of the six policy scenarios for Spain and Germany, with a policy scenario coming into operation as described in section 3.

Reference scenario

In the reference scenario, both conventional and RE power plants as well as batteries are traded in a free market. Investments in these technologies are made with the objective of profit maximisation from the perspective of a private investor.

Standard policy scenario

In this particular policy scenario, RE is taken out of the free market in the event that there is an insufficient overall supply of electricity to meet the demand. RE is then traded under a FIT mechanism for the rest of the period under consideration, while conventional power plants stay on the free market. Our data is based on the actual FIT development in Germany between 2000 and 2016 (Federal Ministry for Economic Affairs and Electricity, 2016b), which we extrapolated until the end of the period under consideration. Generally speaking, the amount of FITs are closely linked to the generation costs of the particular RE. Against this backdrop, we assume around 60% lower FITs for photovoltaic electricity in Spain, based on the assumption that photovoltaic electricity can be produced at lower costs there (due to 1,400 more sunshine hours each year, Handelsblatt, 2008). At the same time, we assume around 10% higher FITs for wind electricity in Spain, since wind is produced at higher costs in Spain than in Germany (due to 10% lower wind resources, Anemos, 2017).

In addition, we assume that RE develops according to the expansion goals of the German government (i.e., the share of RE in total electricity generation should be between 40-45% by 2025 and 55-60% by 2035, see German Federal Government, 2016, Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, 2012) and of the Spanish government, respectively (i.e., the share of RE in total electricity generation should be 35% by 2030 and 100% by 2050, see Ensor, 2018).

Free market green policy scenario

Our assumptions concerning conventional power plants, batteries and supplementary power plants in this scenario are similar to the standard policy scenario. In contrast to the standard policy scenario, RE remains in the free market and RE power plants are decommissioned in the event that their NPV is negative for five years in a row.

Green support policy scenario

Within this scenario, possible shortages in supply are met with a mixture of batteries and supplementary investment in RE power plants. These supplementary RE power plants comprise a combination of onshore and offshore wind electricity, photovoltaic, hydro, geothermal and biomass power plants. For both Germany and Spain, this combination is based on the distribution of RE power plant technologies as per the expansion goals of the German Federal Government (German Federal Government, 2016, Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, 2012). As this combination of RE power plants is technologically diversified, it is able to partly balance out the fluctuating RE supply from different technologies itself.

Green FIT policy scenario

In contrast to the previous scenario, all RE in this policy scenario is subsidised through a FIT mechanism. Compared to the standard policy scenario, shortages in excess supply are met with a mixture of batteries and supplementary investment in RE power plants, whereas, in the standard policy scenario, supply shortages were resolved by a combination of batteries and supplementary investment in gas power plants.

Regulated RE adaptation policy scenario

In this particular scenario we apply the RE adaptation market design, which is a novel electricity market design for conventional power plants based on Coester et al. (2018a). The principal assumption of this market design is that both electricity prices and the profitability of conventional power plants are dependent on the ability of the complex of conventional power plants to optimally react to changes in residual load. In the event of shortages in the electricity supply, we assume that subsidised investment in a mixture of batteries and supplementary conventional power plants is carried out. The type of supplementary conventional power plant corresponds to the optimally adapted power plant. RE is traded under a FIT mechanism.

Free market RE adaptation policy scenario

Similar to the previous scenario, supply shortages in this policy scenario are met with subsidised investments in a mixture of batteries and supplementary conventional power plants based on the new market mechanism. The difference with respect to the previous scenario concerns RE, which is now traded under free market conditions.

4.3 Discussion of the results

In the following subsections we further analyse our simulation results[1]. As a general remark, it may be noted that our simulation results show several regularities. For each German policy scenario, the results of the following variables are independent of the policy scenario in Spain: RE consumed, photovoltaic electricity produced, the electricity supply of batteries, CO_2 emissions, governmental subsidies and external costs. As a consequence, when combining the six different policy scenarios of Spain with one of the German policy scenarios, the results of the above mentioned variables of the particular German policy scenario are the same for all the six combinations with Spain. In contrast to this, both the amount of electricity transfers and wind electricity produced in Germany are dependent on the policy scenarios of Spain. In Spain, the amount of electricity transfers and photovoltaic electricity production are dependent on the policy scenario that is chosen in Germany. The results of the remaining variables for Spain show the same regularities as those described for Germany. For more details concerning regularities and dependencies in the results of wind electricity and photovoltaics, please see subsection 4.3.4.

4.3.1 Electricity transfers

Figures 3 and 4 show the development of installed power plant capacity for Spain and Germany in the reference scenario. It can be seen that, in a free market environment, the electricity supply in Germany falls slightly below the level of demand in 2023, while Spain has excess supply in that year. On that

[1] Table A1 in the appendix provides an overview of the results. The results for the reference scenario as well as the 36 combinations of policy scenarios are represented via the abbreviations "G" for Germany and "S" for Spain and the numbers "0" for the reference scenario, "1" for the standard scenario, "2" for the free market green scenario, "3" for the green support scenario, "4" for the green FIT scenario, "5" for the regulated RE adaptation scenario and "6" for the free market RE adaptation scenario.

basis, the amount of Spanish excess electricity supply (around 2,000 MW of electricity from wind electricity) that is necessary to meet German excess demand is transferred in 2023. In Spain, electricity supply falls below demand in 2024. This is because all Spanish power plants must be decommissioned on economic grounds as electricity prices between 2019 and 2023 are very low, as a result of high volumes of wind electricity in the market. On the contrary, in 2024, Germany has excess supply, particularly because of high investments in wind electricity. Consequently, in 2024, German excess supply (around 41,000 MW from conventional and RE power plants) is transferred to Spain, so that Spanish excess demand can be met. This electricity transfer from Germany, especially the high marginal costs conventional power plants, provides an incentive for Spain to invest in wind electricity from 2025 to 2028. Due to the assumption of relative abundance of wind electricity in Germany, this newly invested wind electricity is produced in Germany and then transferred to Spain. As a result of the transferred amounts of electricity, the supply curves of both countries now include a segment of the former supply curve of the other country (see section 3). The wind electricity that is transferred from Spain to Germany is continuously utilised in Germany due to the low marginal costs of wind electricity and the resulting position on the MOC. The same is true for the RE that has been transferred from Germany to Spain. The conventional electricity that has been transferred from Germany to Spain is also utilised in Spain. This utilisation of conventional electricity decreases every year as ever-more new investments in wind electricity are made. On that basis, from 2025 to 2028, both countries have sufficient supply capacities to meet their domestic electricity demand. However, the high volumes of RE in both countries lead to low electricity prices, with the result being that after five years of unprofitable operation all power plants in the German market and the majority of power plants in the Spanish market have to be decommissioned. Consequently, in 2029, supply falls below demand in both Spain and Germany (see Figures 3 and 4). From 2030 to 2037, no further electricity transfers from Spain to Germany are made in the reference scenario. On the one hand, this is because Germany and

Spain have excess demand in the same years (2030 and 2036). For that reason, no electricity transfers take place on the basis of excess supply. Furthermore, the free market conditions in the reference scenario result in no transfer of photovoltaics from Spain to Germany. This is because German wind energy has lower production costs compared to photovoltaics. For the same reason, Germany continues to transfer wind electricity to Spain from 2030 up until 2036 when all wind electricity is decommissioned because of low prices. After that, in 2037, new investments in wind electricity are made.

Table A1 summarises the results with regard to total electricity transfers for both the reference scenario and the 36 combinations of policy scenarios for the entire 20-year period under investigation. Across all the policy scenarios, the total electricity transfers from Spain to Germany and vice versa range between 3,978 to 5,920 TWh. The electricity transfers from Germany to Spain are consistently higher. On the one hand, this is because the aforementioned excess demand in Spain in 2024 is considerably greater than the German excess demand in 2023, so that high amounts of the German excess supply are utilised to meet Spanish demand. Another reason for the higher electricity transfers from Germany to Spain is the assumption of relative abundance of wind in Germany with corresponding lower costs of production compared to Spain. As a result of this, apart from the pre-existing wind power plants in Spain, the remaining Spanish wind electricity consumption is met by wind electricity that is transferred from Germany. In comparison to this, considerably less photovoltaics is transferred from Spain to Germany. This is because the total costs of German wind electricity remain lower than Spanish photovoltaic electricity, so that Spanish photovoltaic electricity is not transferred in a free market environment to meet German demand. The highest amount of electricity transfers from Spain to Germany are achieved when Germany applies the "Green support" (G3) and the "Green FIT" (G4) policy scenarios (see Figure A7). This is because in these scenarios it is assumed that in the event of excess demand a certain amount of supplementary electricity will come from photovoltaics electricity. As a result of the lower production costs of photovoltaic electricity in Spain compared to Germany, this electricity is transferred from Spain to Germany. When Spain applies the "Green FIT policy scenario", the relative abundance of wind electricity in Germany leads to substantial transfers from Germany to Spain during the period from 2030 to 2037 (see Figure A8).

4.3.2 Security of electricity supply

Our simulation results show that in the reference scenario the security of electricity supply cannot be achieved in both Spain and Germany in 2029, 2030 and 2036 (see Figures 3 and 4). In both countries, the high volumes of low marginal costs RE that are in the market from 2024 to 2028 lead to low electricity prices, with the end result being that after five years of unprofitable operation all German and the majority of Spanish power plants have to be decommissioned. Consequently, in 2029, supply falls below demand in both Spain and Germany and remains insufficient in 2030. From 2031 to 2035, supply exceeds demand in both countries, primarily as a result of strong investment in wind electricity. However, the high volumes of wind electricity in the market once again lead to a low electricity price, which, in turn, means that power plants cannot operate profitably and have to be decommissioned in 2036 after running at a loss for five straight years. In 2037, a similar cycle (as the one observed in 2031) occurs, with substantial investment being made in wind electricity. With the policy scenarios coming into being in 2029 when supply falls short of demand in both Spain and Germany, the security of electricity supply is achieved over the entire simulation period across all the policy scenarios. This is because all of the policy scenarios are designed in such a way that any undercapacities in the market are met with different combinations of RE, conventional electricity and batteries depending on the particular policy scenario.

4.3.3 Renewable electricity consumed

From Table A1., one can discern that for both Germany and Spain all policy scenarios, with the exception of the standard policy scenario (G1 and S1) and the regulated RE adaptation scenario (G5 and S5), result in a higher amount of RE consumption than the reference scenario. The highest RE consumption in each country is achieved in the 'Green support' (G3 and S3) and 'Green FIT' (G4 and S4) scenario. The (other) scenarios that apply free market conditions for RE (G2, S2, G6, S6) result in only slightly lower levels of RE being consumed. While it is evident that free market conditions in the three scenarios lead to high RE consumption, the 'Green FIT' scenario that applies a FIT mechanism for RE results in an equally high level of RE consumption as the 'Green support' scenario because, when the policy scenarios commence in 2029, there is no electricity supply remaining in the market in Germany, while only wind electricity remains in the market in Spain. On that basis, both the 'Green FIT' and 'Green support' scenarios generate a completely green electricity supply, insofar as shortages in the electricity supply are topped up with an optimal mixture of batteries and green power plants in these scenarios (see Figures A5, A6, A7 and A8). In contrast to that, the 'Standard policy' (G1 and S1, Figures A1 and A2) as well as the 'Regulated RE adaptation' (G5 and S5, Figures A9 and A10) scenarios lead to less RE consumed in both Germany and Spain. The combination of utilising conventional power plants as a supplementation in the event of excess demand allied with the application of a FIT mechanism in these scenarios leads to a steady but slower development of RE compared to the free market conditions for RE in the reference scenario.

