Can Germany Move Towards 100% Renewable Electricity Without Major Problems?

by Zahra Mashhadi

Abstract

Germany has as the ambition to move towards an electricity system that is 100% renewable. A well-known complication is variability in renewable solar and wind power that does not match the variability in the underlying electricity demand. A simulation model with a time step of one hour is used to explain historical variations in electricity price and in electricity production from nuclear and fossil energy, given observed variations in renewable electricity. The same model is used to find optimal capacities in future years for all producers of electricity under different assumptions about technological development, underlying demand developments, and CO_2 taxes. The results show that hourly price variations increase within reasonable limits as the amount of renewable electricity increases. This leads to a market for increased demand flexibility and various types of storage. The role of natural gas as a transition source of electricity diminishes over time for economic reasons, with and without CO_2 taxes.

Introduction

Transformation to a 100% renewable energy system has been a hot topic in the energy research fields and projects. Due to the importance of the subject, various plans were proposed, and one of the most important ones was published by Jacobson and Delucchi (2011) who proposed a large-scale renewable energy plan for powering the world with water, wind and solar energies for all purposes without biofuels, nuclear and coal. They are insisting to show this plan is feasible with regards to meeting the demand and cost effectiveness. However, this ambitious theory has faced with different comments and critiques. Examples include periods of oversupply and dumping, additional cost for providing the flexibility by a backup system, limited storage capacity compared with electricity demand, low energy efficiency, high cost of the electricity storage, considerable required investment cost, high transmission cost or lack of social feasibility study (Trainer, 2012; Gilbraith et al., 2013; Clack et al., 2017; Procter, 2018; Harjanne and Korhonen, 2019).

Although the problems and challenges for 100% renewable energy transformation have been mentioned in different publications, but there is still a research gap for modeling of such a large-scaled transformation with system dynamics simulation approach especially based on the hourly changes in electricity market data. Therefore, this study was designed to simulate renewable energy transformation in Germany as a unique country in terms of development and integration of renewable energy systems.

Energiewende, the German term for the country's planned transition to nuclear free and low climate-damaging CO_2 emissions, planned in 2010 with ambitious target of shifting from a heavily fossil fuel and nuclear power dependent energy system towards a renewable energy-based system by 2050. It has generally been successful to reach its goals. For example, the contribution of renewable resources in the electricity generation mix of Germany has been increased from 8.6% in 2002 to over 45% in 2019 (Clean-Energy-Wire, 2020).

Nevertheless, implementing such a large-scale renewable energy plan has had its own challenges for Germany. One of the important challenges is that the electricity industry gets significantly affected by weather conditions both in terms of generation and consumption. The problem arises when maxima or peaks in electricity demand coincide with periods of low renewable energy source availability. A similar problem may happen in case of oversupply on the grid on sunny and windy days with electricity generation even more than twice of the average demand (Trainer, 2012). Therefore, there are difficulties for matching instantaneous energy demands with electricity generation by these variable resources (Gilbraith et al., 2013) which shows a lack of flexibility in the electricity generation system. As a result, the electricity prices become more volatile and susceptible to extreme behaviors, such as spikes or negative values. Negative electricity prices bring additional burden of millions of euro on the renewables surcharge because even during hours when electricity prices are negative, generated electricity by renewable resources should still be sold on the market (Götz et al., 2014).

Regarding these problems, there are concerns about how sustainable, reliable, and profitable the energy transition is. It has arisen questions like: What is the role of the renewable energy supply in occurrence of negative prices, and how is the current electricity market affected by these prices? Where can the required flexibility for 100% renewable electricity market come from in 2030, 2040, or 2050? To address these questions and with regards to the natural variations in the electricity demand and generation, a system dynamics simulation model was developed in this study for the electricity market in Germany where electricity price, demand, and supply from different technologies were simulated hourly.

Model Description

The endogenous view of the system and the whole story behind the model have been provided by the causal loop diagram (CLD) shown in Figure 1. The model documentation, including equations, variables units and comments on variables are available in Table 2 in Appendix. The required historical data to build and validate the model has been provided from literature reviews and also from different data bases like Agora-Energiewende (2020) and Energy-Charts (2020). All the simulations in this study have been performed by the Stella Architect software.

The dynamic interactions between the electricity price, demand and supply form the core structure or the main causal loops of the model. The model structure consists of the following main sectors:

1. Electricity price
2. Electricity supply
3. Net import
4. Electricity demand

Since prices are governed by supply and demand, for price discovery process, it should be found that how electricity prices change when there is an imbalance between demand and supply, and how the market makers find equilibrium prices. In this process, market players form expectations about the level of price (*Traders Expected Price* in Figure 1) that would balance demand and supply and clear the market. As no one knows the correct equilibrium price level, traders would gradually start to change their approximation of the equilibrium price until it finally reaches the actual level of prices (Sterman, 2000).

Given *Traders Expected Price*, prices are set by an anchoring and adjustment process. This process forms a positive *Price Discovery* feedback loop (see Figure 1) in which the prices are anchored to expected prices, and the expected equilibrium price in turn gradually adjusts to the actual level of prices and closing the loop. Here, the anchor itself adjusts to previous experience, forming the negative *Price Adjustment* loop (Sterman, 2000).

In the presented model here, the electricity supply come from both conventional and renewable resources consist of natural gas, coal, nuclear, solar, run-of-the-river, hydroelectric reservoir, offshore and onshore wind power plants. These generators can change the demand to supply ratio. Therefore, there are causal links from these resources to the electricity price (see Figure 1). The generation by both conventional and renewable resources is restricted by their installed capacity which specifies the maximum output that generator can produce (Energy-nmpp, 2020).

For generation from conventional power plants, the electricity price should be high enough to cover the maintenances and operational costs of these plants. Higher prices increase the electricity generation by these resources. It decreases the demand to supply ratio and consequently, decreases the electricity price which closes the negative *Supply Response* loop (Figure 1).

