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Market-based Investment Decisions into Generation Capacities as Part of the Austrian Electricity Market

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Abstract

To reduce the extent of global warming, the members of the European Union have decided to take countermeasures. In Austria, for example, electricity must be generated exclusively from renewable energies. In order to be able to cover the increasing electrical energy demand in the future, an expansion of the generation capacities is essential. In this thesis, optimal investment decisions in Austria for the year 2030 in photovoltaic devices, run-of-the-river hydroelectricity, and wind turbines are to be found and the influence of European energy policy is examined. An expanded transport network takes power trading between the energy markets into account. The linear integer investment model is implemented in MATLAB. Austria is modelled in detail using 17 nodes, and the neighbouring countries each as a separate energy market. Each of these nodes contains the generation capacities currently installed, their individual operating parameters, and power storages. The energy demand and the regionally different generation profiles of renewable energies are specified for the year 2030 as an hourly time series. To cover the demand, there is the possibility of expanding power generation within Austria. In addition to the electrical energy demand, a heating demand must be compensated, which in turn influences the electricity generation via a sector coupling. The influence of coal and nuclear phase-out from Austria's neighbouring countries, the effects of different high CO_2 prices, and an increased photovoltaic expansion are examined in eight scenarios. It shows that the economy of photovoltaic systems differs from the point of view of a central planner and the operator's perspective. The use of coal-fired power plants is strongly influenced by the CO_2 price due to their high emission factors. Their use varies between baseload coverage and complete shutdown in the different scenarios. The phase-out of nuclear power plants with low marginal costs causes a shift in the merit-order effect and thus higher utilization of the remaining power plants. If their capacity is insufficient, the electricity imports are going to rise sharply, and the expansion of the interconnectors between the countries is therefore of great importance. Further improvements in modelling can include the use of power-to-gas and vehicle-to-grid concepts. The latter represents a promising method for stabilizing the power grid, due to the increasing spread of electric vehicles, since these can be used as temporary bidirectional energy storage devices.

Kurzfassung

Um das Ausmaß der globalen Erwärmung zu reduzieren, haben die Mitglieder der Europäischen Union beschlossen Gegenmaßnahmen zu ergreifen. So soll in Österreich die Stromerzeugung ausschließlich durch erneuerbare Energien erfolgen. Um dennoch, den in der Zukunft weiter steigenden, elektrischen Energiebedarf decken zu können ist ein Ausbau der Erzeugungskapazitäten unumgänglich. In dieser Arbeit sollen optimale Investitionsentscheidungen in Österreich für das Jahr 2030 in Photovoltaik, Laufwasser,- und Windkraftwerke gefunden und dabei der Einfluss der europäischen Energiepolitik untersucht werden. Durch ein ausgebautes Transportnetz wird der Stromhandel zwischen den Energiemärkten berücksichtigt. Das lineare ganzzahlige Investitionsmodel wird in MATLAB implementiert. Österreich wird detailliert mittels 17 Knoten, und die Nachbarstaaten jeweils als ein separater Energiemarkt, modelliert. Jeder dieser Knoten enthält die derzeit installierten Erzeugungskapazitäten, deren individuelle Betriebsparameter und Stromspeicher. Der Energiebedarf, sowie die regional unterschiedlichen Erzeugungsprofile der erneuerbaren Energien werden für das Jahr 2030 als stündliche Zeitreihe vorgegeben. Um die Nachfrage decken zu können, besteht innerhalb Österreichs die Möglichkeit des Ausbaus der Stromerzeugung. Neben dem elektrischen Energiebedarf muss ein Heizwärmebedarf gedeckt werden, welcher über eine Sektorenkopplung wiederum die Stromproduktion beeinflusst. Der Einfluss eines Kohle,- und Atomausstiegs von Österreichs Nachbarstaaten, die Auswirkungen von unterschiedlich hohen CO_2 Preisen, sowie Deren von einem verstärkten Photovoltaik-Ausbau werden in acht Szenarien untersucht. Es zeigt sich, dass die Wirtschaftlichkeit von Photovoltaik Anlagen aus der Sicht eines zentralen Planers und des Betreibers deutliche Unterschiede aufweist. Der Einsatz von Kohlekraftwerken wird durch deren hohen Emissionsfaktor stark vom CO_2 Preis beeinflusst. Deren Verwendung variiert zwischen Grundlastdeckung und vollständiger Abschaltung in den unterschiedlichen Szenarien. Die Abschaltung von Atomkraftwerken, mit niedrigen Grenzkosten, bewirkt eine Verschiebung des Merit-Order Effekts und somit höhere Auslastung der verbliebenen Kraftwerke. Ist deren Kapazität nicht ausreichend, so werden die betreffenden Stromimporte stark zunehmen und somit ist der Ausbau der Interkonnektoren von großer Bedeutung. Weitere Verbesserung der Modellierung können insbesondere den Einsatz von Power-to-Gas und Vehicle-to-Grid Konzepten beinhalten. Letztere stellen durch die zunehmende Verbreitung von Elektrofahrzeugen eine zukunftsträchtige Methode zur Stabilisierung des Stromnetzes dar, da diese als temporäre bidirektionale Energiespeicher genutzt werden können.

Contents

Abbreviations

BTU	British thermal unit
CCGT	Combined Cycle Power Plant
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Emission trading system
GEP	Generation expansion problem
GHG	Greenhouse gases
GDP	Gross development product
LP	Linear programming
MILP	Mixed integer linear programming
NECP	National energy and climate plan
P2G	Power to gas
PHS	Pumped-storage hydroelectricity
PV	Photovoltaic
RoR	Run-of-river hydroelectricity
ST	Sustainable Transition
TEP	Transmission expansion problem
TYNDP	Ten years network development plan
V2G	Vehicle to grid

1. Introduction

1.1. Motivation

The climate crisis and global warming represent one of the greatest challenges of the future for the entire world and Europe. With the burning of fossil fuels being the largest contributor to Greenhouse gas (GHG) emissions, future electricity production must rely on renewable energies, which will replace existing thermal power plants. This issue is addressed by the European Commission in the "Clean Energy Package":

> "The gradual transition away from fossil fuels towards a carbon-neutral economy is one of the greatest challenges of our time. How will the EU tackle it? Through the clean and fair energy transition that creates growth and jobs in a modern economy and increases our quality of life as citizens, while at the same time putting us in the lead in the fight against climate change following the Paris Agreement. To do so, the EU has taken a wide range of initiatives. In broad terms, the establishment of the EU Energy Union provides a framework for a consistent approach in all policy areas – and central to the Energy Union is the Clean energy for all Europeans package. The purpose of these measures is to ensure a clean and fair energy transition at all levels of the economy – from energy generation all the way to people's homes, such as increasing renewable electricity and encouraging the use of smart meters. These measures aim to improve energy interconnections between Member States and to make the different actors in the energy field more competitive and innovative. This means finding the right blend between regulatory tools and market forces, encouraging private investment on clean energy where it makes economic sense and using EU funding to stimulate investment where market forces alone are not sufficient."
>
> (European Commission, 2019)

European energy and climate goals

The European Union has made energy and climate goals for the period until 2030. Within this 2030 climate and energy policy framework there exist three main objectives.

- Greenhouse gas (GHG) emissions should be reduced by at least 40 % (compared to 1990)
- Energy efficiency should be increased by at least 32, 5 %
- Renewable energy sources should grow to a share of at least 32 %

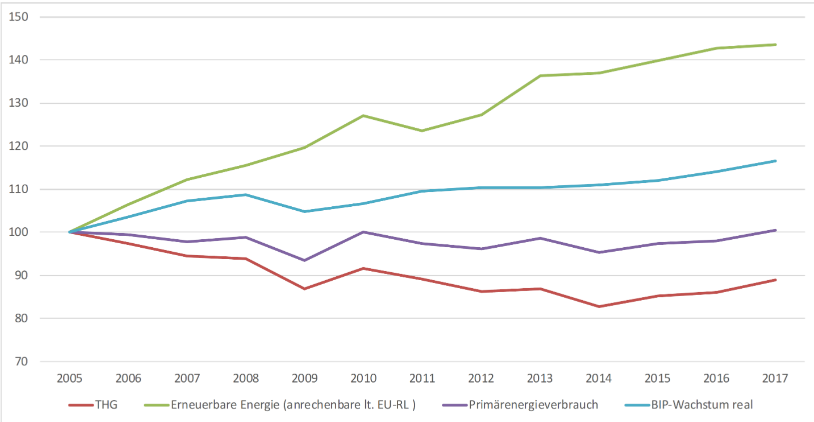
In addition to this pan-European plan, all member states are required to develop and submit a long-term strategy until 2030. These National Energy and climate Plans (NECPs) must be in line with the Paris in agreement on climate change. (European Commission, 2019)

In line with the European wide goals the NECP for Austria contains the objectives:

- Emissions in non-**ETS** sectors should be reduced by at least 36 % (compared to 2005)
- Primary energy intensity should fall by at least 25 % (compared to 2015)
- Renewable energy sources should grow to a share of at least 45 %, with 100 % of the total electricity consumption being covered by renewable energy sources

While energy intensity measures the energy inefficiency of an economy, calculated by Energy per Gross Domestic Product (GDP) usually specified in BTU (British thermal unit) per Dollar. The decarbonization of Austria should, therefore, be done by expanding the share of renewable energy and improving energy efficiency in the main emitting sectors (in particular the transport sector and buildings, see Parliament, Union, and Vienna, 2021. While the share of renewable energy in Austria in 2017 in the gross final energy consumption was 32, 6 % the share in gross electricity consumption was 72, 2 %. Whereby in the transport sector renewable energies make up about 10 % of energy consumption. Due to the increased use of electric vehicles in the future, additional energy requirements can be expected. This must also be considered by investing in generation technology to achieve 100 % renewable energy coverage.

The time course of the relevant three objectives are visualized in figure 1.1, while especially for the last point, the 100 % electrical energy demand compensation by renewable energy sources, should be examined within this thesis.



Source: Federal Ministry for Sustainability and Tourism, 2019

THG	*GHG emissions*
Erneuerbare Energie (anrechenbare lt. EU-RL)	*Renewable energy (according to EU Directive)*
Primärenergieverbrauch	*Primary energy consumption*

Figure 1.1.: Time course of the NECP objectives of Austria

Ten year network development plan

The 10-year network development plan **(TYNDP)** is published by the European Network of Transmission System Operators for Electricity (ENTSO-E) to plan the future power grid. All Europeans aspire to reliable supply, affordable energy prices, and sustainable development. It is a non-binding plan for the upcoming years to ensure greater transparency regarding the necessary expansion of the entire EU-wide electrical transmission system. The expansion of the electricity grid and the expansion of interconnectors between the countries is very important to ensure a future proof stable electricity system. Especially if the share of renewable energy generation increases significantly. These renewable energies are much more volatile due to the dependence on external factors such as the weather. That is why adequate grid development is the core instrument for achieving EU energy and climate goals.

European Union emission trading system

The EU emissions trading system **(ETS)** is an instrument of the European climate policy to reduce greenhouse gas emissions at the lowest possible economic costs by issuing a limited number of emission certificates that can be traded on a market. The European emissions trading system **ETS** works according to the cap & trade this means that on the one hand, the level of greenhouse gas emissions is limited and on the other hand, emission certificates can be freely traded. This should create an economic incentive to reduce emissions of harmful greenhouse gases where it is most cost efficient.

The system is “power plant-based“, which means that each power plants currently covered is recorded individually, and not entire companies or countries. Each of these power plants receives a fixed amount of emission allowances for a certain period, which considers the politically defined emission reduction target. To introduce the emissions trading system as far as possible without economic distortions, the emission allowances were initially allocated free of charge. If a company’s carbon dioxide emissions are lower than the allocated allowances, for example as a result of its emission reductions, the company can sell allowances that are not required, on the market, to other companies. Alternatively, it can also buy emission certificates if measures to reduce emissions would be more expensive. In this case, another market participant receives money, in exchange for the emission allowance, to reduce greenhouse gases. The ton of carbon dioxide saved thus receives a value that is determined on the market based on supply and demand. To ensure that emissions trading works, the number of emission allowances must be less than the desired and the predicted emissions. The European Union plans to successively reduce the number of emission allowances available in the coming years which will raise the CO_2 price. The emissions from thermal power plants with a capacity of 20 MW and more are subject to the **ETS** regulations, so the CO_2 prices for calculating the marginal costs of caloric power plants must be taken into account.

1.2. Research question and methodology

Based on this political background and their motivation, optimal investment decisions for the expansion of renewable energies in Austria for 2030 are calculated in this work and with these, the influence of political and energy-economic decisions of the neighboring countries are examined. Provided that the demand on the energy market is covered at all times, the cost-minimal generation expansion for 2030 should be examined. From an economic point of view, the investment costs into new generation capacities compete with the marginal costs of existing power plants. The investment costs for the year 2030 are evaluated by using a capital recovery factor (CRF). Operating costs, fuel costs, and CO_2 prices result in the power plant-dependent marginal costs. The investment problem is formulated as a linear problem (LP), which can then be solved reliably and time-efficiently with Matlab’s Yalmip and Gurobi libraries. The objective function reduces the sum of all costs while the constraints ensure, the load coverage, the load flow, as well as the compliance with the technical framework conditions of the power plants.

1.3. Structure of the thesis

This thesis is organized with a start of the art analysis and the progress beyond at the beginning in chapter 2. The functionalities of the model are described in general in chapter 3, with a textual, graphical, and a generic mathematical formalization of the model, its objective function and constraints. In the second part of this chapter, the validation of the model is done to prove the accuracy of the used parameters, the level of details of the modelling, and therefore the accuracy of the following calculations. To do so the model is set up with well-known and documented datasets of the year 2018 and the result is compared with the real measured data by the e-control. Because the goal of this thesis is not do calculate energy consumptions and operation strategies in the past but in the future, the dataset used for the upcoming scenarios of 2030 is presented in chapter 4. All used assumptions regarding existing caloric and renewable power plants, demands, transmission power grid, future investment marginal costs are presented in this chapter. This forms the basis for the eight examined scenarios and sensitivities which are described and evaluated in chapter 5. Therefore, the results of this thesis are presented and the influence of CO_2 prices, coal exit strategies, nuclear phase-out, and the increased usage of PV systems are examined and described. Chapter 6 forms the conclusion of the results and further improvements of the model which can be done to better analyze possible technological developments in the future.

2. State-of-the-Art and progress beyond

Since this work aims to find a cost-minimal expansion of various renewable power plants, considering various constraints and sensitivities, a mathematical formulation of the optimization problem has to be done. An essential part of this investment model is an objective function for which a minimum can be found. To solve this task in a time-efficient manner, this is often formulated as a linear program (LP), since there exist no discontinuities in the optimization variables, therefore.

2.1. Sensitivity analysis based on test models

In this thesis, the influence of political and energy decisions is to be examined. Often a smaller generic test model and not a country representative model, which takes into account the specific geographical distribution of power plants and their individual power line parameters, is used to examine the sensitivities of very specific political decisions on the investment decisions.

Influence of transmission charges

In (Tohidi et al., 2017) transmission charges aim to recover the costs of network investments. This aims to build up new generation at nodes, where the energy is used and reduces the investment of generators at nodes where the potential network expansions costs are larger than needed if the generators would have been built at another node. These fees provide locational signals for new generators at a specific node. If the electricity system of a country is deregulated power transmission and generation are in different hands which does not allow a direct company-intern economic competition between these costs. The effects of transmission charges are examined with a test system (IEEE-RTS96), while no change of network topology will be considered.

Different variants of CO_2 prices

As already mentioned there already exists a European-wide system intending to reduce greenhouse gas emissions, the **ETS**. This system leads automatically to a CO_2 price and therefore higher marginal costs for power plants with higher emission factors and lower efficiency. However, this is not the only possibility to encourage an electricity market with lower emissions. The effects of cap and trade CO_2 certificate trade system, like the **ETS**, in comparison to carbon taxes on a test system are evaluated in (He, L. Wang, and J. Wang, 2012).

Joint generation and transmission expansion

With the expansion of much more volatile renewable energy sources also the power transmission grid has to be further expanded to ensure a stable electricity system. A multistage expansion planning (three-year problem with three stages) with joint consideration of generation expansion (GEP) and transition expansion planning (TEP) on a test system is done in (Muñoz-Delgado, Contreras, and José M Arroyo, n.d.). This is formulated as mixed integer linear program (MILP) which considers several alternatives for feeders, transformers, conventional, and wind generators. The model includes and minimizes the total costs including investment, maintenance, production, losses, and costs for unserved energy. The same group of authors has proposed a similar approach to a large test system in (Munoz-Delgado, Contreras, and Jose M. Arroyo, 2014).

Differences between national and European optimum

In my thesis optima are found by minimizing a cost function for Austria and all its neighbouring countries together. This, therefore, represents a European optimum and not imperative a national optimum for each country. The differences in the network expansion strategy between a national optimum and an EU wide optimum are evaluated on a test system in (Huppmann and Egerer, 2015).

Integration of renewable energy sources from the perspective of a central planner

A similar approach as used in this thesis is evaluated by (Sima et al., 2018) on a test model. From the perspective of an independent system operator (ISO) demand supply has to be ensured, while the shutdown of conventional generation facilities is done. A cost minimal optimum should be found by the construction of further renewable power plants (wind power plants) to fulfil the EU 2020 goal of 20 % decreased CO_2 emissions. The planning horizon of the investments is one dedicated year in the future with an assumed energy demand. The modeling of the transmission network is done by a DC approximation with no power losses considered.

2.2. Analyzes of the electricity market

In addition to examining sensitivities using test systems, these are also applied to systems that simulate individual countries.

