# UNIVERSITY

## Master's Degree in ENERGY AND NUCLEAR ENGINEERING

# Model-based analysis for scenarios with high penetration of renewables


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# Abstract

Achieving carbon neutron targets lead the energy generation structure towards high renewable energy share. As the PV and wind capacity is increasing rapidly worldwide, the impacts on the grid system due to the characteristics of variability and uncertainty become more visible and more severe. Those impacts include voltage and frequency fluctuation, unbalance thus threatening the stability and reliability of power systems. Therefore, some solutions aiming to increase the strength and reliability of power systems are sought under this background. However, the metric that could evaluate the impacts of variable renewable energy (VRE) needs to be confirmed before developing the solutions. Focusing on the effects of VRE on the power system, we could find those impacts mainly come from the attributes of variability and uncertainty that VRE technologies own. In a sense, the concept of system costs has been proposed to capture the impacts of VRE on the whole system. Similarly, the concept market value and value factor, first presented by Hirth, are affected by three intrinsic technological properties: variability, uncertainty and location. These metrics were used to analyze the influence of the penetration level on the power system and evaluate possible solutions adapted to new challenges. Against this background, a scenario-based analysis is conducted to evaluate the market values of VRE based on some assumptions. We find that market values of wind and solar decrease with increasing penetration levels. Meanwhile, technology diversity could improve the stability of the system to integrate more VRE generation.

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# 1.Introduction

Carbon neutrality is one of the goals of the Paris Agreement, meaning carbon emissions and sinks need to be zero in the future. On the basis of this consensus, more and more countries committed that they will achieve carbon-neutrality by the middle of this century. The key part of this process is increasing the penetration of renewable energy resources and replacing fossil fuels. However, higher VRE penetration will lead to a series of problems: frequency instability, harmonics distortion, and voltage fluctuation (Gandhi et al., 2020). Due to the variability of variable renewable energy, the high VRE penetration could contribute to transmission congestion, leading to steep ramping, frequent shutting off, starting up of the thermal fleet(Sreekumar et al., 2018). Therefore, increasing the flexibility of the grid system to integrate intermittent renewable generation is necessary under the background of higher penetration of VRE. There are many methods and technologies that could increase the flexibility of the grid system. From the technology point of view, technological diversity may help reduce the VRE-production variability (Tantet et al., 2019). Bett and Thornton analyze the complementarity in the UK between wind and PV(Bett & Thornton, 2016). Coker presents a statistical analysis of complementarity in wind, solar, tidal and demand (Coker et al., 2013). The correlation between supply and demand is found to be the reason making impacts (Heptonstall & Gross, 2021). Besides, from the perspective of the demand side, there are also some solutions. RE clusters(Energy community) were addressed and designed to provide flexibility, interconnectivity, bio-directionality and complementarity (Lowitzsch et al., 2020). However, the regulations and functions of energy communities are different based on region. But whether the Energy community could make contributes to the system need to be discussed and analyzed.

The first challenge is how to assess the impacts of VRE on the power system at high penetration levels. The second challenge is to find the possible solutions that could reduce those impacts.

As defined by International Energy Agency (IEA)/Nuclear Energy Agency (NEA), the levelized cost of electricity (LCOE), indicating the discounted lifetime costs for different baseload technologies, is used for investment planning (OECD, 2015). However, it shows limits as it doesn't cover all the costs to the customers, including infrastructure and associated costs, as it only considers each power plant in isolation without considering the interactions between each other("Full Costs Electr. Provis.," 2018). With increasing VRE participation, the complexity of the system is increasing, the grid costs and other costs like re-dispatch costs are not captured in LCOE. For example, the congestion costs and balancing costs are enlarging with the increasing complexity of the system as they can't be ignored anymore. ("Full Costs Electr. Provis.," 2018). Therefore, some concepts were developed to characterize these costs into three categories: utilization costs/profile costs, balancing costs and grid costs (Hirth et al., 2015). Against this background, Hirth introduced an alternative concept "market value", representing the revenue generators can earn on markets without subsidies. The market value thus could internalize grid-level costs of VREs, representing the intrinsic lower value of electricity during times of high supply, at remote sites, and the economic costs of uncertainty (Hirth, 2014).

To conclude, with increasing penetration of VRE in the system, the complexity of the system is increasing, with risks following up. In extreme conditions, what will happen to the system with high VRE penetrations and what could we do to mitigate the problems? To answer these questions, we need to evaluate and quantify the impacts for a specific case through some merits. To evaluate the impacts of different penetration of VRE and different portfolios, a mode-based analysis is conducted with different scenarios.

In section 2, the theoretical concepts three different costs and "market value","value factor" are introduced. The insights on the market value of VRE technologies are outlined.

In section 3, the electricity market /dispatch model POMATO will be used to conduct analysis which is a dispatch model for the comprehensive analysis of the modern electricity market. The model is used to clear the Germany electricity day-ahead market and obtain the results. Based on the results, the market value and value factor of each case could be derived.

Section 4 illustrated the scenario framework for the analysis, presenting the installed capacity distribution of each scenario.

Section 5 develops the scenario-based analysis considering the different VRE penetration levels and obtains the results.

# 2. Theoretical background

## 2.1 Definition of different costs

As mentioned, with the increasing complexity of the grid system, the plant level costs like LCOE couldn’t capture all the costs from the system point of view. A concern to capture all the costs to the system drive more researchers to work on. These costs could be related to: fuel, transmission and distribution, system operations, CO2, etc. Analyzing these impacts could help us to analyze any technology change from a system point of view.

To evaluate the impacts of variable renewable energy on the whole system, we need to start by analyzing their characteristics. Due to variability, uncertainty, different locations of VRE plants, connecting VRE to a grid system brings several changes: generation varies with time, prediction deviations or errors, geographical distribution (Heptonstall & Gross, 2021). With higher penetration of VRE, these effects on the power system are becoming more apparent, requiring the evaluation of system impacts and the establishment of an appropriate framework to minimize and internalize them. Despite the lack of a rigorous and universally accepted methodology for quantifying those effects, there are a growing amount of studies and progress made in this field. According to the literature, these effects are often divided into the following three broad categories ("Full Costs Electr. Provis.," 2018):

a) Utilization costs/profile costs;
b) Balancing costs;
c) Grid costs.

- Utilization costs/profile costs: Utilization costs or profile costs are related to the variable character of VRE. Variable renewable energy power is highly dependent on weather conditions. During sunny or windy hours, solar or wind power is high. During these hours, a large amount of VRE generation integrated into the grid system means some conventional plants need to be shut down or reduced power. At night, while the solar generation is zero, the residual load then needs to shift from solar to conventional plants again. These costs are incurred due to the variability of VRE. Compared to the system with dispatchable technologies, a system with high penetration of VRE need to pay more for the residual load. These costs are the opportunity costs of generating by VRE, which could be the shutting down or starting up costs of conventional plants. Therefore, the costs could be considered as the differences between generation costs of variable profiles and flat profiles (“Full Costs Electr. Provis.,” 2018)
- Balancing costs are related to the uncertainties in VRE outputs and the forecasting errors. As solar and wind technology is highly correlated with climate conditions, subtle changes in weather could lead to a shaft change of output. In the real-time electricity market, the electricity demand and supply need to be balanced to keep the grid system stable and reliable. Meanwhile, we can’t ensure the accuracy of

VRE generation prediction, require more balancing services, thus bringing more balancing costs correspondingly.

- Grid costs reflect the levels of congestion of the transmission lines due to the locational constraint of generation plants. Compared to conventional plants that could be built anywhere, VRE technologies are restricted by location. Therefore, the corresponding connection costs are incurred especially for offshore wind. Moreover, new transmission lines are also needed to transport the electricity from production sites to the load.

Philip provided a meta figure presenting the ranges of different costs(Heptonstall & Gross, 2021). According to the paper, the costs for balancing costs associated with VRE are below €5 per MWh up to a 35% penetration level and below €10 per MWh up to a 45% penetration level. The profile costs lie in a range of €15-25 per MWh at a 25-35% penetration level. Grid-related costs vary from €14 per MWh up to a 35% penetration level to about €30 per MWh at up to 85% VRE penetration (Heptonstall & Gross, 2021).
Many countries have seen tremendous increases in renewable electricity generation capacity deployment during the last decade, with universal ambitions for even more significant expansion. While the impacts along with related costs of VRE on the whole system keep larging, it might not be valuable anymore with the generation of VRE compared to the production of conventional generators. (Heptonstall & Gross, 2021).
Furthermore, the addition of VRE capacity into a power system could reduce the capacity factors of existing traditional generators and result in lower market price which could undermine the revenues of other conventional plants("Full Costs Electr. Provis.," 2018).
From above, the impacts of VRE are decomposed to several related costs which are complex and profound. Besides, the quantification of system costs are context-specific, strongly dependent on the penetration level, transmission capacities and flexibility sources provided in the system. From a system point of view, we need to consider these different impacts when introducing more VRE technologies into the market.

## 2.2 Market value and value factor

Following with three costs mentioned above, a merit "market value" was defined by Hirth(2013), representing the revenues that VRE generators receive from the electricity market. Figure 2.1 shows the relationship between system base price and market value.

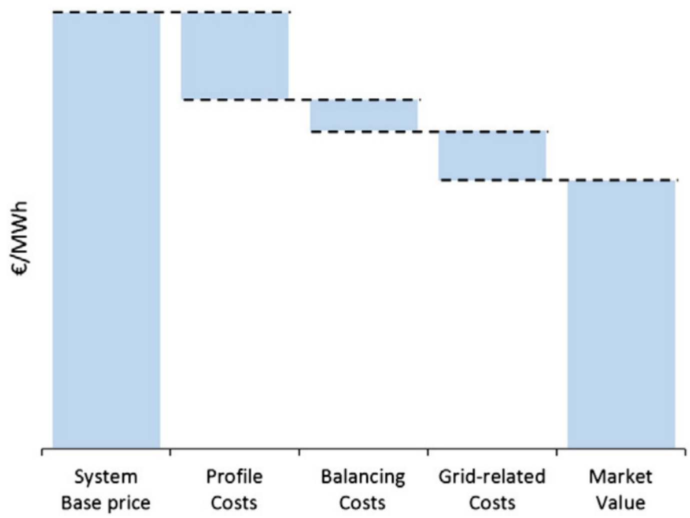


Figure 2.1 The system base price and the market value(Hirth, 2013)

System base price is the time-weighted average wholesale electricity price. Considering the impacts of variability, uncertainties and location restrictions of VRE, the electricity might be less valuable during the times of VRE generation.

To estimate the these costs, the concept "market value" was defined by Hirth. In an electricity market, the market value of VRE could represent their marginal social benefit to the system from a welfare theoretical point of view. From the investors' perspective, the market value also represents the revenues that wind or solar generators could receive from the market. Under a perfect market background, the system costs should be equal to system values. This value thus could internalize the utilization cost mentioned above. Hence, the market value can be higher or lower than the electricity base price. With lower market values, it represents that technology becomes less valuable as generation technology compared to a constant source of electricity. During the time that VRE market value is higher than system base price, it represents that VRE tend to generate when demand is high. These facts could be explained by "correlation effect" and "merit-order effect" which will be explained in the next section.

The market value p is defined as the generation weighted average wholesale price(Hirth, 2016):

$$\bar{p}^{tech} = \frac{\sum_{t=1}^{T} g_t^{tech} * p_t}{\sum_{t=1}^{T} g_t^{tech}}$$

Where:

$g_t^{tech}$ technology-specific generation
$p_t$ electricity price

The market value of VRE represents the total revenues that a VRE power plant can earn from the market. Three intrinsic properties decide the market value of VRE: variability, uncertainty and transmission constraints caused by locations. Therefore, we could find that the three costs mentioned above lead to a lower value of electricity during times of high supply, at remote sites and the economic costs of uncertainty.

Similarly, the value factor is a normalized metric to evaluate the economic values. The value factor $VF_{tech}$ is derived by dividing the short-term market value $\bar{p}_{tech}$ by the average electricity price $\bar{p}$. The equation is shown below (Hirth, 2013):

$$VF^{tech} = \frac{\bar{p}^{tech}}{\bar{p}}$$

$$\bar{p} = \sum_{t=1}^{T} \frac{p_t}{T}$$

When the value factor of a VRE plant is less than 1, it implies that it is less valuable than a traditional source plant. For example, if the base price in the market is 51€/MWh during someday, solar power receives an average price of 58€/MWh(value factor is 1.14) because the PV generate electricity when demand is high.
Both the concepts of market value and value factor are defined by Hirth to evaluate the impacts of VRE. These metrics would be implemented in our analysis.

## 2.3 Correlation effect and merit-order effect

The market value of VRE could be either higher or lower than average wholesale price. The reason for that could be explained by the two effects which are "correlation effect" and "merit-order effect". The correlation effect refers to a situation when the VRE generation profile is positively correlated to the generation profile. At this moment, the demand is high and correspondingly the price is higher. Therefore, the VRE generation receives a higher price. Nevertheless, if the VRE generation profile curve is not positively correlated to the generation curve, the situation is reversed. In this case, if the grid system could not provide flexibility, it will lead to renewable energy curtailment or negative prices. Of course, we hope the generation curve positively correlated to the demand curve, but this is highly dependent on the locations. In Europe, there exists a positive correlation effect for solar and a seasonal correlation effect for wind(Hirth, 2013). VRE will receive lower prices as they generate more when electricity demand is low. Meanwhile, VRE supply itself reduces the market price in high generation periods. As we know, the VRE generation owns a very low or zero marginal cost, so they are the first ones to be cleared in the market to meet the demand. They shift the residual load curve to the dispatchable sources, leading to lower market prices(merit-order effect). During this situation, with more installed capacity, the market value decreases.
Due to the merit-order effect, the revenues per MWh for VRE generators decline as penetration levels increase. This effect is also known as the absolute cannibalization effect(López Prol et al., 2020). Undoubtedly, the cannibalization effect will undermine the market value of VRE thus threatening their competitiveness in the electricity market. López Prol quantified the impact on the VRE market value/value factor based on the California day-ahead wholesale market. The results also confirm the cannibalization effect of both wind and solar. Another interesting finding is that there exists a positive

effect of solar penetration on the wind value factor in some situations. Wind penetration reduces the solar value factor while solar penetration increases wind value factors. Though the merit-order effect itself is not a problem, in the long run, it will pose a challenge to renewable energy investments. Meanwhile, low market prices also introduce a challenge to the dispatchable plants who take the responsibility of maintaining the security of the grid system(Figueiredo & Silva, 2019).

## 2.4 Statistics for value factor.

There are many studies already worked on this and quantifying different systems with market value and value factor.
Professor Hirth made a quantitative analysis of market value. According to the results, at low penetration rates(less than 2% penetration level), the wind value factor was slightly above one and the solar factor was around 1.3. This could be explained by the positive correlation of VRE with demand. With a higher market share, the value factor of both solar and wind drop due to the merit order effect. Making a comparison between PV and wind curves, we can find that PV value factors decline at a steeper rate than wind generation values. Then the value factors of both PV and wind decrease with increasing market share. Another point that could be found is PV decreases faster than wind as the wind curve is flatter than PV. To be mentioned, the analyzed penetration level is 0-8%. Since the total VRE penetration is over 30% in Germany 2020, we will focus on a larger penetration range in the analysis.

French utility EDF made an analysis on value factors with 40% VRE penetration at the scale of Europe NEA(2018). The 40% here represents that VRE would supply 40% of the annual energy demand.
The figure illustrates that the difference in the baseload price strongly correlated to penetration rate. With a higher VRE penetration rate, the difference gets higher. The gap values are in a range depending on individual countries' characteristics. Besides, PV technology and wind show distinct gap values with the same penetration level. Moreover, we could also find that the difference is low for the first MW of wind energy or solar PV installed. However, this gap becomes significant during high penetration levels (NEA,2018). As we can see in the figure, the gap value for different countries is quite different as they own different grid systems.

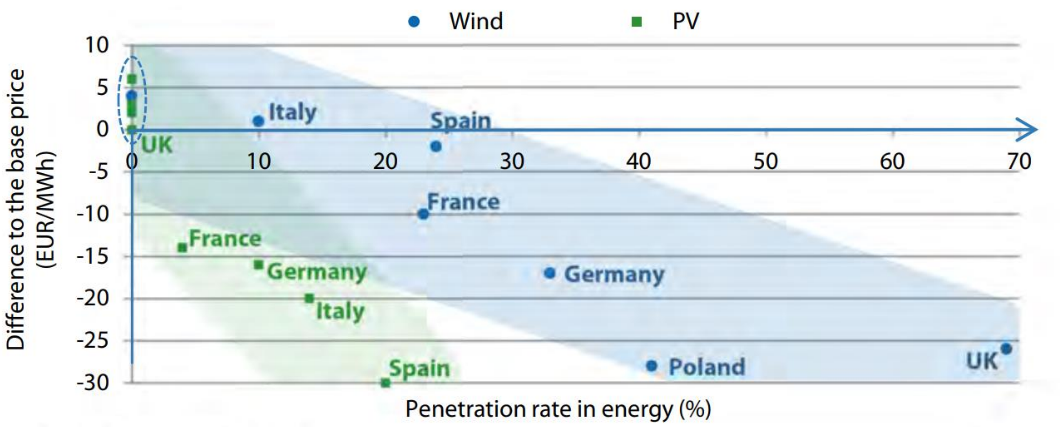


Figure 2.1 Market revenue gap of wind and PV(NEA,2018)

Meanwhile, we could see that the curve is also not linear because VRE penetration is not the only driver that impacts the value factors.

The drivers that could affect the value factors of VRE have been divided into exogenous and endogenous drivers(Eising et al., 2020).

According to the discussion from Eising (2020), Pudlik (2015) and Winkler (2016), exogenous drivers include:

- VRE market shares and market design: As analyzed above, the market value drops with higher VRE market shares. In a market environment, the investors take market prices as income. But there still exists subsidies for VRE in many markets. Under this environment, the gap between market revenues and the FiT(Feed-in tariff) is supported by subsidies((Hirth, 2013)). Different policies implemented in different regions which include feed-in tariffs, feed-in premiums or capacity incentives. They are developed to force in VRE(Brown & Reichenberg, 2021). The market values will differ based on the policies implemented in specific system.
- Storage and demand flexibility: According to model results of (Bistline, 2017), storage could increase the flexibility of the grid system and slightly increase the market value of variable renewables. Demand flexibility could also bring benefits when they support flatten extreme price(Pape, 2018).
- •Fuel and CO2 prices: With increasing fuel and CO2 prices, the marginal costs of conventional plants rise and market values also increase(Winkler et al., 2016). CO2 tax raises the market value of renewable generators by raising their marginal costs. The simulation results in (Brown & Reichenberg, 2021) find that CO2 policy could guarantee VRE cover their costs and avoid cannibalization effect to some extend.
- •Regional connectivity: Regional connectivity affects VRE market values. Greater interconnections with neighboring regions provide more flexibility to the system and therefore impact market values positively(Bistline, 2017)(Hirth, 2014).
- •Power plant portfolio: Different technologies integration will effect the market values of each other. The results in (López Prol et al., 2020) shows solar

penetration has a positive effect on wind value factor. Compared to Nordic countries which own flexible hydro power system, the countries owing thermal power systems like Germany offer limited possibility to take renewable energy generation(Hirth, 2013).

Endogenous drivers directly effect the values of VRE generators as they are related to the technology itself and its design or geographical location. Based on (Mills & Wiser, 2015)and Hirth, endogenous drivers can be summarised as follows:

- Technological diversity: Various studies analyze the integration of PV and wind onshore and offshore(Hirth, 2014; Millstein et al., 2021). The grid system receives benefits of resource diversity(Coker et al., 2013).
- Technological design: In Germany, Engelhorn and Musgens found the modern wind turbines outperform old ones attributed to better normalized standard deviations(Engelhorn & Müsgens, 2018).
- Geographical diversity: Geographical diversity smooth of the intermittence of VRE generation when total production is at reginal level(EDF,2015). Mills and Wiser estimate that geographical diversification has the potential to reduce profile costs at a high penetration level. Eising investigates the market values of VRE deploying strategies concerning geographical diversity. However, the results show geographical diversity doesn't ensure positive impacts on VRE market values(Eising et al., 2020).

The trend that VRE market share increase rapidly will continue since more and more countries introduced policies aiming to move towards carbon neutrality. As discussed, the VRE value factors are derived from the wholesale market electricity prices. The electricity market could be used as a useful tool to investigate the wholesale market prices and value factors. Several studies have used market models to evaluate the impact of various exogenous and endogenous drivers.

In this paper, a model-based analysis is implemented to derive future electricity prices for different market scenarios under varying renewable energy penetrations. Some extreme assumptions were made to see what would happen with very high solar/wind penetration. For example, we will expand the solar capacity to cover the full electricity demand of Germany and simulate proportionally. In some sense, this kind of assumption would exaggerate the "merit-order effect," especially keeping the physical grid parameters at the moment. Besides, the model is run based on the assumption of the perfect market model which is not a real case so far. However, measuring the absolute magnitude of future market values is not the primary objective of this paper. Instead, the focus is to evaluate how VRE penetration levels impact the system. Furthermore, there is a controversy about energy communities. The model could also measure the effects of energy communities on the grid system.

Though many works are analyzing how diverse VRE portfolios impact the electricity system, only a few studies analyze the metric market values which include more external costs.

## 2.5 Zonal and nodal price

In Europe, the zonal electricity market model is currently applied. In each zone, it is assumed that there is no congestion internally, thus showing uniform price within each zone. If there is congestion in the zone, then the operators need to redispatch to change the physical flows to meet the transmission capacity restrictions. The zonal market method is based on simplifications of the grid system(European Commission, 2020). In Europe, usually a country is considered as a zone in the market. On the contrary, for the nodal model, each node in the grid system is represented, implemented with a power distribution factors matrix. Hence, for the nodal model, all transmission constraints are taken into account in the market clearing process.