4.3.4 Electricity produced from wind and photovoltaic

Total wind electricity production is amongst the highest levels for those scenarios in which both Spain and Germany apply a free market for RE, namely combinations of G2, G3, G6 with S2, S3, S6 (see Table A1.). The 'Green FIT' (G4 and S4) scenario which, as aforesaid in subsection 4.3.3, leads to a high level of RE consumption results in a lower wind electricity production compared to the scenarios with a free market for RE. In the Green FIT scenario, a mixture of batteries and green power plants is applied together with a FIT mechanism. For this reason, the production of wind electricity in this scenario is determined by both the expansion goals of the German government (see subsection 4.2) and the amount of excess demand in the market. The application of a FIT mechanism for RE together with conventional power plants as a form of supplementation leads to the lowest levels of wind electricity production (G1, S1 and G5, S5). Wind electricity production in Germany is considerably higher than in Spain, due to the fact that wind electricity can be produced at lower costs in Germany because of the relative abundance of wind there. This wind electricity is partly utilised in Germany and partly transferred to the Spanish market. In the model, this transfer augments the supply curve for Spain and, as such, influences both the formation of electricity prices and future power plant investment in Spain. As Spain is able to buy the less expensive German wind electricity, no new investment in wind electricity are made in Spain, with Spanish wind electricity production solely relying on pre-existing plants.

In contrast to wind electricity, in 32 of the 36 combinations of policy scenarios, photovoltaic electricity production is significantly higher in Spain than in Germany. This is because of the assumption of the relative abundance of solar energy in Spain, which results in lower production costs of photovoltaic electricity in Spain. German photovoltaic electricity production solely comes from pre-existing German power plants. In the reference scenario as well as in four combinations of policy scenarios (G2/S2, G2/S6, G6/S2 and G6/S6), photovoltaic electricity production is lower in Spain than in Germany. This is because in these combinations of policy scenarios RE is traded under completely free market conditions. Within such a market environment, it is not profitable to invest in photovoltaic electricity, as we assume that wind electricity can be generated at lower costs. Consequently, photovoltaic electricity production solely comes from pre-existing plants in Spain and Germany. The highest photovoltaic electricity production is achieved in both the 'Green support' (G3 and S3) and 'Green FIT' (G4 and S4) scenarios, where a mixture of green power plants is utilised to secure the electricity supply. Given that this mixture is based on the distribution of RE power plants (as per the expansion goals of the German government), it thus relies extensively on photovoltaic electricity. In those policy scenarios that apply a FIT mechanism for RE in combination with conventional power plants in the event of excess demand (G1/S1 and G5/S5), photovoltaic electricity production continually increases, albeit on a lower level than those scenarios that utilise photovoltaic electricity as a supplementary power plant.

4.3.5 Electricity supply from batteries

The electricity supply from batteries in both Spain and Germany is equal to zero in the reference scenario (Table A1.). This is because without the application of policy scenarios, it is simply not profitable to invest in batteries (see also Coester et al., 2020). It can also be seen that the highest level of electricity supply from batteries is achieved in those policy scenarios in which RE is assumed to be supported by a FIT mechanism (combinations of G1, G4, G5 and S1, S4, S5). This is because the slower but nevertheless steady development of RE under a FIT mechanism requires a higher level of electricity supply from batteries in order to secure the overall electricity supply. In those scenarios with a free market for RE, the large investment in RE leads to less excess demand, which, in turn, results in lower requirement of electricity supply from batteries.

4.3.6 CO₂ emissions

The lowest CO_2 emissions are achieved when Spain and Germany apply a policy scenario in which shortages in the electricity supply are met with a mixture of batteries and green power plants (G3, G4 and S3, S4). Comparable low levels of CO_2 emissions are achieved when a policy scenario with free market conditions for RE (G2, G6 and S2, S6) is applied. This is in line with the results for RE consumption (see subsection 4.3.3). The scenarios that apply a FIT mechanism for RE along with conventional power plants in the event of excess demand (G1, G5 and S1, S5) lead to the highest CO_2 emissions.

4.3.7 Subsidies and external costs

Governmental subsidies are highest when both countries apply the "Green support" scenario. In this scenario, RE remains in the free market and all necessary investment for securing the electricity supply are made via a mixture of batteries and supplementary RE power plants under free market conditions. As a result, conventional power plants are driven out of the market, which, in turn, reduces the electricity price to close to zero and, as such, requires very high levels of governmental subsidies for RE and batteries. In those scenarios that apply a FIT mechanism for RE, governmental subsidies are at a lower level than those seen in the other policy scenarios with free market conditions for RE. On the one hand, this is because the FIT mechanism leads to a slower but more steady development of different types of RE, which results in higher electricity prices. Furthermore, the application of a FIT mechanism as a renumeration scheme results in lower governmental costs compared to those incurred when compensating for negative NPVs of power plants, which is the case in the policy scenarios with free market conditions for RE. The lowest external costs of electricity generation are achieved in the 'Green support' and 'Green FIT' scenarios. The reason for this is that both these policy scenarios lead to a completely green electricity supply (see Figures A5, A6, A7 and A8). Both the ‘Regulated RE adaptation’ and ‘Free market RE adaptation’ scenarios result in the highest external costs, due to the fact that nuclear power plants, which have the highest external costs of electricity generation, remain in operation within these scenarios. The lowest total costs (subsidies plus external costs) are achieved when both Spain and Germany apply the ‘Green FIT’ scenario. Besides resulting in the lowest external costs, the application of a FIT mechanism in this scenario also leads to low governmental subsidies. Consequently, the total costs for this combination of scenarios are a factor of around three and a half times higher than the costs required to expand and improve the electricity grid .

Compared to the results of policy scenarios in a market environment without electricity transfers (see Table A2.[2]), the amount of necessary governmental subsidies is always lower for both Germany and Spain in the model that does allow for electricity transfers. The external costs of electricity generation in Germany are also lower in the model with electricity transfers. In Spain, the external costs of electricity generation are always higher in the policy scenarios in the model with electricity transfers. Even when the additional costs that are necessary for grid expansion and improvements are excluded, most combinations of policy scenarios in the model with electricity transfers still lead to higher total costs compared to the scenarios in separate markets.

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[2] For more details see Coester et al. (2020)

4.4 Sensitivity analysis

We carried out a sensitivity analysis with regard to changes in the CO_2 price, electricity demand and costs of batteries. A doubling of the CO_2 price does not alter our key findings as these costs can be shifted to the electricity prices. Since, under the policy scenarios, new investments are mainly made in RE, batteries or efficient gas power plants (all of which produce either no or low CO_2 emissions), changes in the CO_2 price only have a very small effect on the amount of CO_2 emissions. The amount of necessary governmental subsidies for conventional power plants increases to a small extent as a result of a doubling of the CO_2 price. Variations in electricity demand (+ 0.50%/year) also do not have a substantial effect on our simulation results. A 10% decrease in the cost of batteries is still not sufficient to lead to more investment in batteries from the perspective of private investors. However, a 10% reduction in the costs of batteries does result in an approximately 10% decrease in the amount of governmental subsidies.

Figure 3. Reference scenario, German installed capacity for conventional power plants and RE

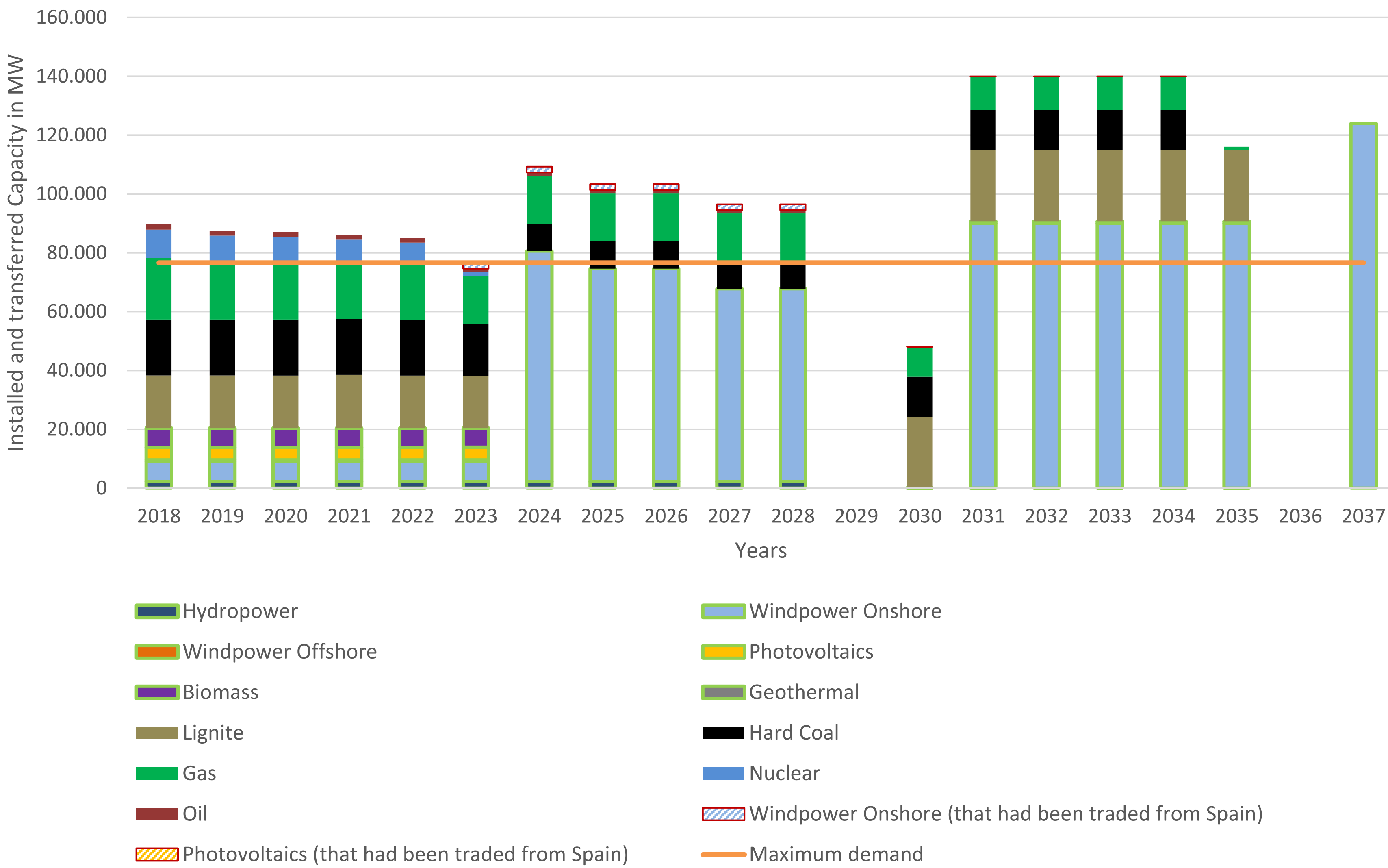
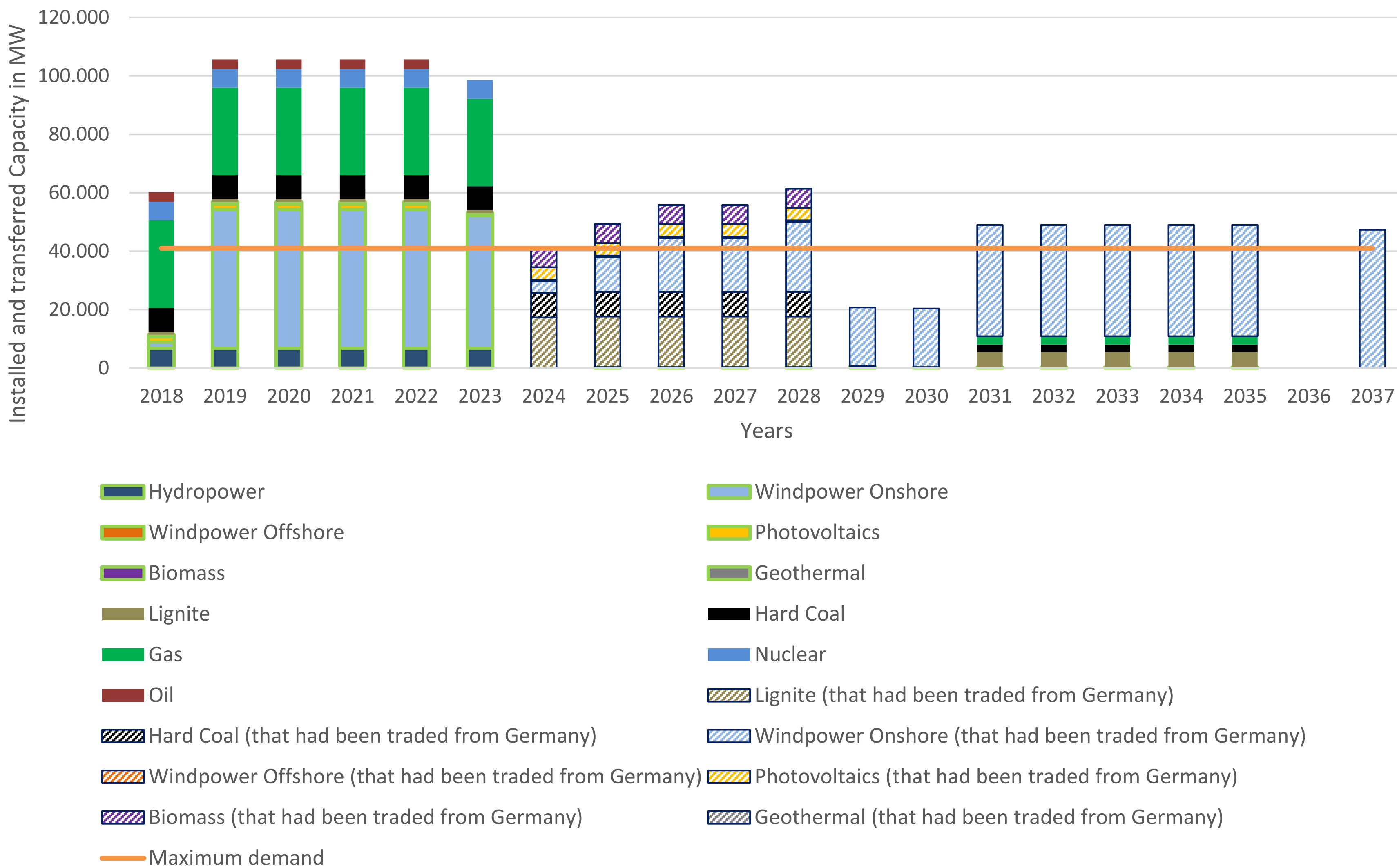