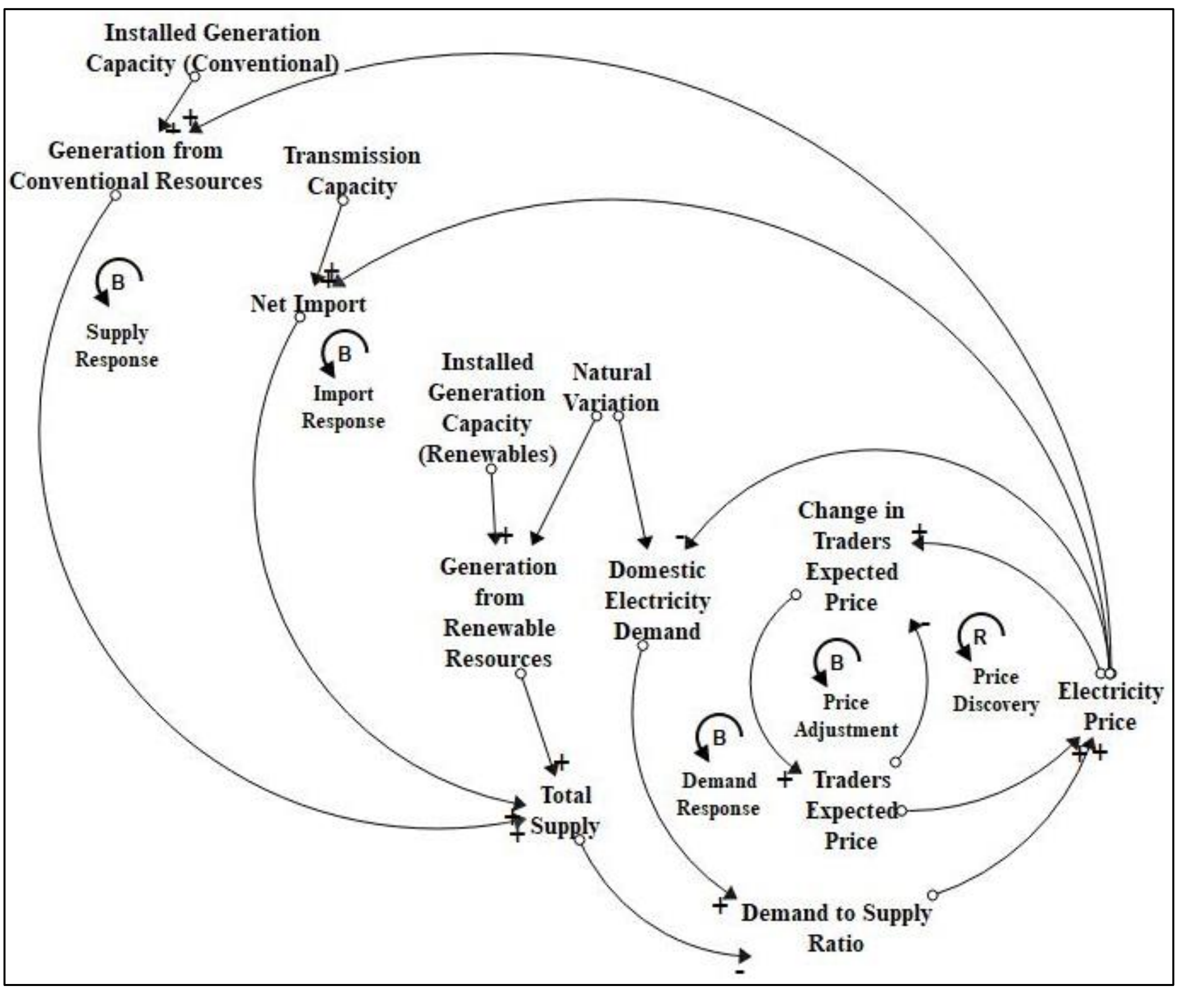

Figure 1: Causal loop diagram (CLD) showing the studied feedback mechanism in the electricity market. Note that investments in renewables is certainly influenced by price, but this study is not modelling investments and this CLD is for operations only.

While conventional energy resources are planned and operated based on the electricity prices, renewable energy resources such as wind and solar vary with weather conditions and solar influx (Maciejowska et al., 2019). Accordingly, an important part of renewable electricity production is characterized by a large degree of intermittency resulted from the natural variability of climate factors (Engeland et al., 2017). Therefore, there is no effect from the electricity price on generation from the renewable resource power plants in the CLD shown in Figure 1, and the negative *Supply Response* loop is only between the conventional power plants and the electricity price. Note that investments in renewables is certainly influenced by price, but this study is not modelling investments, and the CLD shown in Figure 1 is for operations only.

As shown in Figure 1, electricity price affects the electricity demand via negative *Demand Response* loop. The electricity demand is also controlled by the natural variation (or the change in the weather). Typically, electricity demand is higher during the winter and autumn than the summer because the days are shorter, and more lighting is required. A detailed study of demand is beyond the scope of this study, and here, a simplified structure has been used to model electricity demand (see Table 2 in Appendix).

Another important feedback mechanism is between the electricity price and net import (Figure 1). Net import is a part of total supply since it can be added to or subtracted from the domestic generation. Electricity will be exported from areas with lower offered prices to areas with higher demand and higher offered prices. When hourly price defines the direction of the net import, the net import has also effects on the price through the total supply and the demand to supply ratio.

Validation Overview

Different validation tests for the structure and behavior of the model proved that the model is reliable. The equations are robust and backed up by an extensive literature reviews, and all the constant parameters in the model have a clear, real-life meaning. The model behavior is generally non-sensitive to most of the parameters, and the model can replicate the reference mode of behavior.

Indirect extreme condition test is shown here as an example of validity tests performed on the model. This test showed that if the electricity demand becomes 5 times larger than the current values, the electricity prices will increase considerably due to very high demand to supply ratios. When generation becomes 10 times larger, the electricity prices decrease to very small values due to the overcapacity. Therefore, the equations give rise to reasonable behavior.

Simulation Results for Electricity Price

As a result of fluctuations and dynamic changes in the electricity demand and power supply, the simulation of the electricity price shows fluctuations at the daily, weekly and annual levels. In addition, abrupt, short-lived, and generally unexpected price spikes can also be seen in its dynamic behavior (Figure 2).

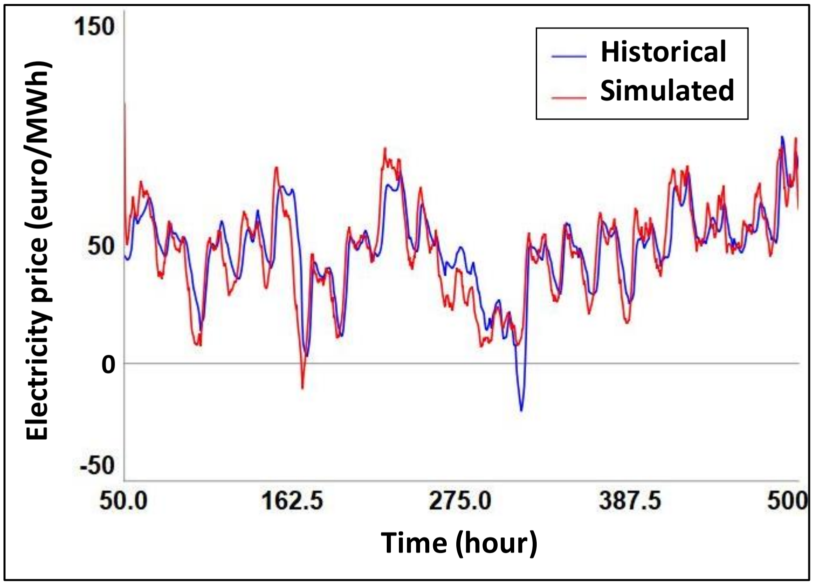

Figure 2: Example of fluctuations in the electricity price behavior in a 3-weeks interval within January 2019 caused by variations in the electricity supply and demand. This figure also shows that the model is able to reproduce the reference mode of behavior very well.