In studies, more and more people state that the nodal market model could adapt to new challenges with higher efficiency. As European Commission (2020) says, "Theoretically, nodal pricing is the most optimal pricing system for electricity markets and networks." Why say so? As mentioned above, the carbon-neutral or decarbonization goals require growing importance for renewable energy technologies and also electrification of transport. Against this background, the grid systems face more challenges with a rapid increase in the installed capacity of VRE which will cause variability and uncertainty. For example, in some places, the RE production may exceed the total demand and if all the renewable energy generation is accepted into networks, the transmission constraints seem to worsen. Therefore, it is more significant for the electricity market to manage data flow about essential information such as energy demand, supply, and potential flexibility.

The EU energy market is divided into several zones with the assumption of the transmission capacity in each zone is adequate. A zone is usually defined as a large area within a country or the whole country (Piotr F. Borowski, 2020). The zonal market model is based on the assumption that there are no transmission constraints within the zone. However, this is not always true in real conditions. In fact, congestion might happen when locational generation is over the transmission capacity. When congestion happens, the network operators have to implement very expensive activities, such as re-dispatching to ensure no overloads transmission lines and the scale of these interventions is growing systematically. Besides, the zonal market couldn't exploit the potential of renewable sources. With the zonal model, the redispatch costs are averaged in the zone for all the nodes. People won't know where the most vulnerable node is since the price is uniform in the same zone. Furthermore, the lack of price signals on the market introduces an issue that it is difficult for investors to expand the capacity of transmission lines and other infrastructure to improve the efficiency of the system. The transmission costs represent the opportunity cost created by congestion in the system. Besides, the grid congestion will lead to "out-of-merit", which means the plants in the market might not rank according to the marginal costs with the transmission restriction. The limited utilization of the plants results in a substantial opportunity cost caused by congestion.

While nodal price(Locational Marginal Price-LMP) represents the locational value of energy, including the cost of energy and also congestion cost, the spot prices reflect the scarcity of the resources (Antonopoulos et al., 2020). The effects and benefits of nodal market model can be summarized into short-term and long-term consequences on efficiency.

Moreover, providing appropriate price signals make it possible for customers to manage their own energy consumption such as storage, EVs and also other activities that could provide flexibility(Demand-side management)(Wojdalski et al., 2015). The concept "prosumers" or "Energy communities" was mentioned frequently in recent years, which play a more and more critical role in the grid system as they typically include demand flexibility, storage and peer-to-peer trading between prosumers or between energy communities and the market (Lowitzsch et al., 2020). The nodal market model can engage customers to become active market participants as it provides a stimulus signal to transfer power load from a high price period to a lower price period (Piotr F. Borowski, 2020).

In the long run, the nodal market pricing signals future investment in upgrading transmission capacity and generation to ensure the adequality and security of energy supply to customers.

Some studies quantify the system costs of these two schemes, it is found that the nodal scheme or a hybrid pricing scheme outperforms the zonal model for analyzed systems(Neuhoff & Boyd, 2011; Bjorndal, et al., 2018; ACER, 2018).

As illustrated, the nodal price scheme seems to outperform the zonal price scheme while it could provide better price signals, thus providing better congestion management and incentives for both investors and consumers to invest in more economical technologies in the system. Of courses, those benefits are also highly dependent on the system. Therefore, the modeling results will be analyzed to discuss these two schemes.

# 3. Methodology

## 3.1 Selected analysis scope

The analysis concentrates on the impacts of the high penetration level of VRE on grid systems and explores potential drivers that contribute to value reduction. Based on the analysis, different pathways to improve the power grid's resilience with renewable energy resources will be proposed.
While the value factor highly depends on the specific system, this analysis is developed based in Germany. Germany sits at the heart of an interconnected European electricity system. Thus Germany physically exchanges electricity with neighboring countries. To consider interactions with neighbouring markets, the power system is in full detail for Germany, together with the countries directly connected to Germany which are Luxembourg, Sweden, Austria, Belgium, Czech Republic, Denmark, France, Germany, Netherland, Norway, Poland, Switzerland. Compared to other countries, Germany has a complex and densely meshed grid system with a partly geographically concentrated renewable energy feed-in system(Schönheit et al., 2020).

Figure 3.1 Geographical relationship between Germany and other countries

## 3.2 Dispatch model description

### 3.2.1 General description

POMATO (POwer MArket TOol), a dispatch model is applied to analyze the electricity market in Germany for a specified period. It is a bottom-up optimization model, minimizing total system costs with some technical constraints including RES availability and curtailment, transmission constraints. Therefore, the model represents an optimization problem minimizing total generation costs subject to restrictions regarding generation capacity and transport limitations.

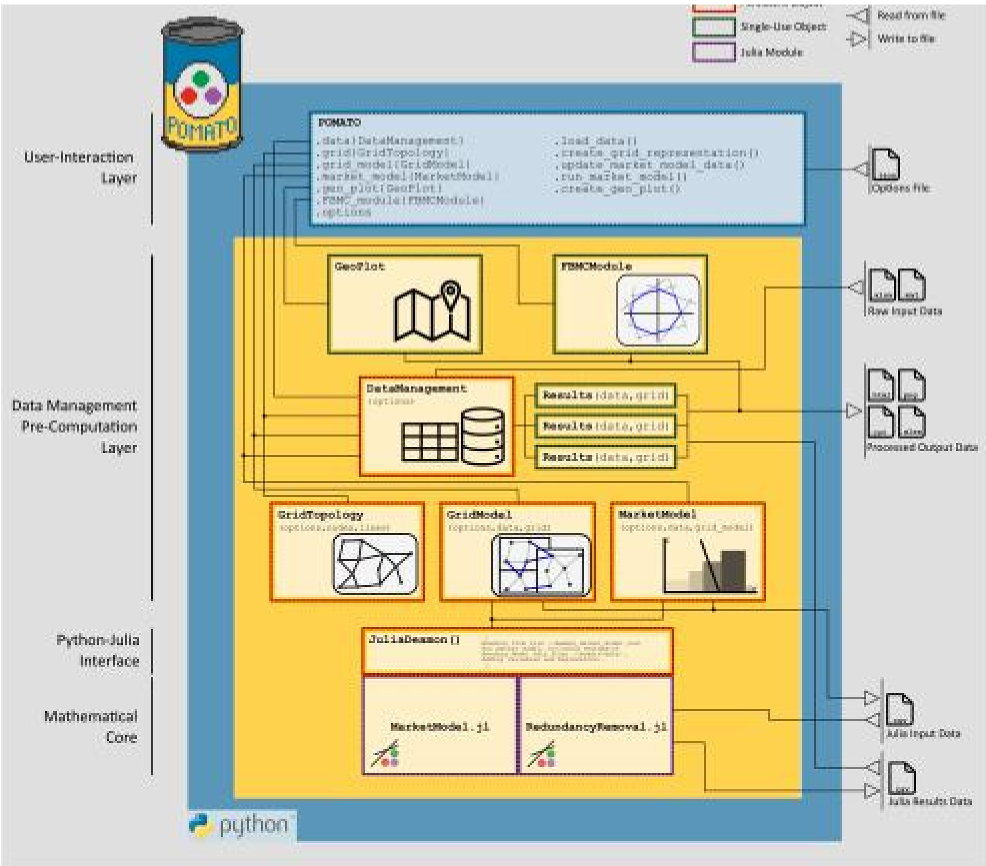


Figure 3.2 The structure of POMATO

The model is structured in three layers as shown in Figure 3.2. The mathematical core part collects the mathematical formulations of the optimization problems. The data calculation and validation are embedded in the data processing layer to avoid recalculating large parameter sets. The data processing layer provides parameters, verifies and processes the model output. Formulation below outlines the core of the model. The full mathematical formulation could be found in Appendix A.

$$min\ OBJ = \sum COST\_G + COST\_H + COST\_CURT + OOM\_PEN$$

| | |
|---|---|
| COST_G | Generation costs |
| COST_H | Heat costs |
| COST_CURT | Curtailment costs |
| OOM_PEN | Out-of-market penalties |

Objective minimises the cost of electricity generation(COST_G), load curtailment(COST_CURT) and out-of-market penalties(OOM_PEN) (cost of redispatch) over all units and time series and is subject to all constraints listed above. It is ensured that generation equals demand with net export at all times for all regions.

## 3.3 Data and assumptions

For this analysis, considering the complexity of data processing and calculating time, the data is obtained from an existing pomato model example named "run_pomato_de". In the examples, only a few days of data are provided. Therefore, we chose two specific days (May 1st and May 2nd ,2019) to do simulation and analysis. Instead of simulating the whole year, this report will only simulate a few days. The demand curve is depicted in Figure 3.3. The results couldn't represent the whole year and may have deviations compared to results in other analyses. However, the goal of this paper is not to obtain the exact market value reduction of VRE in Germany. Instead, we would like to see what will happen in high renewable penetration level and verify trends for market values of VRE when increasing the penetration level and also make analysis on potential drivers that impact market values of VRE. Furthermore, we could see from paper (Heptonstall & Gross, 2021) that VRE market values reduction or profile costs usually fall in a range and it's not a linear curve with variable penetration levels. Therefore, it is reasonable to make an analysis based on a few days.

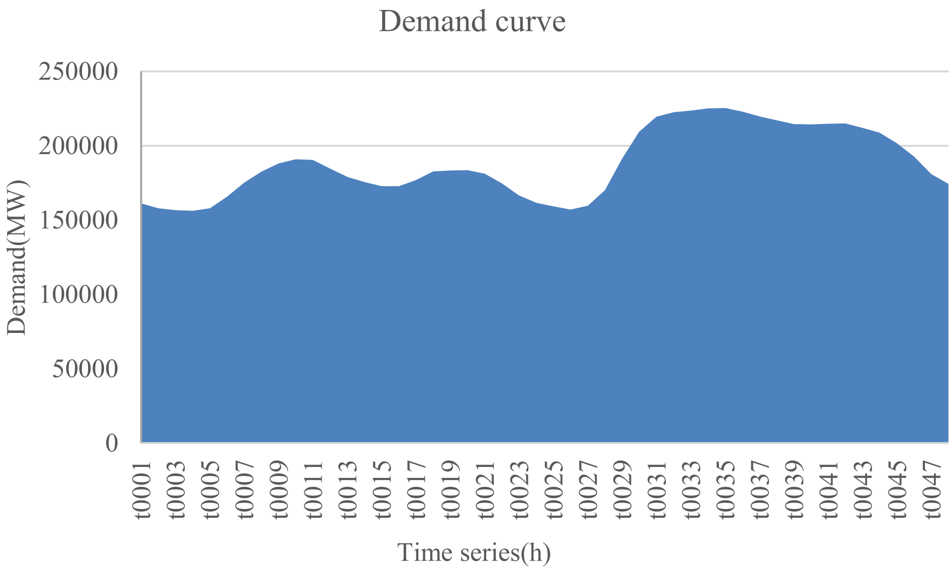


Figure 3.3 Demand curve with time series

The basic scenario simulates the German power system obtained from the example case study of this open-source model. Then the model calculates the day-ahead electricity market prices and generation profiles on an hourly basis with different parameters. This model will be set up for a model clearing in either zonal and nodal models. A set of input data is defined including the availability of each renewable plant, information of each line and each power plant, fuel price, etc. The detailed data is represented in the appendix. Additionally, plants where plant type is either "hydro_res" or "hydro_psp" are considered storages and plants of type "wind onshore", "wind offshore," or "solar" have an availability time series attached to them.

## 3.3.1 Curtailment and infeasibility

In the option, curtailment or infeasibility could be chosen. The curtailment option represents that when renewable energy generation is more than demand, the excess generation will be curtailed. Infeasibility allows the imbalances of energy to exist in the equation. Some studies like Brown and Reichenberg didn't take into account curtailment when quantifying the cannibalization effect. They estimate the values of generated electricity. Since value decline of VRE could be decomposed into profile, transmission congestion and curtailment, others like Millstein , Joos and Staffell include curtailment analysis in their studies. Therefore, we did an analysis of these two option. We run scenario 1 and scenario 2 at 100% penetration with infeasibility option and also curtailment of different values. The results are shown in Appendix B. From the results, we couldn't find that the infeasibility option has an absolute positive or negative effect. For scenario 1, the value factor isn't monotonously changed with increasing curtailment costs. Therefore, to ensure the balance of energy demand and energy generation, curtailment is included. According to Joos and Staffell, 2018, we chose the curtailment option with costs of 100Euro/MWh.

The other data that comes from multiple sources are included in Appendix B.

Based on this model, the capacity of VREs will be modified and several scenarios will be explained in the following parts to explore the impacts of drivers.

## 3.3.2 Theoretical penetration and RES energy share

As we said, the main goal of this report is to observe how solar and wind impact the system with varying penetration. Thus, we set the penetration level varying from 0-100% with the same varying steps.

The methodology to achieve that is stated here: First, we have the information including the capacity, availability of each wind or solar plant. Besides, we also know the demand of each node during the analyzing periods. By multiplying the availability and capacity of each plant we could get the theoretical generation profile of each plant. Then we scale up the technology capacity proportionally to reach the same value of a certain percentage of the total demand. Thus, the wind or solar plants generation could cover the full demand energy theoretically by scaling up the capacity.

However, in reality, the VRE is variable as they generate during certain hours especially for solar. In the day, solar might generate more energy than demand and at night they generate zero. So even though we scale up the capacity to make total generation by solar cover the total demand, the real PV energy penetration won't reach 100%. Therefore, when we analyze the performance of VRE through market value or value factor with varying penetration, we will plot and analyze by both theoretical penetration and solar/wind energy share.

### 3.3.3 Zonal and nodal

The model is able to run different configurations of the market model according to users' needs. Among the options in optimization referring to what kind of grid representation is represented, the "nodal" and "zonal" will be applied for the analysis in this report. For the nodal option, nodal PTDF is represented to clear the market, therefore, enforcing an energy balance for each node with exchanges limited in transmission capacities. On the other hand, zonal markets ensure energy balance for each entire zone which consists of several connected nodes with the assumption that there is no congestion in each zone. However, this assumption is not always valid especially in the zonal background of higher renewable penetration levels. Therefore, a redispatch activity needs to be implemented to reduce overloads transmission lines and mitigate congestion. Redispatch models find the minimum cost change from a given generation schedule and penalty costs while keeping nodal balances are feasible for transmission lines.On the opposite, the nodal model doesn't require redispatch activities while considering all the constraints when clearing the market.
Since the nodal model considers all transmission constraints when clearing the market, thus nodal price could reflect the scarcity of the resources and the situations of congestion. We are more interested in the nodal model in our scope.

Why are we more interested in nodal models? There are several reasons below.
Firstly, our primary goal is to evaluate the impacts of VRE on the whole system. These impacts are mainly coming from the VRE's characteristics of variability, uncertainty and locational constraints. While the uncertainty occurs in real-time electricity market, we only plan to simulate the day-ahead electricity market. Therefore, the imbalance costs due to uncertainties are not included. The other two parts are in our scope. Locational constraints lead to grid-related costs like congestion costs. Since the nodal pricing scheme take into account the transmission constraints, it internalizes the grid-related costs which is what we want.
Secondly, our analysis could be further extended to analyze the mitigation measures such as demand-side management. Besides, the energy community was also concerned at the beginning. All of these considerations should be based on appropriate price signals as they can make it possible to exploit the potential of demand management. Since the nodal model could provide a price for each node, it becomes a preferable model.
Thirdly, since the zonal model needs to implement redispatch measures in the market clearing process, it is not the optimum solution for the system. Meanwhile, the modification of different strategies makes the results different and the problem becomes more complex.
In conclusion, our main results will be based on nodal option to analyze the impacts of VRE on the grid system. Furthermore, we also simulated the system through a zonal model to see the difference between these two models.

# 4. Scenario framework

## 4.1 Scenario background

As described, the focus is to explore the future market value with different VRE penetration levels and other potential drivers. Initially, we would like to explore how energy communities perform in the electricity market system in the background of high renewable penetration levels. Before that, we need to figure out the drivers that make the grid system unreliable and costly first. Specifically, the problems of how solar and wind technologies perform with various penetration levels respectively in the system and the impacts on each other will be explored first.

In this case, some extreme situations are formulated to isolate the impact of the individual drivers of value factors.

For scenario1, the PV capacity is expanded until the PV generation is equal to total demand with the absence of wind technology in the system. We consider that at this moment, the penetration is 100%. Then the model is run several times with varying penetration levels. For scenario 2, wind technology is also processed as solar in scenario 1. In scenario 3, both solar and wind are included and account for half of the total demand.

In each scenario, the market model without grid representation was first solved and then the model within DE zones will be rerun with redispatch costs 50 Euro/MWh.

Figure 4.1 shows the capacity at 100% of 3 scenarios:

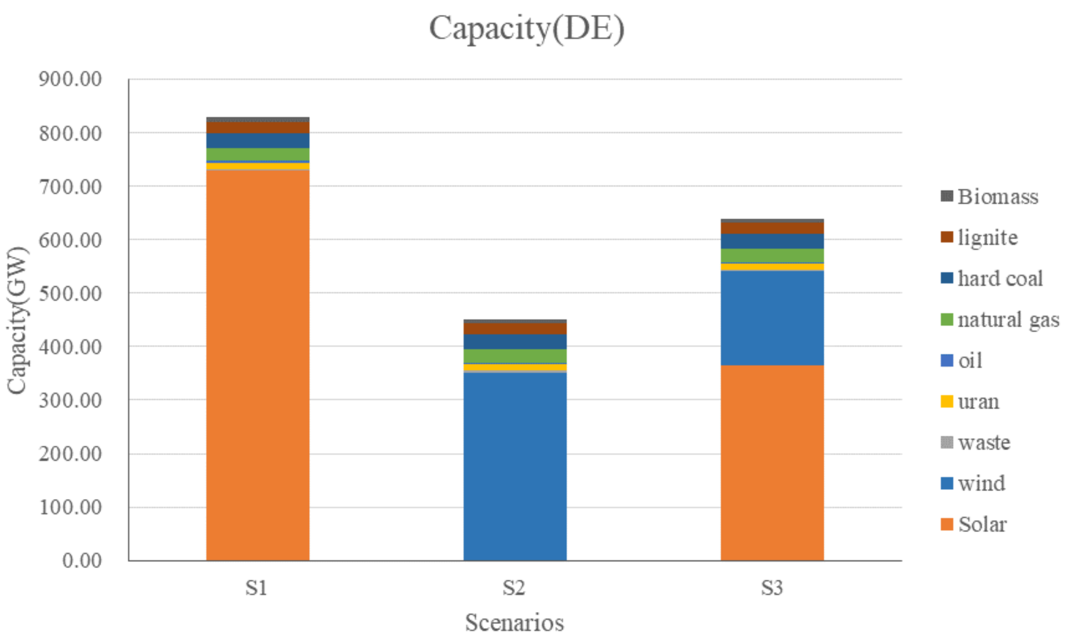


Figure 4.1 Capacity at 100% penetration for S1,S2,S3(Germany)

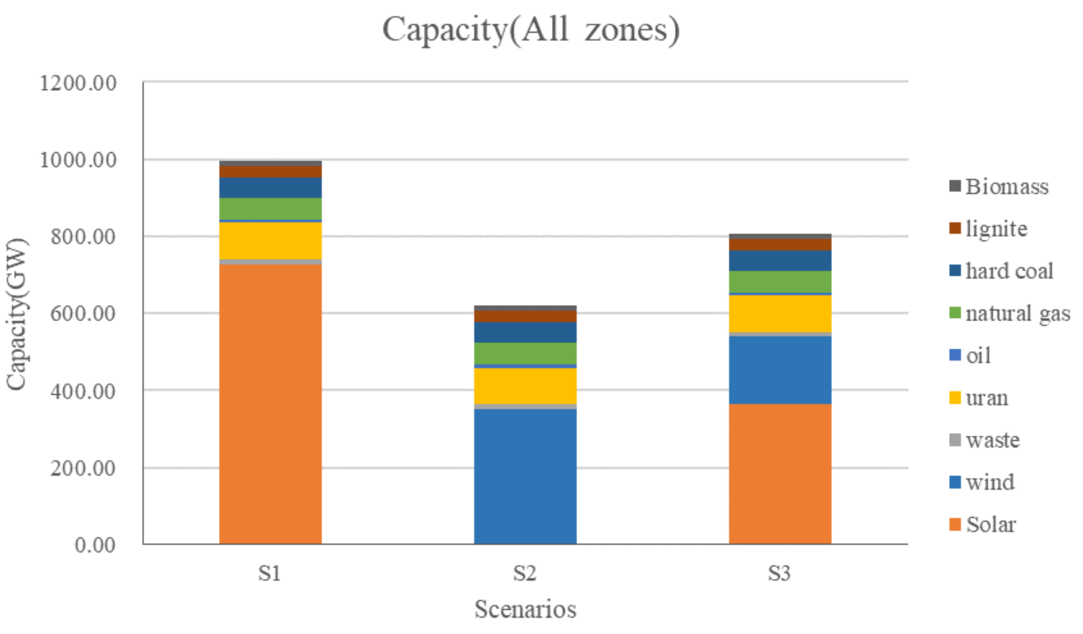


Figure 4.2. Capacity at 100% penetration for S1,S2,S3(All zones)

Since the grid system of Germany is connected with neighboring countries, some plants in these regions are also included.