Power transmission in Austria

The transport grid of Austria and its neighbouring countries is expanded in (Burgholzer and Auer, 2016) with a precise model of the generation capacities and power lines in Austria. The data basis collected for this work regarding the generation capacities of the nodes and their connection via power lines represents the basic dataset for this thesis.

Network fees in Germany

The effects of network fees and therefore the differences between nodal pricing and price zones, like it is done in this thesis, on the expansion of the electricity network and generation capacities in Germany are presented in (Grimm et al., 2019). Whereby investment into power plants is done by private investors while the network expansion is done by the transmission system operator.

Generation and transmission expansion planning in Iran

In (Rouhani, Hosseini, and Raoofat, 2014) a composite generation and transmission expansion problem is similarly evaluated in Iran as it is done in this thesis but without consideration of the neighbouring countries.

2.3. Bottom-up models

There are two possible approaches to modeling investment models. On the one hand, it can be aimed for a holistic optimum, top-down, from the perspective of a central planner, on the other hand, bottom-up, from the perspective of private investors. These are locally bound to certain areas and search for the most economical solution with the highest profit. The focus is no longer on the lowest total investment costs or grid stability, but on individual profit.

Maximum profit for private investors

While generation expansion problems usually seek an optimum from the perspective of a central planner, a private investor based optimum is calculated in (Barati, Jadid, and Zangeneh, 2019). Therefore, the objective function does not aim to find a cost minimal investment decision but maximum profit for private investors under the constraint of a guaranteed power purchase agreement with the government. The presented method which has been developed therefore is applied to a test system.

The volatility of renewable energies

Also in (Allahdadi Mehrabadi, Parsa Moghaddam, and Sheikh-El-Eslami, 2020) a bottom-up approach is chosen to maximize the profit in a system that is divided into several price zones as a multi-market model. Particular attention is paid to the volatility of renewable energies by using stochastic functions and neural networks for their implementation. By combining the objective function from parts of profit maximization and reduction of emissions due to political decisions, both goals can be considered together.

2.4. Non-linear programming

While efforts are usually made to do implement the expansion problem with a linear program to achieve relatively fast and reliable optimization results the following there also have been developed several models that are non-linear. This is often necessary to be able to implement very detailed models.

The volatility of renewable energies as part of the objective function

In (Oree, Sayed Hassen, and Fleming, 2017) several methods are presented which handle the problem of the high volatility of renewable energies and make them a component of the objective function. These multi-criteria decision-making methods enable power system planners to make decisions in the presence of the conflicting objectives of optimized investment costs and a stable and reliable energy supply.

Operational cost model

(Vrionis, Tsalavoutis, and Tolis, 2020) solves a generation expansion problem by formulating an integer non-linear programming with an evolutionary algorithm. In addition to renewable energies, energy storages are also considered. The model embeds a computationally expensive operational cost simulation model which may exhibit a high level of temporal and technical representation of the short-term operation of a power plant and therefore influences the whole electricity market. For example, ramp-up times and constraints are implemented to power plants which makes the model very detailed but time-consuming to solve.

Transmission and generation expansion

The joint expansion of the transmission grid and renewable energies are formulated in an optimization problem by (Roldán et al., 2018). This model minimizes investment and operation costs concerning the volatility of renewable energies. These two cost components are formulated as separate optimization problems and then solved iteratively in the form of a master problem and several sub-problems.

Reduction of investment costs with large-scale energy storages

In (Hemmati, Saboori, and Jirdehi, 2016) the combination of a generation expansion problem with the expansion of large-scale energy storage systems is evaluated to reduce the overall investment costs. This problem is formulated as a mixed integer nonlinear programming and jointly reduces air pollution and overall costs of a test system.

2.5. Own contribution

Based on the research question, described before, the own contribution of my thesis is presented. As already explained many investment models examine the influence of sensitivities, like political decisions, on small test models which should sufficiently model the real energy market of a country or region. In this work, the generation expansion problem is modeled as a linear program whereby Austria is modeled as a 17 node model. This enables a very exact mapping of already existing power plants and energy storages to a specific region. Furthermore, the power-flow between these nodes (regions) can be simulated much more detailed, since the real parameters of the transport grid can be used. This load flow not only affects the investment decisions in Austria but also, will change the effects regarding Austria's neighbouring countries. The model will also not be considered as a model only for Austria, but also the neighbouring countries are considered with one node per country (seven nodes). The renewable energy sources of each nation are taken into account with an individual generation profile that reflects the geographical location and special features. The investment model has the possibility to build three types of renewable energies at each node: PV,- wind,- and run-of-river-power plants while the electrical demand has to be compensated in each country. To take into account, the heavy use of district heating in Austria and especially in Vienna, which uses the waste heat from power generation, a sector coupling was introduced. A heat demand thus influences the operation of certain thermal power plants.

3. Model

3.1. Nomenclature

Indices

c	conventional generation technologies which are already built
b	conventional generation technologies which could be build
r	renewable energy sources which could be built
n	nodes
l	lines between nodes
t	current timestep in the range (1,T)
T	number of the timesteps in [h]

Sets

$\Omega^n_{c,new}$	new build-able fossil fuel power stations c located at node n
$\Omega^n_{c,install}$	already existing fossil fuel power stations c located at node n
$\Omega^n_{r,new}$	new build-able renewable energy r located at node n
$\Omega^n_{r,install}$	already existing renewable energy r located at node n
Ω^n_l	all lines l which are connected with node n
Ω^p_n	all nodes n of a pricezone p

existing fossil fuel power stations

C_c	marginal costs of the specific fossil fuel power station c in [€/MWh]
P_c	produced power of the fossil fuel power station c in [MW]
$P_{max,c}$	maximum power capacity of the fossil fuel power station in [MW]

build-able fossil fuel power stations

C_b	marginal costs of the conventional generator b in [€/MWh]

P_b	produced power of the conventional generator b in [MW]
$P_{max,b}$	maximum power capacity of the conventional energy source in [MW]
I_b	investment costs of the fossil fuel power station in [€/MW]
CRF_b	cost return factor for the conventional generator b

existing renewable energy sources

$P_{install,r}$	maximum power capacity of the already existing renewable energy source in [MW]

build-able renewable energy sources

$P_{max,r}$	maximum power capacity of the renewable energy source in [MW]
$f_{act,p,r}$	factor of the produced power of renewable energy sources, in range [0,1]
$P_{spill,r}(t)$	down regulation of renewable energy sources [MW]
I_r	investment costs of the renewable energy source in [€/MW]
$P_{r,o}$	possible options for the generation capacity in [MW]
CRF_r	cost return factor of the renewable energy source r

Lines between nodes and power flow

P_l	power flow over the line in [MW]
$P_{max,l}$	maximum power-flow over a specific line in [MW]

Demand

D_n	electrical Demand at the node n in [MW]

Storages

P_s	actual charging/discharging power of the storage s [MW]
$P_{max,storage}$	maximum Power of the storage s [MW]
E_s	current charging state of the storage s [MWh]
$Inflow$	natural inflow to a storage s [MW]
$Inflow_{used}$	used power of the natural inflow (downregulation) [MWh]

3.2. The functionality of the model

The used datasets of the examined scenarios are loaded from an Excel file to Matlab. This enables a clear overview of the input parameters and quick changes e.g. of the installed power capacities or the demand. After the optimization process in Matlab has been done the results get stored in binary Matlab "*.MAT" files, which save all the used variables. As a result, the optimization process only has to be carried out once with a set of input parameters and can then be evaluated later without doing the time-consuming optimization process one more time. This process is evident in figure 3.1

Figure 3.1.: Overview of the optimization process

A one-stage investment model is applied to full-fill the demand forecasts of the European Network of Transmission System Operators for Electricity (ENTSO-E) within a time horizon of one year. This means the expansion of renewable energies is done once to optimize the costs in all countries together while the demand is covered at every time.

The model is applied to Austria with power line connections to the neighbour countries and power lines between these countries.

While Austria is modeled with 17 nodes each neighbouring country is modeled as one node. Therefore the generation capacities in Austria can be simulated much more detailed.

The model solves a Generation Expansion Planning (GEP) problem, no Transmission Expansion Planning (TEP) is implemented. This means that only the energy production can be expanded (in this case renewable energies) while the transmission lines stay unchanged and are set by the parameters in the Excel file.

The planning is done from the perspective of a central planner (Sima et al., 2018). In reality, at the specific nodes, local operators will solve their own maximum profit problem. This may leads to other investment decisions than calculated as an overall optimum.

Any number of pre-installed fossil fuel power stations are possible per node and it is theoretically also possible to build new caloric power stations. According to the National Energy and Climate Plans (NECP) EU2030 goals for Austria only renewable energies should be used and therefore the scenarios examined in chapter 5 use only the possibility of building renewable energies. The planning and construction are nevertheless interesting since combined cycle power plants (CCGT) can be used to produce combined heat and power. To prove this implementation also a heat demand, to simulate district heating networks, is implemented.

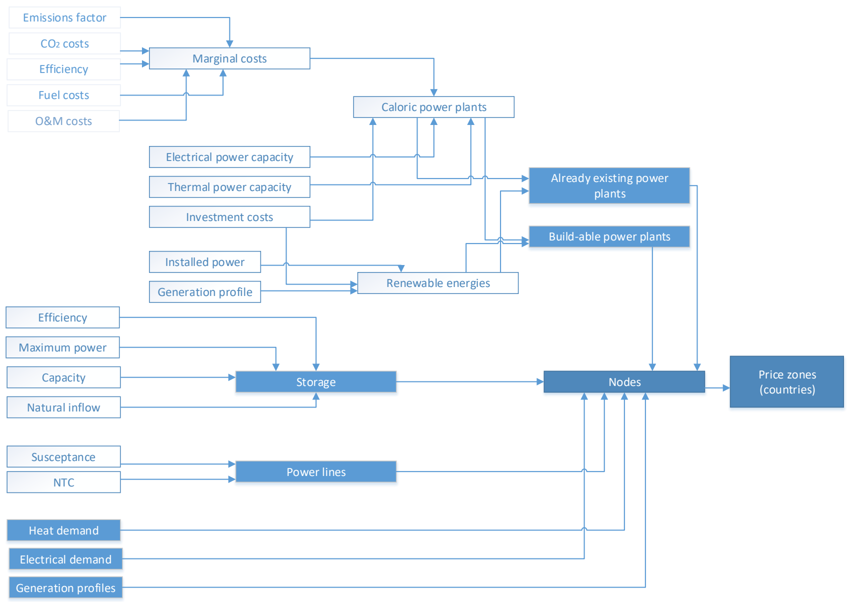


Figure 3.2.: Functionality of the model

The investment costs of new generation technologies are modeled as constant, therefore economy of scales will not be considered. The advantage of this modeling technique is to generate a linear programming (LP) and no mixed integer linear programming (MILP) problem, which can be solved in a shorter time.

Three types of renewable energy sources are implemented which are already installed and could be built at every node in Austria: PV devices, Run-of-the-river hydroelectricity, and wind turbines. At each node, they have their individual power factor profile and could have different investment costs.

Storages are modeled with a bidirectional power-flow and therefore an efficiency factor is used. This efficiency factor will be considered one time for charging the storage and a second time for discharging.

At each node, there could be a storage, which is not upgrade-able. These storage's represent e.g. pumped-storage hydroelectricity or batteries which already exist, but it is not possible to build new ones. Each of these storages has a specific capacity, efficiency, and maximum power to model the physical properties.

Price zones are constructed to include several nodes to one big zone with joint demand compensation. This is done for the nodes of Austria. Therefore Kirchhoff's law will be expanded to full-fill the compensation of a price zone, not the demand of a single node. The lines between the individual nodes remain, and are thermally limited, and therefore influence the load flow of the whole system.

3.3. Mathematical description

3.3.1. Objective function

The objection function minimizes the sum of the production costs of already installed and new-build conventional generators and the annualized investment costs of the new renewable energy sources which produce energy without production costs and the new-build fossil fuel power plants. This model is based on (Conejo et al., 2016) and (Sima et al., 2018).

$$\begin{aligned} \min_{\mathbf{P_c},\mathbf{P_b},\mathbf{P_{max,b}},\mathbf{P_{max,r}}} & \sum_{t=1}^{T}\sum_{c} C_c * P_c(t) + \sum_{t=1}^{T}\sum_{b} C_b * P_b(t) \\ & + \sum_{b} CRF_b * I_b * P_{max,b} + \sum_{r} CRF_r * I_r * P_{max,r} \end{aligned} \tag{3.1}$$

3.3.2. Constraints

The demand D_n at each node n has to be compensated by using Kirchhoffs law (3.2). The sum of the produced energy at every node consists of energy from already installed and new-build renewable energy sources, in which their production depends on the power factor and the produced energy from caloric power plants, the power flow over the power lines to/from other nodes and energy which charges/discharges the storage and the node.

$$\begin{aligned} & \sum_{c\in\Omega^n_{c,install}} P_c(t) + \sum_{b\in\Omega^n_{c,new}} P_b(t) + \sum_{r\in\Omega^n_{r,new}} f_{act,p,r}(t) * P_{max,r} \\ & + \sum_{r\in\Omega^n_{r,install}} f_{act,p,r}(t) * P_{max,r} - \sum_{l\in\Omega^n_l} P_l(t) - P_s(t) = D_n(t) \\ & \qquad \forall n \\ & \qquad \forall t \in (0,T) \end{aligned} \tag{3.2}$$

To meet the demand exactly in each timestep a down-regulation (3.3) of PV, Wind, and RoR power plants have to be considered.

$$\sum_{c\in\Omega^n_{c,install}} P_c(t) + \sum_{b\in\Omega^n_{c,new}} P_b(t) + \sum_{r\in\Omega^n_{r,new}} f_{act,p,r}(t) * P_{max,r} - P_{spill,r}(t) + \sum_{r\in\Omega^n_{r,install}} f_{act,p,r}(t) * P_{max,r} - P_{spill,r}(t) + \sum_{l\in\Omega^n_l} P_l(t) - P_s(t) = D_n(t) \quad \forall n \quad \forall t \in (0,T) \tag{3.3}$$

The final model must operate with different price zones, one for each country. Where a price zone could consists of several nodes.

$$\begin{aligned} &\sum_{n\in\Omega^p_n}\sum_{c\in\Omega^n_{c,install}} P_c(t) + \sum_{n\in\Omega^p_n}\sum_{b\in\Omega^n_{c,new}} P_b(t) \\ &+ \sum_{n\in\Omega^p_n}\sum_{r\in\Omega^n_{r,new}} f_{act,p,r}(t) * P_{max,r} - P_{spill,r}(t) \\ &+ \sum_{n\in\Omega^p_n}\sum_{r\in\Omega^n_{r,install}} f_{act,p,r}(t) * P_{max,r} - P_{spill,r}(t) \\ &- \sum_{n\in\Omega^p_n}\sum_{b\in\Omega^n_s} P_s(t) + \sum_{l\in\Omega^p_l} P_l(t) = \sum_{n\in\Omega^p_n} D_n(t) \\ &\forall p \\ &\forall t \in (0,T) \end{aligned} \tag{3.4}$$

While equation 3.2 and 3.3 show the approach which has been done, equation 3.4 is implemented in the model. As already mentioned in (3.3) $P_{spill,r}(t)$ represents the opportunity to regulate the renewable sources down, if there is higher energy production through the generation profile than there is a demand on the energy market. This results in the constraint that the down-regulation power could not be higher than the sum of the energy production from the three different types of renewable energy sources wind, PV, and RoR.

$$0 \leq P_{spill,r}(t) \leq f_{act,p,r}(t) * P_{max,r}$$
$$\forall t \in (0,T)$$
$$\forall r \in \Omega^{n}_{r,new} \bigwedge \Omega^{n}_{r,install} \tag{3.5}$$

The power flow between the nodes/zones is calculated with a PTDF (power transfer distribution factor) matrix which presupposes that the voltage angle between neighbour nodes is small so that a DC approximation of the power flow can be done (Van Den Bergh, Delarue, and D'haeseleer, 2014). The matrix A is an incidence matrix, which describes which nodes are connected by a specific transmission line. The matrix B_d is a diagonal matrix of the susceptances of the lines.

$$PDTF = (B_d * A) * (A^T * B_d * A)^{-1} \tag{3.6}$$

The powerflow over a specific line is calculated as follows: P_l = PTDF * Exchange, where Exchange = A * P_l

Each element of the PTDF matrix corresponds to the power flow over a specific power line l, caused by a power injection at a specific node n. This power injection represents that equation 3.4 would be unbalanced without a power flow to other nodes. Therefore a perfect fit of generation an demand at a node n would not cause a power flow over the power lines connected with this node. However, it should be noted that a dysbalance in neighbouring nodes still causes a power flow. The exchange represents the energy balance at a specific node and therefore closely relates to P_l.

The maximum capacities of the installed conventional generation technologies

$$0 \leq P_c(t) \leq P_{max,c}$$
$$\forall c$$
$$\forall t \in (0,T) \tag{3.7}$$

and the new build ones

$$0 \leq P_b(t) \leq P_{max,b}$$
$$\forall b$$
$$\forall t \in (0,T) \tag{3.8}$$

has to be considered.

There is also a heat demand considered which could be severed by specific combined cycle gas turbines. It is considered that there is a linear function between the heat and the electrical generation of these power plants. Therefore, a specific heat demand directly results also in a minimum produced power of the specific plants. This transforms 3.9 to:

$$\begin{aligned} P_{min,c}(t) \leq P_c(t) \leq P_{max,c} \\ \forall c \\ \forall t \in (0,T) \end{aligned} \tag{3.9}$$

Where $P_{min,c}(t)$ is calculated with the Heat Demand and the maximum electrical and thermal energy of the specific power plant.

