Diploma Thesis

Optimal Composition of Electricity Generation for Power Plants of Different Technologies in Austria

submitted in satisfaction of the requirements for the degree

Master of Science (MSc)

of the TU Wien, Faculty of Mathematics and Geoinformation

Diplomarbeit

Optimale Stromerzeugung durch Stromkraftwerke mit verschiedenen Technologien in Österreich

ausgeführt zum Zwecke der Erlangung des akademischen Grads

Diplom-Ingenieur

eingereicht an der TU Wien, Fakultät für Mathematik und Geoinformation

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Vienna, in June 2025

Abstract

This thesis addresses the optimal economic deployment of various technologies of power plants under current regulatory and market conditions. Using a Mixed-Integer Nonlinear Programming (MINLP) approach, a mathematical optimization model is developed to maximize the profit from electricity generation while incorporating real-world constraints and parameters. Although the model optimizes solely for profit, the results clearly demonstrate how political instruments such as CO_2 certificate pricing, emission taxes, and subsidies for low-emission technologies can effectively guide the energy transition by influencing economic decisions. The work begins with a characterization of different power plant technologies and a discussion of relevant environmental policy mechanisms. The core of the work involves the formulation and solution of the optimization problem using realistic input data. The results are analyzed to reveal both economic and environmental implications of various policy scenarios. The findings highlight how regulatory frameworks can indirectly steer energy system decarbonization through market-based incentives. This research contributes to the understanding of how profitability-oriented models can serve as tools for aligning economic and environmental objectives in energy policy.

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Chapter 1

Introduction

The ongoing energy transition poses complex challenges for modern energy systems. In particular, the optimal scheduling of power plant operations is becoming increasingly important in the light of growing demands for security of supply, economic efficiency, and environmental sustainability. In this context, the question arises as to how different types of power plants – such as hydropower, wind, solar, biomass, gas, and oil – can be deployed in a way that not only maximizes economic objectives like profit, but also enables the effective use of political instruments aimed at reducing CO_2 emissions. This thesis investigates an optimization problem for determining the profit-optimal deployment of power plants under current regulatory conditions.

At the core of this work is a Mixed-Integer Nonlinear Programming (MINLP) model that schedules power plant operations to maximize profit from electricity sales. The model takes into account the technical characteristics of different power plant types as well as relevant economic parameters, including fuel costs, electricity market prices, CO_2 certificate costs, emission taxes, and subsidies for specific technologies. While the model's objective function focuses solely on economic efficiency, the analysis reveals that environmental goals – particularly the reduction of greenhouse gas emissions – can be influenced indirectly through the economic framework. This includes mechanisms such as carbon pricing and targeted support for low-emission technologies.

The structure of the thesis follows a clear progression: It begins by introducing the current political and regulatory instruments used to promote the energy transition. These include market-based mechanisms such as emissions trading systems and carbon taxes, as well as governmental interventions like investment subsidies. Subsequently, various power plant types are described, highlighting their technical features, operational constraints, and economic indicators. The following section focuses on the Austrian power grid and the electricity market. Chapter 5 imposes the main part: It develops and explains the mathematical optimization model in detail, covering its structure, decision variables, objective function, constraints, and the assumptions made in modeling the technical processes. After the model, key aspects of the according Python code are explained.

The model is then parameterized using realistic data and solved numerically across several scenarios. The simulation results are analyzed in terms of both economic and ecological outcomes. The study demonstrates which types of power plants are most profitable under different regulatory conditions and how political instruments affect the deployment of fossil-based versus renewable technologies. Finally, the results are critically evaluated with respect to their limitations, and the findings are discussed in the broader context of energy policy.

The aim of this thesis is thus not only to develop a practical optimization model for economically optimal power plant deployment, but also to illustrate how economic objectives can be effectively aligned with environmental policy instruments – a crucial aspect for the success of the energy transition.

Chapter 2

Political Regulations on Power Plants

2.1 Costs of Climate Change

As climate change affects many different sectors, it obviously has an impact on the economy as well. To measure the effect of a natural disaster, one usually considers the welfare that changed due to the event. Welfare can be affected directly and indirectly. Direct impacts of a natural disaster are typically the physical damages, i.e., damaged buildings, crops, and livestock or non-market items like family heirlooms. Indirect impacts are the follow-on consequences like the impossibility of businesses to continue working due to power loss, evacuated workers, or supplies that could not be delivered [33]. In 2011, worldwide welfare losses due to natural catastrophes were estimated at $ 370 billion [33].

There are many different climatic factors that cause economic damage, such as daily variability of temperature, severe rainfall, the number of rainy days per year, or total annual precipitation. However, among all kinds of climatic changes, increasing temperature has the greatest impact on the welfare of the population[32]. Considering several models in the IPCC AR6 database, one can see that the costs of climate change until 2050 are already six times higher than possible mitigation costs [32]. One of the top sectors affecting the climate is the generation of electricity. To reduce the CO_2 emissions of power plants, there exist some political regulations, which will be discussed in the following sections.

2.2 Government-Based Ways to Reduce CO_2 Emissions

There are several possibilities for governments to regulate CO_2 emissions in a macroeconomic way. Two main instruments will be discussed here: Taxes and CO_2 certificate trading systems. In the European Union, CO_2 taxes are defined by the governments of the member states and cover all emitters (consumers and businesses). Trading participants who place fossil energy sources on the market (for example, wholesalers, manufacturers, and importers of energy sources) have to buy certificates per ton of CO_2 equivalent. The emissions of energy sources are calculated taking into account several parameters such as the amount and other emission factors per unit. In Austria, CO_2 taxes have been implemented in 2022 as a part of the "eco-social tax reform" and started at € 30 per ton of CO_2 equivalent. The height of the tax was determined to increase every year: € 35 per ton of CO_2 equivalent in 2023, € 45 and € 55 in the years 2024 and 2025, respectively. Although companies have to buy certificates for the amount of CO_2 equivalent they produce, one can speak of a tax, as there is an infinite number of such certificates and the price is fixed [38].

Other taxes related to CO_2 in Austria are the mineral oil tax, the natural gas tax, coal tax. Those taxes are not specifically designed to reduce greenhouse gas emissions, but to reduce the overall energy consumption and finance the state budget.

Renewables Subsidy Flat Rate (Erneuerbaren Förderpauschale)

This is a flat rate that must be paid by all end consumers of electricity to support renewable energy. For the years 2025-2027 the flat rate was set to € 19.02 per year. During the years 2022-2024, the "Erneuerbaren Förderpauschale" was paused to reduce financial stress on end consumers. In January 2025 it was deployed again (see EAG §73) [2].

2.3 The European Union Emissions Trading System (EU ETS)

In 2005 the European Commission [13] first introduced the EU Emissions Trading System, which aims at reducing greenhouse gas (GHG) emissions while financing the green transition. Sectors currently affected by the EU ETS are electricity and heat generation, industrial manufacturing, aviation, and maritime transport. The operation of the EU ETS takes place in all EU member states, Liechtenstein, Iceland, Norway, and Northern Ireland, and is linked to the Swiss ETS. It follows the "cap and trade" principle, which requires a maximum amount of total greenhouse gas emissions of the covered sectors, i.e., the cap, which is set by the EU on a yearly basis. All companies covered by the ETS must monitor and report their greenhouse gas emissions yearly to ensure transparency. The actual price (in € per ton of CO_2 equivalent) is determined by the market. Companies have to buy allowances in auctions, but can also trade among themselves or use spare allowances in the future. Since 2013, the EU ETS raised more than € 175 billion, which was distributed among the member states which have to invest the money in projects and technologies to reduce greenhouse gas emissions. Furthermore, the EU ETS is anchored in the European law, and therefore participation is mandatory for all member states.