## 4.2 Installed capacity for each scenario

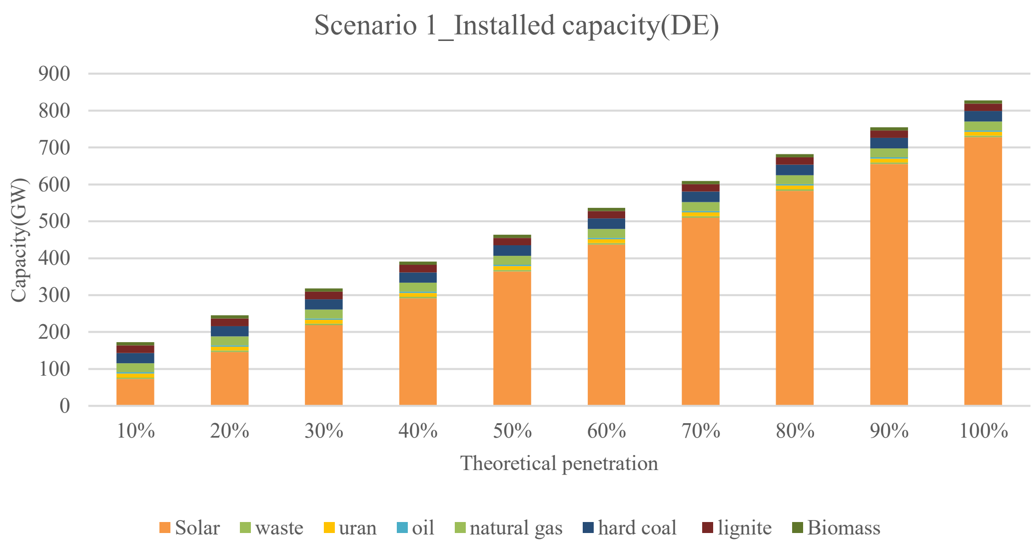


Figure 4.3 Installed capacity of cases in Scenario 1

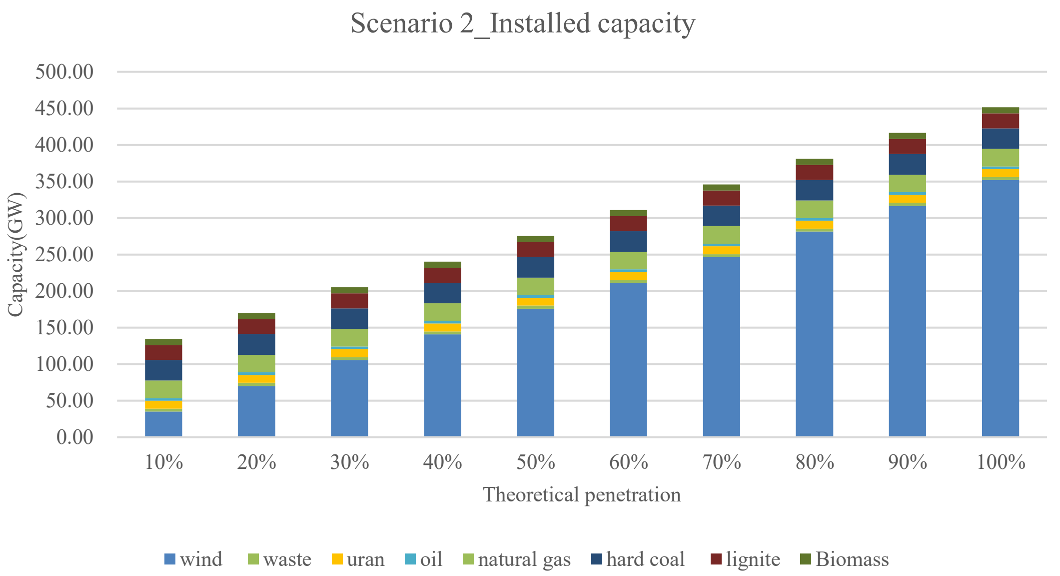


Figure 4.4 Installed capacity of cases in Scenario 1

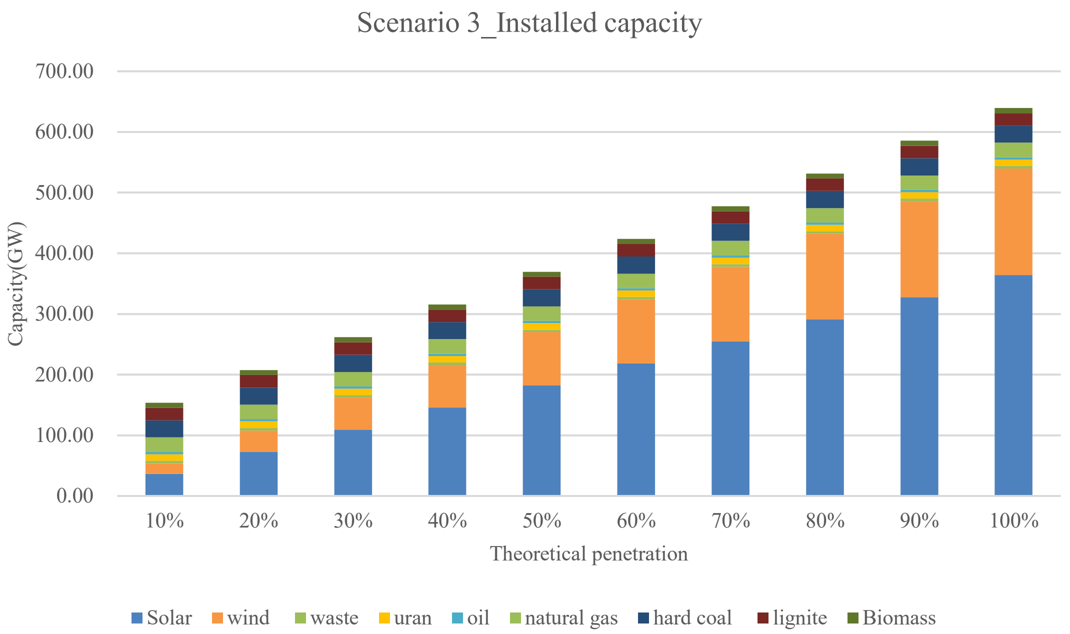


Figure 4.5 Installed capacity of cases in Scenario 1

As shown in figure 4.3, 4.4 and 4.5, the varying installed capacity cases for each scenario are depicted. With increasing theoretical penetration, the corresponding VRE technology capacity is expanded proportionally. The data for this part is in Appendix E.

# 5. Results

In the following sections, we explore the changes in the market values and value factors of solar and wind technology with varying penetration levels. By running scenarios with different penetration rates, the corresponding curves can be derived by calculating the market values and value factors based on the day-ahead market prices. On this basis, we can observe the pattern of changes in the value factors of VRE as the penetration rate increases. With the increasing amount of VRE installed capacity, it is significant to make an analysis of the performance of VRE at high penetration levels. Furthermore, we will also explore how value factors change when both wind and solar technology participate in the market with the same energy penetration level and how they affect each other. While the results can be used to illustrate the "merit-order effect" and "cannibalization effect" better, our next goals are to dig out the causes for VF changes. The prices and generation profiles will be plotted to find the possible reasons. Based on that, more analysis could be done in further research to quantify the impacts of different exogenous and endogenous drivers: technology diversity, zonal/nodal market models, energy communities, CO2 prices, etc. In the end, we list the possible risks of value declines and challenges of the energy transition. Some possible solutions will be proposed to mitigate market value drop of VRE in some dimensions.
The model was run with "nodal" option to estimate VRE market values at various penetration levels as the nodal model performs better. This section explores how VRE value differs with increasing penetration levels (wind and solar value). Then we try to explain the results by the theories we discussed before and investigate the different impacts of wind and solar profiles.

## 5.1 Solar（Scenario1）

### 5.1.1 Market value and value factor

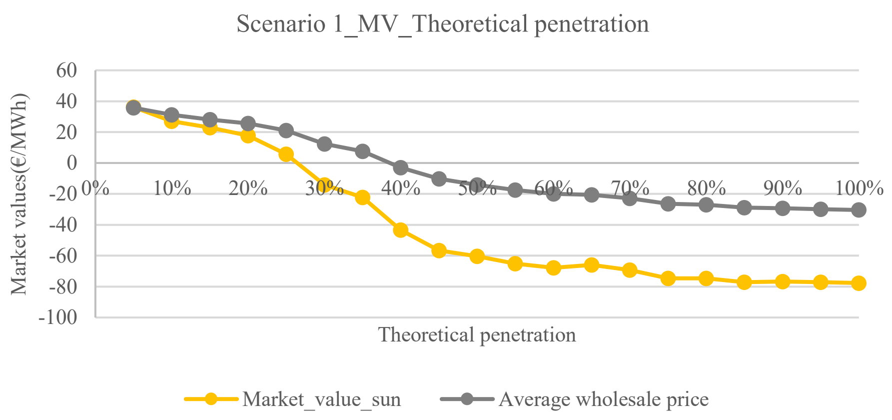


Figure 5.1 Market value/average wholesale price curve with increasing theoretical penetration levels

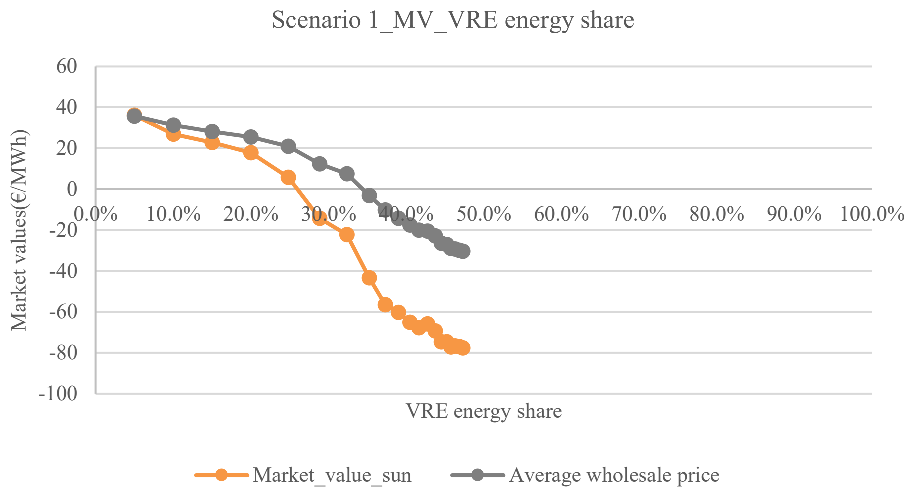


Figure 5.2 Market value/average wholesale price curve with increasing VRE market shares

Figure 5.1 shows the trend of the market value of PV with increasing theoretical penetration level. The market value of solar means the economic value of PV and it represents the revenues of PV in the electricity market. The grey curve is the average day-ahead wholesale market price.  As we can see, both the market value of solar and the average price decreases with higher penetration monotonically. Starting from around 36.1 €/MWh with the solar penetration level of 5%, then PV market value decreases rapidly during the penetration range 20%-40% and becomes negative at 30%. Lower market value means PV plants generate when the price is lower than the average market price.

Based on the perfect market assumption, the market price fluctuations reflect interactions between demand and supply. Thus, we can infer that solar generations are not positively correlated with the demand with higher penetration. On the one hand, with more capacity, the PV generation is concentrated on a few hours around noon during which the market price is lower than the average wholesale market price. The decline of revenues proves that increasing PV penetration undermines its own value, which could be called the cannibalization effect. Meanwhile, the residual load for conventional and dispatchable power plants is diminishing which is called the merit-order effect. Given the extremely low marginal cost of solar plants, the wholesale market price also drops with more installed PV capacity. When the penetration level is high, the wholesale market price could close to zero which will undermine the revenues of conventional power plants.

Figure 5.2 depicts the same values as the real solar energy share in the market. The decreasing trend keeps the same but both curves go down faster. With the same increased installed capacity, the PV generation share increases less as the dots in the figure get more intensive. When theoretical penetration reaches 100%, the actual solar generation share is only 47.3%. The figure below shows how actual solar generation share varies with theoretical penetration level. The curve becomes more stable which means, the actual solar generation into the market is not increasing as much as the increase in installed capacity. With higher installed capacity, the utilization rates of PV become lower.

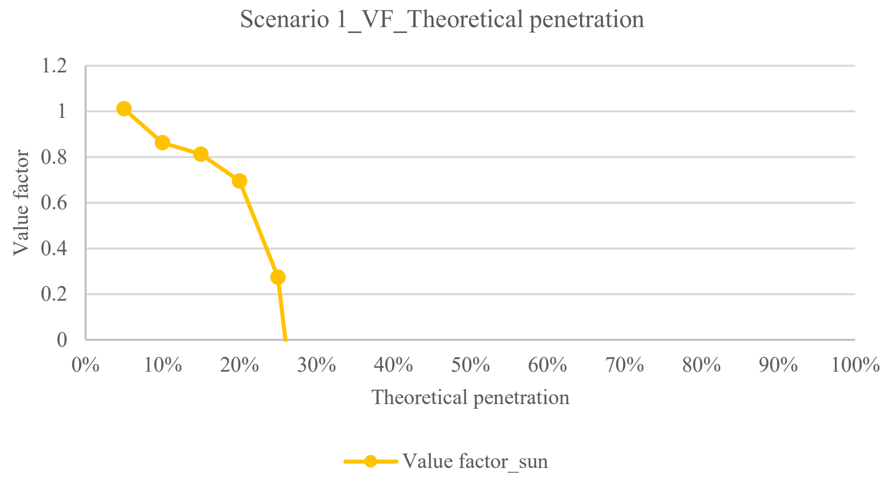


Figure 5.3 Value factor of solar with increasing VRE theoretical penetration

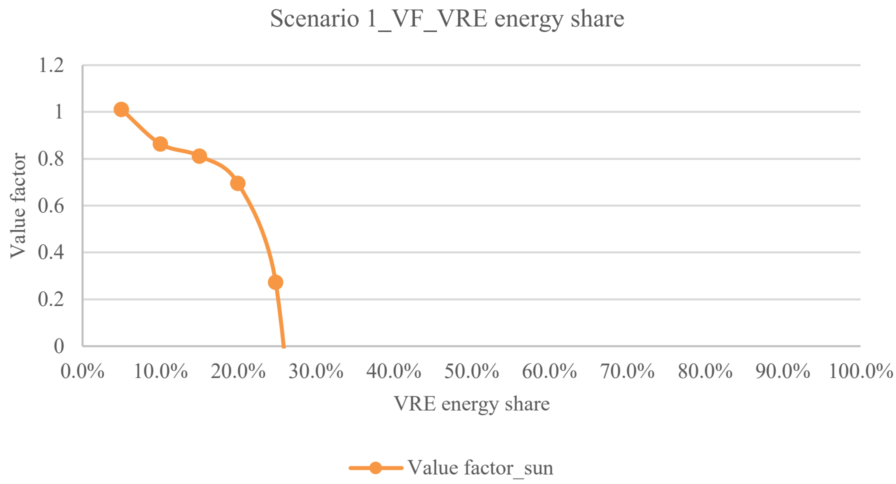


Figure 5.4 Value factor of solar with increasing VRE energy share

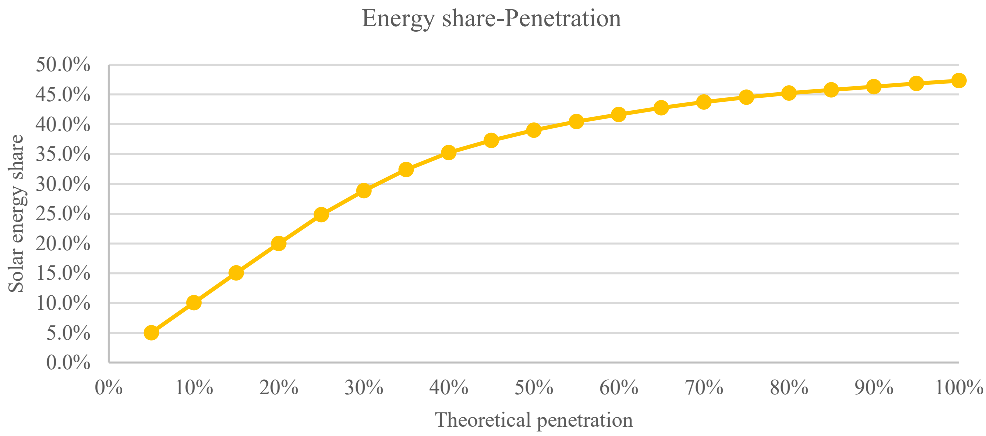


Figure 5.5 Energy share-Theoretical penetration

We will only analyze the value factor when it's positive. As the value factor is a normalized metric to evaluate the economic values, it is meaningful when both the

market value of VRE and average wholesale price are positive.
Likewise, figure 5.3 and figure 5.4 illustrate the trend of the value factor of PV. The value factor of solar is more than one at 5% penetration, representing solar generation is valuable at this level for the system. During 0-15%, the curve is downward linearly, reaching around 0.8 at 15%. Then there is a collapse starting from 15%. We can observe that the intersection of the curve with the x-axis is between 25% and 30%. As solar's market share rose from 20% to nearly 25%, the value factor declined by 60%. According to Hirth, a decreasing VF implies that solar technology becomes less valuable than a constant electricity source. When the VF is higher than during a low penetration level, the PV generation is positively correlated to the demand. Then with more installed capacity, it becomes non-marginal. Solar generation reduces the market price during sunny hours. Why the collapse happens during a certain penetration range could be an interesting question. Following up, we will analyze the system costs later on to find the possible reasons.
Comparing figure 5.3 and figure 5.4, we could observe they are almost the same. That is because the theoretical penetration is almost equal to energy share during low penetration range. Figure 5.5 shows how solar energy share varies with theoretical penetration. The curve becomes more stable when increasing the theoretical penetration as it is not linear, representing the utilization rate of solar is decreasing with a higher penetration level.

## 5.1.2 Generation profiles and price curve

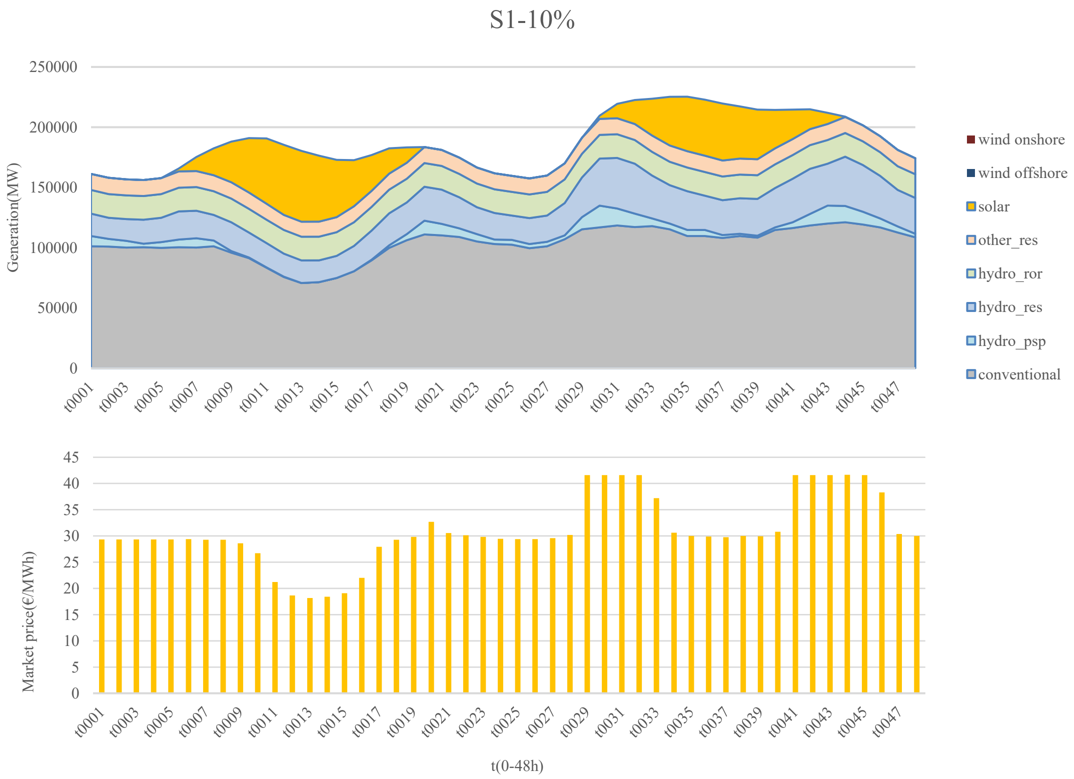


Figure 5.6 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 1 with theoretical solar penetration of 10%. The yellow part on the top is electricity generation by solar.

Figure 5.6 shows how wholesale market price and generation profiles change with time during analyzing hours at 10% penetration level. As we can see, solar generation is concentrated in the daytime during t0009-t0019, t0033-t0043. During these periods, other conventional source generations have been cut down. Looking at the generation profiles, we could find that the residual load on conventional source become variable during t0009-t0019. Correspondingly, we could see lower market prices during this period in the price figure due to merit-order effect. With more solar generation in the market, the price will shift from expensive plants to lower ones. Another interesting thing in the price figure is that: we find higher prices in the market during t0029-t0033 and t0041-t0046 which are the early morning and early evening of the second day. The reason for that could be the variability of solar generation. When the sun rises or sets, the solar generation ramps up or ramps down steeply and the residual load also need to be shifted by conventional power plants fast. Usually, those flexible plants like gas turbines in the grid system will take the responsibility to react which is more expensive, causing an increase in wholesale prices.