The lines between the nodes are thermal limited

$$\begin{aligned} -P_{max,l} \leq P_l(t) \leq P_{max,l} \\ \forall l \\ \forall t \in (0,T) \end{aligned} \tag{3.10}$$

and could not be expanded in this model. In a more complex model with a combination of transmission expansion planning and generation expansion planning this problem could be solved.

The power of a storage flow (in both directions) is limited

$$\begin{aligned} -P_{max,storage} \leq P_s(t) \leq P_{max,storage} \\ \forall n \\ \forall t \in (0,T) \end{aligned} \tag{3.11}$$

Storage charge is limited

$$\begin{aligned} 0 \leq E_s(t) \leq E_{max,storage} \\ \forall n \\ \forall t \in (0,T) \end{aligned} \tag{3.12}$$

Storage charge state

$$\begin{aligned} E_s(t) = E_s(t-1) + P_s(t) * t * \eta + Inflow_{used,n}(t) * \eta \\ E_s(0) = E_s(T) = 0 \\ \forall n \\ \forall t \in (1, T) \end{aligned} \tag{3.13}$$

The natural inflow can but must not be used (e.g. to avoid reaching the upper charge limit).

$$\begin{aligned} 0 \leq Inflow_{used,n}(t) \leq Inflow_n(t) \\ \forall n \\ \forall t \in (1, T) \end{aligned} \tag{3.14}$$

3.4. Model Validation (year 2018)

The model of this thesis is validated with real measured historical data from the Austrian e-control in the following chapter. This validation process uses, if possible, the same data as used for the forecast and results in chapters 4 and 5.

Therefore, only the differences and parameter changes compared to chapter 4 are dealt with below.

In summary, the validation is carried out with this data set:

- electrical grid based on the power limitations of 2018
- detailed generation capacities in Austria with status 2018
- aggregated generation capacities in foreign countries based on the ENTSO-E transparency data for 2018
- renewable energy generation profiles based on the ENTSO-E transparency, for each country individual.
- One aggregated storage per node, with status 2018
- natural inflow to the storages
- marginal costs are calculated based on historical fuel price data or are assumed
- electrical energy demand based on the ENTSO-E transparency data for 2018
- heat demand is modeled based on the 2018 data of Wien Energie [1]

[1] `https://www.wien.gv.at/statistik/verwaltung/tabellen/strom-zr.html`

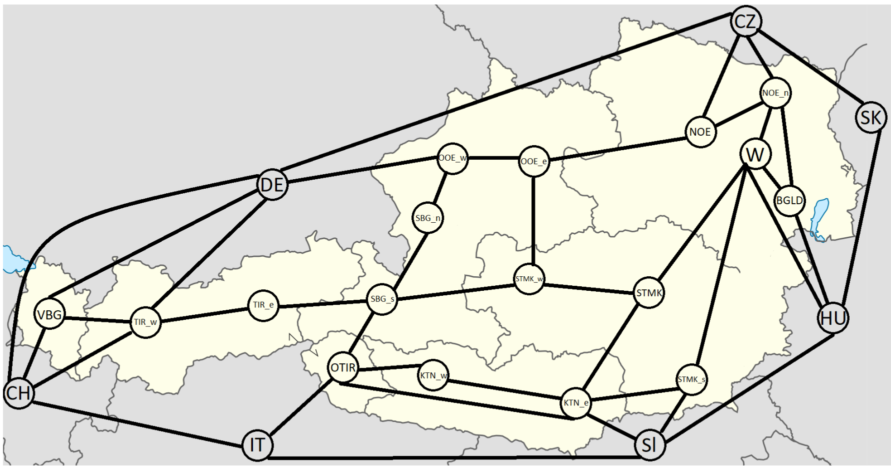


Figure 3.3.: Nodes and power lines of the validation model for the year 2018

3.4.1. Parameters and data sources

The modeling of the electrical grid is described in detail in chapter 4.1. For 2018 the NTC value (power limitation) and susceptance (power distribution) as listed in table A.1 are used.

The already installed renewable energy sources, caloric power plants, and storages are used as described in chapter 4.2. The implemented power plants and storages are listed in the Appendix in table A.3 and table A.6.

The marginal costs

$$marginal_{costs}[€/MWh] = O\&M_{costs} + \frac{Fuel_{costs}}{efficiency} \tag{3.15}$$

of the caloric power plants in Austria are calculated based on their efficiency and O&M costs. The emission factor is not used for the year 2018, since there are no CO2 costs considered. The used fossil fuel costs are assumed based on the market in 2018.

The marginal costs for caloric power plants in the foreign countries are assumed as the weighted average costs of all power plants in Austria which use the same fuel. An exception to this is made by nuclear, coal, and lignite power plants since there does not exist any of them in Austria these costs are based on historical data.

The generation profiles for the renewable energy sources PV, wind, and Run-of-river hydroelectricity are the same as used for the 2030 scenarios in chapter 4.5.

The energy demand for the year 2018 is based on the data of the ENTSOE transparency platform and the heat demand is the same as used in chapter 4.6.

3.4.2. Validation results

To prove the implementation of the heat demand as part of the sector coupling the year 2018 was optimized with no heat demand and natural PHS inflow implemented (see figure 3.4) and a second time with these two model extensions (see figure 3.5) for January 2018. It is evident in figure 3.4 that there is always a constant caloric energy production even though the combined heat and power gas **CCGT** plants are not forced to produce energy by a heat demand. This is done by other renewable energy sources like biomass power plants which have very low marginal costs.

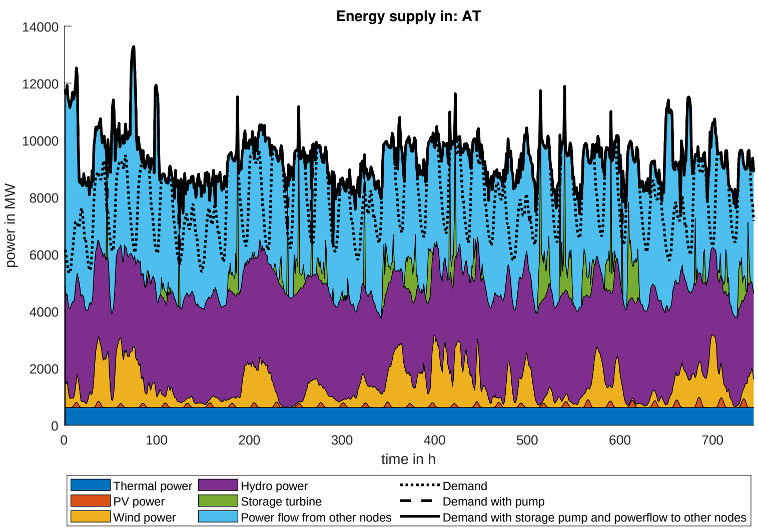


Figure 3.4.: energy supply in January 2018 without heat demand and PHS inflow

The comparison of these two model variations shows the influence of a head demand to the whole model. The Combined heat and power plants produce constantly around 2000 MW electrical energy during the winter period which reduces the demand for electrical energy from foreign countries and other power plants.

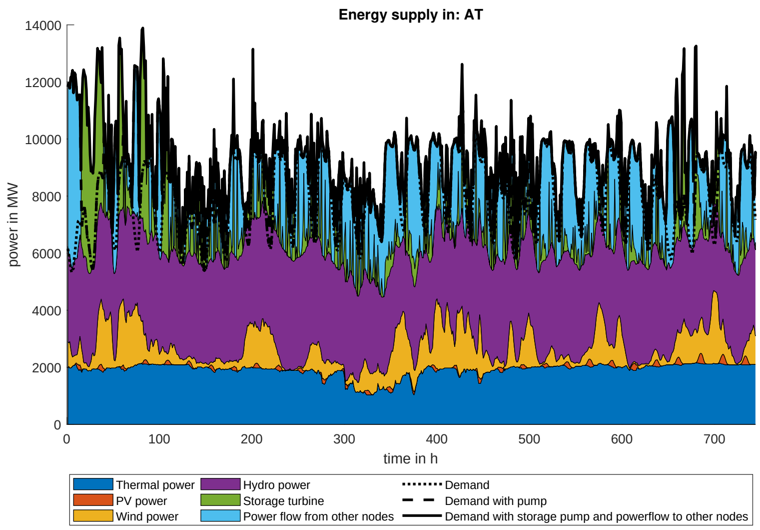


Figure 3.5.: energy supply in January 2018 with heat demand and PHS inflow

To check the accuracy of the model and the chosen parameters a comparison with the historical data provided by the e-control (see figure 3.7 and 3.6) is done.

It is evident that the power provided by caloric and run-over-river power plants have a very similar course. The Storage turbines (from the PHS) in the model are significantly more volatile than in the e-control data provided. This is because several physical effects and energy management decisions are not considered in the model. This represents the optimum usage of these storages. A difference in the definition is also made by the e-control "not defined" power sources, which are considered in the model of this thesis as PV plants or as "other renewables" and "other non renewables" which both are printed as thermal power plants in figure 3.5. Another big difference makes the restriction of the e-control, to only consider power plants with an installed power of at least 25 MW. As can be seen in table A.3 in particular many caloric power plants which are considered are below this limit and also some run-over-river power plants. Additional to the graphical comparison with these two figures which displays the energy usage over time also the sum of the electrical power is compared numerically in figure 3.8 and in table 3.2.

As described the differences from the power plants mainly occur by the different considerations of the power plants. It is very interesting to see that the usage of the storages has a huge temporary difference, as described, mainly through physical reasons but the produced energy in a month is very similar. The difference in net imports (imports minus

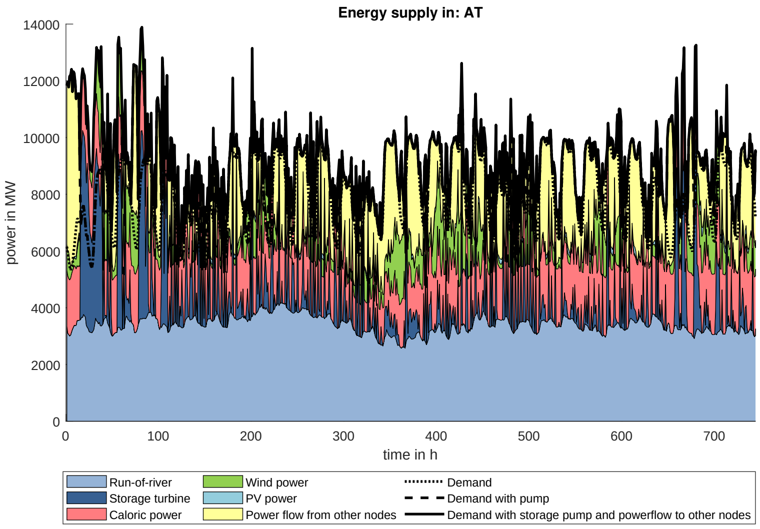


Figure 3.6.: energy supply in January 2018 model calculation

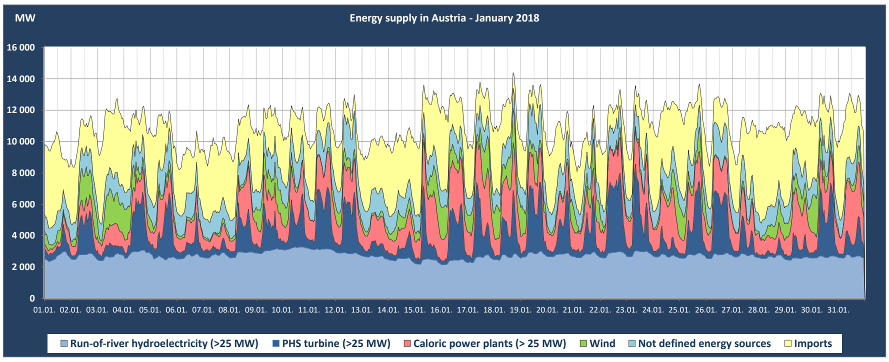


Figure 3.7.: energy supply in January 2018 provided by e-control

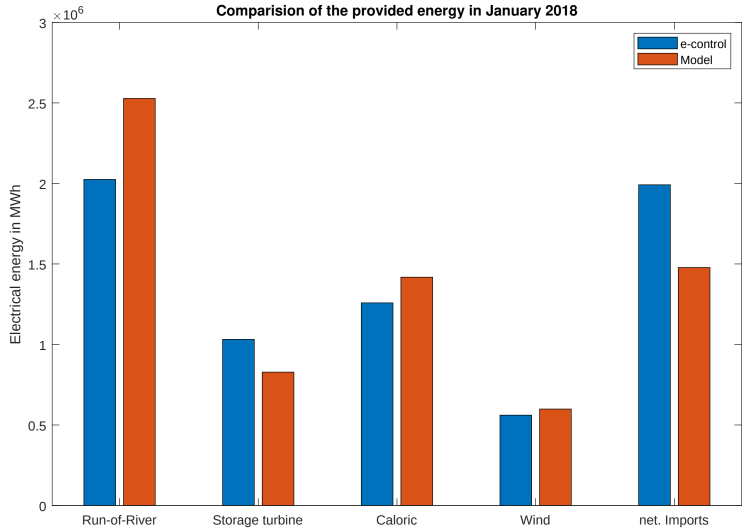


Figure 3.8.: comparison between the e-control and the model for January 2018

transfer and transformation losses) arise from the fact that the model is a closed model, between Austria and the neighbour countries. In reality, there is also a power flow from these countries to their neighbour countries etc. This will result also to another power flow to Austria.

	e-control [MWh]	model [MWh]	rel. error [%]
RoR	2024703	2527700	24,8
PHS	1031530	828220	-19,7
Caloric	1258271	1417761	12,7
Wind	560890	599030	6,8
Imports net	1991387	1477800	-25,8
Sum	6866781	6850511	-0,2

Table 3.2.: comparison of the e-control data with the model results for January 2018

4. Empirical settings of the general parameters in the different scenarios

There are seven scenarios modeled and their effects examined in this thesis. In one of them, the “ENTSO-E Master Plan“ forms the basis for all the other scenarios. This scenario is based on the ENTSO-E dataset [1] with changes regarding the expansion of coal and nuclear power plants. These are unchanged to the actual installed power in 2018, to make it possible to see the sensitivities of these generation capacity changes to the whole electricity market model.

Hereinafter the capacity of already build power plants in the neighbour countries and Austria changes. On the one hand changes regarding coal and nuclear power plants and on the other hand also changes regarding the CO_2 prices and pre-build generation capacities in Austria are considered. In this chapter, all parameters of the model will be discussed. They stay mainly the same in the different scenarios, which will be presented in chapter 5.

The following general parameters are presented in the following in detail:

- electrical grid based on the **TYNDP** 2030
- detailed generation capacities in Austria with status 2018
- aggregated generation capacities in foreign countries based on the ENTSO-E for 2030
- renewable energy generation profiles based on the ENTSO-E transparency, for each country individual.
- One aggregated storage per node, with status 2018
- natural inflow to the storages
- marginal costs are calculated with future CO_2 and fuel prices
- electrical energy demand based on the ENTSO-E ST 2030 data
- heat demand is modeled based on the 2018 data of ”Wien Energie”.
- PV,- wind,- and run-of-river power plants are build-able at all nodes in Austria

[1] `https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenarios%20Data%20Sets/ENTSO%20Scenario%202018%20Generation%20Capacities.xlsm`

Country	Interconnector NTC 2018 [MW]	Interconnector NTC 2030 [MW]
Switzerland	1200	1700
Czech	600	1200
Germany	4900	7500
Hungary	400	800
Italy	295	1335
Slovenia	950	2200

Table 4.1.: Interconnectors in 2018 and 2030 between Austria and its neighbouring countries

4.1. Electrical grid

The electrical grid in the model (both for 2018 and 2030) (see figure 3.3) is assumed as many bidirectional one-to-one connections between the nodes. Each power line is parametrized with a specific constant susceptance (which determines the power flow between the nodes) and a constant NTC value. This NTC values in MW, represents the thermal limitations of the power lines. The NTC values stay constant during the whole optimization period and are the same for power flows in both directions.

The used parameters for the power lines from 2018 (see chapter 3.4.1) are changed to model the network expansion plans which will be done in the upcoming years. This expansion will not add any new power lines between the nodes to the model, but allow a higher power flow, particularly between Austria and it's neighbour countries. These plans are made and listed in the **TYNDP** (ten years network development plan) to ensure a stable Europe-wide electricity system, taking into account the increased volatile generation from renewable energy sources.

The new values of the interconnectors, which allow power flows between the countries are listed in table 4.1.

This leads to new power line parameters, which are used for all scenarios, which are listed in table A.2.

4.2. Generation capacities

As evident in figure 3.3 Austria is modeled with 17 nodes, while the neighbour countries (7) are modeled as one node per country. This directly results in a different modeling of the generation capacities for the countries.

In Austria, every node has installed one PV,- wind,- and Run-over-River power plant and several different caloric power plants. These caloric power plants differ not only through their individual power capacity but also through their efficiency, emission factor, used fuel and operation and maintenance costs. This results in various marginal costs. Furthermore, several heat and steam plants are able to deliver combined heat and power. This is described with an individual factor that characterises the correlation between electrical and thermal energy production for the specific power plant.

On the other hand in the foreign countries, each type of renewable energy sources (PV, wind, and Run-over-river) and caloric power plants (gas, lignite, oil, coal, "other renewables", nuclear and "other non-renewables") are installed only one time per node. There is also no heat demand considered for these nodes. This also means that, in contrast to Austria, the marginal costs for a specific type of power plant are always the same, while in Austria there exist cheaper and more expensive power plants based on the same fuel.

Additional each node may contain one storage, which is specified through his maximum power, capacity, and efficiency.

Since this thesis aims to find optimal investment decisions for Austria in the year 2030, the existing power plants and storages in 2018 are used as a starting point of the optimization process. While new power plants, and therefore new generation capacities, can be built in the year 2030 the capacity of storages stays constant.