The Cap

The size of the cap is chosen according to the goal of reducing emissions. Until 2020 the cap was reduced by a factor of 1.74% per year. From then on, his factor was systematically increased: In 2021 it was 2.2%, and the union-wide number of allowances was limited to 1 571 583 007 [9]. The reduction factor for the period 2024 - 2027 was set to 4.3% per year, resulting in the total amount of allowances in 2024 of 1 386 051 745 [10]. From 2028 on the cap will be reduced by 4.4% per year. As the EU decreases the cap, the incentive to reduce greenhouse gas emissions for every company increases on the one hand because of the scarcity of allowances and on the other hand due to the market reaction to the scarcity, which will result in higher prices per ton of CO_2 equivalent. The intended regulation of the cap stays in line with the European Green Deal that dictates climate neutrality of the EU by 2050.

Table 2.1 shows the differences between CO_2 taxes, energy taxes, and the emission trading system. The most important aspect is that the ETS is market-based, compared to taxes, which means that the price per ton of CO_2 equivalent varies according to demand and supply rather than being fixed by the government like taxes.

Table 2.2 describes the difference between a CO_2 tax and a CO_2 price. Again, the market-driven CO_2 price (e.g., ETS) can fluctuate due to market-based causalities and is therefore harder to predict.

Summing up all of the government's mechanisms to reduce greenhouse gas emissions by looking at an oil power plant in particular, one can see that operating an oil power plant will be targeted by all of the discussed mechanisms: The CO_2 tax, the energy tax, and the Emissions Trading System (see Table 2.3).

Characteristic	CO_2 Taxes	Energy Taxes	EU ETS
Level	National (Austria)	National	EU-wide
Target Group	Consumers	Consumers, businesses	Large industry, energy
Link to CO_2	Direct	Indirect, not CO_2-specific	Direct, via certificates
Market-based?	No	No	Yes
Scope	All fossil fuels	Specific energy products	Large emitters
Goal Focus	Fixed CO_2 reduction	Increase country's budget	Market-driven CO_2 cut

Tab. 2.1: Comparison of CO_2 Taxes, Energy Taxes, and EU Emissions Trading

Aspect	CO_2 Tax	CO_2 Price
Determined by	Government (fixed rate per ton)	Market
Predictability	Price is fixed	Price can fluctuate (ETS)
Mechanism	Direct taxation	Tax or trading-based pricing
Goal Focus	Stable cost for emissions	Market-driven reductions

Tab. 2.2: Comparison of CO_2 Tax and CO_2 Price

Cost Type	When is it due?	Who bears the cost?
CO_2 Pricing	When purchasing the oil	Power plant (indirectly via the oil price)
Energy Taxes	When purchasing the oil	Power plant (indirectly via the oil price)
EU ETS	Yearly during operation	Power plant (directly when buying certificates)

Tab. 2.3: Overview of Costs for Operating an Oil Power Plant

2.4 Financial Support for Power Plants

Financial support for power plants is a political tool to achieve the goal of a drastic reduction in greenhouse gases. Therefore all of the following support mechanisms focus on renewable energy sources and the development of innovative technologies. Funding projects for coal fired, oil, or gas power plants could not be found after intense research.

2.4.1 European Union

2.4.1.1 European Regional Development Fund (ERDF) Europäischer Fonds für regionale Entwicklung (EFRE)

This is a funding rate depending on eligible costs of the project. For example, 20% for large projects, 35% for medium projects, and 50% for small projects. In the years from 2021 to 2027, the ERDF has a total of € 486 208 864 of financial support for projects concerning energy efficiency and reduction of GHG emissions in Austria [34].

The purpose of the ERDF is to support

- Priority 1 (P1) Innovation: Research and technology infrastructure
- Priority 2 (P2) Sustainability: Energy efficiency and GHG reduction
- Priority 3 (P3) Territorial Development: Integrated sustainable urban development
- Priority 4 (P4) Just Transition Fund: Managing the transition to a climate-neutral economy

A project has to meet all of the following **formal (k.o.) criteria** in order to apply for financial support:

- Compliance with national legal regulations (e.g., tax law, public procurement law).
- The project starts only after the submission of the application (or the fulfillment of relevant legal provisions if started earlier).
- Alignment with the EFRE program (must correspond to a specific priority axis and objective).
- Appropriate funding amount (costs must match project size and objectives).
- Secured financial and organizational capacity of the applicant.
- Assessment of climate compatibility and environmental impact for infrastructure investments.
- No relocation of operations, ensuring long-term impact.

The appropriate funding amount depends on several conditions, such as the state of development of the specific region, which is determined by comparing the GDP per capita of the region with the average GDP per capita of the EU-27. *Less developed regions* have 75% or less of the average GDP, *transition regions* are between 75% and 100% of the average GDP of the EU, and *more developed regions* exceed 100% of the average GDP per capita of the EU-27. Other factors that influence the possible funding rate are the type of project, whether it is public or private, or how much CO_2 emissions can be saved by the project [18]. All of these factors must be calculated by local institutions, which can then derive the appropriate funding rate for each project.

In addition, projects are evaluated on the basis of specific **content criteria**. For renewable energy projects, the content criteria and their respective scores are listed in Table 2.4. The total score is determined by the individual assessment of each project. To be eligible for funding, a project must achieve at least **60% of the possible points**, which is very likely in the case of green energy-based power plants. The ERDF evaluation system is designed so that in general an application that meets the formal criteria and achieves at least 60% of the content criteria is granted the requested funding volume [29].

As a third and last group of conditions, there are **cross-divisional criteria**, which can bring additional 6% on top of the percentage of the content criteria. The cross-divisional criteria are divided into the following four parts, which represent 1.5% each:

- Sustainability – Recommendations according to the Strategic Environmental Assessment
- Sustainability – Other important aspects

Criterion	Average Renewable Power Plant (Max. Points = 3)
Contribution to regional energy efficiency	High (3)
Reduction of greenhouse gas (GHG) emissions	High (3)
Use of innovative technologies	Medium to High (1.5–3)
Regional significance	Medium to High (1.5–3)
Circular economy & sustainability	Medium to High (1.5–3)
Digitalisation component	Low (0–1.5)

Tab. 2.4: Evaluation criteria for average power plant projects

- Equality between women and men
- Equal opportunities and non-discrimination

Each of those four parts is determined by a set of questions. To get the full 1.5% for the first two parts, it is necessary to be able to answer at least three questions with "yes". The full points of the last two parts are received, if at least two questions can be answered with "yes".

2.4.1.2 Horizon Europe

Horizon Europe is the main source for funding projects in the EU and comprises three pillars:

- Excellent science
- Global challenges & European industrial competitiveness
- Innovative Europe

Horizon Europe has an available budget of € 93.5 [14] - € 95.5 [15] billion for the years 2021 to 2027. 53% [15] - 56% [14] of the budget are assigned to the second pillar which focuses on green energy. The second pillar can be clustered into several more parts, one of which is named *Climate, Energy & Mobility*. This part is the one dealing with power plants and responsible for funding green energy projects with an amount of € 15.123 billion [15]. One special goal is to support 100 European cities to become climate-neutral by 2030 [15]. The Horizon funding model is designed to support up to 100% of direct costs with a single set of rules principle. The programme is also coordinated with other Union programmes like *LIFE*, *ERDF*, *Innovation Fund*, and others [15]. There is a maximum funding volume for each project, which is announced in every call. The main purpose of Horizon Europe is to support transnational and radical research projects in the field of the three pillars mentioned above [23].

2.4.1.3 Union Renewable Energy Financing Mechanism (RENEWFM)

The Union Renewable Energy Financing Mechanism (RENEWFM) is designed to support the transition to clean energy. In the program, two different sets of countries are taken into account: *Contributing countries* and *host countries*. Contributing countries voluntarily pay into the system to get statistical benefits like contribution to the green energy transition, which is mandatory for EU member states. That means contributing states support projects concerning clean energy in host countries to ensure compliance with the green energy transition targets of the EU. The decision on which contribution of which country is used to support which country is made by the European Commission. In a tender procedure only the most competitive projects will be supported [20]. In one specific call, which was active between July 30, 2024 and March 4, 2025, Luxembourg is the contributing country with an amount of € 52.4 million and the host countries are Finland and Estonia. The call considers photovoltaic power plants and onshore wind power plants of companies and organizations (i.e., natural persons are excluded) and there is a ceiling price of € 300 000 per project [21]. The tender volume is granted in € per MW, which means it depends on the expected output of the power plant. For this call, a special calculator [19] is provided to sort the applications by funding rate per MWh (see Equation 5.6). The calculator multiplies the bidding price per MW of each application by the total size of the project (in MW) to get the total maximum lump sum. In the next step, the calculator multiplies the full load hours (FLH) by the total size of the project times 15 to receive the total MWh in 15 years. In the final step, the total maximum lump sum is divided by the total MWh in 15 years to get the transposed grant support per MWh in €. (It is obvious, that the total size of the project has no effect on the ranking, as it cancels out.) The values derived in this way of each applicant are then ranked in ascending order. If two calls have the same transposed price per MWh, the earlier application is ranked first. The bidding prices per MW are granted in the order of the sorted list. If the sum of the bidding prices times the size of the project exceeds the total volume of the call, the applications still left are excluded from the call (see Equation 5.5) [21].