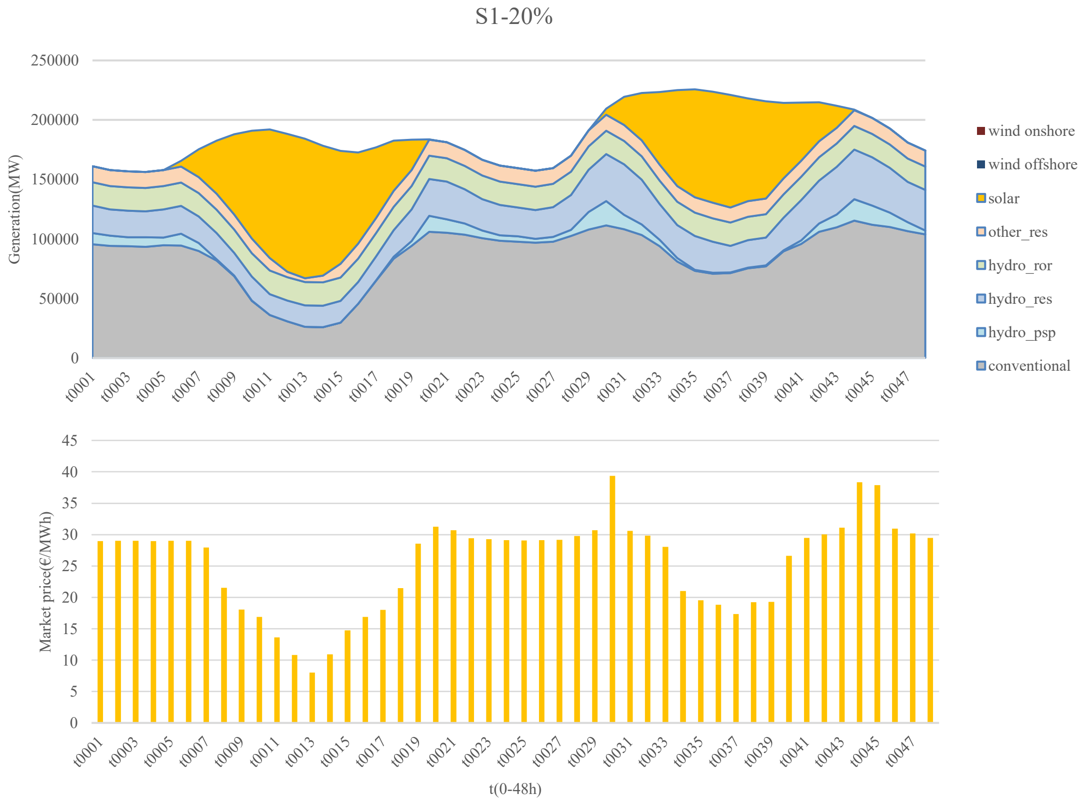


Figure 5.7 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 1 with theoretical solar penetration of 20%. The yellow part on the top is electricity generation by solar

With higher energy penetration, figure 5.7 shows how generation profiles and price vary with time at 20% penetration level. In the generation profile, the solar generation parts is larger, shifting more loads from conventional power plants to solar, thus leading to a more variable residual load curve. Accordingly, we could observe an obvious price decrease during solar generation hours t0008-t0019, t0033-t0043. The lowest price reaches 7.5 Euro/MWh, which is only 25% of the highest price. Therefore, we could say the introduction of more solar in the electricity market would lead to a more fluctuated price with time. The difference between peak price and valley price will be larger.

Figure 5.8 shows the case at 40%. With a larger solar generation, the residual load becomes more variable. Especially during the sunrise and sunsets hours, the conventional power generation decrease or increase steeply. The price reduction during sunny hours gets more significant, even reaching negative during these hours. The negative price is 100 Euro/MWh which is exactly the curtailment costs. It happens that excess electricity production from solar, with priority access to the grid, drives the prices down and it is more profitable for PV plants to pay users to consume energy instead of curtailment. Negative pricing is a method to clear supply surplus, enabling market participants to consume excess production to avoid curtailment from supply surplus(AESO, n.d.). The figures below could explain it better.

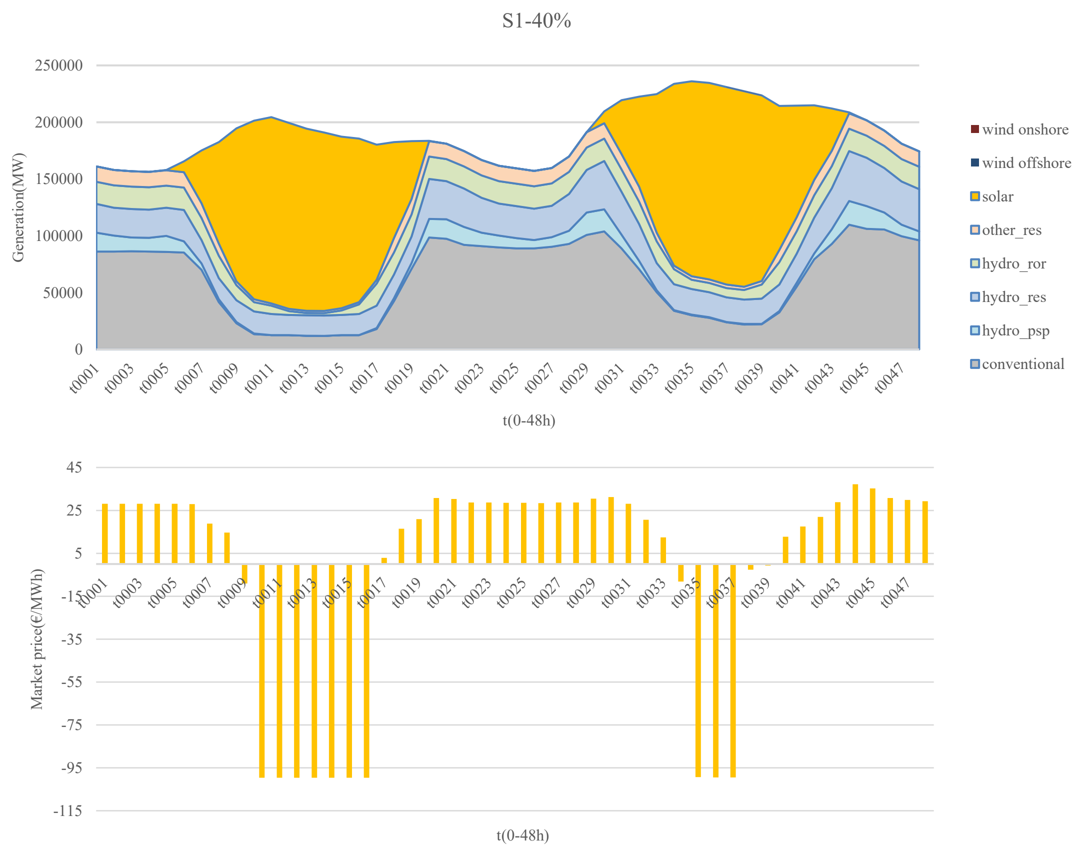


Figure 5.8 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 1 with theoretical solar penetration of 40%. The yellow part on the top is electricity generation by sola

## 5.1.3 Generation costs and curtailment costs

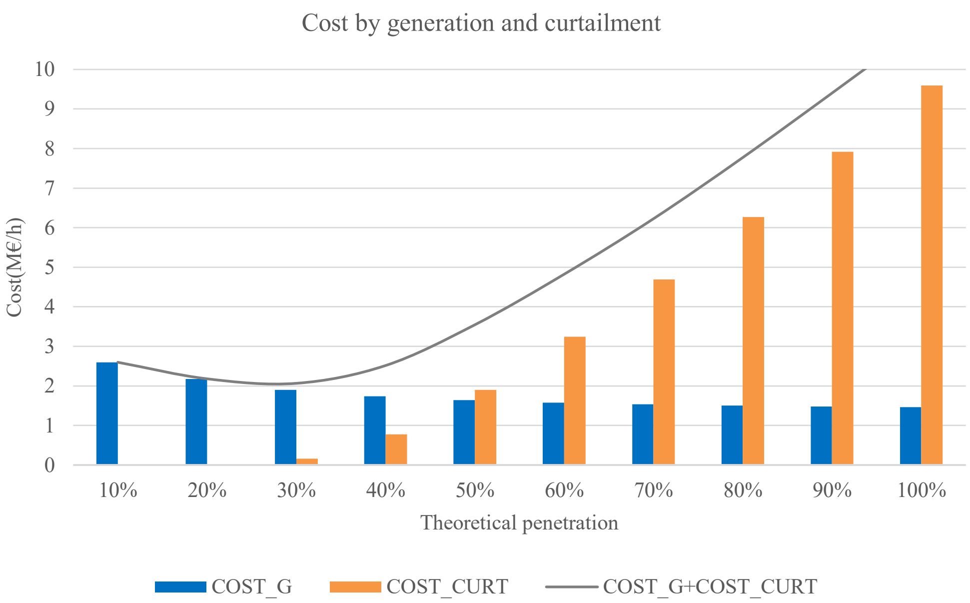

Figure 5.9 Cost distribution by generation and curtailment

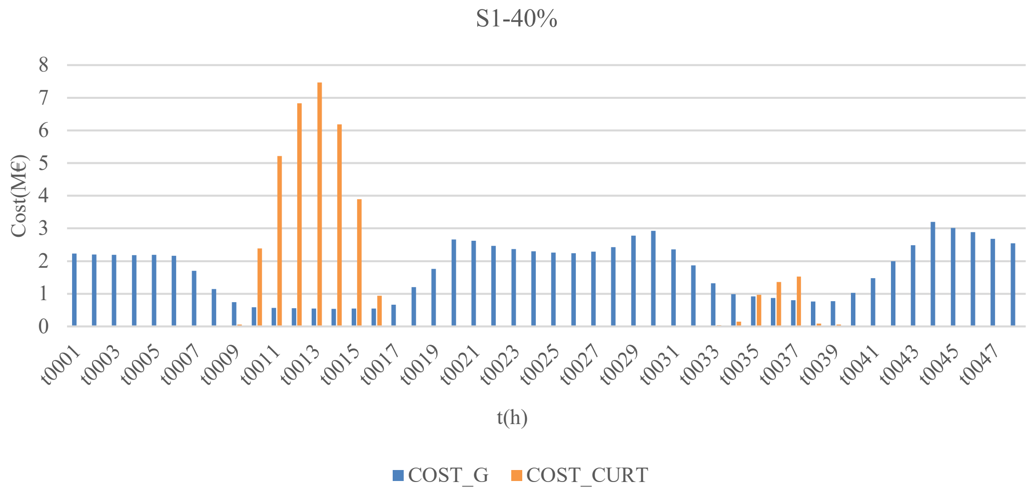


Figure 5.10 Hourly generation costs and curtailment costs of S1

Figure 5.9 shows how generation costs and curtailment costs change with varying theoretical penetration. With increasing penetration, the costs of generation are monotonically decreasing as the curtailment costs keep increasing. While solar has almost zero marginal cost, an increased amount of solar generation in the market will cut down the generation costs of the system. From 0-30% in the figure, the curtailment costs are nearly zero or keep in a low level. Starting from 30%, the numbers increase rapidly. However, we could observe the rate of descent is not as fast as the increase rate, representing the sum of these two costs first decline then climb up. If we only consider generation costs and curtailment costs in the system, we could obtain an optimal point of which the theoretical penetration is around 30%.
Figure 5.10 shows how these costs change every hour. Generation costs are very low during solar generation time and the changes during other hours are in line with the laws of market supply and demand. During the noon of the first day, the curtailment costs are very high. According to the graph, solar generation is very variable as it can generate a large amount of energy in a few hours.

## 5.2 Wind (Scenario 2)

### 5.2.1 Market value and value factor

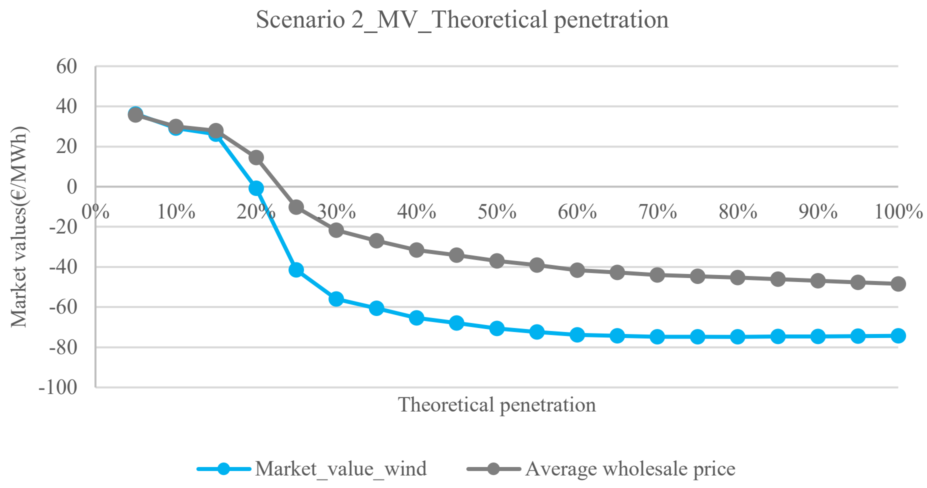


Figure 5.11 Market value/average wholesale price curve with increasing theoretical penetration levels

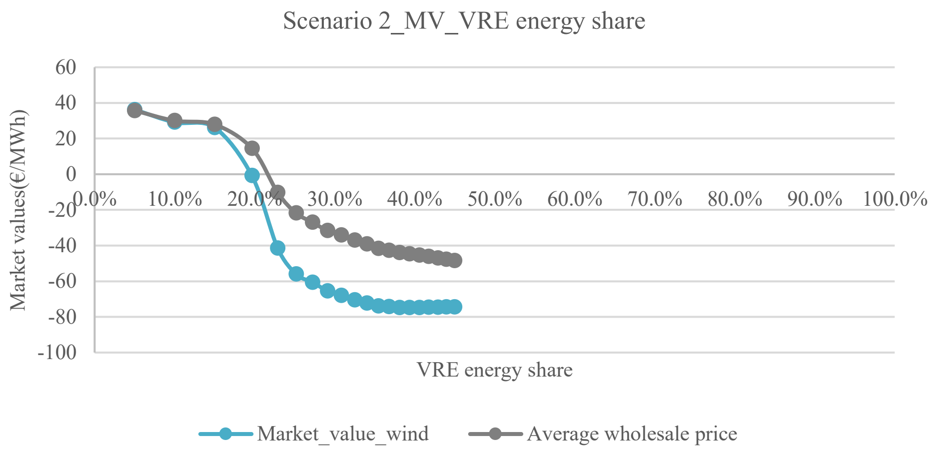


Figure 5.12 Market value/average wholesale price curve with increasing VRE market shares

Figure 5.11 shows how the market values of wind change with increasing theoretical penetration levels. The results show a similar trend with scenario one. Starting from 35 €/MWh, the wind values decreased with increasing penetration, reaching zero at around 20%. Both market value of wind curve and average wholesale price curve decline with higher wind penetration, implying decreased revenues for electricity suppliers in the market. Starting from 15%, it is apparent that wind plants receive fewer revenues per unit of generation than other power plants. Therefore, wind technology has become less valuable for investors.

Likewise, figure 5.12 with energy share as x-axis depicts steeper declined curves with an upper bound of 45%. In scenario 2, designed 100% penetration installed capacity only reach 45% energy share in total. The tail of the market value curve is flat, meaning installing more wind capacity at a high penetration level is not efficient at all.

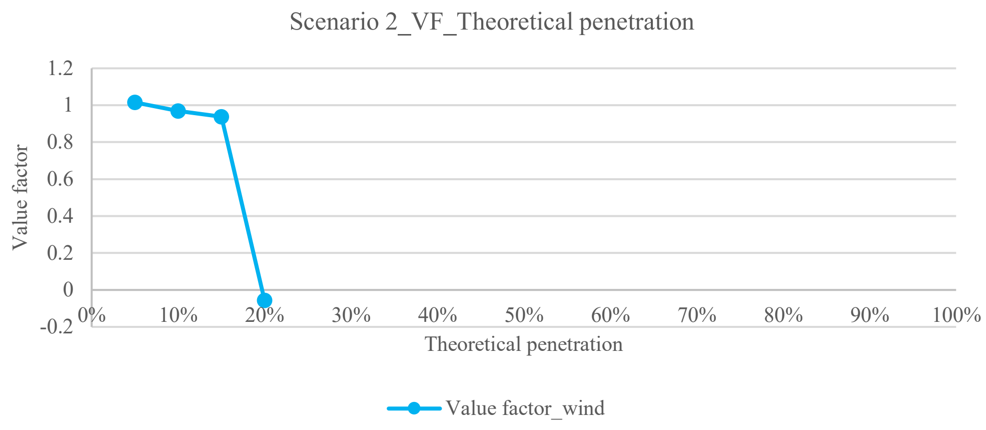


Figure 5.13 Value factor of wind with increasing VRE theoretical penetration

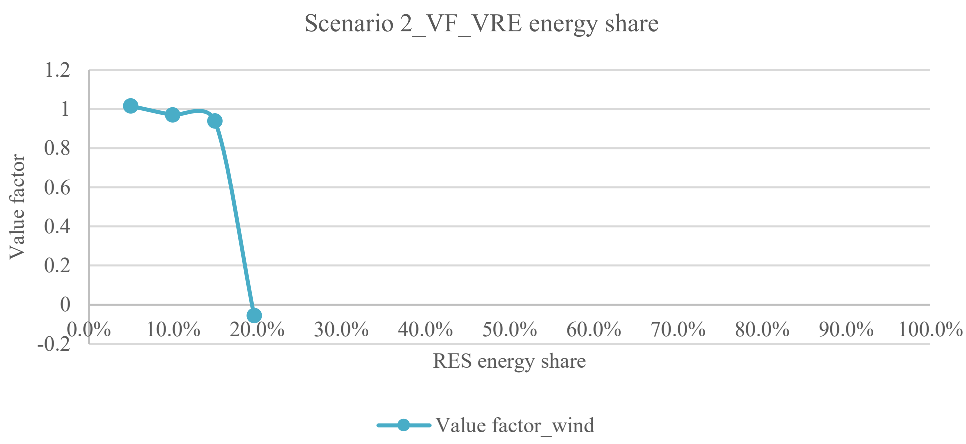


Figure 5.14 Value factor of wind with increasing VRE energy share

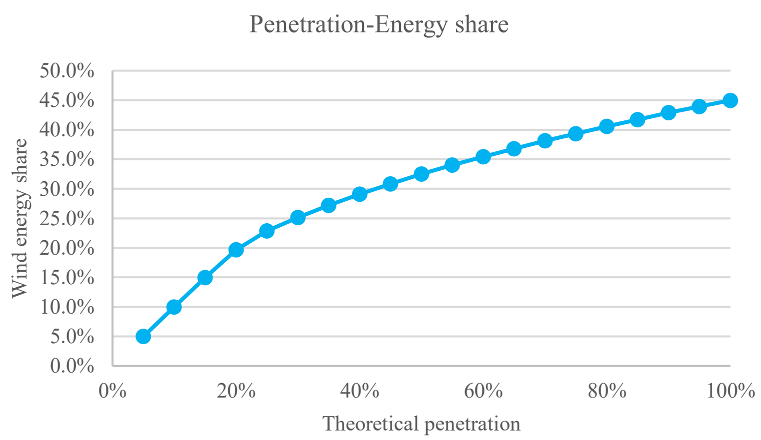


Figure 5.15 Energy share-Theoretical penetration

Looking at figure 5.13, the value factor of wind decreases with higher penetration levels. We could observe that the value factor of wind technology is above one at 5%. As mentioned, when the value factor is above one the technology tends to generate when demand is high and positively correlated to the demand. The curve is also linear during the range 0-15% and reaches 0.94 at 15%. Then it goes down sharply and reaches even below 0 at 20%. Likewise, figure 5.14 shows a similar downward trend of value factor with wind energy share.

Figure 5.15 illustrates the relationship between wind energy share and theoretical penetration. During 0-15%, the curve shows a proportional function, implying that wind energy share is equal to theoretical penetration during this range. Then the slope decreases, both lines A large amount of energy generated by wind is curtailed to ensure the balance of the system. In other words, the grid system is not flexible enough to integrate more wind generation.