Figure 4. Reference scenario, Spanish installed capacity for conventional power plants and RE



5. CONCLUSIONS

The findings in this paper are partly counterintuitive. At first sight, the electricity transfers between countries appear to be completely advantageous. A developed grid infrastructure allied with electricity transfers between the two countries serves to balance out the fluctuating electricity supply and allows for the utilisation of RE from those countries with abundant solar or wind resources. With regard to the different policy scenarios, our research has shown that the lowest total costs result from the application of the ‘Green FIT’ scenario in both Spain and Germany. In this scenario, a completely green electricity supply can be achieved that leads to the lowest external costs. Furthermore, the FIT mechanism in this scenario also results in low governmental subsidies. While these advantages that come along with electricity transfers hold true, our analysis also draws attention to an additional downside. With electricity transfers also the excess capacities of conventional power plants can be utilised to meet excess demand. On the one hand, this leads to a postponement of the starting point of policy scenarios, thus resulting in lower governmental subsidies that are required to secure the electricity supply and ensure RE expansion (compared to the scenarios without electricity transfers). On the other hand, the higher utilisation of conventional power plants leads to an increase in CO_2 emissions as well as external costs of electricity generation. When the additional costs of the grid infrastructure are included, all combinations of policy scenarios with electricity transfers lead to higher total costs compared to the scenarios in the model without electricity transfers.

To draw a conclusion, in order to achieve the objective of completely sustainable electricity generation in the future, it is crucial to utilise the balancing effect of electricity transfers on a fluctuating electricity supply, for which a developed national and international grid is a necessary condition. Furthermore, the application of RE from those regions/countries with the most abundant renewable resources is decisive in guaranteeing low costs of electricity generation. However, policymakers should also be aware that free cross-border electricity transfers may increase conventional power utilisation. This is because conventional power plants can also be utilised to meet excess demand depending on both existing power plant capacities and the development of demand and supply in the connected electricity markets. Although this might be appealing in the short-term due to the lower levels of governmental subsidies required, policymakers should especially consider the negative long-term effects of higher external costs. Against this backdrop, when supporting electricity transfers, governments should carefully consider the impact of a potential increase in conventional power utilisation. One potential measure through which governments can counteract this could be the determination of maximum generation volumes per power plant technology per year. While our results could also be extended to countries with similar natural resources and comparable existing power plant capacities, future research may seek to extend our analysis further by simulating the effects of electricity transfers amongst more than two countries. Future research could also consider the option of short-term trade based on prices. This could lead to a reduction in costs and CO_2 emissions if the excess supply in one country is cheaper and greener than the utilised supply in the other country. Furthermore, future research could include the impact of the increasing utilisation of electricity in both vehicles and heating upon the costs and benefits of electricity transfers between countries. This may alter some of our key findings, as, if the overall level of electricity demand increases, then the costs and benefits of electricity transfers might change. Moreover, the utilisation of electric vehicles as storage facilities, particularly for excess RE, may also impact upon our simulation results.

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Figure A1. Standard policy scenario, German installed capacity for conventional power plants and RE

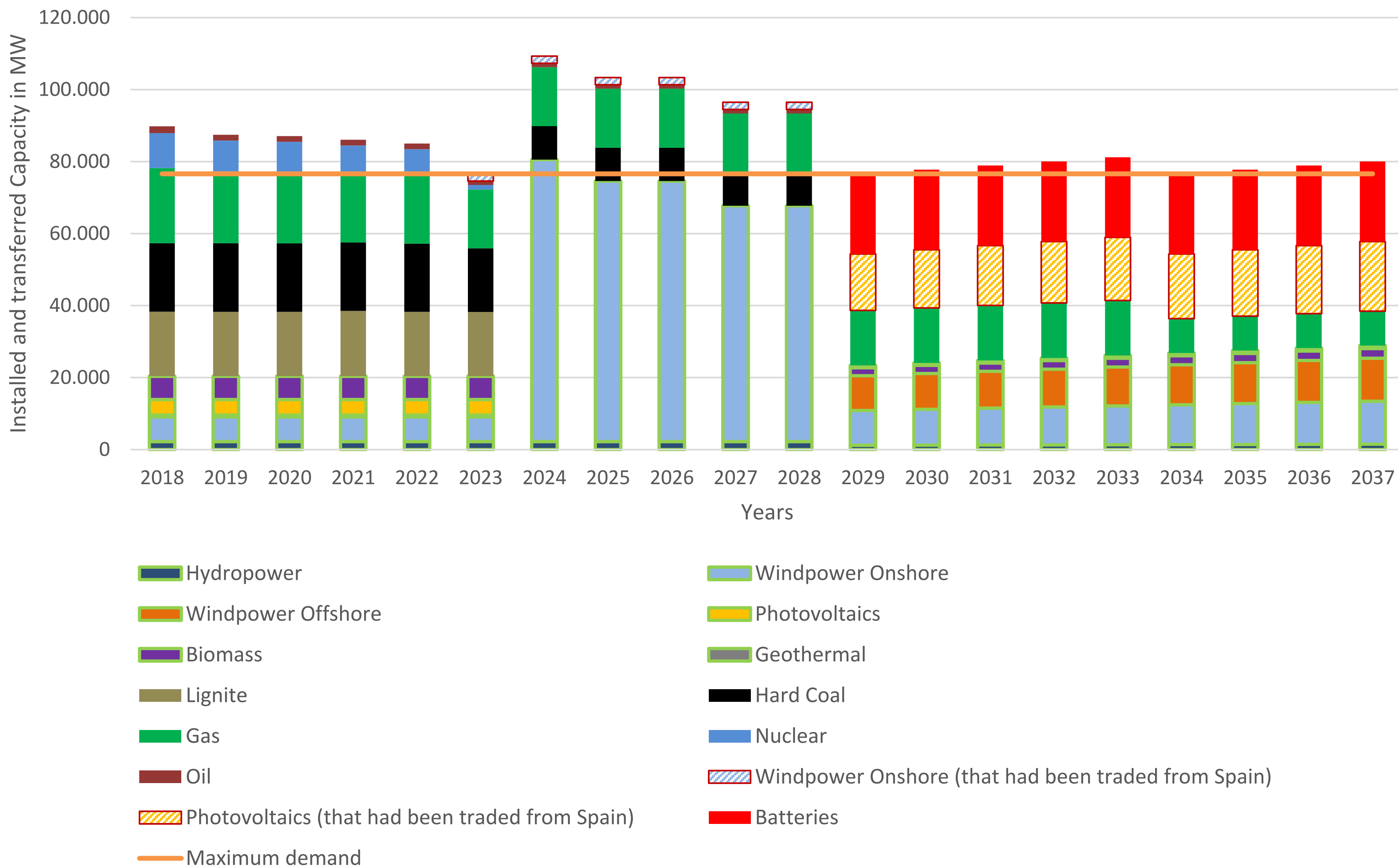

Figure A2. Standard policy scenario, Spanish installed capacity for conventional power plants and RE