The starting point of the model for Austrias neighbouring countries are the results of the ENTSO-E 2030 Sustainable Transition (ST) scenario. This takes into account the expansion of especially renewable energy sources but also in some cases caloric power plants.

Coal and nuclear power plants are not adapted (usually downsized) based to the ENTSO-E because the effects of an exit are to be examined in chapter 5.

4.3. Marginal costs

The marginal costs

$$marginal_{costs}[€/MWh] = O\&M_{costs} + \frac{Fuel_{costs}}{efficiency} + \frac{emission_{factor} * CO_{2_{price}}}{efficiency} \quad (4.1)$$

of the caloric power plants in Austria are calculated based on their efficiency, emission factor, and O&M costs. The used values for Austria can be found in table 4.2

Type	Fuel	Efficiency [%]	Emission factor [t CO2/MWh]	O&M costs [€/MWh]
thermal	Gas1	34%	0,20196	1,6
thermal	Gas2	45%	0,20196	1,6
thermal	Gas3	56%	0,20196	1,6
thermal	Oil1	32%	0,27	3,3
thermal	Oil2	35%	0,27648	3,3
thermal	Oil3	38%	0,28296	3,3
thermal	OtherNonRES	35%	0,28296	3,3
thermal	OtherRES	46%	0	0
thermal	Coal	40%	0,38	3,3
thermal	Nuclear	33%	0	9

Table 4.2.: Parameters for the calculation of the marginal costs for different power plants

€/net GJ	Nuclear	0,47
	Lignite	1,1
	Coal	2,7
	Gas	8,8
	Oil	21,8
€/ton	CO_2 price	84,3

Table 4.3.: fuel and CO_2 costs based on the ENTSO-E ST scenario

The emission factor in combination with significant CO_2 costs leads to higher marginal costs for power plants with high CO_2 emission. The used fossil fuel and CO_2 costs are listed in table 4.3 based on the ENTSO-E ST scenario.

The marginal costs for caloric power plants with the fuel gas, oil, "other renewables"and "other non-renewables "in the foreign countries are assumed as the weighted average costs of all power plants in Austria which use the same fuel. The marginal costs of nuclear and coal power plants are calculated with assumed values as listed in table 4.2, while those for lignite power plants are assumed as if they were the same as for gas turbines.

This results in the implemented, already installed, power plants for all nodes with their individual marginal costs and power capacity as listed in table A.4. Whereby the capacities and marginal costs in this table may change in the following scenarios. The storages for all future scenarios stay the same as in 2018 (table A.6) and there is no option to build new ones.

Type	Investment costs sum [€/MW]	Depreciation period [a]	Interest rate [%]	CRF	Investment costs 2030 [€/MW]
PV	800 000	20	5	0,0802	64 194
Wind	1 200 000	16	5	0,0923	110 724
RoR	3 290 000	50	5	0,0548	180 215

Table 4.4.: Investment costs and used parameters for build-able power plants

4.4. Investment costs

Political decisions in all countries affect not only the expansion but also the reduction of specific types of power plants. Coal and nuclear power plants are particularly affected by these measures. To investigate the effects of these changes have on investment in generation capacities in Austria there has to be an option in the model to build new ones in Austria.

To fulfil the goal of the NECP for Austria only renewable energy sources are taken into accounts, which means PV,- wind,- and run-of-river power plants. The overall investment costs of the report "Future of electricity in Austria - 2030"(Haas et al., 2017) are included in the model with a capital recovery factor to get annualized investment costs,

$$investment_{costs,2030}[€/MWh] = investment_{costs,sum} * \frac{i*(1+i)^n}{(1+i)^n - 1} \tag{4.2}$$

to get comparable costs with the marginal costs of already installed power plants. The used total investment costs (Haas et al., 2017), the depreciation period, the interest rate for the capital recovery factor calculation, and the resulting investment costs, which are used as model parameters, are listed in table 4.4.

Because for each country (price zone) different renewable generation profiles and load profiles are assumed, the economic importance of the renewable generation depends on the location they are operated.

4.5. Generation profiles of renewable sources

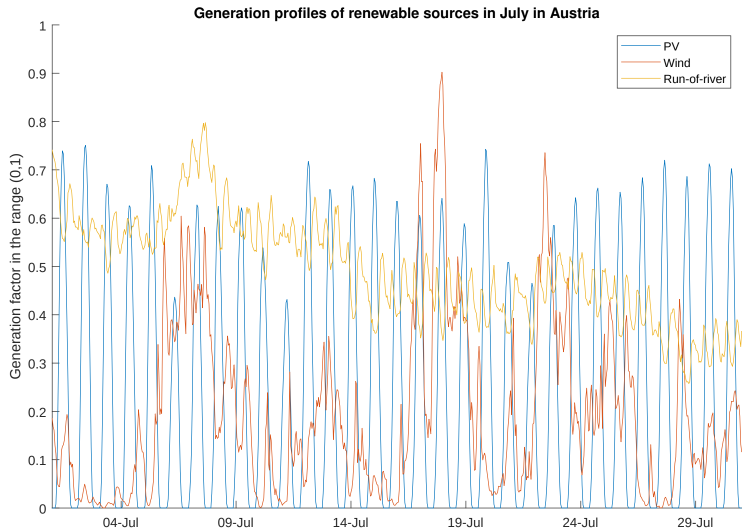


Figure 4.1.: Generation profiles in Austria during July

The generation profiles of the implemented renewable energy sources (PV, wind, and run-of-river) are calculated with the dataset of the ENTSO-E transparency platform. Based on the hourly produced energy per power plant type and the installed power of a specific type these generation profiles are calculated. An example of this generation profiles for the month July in Austria can be seen in figure 4.1. While the PV profile shows a regular peak at lunchtime and logically there is no energy production at night, the production of wind energy is much more irregular. The profile of the run-of-river power plants is the most constant and therefore the most suitable for covering the baseload demand.

According to their used generation profiles, the sum up of the whole year results in the full load hours of table 4.5. As well as their generation profiles they differ from country to country. This makes for example PV devices much more economically attractive in Italy than in other countries.

	Austria	Germany	Switzerland	Czech	Slovakia	Hungary	Italy	Slovakia
PV	1193	963	1193	1143	893	893	2904	931
Wind	2216	1733	2216	1968	1569	1758	1874	1758
RoR	4525	3719	2900	2229	4337	2966	3313	2623

Table 4.5.: Full load hours of the renewable generation

4.6. Energy demand

The electricity demand in all countries (one price zone per country) is based on the ENTSO-E 2030 Sustainable Transition scenario. This assumes that the decarbonisation of the energy system is a big goal of the EU, the governments, and their NECPs. Therefore national regulations are causing CO_2 and fuel prices to rise. It is believed that these costs can provide support for renewable energy sources to ensure a stable EE-wide electrical energy system.

Since the neighbouring countries are only represented by one node, the whole electrical energy in this country is demanded at this node. In Austria however, the whole energy demand has to be split to the 17 nodes (all nodes together form one price zone) of the model what is being done by the constant factors of table A.7.

Additionally, for Austria, a heat demand is considered. With this heat demand a sector coupling by combined heat and power plants in Vienna can be simulated. These CCGT power plants are able to produce electrical and thermal energy at the same time.

To model the heat demand for Austria (in Vienna in the following scenarios), a correlation between temperature and heat demand was assumed. Thus, by standardizing the temperature profile for 2018, there is a demand profile for heat. This profile was converted into an hourly heat demand using the total amount of heat generated by "Wien Energie" in 2018 (minus 22 % to cover heat generation from other sources) [2]. Since the heat demand in Vienna can only be delivered by a few power plants, this can be converted directly into a time-dependent minimum electrical power output of the specific gas power plants using the heat electricity factor (see table A.4) and is thus adopted in the model.

[2] https://www.wien.gv.at/statistik/verwaltung/tabellen/strom-zr.html

5. Results

Based on the NECPs of all European nations, political decisions regarding the expansion and decommissioning of generation capacities are made. The cross-national electricity network and in particular the interconnectors between Austria and neighboring countries mean that these decisions have an impact on the optimal expansion of generation capacities in Austria. Some possible measures, which primarily concern the decarbonization of the electricity market and the nuclear phase-out of Austria's neighboring countries, are discussed below. An overview of the installed power capacities which are varied in the following sections in the neighboring countries is shown in figure 5.1.

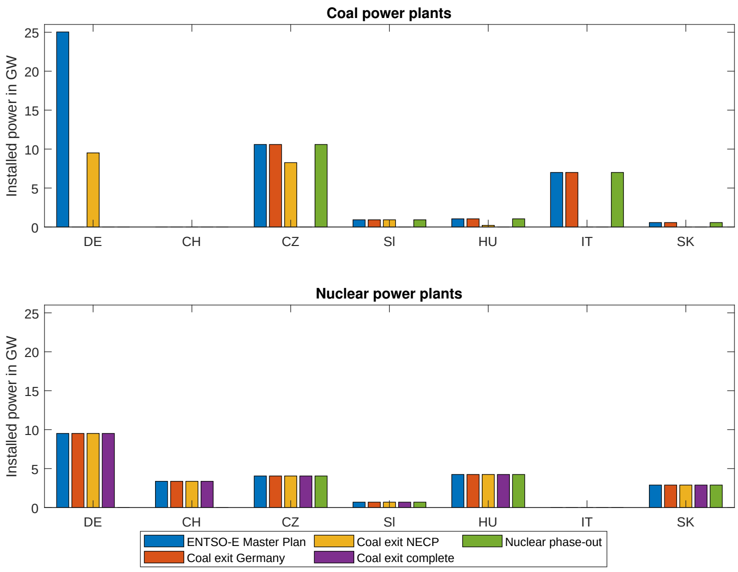


Figure 5.1.: Overview of the installed power of coal and nuclear power plants

	New build power capacity [MW]		
Node	PV	Wind	Run-of-river
VBG	0	48	2048
TIR_w	0	1983	1434
TIR_e	0	1598	1984
OTIR	0	0	2641
SBG_s	0	0	1232
SBG_n	0	0	38
OOE_e	0	479	0
OOE_w	0	1067	2805
NOE	0	0	722
NOE_n	0	0	0
BGLD	0	1378	3033
W	0	0	1405
STMK_w	0	0	2906
STMK	0	0	1979
STMK_s	0	0	199
KTN_e	0	45	1854
KTN_w	0	2498	1555
sum	**0**	**9096**	**27625**

Table 5.1.: new build power capacities according to “ENTSO-E Master Plan“

5.1. ENTSO-E Master Plan

5.1.1. Description

This chapter forms the starting point for all the following considerations and is based on the model parameters, which have already been described in chapter 4.

- Coal and nuclear power plants will not be decommissioned but will be considered as of 2018

5.1.2. Modeling Results

The new installed power capacities in Austria are listed in table 5.1.

There are no PV systems expanded at any of the nodes in Austria. This is due to the fact that the full load hours according to the generation profiles are significantly less than those of wind and Run-of-river power plants (see table 4.5). In combination with the investment costs used according to table 4.4, there is no economically optimal investment in PV systems from the point of view of the overall system. However, PV systems make economic sense from the perspective of house owners and small companies, since they consider their economy over a retail electricity price and do not compete directly with the marginal costs of other generation technologies. These installed devices reduce the local energy demand and can be seen as negative energy demand.

If one considers the downregulation of renewable energy generation, in this scenario about 10 % of the available energy in Austria is not used regardless of the technology. The obvious thing to do here would be to expand the storage facilities so that less renewable energy sources have to be down-regulated. Due to the lack of expansion options in neighboring countries, renewable energies are never curtailed there.

Besides, the power flow through the interconnectors of Austria is almost exclusively positive (therefore Austria exports significantly more energy than gets imported). The current power flow is largely near the limitations of the line capacities. This shows how important the expansion of the Europe-wide transport network is as it will be done according to the **TYNDP**.

5.2. Coal exit

In these scenarios, various possibilities regarding the future of coal fired power plants are examined. All these have in common that a coal exit takes place while maintaining the assumed CO_2 prices. The proportion of coal fired power plants that are shut down differs depending on the scenario and nation and is described below.

5.2.1. Description - Coal exit: Germany

There are no coal fired power plants in use in Germany anymore.

This results in reduced generation capacities in Germany of 25035 MW as can be seen in table A.4.

5.2.2. Description - Coal exit: National energy and climate plans

According to the NECPs of the neighboring countries (Flisowska and Moore, 2019) their capacity of coal fired power plants is reduced as listed in table 5.2.

This forms the most realistic scenario of the coal exit for 2030.

Country	installed capacity is reduced to [%]
Germany	38
Czech	78
Slovenia	100
Hungary	20
Italy	0
Slovakia	0
Switzerland	0 (as already in 2018)

Table 5.2.: Coal fire power plants reduction according to national energy and climate plans

5.2.3. Description - Coal exit: complete

All coal fired power plants in all neighboring countries are shut down completely.

This scenario, which is unrealistic until 2030, should nevertheless be examined to show the effects of the complete coal exit.

5.2.4. Modeling Results - high CO_2 price

The results of the coal exit scenarios are listed in table A.8.

The marginal costs of coal-fired power plants are slightly higher than those of lignite and gas power plants. Therefore, already in the "Master Plan scenario", these were used only to a very small extent. As a result, the optimal investment decisions in Austria change slightly overall.

It is evident in figure 5.2 that, even before the coal exit, coal fired power plants are only used to a very small extent for a few hours per years, therefore the exit does not change the composition of the produced energy within a country.

Since the coal fired power plants are not important anymore under these conditions the produced electrical energy from caloric power plants differs only a little in all these scenarios.

As evident in figure 5.3 the very low priced nuclear power plants are generating electricity at their maximum capacity nearly all the time. The same applies to "Other Renewables". The next more expensive technology, gas,- and lignite fired power plants are used to cover demand peaks. It follows that coal fired power plants are not used very often and therefore the coal exit has no big impact under the assumption of the used marginal costs. Lower CO_2 prices, and therefore lower marginal costs can change the results, as it will be examined in chapter 5.2.5.

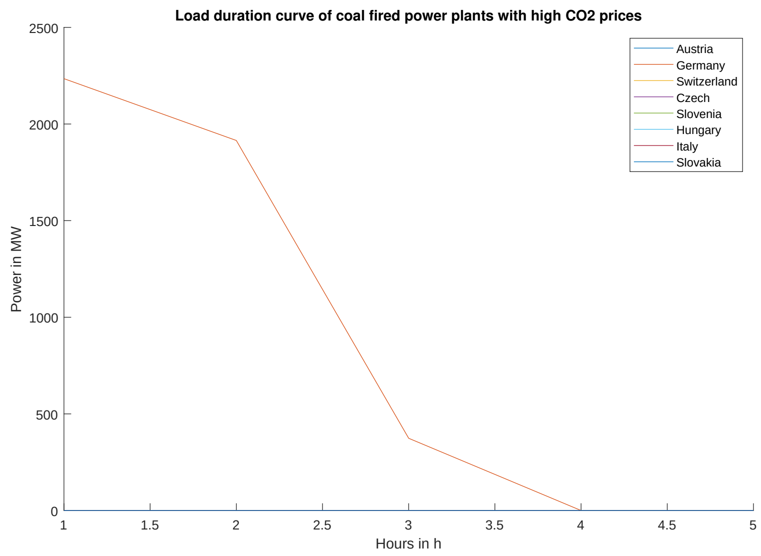


Figure 5.2.: Load duration curve of coal fired power plants before the coal exit

This also results in the effect, that in each of these “coal exit“ scenarios nearly the same power capacity of Wind turbines and run-of-river power plants is installed in Austria, and there are no big investment changes in comparison to the “Master Plan“ scenario. Only the location differs depending from scenario to scenario to ensure an optimal load flow.

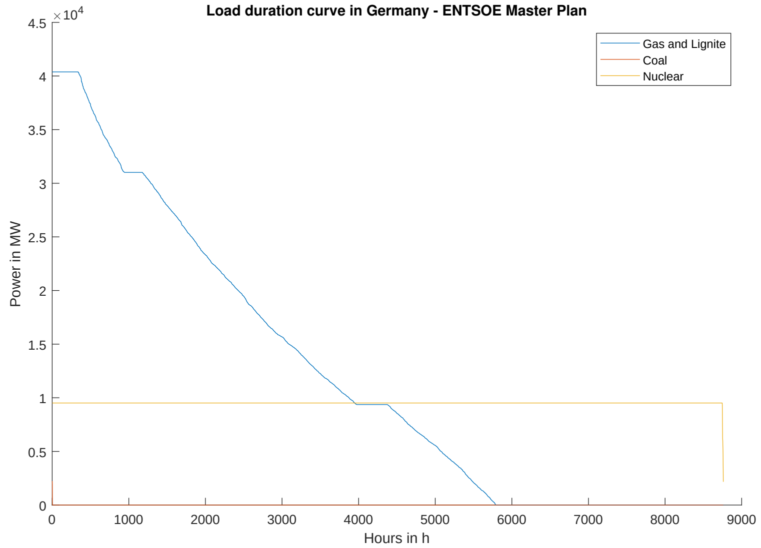


Figure 5.3.: Generated power in Germany in the "ENTSO-E Master Plan"

5.2.5. Description - Coal exit: National energy and climate plans - lower CO_2 price

According to the NECP of the neighboring countries (Flisowska and Moore, 2019) their capacity of coal fired power plants is reduced as listed in table 5.2. The CO_2 costs are reduced to 50 €/ton

The most realistic scenario for the exit of coal fired power plants is examined one more time but with slightly reduced CO_2 costs. Now they are 50 €/ton and not 84,3 €/ton anymore. Therefore the marginal costs of coal fired power plants are now lower than the one of gas turbines (see table A.5).