2.4.1.4 LIFE Programme

> The LIFE Programme is the EU's funding instrument for the environment and climate action.

[16] One of the sub-programmes is called *Clean Energy Transition* and represents the part which is responsible for supporting power plants. It is a tool to implement EU policies like the European Green Deal or the Energy Union and has a budget of € 1 billion for the years 2021-2027. There are five areas, which are particularly supported by the LIFE Clean Energy Transition sub-programme of which two areas affect power plants directly:

- Accelerating technology roll-out, digitalisation, new services and business models and enhancement of the related professional skills on the market
- Supporting the development of local and regional investment projects

Eligible projects have to be private or public organizations, NGOs, or SME with a sustainable and innovative target. Depending on the type and the expected effect of the project, 60-90% of the eligible costs can be supported. Eligible costs include material costs, personnel costs, travel costs, and services. Projects on the topic of energy transition have chances of receiving the highest support of up to 95% [24].

2.4.1.5 Innovation Fund of the EU

The aim of the Innovation Fund of the EU is to support projects that reduce greenhouse gas (GHG) emissions according to the target of the Paris Climate Agreement to reach climate neutrality in 2050. For new projects it is common to use reference values of CO_2 emissions for a certain scenario. The main operational objectives for the Innovation Fund are:

- Support of highly innovative and sufficiently mature technologies, processes and products which aim to reduce GHG emissions
- Financial support depending on the actual needs of the market and the risk profiles of eligible projects

[11] In most of the cases, support is in the form of grants or funding for blending operations through the Union investment support instrument. The funding rate depends on the effectiveness of preventing GHG emissions, the degree of innovation, the maturity of the project, the scalability, and the cost efficiency. The main point concerning power plants is the innovative and renewable production of electricity, which is listed as one of the top factors to receive support from the Innovation Fund of the EU. Eligible costs are additional capital and operating costs related to the innovation. Those can be supported with a funding rate of up to 60% [35]. A special part of the Innovation Fund is that the selection criteria for a project include a term of efficiency, namely a fraction of the costs divided by the amount of saved GHG emissions [11].

2.4.1.6 Connecting Europe Facility (CEF)

The CEF does not directly support electricity power plants, but rather infrastructure projects that support the integration of renewable energy sources such as wind or solar power plants. Examples include high-voltage lines, grid connection points, and storage solutions that enable electricity to be transported from power plants to consumption centers. Since 2013 the Trans-European Networks for Energy (TEN-E) policy, aimed at connecting the energy infrastructure across EU countries, has played a key role in modernizing the EU's cross-border energy infrastructure [12].

2.4.1.7 European Investment Bank (EIB)

The aim of the EIB is to support investment projects to meet the requirements of the Paris Climate Agreement. The bank can invest into a variety of projects in the energy sector including renewable energy power plants. As a part of the Energy Transition Package, eligible costs can be funded at a rate of up to 75%. Projects have to fulfill criteria like having a location in certain member states. Another main aspect of the EIB is to accompany the transition from CO_2 intensive businesses, as the shut-down of a power plant or the elimination of fuel subsidization has significant effects on regional economics [22].

2.4.1.8 Just Transition Mechanism (JTM)

The purpose of the Just Transition Mechanism is to support people, economy, and environment of regions that have to bear major challenges due to political decisions in order to fulfill the EU's targets on environment and climate until 2030. In the years 2021-2027, a budget of € 7.5 billion is made available. The distribution of the fund is organized on a national level: The portion of every member state depends on the amount of reduced CO_2 emissions in comparison to the rest of the other member states. The decision about which projects get support is in the hands of each state [17].

2.4.2 Austria

2.4.2.1 Renewables Expansion Law (Erneuerbaren-Ausbau-Gesetz EAG)

The purpose of the "Erneuerbaren Ausbau Gesetz" (Renewable Energy Expansion Act) is to contribute to achieving climate neutrality in Austria by 2040. Its primary goal is to support the production of electricity and gas from renewable energy sources. To ensure that, by 2030, 100% of Austria's energy demand can be met with renewable energy, the act promotes [2]:

- generation of electricity from certain renewable sources through a market premium,
- construction and expansion of new power plants via investment grants, and
- construction and conversion of gas plants to produce renewable gas and renewable hydrogen.

The EAG is primarily funded through national resources [2]. One funding agency associated with the EAG is OeMAG (Ökostrom Management AG), which administers the "Ökostromförderung" (Green Electricity Funding). The "Ökostromförderung" operates on the principle of the market premium but can also provide investment grants to support the construction or expansion of power plants [37].

Market Premiums. One significant support mechanism is the market premium, which is designed to offset the difference between the production costs of renewable energy and the actual electricity price. Eligible for the market premium are wind power plants, the first 25 MW of new or expanded hydroelectric plants, the first 10 kW_{peak}[1] of new or expanded solar power installations, the first 5 MW of new or expanded biomass plants, and the first 250 kW of new or expanded biogas plants. Each type of power plant is subject to a maximum market premium. The request volume is the capacity to be installed in kW for which the bidder submits a request. The request value is the reference value in cents per kWh specified by the bidder in their request. The selection of the eligible projects is carried out by sorting the request values in ascending order. The funding processing agency of the EAG awards permissible bids up to the extent of their bid as long as the tender volume is not exceeded.

Table 2.5 lists the market premiums for various energy sources from January to June 2024, including the feed-in volume, net compensation, and average compensation per kWh.

Energy Source	**Feed-in Volume** (in kWh)	**Net Compensation** (in EUR)	**Average Compensation** (in Cent/kWh)
Hydropower	955 343	36 749,70	3.85
Wind Energy	875 072 172	8 065 310,80	0.92
Biomass	211 147 272	8 105 893,67	3.84
Biogas	217 405 534	26 736 035,57	12.30
Photovoltaics	136 261 788	5 690 831,60	4.18
Total	1 440 842 109	48 634 821,34	3.38

Tab. 2.5: EAG Market Premiums January - June 2024 [7]

Investment Grants. Investment grants regulated by the EAG follow a tender twice a year and differentiate between the technologies of the power plants. The financial support must be paid in the first period of commissioning. Investment grants and market premiums cannot be received for the same project.

[1] kW_{peak} is the unit of measurement for the maximum (peak) output of a photovoltaic system under optimal conditions.

Photovoltaic power plants are divided into four categories:

- Category A: Funding up to 10 kW_{peak}
- Category B: Funding > 10 kW_{peak} up to 20 kW_{peak}
- Category C: Funding > 20 kW_{peak} up to 100 kW_{peak}
- Category D: Funding > 100 kW_{peak} up to 1000 kW_{peak}

For categories A and B, the selection of eligible projects is carried out by sorting the requests by date, as the funding volume per kW_{peak} is given by the funding call. Projects belonging to categories C or D must indicate their need for support per kW_{peak} . The selection of eligible projects for categories C and D is based on sorting the requests per category by the requested funding volume per kW_{peak} starting with the lowest. The amount of the subsidy is calculated by multiplying the requested funding volume per kW_{peak} by the newly installed capacity and is limited by 30% of the total investment costs. The level of innovation PV power plants can be rewarded with an addition of up to 30%. In this case, the support is limited by 45% of the total investment costs. In addition, there is a maximum support per kW_{peak} that is stated in every call.