Negative Electricity Prices

Negative prices occur in energy surplus conditions called minimum residual load. It described by a large supply of renewable energies which overlaps with relatively low levels of demand. Based on the CLD shown in Figure 1, this situation leads to smaller demand to supply ratios and lower electricity prices. Periods with low levels of demand occur for example on Sundays, holidays or during the night (Götz et al., 2014). Since there are no fuel costs for the renewable resources, large volumes of cheap electricity go on the stock market and due to market imbalances, the electricity market lowers the average electricity stock exchange price and set negative price policies into place (Luh, 2014). Due to the inflexibility of renewable energy sources, their generation cannot be shut down or restarted in a quick and cost-efficient way.

Simulation results in Figure 3 show one of the cheapest hours with negative electricity prices in June 2019 which resulted from an oversupply on the grid. This event occurred when high electricity generation by PV systems at mid-day overlapped with high generation by wind power on land and at sea. Consequently, renewable energies had the highest share of generation, and they supplied more than 70 percent of the electricity consumption.

At these periods of minimum residual load and low electricity prices, the production from conventional power plants is not affordable and expected to be reduced or taken off the grid by negative *Supply Response* loop (see CLD in Figure 1). However, the studied case in June 2019 show conventional power plants could only partially meet the necessary flexibility. They reduced their generation to some extent, but they still generated considerable amounts of electricity despite the negative prices (Figure 4). This can be due to technical and economic aspects of starting up and shutting down these power plants (Götz et al., 2014).

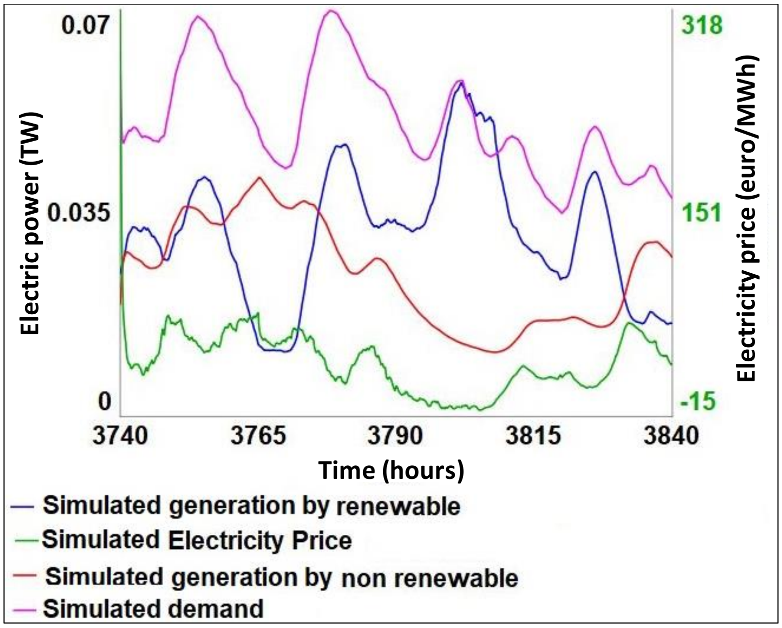

Figure 3: One example of negative electricity price in June 2019 which shows an oversupply in the grid due to low demand and high renewable generation.

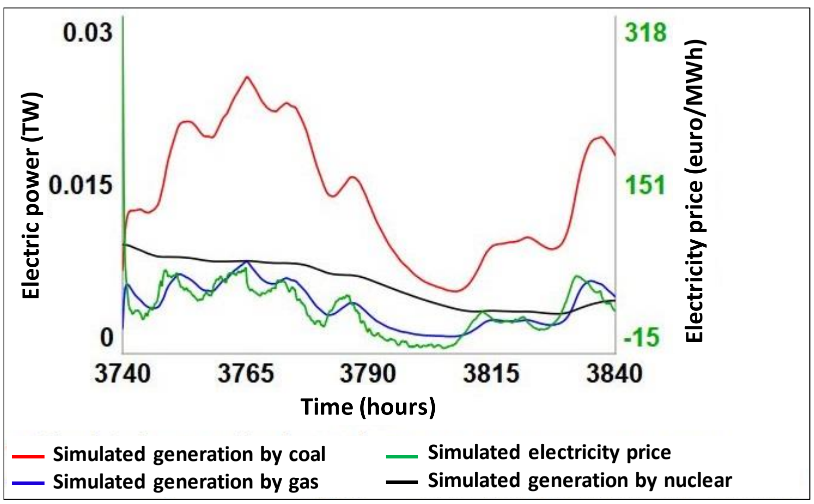

Figure 4: Lack of flexibility in conventional power plants (especially nuclear units) to ramp down their generation when electricity price is negative due to oversupply in the grid.

Optimizations and Scenario Study

By considering different technologies, different costs and natural variations in different energy resources, the optimization with the goal of maximizing the social benefits has been done for the market conditions. The Stella Architect has been used here to identify combinations of capacities for different energy resources that maximize the social benefits in 2030, 2040 and 2050. The objective function of the optimization model minimizes the total cost of electricity generation which is determined by capital cost of different technologies, fuel costs and carbon taxes in the model. The results of these optimizations give some clues to what types of power generators will be needed in future years. These types of generators may be different from what seems obvious today. (see Table 2A in Appendix for details of formulas and equations)

Optimized Energy Mix for 2019

Despite the significant growth in the renewable shares, the German electricity market was described by the dominance of fossil fuels in 2019. In this year, the share of the conventional resources in the total power generation (54.0%) predominated over the share of the renewable resources (46.0%) in Germany. Coal was the major source of the generated electricity, however, wind power surpassed both nuclear and natural gas to become the second-largest source of electricity generation (Lindberg, 2015).

First optimization was done for the market condition in 2019 (or Reference Case) to find out what energy mix would be optimal in this year. The results of this optimization shown in Figure 5 represent that the real power installations in 2019 did not lead to the most cost-effective power generation, and even a lower total capacity would be the most optimal. The real energy mix is mainly inherited from earlier years with different cost numbers and other preferences.

The renewable resources are characterized by high capital costs, but their variable costs are negligible due to low fuel and operational costs. With current technologies, conventional power plants are more expensive source of electricity generation than the renewable resources which appear to be more economical (Kaplan, 2010). Solar units and onshore wind turbines are the cheapest technologies in Germany, both among renewable energies and fossil fuel power plants. Therefore, under the optimization, onshore wind would be the largest source of generation in 2019, and solar would be the second-largest source of electricity generation. Due to solar energy limitations, PV units have lower capacity factors (full load hours) than onshore wind installations. Therefore, onshore wind technologies are more efficient than the solar power plants and their development is more cost effective (IRENA, 2015).