5.2.6. Modeling Results - lower CO_2 price

The lower CO2 price and thus falling marginal costs lead to a significantly reduced expansion of generation capacities in Austria. In addition to the PV systems, no wind power plants are being built. The expansion of run-of-river power plants is also reduced by 6 %. This is because significantly more energy can now be produced by existing power plants and it is no longer economically viable to expand and export renewable energies in Austria.

The lower expansion of capacities in Austria leads directly to lower energy exports. This amount of energy must now be provided by neighboring countries via caloric production. In the “Coal exit“ scenarios it was already described that the coal-fired power plants are used very rarely due to the high marginal costs.

The lower CO_2 prices now result in a shift in the merit-order ranking due to the associated lower marginal costs of coal fired power plants. These are now cheaper than gas/lignite power plants and are therefore used primarily.

In Germany, coal-fired power plants are now cheaper than gas turbines, coal-fired power plants now work to cover the base load. However, since their capacity is significantly lower than that of the gas turbines, these are additionally used, but with lower full load hours (compare figure 5.3 with figure 5.4).

Comparison between figure 5.2 with high CO_2 prices and figure 5.5 with lower ones, shows that this price component affects the use of these power plants to a very high degree.

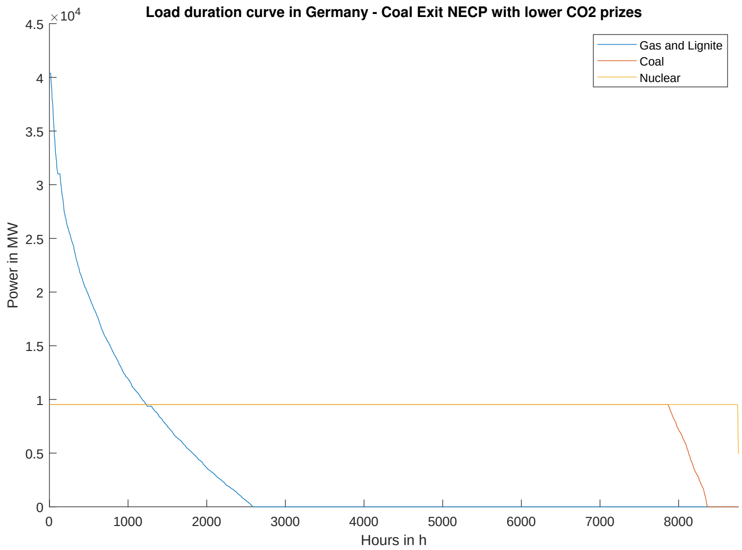


Figure 5.4.: Generated energy in Germany in the “lower CO_2 costs scenario“

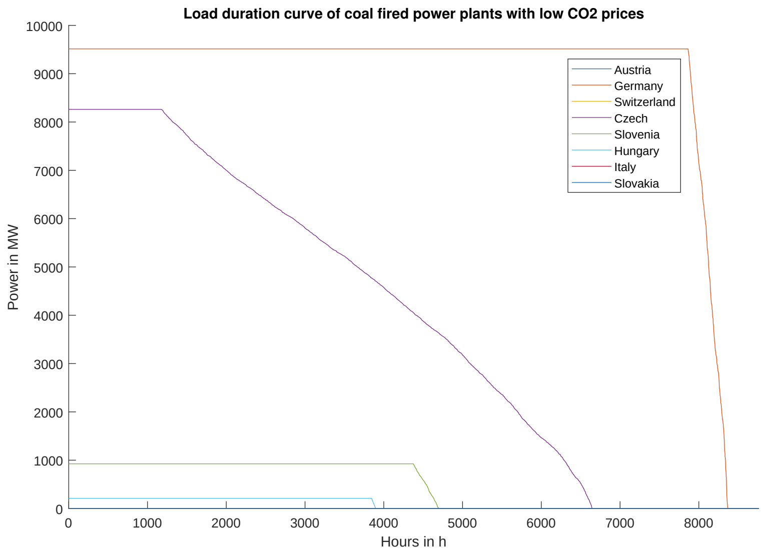


Figure 5.5.: Load duration curve of coal fired power plants with reduced CO_2 prices

Big differences in the energy generation can be also seen in the Czech Republic, where the previously little-used but heavily expanded coal-fired power plants are now being used significantly more, with a large proportion of the energy generated thereby being exported. This energy is used to cover the energy demand in Italy via load flow. Because of their NECPs, there is no longer a coal-fired power plant in operation so the energy import and gas fired power plants are used to cover the demand. As can be seen in figure 5.6 all still available coal fired power plants are working now to cover the baseload.

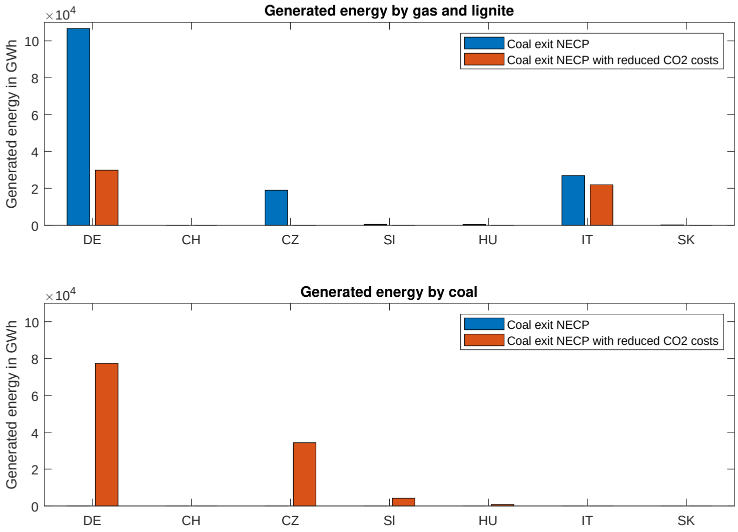


Figure 5.6.: Generated energy according to NECP plans with high and low CO_2 prices

5.3. Nuclear phase-out - Germany and Switzerland

5.3.1. Description

The coal exit of Germany, (Switzerland has no coal fired power plants in all scenarios), and the planned nuclear exit of these both countries is examined in this chapter. These decisions are already made and their implementation is planned in both countries. Therefore the coal fired power plants in Germany and the nuclear power plants in Germany in Switzerland are shut down.

5.3.2. Modeling Results

Due to the dismantling of the cheap nuclear power plants, which were previously operated almost permanently at the capacity limit to cover the baseload, compensation of this energy is now required. While the actions taken, in Germany reduce the energy supply from caloric power plants by only approx. 2 %, it is in Switzerland 72 %. This is compensated by a drastic increase in energy imports and lower exports as shown in figure 5.7.

This is also due to the fact that Switzerland previously generated all the caloric energy from nuclear power and “other renewables“, and that there are currently no alternatives within the country installed. Therefore, with the phase-out of nuclear power, it will be necessary to install CCGT power plants with combined heat and power supply in Switzerland as well, so as not to be completely dependent on energy imports from neighboring countries while the energy generation from renewable energies is low. This issue is also already being discussed nationally in politics.

In Germany the not longer available cheap energy from nuclear power plants is now compensated by higher full load hours of the gas and lignite power plants (compare figure 5.3 with figure 5.8) and also the very expensive “other non-renewables“ fired power plants are used to compensate demand peaks.

To meet the increased demand, there is a higher expansion of generation capacity in Austria. While under the assumption of a coal exit the expansion of wind power plants in Austria remained constant, it has now increased by 329 MW and that of Run-of-river power plants by 173 MW.

The lines from Germany in the Master Plan are 72 % used to capacity after the nuclear phase-out it is 76 %. This shows that there are still capacities available in terms of lines between the countries. The lines from Austria, on the other hand, are always used to capacity to about 92 % before and after the nuclear phase-out. This shows that the increased energy requirement is mainly compensated by power flows between neighboring countries.

Therefore, the decommissioning of 13 GW of nuclear power plants, which previously covered the baseload in continuous operation, will be compensated with the construction of only approx. 500 MW of renewable energies in Austria.

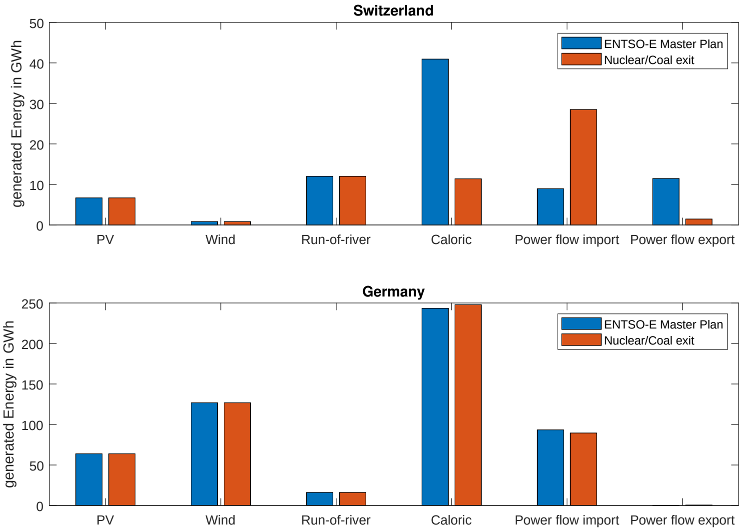


Figure 5.7.: Generated power comparison between the "ENTSO-E Master Plan" and the "Nuclear phase-out"

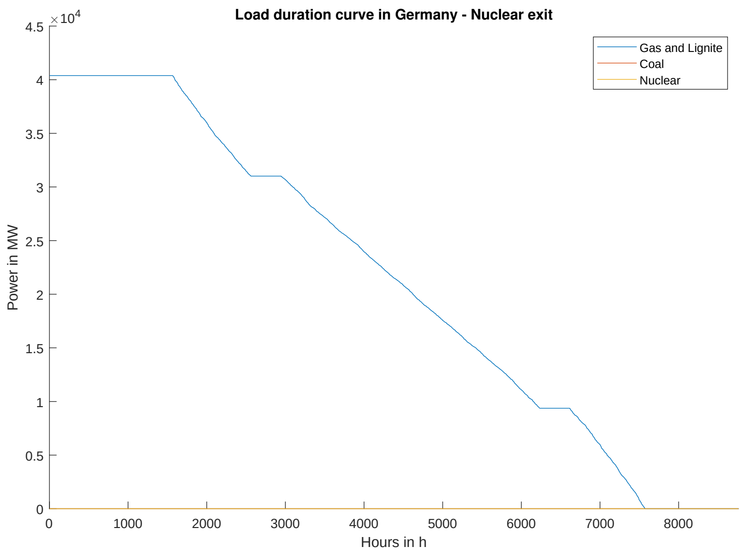


Figure 5.8.: Generated power in Germany after the nuclear phase-out

5.4. PV Expansion

As already mentioned as a result of the “ENTSO-E Master Plan“ scenario in section 5.1, there will be no PV expansion in Austria under the given framework conditions that the economic optimum should be determined from the perspective of the overall system. In reality, it will be economically reasonable for some households since they consider their economy over a retail electricity price. Because in the investment model all three types of renewable energies compete directly with the marginal costs of the existing power plants and thus with the EXAA. From the point of view of the private investor or homeowner, however, state-subsidized feed-in tariffs often exist, and a significant proportion of the energy produced is self-consumed. Therefore, the profitability for the owner of the PV system is considerably better since less energy has to be obtained from the energy provider. These installed PV devices have an effect on the whole electricity market, since they reduce the energy demand and will lead to an oversupply especially in summer, and therefore affect the investment decisions into generation capacities.

5.4.1. Description - expansion to 4,5 GW

Therefore in this scenario in sum 4500 MW of PV power plants (instead of 1200 MW) are installed in Austria as assumed by the ENTSO-E 2030 ST scenario. These PV devices are distributed over all the nodes in Austria, depending on the installed power capacity in 2018. Therefore an even relative expansion through the nodes is assumed.

The other parameters stay the same as in the “ ENTSO-E Master Plan“, this will show the effects the PV expansions has on the expansion of Run-of-river and Wind power plants.

5.4.2. Modeling Results

The additional expansion to 4500 MW (this means a plus of 3.3 GW) leads to a total decline in the expansion of approx. 1 GW for wind and run-of-river power plants, as can be seen in figure 5.9. This figure shows the total amount of new-built generation capacities in 2030, although it should be noticed that the PV expansion of 4500 MW was forced by the scenario. If the amount of energy generated in the whole year is calculated taking the full load hours of the technologies into account, the result is that approx. 1.5 % less energy is produced. Meanwhile, the total investment costs remain almost constant.

To compensate for the somewhat lower generated energy by renewable sources, gas turbines are now being used in Austria with their low marginal costs. Before that, they were only used to compensate the heat demand by combined heat and power and to compensate the electrical peak demand, which sums up in relatively few full load hours.

This does not change the energy supply of neighboring countries and their energy flows via the interconnectors, but only the energy generation within Austria.

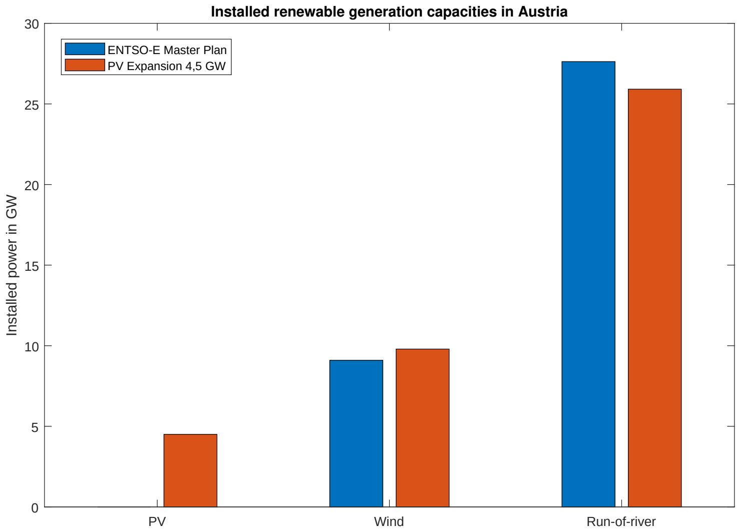


Figure 5.9.: Investment in renewable energy in Austria with/without PV investment of 4,5 GW

5.4.3. Description - expansion to 11,9 GW

In this scenario, the installed power of PV power plants gets further expanded up to 11,9 GW. This value was taken into account for the calculation of the NECP for Austria. To achieve 100 % electrical energy by renewable sources 7 GW wind, 11,96 GW PV, and 18 GW run-of-river power plants were installed. Haas et al., 2017

5.4.4. Modeling Results

From the point of view of the neighboring countries, little will change due to the increased expansion of PV systems. Due to the high CO_2 prices, the expansion of renewable energies in Austria and following energy exports are still cheaper than operating the existing thermal power plants.

Further expansions in Austria done by 13 GW wind and 21 GW run-of-river power plants as can be seen in figure 5.10. Due to the fact that PV systems, in contrast to the other two types of renewable energies considered, have a significantly larger volatile energy production over the course of the day, this in turn leads to increased use of CCGT power plants with the lowest marginal costs, and therefore the highest efficiency.

If the gas power plants used are operated with renewable fuel, the goal of the Austrian NECP can be achieved. (Parliament, Union, and Vienna, 2021)

Due to increased expansion, also in the neighboring countries, and the associated lower export from Austria, a significantly lower expansion is sufficient. If exports are assumed similar to those considered in Haas et al., 2017, the models deviate by 21 %, which can be justified by the different CO_2 prices and demand profiles.

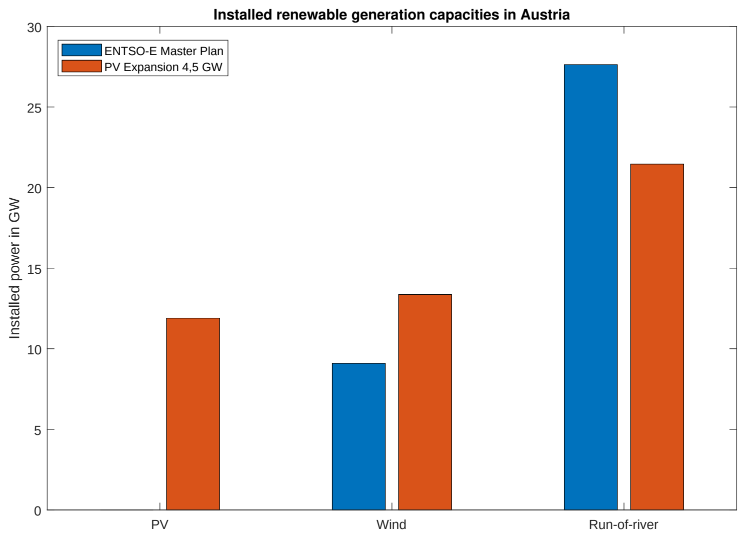


Figure 5.10.: Investment in renewable energy in Austria with/without PV investment of 11,9 GW

5.5. Investment decisions summary

The investments of all seven scenarios of this thesis are compared in figure 5.11 and listed in table A.9. As already described, the coal phase-out, taking into account high CO_2 prices, hardly influences investment decisions. By reducing these costs, the economic reasonable need for new generation capacities is shortened. Also, a predefined expansion of PV systems influences the need for wind and run-of-river power plants depending on the extent of the expansion of these.