Water Power Plants are divided into two categories:

- Category A: New construction
- Category B: Extension

The total annual funding of € 5 million is divided into € 2 million for Category A and € 3 million for Category B. The funding rate per kW is given by the funding call and is limited by 30% of the total investment costs. Projects up to 2MW are eligible for funding. If there are unspent funds, then projects between 2MW and 25MW can be supported in the range of unspent funds. Applications are ranked according to the time at which they were received by the EAG funding processing office. Also there is a maximum support per kW which is stated in every call.

Wind Power Plants can be supported by an investment grant, if the rated power is between 20 kW and 1 MW. The total of € 1 million per year is divided among the applicants in the same way as for categories C and D of PV power plants: Each applicant has to indicate their need for support per kW. The selection of eligible projects for categories C and D is based on sorting the applications by the requested funding volume per kW starting with the lowest. If the total amount of support of the call is exceeded, the rest of the requests are excluded from financial support. Also, there is a maximum support per kW, which is stated in every call.

Biomass Power Plants can be supported if the following environmentally related restrictions are met:

- achieves a fuel utilization efficiency of at least 60%,
- implements state-of-the-art measures to minimize fine dust emissions,
- is equipped with a heat meter that meets the latest technological standards, and
- has a raw material supply plan in place for at least the first five years of operation.

Eligible costs are investment costs for the first 50 kW of newly built or extended power plants. To receive part of the annual € 4 million funding volume, applicants must state their needed support volume per kW. Applications will be sorted in ascending order and if the total annual volume is exceeded, extant applications are canceled from the call. Also, there is a maximum support per kW which is stated in every call.

Biogas Power Plants have varying support application requirements depending on whether they involve new construction or the retrofitting of an existing facility. Investment grants for constructing biogas power plants have to meet at least the following conditions:

- The fuels used consist exclusively of biomass in the form of biodegradable waste and/or residual materials.
- A raw material supply plan is in place, along with an additional utilization plan for biogas slurry, if generated, covering at least the first five years of operation.

The maximum funding rate of up to 45% is determined separately for each call. As a result, project selection for funding is based solely on the timing of the application. If the total annual funding volume is exceeded, any remaining applications will be excluded from consideration in that call.

Type	Max. Funding Rate	Annual Funding		Max. Request Volume	
Photovoltaic	30% (45%[2])	€	60 000 000	10 000	kW_{peak}
Water	30%	€	5 000 000	250 000	kW
Wind	30%	€	1 000 000	1000	kW
Biomass	30%	€	4 000 000	50	kW
Biogas	45%	€	25 000 000		N/A

Tab. 2.6: EAG Investment Grants [2]

2.4.2.2 Climate and Energy Fund (Klima- und Energiefonds KLIEN)

The Climate and Energy Fund was an Austrian government funding initiative that operated from 2007 to 2024, aimed at supporting innovative projects addressing climate change. Support of up to 30% of eligible investment costs was available, with a maximum funding amount of $25\ 000\ 000 \cdot 30\% = €\,7\ 500\ 000$, depending on the location and the technological standard of the project. During its duration, KLIEN had a total budget of € 3,2 billion and supported approximately 370 000 projects [5].

2.4.2.3 Domestic Environmental Support (Umweltförderung im Inland UFI)

[4] The objective of the Domestic Environmental Support is to protect the environment and human health first of all by reducing greenhouse gas emissions and other pollutants as well as by promoting renewable energy and energy efficiency. Another key aspect is to support circular economy and resource efficiency. The UFI aligns with the EU 2030 targets and the Austrian goal of becoming climate neutral by 2040. Power plants must meet general conditions:

[2]Including the level of Innovation

- Only renewable energy power plants are eligible
- Technologies must be energy efficient
- Compliance with the EU standards
- Prove environmental benefits

For companies, the funding rate is up to 50% of eligible costs and even higher for special ecological innovations. Non-competitors like NGOs can be supported with up to 100% of the eligible costs. Eligible costs exclude land costs, administrative fees, or projects that simply relocate emissions. Applications are coordinated at the "Abwicklungsstelle" of the UFI project. Grants are permitted once as a total grant or as operational subsidies.

2.4.2.4 Federal State Support

In addition to national funding projects, there are support mechanisms for power plants at the federal state level. As the aim of Austria's energy politics is to drastically reduce greenhouse gas emissions, the support from federal states also focuses on renewable energy power plants. The idea is to support more efficient on a lower level and, above all, to support private or small public power plants.

Chapter 3

Different Kinds of Power Plants

Since the late 17th century, the generation of electricity was a key focus of science. Nowadays it is obvious that the world doesn't work without electricity. There are many different ways to produce electricity and there are still possibilities to be found and optimized. In this section the main types and technologies of power plants will be described. To compare the costs of different kinds of power plants one usually takes a look at the levelized cost of electricity (LCOE). This measure describes the total costs of a power plant project divided by the production volume over the entire life cycle [1]:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}} \tag{3.1}$$

$LCOE$	Levelized Cost of Electricity in EUR per kWh
I_0	Investment expenditure in EUR
A_t	Annual total cost in EUR per year t
$M_{t,el}$	Produced amount of electricity in kWh per year
i	Real interest rate $\in [0,1]$
n	Economic lifetime in years
t	Year of lifetime $(1, 2, \ldots, n)$

Energy sources can basically be assigned to two main groups: Renewable energy sources and fossil energy sources. Renewable energy sources are wind, solar power, biomass, and the flow of water. On the other hand, coal, natural gas and oil can be counted to fossil energy resources. Due to a permanent increase in energy demand around the world, the total capacity of power plants has to increase too. The total capacity of renewable energy sources worldwide changed from 1 698 295 MW in 2014 to 3 864 522 MW in 2023 [27].

3.1 Photovoltaic Power Plant

In 2023, solar power capacity continued the upward trend with 346 GW of worldwide additions compared to 2022. China is responsible for about 25% of the additions and Europe accounts for 16% (56 GW) of extra solar power capacity [8]. In Austria, approximately 8.2% (6091 GWh) of the total national energy generation was provided by photovoltaic power plants [26].

The sun is an inexhaustible and above all a massive energy source. The amount of energy used on the whole earth in one year is about 4.6×10^{22} joules. It takes the sun only one hour to supply that amount of energy to the earth. However, it is not easy to convert solar energy into electricity, which results in different ways to use solar energy [6]. Therefore it is not surprising that engineers all over the world try to collect solar energy in an efficient way. For example, solar energy can be used for artificial photosynthesis to produce chemical fuels or by using concentrated solar power technology (CSP). CSP uses mirrors to reflect sunlight and concentrate heat at one certain spot, where heat is converted to electricity via a generator. Although there are many different ways to use solar energy, photovoltaic (PV) cells developed as the most effective power generators using solar radiation, as they have an efficiency rate of up to 35% [25]. Photovoltaic power plants convert light into electricity. When sun radiation hits the photovoltaic cell, it is absorbed and directly transformed into current electricity. There are three main types of photovoltaic cells [25]:

- **First Generation PV Cells.** Photovoltaic cells of the first generation are the most common type of cells and are made of crystalline silicon. While monocrystalline silicon cells have an efficiency of up to 25%, polycrystalline silicon cells are slightly less efficient (20.4%). However, the efficiency gap is compensated by lower production costs and less defects in the crystal structure. Further developments of first generation cells brought up the technology of emitter wrap-through cells, where the surfaces of the crystals are increased by drilling tiny holes with a laser into the cells. With this improvement, the overall costs could be reduced. The main downside of first generation PV cells is the reduction of performance at higher temperature.
- **Second Generation PV Cells.** Photovoltaic cells of the second generation are made of thin-film cells. One type of thin-film cells are the amorphous silicon (AS) solar cells which are quite cheap, however they have an efficiency of only 10.1% and the output is reduced to 80% when being used over a long time. Another type of second generation cells are cadmium telluride (CdTe) solar cells, which are more efficient than AS cells (17%). CdTe cells have the disadvantage that they contain toxic materials and tellurium is a limited resource. Even more efficient (20%) are copper indium gallium selenide solar cells. The main advantage compared to first generation PV cells are lower production costs, as less silicon material is used, while toxic and scarce materials are a key drawback of second generation solar cells.
- **Third Generation PV Cells.** Photovoltaic cells of the third generation are similar to the cells of the second generation with the difference of being more efficient and less harmful to the environment. Most popular cells of this type are organic solar (OS) cells and dye sensitized (DS) cells. Both of them are more environmental friendly but the efficiency of only 10% has to be improved yet.