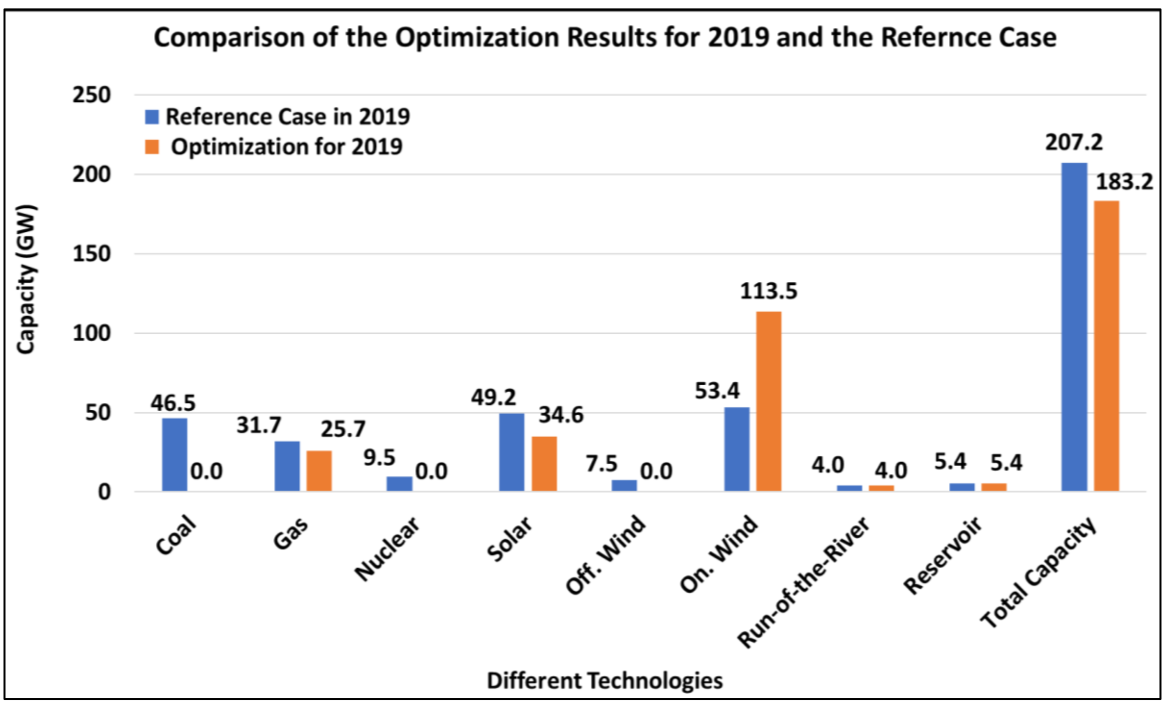

Figure 5: In the optimized energy mix for 2019, onshore wind is the major energy resource, and the total installed capacity is lower than the historical energy mix or the Reference Case in this year.

Although offshore wind is another significant source of clean energy, but due to its very high costs, not mature technologies and development constraints, it is not the best investment right now (Boythorpe-Wind-Energy, 2020). Therefore, there is no generation by offshore wind in the optimized energy mix for 2019.

The shares of coal and nuclear power plants in the optimized energy mix decrease to zero (Figure 5), and gas power plants are the only conventional units which provide flexibility to the power system. It causes that the gas-fueled units are turned on and off more often, and their capacity utilization ramps a full cycle from full production to almost no production (Figure 6). This partial loading and frequent cycling of a gas engine or turbine causes more wear on mechanical components, needs more frequent maintenance and increased operating cost. It also decreases efficiency and brings increased emissions per unit of energy generated (ESMAP, 2015).

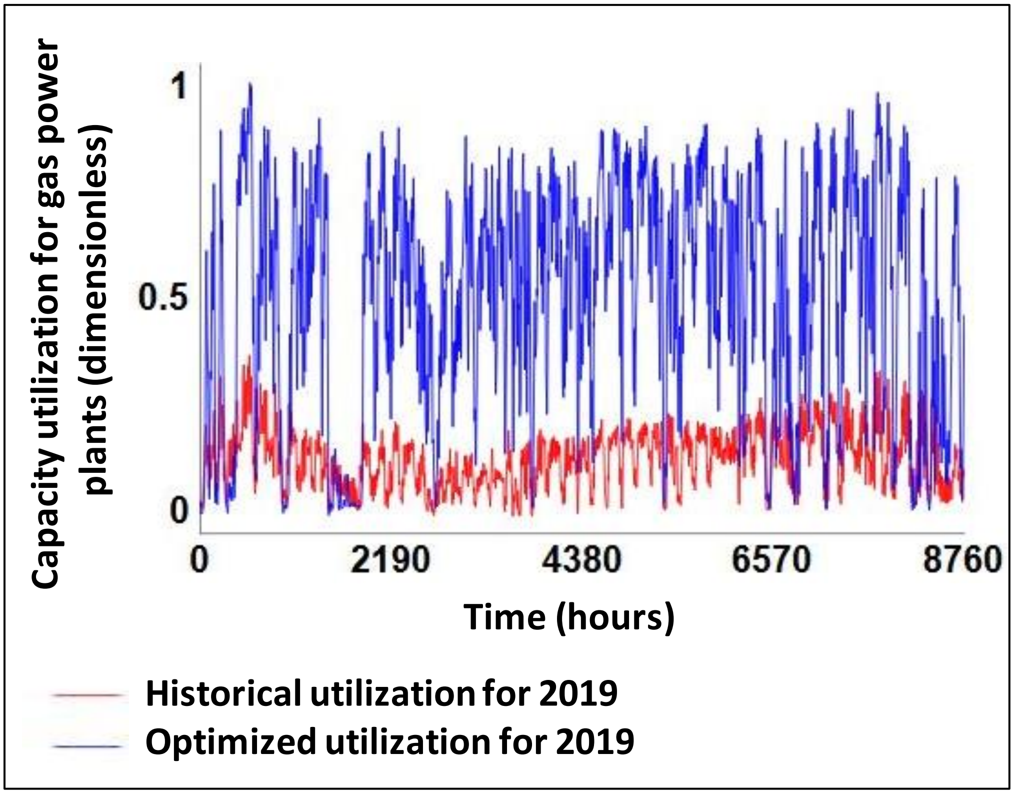

Figure 6: Highly fluctuating capacity utilization for the gas power plants resulted from high penetration of the intermittent renewables after optimization in the optimized energy mix of 2019.

Scenario Studies and Their Assumptions

By using the market model and considering the impact of different fundamental input data, two different scenarios were studied. By building several scenarios and projection of future generation by renewable energies, possible ways of integrating these sources into the German electricity market can be investigated. For the scenario studies, phasing out the nuclear power plants by 2022 and coal fueled units by 2038 (Power-magazine, 2020), and constant capital costs and capacities for hydropower by 2050 (Energy-Charts, 2020) have been assumed. Other assumptions are also presented in Table 1.