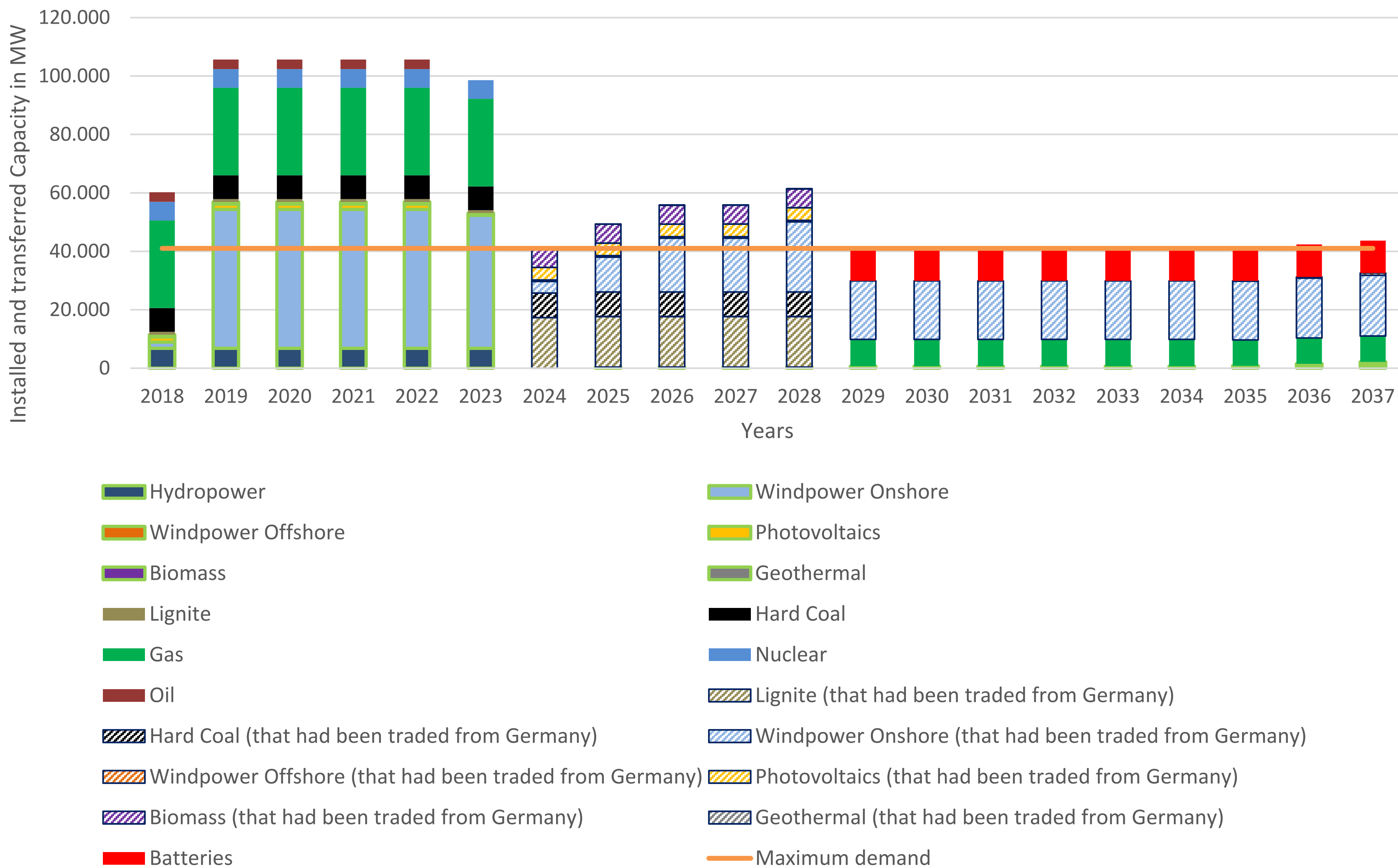

Figure A3. Free market green policy scenario, German installed capacity for conventional power plants and RE

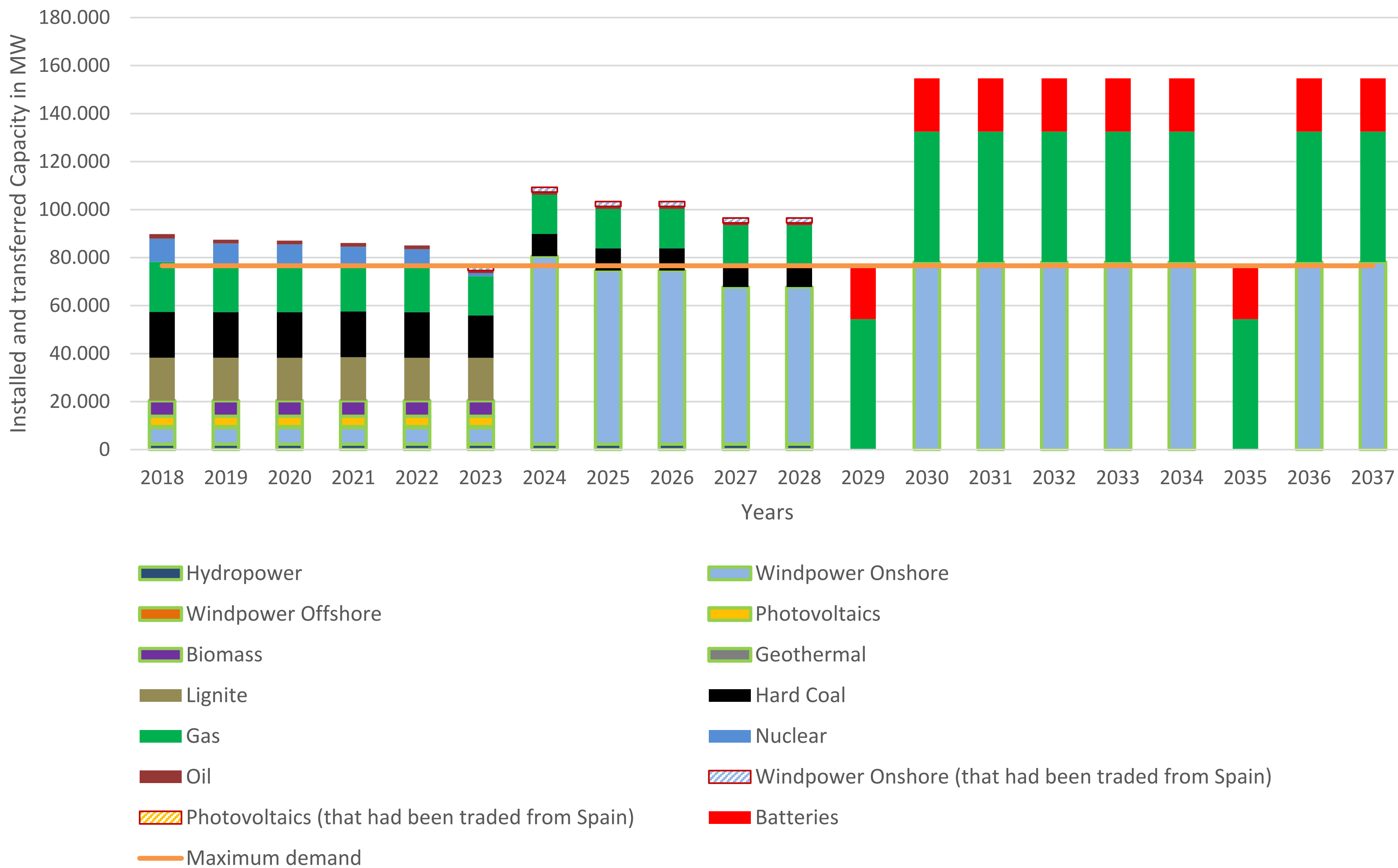

Figure A4. Free market green policy scenario, Spanish installed capacity for conventional power plants and RE

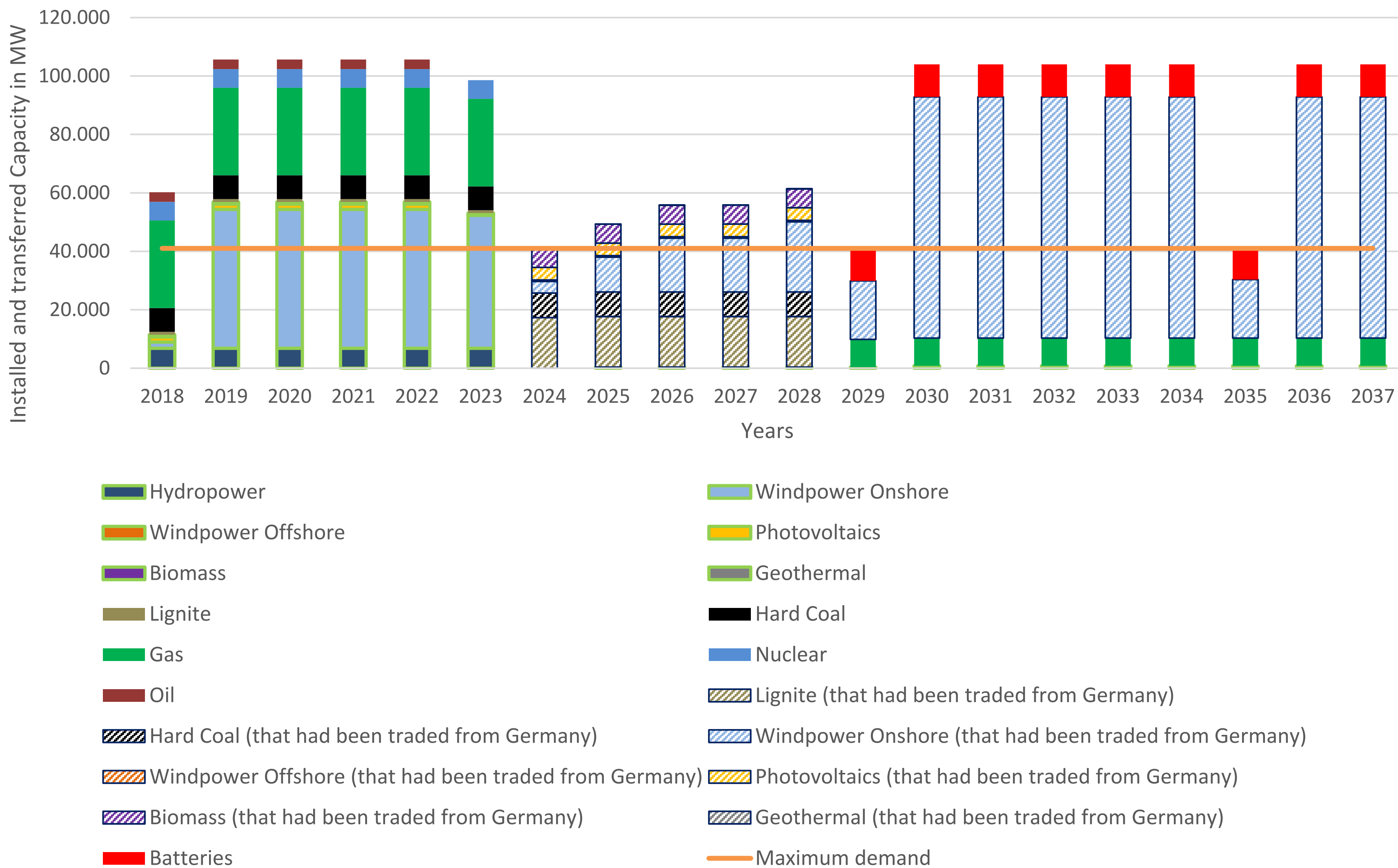

Figure A5. Green support policy scenario, German installed capacity for conventional power plants and RE