Solar powered generators have one big downside which is the dependency on the weather conditions. It is obvious that on a cloudy or rainy day PV cells cannot generate as much electricity as on a sunny day. Yet there are a lot more factors influencing the performance of a PV power plant. Some of those factors are: the angle in which the radiation hits the cell, the different length of days during a year, the angle in which the radiation hits the earth, and a big issue is the dust accumulating on solar cells (happening in areas where there is a lot of sun but not much rain, i.e., the preferred area to set up a solar power plant).

The fill factor (FF) is an important number to describe the effectiveness of solar cells. It is the ratio of the maximum power ($\mathrm{P_m}$) of the cell and the product of the open circuit voltage ($\mathrm{V_{OC}}$) and the short circuit current ($\mathrm{I_{SC}}$):

$$FF = \frac{P_m}{V_{OC} \cdot I_{SC}}$$

Shimura et al. [41] found that the LCOE for photovoltaic power plants varies from US$ 115.31/MWh to US$ 150.67/MWh. Availability lies between 98.51% and 99.01%. However, the

International Renewable Energy Agency found that during the years 2010 to 2023, the global weighted average LCOE of utility-scale photovoltaic power plants decreased by 90% from US$ 460/MWh to US$ 44/MWh [28]. The global average weighted costs for installing a new PV power plant were about US$ 758/kW, which corresponds to the downward trend of the years 2010 to 2022 [28].

3.2 Wind Power Plant

Wind energy is a key component of the global transition towards renewable energy. In 2023, approximately 10.8% (8036 GWh) of the total electricity generation in Austria was provided by wind energy [26]. The cost of wind power has significantly decreased over the past decade, making it one of the most competitive sources of electricity. However, costs differ notably between onshore and offshore wind power due to differences in installation, operation, and maintenance conditions. A wind power plant usually consists of a group of wind turbines. Each turbine has a tower or mast, on top of which there sits a generator that typically works horizontally and has three wind blades. If wind reaches at least the so called cut-in power, the blades start to rotate and conduct the kinetic energy via several gears to the generator. Onshore wind power is generally more cost-effective due to lower capital expenditure and simpler logistics, whereas offshore wind, while benefiting from stronger and more stable wind resources, incurs higher costs related to installation, maintenance, and grid connection. The comparison of main factors of onshore and offshore wind power plants is shown in Table 3.1.

Parameter	Onshore Wind	Offshore Wind
Total Installed Cost (USD/kW)	1,160	2,800
Global Capacity (GW)	944	73
Capacity Factor (%)	36	41
LCOE (US$/kWh)	0.033	0.075
O&M Costs (US$/kW/year)	20-100	77-108
Cost Reduction Since 2010 (%)	70%	63%

Tab. 3.1: Comparison of Onshore and Offshore Wind Power Costs (2023) [28]

The costs of a wind power plant consist of the following components: The highest costs are the wind turbines with a share of 64% to 84% of the total costs. Further expenses flow into towers, installation, and delivery. Another component of the total costs represent grid connection, development costs, environmental impact assessments, and land cost [28]. LCOE of onshore wind power plants declined in the years from 2010 to 2023 by 70% from about 0.111 US$/kWh to 0.033 US$/kWh. In Europe, onshore wind farms at coastal strong wind sites with 3,200 full-load hours, LCOE ranges between € 0.043 and € 0.055 per kWh. Inland sites with lower wind speeds and fewer full-load hours generally experience higher costs [31]. Offshore wind experienced a 63% cost reduction over the same period, falling from USD 0.203/kWh to USD 0.075/kWh. Between 2010 and 2023, the global weighted average total installed cost of onshore wind decreased by 49%, from USD 2,272/kW to USD 1,160/kW, including a 12% year-on-year decline in 2023. This reduction was primarily driven by lower wind turbine prices and decreases in balance-of-plant costs [28]:

- **Technological Advancements**: Larger turbines, improved blade designs, and more efficient generators have increased energy output while reducing material costs.
- **Economies of Scale**: The rapid expansion of wind energy deployment has led to lower per-unit costs for manufacturing and installation.
- **Improved Operations and Maintenance (O&M)**: Digital monitoring, predictive maintenance, and advanced analytics have helped to reduce O&M costs, particularly for offshore installations.
- **Competitive Supply Chains**: Increased competition among manufacturers and suppliers has driven down equipment costs.

The global capacity rose from about 178 GW to 944 GW [28]. Costs for onshore wind power plants are estimated to be between US$ 986/kW and US$ 1746/kW. The price of a wind turbine ranges from US$ 706/kW to US$ 1040/kW [28]. In Europe, wind power plants have average costs for installation of approximately € 1600/kW. With 3200 full load hours per year, the LCOE is about € 0.043/kWh. As the maximum of 3200 full load hours can only be reached in rare spots, LCOE can range up to € 0.092/kWh [31].

3.3 Water Power Plant

Water power plants, or hydropower plants are the main electricity generation sources of Austria and accounted for 60% (44 523 kWh in 2023) of the total Austrian electricity volume [26]. Hydropower plants use the kinetic energy of falling or flowing water to generate electricity. There are four main types of water power plants:

- Reservoir (storage) power plants
- Pumped-storage power plant
- Run-of-river power plants
- Tidal power plants (not in Austria)

Each of the listed types of hydropower plants has distinct technical setups; for example, run-of-river plants rely on the continuous flow of a river, whereas storage plants use dams to control water release.
Water power plants are cost-effective and reliable in terms of constant electricity output. Although especially storage power plants and pumped-storage power plants are very expensive during the building process, as initial investments for infrastructure and dam constructions are typically very high, the operating costs are quite low and the lifespan often exceeds 50 years. Therefore, hydropower provides stable electricity prices and contributes to energy security.
In terms of ecology, hydropower is considered a renewable energy source with no direct carbon emissions. However, large dams can disrupt river ecosystems, affecting fish populations and altering natural water flow. Some modern plants incorporate fish ladders and sediment management systems to mitigate environmental impacts.
The global weighted average levelized cost of electricity (LCOE) for newly commissioned hydropower projects dropped to USD 0.057/kWh in 2023, 7% lower than in 2022 but 33% higher than in 2010. All newly deployed hydropower capacity in 2023 had an LCOE lower than the regional average for new fossil-fuel power plants. The increase in LCOE since 2010 was driven by higher installation costs, particularly in Asia, due to more challenging site conditions and supply

chain inflation[28].
In 2023, the global weighted average total installed cost of new hydropower projects fell to USD 2,806/kW, down from USD 3,053/kW in 2022. This decline followed a record high in 2022, largely due to site location differences. Cost overruns in large projects in Canada and Laos contributed to the 2022 peak. Between 2010 and 2023, the global weighted average capacity factor for commissioned hydropower projects ranged from a low of 44% (2010-2011) to a high of 53% in 2023. The operation and maintenance costs for hydropower plants are assumed to be about 2.5% of the total installed costs per year, which results in approximately US$ 70/kW per year [28]. The key cost metrics for hydropower plants are shown in Table 3.2

Category	Value 2010	Value 2023	Change
Total installed costs (USD/kWh)	1.459	2.806	92%
Capacity factor (%)	44	53	20%
LCOE (USD/kWh)	0.043	0.057	33%

Tab. 3.2: Key Cost Metrics for Hydropower (2010-2023)[28]

3.4 Nuclear Power Plant

As there are no nuclear power plants in Austria, they should just be mentioned here for the sake of completeness. Nuclear power plants face a difficult reputation as the danger of nuclear radiation is enormous. On the one hand, nuclear reactors are counted as ”green” power plants as during operation there are hardly any emissions but on the other hand, final storage of nuclear fuel rods is still risky and above all limited.