## 5.2.2 Generation profiles and price curve

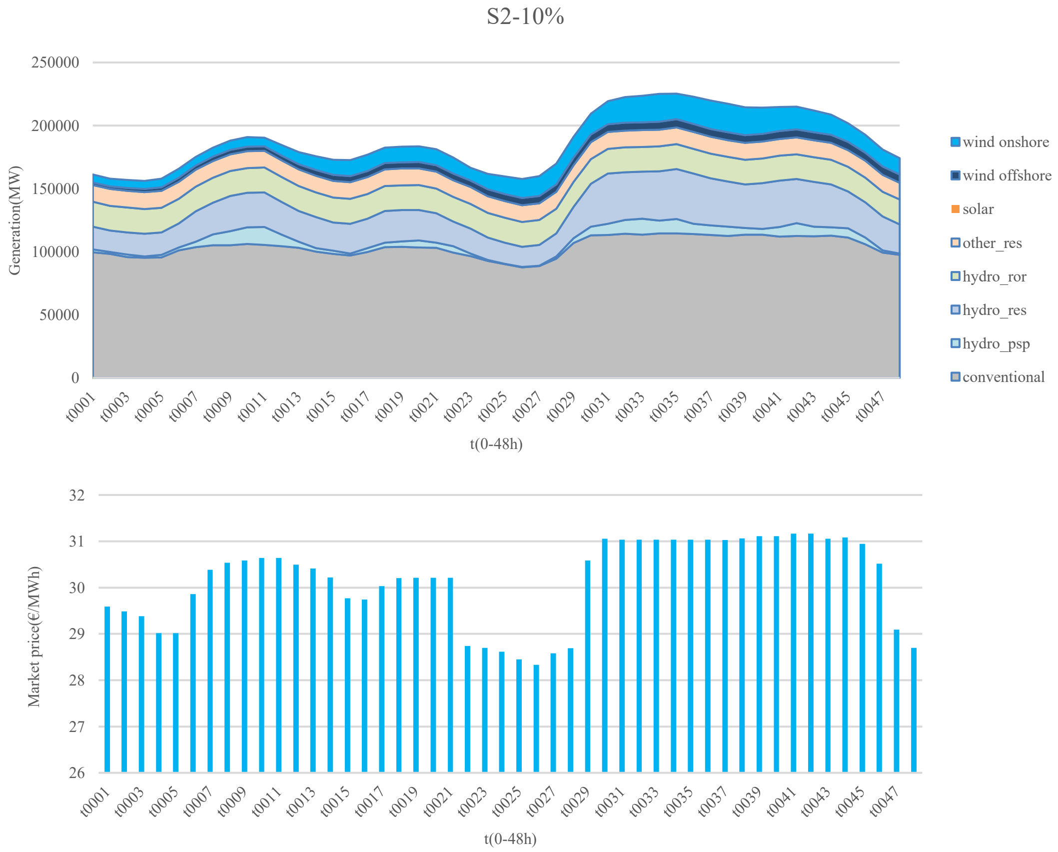


Figure 5.16 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 2 with theoretical wind penetration of 10%. The blue part on the top is electricity generation by wind.

Figure 5.16 displays the generation profiles and average wholesale market price of scenario 2 at 10% penetration level. Compared to solar scenario, we could observe that wind generation is distributed to all the hours. At 10% penetration which not so high, the conventional power generation is not fluctuating and keeps stable with time. Hence, when we look at the price figure, we could observe that the lower prices happen during the low demand hours with a lowest price of 28.5 €/MWh. For this case, it seems the demand variability is the main reason for price changes instead of VRE variability.

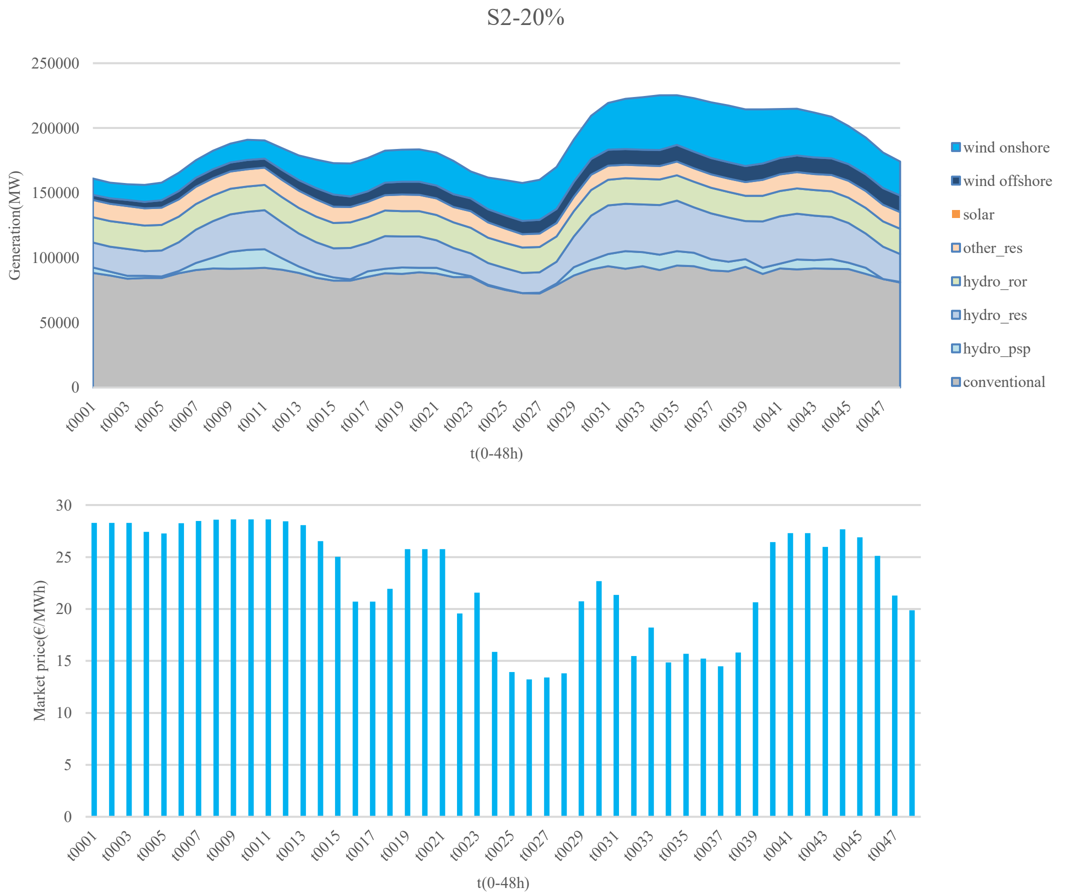


Figure 5.17 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 2 with theoretical wind penetration of 20%. The blue part on the top is electricity generation by wind.

With higher wind penetration which is 20%, figure 5.17 depicts how generation profiles and wholesale market electricity price vary with time at 20% penetration level. From generation profiles, it can be seen that the wind power of the second day is stronger than the first day especially during t0031-t0043. Correspondingly, when we analyze the price figure below the generation profiles, we found two low price periods which are t0024-t0029 and t0031-t0039 respectively. For the first period which is also the low demand period, the demand variability plays a more significant role in influencing the prices. For the second period with a high demand curve, strong wind power plays the main role in lowering the price.

Compared to the 10% case, we can also find the price during the analyzing time decreased with a maximum price of around 28 €/MWh. As wind generation has very low marginal cost, the participation of wind generation in the electricity market will decrease the market price(merit-order effect). Moreover, the lowest price is 46% of the highest one. Therefore, the price difference in wind scenario is smaller than solar scenario.

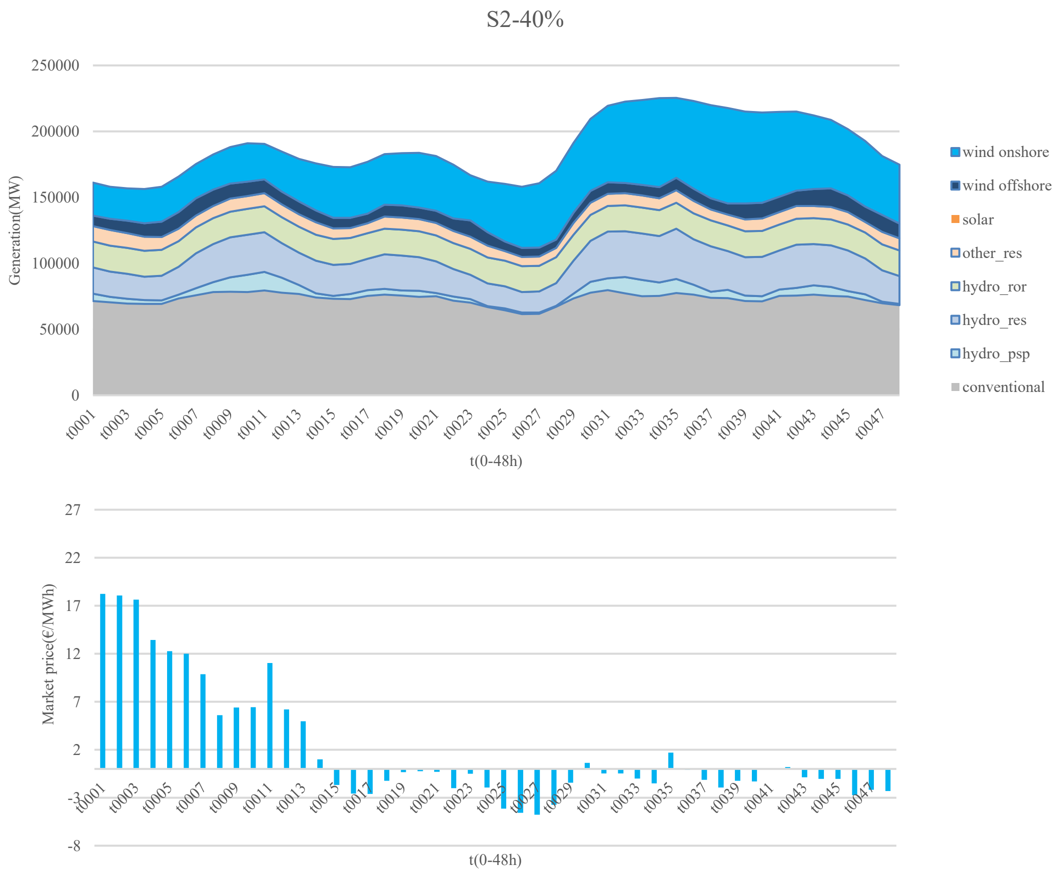


Figure 5.18 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 2 with theoretical wind penetration of 40%. The blue part on the top is electricity generation by wind.

Figure 5.18 shows the wind scenario at 40%. With a larger wind generation, the price gets lower and even reach negative during some hours. We could observe that the negative prices occurred during strong wind hours. It represents that the wind generation curtailment contributes to the locational negative prices. In this case, the lowest price is around -5 €/MWh which is much less than solar case.

To conclude from the generation profile we could observe that wind generation profiles is more stable than solar. In 10% energy share, the price fluctuates with the demand curve. When demand is lower, the price is also low, as we call valley time price. During the peak time, the price is higher, keeping around 31 €/MWh. In 20%, the demand variability hasn't been the main reason for price fluctuations anymore. From t0031-t0045, the wind generates more and we could see lower market prices correspondingly. It is more apparent in 30% penetration level. With strong wind generation from t0015, the market price drops sharply to lower than 5 €/MWh. During some hours, the price even becomes negative.

Compared to solar, the differences also present the characteristics of these two renewable technologies. While solar generation is concentrated during sunny hours, wind generation is more distributed.

## 5.2.3 Generation costs and curtailment costs

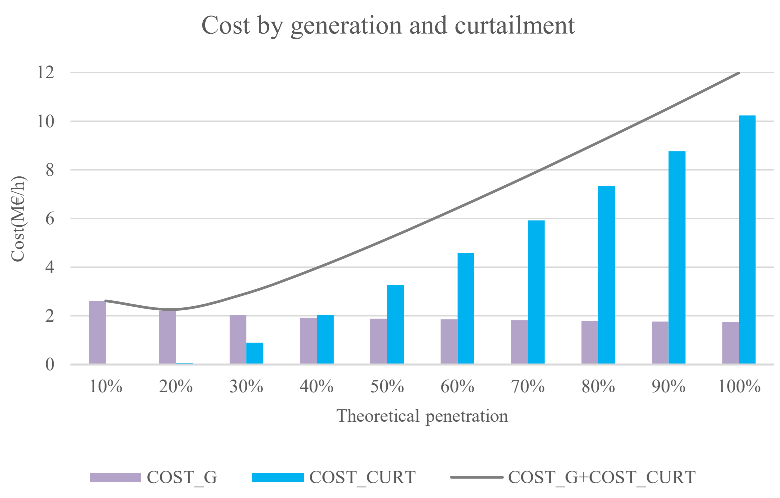


Figure 5.19 Cost distribution by generation and curtailment

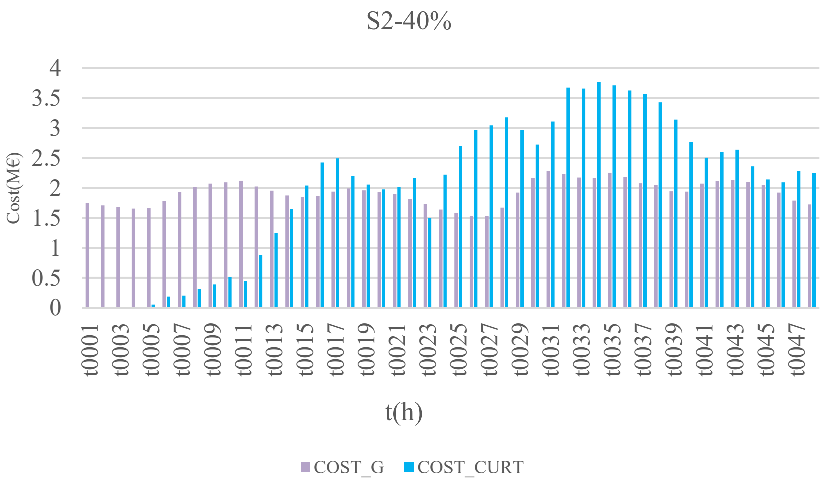


Figure 5.20 Hourly generation costs and curtailment costs of S2

Figure 5.19 shows how generation costs and curtailment costs vary with theoretical penetration. We see a similar trend of sum up value in the figure as solar but with a minimum point at around 20%. When the penetration is less than 30%, it is negligible for curtailment costs compared to generation costs. Then they are growing fast with penetration and even beyond generation costs. Therefore, starting from a penetration level, the system costs would increase due to the high curtailment costs, implying that the ability of the system to integrate more VRE into the grid needs to be improved. Accordingly, we draw the figure of costs with a time of theoretical penetration in 40%(30% energy share), as shown in figure 5.20. During most hours, wind generations need to be curtailed.

The results of wind and solar show a similar trend but still exists some differences.

However, the variable renewable energy generation is highly dependent on the weather conditions and locations. Since the analyzing time in this report does not cover the whole year, it is not proper to draw any conclusion by quantifying the results. But we could observe some general features of solar and wind through the results.

# 5.3 Solar and wind (Scenario3)

## 5.3.1 Market value and value factor

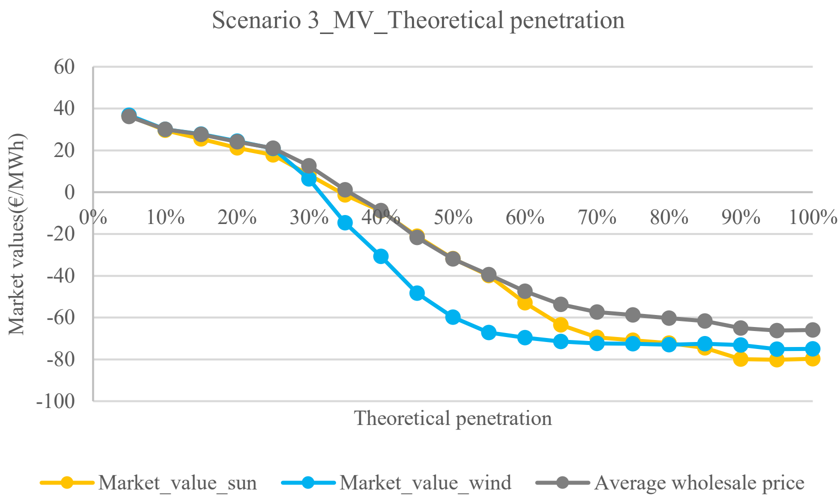


Figure 5.21 Market value/average wholesale price curve with increasing theoretical penetration levels

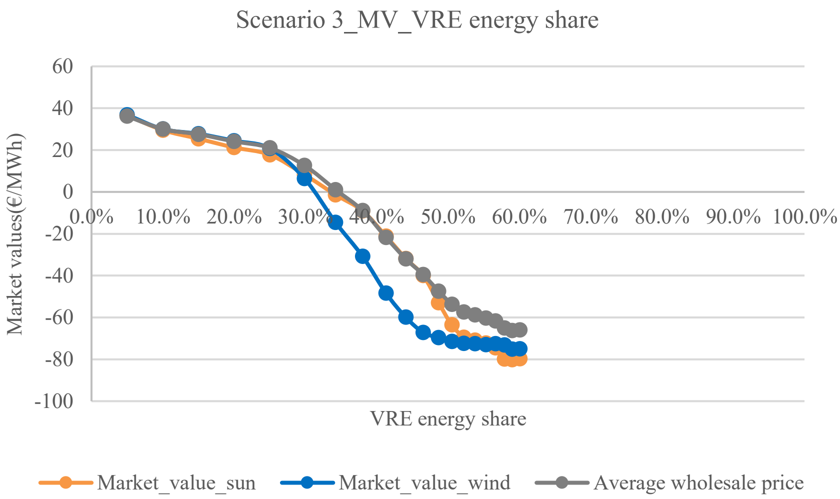


Figure 5.22 Market value/average wholesale price curve with increasing VRE market shares

In scenario 3, both wind and PV installed capacity account for 50% of the current total demand in Germany. Figure 5.21 illustrates how wholesale price and market value of wind and solar varying with RES penetration. With a higher penetration level, the market value of both wind and PV decrease, presenting a similar trend as scenario 1 and scenario 2. However, compared to scenario 1 and scenario 2, we could find some differences. Firstly, the curves go down smoother than S1 and S2 especially for solar as the solar curve almost overlaps with the wholesale price curve. Besides, when the market values of solar and wind reach zero, the corresponding penetration is higher. For S1, the market value of solar reaches 0 between 25% to 30% and for S2 wind market value is close to zero in 20% penetration. In S3, both wind and solar market values reach 0 between 30%-35% penetration. Looking at figure 5.18, the upper boundary is 60% VRE energy share, which is 17% more than S1(47%) and 33% more than S2(45%). It implies that technology diversity could help the grid system to integrate more VRE energy generation.

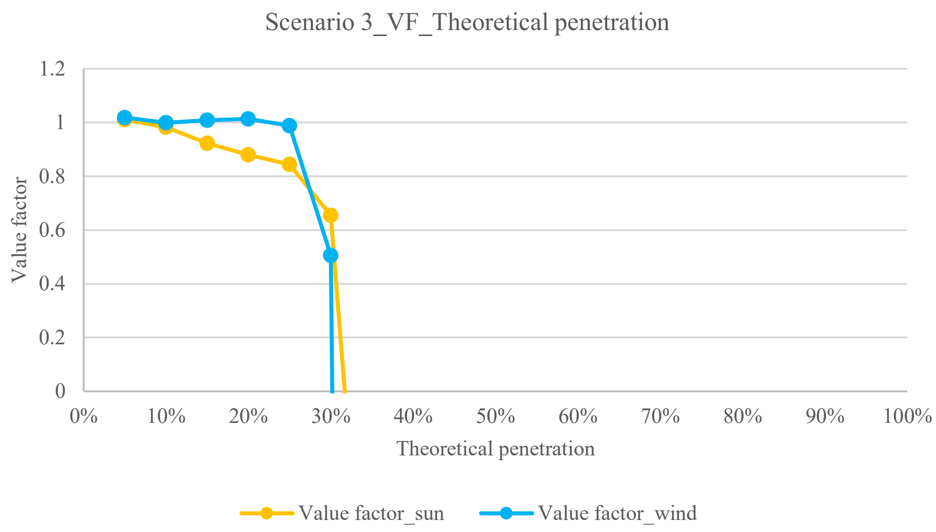


Figure 5.23 Value factor of solar and wind with increasing VRE theoretical penetration

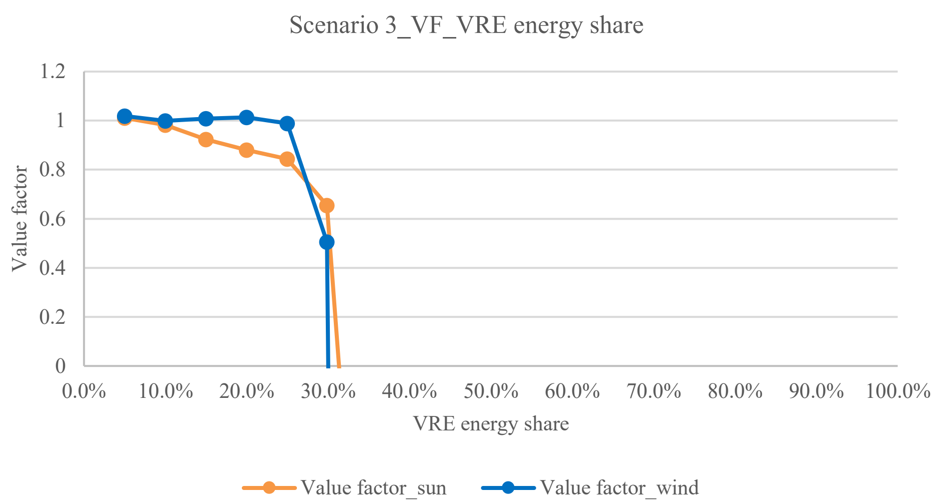


Figure 5.24 Value factor of solar with increasing VRE energy share

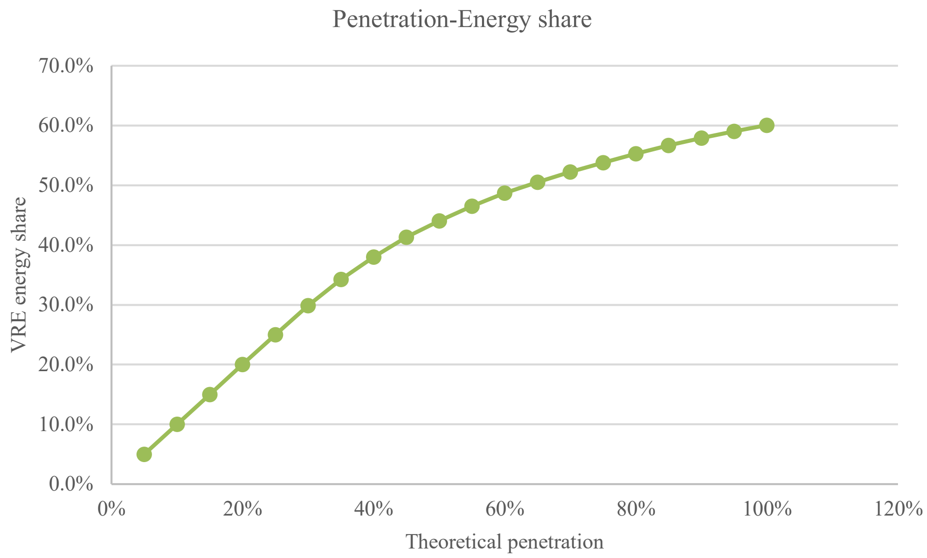


Figure 5.25 Energy share-Theoretical penetration

Figure 5.23 and 5.24 shows the value factor of scenario 3. These two figures look almost the same because during low penetration level, the theoretical penetration is equal to actual energy share as few VRE energy generation is curtailed. Comparing the values to S1 and S2, the VF of both wind and solar keep high during 0-25%, with solar VF 0.84 at 25% and wind VF 0.99 at 25%. Then the curves start to collapse at around 30%. During the positive parts, if we compare the VF of wind and solar to S1 and S2 at the same penetration level, we could find the VF of both wind and solar in S3 is higher. This indicates that wind and solar penetration could benefit each other in this system. Similar conclusions are drawn by Eising (2020), Mills (2015), wind power could help to stabilize the market value of VRE technologies.