Table 1: Assumptions used for different scenarios.

Assumptions	Technologies	Year 2019	2030	2040	2050	Note
Burner Efficiency (dimensionless)	Coal	0.48	0.49	0.5	0.51	1
	Gas	0.6	0.61	0.62	0.63	
CO_2 Emission per kWh Electricity Generation (tonne of CO_2 per kWh)	Coal	0.00110	0.00107	0.00104	0.00101	
	Gas	0.00055	0.00054	0.00053	0.00052	
Capital Costs (euro per kW) in Cheaper Renewables Scenario	Coal	4500	4500	4500	4500	2
	Natural gas	600	600	600	600	
	Nuclear	9200	9200	9200	9200	
	Offshore wind	3000	2350	1904	1714	
	Onshore wind	1400	1200	1020	918	
	Solar	1000	650	488	415	
Carbon Tax (euro per tonne of CO_2) in High Carbon Tax Scenario		25	50	90	125	3

Notes of Table 1:

1. 5% increase in burner efficiency and 5% decreases in CO_2 emission per kWh electricity generation by 2050 (Capros et al., 2010).

2. Constant capital costs for conventional power plants and decreasing capital costs for renewable resources (Kaplan, 2008; Hayward et al., 2011; Boldt et al., 2012).

3. An increase of about four times in carbon tax by 2050 (Hein et al., 2020).

Cheaper Renewables Scenario

One of the main inputs for the quantitative energy modeling, especially when the purpose of the modeling is concerning the future energy system, is assumptions about capital costs for both renewable and conventional technologies (Kaplan, 2008). The Cheaper Renewables Scenario is a projections of future development of renewable energies when the capital cost of these technologies is reducing by 2050.

Based on the literature reviews, different assumptions have been made for the capital costs of different technologies in the period of 2019-2050 (Table 1). In the proposed set of capital costs, it has been assumed that mature generation technologies in the field of conventional power generation keep a stable level of capital costs at increasing efficiency rates (Boldt et al., 2012). The capital costs of the run-of-the-river and hydro reservoir can also be assumed constant, since they will have no considerable cost reductions (Hayward et al., 2011). For the renewable resources, cheaper technologies over time and cost reductions is expected based on the learning and technological progress (Hayward et al., 2011). More developed renewable technologies like onshore wind has less capital cost reductions than the less mature technologies such as solar and offshore wind (PÖYRY-Management-Consulting, 2014).

The results of optimization for this scenario have been shown in Figure 7. Assuming considerably lower capital costs for the renewable technologies in the coming years would significantly increase the generation from renewable resources. Wind and solar technologies see a major growth under the Cheaper Renewables Scenario. From 2030, solar is certainly the cheapest renewable option; onshore wind is the next lowest-cost renewable, and both of them are less expensive than gas power plants. In 2050, the main part of the electricity demand is met by the renewable generation, and the share of intermittent renewable energy resources rises to more than 90% of domestic power generation, almost double of 46% in the Reference Case (Figure 7). The total installed capacity in this scenario is higher than both the Reference Case and the optimized energy mix of 2019.

Offshore wind technologies usually have higher installation and capital costs than onshore wind power plants. Therefore, as shown in Figure 7, there is no offshore wind power in 2030. In 2040 and 2050, when the capital costs of offshore wind decline more, offshore wind has an impact on the generation mix. At this time, development of offshore wind energy will be beneficial, and this technology takes up some onshore wind capacities.

Due to the restricted total energy resource, hydro power plants have reached to its limits for development in Germany (Hecking et al., 2018). Under this scenario, hydropower and run-of-the-river capacities have been assumed to be constant by 2050, and their generation represents only a small fraction of total German energy supply in the coming years.

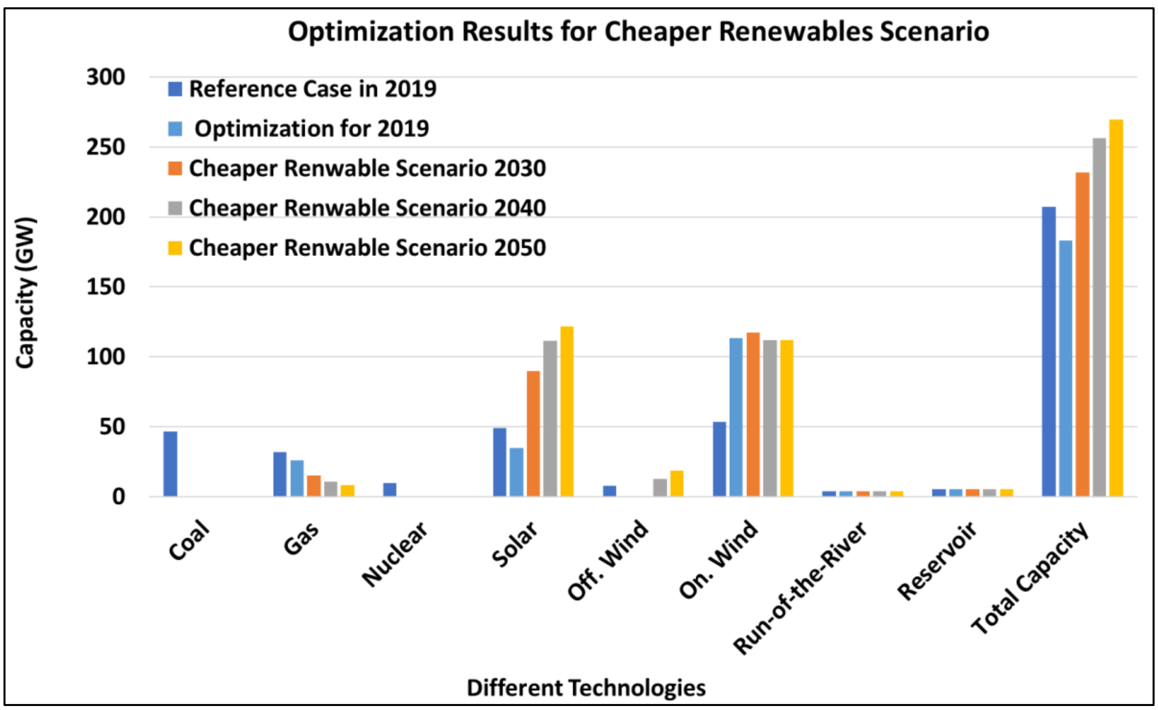

Figure 7: Results of the Cheaper Renewables Scenario and their comparison with the Reference Case and optimization results for 2019. In this scenario, the share of intermittent renewable energy sources rises to more than 90% of domestic power generation by 2050.