3.5 Biomass-Fired Power Plant

Biomass power plants generate electricity by burning organic materials, such as wood, agricultural residues, or dedicated energy crops. In 2022, biomass-fired power plants accounted for 4690 GWh in Austria [27]. They provide a renewable energy source with the advantage of dispatchability, unlike some intermittent renewables. However, their economic feasibility depends on various factors, including feedstock availability, conversion technology, and operational expenses. The most common types of biomass power plants are:

- Direct combustion steam turbine
- Gasification
- Pyrolysis
- Anaerobic digestion (biogas power plant)
- Co-firing power plants
- Liquid biofuel power plants

The costs associated with biomass power plants can be categorized into capital expenditures (CAPEX), operational and maintenance (O&M) costs, and the levelized cost of electricity (LCOE). Between 2010 and 2023, the global weighted average levelized cost of electricity for bio energy fell from US$ 0.084/kWh to US$ 0.072/kWh, though it increased from 2022's US$ 0.063/kWh. Despite this rise, bio energy remains among the lower-cost electricity sources compared to fossil fuel projects. In 2023, the global weighted average total installed cost for new bioenergy projects increased to US$ 2730 /kW from US$ 2242/kW in 2022. The capacity factors for bioenergy plants fluctuate according to technology and feedstock availability, ranging from 67% (2012, 2016) to 86% (2017), with a 2023 average of 72%. By region, LCOE in 2023 was lowest in India (USD 0.063/kWh) and China (USD 0.066/kWh) and highest in North America (USD 0.107/kWh) and Europe (USD 0.097/kWh). Biomass power plants require substantial initial investment for plant construction, fuel handling systems, and emissions control technology. As shown in Table 3.3, total installed costs have declined by 9% over the past decade. O&M costs include fuel procurement, labor, and routine maintenance. Fuel costs vary depending on location and biomass availability, making regional variations significant. In general, O&M costs are assumed to be in the range of 2% to 6% of the total installed costs per year, which leads to fixed O&M costs for biomass power plants of approximately US$ 10.9 per kW per year (4% of 2730 installed costs) [28].

Cost Component	2023 Value	2010 Value	Change
Total Installed Cost (USD/kW)	2,730	3,010	-9%
Capacity Factor (%)	67	72	-7%
LCOE (USD/kWh)	0.072	0.084	-14%

Tab. 3.3: Cost trends for biomass power plants (2010-2023) [28].

3.6 Coal-Fired Power Plant

Coal-fired power plants are the top pollutants among all power plants, as burning coal causes massive CO_2 emissions. In Austria there are no active coal-fired power plants anymore, as the last one was taken off the grid in 2020. There are two main types of coal-fired power plants: lignite power plants and hard coal/bituminous coal power plants [40].

In 2023, China broke the record of the previous year in coal production and accounts for 56% of it, while Europe and Northern America reduced the capacity of coal-fired power plants. In 2023, four states accounted for about 80% of world wide energy generated by coal-fired power plants: China, Australia, and India [8]. After breaking records in 2022 coal prices decreased about 46% in 2023 to a level of $130 per ton in Europe [8].

Due to political regulations in the form of CO_2 certificates and other taxes (see Section 2.2) the LCOE of newly built lignite power plants is between € 0.151 and € 0.257 per kWh, while the LCOE of hard coal power plants is about € 0.173 to € 0.293 per kWh [31]. Kelter [30] found that the LCOE for both types of coal-fired power plants is about € 0.045 to € 0.06 per kW when taking into account a lifespan of 40 years. Initial investment costs for lignite power plants are approximately € 1800/kW. Building a hard coal power plant is less costly with investments of € 1600/kW. The numbers for initial investment costs or construction costs of coal-fired power plants must be interpreted with caution, as they are rough estimates. Due to the political goals of reducing greenhouse gas emissions, coal-fired power plants are rarely built anymore, which leads to a lack of recent data.

3.7 Natural Gas Power Plant

7494 GWh or about 10% of Austria's electricity generation was provided by natural gas power plants in 2023 [26]. These power plants play an important role in electricity generation, as they provide a balance between efficiency, cost, and environmental impact. One main advantage of natural gas power plants is the reliability compared to PV and wind power plants. Natural gas power plants are widely used, as the ramping time is comparatively short and they can therefore be used to bridge power shortages. Another benefit is that a natural gas power plant can be built almost everywhere in contrast to water storage power plants that can only be installed in the mountains. Another advantage of natural gas power plants is the efficiency, which can reach up to 60%. However, natural gas is an exhaustible resource which causes greenhouse gas emissions when being burned.
Gas turbine power plants in general use the heat of burning gas to produce steam, which powers the generator. There are two main types: open-cycle gas turbines (OCG), which are simpler and used for peak demand, and combined-cycle gas turbines (CCG), which utilize waste heat to generate additional power. OCG turbines offer flexibility but low efficiency (35–40%), while combined-cycle plants can achieve 60% efficiency, although they typically use natural gas. OCG turbines come at lower costs (€ 400/kW) than CCG turbines, which are twice as expensive (€ 800/kW) [30].

Economically, natural gas power plants are popular as initial investment costs are lower compared to hydroelectric power plants, for example. The price of natural gas is often given in dollars per million British thermal unit ($/mmBtu). The (LCOE) for gas power plants is not constant, as it varies depending on technology, fuel prices, carbon costs, and operating hours:

- Combined cycle gas (CCG) power plants: LCOE in 2024 ranges between € 0.109 and € 0.181/kWh [31] (€ 0.08 - € 0.1/kWh [30])
- Open cycle gas (OCG) power plants: LCOE in 2024 ranges between to € 0.088 to € 0.156/kWh [31] (€ 0.1 - € 0.22/kWh [30])

3.8 Oil Power Plant

Oil power plants are only rarely used to generate electricity in Austria any more. In 2023, only 781 GWh were generated by oil [26]. Oil power plants generate electricity using petroleum-based fuels, mainly heavy or light crude oil. Due to high fuel costs, they are rarely used in Europe, except for peak load demand or as backup power. In oil-producing countries, they sometimes serve as baseload plants, often with waste heat recovery. Large oil plants use steam or gas turbines, while smaller ones rely on diesel engines, often in combined heat and power (CHP) systems. Some oil power plants can switch between oil and gas, allowing for fuel flexibility based on cost and availability. Many have been converted to run entirely on natural gas [39]. In general, oil power plants can be categorized in the following way:

- Steam turbine oil power plant
- Gas turbine oil power plant
- Internal combustion (reciprocating engine) power plant
- Combined cycle oil power plant
- Diesel power plants

Global oil production, with the USA being the largest producer, increased in 2023 to 96 million barrels per day. In 2023, the worldwide oil consumption exceeded 100 million barrels per day. While all around the world oil consumption is still rising, Europe is the only region with a decrease of 1% to 13.9 million barrels per day [8]. Brent is the most important type of crude oil and is used as a reference for other types. Usually, the price of oil is given in US dollars per barrel of Brent crude oil ($ /bbl), and different types of oil are traded with a premium or a discount, depending on their characteristics. One barrel crude oil equals about 159 liters.

The investment costs for oil power plants are relatively low at approximately € 500/kW. With a lifespan of 25 years and 3260 full load hours the LCOE is at € 0.0941/kWh [30].

3.9 Comparison of Power Plants

Table 3.4 is an attempt to compare key aspects of different types of power plants. The purpose of this table is to get a rough idea of the differences in costs, emissions, and lifespan of the mentioned power plants. There are several factors influencing the calculation of each of the given numbers, which make a quantitative analysis impossible:

- Specific type of power plant (for example run of river power plants and pumped storage power plants are grouped together as water power plants)
- Size of each power plant (costs per kW may be non linear)
- Date of data survey (especially in economically difficult times, prices and interest rates vary much)
- Location of the power plant (different property costs, network accessibility, etc.)
- Style of data survey (as seen in the sections above, two papers often provide different numbers)

The installation costs are given in US$ per kW. As Hydropower plants (especially storage- and pumped storage power plants) are usually among the largest plants, one can see that the total installation costs for hydropower plants are the highest among the listed power plants. However, the lifespan of up to 50 years makes hydropower plants more attractive, which can also bee seen in the average levelized cost of energy (LCOE) of about 0.05 US$/kWh. The highest LCOE arises for oil power plants, which is caused by high fuel prices and the comparatively short lifespan of about 25 years. Wind and PV power plants face the lowest LCOE, as their energy sources cost nothing and the installation is easier (and therefore cheaper) compared to hydropower plants, for example.