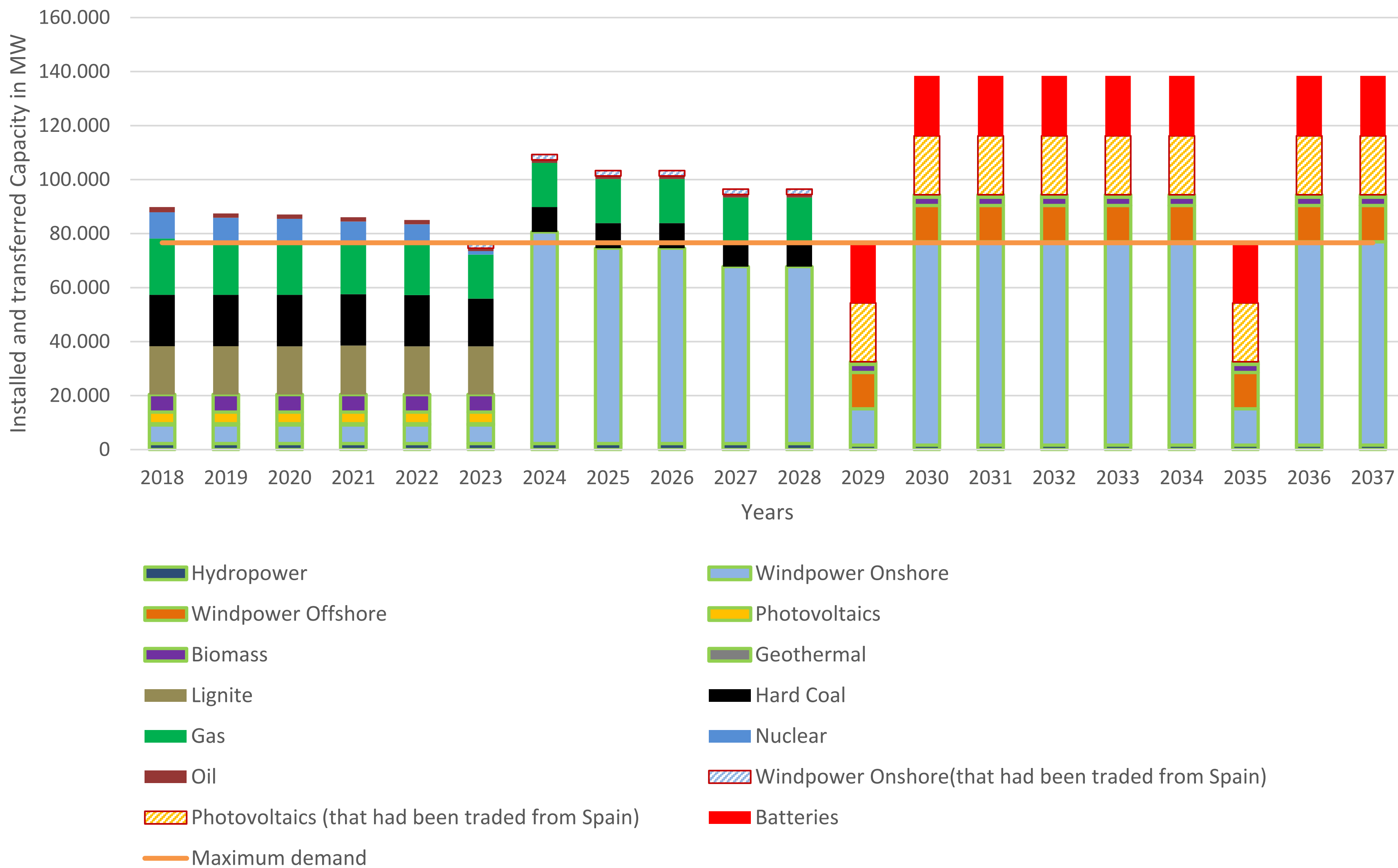

Figure A6. Green support policy scenario, Spanish installed capacity for conventional power plants and RE

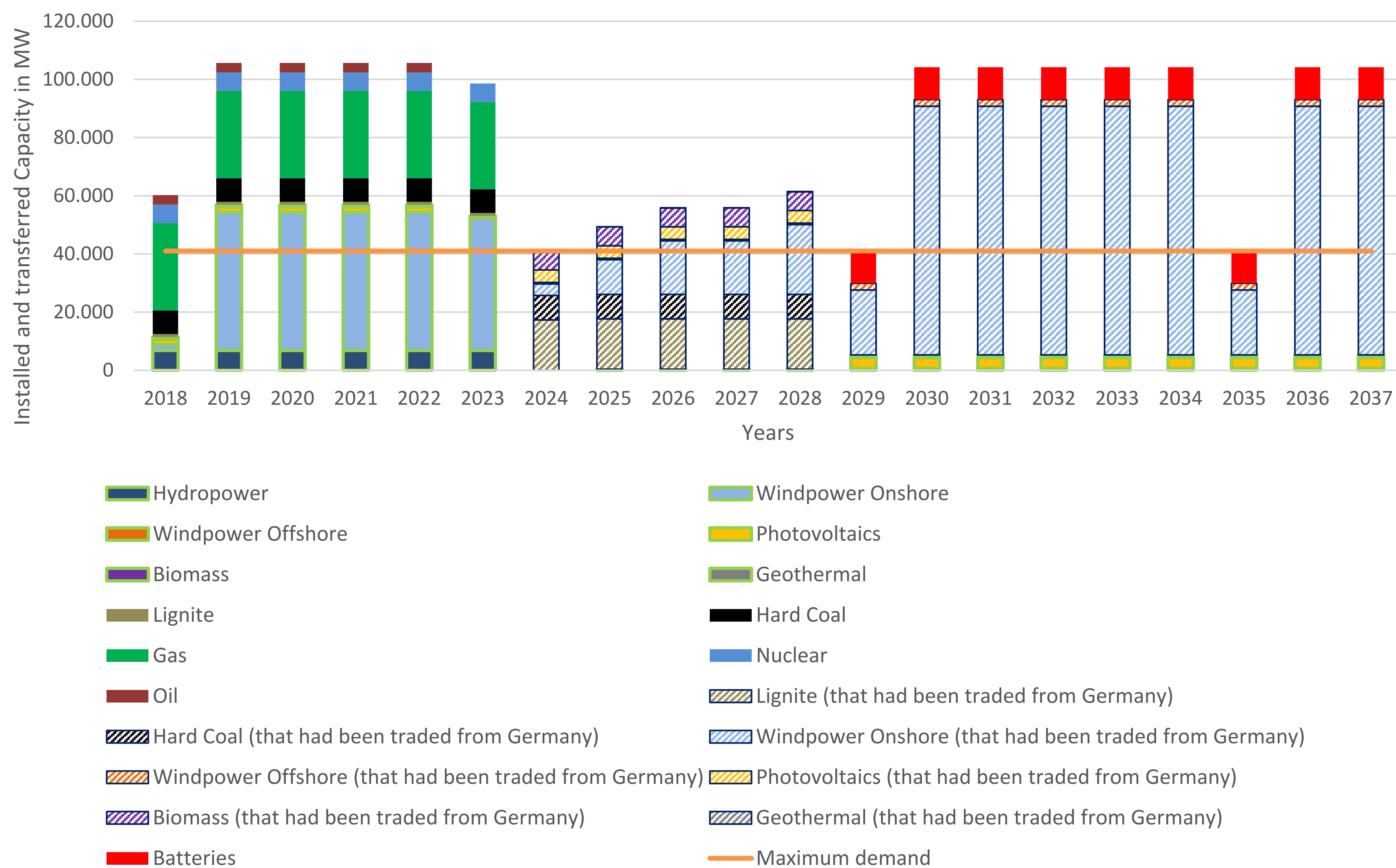

Figure A7. Green FIT policy scenario, German installed capacity for conventional power plants and RE

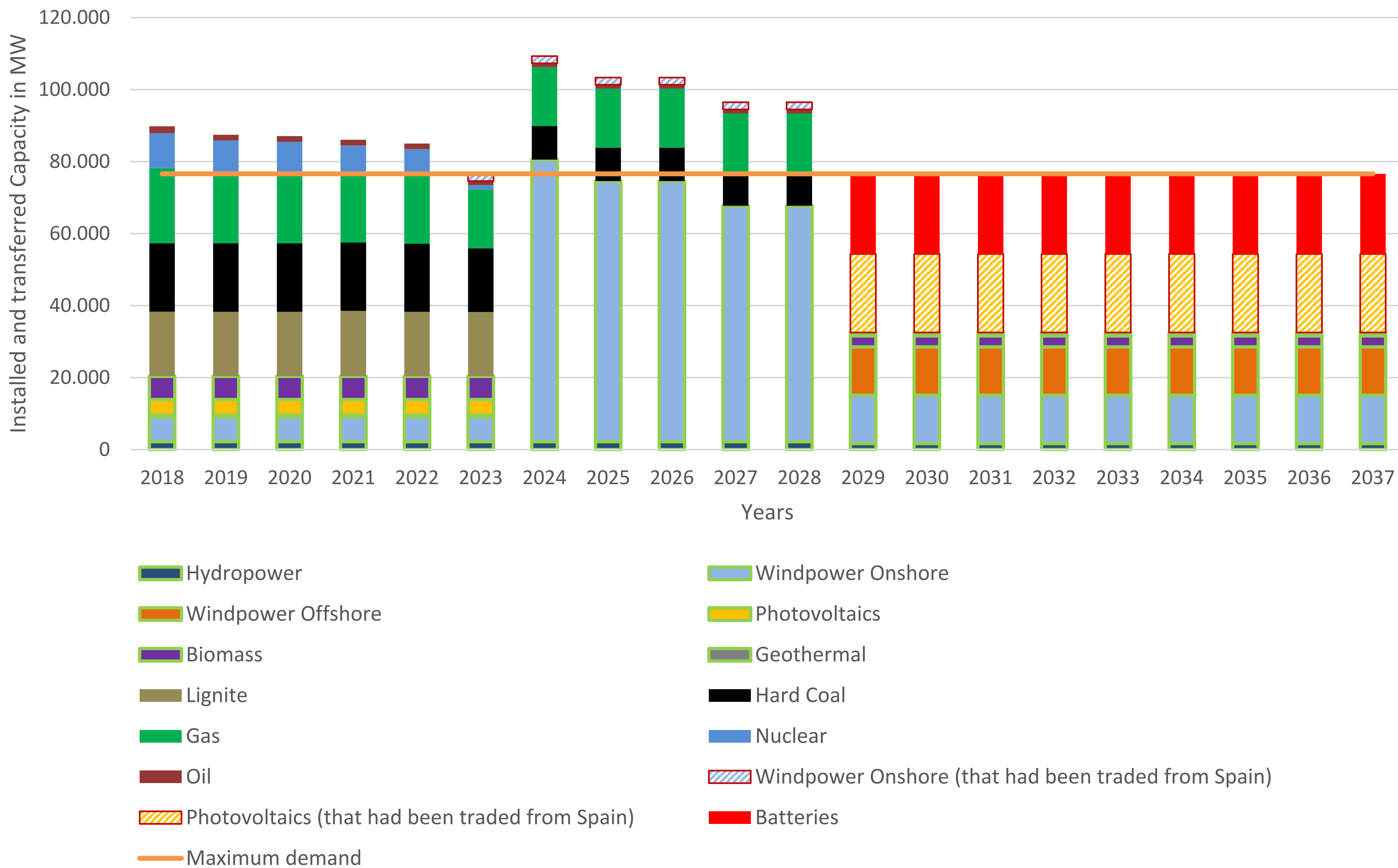

Figure A8. Green FIT policy scenario, Spanish installed capacity for conventional power plants and RE