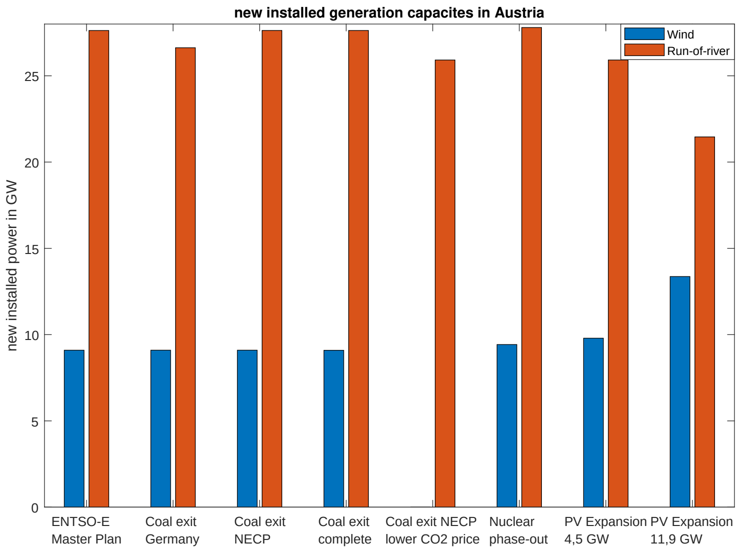


Figure 5.11.: Comparison of the investment decisions in all scenarios

6. Conclusion

The high CO_2 costs in combination with the depreciation periods of renewable energies create a strong incentive to expand them and thus replace CO_2 emitting caloric power plants.

From the point of view of a central planer, an economic optimum does not build any PV devices with any of the used input parameters. According to the generation profiles in Austria, there was no investment taken, but in other countries, especially in Italy PV power plants are economically much more interesting since their full load hours are significant higher. But also in Austria, PV systems will certainly be expanded, since from the operator's point of view these can make economic sense. Especially taking into account government grants and economic competition between the investment and the retail electricity price and not the marginal costs. This shows that the investment decisions will change depending on whether a top-down central-planer or a bottom-up operator model is used.

In the examined scenarios, approximately 10 % of the energy production of renewable energies is down-regulated relatively constantly. This happens due to the depreciation period, investments in renewable energies, in relation to marginal costs of the caloric power plants, make economic sense even if their "potential" is not fully used. This is through the fact that the introduction of CO_2 prices results in higher marginal costs of already existing caloric power plants. Since a real prospective decentral energy system will contain many small distributed generation capacities, it will be very important to implement a possibility, to regulate them by the network operator as soon as a large part of the energy production is to be carried out by these renewable energy sources. In addition to the possibility of a down-regulation, which reduces the economic efficiency from the point of view of the operator, the expansion of storage capacities is becoming very interesting. The capacities of the lines (which were previously expanded based on the **TYNDP** 2030) are being very well utilized, which shows how important network expansion in combination with the volatile renewable energies is.

The high CO_2 prices make the marginal costs of coal-fired power plants higher than those of nuclear and CCGT plants. As a result, little will change in the entire electricity market depending on the exit decision of the coal-fired power plants. Only the reduction of CO2 costs makes coal-fired power plants economical more attractive than other caloric power plants and therefore they are used to cover the baseload. This would lead to a reduced need for renewable energies but would increase the greenhouse gas emissions of the produced/used electricity mix in all countries. This shows the strong influence of the politically determined CO_2 prices on the use of coal-fired power plants.

The examined nuclear phase-out in Germany and Switzerland shows the effects on the European electricity market, with the elimination of the inexpensive nuclear power plants and thus the baseload coverage. If other caloric power plants are available, they are used to cover the energy demand, but if there is insufficient capacity, as in Switzerland, energy has to be imported. Thus the nuclear phase-out requires on the one hand the expansion of alternative generation capacities and on the other hand sufficient expanded power lines between the countries. Run-of-river power plants could be used to generate the energy for this base demand.

Further improvements of the investment model used in this thesis may include a much more detailed sector coupling of the heat demand. In many cities and also more rural regions district heating gets expanded and more important especially since oil will become forbidden in Austria and so about 600 000 oil heatings have to be replaced. Near industrial areas waste energy can be used to compensate this demand and if this energy is not sufficient CCGT power plants as modeled in this thesis have to be used. If the usage of these power plants is combined with a Power to Gas (P2G) process another problem that has been discussed in this thesis can be solved, namely the downregulation of renewable energies. The energy peaks which can not be used or stored at the moment do not have to be down-regulated, they can be stored by a P2G progress in hydrogen. With this hydrogen CCGT power plants can be used in a CO_2 neutral way which will further improve the decarbonization of the gas infrastructure and their competitiveness on an electricity market with a high share of renewable energies.

Furthermore, the investment model could be expanded to a combined generation and transmission expansion problem.

Through the modeled costs of infrastructure expansion and power transmission fees (Grimm et al., 2019) incentives can be affected to build local decentral renewable generation technologies that will not use the power lines that much. Transmission charges aim to recover the costs of network investments. This aims to build up new generation at nodes, where the energy is used and therefore change the geographic distribution of investment decisions to a more decentral way with lower power transmissions. Also, the possibility to build carbon storages and therefore reduce the marginal costs of power stations, since there are less CO_2 emissions, could affect the competitiveness of thermal power plants in a market environment with high CO_2 prices.

As is evident in the scenarios down regulations of renewable energy sources are widely used. To do not waste energy, energy storages can be used. On effective way to do this could by implementing a sector coupling to the model with electrical cars and a vehicle to grid (V2G) system. So the more and more rising numbers of electrical cars are not only used and modeled as geographically moving consumers. They can also be used to provide energy to the electricity net if they are currently not used and there are peak demands which have to be compensated. This could positively affect the network stability and avoid costs of network expansion and the investment into further energy storages since these already exist due to the electric vehicles.

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Appendix

Appendix A.

Parameters

Type	Fuel	installed power [MW]	marginal costs [€/MWh]	Node	heat electricity factor
PV	PV	77,05	0	VBG	0
PV	PV	25,53	0	TIR_w	0
PV	PV	34,02	0	TIR_e	0
PV	PV	0	0	OTIR	0
PV	PV	0,02	0	SBG_s	0
PV	PV	43,08	0	SBG_n	0
PV	PV	111,47	0	OOE_e	0
PV	PV	83,51	0	OOE_w	0
PV	PV	222,29	0	NOE	0
PV	PV	119,39	0	NOE_n	0
PV	PV	9,28	0	BGLD	0
PV	PV	69,4	0	W	0
PV	PV	86,04	0	STMK_w	0
PV	PV	36,56	0	STMK	0
PV	PV	219,54	0	STMK_s	0
PV	PV	23,06	0	KTN_e	0
PV	PV	11,15	0	KTN_w	0
wind	wind	0	0	VBG	0
wind	wind	0,75	0	TIR_w	0
wind	wind	0	0	TIR_e	0
wind	wind	0	0	OTIR	0
wind	wind	0	0	SBG_s	0
wind	wind	0	0	SBG_n	0
wind	wind	30,42	0	OOE_e	0
wind	wind	9,43	0	OOE_w	0
wind	wind	588,23	0	NOE	0

wind	wind	882,48	0	NOE_n	0
wind	wind	1 163,42	0	BGLD	0
wind	wind	87,79	0	W	0
wind	wind	64,81	0	STMK_w	0
wind	wind	0	0	STMK	0
wind	wind	58,83	0	STMK_s	0
wind	wind	0	0	KTN_e	0
wind	wind	0,84	0	KTN_w	0
hydro	hydro	172,80	0	VBG	0
hydro	hydro	213,82	0	TIR_w	0
hydro	hydro	194,87	0	TIR_e	0
hydro	hydro	50,77	0	OTIR	0
hydro	hydro	392,33	0	SBG_s	0
hydro	hydro	74,370	0	SBG_n	0
hydro	hydro	1 645,95	0	OOE_e	0
hydro	hydro	8,72	0	OOE_w	0
hydro	hydro	944,08	0	NOE	0
hydro	hydro	358,53	0	NOE_n	0
hydro	hydro	1,63	0	BGLD	0
hydro	hydro	182,97	0	W	0
hydro	hydro	191,41	0	STMK_w	0
hydro	hydro	72,65	0	STMK	0
hydro	hydro	221,97	0	STMK_s	0
hydro	hydro	568,08	0	KTN_e	0
hydro	hydro	310,05	0	KTN_w	0
thermal	Gas1	1,5	49,84	VBG	0
thermal	Gas1	18	49,84	TIR_e	0
thermal	Gas2	1	37,92	TIR_e	0
thermal	Gas2	78	37,92	SBG_n	0
thermal	Gas1	50	49,84	OOE_e	0
thermal	Gas2	304	37,92	OOE_e	0,56
thermal	Gas3	112	30,73	OOE_e	1,34
thermal	Gas1	96	49,84	OOE_w	0
thermal	Gas2	19	37,92	OOE_w	0
thermal	Gas3	395	30,73	OOE_w	0
thermal	Gas1	310	49,84	NOE	0
thermal	Gas2	241	37,92	NOE	0
thermal	Gas2	121,8	37,92	NOE_n	0

thermal	Gas1	14	49,84	BGLD	0
thermal	Gas2	5	37,92	BGLD	0
thermal	Gas1	63	49,84	W	2,38
thermal	Gas3	700	30,73	W	0,64
thermal	Gas2	365	37,92	W	0,96
thermal	Gas3	350	30,73	W	0,71
thermal	Gas3	140	30,73	W	1,21
thermal	Gas1	27	49,84	STMK_w	0
thermal	Gas2	5	37,92	STMK_w	0
thermal	Gas1	7	49,84	STMK	0
thermal	Gas2	23	37,92	STMK_s	0
thermal	Gas3	295	30,73	STMK_s	1,21
thermal	Gas1	16	49,84	KTN_e	0
thermal	Gas2	9	37,92	KTN_e	0
thermal	Gas3	395	30,73	KTN_e	0
thermal	Gas1	1,3	49,84	KTN_w	0
thermal	Gas2	0,3	37,92	KTN_w	0
thermal	Oil3	0,38	89,83	VBG	0
thermal	Oil2	0,7	107,53	TIR_e	0
thermal	Oil2	0,32	107,53	SBG_n	0
thermal	Oil1	11	128,55	OOE_e	0
thermal	Oil2	9	107,53	OOE_e	0
thermal	Oil1	51	128,55	NOE	0
thermal	Oil2	2	107,53	NOE	0
thermal	Oil2	2,5	107,53	NOE_n	0
thermal	Oil2	76	107,53	W	0
thermal	Oil2	0,6	107,53	STMK_w	0
thermal	Oil2	0,02	107,53	STMK	0
thermal	Oil1	20	128,55	STMK_s	0
thermal	Oil2	1	107,53	STMK_s	0
thermal	OtherNonRES	76,8	227,53	OOE_e	0
thermal	OtherNonRES	131,59	227,53	OOE_w	0
thermal	OtherNonRES	354,5	227,53	NOE	0
thermal	OtherNonRES	64,17	227,53	STMK_w	0
thermal	OtherNonRES	5,08	227,53	STMK	0
thermal	OtherNonRES	269,74	227,53	STMK_s	0
thermal	OtherNonRES	82,14	227,53	KTN_e	0
thermal	OtherRES	1,83	21,74	VBG	0

thermal	OtherRES	0,87	21,74	TIR_w	0
thermal	OtherRES	8,66	21,74	TIR_e	0
thermal	OtherRES	0,95	21,74	OTIR	0
thermal	OtherRES	1,17	21,74	SBG_s	0
thermal	OtherRES	31,81	21,74	SBG_n	0
thermal	OtherRES	151,36	21,74	OOE_e	0
thermal	OtherRES	56,18	21,74	OOE_w	0
thermal	OtherRES	34,69	21,74	NOE	0
thermal	OtherRES	130,29	21,74	NOE_n	0
thermal	OtherRES	43,2	21,74	BGLD	0
thermal	OtherRES	16	21,74	W	0
thermal	OtherRES	6	21,74	W	0
thermal	OtherRES	11	21,74	W	0
thermal	OtherRES	9	21,74	W	0
thermal	OtherRES	0,37	21,74	STMK_w	0
thermal	OtherRES	27,82	21,74	STMK	0
thermal	OtherRES	78,26	21,74	STMK_s	0
thermal	OtherRES	2,9	21,74	KTN_e	0
thermal	OtherRES	7,67	21,74	KTN_w	0
thermal	Nuclear	9 516	10	DE_1	0
thermal	Coal	25 035	30,53	DE_1	0
wind	wind	72 908	0	DE_1	0
thermal	Lignite	21 275	30,53	DE_1	0
hydro	hydro	3 860	0	DE_1	0
thermal	OtherRES	9 616	21,74	DE_1	0
PV	PV	42 804	0	DE_1	0
thermal	Gas	31 361	35,53	DE_1	0
thermal	Oil	4 271	117,37	DE_1	0
thermal	OtherNonRES	1 418	227,53	DE_1	0
thermal	Nuclear	3 373	10	CH_1	0
thermal	Gas	315	35	CH_1	0
hydro	hydro	7 000	0	CH_1	0
wind	wind	75	0	CH_1	0
thermal	Nuclear	4 000	10	CZ_1	0
thermal	Coal	10 592	30,53	CZ_1	0
wind	wind	310	0	CZ_1	0
hydro	hydro	334	0	CZ_1	0
PV	PV	2 040	0	CZ_1	0

thermal	OtherRES	750	21,74	CZ_1	0
thermal	Gas	1 606	35,53	CZ_1	0
thermal	Nuclear	700	10	SI_1	0
thermal	Coal	925	30,53	SI_1	0
hydro	hydro	1 053	0	SI_1	0
PV	PV	275	0	SI_1	0
thermal	Gas	491	35,53	SI_1	0
thermal	Nuclear	1 900	10	HU_1	0
wind	wind	325	0	HU_1	0
thermal	Coal	1 050	30,53	HU_1	0
hydro	hydro	28	0	HU_1	0
thermal	OtherRES	355	21,74	HU_1	0
PV	PV	336	0	HU_1	0
thermal	Gas	4 107	35,53	HU_1	0
thermal	Oil	412	117,37	HU_1	0
thermal	Coal	7 000	30,53	IT_1	0
Wind	Wind	10 000	0	IT_1	0
hydro	hydro	11 000	0	IT_1	0
PV	PV	5 000	0	IT_1	0
thermal	Gas	40 000	35,53	IT_1	0
thermal	OtherRES	45 000	21,74	IT_1	0
thermal	Nuclear	2 000	10	SK_1	0
thermal	Coal	570	30,53	SK_1	0
hydro	hydro	420	0	SK_1	0
PV	PV	530	0	SK_1	0
thermal	OtherRES	2 778	21,74	SK_1	0
thermal	Gas	1 100	35,53	SK_1	0
thermal	Oil	260	117,37	SK_1	0

Table A.3.: installed power plants in the year 2018

Type	Fuel	installed power [MW]	marginal costs [€/MWh]	Node	heat electricity factor
PV	PV	77,05	0	VBG	0
PV	PV	25,53	0	TIR_w	0
PV	PV	34,02	0	TIR_e	0
PV	PV	0	0	OTIR	0
PV	PV	0,02	0	SBG_s	0

PV	PV	43,08	0	SBG_n	0
PV	PV	111,47	0	OOE_e	0
PV	PV	83,51	0	OOE_w	0
PV	PV	222,29	0	NOE	0
PV	PV	119,39	0	NOE_n	0
PV	PV	9,28	0	BGLD	0
PV	PV	69,54	0	W	0
PV	PV	86,04	0	STMK_w	0
PV	PV	36,56	0	STMK	0
PV	PV	219,54	0	STMK_s	0
PV	PV	23,06	0	KTN_e	0
PV	PV	11,15	0	KTN_w	0
wind	wind	0	0	VBG	0
wind	wind	0,75	0	TIR_w	0
wind	wind	0	0	TIR_e	0
wind	wind	0	0	OTIR	0
wind	wind	0	0	SBG_s	0
wind	wind	0	0	SBG_n	0
wind	wind	30,41	0	OOE_e	0
wind	wind	9,43	0	OOE_w	0
wind	wind	588,23	0	NOE	0
wind	wind	882,48	0	NOE_n	0
wind	wind	1 163,42	0	BGLD	0
wind	wind	87,79	0	W	0
wind	wind	64,81	0	STMK_w	0
wind	wind	0	0	STMK	0
wind	wind	58,83	0	STMK_s	0
wind	wind	0	0	KTN_e	0
wind	wind	0,84	0	KTN_w	0
hydro	hydro	172,80	0	VBG	0
hydro	hydro	213,82	0	TIR_w	0
hydro	hydro	194,87	0	TIR_e	0
hydro	hydro	50,77	0	OTIR	0
hydro	hydro	392,33	0	SBG_s	0
hydro	hydro	74,370	0	SBG_n	0
hydro	hydro	1 645,95	0	OOE_e	0
hydro	hydro	8,72	0	OOE_w	0
hydro	hydro	944,08	0	NOE	0

hydro	hydro	358,53	0	NOE_n	0
hydro	hydro	1,63	0	BGLD	0
hydro	hydro	182,97	0	W	0
hydro	hydro	191,41	0	STMK_w	0
hydro	hydro	72,65	0	STMK	0
hydro	hydro	221,97	0	STMK_s	0
hydro	hydro	568,08	0	KTN_e	0
hydro	hydro	310,05	0	KTN_w	0
thermal	Gas1	1,5	144,85	VBG	0
thermal	Gas1	18	144,85	TIR_e	0
thermal	Gas2	1	109,47	TIR_e	0
thermal	Gas2	78	109,47	SBG_n	0
thermal	Gas1	50	144,85	OOE_e	0
thermal	Gas2	304	109,47	OOE_e	0,56
thermal	Gas3	112	88,11	OOE_e	1,34
thermal	Gas1	96	144,85	OOE_w	0
thermal	Gas2	19	109,47	OOE_w	0
thermal	Gas3	395	88,11	OOE_w	0
thermal	Gas1	310	144,85	NOE	0
thermal	Gas2	241	109,47	NOE	0
thermal	Gas2	121,8	109,47	NOE_n	0
thermal	Gas1	14	144,85	BGLD	0
thermal	Gas2	5	109,47	BGLD	0
thermal	Gas1	63	144,85	W	2,38
thermal	Gas3	700	88,11	W	0,64
thermal	Gas2	365	109,47	W	0,96
thermal	Gas3	350	88,11	W	0,71
thermal	Gas3	140	88,11	W	1,21
thermal	Gas1	27	144,85	STMK_w	0
thermal	Gas2	5	109,47	STMK_w	0
thermal	Gas1	7	144,85	STMK	0
thermal	Gas2	23	109,47	STMK_s	0
thermal	Gas3	295	88,11	STMK_s	1,21
thermal	Gas1	16	144,85	KTN_e	0
thermal	Gas2	9	109,47	KTN_e	0
thermal	Gas3	395	88,11	KTN_e	0
thermal	Gas1	1,3	144,85	KTN_w	0
thermal	Gas2	0,3	109,47	KTN_w	0