## 5.3.2 Generation profiles and price curve

In this section, 3 cases were chosen to present the generation profiles and price curve for scenario 3 at 10%, 20% and 40% theoretical penetration levels.

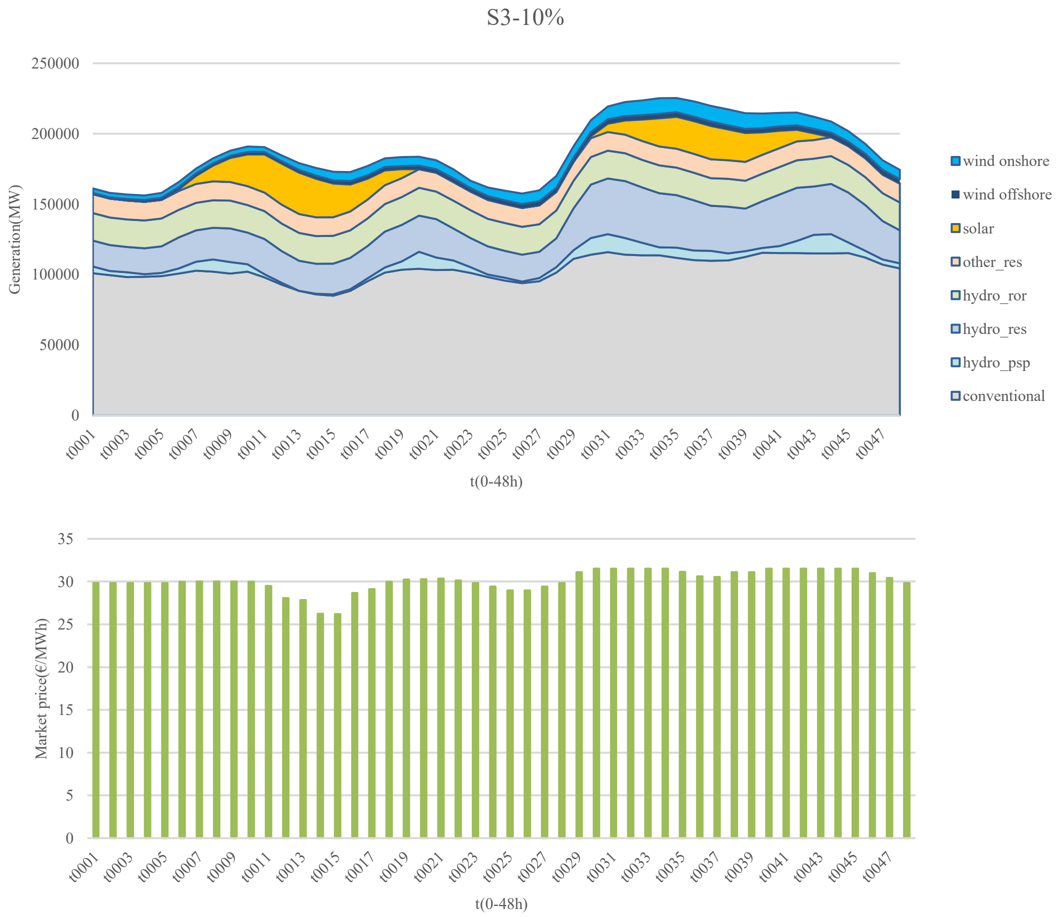


Figure 5.26 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 3 with theoretical wind penetration of 10%.

Figure 5.26 depicts the generation profiles and how price change with time for scenario 3 at 10% penetration level. As can be seen, the high demand period is t0007-t0019, t0031-t0043. Solar also generated during these hours. Therefore, to some extent, solar generation during these periods tend to supply energy when demand is high. According to the figure, the price is keeping around 30 €/MWh. The lowest price happens in t0014 which is around 26 €/MWh. The difference between the highest price and the lowest price is only 4 €/MWh which is smaller than the difference in scenario 1 and scenario 2. It seems that solar generation plays a more important role in influencing the price. Therefore with moderate VRE generation, the price is more stable than scenario 1 and scenario 2 due to a positive correlation effect of PV generation.

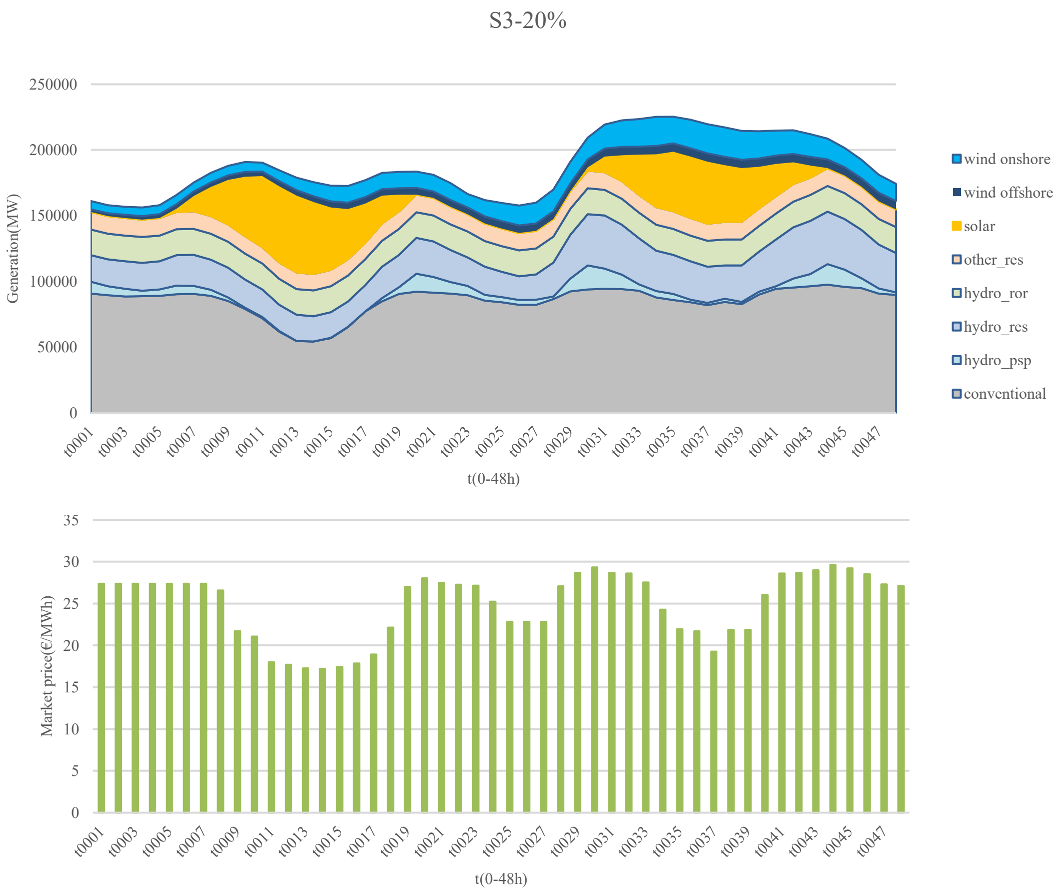


Figure 5.27 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 3 with theoretical wind penetration of 20%.

As displayed in figure 5.27, it shows the generation profiles and price curve for scenario 3 at 20% penetration level. From generation graph we can find that solar generation is more concentrated during t0007-t0019, t0031-t0043. Correspondingly, we could observe a price drop during these periods. In another period t0024-t0029 when the price is also low, the demand variability still impacts the price. During the night hours, the price is smaller than 30 €/MWh, representing the connection of wind power also lower the price. The lowest price is 56% of the highest price, showing the peak-valley price difference is smaller than it in S1 and S2.

Figure 5.28 displays the case at 40%  for scenario three. Both wind and solar generation increase, but we could find that solar generation is more focused on several hours. During these hours, the price drop is larger and reaches negative. For other hours, the price decrease but keep stable and positive. The difference between the highest price and the lowest price is 44 €/MWh. Compared to scenario 1 at 40%, the lowest price in this scenario is higher, representing that the participation of wind could help mitigate price fluctuation while with the same VRE penetration. Compared to scenario 2 with only 13 in positive prices, there are 30 hours that price is positive in scenario 3.

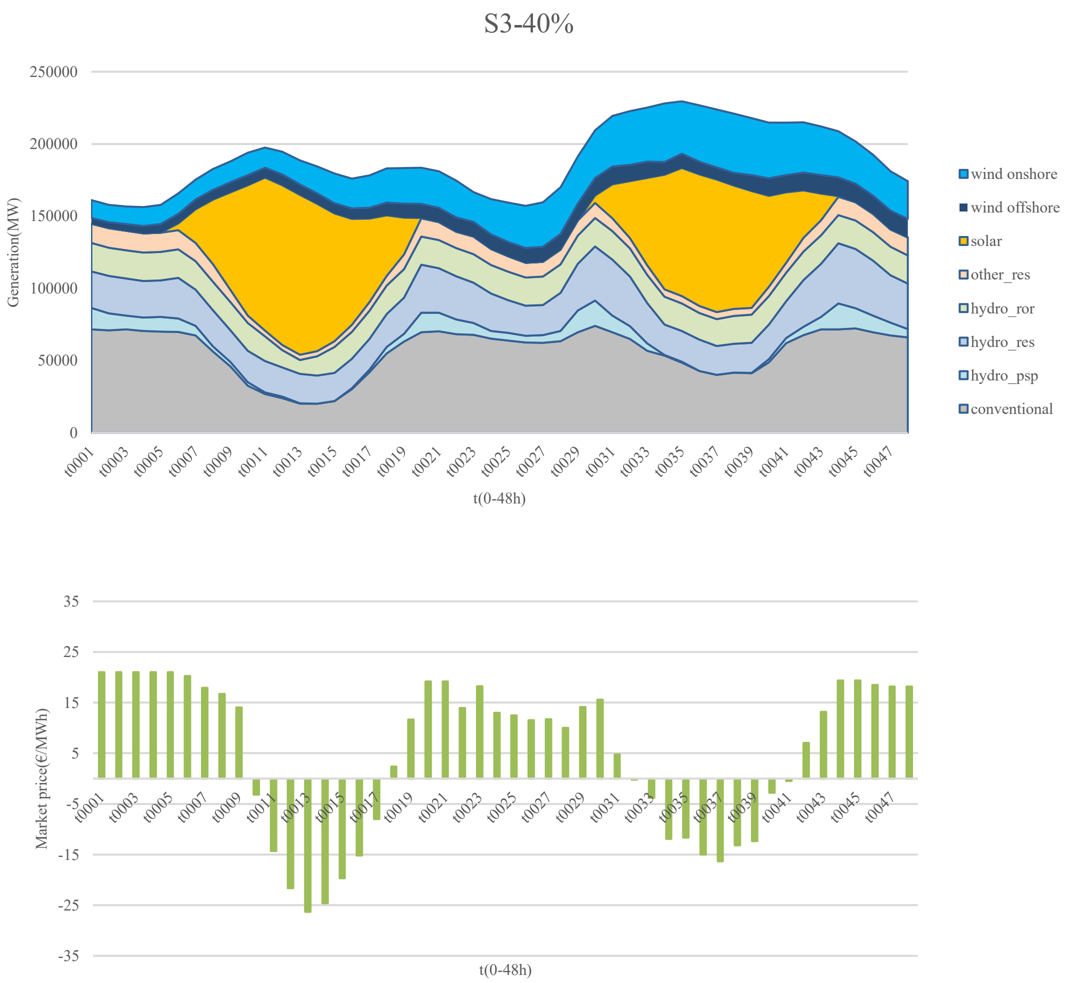


Figure 5.28 Generation profiles with time series sorted by plant type and hourly wholesale market average price in scenario 3 with theoretical wind penetration of 40%.

To conclude, the results in this section confirm the cannibalization effect and merit-order effect. As explained previously, the cannibalization effect means the revenues per MWh for VRE generators decline as penetration levels increase.

With a higher penetration level, the solar generators tend to receive fewer revenues since they tend to generate during sunny hours. During these hours, solar generation becomes the main factor that impacts prices. Hence, the cannibalization effect of solar is larger than wind.

Moreover, due to merit-order effect, the penetration of VRE will decrease the wholesale market electricity price. The negative price could occur during some hours with high VRE penetration. This negative price is capped by curtailment costs. Therefore, these effects lead to price fluctuations at high penetration levels.

## 5.3.3 Generation costs and curtailment costs

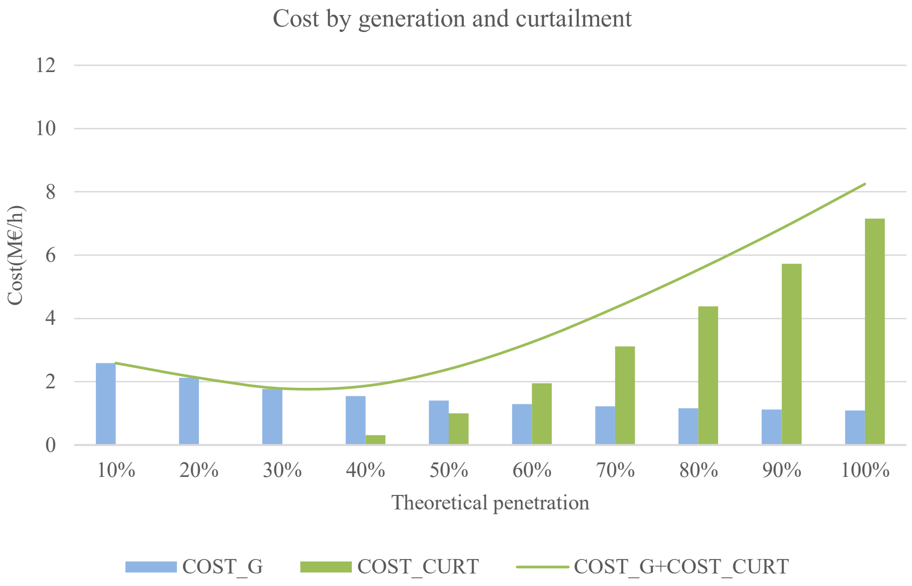


Figure 5.23 Cost distribution by generation and curtailment

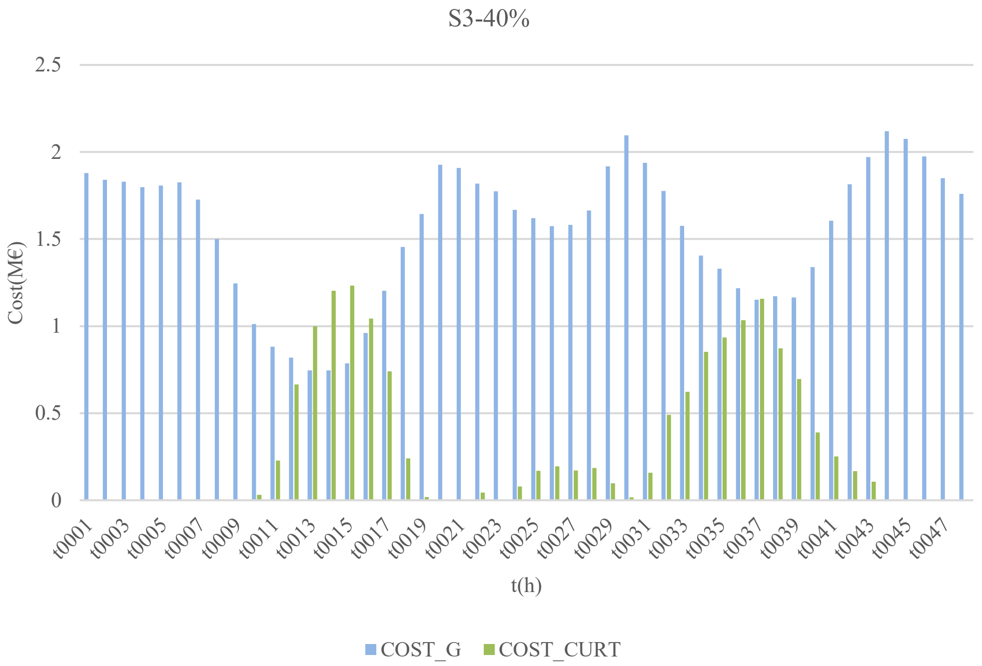


Figure 5.24 Hourly generation costs and curtailment costs of S3

Figure 5.23 plots the generation costs and curtailment costs of scenario 3 with the same pattern as S1 and S2. Compared to S1 and S2, the lowest point of the curve is moving towards the right at around 35% penetration. If we only consider certain these costs in the system, we could say before 35% VRE theoretical penetration, with more installed capacity of VRE technology it reduces the costs of the system. In 40%, only in 3 hours the curtailment costs is over generation costs as depicted in figure 5.24. However, the corresponding figure in S1 shows10 hours when curtailment costs is higher with large differences, while in S2 there are 32 hours but with more minor differences than S2.

## 5.4 Zonal and nodal

Simultaneously, we also did an analysis through the zonal model. As mentioned, the zonal model will be solved based on the assumption that there is no congestion in each zone. Then the redispatch actions will be implemented to reduce the overloads line. However, the zonal results show weak stability as the results vary with every simulation.