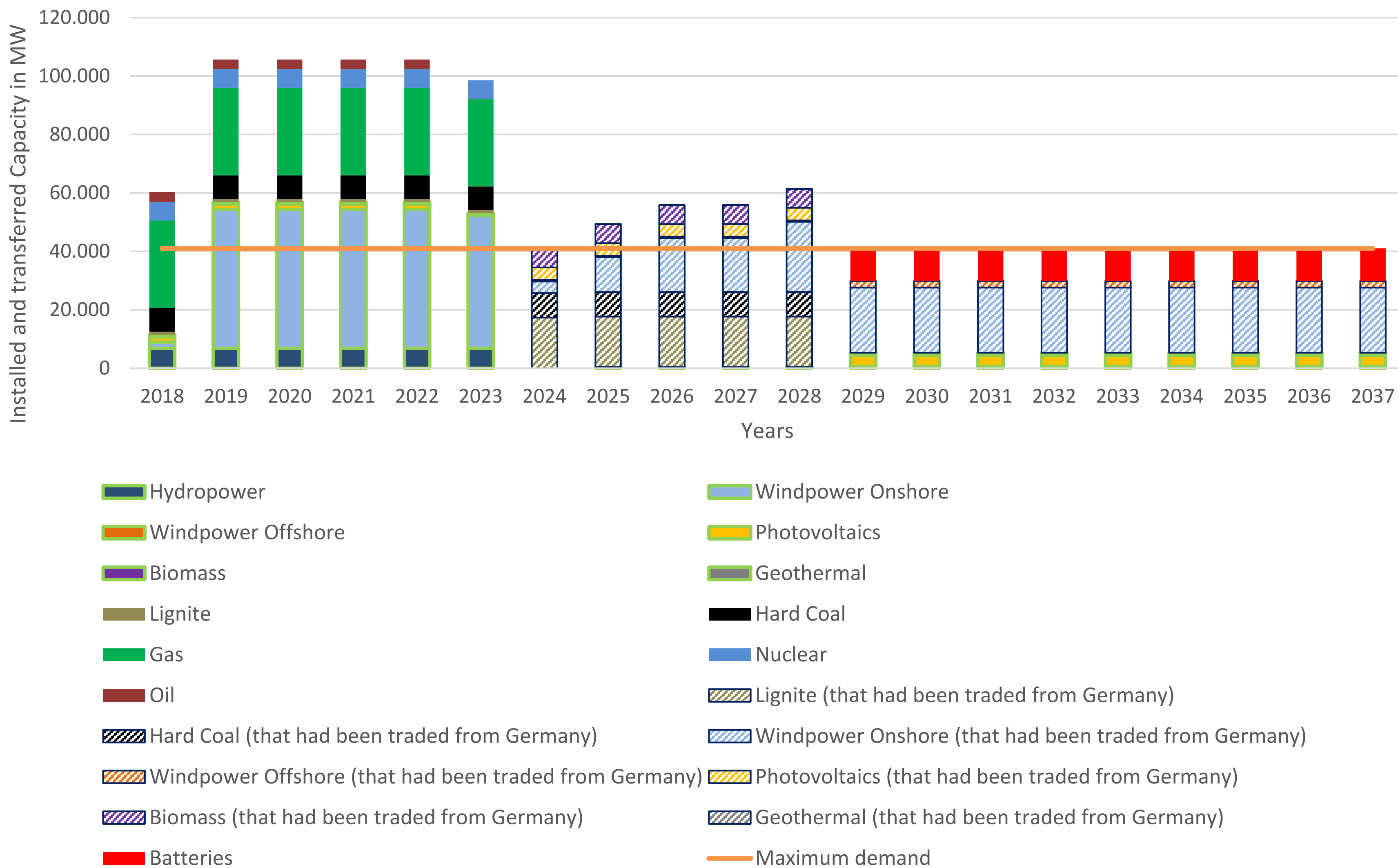

Figure A9. Regulated RE adaptation policy scenario, German installed capacity for conventional power plants and RE

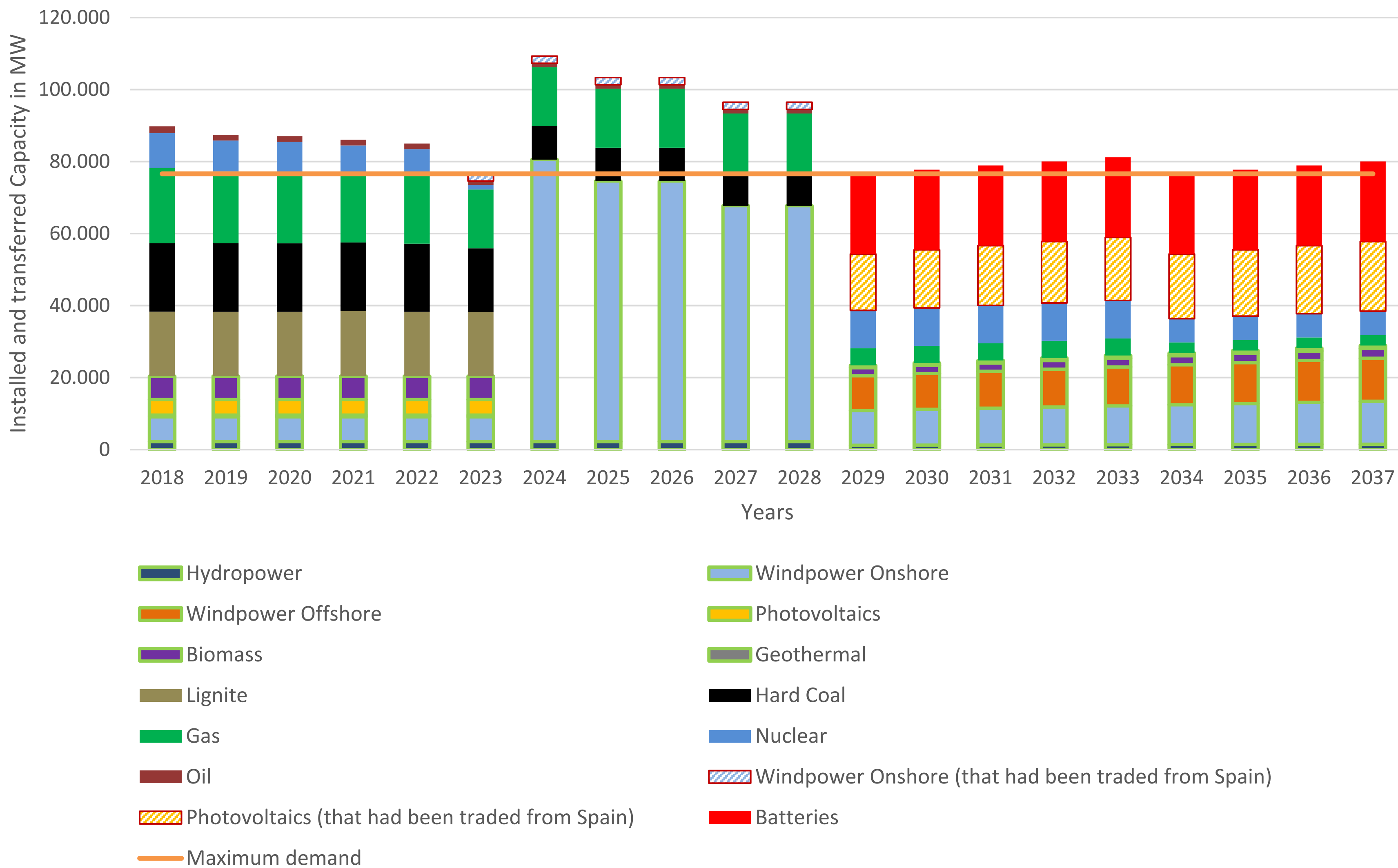

Figure A10. Regulated RE adaptation policy scenario, Spanish installed capacity for conventional power plants and RE

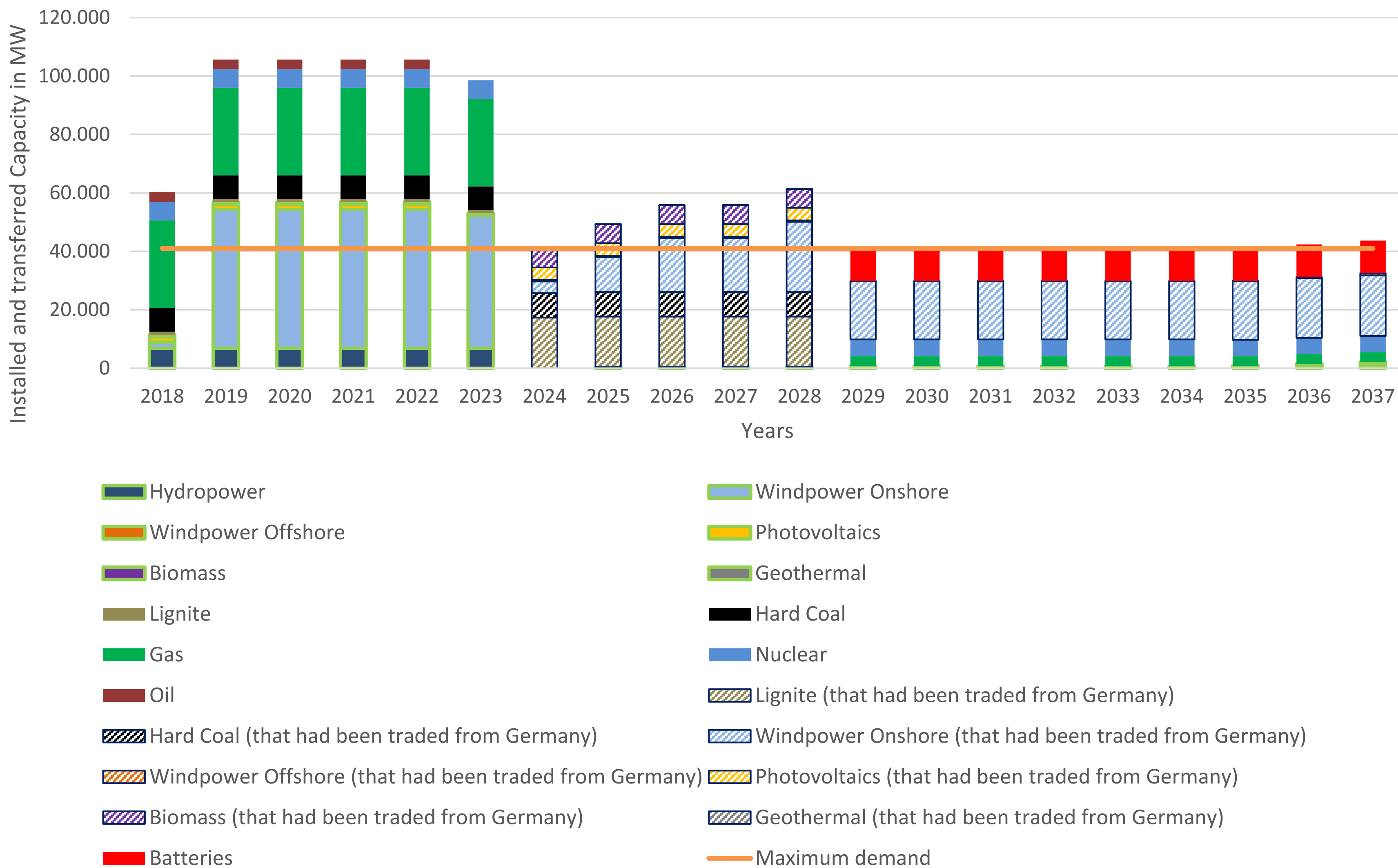

Figure A11. Free market RE adaptation policy scenario, Spanish installed capacity for conventional power plants and RE