thermal	Oil3	0,38	272,6	VBG	0
thermal	Oil2	0,7	294,12	TIR_e	0
thermal	Oil2	0,32	294,12	SBG_n	0
thermal	Oil1	11	319,68	OOE_e	0
thermal	Oil2	9	294,12	OOE_e	0
thermal	Oil1	51	319,68	NOE	0
thermal	Oil2	2	294,12	NOE	0
thermal	Oil2	2,5	294,12	NOE_n	0
thermal	Oil2	76	294,12	W	0
thermal	Oil2	0,6	294,12	STMK_w	0
thermal	Oil2	0,02	294,12	STMK	0
thermal	Oil1	20	319,68	STMK_s	0
thermal	Oil2	1	294,12	STMK_s	0
thermal	OtherNonRES	76,8	295,68	OOE_e	0
thermal	OtherNonRES	131,59	295,68	OOE_w	0
thermal	OtherNonRES	354,5	295,68	NOE	0
thermal	OtherNonRES	64,16	295,68	STMK_w	0
thermal	OtherNonRES	5,08	295,68	STMK	0
thermal	OtherNonRES	269,74	295,68	STMK_s	0
thermal	OtherNonRES	82,14	295,68	KTN_e	0
thermal	OtherRES	1,83	21,74	VBG	0
thermal	OtherRES	0,87	21,74	TIR_w	0
thermal	OtherRES	8,66	21,74	TIR_e	0
thermal	OtherRES	0,95	21,74	OTIR	0
thermal	OtherRES	1,17	21,74	SBG_s	0
thermal	OtherRES	31,81	21,74	SBG_n	0
thermal	OtherRES	151,36	21,74	OOE_e	0
thermal	OtherRES	56,18	21,74	OOE_w	0
thermal	OtherRES	34,69	21,74	NOE	0
thermal	OtherRES	130,29	21,74	NOE_n	0
thermal	OtherRES	43,2	21,74	BGLD	0
thermal	OtherRES	16	21,74	W	0
thermal	OtherRES	6	21,74	W	0
thermal	OtherRES	11	21,74	W	0
thermal	OtherRES	9	21,74	W	0
thermal	OtherRES	0,37	21,74	STMK_w	0
thermal	OtherRES	27,82	21,74	STMK	0
thermal	OtherRES	78,26	21,74	STMK_s	0

thermal	OtherRES	2,09	21,74	KTN_e	0
thermal	OtherRES	7,67	21,74	KTN_w	0
thermal	Gas	31 013	102,36	DE_1	0
thermal	Coal	25 035	107,69	DE_1	0
thermal	Lignite	9 368	102,36	DE_1	0
hydro	hydro	4 329	0	DE_1	0
thermal	Oil	835	306,08	DE_1	0
PV	PV	66 300	0	DE_1	0
wind	wind	73 164	0	DE_1	0
thermal	OtherRES	6 631	21,74	DE_1	0
thermal	OtherNonRES	10 321	295,68	DE_1	0
thermal	Nuclear	9 516	14,13	DE_1	0
hydro	hydro	4 139	0	CH_1	0
thermal	Nuclear	3 373	14,13	CH_1	0
wind	wind	370	0	CH_1	0
PV	PV	5 600	0	CH_1	0
thermal	OtherRES	1 300	21,74	CH_1	0
thermal	OtherNonRES	985	295,68	CH_1	0
thermal	Gas	1 379	102,36	CZ_1	0
thermal	Coal	10 592	107,69	CZ_1	0
thermal	Lignite	4 760	102,36	CZ_1	0
thermal	Nuclear	4 055	14,13	CZ_1	0
wind	wind	950	0	CZ_1	0
hydro	hydro	365	0	CZ_1	0
PV	PV	3 540	0	CZ_1	0
thermal	OtherRES	1 167	21,74	CZ_1	0
thermal	OtherNonRES	1 505	295,68	CZ_1	0
thermal	Gas	395	102,36	Sl_1	0
thermal	Coal	925	107,69	Sl_1	0
thermal	Lignite	539	102,36	Sl_1	0
thermal	Nuclear	696	14,13	Sl_1	0
hydro	hydro	1 500	0	Sl_1	0
PV	PV	320	0	Sl_1	0
wind	wind	80	0	Sl_1	0
thermal	OtherRES	67	21,74	Sl_1	0
thermal	OtherNonRES	159	295,68	Sl_1	0
thermal	Gas	3 179	102,36	HU_1	0
thermal	Coal	1 050	107,69	HU_1	0

thermal	Lignite	682	102,36	HU_1	0
thermal	Nuclear	4 248	14,13	HU_1	0
thermal	Oil	410	306,08	HU_1	0
hydro	hydro	60	0	HU_1	0
PV	PV	2 000	0	HU_1	0
wind	wind	1 000	0	HU_1	0
thermal	OtherRES	410	21,74	HU_1	0
thermal	OtherNonRES	355	295,68	HU_1	0
thermal	Gas	32 705	102,36	IT_1	0
thermal	Coal	7 000	107,69	IT_1	0
thermal	Oil	354	306,08	IT_1	0
hydro	hydro	5 637	0	IT_1	0
PV	PV	25 420	0	IT_1	0
wind	wind	16 230	0	IT_1	0
thermal	OtherRES	5 253	21,74	IT_1	0
thermal	OtherNonRES	5 785	295,68	IT_1	0
thermal	Gas	241	102,36	SK_1	0
thermal	Lignite	240	102,36	SK_1	0
hydro	hydro	974	0	SK_1	0
PV	PV	716	0	SK_1	0
wind	wind	265	0	SK_1	0
thermal	OtherRES	505	21,74	SK_1	0
thermal	OtherNonRES	899	295,68	SK_1	0
thermal	Nuclear	2 890	14,13	SK_1	0
thermal	Coal	570	107,69	SK_1	0

Table A.4.: pre-installed power plants in the year 2030

Type	Fuel	installed power [MW]	marginal costs [€/MWh]	Node	heat electricity factor
PV	PV	77,05	0	VBG	0
PV	PV	25,53	0	TIR_w	0
PV	PV	34,02	0	TIR_e	0
PV	PV	0	0	OTIR	0
PV	PV	0,02	0	SBG_s	0
PV	PV	43,08	0	SBG_n	0
PV	PV	111,47	0	OOE_e	0
PV	PV	83,51	0	OOE_w	0

PV	PV	222,29	0	NOE	0
PV	PV	119,39	0	NOE_n	0
PV	PV	9,28	0	BGLD	0
PV	PV	69,54	0	W	0
PV	PV	86,04	0	STMK_w	0
PV	PV	36,56	0	STMK	0
PV	PV	219,54	0	STMK_s	0
PV	PV	23,06	0	KTN_e	0
PV	PV	11,15	0	KTN_w	0
wind	wind	0	0	VBG	0
wind	wind	0,75	0	TIR_w	0
wind	wind	0	0	TIR_e	0
wind	wind	0	0	OTIR	0
wind	wind	0	0	SBG_s	0
wind	wind	0	0	SBG_n	0
wind	wind	30,42	0	OOE_e	0
wind	wind	9,43	0	OOE_w	0
wind	wind	588,23	0	NOE	0
wind	wind	882,48	0	NOE_n	0
wind	wind	1 163,42	0	BGLD	0
wind	wind	87,79	0	W	0
wind	wind	64,81	0	STMK_w	0
wind	wind	0	0	STMK	0
wind	wind	58,83	0	STMK_s	0
wind	wind	0	0	KTN_e	0
wind	wind	0,84	0	KTN_w	0
hydro	hydro	172,80	0	VBG	0
hydro	hydro	213,82	0	TIR_w	0
hydro	hydro	194,87	0	TIR_e	0
hydro	hydro	50,77	0	OTIR	0
hydro	hydro	392,33	0	SBG_s	0
hydro	hydro	74,37	0	SBG_n	0
hydro	hydro	1 645,95	0	OOE_e	0
hydro	hydro	8,72	0	OOE_w	0
hydro	hydro	944,08	0	NOE	0
hydro	hydro	358,53	0	NOE_n	0
hydro	hydro	1,63	0	BGLD	0
hydro	hydro	182,97	0	W	0

hydro	hydro	191,41	0	STMK_w	0
hydro	hydro	72,65	0	STMK	0
hydro	hydro	221,97	0	STMK_s	0
hydro	hydro	568,08	0	KTN_e	0
hydro	hydro	310,05	0	KTN_w	0
thermal	Gas1	1,5	124,48	VBG	0
thermal	Gas1	18	124,48	TIR_e	0
thermal	Gas2	1	94,13	TIR_e	0
thermal	Gas2	78	94,13	SBG_n	0
thermal	Gas1	50	124,48	OOE_e	0
thermal	Gas2	304	94,13	OOE_e	0,56
thermal	Gas3	112	75,81	OOE_e	1,34
thermal	Gas1	96	124,48	OOE_w	0
thermal	Gas2	19	94,13	OOE_w	0
thermal	Gas3	395	75,81	OOE_w	0
thermal	Gas1	310	124,48	NOE	0
thermal	Gas2	241	94,13	NOE	0
thermal	Gas2	121,8	94,13	NOE_n	0
thermal	Gas1	14	124,48	BGLD	0
thermal	Gas2	5	94,13	BGLD	0
thermal	Gas1	63	124,48	W	2,38
thermal	Gas3	700	75,81	W	0,64
thermal	Gas2	365	94,13	W	0,96
thermal	Gas3	350	75,81	W	0,71
thermal	Gas3	140	75,81	W	1,21
thermal	Gas1	27	124,48	STMK_w	0
thermal	Gas2	5	94,13	STMK_w	0
thermal	Gas1	7	124,48	STMK	0
thermal	Gas2	23	94,13	STMK_s	0
thermal	Gas3	295	75,81	STMK_s	1,21
thermal	Gas1	16	124,48	KTN_e	0
thermal	Gas2	9	94,13	KTN_e	0
thermal	Gas3	395	75,81	KTN_e	0
thermal	Gas1	1,3	124,48	KTN_w	0
thermal	Gas2	0,3	94,13	KTN_w	0
thermal	Oil3	0,38	247,06	VBG	0
thermal	Oil2	0,7	267,03	TIR_e	0
thermal	Oil2	0,32	267,03	SBG_n	0

thermal	Oil1	11	290,74	OOE_e	0
thermal	Oil2	9	267,03	OOE_e	0
thermal	Oil1	51	290,74	NOE	0
thermal	Oil2	2	267,03	NOE	0
thermal	Oil2	2,5	267,03	NOE_n	0
thermal	Oil2	76	267,03	W	0
thermal	Oil2	0,6	267,03	STMK_w	0
thermal	Oil2	0,02	267,03	STMK	0
thermal	Oil1	20	290,74	STMK_s	0
thermal	Oil2	1	267,03	STMK_s	0
thermal	OtherNonRES	76,8	295,68	OOE_e	0
thermal	OtherNonRES	131,59	295,68	OOE_w	0
thermal	OtherNonRES	354,5	295,68	NOE	0
thermal	OtherNonRES	64,16	295,68	STMK_w	0
thermal	OtherNonRES	5,08	295,68	STMK	0
thermal	OtherNonRES	269,74	295,68	STMK_s	0
thermal	OtherNonRES	82,14	295,68	KTN_e	0
thermal	OtherRES	1,83	21,74	VBG	0
thermal	OtherRES	0,87	21,74	TIR_w	0
thermal	OtherRES	8,66	21,74	TIR_e	0
thermal	OtherRES	0,95	21,74	OTIR	0
thermal	OtherRES	1,17	21,74	SBG_s	0
thermal	OtherRES	31,81	21,74	SBG_n	0
thermal	OtherRES	151,36	21,74	OOE_e	0
thermal	OtherRES	56,18	21,74	OOE_w	0
thermal	OtherRES	34,69	21,74	NOE	0
thermal	OtherRES	130,29	21,74	NOE_n	0
thermal	OtherRES	43,2	21,74	BGLD	0
thermal	OtherRES	16	21,74	W	0
thermal	OtherRES	6	21,74	W	0
thermal	OtherRES	11	21,74	W	0
thermal	OtherRES	9	21,74	W	0
thermal	OtherRES	0,37	21,74	STMK_w	0
thermal	OtherRES	27,82	21,74	STMK	0
thermal	OtherRES	78,26	21,74	STMK_s	0
thermal	OtherRES	2,092	21,74	KTN_e	0
thermal	OtherRES	7,678	21,74	KTN_w	0
thermal	Gas	31 013	88,03	DE_1	0

thermal	Coal	9 513,3	75,1	DE_1	0
thermal	Lignite	9 368	88,03	DE_1	0
hydro	hydro	4 329	0	DE_1	0
thermal	Oil	835	278,12	DE_1	0
PV	PV	66 300	0	DE_1	0
wind	wind	73 164	0	DE_1	0
thermal	OtherRES	6 631	21,74	DE_1	0
thermal	OtherNonRES	10 321	267,95	DE_1	0
thermal	Nuclear	9 516	14,13	DE_1	0
hydro	hydro	4 139	0	CH_1	0
thermal	Nuclear	3 373	14,13	CH_1	0
wind	wind	370	0	CH_1	0
PV	PV	5 600	0	CH_1	0
thermal	OtherRES	1 300	21,74	CH_1	0
thermal	OtherNonRES	985	267,95	CH_1	0
thermal	Gas	1 379	88,03	CZ_1	0
thermal	Coal	8 261,76	75,1	CZ_1	0
thermal	Lignite	4 760	88,03	CZ_1	0
thermal	Nuclear	4 055	14,13	CZ_1	0
wind	wind	950	0	CZ_1	0
hydro	hydro	365	0	CZ_1	0
PV	PV	3 540	0	CZ_1	0
thermal	OtherRES	1 167	21,74	CZ_1	0
thermal	OtherNonRES	1 505	267,95	CZ_1	0
thermal	Gas	395	88,03	Sl_1	0
thermal	Coal	925	75,1	Sl_1	0
thermal	Lignite	539	102,36	Sl_1	0
thermal	Nuclear	696	14,13	Sl_1	0
hydro	hydro	1 500	0	Sl_1	0
PV	PV	320	0	Sl_1	0
wind	wind	80	0	Sl_1	0
thermal	OtherRES	67	21,74	Sl_1	0
thermal	OtherNonRES	159	267,95	Sl_1	0
thermal	Gas	3 179	88,03	HU_1	0
thermal	Coal	210	75,1	HU_1	0
thermal	Lignite	682	88,03	HU_1	0
thermal	Nuclear	4 248	14,13	HU_1	0
thermal	Oil	410	278,12	HU_1	0

hydro	hydro	60	0	HU_1	0
PV	PV	2 000	0	HU_1	0
wind	wind	1 000	0	HU_1	0
thermal	OtherRES	410	21,74	HU_1	0
thermal	OtherNonRES	355	267,95	HU_1	0
thermal	Gas	32 705	88,03	IT_1	0
thermal	Coal	0	75,1	IT_1	0
thermal	Oil	354	278,12	IT_1	0
hydro	hydro	5 637	0	IT_1	0
PV	PV	25 420	0	IT_1	0
wind	wind	16 230	0	IT_1	0
thermal	OtherRES	5 253	21,74	IT_1	0
thermal	OtherNonRES	5 785	267,95	IT_1	0
thermal	Gas	241	88,03	SK_1	0
thermal	Lignite	240	88,03	SK_1	0
hydro	hydro	974	0	SK_1	0
PV	PV	716	0	SK_1	0
wind	wind	265	0	SK_1	0
thermal	OtherRES	505	21,74	SK_1	0
thermal	OtherNonRES	899	267,95	SK_1	0
thermal	Nuclear	2 890	14,13	SK_1	0
thermal	Coal	0	75,1	SK_1	0

Table A.5.: pre-installed power plants in the year 2030 with a reduced CO_2 price

capacity [MWh]	max. power [MW]	efficiency [%]	Node
279 309,29	2 371	92,74%	VBG
504 040	2 772,5	92,74%	TIR_w
1 282,3	606	92,74%	TIR_e
0	0	100%	OTIR
437 268,5	2 473,7	92,74%	SBG_s
7 224	43	92,74%	SBG_n
3 600	450	92,74%	OOE_e
12 395,4	352,8	92,74%	OOE_w
7 764	80,5	92,74%	NOE
0	0	100%	NOE_n
0	0	100%	BGLD
0	0	100%	W

3 686,4	102,6	92,74%	STMK_w
1 512	63	92,74%	STMK
29 520	41	92,74%	STMK_s
3 562,5	67	92,74%	KTN_e
251 889,8	1 841,5	92,74%	KTN_w
1 477 699,79	10 788	92,74%	DE_1
1 860 223,7	13 580	92,74%	CH_1
143 831,73	1 050	92,74%	CZ_1
82 189,56	600	92,74%	Sl_1
0	0	100%	HU_1
2 254 167,8	16 455,87	92,74%	IT_1
182 734,79	1 334	92,74%	SK_1