Type	Installation ($/kW)	Costs O&M/year ($/kW/year)	LCOE ($/kWh)	Emissions (t/MWh)	Lifespan (years)	Marg. Costs ($/MWh)
PV	758	10	0.044	0.0	25	0
Wind	1160	20	0.033	0.0	25	0
Water	2806	70	0.050	0.0	50	0
Biomass	2730	10	0.072	0.1	25	20
Coal	1700	20	0.050	0.9	40	25
Gas	900	15	0.060	0.4	30	40
Oil	1100	20	0.150	0.7	25	150

Tab. 3.4: Comparison of Power Plants

Chapter 4

Power Grid and Electricity Market

4.1 The Power Grid in Austria

The power grid is the basic structure of the entire electricity supply in a country. Every country has its own power grid, but all of the power grids are connected beyond national borders. Electricity is generated in power plants and initially fed into the highest-voltage grid. The voltage is gradually reduced via substations until the electricity arrives in the low-voltage network. This serves both to minimize losses (high voltage = fewer losses) and to ensure security of supply. A national-wide power grid consists of the following key parts:

- Power plants
- Networks (different voltages)
- Transformation stations
- End consumers

Power plants have already been described in Chapter 3 in detail. Electricity networks transport electric energy from power plants to consumers. In Austria, there is an hierarchically designed network, which is structured by different voltage levels. Each voltage level has a certain task to fulfill in the power grid.
Highest voltage power lines are the backbone of the power grid and are built to transport electricity over long distances and to connect to neighboring power grids. They have a voltage of 380 kV and 220 kV. The more electricity needs to be transported and the longer the distances are, the higher the voltage needs to be. Highest voltage power grids connect transformation stations and sometimes power plants with transformation stations, but are never used to supply end consumers.
High voltage power lines which have a voltage of 110 kV connect power plants with transformation stations and can also supply larger industrial plants. Another task is to feed in into medium voltage networks via high- to medium voltage transformation stations.
Medium voltage power lines (10 kV - 30 kV) supply smaller businesses, local networks, and other larger consumers. Another task is the connection of substations to transformation stations in towns.
Low voltage power lines have voltages of 230 V or 240 V and represent the last step of electricity supply. The main task is to supply households, shops, or other small businesses.
Transformation stations or substations connect power lines with different voltage. Important substations are for example the station ”Wien Südost” which is an important junction between 380 kV and 220 kV, or the transformation station ”Lienz”, which connects western and eastern parts of Austria. A special case are switching derailleurs without voltage transformation, which are only used to distribute or control electricity without any voltage conversion.

In every country, the power grid has to meet different criteria because of geographical, demographical, or political challenges as well as the given infrastructure. One main challenge for the Austrian power grid is that about one fourth of the Austrian population lives in Vienna. Therefore, about 13 TWh per year of Austria's electricity demand (67 TWh/year) arises in only one city. As transportation of electricity comes with high losses of energy, many power plants are built close to bigger cities like Vienna or Graz. However, there is the geographical component to be observed, if considering the installation of renewable power plants, as storage or pumped storage power plants can only be built in mountainous areas (i.e., the Western part of Austria). The most powerful renewable power plants are pumped storage power plants, which are located in the West and South of Austria (Salzburg, Carinthia, and Tyrol), but the biggest demand for electricity is in the Eastern part (Vienna, Graz). This causes the need of highest voltage power lines (380 kV) to transport green energy from the West to the East of Austria. Due to heavy protests of conservationists, there is no continuous 380 kV power line from the west to the east, which imposes the need for other power plants to cover the demand. As wind power plants, solar power plants, and run of river power plants are not sufficiently big to supply metropolitan areas with electricity, gas and oil power plants have to cover the remaining demand. This dilemma between nature protection and climate protection implies an inefficiency of the Austrian power grid. In Salzburg, there is a highest voltage power line in the construction process, which will enter service sometime in 2025[3]. This power line will then connect the West with the East and represent the possibility to cover more of the electricity with green energy generated in Austria. Another possibility to optimize the Austrian power grid is to install a 380 kV power line between Obersielach in Carinthia and Lienz in Tyrol, to complete the ring connection of highest voltage power lines. Figure 4.1 represents the highest voltage network in Austria and the key implications described above.

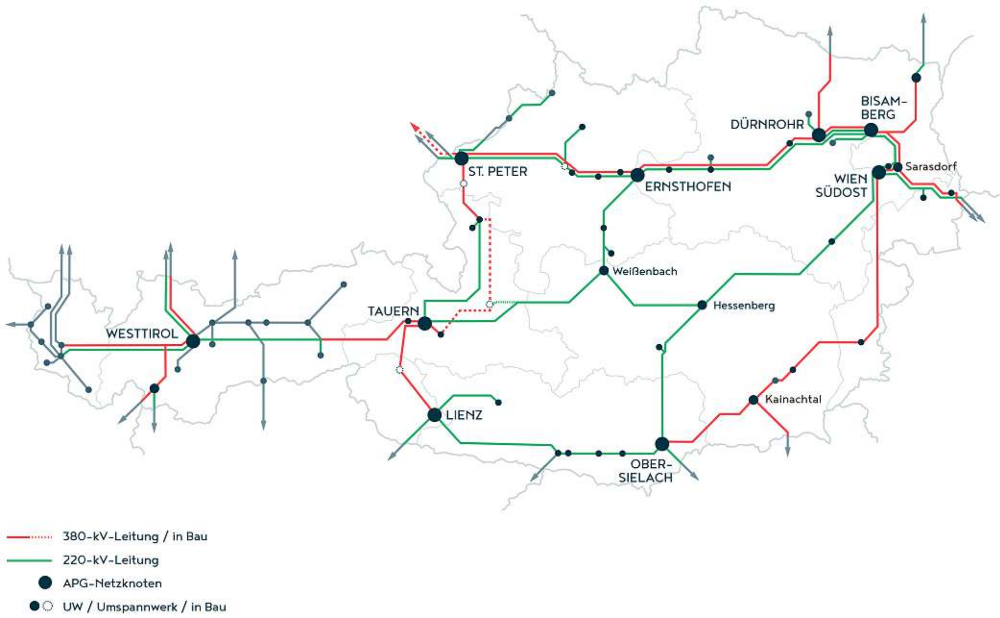


Fig. 4.1: Schematic representation of the Austrian power grid [3].

4.2 Electricity Market

The Austrian electricity market is part of the European internal market, but at the same time follows its own national structures. It is divided into different time levels, which depend on when electricity is traded or provided. Involved actors are:

- Producers (e.g., Verbund, Wien Energie)
- Suppliers and dealers (e.g., oekostrom AG)
- Network operator (APG for the transmission network)
- Electricity exchanges (e.g., EXAA, EPEX Spot)
- Regulators (E-Control Austria)

The temporal structure of the electricity market has three different planning horizons with different market regulations. The Futures Market has the longest horizon of weeks, months, or year. The main purpose is to guarantee price hedging and the security of supply as the trades are done via so-called OTC contracts (over-the-counter), i.e., bilateral contracts between producers and large buyers. Futures and forwards are also possible on electricity exchanges (e.g., EEX – European Energy Exchange). The day-ahead market has the purpose of short-term planning based on generation forecasts. In Austria, the trades are done via the EPEX Spot (for Central Europe) and EXAA (Vienna) exchanges. The process of the day-ahead market is organized such that on the day before, suppliers and buyers submit their price and quantity offers for each hour of the following day. The market price per hour is then determined from theses offers, which is also known as the "spot price". The goal of the intraday market is the compensation for short-term fluctuations or forecast errors. Trading is possible up to fifteen minutes before delivery time, which is ideal for fluctuating feed-in from wind or solar power. Actors on this market are power generators but also suppliers that need to cover sudden increased demand. The specialty is that the intraday market works continuously (not via auctions like the day-ahead). Table 4.1 sums up the differences of the three market horizons.