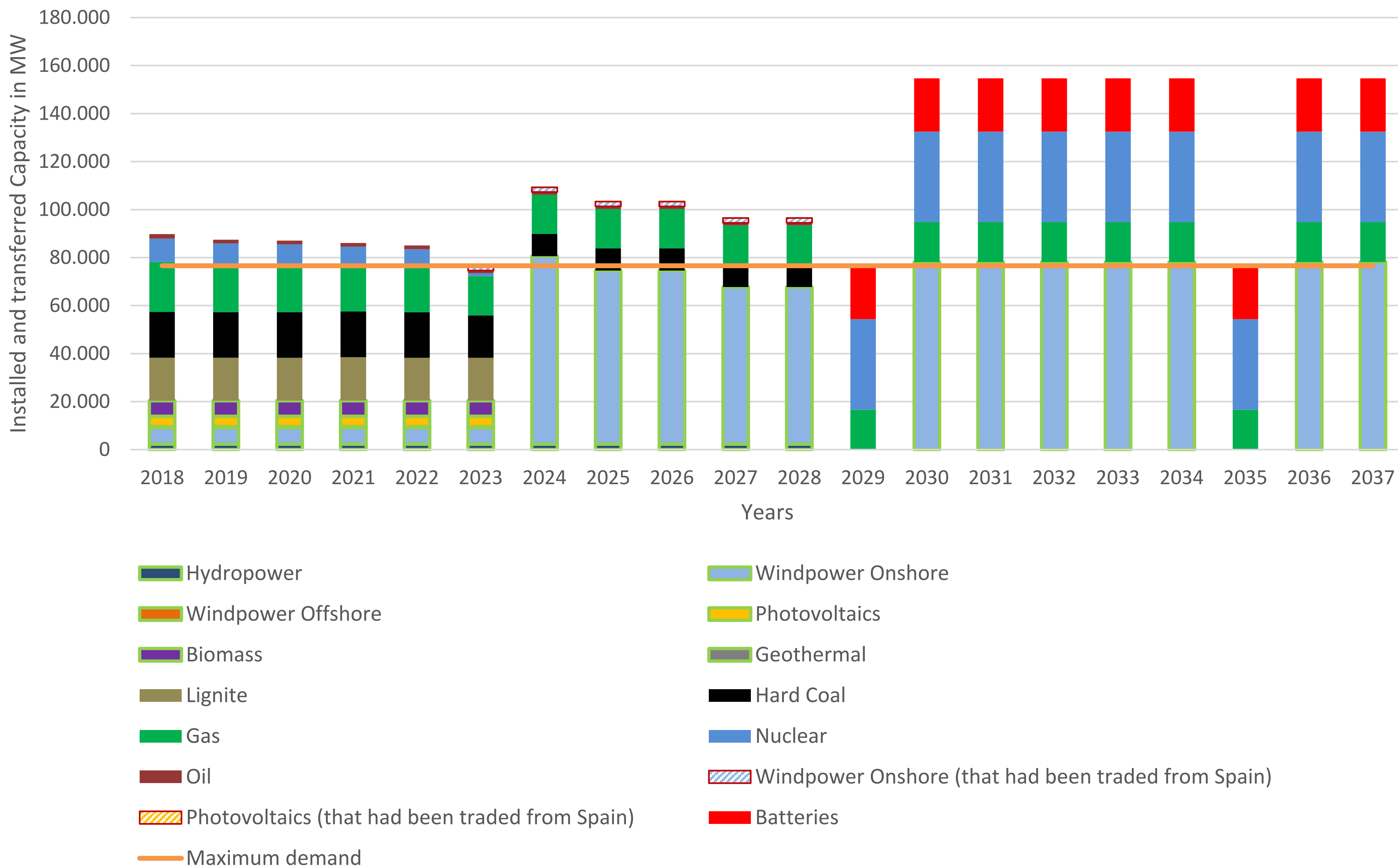

Figure A12. Free market RE adaptation policy scenario, Spanish installed capacity for conventional power plants and RE

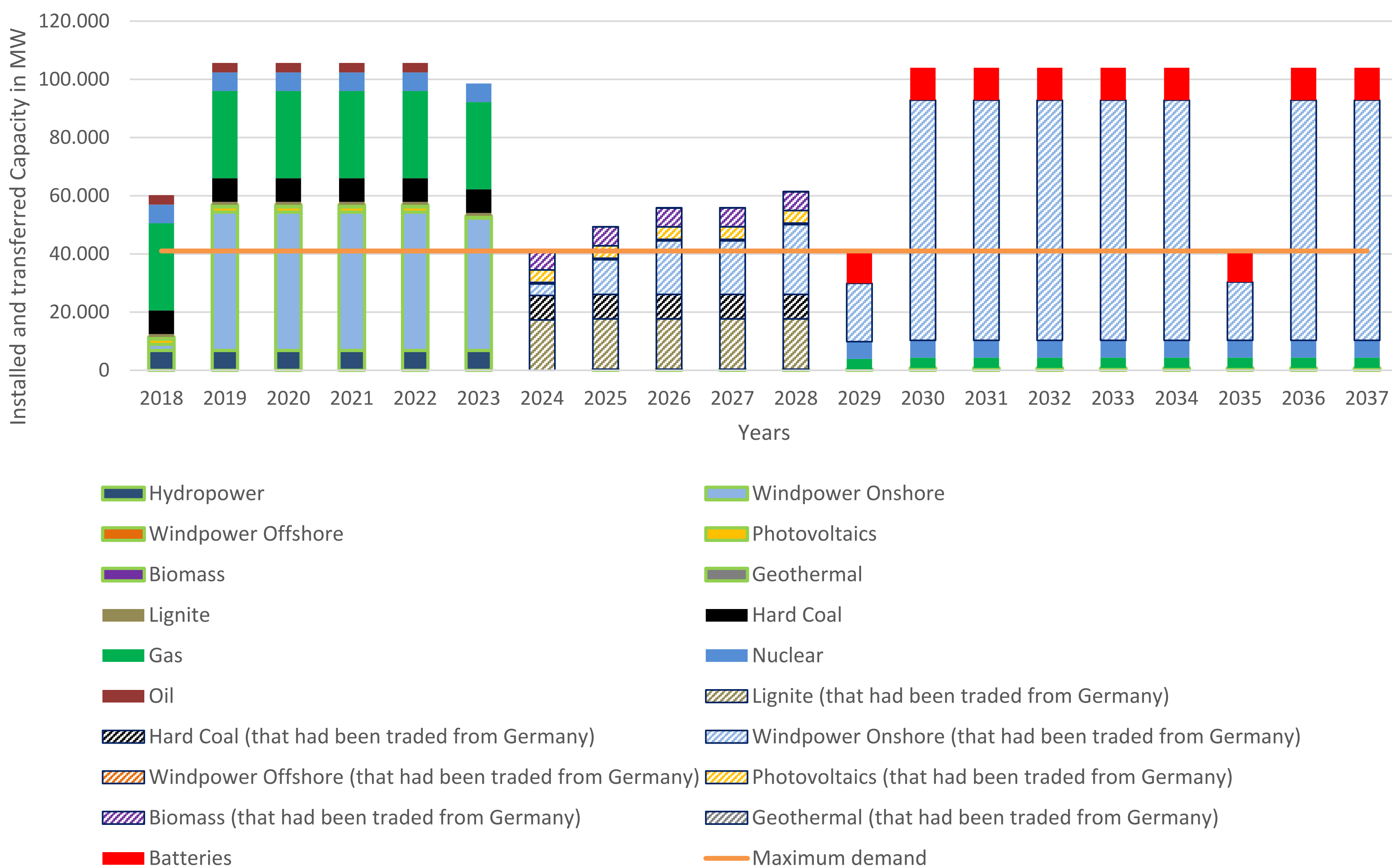

Table A1. Results for the Spanish and German electricity market (cumulative over the simulation period)

No.	Reference and policy scenarios	Assumption RE	Assumption Conventional electricity	Electricity transfer in GWh	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	Grid costs in € million
G0	Reference scenario	Free market	Free market	G-S 3,456,932	No	5,369,523	12,134,892	561,871	0	1,458	0	35,276	13,239
S0	Reference scenario	Free market	Free market	S-G 67,426	No	3,356,821	108,987	66,849	0	1,279	0	34,193	6,486
G1	Standard scenario	FIT	Subsidised gas power plants	G-S 3,910,694	Yes	3,953,022	5,502,623	561,871	105,479	3,763	2,103	42,284	13,239
S1	Standard scenario	FIT	Subsidised gas power plants	S-G 298,925	Yes	2,538,721	108,987	719,234	21,806	1,455	1,252	40,696	6,486
G1	Standard scenario	FIT	Subsidised gas power plants	G-S 4,172,119	Yes	3,953,022	10,794,677	561,871	105,479	3,763	2,103	42,284	13,239
S2	Free market green scenario	Free market	Subsidised gas power plants	S-G 298,925	Yes	3,429,052	108,987	284,528	4,845	1,194	3,289	36,894	6,486
G1	Standard scenario	FIT	Subsidised gas power plants	G-S 4,291,301	Yes	3,953,022	10,895,441	561,871	105,479	3,763	2,103	42,284	13,239
S3	Green support scenario	Free market + subsid. green pow. plant.	Free market	S-G 298,925	Yes	3,512,175	108,987	1,050,620	4,845	1,122	219,481	33,919	6,486
G1	Standard scenario	FIT	Subsidised gas power plants	G-S 4,002,016	Yes	3,953,022	5,668,423	561,871	105,479	3,763	2,103	42,284	13,239
S4	Green FIT scenario	FIT + subsid. green power plants	Free Market	S-G 298,925	Yes	3,512,175	108,987	974,034	21,806	1,122	1,989	33,919	6,486
G1	Standard scenario	FIT	Subsidised gas power plants	G-S 3,910,694	Yes	3,953,022	5,502,623	561,871	105,479	3,763	2,103	42,284	13,239
S5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	S-G 298,925	Yes	2,538,721	108,987	719,234	21,806	1,370	2,198	66,137	6,486
G1	Standard scenario	FIT	Subsidised gas power plants	G-S 4,172,119	Yes	3,953,022	10,794,677	561,871	105,479	3,763	2,103	42,284	13,239
S6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	S-G 298,925	Yes	3,512,175	108,987	284,528	18,642	1,230	3,313	42,568	6,486

No.	Reference and policy scenarios	Assumption RE	Assumption Conventional electricity	Electricity transfer in GWh	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	Grid costs in € million
G0	Reference scenario	Free market	Free market	G-S 3,456,932	No	5,369,523	12,134,892	561,871	0	1,458	0	35,276	13,239
S0	Reference scenario	Free market	Free market	S-G 67,426	No	3,356,821	108,987	66,849	0	1,279	0	34,193	6,486
G2	Free market green scenario	Free market	Subsidised gas power plants	G-S 3,910,694	Yes	5,597,832	10,711,486	561,871	23,439	1,728	3,701	38,738	13,239
S1	Standard scenario	FIT	Subsidised gas power plants	S-G 67,426	Yes	2,538,721	108,987	528,566	21,806	1,317	1,252	40,696	6,486
G2	Free market green scenario	Free market	Subsidised gas power plants	G-S 4,172,119	Yes	5,597,832	15,352,958	561,871	23,439	1,728	3,701	38,738	13,239
S2	Free market green scenario	Free market	Subsidised gas power plants	S-G 67,426	Yes	3,429,052	108,987	66,849	4,845	1,194	3,289	36,894	6,486
G2	Free market green scenario	Free market	Subsidised gas power plants	G-S 4,291,301	Yes	5,597,832	15,486,980	561,871	23,439	1,728	3,701	38,738	13,239
S3	Green support scenario	Free market + subsid. green pow. plant.	Free market	S-G 67,426	Yes	3,512,175	108,987	756,354	4,845	1,122	219,481	33,919	6,486
G2	Free market green scenario	Free market	Subsidised gas power plants	G-S 4,002,016	Yes	5,597,832	10,877,286	561,871	23,439	1,728	3,701	38,738	13,239
S4	Green FIT scenario	FIT + subsid. green power plants	Free Market	S-G 67,426	Yes	3,512,175	108,987	756,354	21,806	1,122	1,989	33,919	6,486
G2	Free market green scenario	Free market	Subsidised gas power plants	G-S 3,910,694	Yes	5,597,832	10,711,486	561,871	23,439	1,728	3,701	38,738	13,239
S5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	S-G 67,426	Yes	2,538,721	108,987	528,556	21,806	1,370	2,198	66,137	6,486
G2	Free market green scenario	Free market	Subsidised gas power plants	G-S 4,172,119	Yes	5,597,832	15,352,958	561,871	23,439	1,728	3,701	38,738	13,239
S6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	S-G 67,426	Yes	3,512,175	108,987	66,849	18,642	1,230	3,313	42,568	6,486