Table A.6.: installed storages

ENTSO-E Master Plan

energy generated [GWh]

Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	1 262	23 913	132 816	13 323	9	103 806
DE	63 865	126 818	16 099	247 854	89 514	583
CH	6 682	820	12 005	40 935	8 940	11 454
CZ	4 045	1 870	814	64 665	5 004	6 361
Sl	286	126	6 505	7 094	3 234	823
HU	1 785	1 758	178	41 093	4 314	1 547
IT	73 810	30 419	18 676	72 832	19 282	4 627
SK	666	465	2 555	29 866	3 005	4 100

Coal exit Germany

energy generated [GWh]

Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	1 262	23 910	132 788	13 323	9	103 802
DE	63 865	126 818	16 099	247 829	89 534	579
CH	6 682	820	12 005	40 935	8 944	11 458
CZ	4 045	1 870	814	64 677	4 998	6 366
Sl	286	126	6 505	7 095	3 237	827
HU	1 785	1 758	178	41 102	4 310	1 552
IT	73 810	30 419	18 676	72 843	19 280	4 636
SK	666	465	2 555	29 863	3 009	4 102

Coal exit NECP

energy generated [GWh]

Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	1 262	23 894	132 828	13 323	9	103 805
DE	63 865	126 818	16 099	247 862	89 501	579
CH	6 682	820	12 005	40 935	8 950	11 464
CZ	4 045	1 870	814	64 664	5 001	6 357
Sl	286	126	6 505	7 094	3 238	827
HU	1 785	1 758	178	41 094	4 315	1 549
IT	73 810	30 419	18 676	72 826	19 291	4 630
SK	666	465	2 555	29 864	3 010	4 103

Coal exit complete

energy generated [GWh]

Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	1 262	23 910	132 788	13 323	9	103 802
DE	63 865	126 818	16 099	247 829	89 534	579
CH	6 682	820	12 005	40 935	8 944	11 458
CZ	4 045	1 870	814	64 677	4 998	6 366
Sl	286	126	6 505	7 095	3 237	827
HU	1 785	1 758	178	41 102	4 310	1 552
IT	73 810	30 419	18 676	72 843	19 280	4 636
SK	666	465	2 555	29 863	3 009	4 102

Coal exit NECP lower CO2 price

energy generated [GWh]

Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	1 298	607	138 292	10 464	267	89 161
DE	63 865	126 818	16 099	24 847	89 591	1 279
CH	6 682	820	12 005	40 935	10 169	12 683
CZ	4 045	1 870	814	80 050	2 722	19 464
Sl	286	126	6 505	10 670	1 642	2 807
HU	1 7853	1 758	178	41 560	3 975	1 676
IT	73 810	30 419	18 676	67 842	22 279	2 635
SK	67	465	2 555	29 712	2 999	3 941

Nuclear Exit Germany and Switzerland

energy generated [GWh]

Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export

AT	1 266	24 547	132 911	12 948	0	104 163
DE	63 865	126 818	16 099	243 433	93 399	47
CH	6 682	820	12 005	11 388	28 490	1 457
CZ	4 045	1 870	814	71 512	257	8 461
Sl	286	126	651	7 288	3 078	861
HU	1 785	1 758	18	41 090	4 337	1 567
IT	73 810	30 419	18 676	99 406	3 281	15 200
SK	666	465	2 555	29 857	2 919	4 005

PV Expansion 4,5 GW						
	energy generated [GWh]					
Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	4 818	25 422	127 029	13 757	8	103 578
DE	63 865	126 818	16 099	248 013	89 360	588
CH	6 682	820	12 005	40 935	8911	11424
CZ	4 045	1 870	814	64 624	5 040	6 356
Sl	286	126	6 505	7 092	3 245	832
HU	1 7853	1 758	178	41 162	4 270	1 572
IT	73 810	30 419	18 676	72 864	19 321	470
SK	67	465	2 555	29 876	3 002	4 108

PV Expansion 11,9 GW						
	energy generated [GWh]					
Node	PV	Wind	Run-of-river	Caloric	Power flow import	Power flow export
AT	12 687	32 832	110 854	14 241	10	103 275
DE	63 865	126 818	16 099	248 106	89 310	630
CH	6 682	820	12 005	40 935	8 916	11 430
CZ	4 045	1 870	814	65 155	4 814	6 661
Sl	286	126	6 505	7 070	3 268	833
HU	1 785	1 758	178	41 207	4 263	1 610
IT	73 810	30 419	18 676	72 531	19 580	4 624
SK	666	465	2 555	29 869	3 054	4 153

Table A.8.: Energy produced in all coal exit scenarios

node 1	node 2	NTC [MW]	susceptance [S]
VBG	TIR_w	1 900	2,5
VBG	DE_1	1 000	3,6
VBG	CH_1	400	3,41
TIR_w	TIR_e	3 000	1,8
TIR_w	DE_1	1 000	9
TIR_w	CH_1	800	2,5
TIR_e	SBG_s	2 685	2,67
OTIR	SBG_s	2 573	2,22
OTIR	KTN_e	3 500	1,8
OTIR	KTN_w	1 400	4,41
OTIR	IT_1	295	1,8
SBG_s	SBG_n	4 000	5,2
SBG_n	OOE_w	2 800	1,5
SBG_n	STMK_w	492	1
OOE_e	OOE_w	3 092	2,3
OOE_e	NOE	3 092	2,96
OOE_e	STMK_w	518	1,26
OOE_w	DE_1	2 900	7,5
NOE	NOE_n	5 400	7,41
NOE	CZ_1	500	1,8
NOE_n	BGLD	5 400	7
NOE_n	W	777	5,3
NOE_n	CZ-1	100	1
BGLD	W	5 400	13
BGLD	HU_1	400	2
W	STMK	518	1,1
W	STMK_s	2 417	1
W	HU_1	100	0,3
STMK_w	STMK	518	2,01
STMK	KTN_e	518	1,2
STMK_s	KTN_e	2 573	2,67
STMK_s	Sl_1	800	3,3
KTN_e	KTN_w	389	2,13
KTN_e	Sl_1	150	1,7
DE_1	CH_1	4 700	5,2
DE_1	CZ_1	2 600	2,67
CH_1	IT_1	4 860	5,2
CZ_1	SK_1	1 100	3,33
Sl_1	HU_1	1 700	2,5
Sl_1	IT_1	1 380	4,41
HU_1	SK_1	2 000	2,5

Table A.1.: power lines between the nodes of the model in 2018

node 1	node 2	NTC [MW]	susceptance [S]
VBG	TIR_w	1 900	2,5
VBG	DE_1	1 588	3,6
VBG	CH_1	483	3,41
TIR_w	TIR_e	3 000	1,8
TIR_w	DE_1	1 577	9
TIR_w	CH_1	1 217	2,5
TIR_e	SBG_s	2 685	2,67
OTIR	SBG_s	2 573	2,22
OTIR	KTN_e	3 500	1,8
OTIR	KTN_w	1 400	4,41
OTIR	IT_1	1 335	1,8
SBG_s	SBG_n	4 000	5,2
SBG_n	OOE_w	2 800	1,5
SBG_n	STMK_w	492	1
OOE_e	OOE_w	3 092	2,3
OOE_e	NOE	3 092	2,96
OOE_e	STMK_w	518	1,26
OOE_w	DE_1	4 336	7,5
NOE	NOE_n	5 400	7,41
NOE	CZ_1	1 026	1,8
NOE_n	BGLD	5 400	7
NOE_n	W	777	5,3
NOE_n	CZ_1	174	1
BGLD	W	5 400	13
BGLD	HU_1	681	2
W	STMK	518	1,1
W	STMK_s	2 417	1
W	HU_1	119	0,3
STMK_w	STMK	518	2,01
STMK	KTN_e	518	1,2
STMK_s	KTN_e	2 573	2,67
STMK_s	SI_1	1 054	3,3
KTN_e	KTN_w	389	2,13
KTN_e	SI_1	150	1,7
DE_1	CH_1	4 700	5,2
DE_1	CZ_1	2 600	2,67
CH_1	IT_1	4 860	5,2
CZ_1	SK_1	1 100	3,33
SI_1	HU_1	1 700	2,5
SI_1	IT_1	1 380	4,41
HU_1	SK_1	2 000	2,5

Table A.2.: power lines between the nodes of the model in 2030

Node	demand factor
VBG	0,042
TIR_w	0,016
TIR_e	0,066
OTIR	0,006
SBG_s	0,023
SBG_n	0,042
OOE_e	0,156
OOE_w	0,064
NOE	0,092
NOE_n	0,087
BGLD	0,026
W	0,138
STMK_w	0,025
STMK	0,020
STMK_s	0,117
KTN_e	0,045
KTN_w	0,036

Table A.7.: Divison of the electrical demand in Austria to the nodes

	ENTSO-E Master Plan		Coal exit Germany		Coal exit NECP		Coal exit complete		Nuclear exit		PV Expansion 4,5 GW		PV Expansion 11,9 GW		Coal exit NECP lower CO2 price
	Wind	RoR	Wind	RoR	Wind	RoR	Wind	RoR	Wind	RoR	Wind	RoR	Wind	RoR	RoR
VBG	48	2 048	0	2 442	0	2 737	0	2 442	0	2 226	219	2 569	0	1 851	2 900
TIR_w	1983	1 434	3 737	1 966	2 530	1 321	3 737	1 966	1 705	1 624	3 304	1 314	2 882	1 341	1 491
TIR_e	1598	1 984	0	2 286	0	2 082	0	2 286	1 301	1 710	1 272	1 938	264	1 520	2 529
OTIR	0	2 641	340	2 070	0	1 359	334	2 070	0	1 652	0	2 009	1 021	1 444	2 081
SBG_s	0	1 232	0	1 914	0	1 429	0	1 914	0	973	0	1 529	0	1 096	1 404
SBG_n	0	38	0	203	0	0	0	203	0	1410	0	287	0	0	478
OOE_e	479	0	556	0	2 289	0	556	0	676	0	541	0	920	0	0
OOE_w	1 067	2 805	0	2 485	673	2 324	0	2 485	993	2 639	301	2 319	1 302	2 047	2 441
NOE	0	722	347	193	0	621	347	193	0	0	0	604	0	199	472
NOE_n	0	0	0	0	0	110	0	0	0	0	0	0	0	0	336
BGLD	1 378	3 033	0	1 855	0	3 449	0	2 855	924	2 442	0	2 648	0	2 681	2 621
W	0	1 405	227	1 037	0	1 664	227	1 037	0	1 928	24	1 791	1 323	2 030	2 024
STMK_w	0	2 906	1 402	2 468	734	2 164	1 402	2 468	2 071	2 579	1 782	2 413	1 287	1 555	220
STMK	0	1 979	0	2 570	0	2 404	0	2 570	0	2 513	0	1 881	0	1 779	1 810
STMK_s	0	1 989	0	1 670	806	1 278	0	1 670	127	1 735	0	1 203	4	1 394	1 549
KTN_e	45	1 854	202	2 518	0	2 822	202	2 518	444	2 670	1 154	2 307	651	1 619	1 864
KTN_w	2 498	1 555	2 286	949	2 065	1 863	2286	949	1 184	1 697	1 195	1 103	3 712	902	1 534
sum	9 096	27 625	9 097	26 626	9 097	27 627	9 091	27 626	9 425	27 798	9 792	25 915	13 366	21 458	25 915

Table A.9.: Comparison of the investment decision in all scenarios in MW

Appendix B.

Matlab Model

This Matlab code contains the main functionalities used in this thesis.

```
%% Decision variables
Power_th = sdpvar(T,sum(strcmp(PPlants.GenerationType,'thermal')));
Power_storage = sdpvar(T,size(Storage.StorageIndex,1));
Charge_storage = sdpvar(T,size(Storage.StorageIndex,1));
PHS_inflow_used = sdpvar(T,size(Storage.StorageIndex,1));

Exch = sdpvar(number_of_nodes,T); % per node
Flow = sdpvar(number_of_lines,T); % per power line

% Down regulation of renewables energy sources
regulate_PV = sdpvar(T,number_of_nodes);
regulate_Wind = sdpvar(T,number_of_nodes);
regulate_RoR = sdpvar(T,number_of_nodes);

% Investment decisions
Inv_therm = sdpvar(1,sum(strcmp(PPlants.GenerationType,'thermal')));
Inv_PV = sdpvar(1,sum(strcmp(PPlants.GenerationType,'PV')));
Inv_Wind = sdpvar(1,sum(strcmp(PPlants.GenerationType,'wind')));
Inv_RoR = sdpvar(1,sum(strcmp(PPlants.GenerationType,'hydro')));
%% Constraints
Constraints = [];

% Kirchhoff energy balance per price zone

% PV generation
PV_sum = ...
    PPlants.GenerationMaxCap(strcmp(PPlants.GenerationType,'PV'))' + ...
    Inv_PV;
PVAux = PV_sum * AMPV;
PV =(repmat(PVAux,T,1)) .* PV_profile;
clear PV_sum PVAux

% Wind generation
```

```
Wind_sum = ...
    PPlants.GenerationMaxCap(strcmp(PPlants.GenerationType,'wind'))' + ...
    Inv_Wind;
WindAux = Wind_sum * AMWind;
Wind = (repmat(WindAux,T,1)) .* Wind_profile;
clear Wind_sum WindAux

% RoR generation
RoR_sum = ...
    PPlants.GenerationMaxCap(strcmp(PPlants.GenerationType,'hydro'))' ...
    + Inv_RoR;
RoRAux = RoR_sum * AMRoR;
RoR = (repmat(RoRAux,T,1)) .* Hydro_profile;
clear RoR_sum RoRAux

Constraints = [Constraints,...
    (Demand * Zones == ... % electrical demand
    PV * Zones... % PV generation
    - regulate_PV * Zones... % PV down-regulation
    + Wind * Zones... % Wind generation
    - regulate_Wind * Zones... % Wind down-regulation
    + RoR * Zones... % RoR generation
    - regulate_RoR * Zones... % RoR down-regulation
    + Power_th * AMth * Zones... % caloric power plant generation
    - Exch' * Zones... % power flow to other zones
    - Power_storage * AMStorage * Zones):'dual_load']; % storage power

    % Thermal power cap
    Constraints = [Constraints,...
    (Power_th ≤ ...
        repmat(PPlants.GenerationMaxCap(strcmp(PPlants.GenerationType,
    'thermal'))',T,1) + repmat(Inv_therm,T,1)):'dual_maxima_power',...
    (Power_th ≥ min_power_cap):'heat_Demand'];

    % Investments have to be always positive
    Constraints = [Constraints,...
    Inv_PV  ≥ 0,...
    Inv_Wind ≥ 0,...
    Inv_RoR ≥ 0,...
    Inv_therm ≥ 0];

    % Power flow
    Constraints = [Constraints,...
    (Flow ≤ repmat(Lines.NTC,1,T)):'dual_maxima_transmission_NTC',...
    (Flow ≥ repmat(-Lines.NTC,1,T)):'dual_minima_transmission_NTC',...
    (Flow == PTDF * Exch):'dual_PDTF_Spot',...
    (sum(Exch,1)==0),...
    (Zones' * Exch == Zones' * A * Flow)];

    % Down-regulation of renewable energy sources
```

```
    Constraints = [Constraints,...
    (regulate_PV ≥ 0),...
    (regulate_PV ≤ PV),...
    (regulate_Wind ≥ 0),...
    (regulate_Wind ≤ Wind),...
    (regulate_RoR ≥ 0),...
    (regulate_RoR ≤ RoR)];

    % Storage
    Constraints = [Constraints,...
    (- repmat(Storage.StoragePower',T,1) ≤ Power_storage ≤ ...
        repmat(Storage.StoragePower',T,1)):'storage_power_max1'...
    (0 ≤ Charge_storage)...
    (Charge_storage ≤ ...
        repmat(Storage.StorageCapacity',T,1)):'storage_charge_limit'];

    % calculate storage charge status
    Constraints = [Constraints, (Charge_storage(1,:) == ...
        Power_storage(1,:) .* Storage.StorageEfficiency' + ...
        PHS_inflow_used(1,:)):'storage_charge_1_'];

    for t = drange(2,T)
        Constraints = [Constraints, (Charge_storage(t,:) == ...
            Charge_storage(t-1,:) + Power_storage(t,:) .* ...
            Storage.StorageEfficiency' + ...
            PHS_inflow_used(t,:)):'storage_charge_'+t];
    end
    clear t

    Constraints = [Constraints, (Charge_storage(end,:) == ...
        0):'storage_charge_end'];

    % used natural inflow
    Constraints = [Constraints, (0 ≤ PHS_inflow_used ≤ ...
        PHS_inflow):'storage_inflow_used'];

%% Optimization

% objective investment decision function
objective = ...
    sum(PPlants.MarginalCost(strcmp(PPlants.GenerationType,'thermal'))' ...
    * Power_th')... % thermal marginal costs
+ ...
sum(PPlants.GenerationInvCost(strcmp(PPlants.GenerationType,'thermal'))'
* Inv_therm') +  % thermal investment costs
...
sum(PPlants.GenerationInvCost(strcmp(PPlants.GenerationType,'PV'))' * ...
    Inv_PV')... % PV investment costs
+ ...
sum(PPlants.GenerationInvCost(strcmp(PPlants.GenerationType,'wind'))' ...
```

```
    * Inv_Wind')... % Wind investment costs
+ ...
sum(PPlants.GenerationInvCost(strcmp(PPlants.GenerationType,'hydro'))' ...
    * Inv_RoR'); % RoR investment costs

% solve
options = sdpsettings('solver', 'gurobi', 'verbose', 2, 'warning', 1);
result = solvesdp(Constraints, objective, options);
```

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Wien, ______________________ ______________________

Date Signature