### 5.4.1 Solar(zonal)

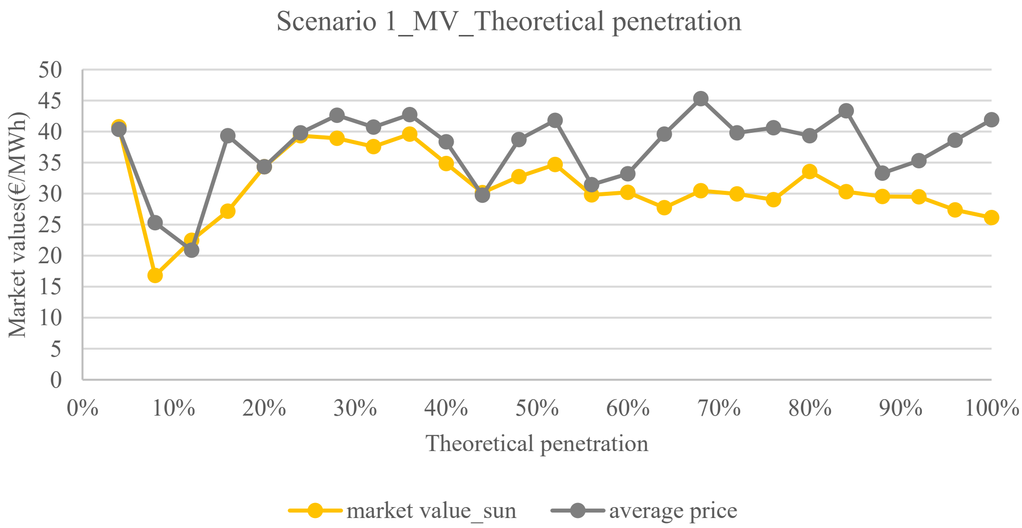


Figure 5.25 Market value/average wholesale price curve with increasing theoretical penetration levels

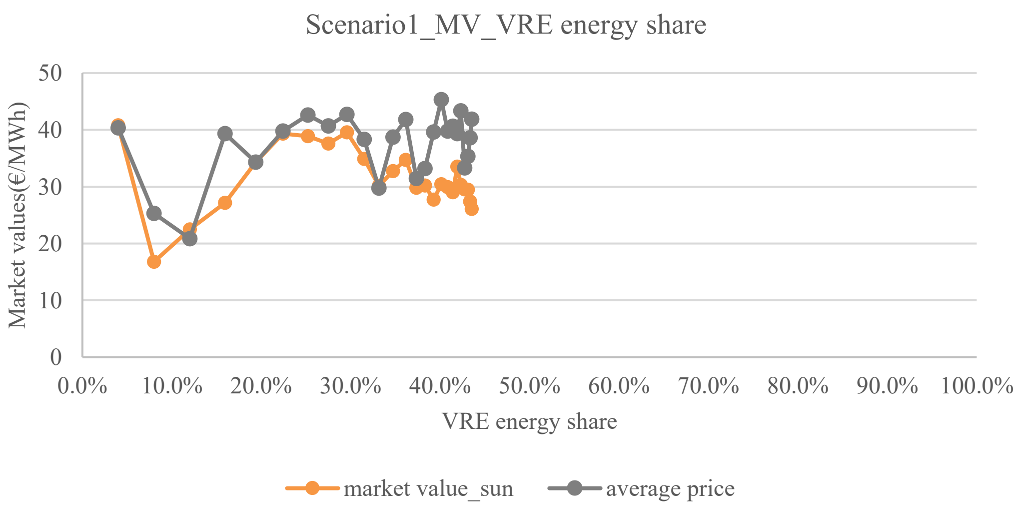


Figure 5.26 Market value/average wholesale price curve with increasing VRE market shares

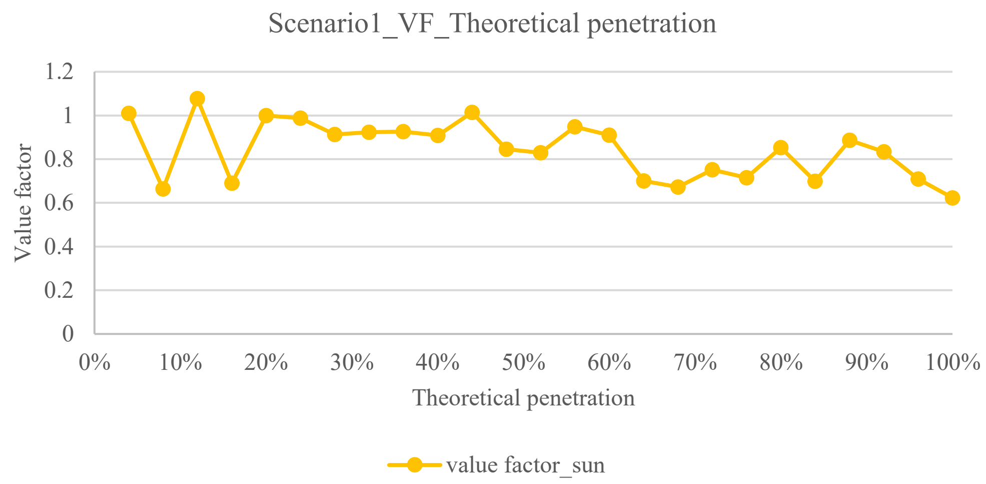


Figure 5.27 Value factor of solar with increasing VRE theoretical penetration

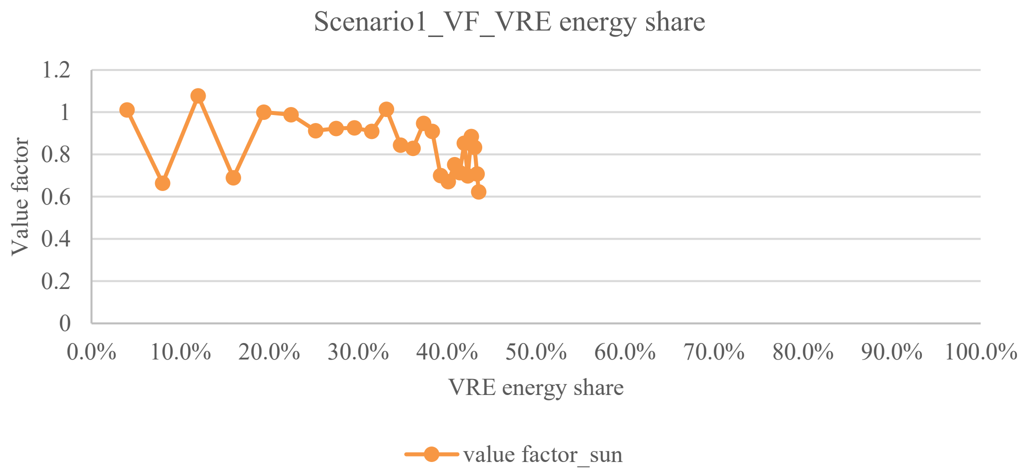


Figure 5.28 Value factor of solar with increasing VRE energy share

Figure 5.25 shows the market value and average market price varying with time. Both curves in the figure are fluctuated and could describe in two parts. During the range 0-20%, the market value first decrease sharply and then increase until 24%. From 20% to the end, the curve is generally going down but still with slight fluctuations. Figure 5.26 shows a similar pattern but with an upper bound of 45%. The reason for that is already explained in the previous parts. However, we could find that the market value never reaches negative in the zonal model. The reason for that could be the congestion and limitation of transmission costs are not included in the system. Instead, these costs could be transformed into redispatch costs.

Figure 5.27 displays the value factor of solar. Generally speaking, it declines with increasing penetration, but the fluctuations are too large to be ignored. Likewise, figure 5.28 also depicts a similar trend but was limited to 45%.

## 5.4.2 Wind(zonal)

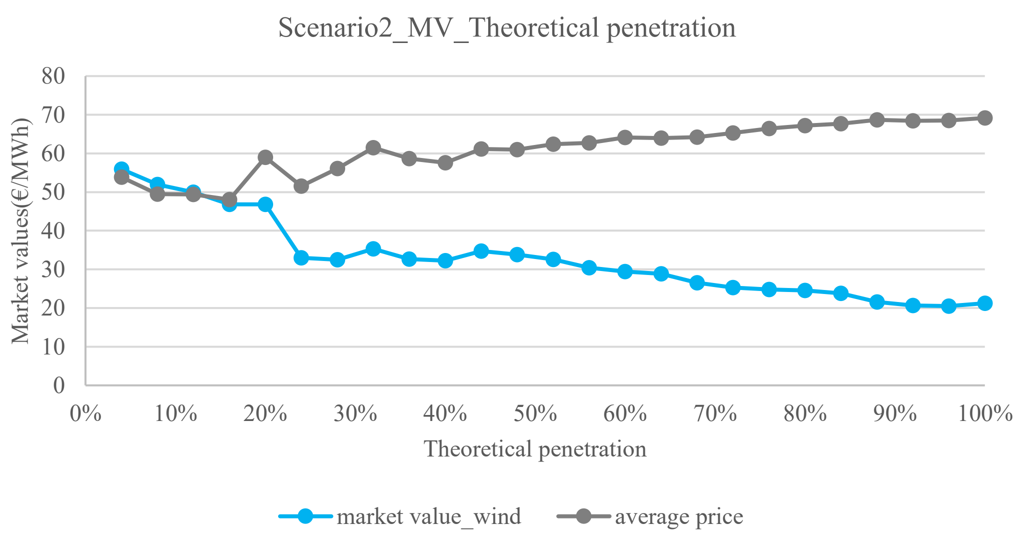


Figure 5.29 Market value/average wholesale price curve with increasing theoretical penetration levels

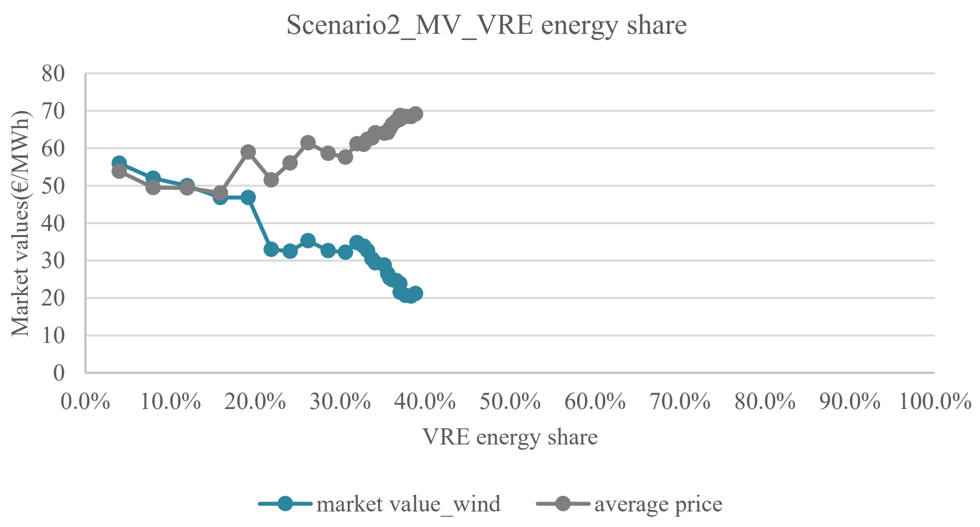


Figure 5.30 Market value/average wholesale price curve with increasing VRE market shares

Figure 5.29 shows how market value of wind and average wholesale price vary with increasing penetrations. The wind market value keep decreasing during the analyzing range. Starting from 56 €/MWh, it decreases and reaches 20 €/MWh in the end. At 20%, there is a significant drop. Meanwhile, during 0-20%, the average wholesale market is decreasing and then start to increase, reaching 70 €/MWh at 100% theoretical penetration.

Figure 5.20 also shows a similar trend with a limited energy share of 38.9%, which is smaller than solar scenario.

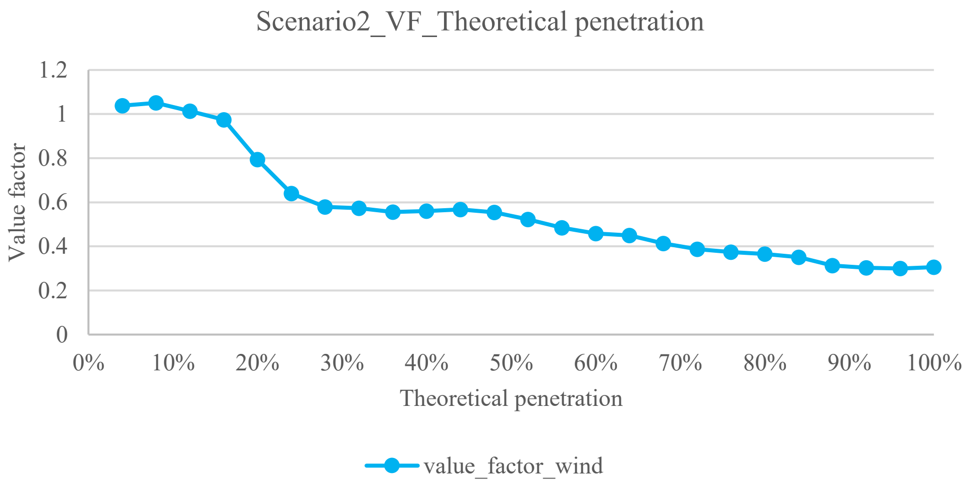


Figure 5.31 Value factor of wind with increasing VRE theoretical penetration

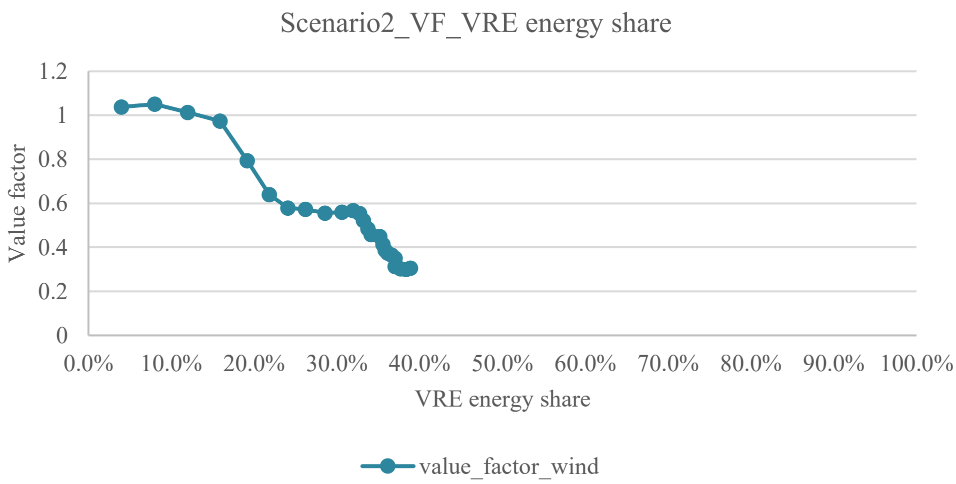


Figure 5.32 Value factor of wind with increasing VRE energy share

Figure 5.31 illustrates the value factor of wind varying with theoretical penetration. The curve is going down during the whole range. From 0-12%, the value factor is beyond one and then from 16% it decreases fast, reaching around 0.6 at 30%. At 100%, the value factor of wind is 0.3, around 28.5% of the highest one.

Similarly, as displayed in figure 5.32, the wind value factor with VRE energy share decreases faster than that in 5.31. The closer to the tail of the curve, the dots are more intensive, implying that at high penetration level the utilization rate of wind generators is low. At a high penetration level, with more installed capacity, more VRE energy generation will be curtailed.

For wind scenario, the curve shows a similar trend with nodal results. It also drops sharply between 20% to 30% and keep decreasing during the range. However, the value factor never reach negative here. From the results, it also shows that there still exists overloaded lines. On the contrary, the nodal model was solved without any overloaded transmission lines. Therefore, some costs are not captured in zonal model.

### 5.4.3 Solar and wind(zonal)

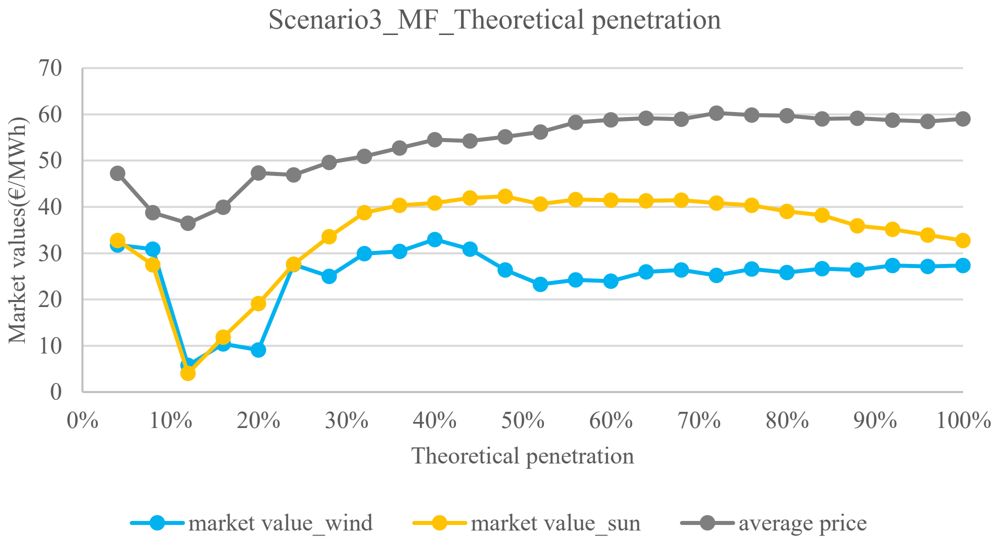


Figure 5.33 Market value/average wholesale price curve with increasing theoretical penetration levels

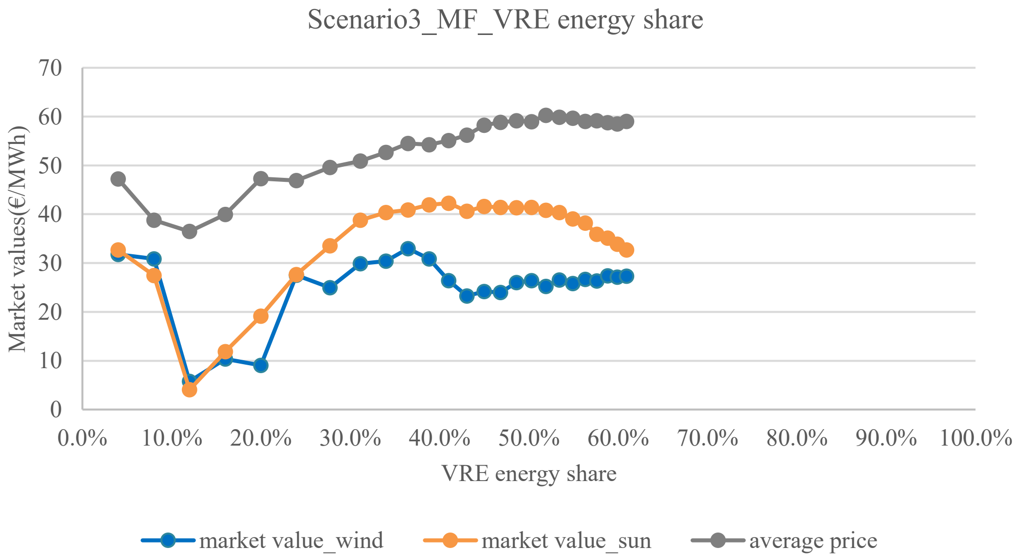


Figure 5.34 Market value/average wholesale price curve with increasing VRE market shares

Figure 5.33 and figure 5.34 shows how wind market value, solar market value and average wholesale price change with varying penetration levels.
From both figures we can observe the VRE market values decrease first and then increase. From 40% of theoretical penetration, the VRE market values keep relatively stable.
Besides, the VRE energy share reaches 61% of 100% designed penetration level, representing that combination of technologies could help increase the total VRE energy share in the system. This conclusion is similar to the nodal ones.

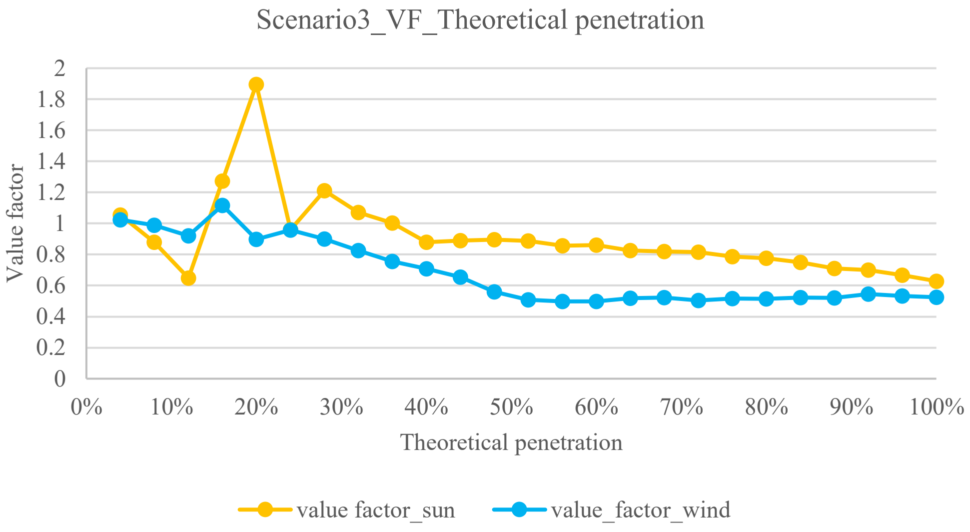


Figure 5.35 Value factor of solar and wind with increasing VRE theoretical penetration

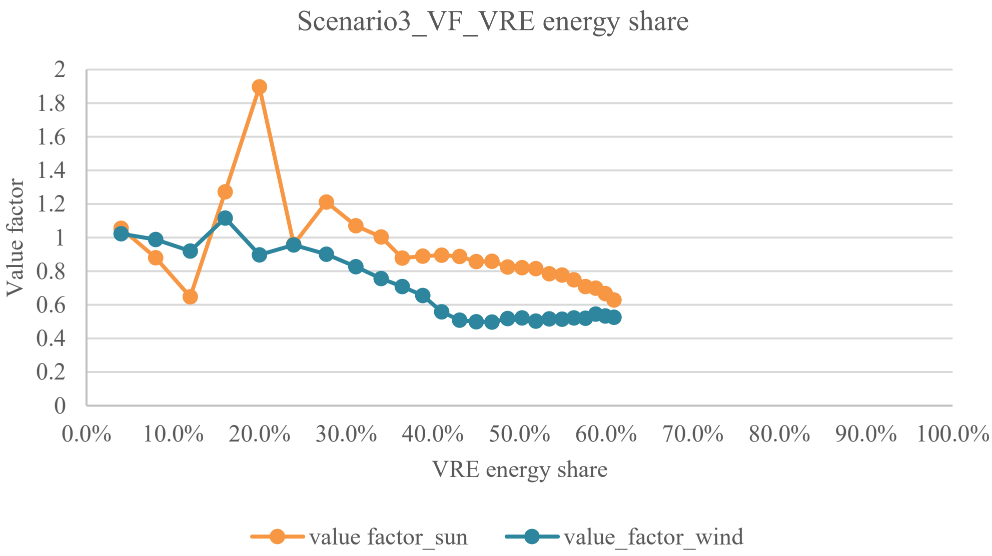


Figure 5.36 Value factor of solar and wind with increasing VRE energy share

Figure 5.35 shows the value factor of wind and solar. As can be seen, during 0-30% theoretical penetration, the solar value factor is highly volatile while the wind value factor curve is more smooth. From 30% to the end, both solar and wind curves are dropping, reaching 0.63 and 0.53 respectively. Likewise, figure 5.36 displays a similar curve with an energy share limitation of around 61%.

To conclude, we can observe that the solar performs a great fluctuation in zonal results. While the wind scenario is more stable, the penetration of solar also makes the wind market value fluctuate. Moreover, the market values of VRE in zonal results is always positive. One of the possible reasons could be that the redispatch costs are averaged in the zone for all the nodes which couldn't reflect the price signals.
All of these points could be further analyzed in the future.