The Cheaper Renewable Scenario shows a major contraction in the share of fossil fuels for the electricity generation compared to the Reference Case because with technological development, the cost of electricity generation by new solar and onshore wind will increasingly be below the levels for all conventional power plants (Kost et al., 2018). The nuclear and coal power plants have been assumed to be phased out in 2022 and 2038, respectively. However, the optimizations this scenario projected that coal would lose its competitiveness even earlier than 2030. Based on the obtained results, power production from coal is replaced by generation from natural gas, wind, and solar energies.

The gas-fueled units would be the only conventional power plants maintained in the energy mix of this scenario. However, between 2030 and 2050, the renewable technologies become progressively cheaper and due to their considerable development, the generation capacity of gas power plants would decrease to a quarter of its value in the Reference Case (see Figure 7).

High Carbon Tax Scenario

The High Carbon Tax Scenario investigates how the energy mix and the need for flexibility will be changed by a different carbon pricing. The basic idea of the carbon tax is to make fossil fuels progressively more expensive (Parry, 2019).

Current carbon tax has been approximately 25 euro per tonne of CO_2 in Germany (Hein et al., 2020), and for the High Carbon Tax Scenario, an increase of two times by 2030, almost four times by 2040 and five times by 2050 has been assumed (see Table 1). For this scenario, the capital costs of all technologies have been assumed constant by 2050.

The results of optimization for this scenario have been shown in Figure 8. When carbon tax increases, more generation from low-emission technologies becomes necessary to reduce the cost of power generation. Therefore, under the High carbon Tax Scenario, renewable energies represent majority of the overall capacity investments accounting for more than 95% share in the energy mix between 2030 and 2050 (Figure 8).

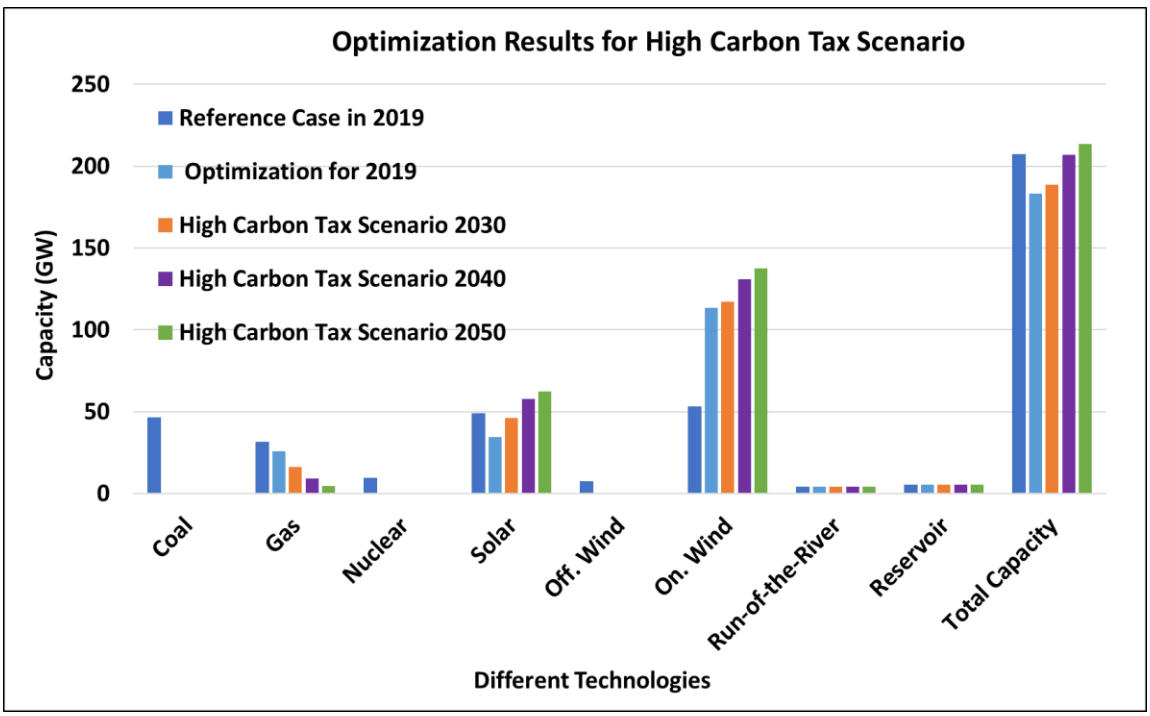

Figure 8: Results of the High Carbon Tax Scenario and their comparison with the Reference Case and optimization results for 2019. The electricity generation is largely carbon-free, and renewable energies represent the bulk of overall investment in the capacity.

Since the capital costs of renewables technologies have been assumed constant for this scenario, development of the onshore wind technology with higher capacity factor is more cost effective than the solar power plants (IRENA, 2015). As a result, onshore wind is the largest source of electricity generation followed by solar units.

Due to constant capital costs assumption for this scenario, the generation by offshore wind does not become cost-effective, and these units do not make any contribution in the electricity generation between 2030 and 2050. This indicates that reducing the overall cost of offshore wind plants can have a large effect on the uptake of this technology.

By a greater carbon tax, coal technologies need to pay more than gas power plants for their emissions. Therefore, due to higher variable operating costs, coal power plants would start to retire quite rapidly from the year 2030 (Figure 8). However, the capacity of gas power plants also drops steadily, and only 4.5 GW gas-fired conventional power stations would remain to balance for the high amount of intermittent renewables in the system. It shows that the carbon tax can be a strong tools to combat climate change (Newburger, 2019).

Volatility in Electricity Price Under Two Studied Scenarios

According to the results, structural change of capacities and increasing the penetration of intermittent renewable resources causes very high volatility in the wholesale electricity prices (Figure 9) because it increases the influence of climate conditions on the power supply and causes very large and rapid variations in total generation (Engeland et al., 2017).

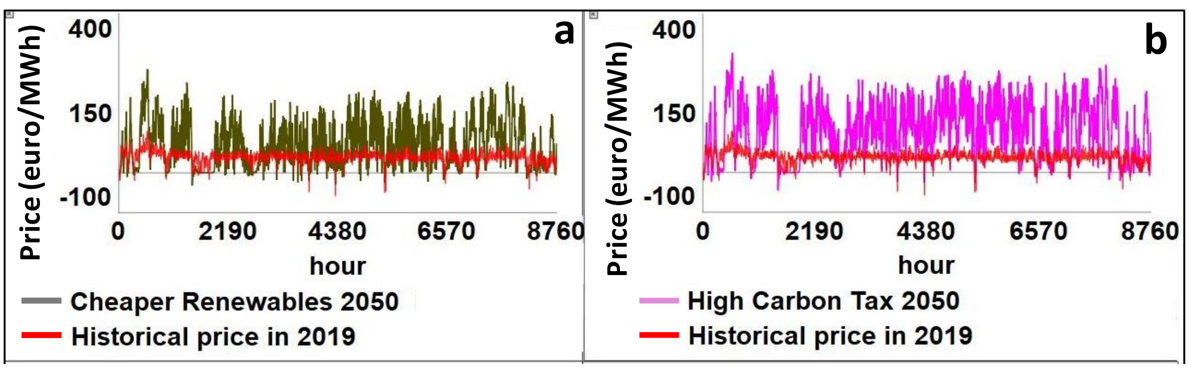

Figure 9: Comparison of the historical prices in 2019 with the optimized prices in 2050 for studied scenarios show that high volatility in the wholesale electricity prices would be an issue in 2050 following higher penetration of intermittent renewable resources in the energy mix.