No.	Reference and policy scenarios	Assumption RE	Assumption Conventional electricity	Electricity transfer in GWh	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	Grid costs in € million
G0	Reference scenario	Free market	Free market	G-S 3,456,932	No	5,369,523	12,134,892	561,871	0	1,458	0	35,276	13,239
S0	Reference scenario	Free market	Free market	S-G 67,426	No	3,356,821	108,987	66,849	0	1,279	0	34,193	6,486
G3	Green support scenario	Free market + subsid. green pow. plant.	Free market	G-S 3,910,694	Yes	6,627,126	11,687,427	561,871	23,439	1,144	371,237	32,756	13,239
S1	Standard scenario	FIT	Subsidised gas power plants	S-G 1,245,356	Yes	2,538,721	108,987	1,948,009	21,806	1,317	1,252	40,696	6,486
G3	Green support scenario	Free market + subsid. green pow. plant.	Free market	G-S 4,172,119	Yes	6,627,126	15,692,713	561,871	23,439	1,144	371,237	32,756	13,239
S2	Free market green scenario	Free market	Subsidised gas power plants	S-G 1,245,356	Yes	3,429,052	108,987	1,486,302	4,845	1,194	3,289	36,894	6,486
G3	Green support scenario	Free market + subsid. green pow. plant.	Free market	G-S 4,291,301	Yes	6,627,126	15,869,803	561,871	23,439	1,144	371,237	32,756	13,239
S3	Green support scenario	Free market + subsid. green pow. plant.	Free market	S-G 1,245,356	Yes	3,512,175	108,987	2,175,807	4,845	1,122	219,481	33,919	6,486
G3	Green support scenario	Free market + subsid. green pow. plant.	Free market	G-S 4,002,016	Yes	6,627,126	11,998,201	561,871	23,439	1,144	371,237	32,756	13,239
S4	Green FIT scenario	FIT + subsid. green power plants	Free Market	S-G 1,245,356	Yes	3,512,175	108,987	2,175,807	21,806	1,122	1,989	33,919	6,486
G3	Green support scenario	Free market + subsid. green pow. plant.	Free market	G-S 3,910,694	Yes	6,627,126	11,687,427	561,871	23,439	1,144	371,237	32,756	13,239
S5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	S-G 1,245,356	Yes	2,538,721	108,987	1,948,009	21,806	1,370	2,198	66,137	6,486
G3	Green support scenario	Free market + subsid. green pow. plant.	Free market	G-S 4,172,119	Yes	6,627,126	15,692,713	561,871	23,439	1,144	371,237	32,756	13,239
S6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	S-G 1,245,356	Yes	3,512,175	108,987	1,486,302	18,642	1,230	3,313	42,568	6,486

No.	Reference and policy scenarios	Assumption RE	Assumption Conventional electricity	Electricity transfer in GWh	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	Grid costs in € million
G0	Reference scenario	Free market	Free market	G-S 3,456,932	No	5,369,523	12,134,892	561,871	0	1,458	0	35,276	13,239
S0	Reference scenario	Free market	Free market	S-G 67,426	No	3,356,821	108,987	66,849	0	1,279	0	34,193	6,486
G4	Green FIT scenario	FIT + subsid. green power plants	Free Market	G-S 3,910,694	Yes	6,627,126	7,474,507	561,871	105,479	1,144	2,453	32,756	13,239
S1	Standard scenario	FIT	Subsidised gas power plants	S-G 1,628,934	Yes	2,538,721	108,987	2,397,463	21,806	1,317	1,252	40,696	6,486
G4	Green FIT scenario	FIT + subsid. green power plants	Free Market	G-S 4,172,119	Yes	6,627,126	12,509,778	561,871	105,479	1,144	2,453	32,756	13,239
S2	Free market green scenario	Free market	Subsidised gas power plants	S-G 1,628,934	Yes	3,429,052	108,987	1,935,756	4,845	1,194	3,289	36,894	6,486
G4	Green FIT scenario	FIT + subsid. green power plants	Free Market	G-S 4,291,301	Yes	6,627,126	11,513,130	561,871	105,479	1,144	2,453	32,756	13,239
S3	Green support scenario	Free market + subsid. green pow. plant.	Free market	S-G 1,628,934	Yes	3,512,175	108,987	2,625,262	4,845	1,122	219,481	33,919	6,486
G4	Green FIT scenario	FIT + subsid. green power plants	Free Market	G-S 4,002,016	Yes	6,627,126	7,663,154	561,871	105,479	1,144	2,453	32,756	13,239
S4	Green FIT scenario	FIT + subsid. green power plants	Free Market	S-G 1,628,934	Yes	3,512,175	108,987	2,625,262	21,806	1,122	1,989	33,919	6,486
G4	Green FIT scenario	FIT + subsid. green power plants	Free Market	G-S 3,910,694	Yes	6,627,126	7,474,507	561,871	105,479	1,144	2,453	32,756	13,239
S5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	S-G 1,628,934	Yes	2,538,721	108,987	2,397,463	21,806	1,370	2,198	66,137	6,486
G4	Green FIT scenario	FIT + subsid. green power plants	Free Market	G-S 4,172,119	Yes	6,627,126	12,509,778	561,871	105,479	1,144	2,453	32,756	13,239
S6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	S-G 1,628,934	Yes	3,512,175	108,987	1,935,756	18,642	1,230	3,313	42,568	6,486

No.	Reference and policy scenarios	Assumption RE	Assumption Conventional electricity	Electricity transfer in GWh	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	Grid costs in € million
G0	Reference scenario	Free market	Free market	G-S 3,456,932	No	5,369,523	12,134,892	561,871	0	1,458	0	35,276	13,239
S0	Reference scenario	Free market	Free market	S-G 67,426	No	3,356,821	108,987	66,849	0	1,279	0	34,193	6,486
G5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Subsidised	G-S 3,910,694	Yes	3,953,022	5,502,623	561,871	105,479	3,657	1,420	76,236	13,239
S1	Standard scenario	FIT	Subsidised gas power plants	S-G 298,925	Yes	2,538,721	108,987	719,234	21,806	1,317	1,252	40,696	6,486
G5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Subsidised	G-S 4,172,119	Yes	3,953,022	10,794,677	561,871	105,479	3,657	1,420	76,236	13,239
S2	Free market green scenario	Free market	Subsidised gas power plants	S-G 298,925	Yes	3,429,052	108,987	284,528	4,845	1,194	3,289	36,894	6,486
G5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Subsidised	G-S 4,291,301	Yes	3,953,022	10,895,441	561,871	105,479	3,657	1,420	76,236	13,239
S3	Green support scenario	Free market + subsid. green pow. plant.	Free market	S-G 298,925	Yes	3,512,175	108,987	974,034	4,845	1,122	219,481	33,919	6,486
G5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Subsidised	G-S 4,002,016	Yes	3,953,022	5,668,423	561,871	105,479	3,657	1,420	76,236	13,239
S4	Green FIT scenario	FIT + subsid. green power plants	Free Market	S-G 298,925	Yes	3,512,175	108,987	974,034	21,806	1,122	1,989	33,9191	6,486
G5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	G-S 3,910,694	Yes	3,953,022	5,502,623	561,871	105,479	3,657	1,420	76,236	13,239
S5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	S-G 298,925	Yes	2,538,721	108,987	719,234	21,806	1,370	2,198	66,137	6,486
G5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	G-S 4,172,119	Yes	3,953,022	10,794,677	561,871	105,479	3,657	1,420	76,236	13,239
S6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	S-G 298,925	Yes	3,512,175	108,987	284,528	18,642	1,230	3,313	42,568	6,486

No.	Reference and policy scenarios	Assumption RE	Assumption Conventional electricity	Electricity transfer in GWh	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	Grid costs in € million
G0	Reference scenario	Free market	Free market	G-S 3,456,932	No	5,369,523	12,134,892	561,871	0	1,458	0	35,276	13,239
S0	Reference scenario	Free market	Free market	S-G 67,426	No	3,356,821	108,987	66,849	0	1,279	0	34,193	6,486
G6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Subsidised	G-S 3,910,694	Yes	5,597,832	10,711,486	561,871	57,341	2,112	3,401	72,667	13,239
S1	Standard scenario	FIT	Subsidised gas power plants	S-G 67,426	Yes	2,538,721	108,987	528,556	21,806	1,317	1,252	40,696	6,486
G6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Subsidised	G-S 4,172,119	Yes	5,597,832	15,352,958	561,871	57,341	2,112	3,401	72,667	13,239
S2	Free market green scenario	Free market	Subsidised gas power plants	S-G 67,426	Yes	3,429,052	108,987	66,849	4,845	1,194	3,289	36,894	6,486
G6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Subsidised	G-S 4,291,301	Yes	5,597,832	15,486,980	561,871	57,341	2,112	3,401	72,667	13,239
S3	Green support scenario	Free market + subsid. green pow. plant.	Free market	S-G 67,426	Yes	3,512,175	108,987	756,354	4,845	1,122	219,481	33,919	6,486
G6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Subsidised	G-S 4,002,016	Yes	5,597,832	10,877,286	561,871	57,341	2,112	3,401	72,667	13,239
S4	Green FIT scenario	FIT + subsid. green power plants	Free Market	S-G 67,426	Yes	3,512,175	108,987	756,354	21,806	1,122	1,989	33,919	6,486
G6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	G-S 3,910,694	Yes	5,597,832	10,711,486	561,871	57,341	2,112	3,401	72,667	13,239
S5	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	S-G 67,426	Yes	2,538,721	108,987	528,556	21,806	1,370	2,198	66,137	6,486
G6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	G-S 4,172,119	Yes	5,597,832	15,352,958	561,871	57,341	2,112	3,401	72,667	13,239
S6	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	S-G 67,426	Yes	3,512,175	108,987	66,849	18,642	1,230	3,313	42,568	6,486

Table A2. Results for the Spanish and German electricity market without electricity transfer (cumulative over the simulation period)

No.	Reference scenario and policy scenarios	Assumption RE	Assumption Conventional electricity	Assumption Batteries	Country	Security of Supply	RE consumed in GWh	Wind produced in GWh	Photovol. produced in GWh	Elec. sup. batteries in GWh	CO_2 emissions in Megat.	Subsidies in € million	External costs in € million	∑ Subsidies, external costs in € million
0.	Reference	Free market	Free market	Free Market	Germany	No	4,812,965	6,231,319	453,572	0	1,613	0	39,026	39,026
					Spain	No	1,757,320	5,691,326	66,849	0	1,437	0	38,417	38,417
1.	Standard	FIT	Subsidised gas power plants	Subsidised	Germany	Yes	3,443,321	2,113,247	827,538	110,839	4,041	2,327	64,314	66,641
					Spain	Yes	3,242,997	2,676,538	732,743	26,928	609	2,012	14,875	16,887
2.	Free market green scenario	Free market	Subsidised gas power plants	Subsidised	Germany	Yes	6,108,663	6,671,528	453,572	59,712	1,946	3,842	42,385	46,227
					Spain	Yes	5,455,345	7,535,136	66,849	23,021	554	3,647	12,311	16,887
3.	Green support scenario	Free market + subsid. green pow. plant.	Free market	Subsidised	Germany	Yes	6,139,556	6,896,350	2,254,785	59,712	1,343	378,939	34,769	413,708
					Spain	Yes	4,421,231	7,535,136	992,083	23,021	525	221,435	9,700	231,134
4.	Green FIT scenario	FIT + subsid. green power plants	Free Market	Subsidised	Germany	Yes	3,717,662	2,313,277	989,881	110,839	3,849	2,575	62,546	65,121
					Spain	Yes	4,421,231	3,007,711	905,512	26,928	525	1,953	9,700	11,653
5.	Regulated RE adaptation scenario	FIT	Optimal adaptation/ Conventional subsid.	Subsidised	Germany	Yes	3,443,321	2,113,247	827,538	110,839	3,942	3,741	83,427	87,168
					Spain	Yes	3,242,997	2,676,538	732,743	26,928	645	3,450	23,589	27,039
6.	Free market RE adaptation scenario	Free market	Optimal adaptation/ Conventional subsid.	Subsidised	Germany	Yes	6,108,663	6,671,528	453,572	59,712	2,673	3,970	73,317	77,287
					Spain	Yes	5,455,345	7,535,136	66,849	23,021	568	3,389	19,749	23,138