## 5.5 Discussion

As we see, the market value of both PV and wind decreases with increasing penetration levels. This result is consistent with most findings in other studies. At moderate penetration levels, the value factor for wind and solar is over 1, implying a positive correlation between the demand curve, which is the so-called correlation effect. In Europe, there is a positive correlation effect for solar and a seasonal correlation for wind. When the generation profile is positively correlated to the demand curve, the technology is valuable because generally, it generates when demand is high. This happens during the low penetration range for both wind and PV during analyzed hours. During this range, the renewable generators receive more unit revenues than other plants and accordingly, the total system cost is also decreasing.
However, with increased capacity, the results confirm that both wind and solar's market value and value factors are decreasing. It represents that VRE technologies become less valuable when increasing their penetration level. Meanwhile, the wholesale market price is also following downwards due to the merit order effect. As we know, the electricity market in Europe is based on marginal prices and plants are ranked according to the price order for each trading period. Renewable energy generation (PV and wind) rank first in the merit-order with almost zero marginal cost. The residual load will be shifted from expensive fleets to cheaper ones thus decreasing the market prices. Therefore, if significant VRE capacity is installed, the price during VRE generating peak hours will be very low and even reach zero or negative. At this moment, the VRE plants would rather pay users to consume the excess generation energy than curtailment as other conventional power plants would rather do the same instead of shutting off or starting the machines which is more costly.
Actually negative prices is happening in Germany more frequently. According to Epex Spot, there has been a rapid rise in negative settlements in Germany's day-ahead market in 2020. From January 1st to June 2nd in 2020, there are 208 hours of negative price. In fact, this phenomenon reflects the lack of flexibility of the system to integrate more VRE generation. We could observe from the generation profiles fig.5.6, that Germany is a thermal power-based system. Therefore, it is expensive for some traditional, old plants to shut down, start up or ramp. Besides, the possible reason could also be transmission congestion or weak interconnections with neighboring countries. Meanwhile, the decline of the wholesale market price will also limit the development of VRE installations in the long run. Due to the uncertainties of VRE, energy supply shortage could also happen with the temporary decrease in VRE power production especially with a large installed VRE capacity.
Because of the variability of wind and solar technology, the system needs to be flexible enough to integrate more VRE generation.

Fig 5.28 also display the pattern of solar generation and wind generation. While the PV generation is more concentrated during sunny hours, the wind generation is more distributed with time. Therefore, in fig 5.23 during 0-25%, we could observe that the

VF of solar decreases faster than the VF of wind. A similar trend is also found in (Hirth et al., 2015)(Eising et al., 2020). However, this is also highly dependent on the characteristics of the system based on the relationship between wind and solar generation profiles and demand patterns.

When comparing S3 to S1 and S2, we surprisingly find that the combination of wind and solar perform better. Not only the value factors of both solar and wind drop less, the grid system could also integrate more VRE energy generation. Some analysis has been done in other studies and similar conclusions were drawn by Eising (2020), Mills (2015). Based on the model analysis, Eising proved that increasing offshore wind generation shares in the total wind portfolio could help to mitigate value factor drops. As explained in previous parts, the technology itself is the endogenous drive to impact on value factors. Therefore, according to the analysis, the combination of wind and solar could be an option to mitigate the value drop. Further studies can also evaluate the mitigation effect by varying the proportion of them based on a specific system.

According to ISE, the wind generation share in Germany 2020 is 27% and PV takes account 10.5%, reaching a high level. However, according to the results, we would find both the market value and value factor of wind and solar will face a collapse at a certain penetration range. The possible reason could be the large curtailment or congestion problems. Therefore, a more flexible grid system is required with a quick response to the variability and uncertainty of the VRE generation. To be mentioned, since the report only considers the effect of variability of VRE, we simulate the day-ahead market without considering the uncertainties of VRE. In reality, the balance costs are also important to be analyzed with increasing VRE penetration. Hence, there are many possible solutions: add more flexible technologies like storage systems and flexible conventional plants; demand-side management; expand interconnections with other countries; expand the capacity of transmission lines; policies etc. There are many studies analyzing these options and how they affect the system. Of course, the impacts are context and system-specific. Hence, it is essential to focus on the same region with uniform conditions.

# 6. Conclusion

In this report, we analyzed the impacts of variable renewable energy resources(wind and solar) on the grid system. The metrics market value and value factor are utilized to evaluate these impacts. As market value of VRE could represent their marginal social benefit to the system as well as the revenues that wind or solar generators could receive from the market, it is meaningful to evaluate the impacts of VRE both from the system point of view and from the insvetors' view. Accordingly, the value factor could also represent the relative value of VRE compared to other dispatchable resources.

Both zonal and nodal models are simulated, but we will summarize the conclusion mainly based on nodal results. The reasons have already been listed in the methodology part. The market values and the value factors of both wind and solar with varying penetration level is obtained through model-based analysis. The POMATO model is deployed in out analysis. The main findings of this analysis are concluded below:

1. Both market values and value factors of VRE technology keep decreasing with increasing penetration level due to its variability, which could also be explained by the merit-order effect and cannibalization effect. With higher penetration, VRE technology becomes less valuable. At a high penetration level, installing more VRE capacity brings more curtailment costs and also other problems due to the transmission constraints. Take an example, negative price hours rise more frequently. Besides, with the current system, increasing the capacity of VRE is not efficient as a large amount of generation is curtailed, which requires a more flexible system that owns a strong capability to integrate more VRE generation.
2. PV generation profile is more variable compared to wind power generation since solar always generate during sunny hours. Accordingly, the value factor of solar declines more rapidly with the same penetration level. The generation profile of scenario 1 shows a large amount of load shifted from conventional power plants in a short time. Thus, for solar technology, the cannibalization effect is larger than wind.
3. The combination of wind and solar technology could reduce the value drop respectively. Technology diversity could bring benefits for the grid system and help to improve the capability of the grid system to integrate more VRE energy generation.
4. Since the nodal pricing scheme take into account the transmission constraints and could reflect a price signal precisely, we analyzed the results based on the nodal model because we aim to catch as many impacts of VRE as we can. It is also helpful for continuous research in the future. Moreover, the zonal results are also simply analyzed with more fluctuations. The reasons behind that could be further analyzed.

The analysis verified the value factor drop of VRE with higher penetration and the benefits of technology combination. The research could be extended in many directions. In the beginning, one of the goals is to evaluate the impact of the energy community on the grid system under the background of high VRE penetration. Before that, we need to figure out what will happen to the grid system with high VRE penetration level and the reasons behind it. Meanwhile, specific merit is required to quantify these impacts from the system point of view. Therefore, the market value and the value factor are adopted in our analysis to evaluate the partial effects of VRE on the grid system. Profile costs due to the variability of VRE are in the scope which accounts for a significant part of total influences. Hence, in further studies, the mitigation measures including energy community implementation, could be evaluated through these merits.

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# Appendix A: model formulation

P: Conventional power plants.
TS: Plants that have a timedependant capacity factor (availability).
ES⊂P : Electricity storages.

HE⊂P: Plants that produce heat.

CHP⊂P: Plants that provide both heat and electricity.
PH⊂P: Power to heat plants.
HS⊂P: Heat Storages.

G: Electricity generation
D: Electricity demand, for plants of type ES and PH.
CURT: Curtailment variable for plant of type TS.
$L_{es}$: Storage level for electricity storages (plant type ES).
H: Heat generation for all plants of type HE.

$L_{hs}$Lhs: Storage level for heat storages (plant type HS).

Generation Constraints:

$$0 \leq G_{p,t} \leq g_p^{max} \qquad \forall p \in \mathcal{P}, t \in \mathcal{T}$$
$$0 \leq CURT_{ts,t} \leq g_p^{max} \cdot \text{availability}_{ts,t} \qquad \forall ts \in \mathcal{TS}, t \in \mathcal{T}$$

$$L_{es,t} = L_{es,t-1} - G_{es,t} + \eta \cdot D_{es,t} + \text{inflow}_{es,t} \qquad \forall es \in \mathcal{ES}, t \in \mathcal{T}$$
$$0 \leq L_{es,t} \leq l_{es}^{max} \qquad \forall es \in \mathcal{ES}, t \in \mathcal{T}$$
$$0 \leq D_{es,t} \leq d_{es}^{max} \qquad \forall es \in \mathcal{ES}, t \in \mathcal{T}$$

$$COST\_G = \sum_{p \in \mathcal{P}, t \in \mathcal{T}} mc_p \cdot G_{p,t}$$
$$COST\_CURT = \sum_{ts \in \mathcal{TS}, t \in \mathcal{T}} \text{curt\_cost} \cdot CURT_{ts,t}$$

Energy Balance:

$$\begin{aligned} INJ_{n,t} = & \sum_{p \in \mathcal{P}_n} G_{p,t} - D_{p,t} + \sum_{ts \in \mathcal{TS}_n} g_{ts}^{max} \cdot \text{availability}_{ts,t} - CURT_{ts,t} \\ & + \sum_{dc \in \mathcal{DC}} \text{incidence}_{dc,n} \cdot F_{dc,t}^{dc} \\ & + \text{net\_export}_{n,t} - \text{demand}_{n,t} \qquad \forall n \in \mathcal{N}, t \in \mathcal{T} \end{aligned}$$

$$\begin{aligned} \sum_{zz \in \mathcal{Z}} EX_{z,zz,t} - EX_{zz,z,t} = & \sum_{p \in \mathcal{P}_z} G_{p,t} - D_{p,t} + \sum_{ts \in \mathcal{TS}_z} g_{ts}^{max} \cdot \text{availability}_{ts,t} - CURT_{ts,t} \\ & + \sum_{n \in \mathcal{N}_z} \text{net\_export}_{n,t} - \text{demand}_{n,t} \qquad \forall z \in \mathcal{Z}, t \in \mathcal{T} \end{aligned}$$

Objective Value:

$$\min \ \text{OBJ} = \sum COST\_G + COST\_H + COST\_CURT$$
$$\text{s.t.}$$
$$\text{Generation Constraints}$$
$$\text{Heat Constraints}$$
$$\text{Transport Constraints}$$
$$\text{Energy Balances}$$

PDTF Formulation:

$$\begin{aligned} F_t^+ - F_t^- &= PTDF \cdot INJ_t && \forall t \in \mathcal{T} \\ 0 \le F_t^+ &\le f^{max} && \forall t \in \mathcal{T} \\ 0 \le F_t^- &\le f^{max} && \forall t \in \mathcal{T} \end{aligned}$$

Angle Formulation

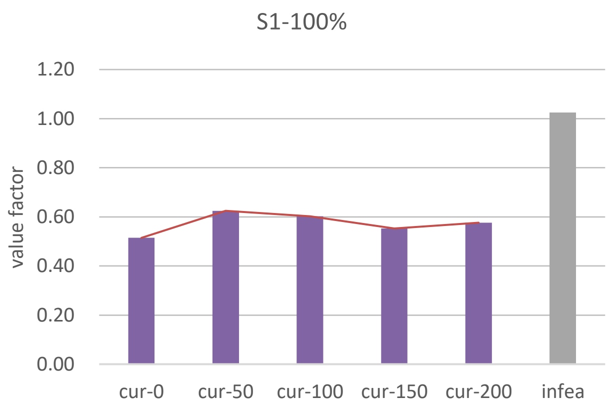
$$\begin{aligned} F_{l,t} &= \frac{1}{x_l} \sum_{n \in \mathcal{T}} A_{n,l} \cdot \Theta_{n,t} && \forall l \in \mathcal{L}, t \in \mathcal{T} \\ INJ_{n,t} &= \sum_{l \in \mathcal{L}} A_{n,l} \cdot F_{l,t} && \forall l \in \mathcal{L}, t \in \mathcal{T} \\ -f_{l,t}^{max} &\le F_{l,t} \le f_{l,t}^{max} && \forall l \in \mathcal{L}, t \in \mathcal{T} \\ \Theta_{slack,t} &= 0 && t \in \mathcal{T} \end{aligned}$$

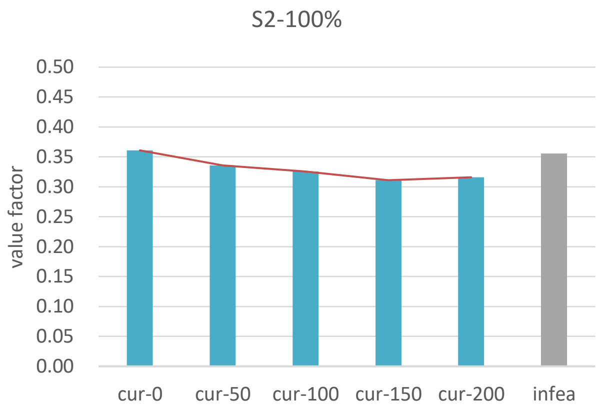
# Appendix B: Data input source

Conventional power plant data is taken from the Open Power System Data Platform (OPSD). Geographic information is used from the ExtremOS project of Forschungsstelle für Energiewirtschaft (FfE) and their FfE Open Data Portal. Wind and PV capacities are distributed using the NUTS3 Potentials from FfE. Future capacities are taken from results of the large scale energy system model AnyMod. NUTS3 availability timeseries for wind and solar are generated using the atlite, package. Offshore availability based on EEZ regions of FfE. The grid data comes from the GridKit project, more specifically PyPSA/pypsa-eur fork, which contains more recent data. Hydro Plants are taken from the JRC Hydro-power plants database and inflows are determined using the atlite hydro capabilities and scaled using annual generation. Load, commercial exchange from ENTSO-E Transparency platform.

# Appendix C: Curtailment and infeasibility analysis

| Scenario | Option | €/MWh | Market value_wind (€/MWh) | Market value_sun (€/MWh) | Average price (€/MWh) | Value_factor_wind | Value factor_sun |
|---|---|---|---|---|---|---|---|
| S1 | curtailment` | 0 | | 27.32 | 53.11 | | 0.51 |
| | | 50 | | 27.36 | 43.80 | | 0.62 |
| | | 100 | | 26.46 | 43.97 | | 0.60 |
| | | 150 | | 26.18 | 47.31 | | 0.55 |
| | | 200 | | 25.73 | 44.66 | | 0.58 |
| | infeasibility | 100 | | 30.77 | 30.00 | | 1.03 |
| S2 | curtailment | 0 | 23.80 | | 65.95 | 0.36 | |
| | | 50 | 22.49 | | 66.96 | 0.34 | |
| | | 100 | 21.86 | | 67.16 | 0.33 | |
| | | 150 | 20.92 | | 67.27 | 0.31 | |
| | | 200 | 21.27 | | 67.28 | 0.32 | |
| | infeasibility | 100 | 16.88 | | 47.46 | 0.36 | |



# Appendix D: Results

Scenario 1

| Theoretical penetration | Solar energy share | Market value_sun | Average wholesale price | Value factor_sun |
|---|---|---|---|---|
| 5% | 5.0% | 36.15 | 35.76 | 1.01 |
| 10% | 10.0% | 27.00 | 31.25 | 0.86 |
| 15% | 15.0% | 22.88 | 28.17 | 0.81 |
| 20% | 20.0% | 17.77 | 25.55 | 0.70 |
| 25% | 24.8% | 5.74 | 21.00 | 0.27 |
| 30% | 28.9% | -14.23 | 12.37 | -1.15 |
| 35% | 32.4% | -22.17 | 7.52 | -2.95 |
| 40% | 35.2% | -43.32 | -3.06 | 14.14 |
| 45% | 37.3% | -56.53 | -10.24 | 5.52 |
| 50% | 39.0% | -60.28 | -14.16 | 4.26 |
| 55% | 40.5% | -65.14 | -17.49 | 3.73 |
| 60% | 41.6% | -67.72 | -20.05 | 3.38 |
| 65% | 42.8% | -65.94 | -20.50 | 3.22 |
| 70% | 43.7% | -69.33 | -22.85 | 3.03 |
| 75% | 44.5% | -74.67 | -26.37 | 2.83 |
| 80% | 45.2% | -74.68 | -27.04 | 2.76 |
| 85% | 45.8% | -77.20 | -28.88 | 2.67 |
| 90% | 46.3% | -76.75 | -29.30 | 2.62 |
| 95% | 46.8% | -77.04 | -29.86 | 2.58 |
| 100% | 47.3% | -77.67 | -30.43 | 2.55 |

Scenario2

| Theoretical penetration | Wind energy share | Market value_wind | Average wholesale price | Value_factor_wind |
|---|---|---|---|---|
| **5%** | 5.0% | 36.26 | 35.71 | 1.02 |
| **10%** | 10.0% | 29.12 | 30.03 | 0.97 |
| **15%** | 15.0% | 26.20 | 27.92 | 0.94 |
| **20%** | 19.7% | -0.82 | 14.49 | -0.06 |
| **25%** | 22.9% | -41.39 | -10.25 | 4.04 |
| **30%** | 25.2% | -55.95 | -21.73 | 2.57 |
| **35%** | 27.2% | -60.56 | -26.98 | 2.24 |
| **40%** | 29.1% | -65.44 | -31.62 | 2.07 |
| **45%** | 30.8% | -67.92 | -34.17 | 1.99 |
| **50%** | 32.5% | -70.56 | -36.92 | 1.91 |
| **55%** | 34.0% | -72.37 | -39.12 | 1.85 |
| **60%** | 35.4% | -73.81 | -41.54 | 1.78 |

| | | | | |
|---|---|---|---|---|
| **65%** | 36.8% | -74.29 | -42.74 | 1.74 |
| **70%** | 38.1% | -74.77 | -43.93 | 1.70 |
| **75%** | 39.3% | -74.79 | -44.63 | 1.68 |
| **80%** | 40.6% | -74.82 | -45.32 | 1.65 |
| **85%** | 41.7% | -74.68 | -46.12 | 1.62 |
| **90%** | 42.9% | -74.54 | -46.92 | 1.59 |
| **95%** | 43.9% | -74.45 | -47.66 | 1.56 |
| **100%** | 45.0% | -74.35 | -48.39 | 1.54 |

# Scenario 3

| Theoretical penetration | VRE energy share | Market value_wind | Market value_sun | Average wholesale price | Value factor_sun | Value_factor_wind |
|---|---|---|---|---|---|---|
| **5%** | 5.0% | 36.82 | 36.54 | 36.15 | 1.01 | 1.02 |
| **10%** | 10.0% | 30.05 | 29.53 | 30.06 | 0.98 | 1.00 |
| **15%** | 15.0% | 27.78 | 25.42 | 27.54 | 0.92 | 1.01 |
| **20%** | 20.0% | 24.44 | 21.23 | 24.13 | 0.88 | 1.01 |
| **25%** | 25.0% | 20.83 | 17.77 | 21.07 | 0.84 | 0.99 |
| **30%** | 29.9% | 6.39 | 8.28 | 12.65 | 0.65 | 0.51 |
| **35%** | 34.2% | -14.60 | -1.36 | 1.07 | -1.28 | -13.69 |
| **40%** | 38.0% | -30.77 | -9.03 | -8.87 | 1.02 | 3.47 |
| **45%** | 41.3% | -48.32 | -21.13 | -21.69 | 0.97 | 2.23 |
| **50%** | 44.1% | -59.85 | -31.77 | -31.97 | 0.99 | 1.87 |
| **55%** | 46.5% | -67.15 | -39.94 | -39.48 | 1.01 | 1.70 |
| **60%** | 48.7% | -69.65 | -52.94 | -47.39 | 1.12 | 1.47 |
| **65%** | 50.5% | -71.47 | -63.56 | -53.66 | 1.18 | 1.33 |
| **70%** | 52.2% | -72.35 | -69.42 | -57.38 | 1.21 | 1.26 |
| **75%** | 53.8% | -72.50 | -70.92 | -58.77 | 1.21 | 1.23 |
| **80%** | 55.3% | -73.03 | -72.20 | -60.25 | 1.20 | 1.21 |
| **85%** | 56.7% | -72.57 | -74.50 | -61.60 | 1.21 | 1.18 |
| **90%** | 57.9% | -73.20 | -79.88 | -65.04 | 1.23 | 1.13 |
| **95%** | 59.0% | -75.11 | -80.19 | -66.20 | 1.21 | 1.13 |
| **100%** | 60.1% | -75.01 | -79.75 | -65.92 | 1.21 | 1.14 |

# Appendix E: Installed capacity for each scenario

Scenario 1

| Penetration | Solar | Wind GW | Waste GW | Uran GW | Oil GW | natural gas GW | hard coal GW | Lignite GW | Biomass GW |
|---|---|---|---|---|---|---|---|---|---|
| 10% | 72.8 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 20% | 145.6 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 30% | 218.4 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 40% | 291.2 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 50% | 364 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 60% | 436.8 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 70% | 509.6 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 80% | 582.4 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 90% | 655.2 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 100% | 728.00 | 0.00 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |

Scenario 2

| Penetration | Solar | Wind GW | Waste GW | Uran GW | Oil GW | natural gas GW | hard coal GW | Lignite GW | Biomass GW |
|---|---|---|---|---|---|---|---|---|---|
| 10% | 0.00 | 35.19243 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 20% | 0.00 | 70.38486 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 30% | 0.00 | 105.5773 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 40% | 0.00 | 140.7697 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 50% | 0.00 | 175.9621 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 60% | 0.00 | 211.1546 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 70% | 0.00 | 246.347 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 80% | 0.00 | 281.5394 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 90% | 0.00 | 316.7319 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 100% | 0.00 | 351.92 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |

Scenario 3

| Penetration | Solar | Wind GW | Waste GW | Uran GW | Oil GW | natural gas GW | hard coal GW | Lignite GW | Biomass GW |
|---|---|---|---|---|---|---|---|---|---|
| 10% | 36.40 | 17.60 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 20% | 72.80 | 35.19 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 30% | 109.20 | 52.79 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 40% | 145.60 | 70.38 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 50% | 182.00 | 87.98 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 60% | 218.40 | 105.58 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 70% | 254.80 | 123.17 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 80% | 291.20 | 140.77 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 90% | 327.60 | 158.37 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |
| 100% | 364.00 | 175.96 | 4.07 | 10.80 | 3.65 | 23.97 | 28.20 | 20.60 | 8.31 |