Discussion and Recommendations

The optimization results in this study forecasted a system based on solar and wind powers for the German power system in the coming years with lower fossil fuel consumption than the Reference Case due to the renewable deployment. It has a positive effect on security of supply and reducing the necessity of fossil fuel imports (IRENA, 2019). However, renewables are intermittent resources in electricity production relying on the weather conditions. This intermittency is an undesirable and challenging aspect of renewable energy transformation (Neill and Hashemi, 2018). This arises this complicated question of how to design a sustainable energy system relying basically on fluctuating energy sources (Schleicher-Tappeser, 2011).

Finding the drivers of the negative prices seems of increasing importance and can help to improve the energy price risk management (Aust and Horsch, 2020). Since negative prices contradict the usual structure of exchanges, they can significantly weaken economic calculations of market actors (Götz et al., 2014). In the long run, it is German households who are paying for the energy transition and market developments. They are paying one of the highest electricity prices in Europe despite the fact that German wholesale price is amongst the lowest in this region. Now, more than half of the domestic electricity price is composed of taxes and surcharges. It has led to higher energy expenditures for the households and even energy poverty or fuel poverty for the low-income households (Aust and Horsch, 2020).

Flexible Electricity Demand

With growing renewable electricity generation, a potential solution for ensuring a more flexible electricity system is demand control. It relates to decrease or increase in the load to adapt the changes in power supply. In times with high demand but low renewable supply, industry, commerce, and households can relatively decrease their power demand. They can shift their demand to the times with high renewable supply if it helps them to increase their profitability (Farag and Groen, 2016). To benefit from demand flexibility, it should be considered in all stages of grid design and planning (Junker et al., 2018).

Electricity Storage

Storage can guarantee a secure supply in all power systems. By connecting wind and solar plants to the electricity storage, the variable renewable generation can be firm because electricity generated in the peak period can be saved to be used in off-peak times (Luh, 2014). Various forms of storage are available now, including pumped hydro, compressed air energy storage, batteries, flywheels, and power-to-gas and power-to-heat (Saraber, 2016). Each storage technology can solve particular problems and there is no “one size fits all” solution. With present technology, large-scale electricity storage options are limited and expensive (Kaplan, 2008; Luh, 2014). For facilitating the integration of renewables, a reliable, efficient, and cost-effective storage is crucial, and their deployment should be an important part of the future energy planning (Skar et al., 2018).

Improved Market Integration

Germany has high potential for integration with neighboring electricity markets (AleaSoftEnergy, 2019). Interconnectors and improved market integration make imports and exports easier and are regarded as important flexibility providers. Cross-border exchange minimizes extra renewable generation by spatial smoothing. Different weather conditions over Europe is the basis for this smoothing effect since each area has its annual peak load at dissimilar times of the day and the year. However, significant investments for Europewide improved flexible connections and power grids, and agreement with local populations to construct extra power lines are essential (Schleicher-Tappeser, 2011).

Limitations for Renewable Resource Deployment

Different from conventional power plants, the geographic location of renewable resource generators is determined based on the access to enough resources to ensure relatively high energy yield (Clean-Energy-Wire, 2020). Limitations on suitable locations where such technologies can be deployed is an important factor that should be included in planning for system adequacy, particularly transmission adequacy (ESMAP, 2015).

Summary and Conclusions

Renewable resources are dependent on weather conditions, and their generation is variable and inflexible (Fraunhofer-IWES, 2015). As a result, renewable based power systems have faced with some challenges to cover the electricity demand and to retain stable (Deloitte, 2019). It has also developed negative electricity prices which causes greater burden on the renewables surcharge and may place a roof limit to expand the renewable energy share in electricity supply (Götz et al., 2014). There are many questions about how renewable energy supply influences the occurrence of negative electricity prices, and how the current electricity market is affected by these prices. Where the required flexibility for 100% renewable energy transformation can come from in 2030, 2040, or 2050?

To address these research questions and with regarding the intermittency of renewable resources, a quantitative system dynamics modeling has been performed in this study. Enormous amounts of data from the German market, including, but not limited to, conventional generation, renewable generation, electricity demand, transmission and different generation costs was used to develop the model.

The results of this study show that when there is a sudden increase in wind and solar productions, particularly during the summer days and during windy periods over the year, the surplus situations occur in the German grid. Therefore, larger contribution from renewable resources increases the volatility in the market and the total number of hours with negative electricity prices. Renewable resources have lower variable costs, and the generated electricity by these energies will largely replace the electricity from high-cost power plants in the market which also causes a reduction of the electricity price (Coester et al., 2018). The results of this study also show that a relatively high minimum generation by conventional power plants is always connected to the grid which leads to excess electricity in the system. Therefore, for providing the electricity by a renewable-based system, both the conventional and renewable power plants should become more flexible for generating energy.

By considering different technologies, different costs and natural variation of different energy resources, an optimization was done for the energy mix in Germany during 2019 to find out what energy mix would be the most optimal at this year. Compared to the historical total installed capacity in 2019, the optimization results show that a lower power installation size especially for the conventional power plants would be more optimal for the system. This optimal energy mix can cause a transition from the situation of overcapacity to a lower supply which prevents the negative electricity prices in the market.

Based on different assumptions, scenario study was done to show how decreasing the investment cost of renewable technologies and increasing the carbon tax will affect the flexibility requirements in the German's power system by 2050. The results show that based on this assumptions the

German power system will see renewables as the main generation source by 2050. Conventional plants will be less involved in the daily energy production as gas gets a minor role as a flexibility provider and coal will be outcompeted from the energy mix.

For large integration of highly volatile and unpredictable renewable energy sources, the current market design needs to be changed to become the right rewarding system to provide this flexibility (Kleb, 2017). In the mid- to long-term, clean solutions like storage technologies can balance the market and provide power when the wind and sun are not available (Agora-Energiewende, 2017). Activating the flexibility potential of the demand side will also be vital to manage flexibility challenges (Fraunhofer-IWES, 2015). To guarantee a balanced local electricity market, there is also need for more extensive transmission capacity to distribute the energy supply in a more diverse geographical area (Saraber, 2016).

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Appendix:

Table 2: Model documentation including formulas and equations for different sectors.

Formulations and comments	**Units**
Electricity Price = Traders Expected Price * ((Domestic Demand/Total Supply)-1) *Sensitivity of Price+1)	EUR/MWh
Traders Expected Price = SMOOTH (Electricity Price, Expectation Adjustment Time)	EUR/MWh
= INTEGRAL (Change in Traders Expected Price, Traders Expected Price $_{t0}$)	
The *Traders Expected Price* is the stock which represents the state of the mind and perception of the market players.	
Change in Traders Expected Price =	EUR/MWh /hour
(Electricity Price – Traders Expected Price)/ Expectation Adjustment Time	
Sensitivity of Price=0.1	dimensionless
It defines how responsive *Electricity Price* is to demand to supply ratio (defined by calibrating the historical and simulated electricity prices).	
Expectation Adjustment Time=24	hour
Capacity Utilization (i) =	dimensionless
SMOOTH (Indicated Capacity Utilization (i), Adjustment Time of Utilization (i))	
= INTEGRAL (Change in Capacity Utilization (i), Capacity Utilization t0 (i))	
The central stock in the structure of the conventional power plants. It's the ratio of the power which is generated by the power plants to the potential power which could be generated if the installed capacity was fully used (Morcillo et al., 2018).	
In these equations, (i) can be gas, nuclear or coal.	
Change in Capacity Utilization (i) =	1/hour

(Indicated Capacity Utilization (i)–Capacity Utilization (i))/ Adjustment Time of Utilization (i)

Indicated Capacity Utilization (i) = dimensionless

Maximum Capacity Utilization (i) / (1+ EXP ((Variable Operating Cost (i) - Electricity Price) /Range (i)))

Indicated Capacity Utilization of conventional resources is determined based on a S-shaped growth logistic function which represents a nonlinear relationship between the capacity utilization, variable cost of generation and electricity price

Maximum Capacity Utilization = 100% dimensionless

Variable Operating Cost (i)= Other Operating Cost (i)+(Fuel Price (i) /Burner Efficiency (i)) + Carbon Tax (i)*CO_2 per kWh (i) EUR/kWh

Variable operating cost changes with different outputs and consists mostly of expenditures for fuel supply, operation and maintenance and the specific costs of CO2 emissions (Groscurth, 2009).

Other Operating Cost=0.0019, 0.0028 and 0.003 for nuclear, gas and coal power plants, respectively. It is the cost of performing some periodic operational and maintenance works to hold the power plants in a well-ordered and acceptable shape (California-ISO, 2018). EUR/kWh

Burner Efficiency= 0.37, 0.6 and 0.48 for nuclear, gas and coal power plants, respectively. It is the efficiency with which the plant converts fuel to electricity and is defined as the required fuel input to produce 1 MWh of electricity output (Kost et al., 2018). dimensionless

Carbon Tax=25 euro per tonne of CO_2

It is the social cost of mitigating one tonne of CO2-equivalent greenhouse gas emissions (IRENA, 2015).

Historical Capacity Utilization Factor (i) =Historical Generated Electricity (i) / Historical Installed Capacity (i) dimensionless

The historical capacity utilization factor of renewable resources is used to capture the intermittency and variability of renewable productions and incorporate the seasonal dynamics of these resources into the model. This parameter is defined based on the ratio of the historical electricity generation by these resources to their installed capacities in 2019.

Generated Electricity (i) = Installed Capacity (i) ∗ Capacity Utilization (i) Terawatt

With a fixed installed capacity, the electricity supply is determined by the capacity utilization. (i) can be coal, gas, nuclear, solar, run-of-the-river, offshore or onshore wind power plants

Effect of Price on Demand=SMOOTH (Indicated Demand Adjustment, Adjustment Time of Price Effect) Terawatt

= INTEGRAL (Change in Effect of Price on Demand, Effect of Price on Demand t_0)

Change in Effect of Price on Demand = Terawatt/hour

(Indicated Demand Adjustment – Effect of Price on Demand)/ Adjustment Time of Price Effect

Indicated Demand Adjustment = -Underlying Demand*Price Sensitivity of Demand*(Electricity Price - Reference Price)/ Reference Price Terawatt

Indicated Demand Adjustment captures the variations in demand caused by price variation. It is defined based on the difference between hourly electricity price and a reference price.

Underlying Demand= Terawatt

MAX (0.001, Historical Demand / (1- Price Sensitivity of Demand *(Historical Price - Reference Price)/ Reference Price))

Underlying Demand is expected customer demand. Two exogenous variables of Historical Demand and Historical Price are used to develop an estimate for Underlying Demand. Since Underlying Demand cannot be negative, a max function has been used to prevent the negative values.

Domestic Demand= MAX (0.0001, Underlying Demand + Effect of Price on Demand) Terawatt

Demand adjustment is made to translate energy consumption forecasts from an Underlying Demand basis to a Domestic Demand basis. In fact, an estimation based on the historical data is used to estimate future demand.

Reference Price=30 EUR/MWh

It is the standard price used in decision-making, and by which the purchase price of a product is assessed.

Price Sensitivity of Demand=0.1 dimensionless

It shows how elastic demand is to the hourly price variations in the electricity market (Chauhan, 2019). By calibration tools in the Stella Architect, price sensitivity for demand was taken as 0.1.

Net Imports = SMOOTH (Indicated Net Imports, Adjustment Time of Net Import) Terawatt

= INTEGRAL (Change in Net Import, Net Imports t_0)

Change in Net Import = Terawatt/hour

(Indicated Net Imports – Net Imports)/ Adjustment Time of Net Import

Indicated Net Imports= Terawatt

Transmission Capacity*(1- 2/(1+EXP ((Electricity Price - Nord Pool Prices)/Reference Import Price)/Spread in Net Imports))

Total Generation Cost (i)= billion euro

Installed Capacity (i) * (Leasing Cost per Year (i) + Fixed Operating Cost (i))/Hours per Year + (Generated Electricity (i) *Variable Operating Cost (i))

In this study, the costs of generation are broken down into three main components including the investment or capital costs, fixed operating costs and variable operating costs (Groscurth, 2009).

Leasing Cost per Year (i)= Capital Cost (i)*(Interest Rate (i) +(1/Lifetime (i)))	(euro/kW)/year
Social Benefits= Total Benefits – Total Cost	billion euro

In the present study, the optimization maximizes social benefits. Net society benefit is defined as the difference between benefits and costs, while both the producers and consumers interests have been considered in this parameter.

Total Benefits = INTEGRAL (Hourly Total Benefits, Total Benefits $_{t0}$)	billion euro
Hourly Total Benefits=	billion euro/hour

Domestic Demand * (Reference Price + Reference Price / Price Sensitivity of Demand - Reference Price * Domestic Demand /2 * Price Sensitivity * Underlying Demand

Leasing Cost per Year (i)= Capital Cost (i)*(Interest Rate (i) +(1/Lifetime (i))) (euro/kW)/year