Market	Horizon	Purpose	Organization
Futures Market	Months	Price hedging and security of supply	Continuous trading, pay as bid
Day-ahead Market	Day ahead	Short-term planning based on generation forecasts	Supply/ demand determined by algorithm EUPHIMIA, pay as cleared
Intraday Market	15 min	Cover sudden power changes	continuous trading, pay as bid

Tab. 4.1: Comparison of the different electricity market horizons, their purposes, and the organization.

4.3 Merit-Order Principle

The **Merit Order Principle** is the mechanism by which electricity prices are determined in wholesale electricity markets. It describes how power plants are ranked based on their marginal costs and how this influences the final electricity price.

The process follows these steps (see also Figure 4.2):

1. **Ranking Power Sources**: Power plants are ranked from the lowest to highest marginal cost. Renewable energy sources (solar, wind) and nuclear power typically have the lowest costs, followed by coal, gas, and oil-fired plants.

2. **Meeting Demand**: Electricity demand is met by progressively dispatching power sources from the cheapest upwards.

3. **Setting the Price**: The last (most expensive) plant required to meet demand sets the market-clearing price for all electricity sold during that period.

Key Implications

- **Merit Order Effect**: Since renewable power plants have near-zero marginal costs (no fuel costs), increasing their share in the grid pushes expensive fossil fuel plants out of the market, leading to lower electricity prices. The more renewables enter the market, the lower the electricity prices become, potentially reducing the profitability of renewable energy sources and making them economically less viable without subsidies or market adjustments.

- **Price Volatility**: When electricity demand is high, more expensive power plants are activated, leading to higher prices. Conversely, high renewable generation can significantly reduce prices.

The Merit Order Effect is a crucial factor in the energy transition, demonstrating how increasing the share of low-cost renewable power plants can reduce wholesale electricity prices and lower dependence on fossil fuels.

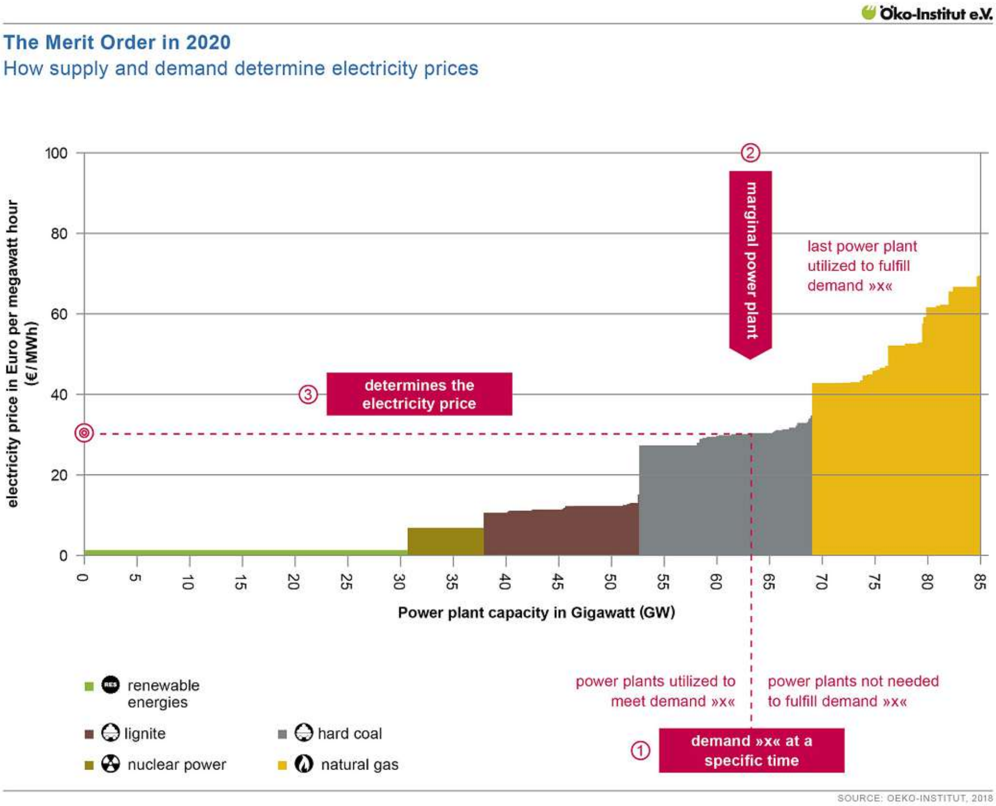


Fig. 4.2: Schematic representation of the Merit-Order Principle [36].

Chapter 5

The Model

The idea of this non-linear model is to find an optimal solution for the output of a set of power plants. Modeling the costs, the revenues, and the financial support for each power plant, an optimal size of output will be calculated. As the electricity price is modeled depending on the actual output of all power plants, the result of the optimization tells the operator of all power plants, which power plant should produce which amount of electricity in an optimal way for the whole portfolio of power plants. In addition, there is the possibility of varying power plants over time, which means that one can construct or shut down power plants at any time t. The model returns the overall optimal solution for each time t. The time steps t can be chosen at will, as long as they match the time steps of the data. The model is non-linear, as the product of the variables for output and for the electricity price occurs. Furthermore, the price of electricity depends on the output itself (see Section 5.2.5). Due to the non-linearity, we face a mixed integer non-linear problem.

Variables

The variables in the following model are the output O_{ti} of all power plants i at each time t.

O_{ti}	Control variable for total output of power plant i during time period Δt (in MWh)
P_t^{el}	Endogenous variable for the price of electricity at time t (in €)

5.1 Objective Function

The objective function is designed to maximize the difference between the total revenues R_{ti} and the costs C_{ti} over all power plants i and time steps t. Variables of the model are the output O_{ti} of each power plant i at every time t and the electricity price P_t^{el} at every time t. Both the revenues R_{ti} and the costs C_{ti} are calculated as shown in what follows.

$$\max_{O_{ti}} \left(\sum_{t=1}^{n} \sum_{i \in I} R_{ti} - \sum_{t=1}^{n} \sum_{i \in I} C_{ti} \right) \tag{5.1}$$

t	Point in time
Δt	Time interval $(t-1, t]$
$i \in I$	Power plant i
I	Set of all power plants
j	Type of power plant
J	Set of all types of power plants
R_{ti}	Total revenue of power plant i during time period Δt (in €)
C_{ti}	Total costs of power plant i during time period Δt (in €)

Equation (5.2) is the most crucial part of the model, as the product $P_t^{el} \cdot O_{ti}$ makes the model nonlinear. This product might seem like a typical bilinear term, but the problem is that P_t^{el} depends on O_{ti} in a noncontinuous way due to the merit order system (see Section 5.2.5). The calculation of the electricity price had to be implemented via four additional constraints to construct a bilinear optimization problem, which still features the desired link between output and electricity price (see Section 6.2.2.2).

$$R_{ti} = P_t^{el} \cdot O_{ti} + S_{ti} \tag{5.2}$$

P_t^{el}	Average price of electricity during time period Δt (in €/MWh)
O_{ti}	Total output of power plant i during time period Δt (in MWh)
S_{ti}	Total financial support for power plant i during time period Δt (in €)

5.1.1 Support Functions

The total support S_{ti} for a power plant i at time t can be split up into four separate parts: Support for building/constructing a power plant S_{ti}^b, support for extending or improving a power plant S_{ti}^e, support for operating a power plant S_{ti}^o, and support for maintaining a power plant S_{ti}^m:

$$S_{ti} = S_{ti}^b + S_{ti}^e + S_{ti}^o + S_{ti}^m \tag{5.3}$$

S_{ti}^b	Total financial support for building power plant i during time period Δt (in €)
S_{ti}^e	Total financial support for extending or improving an existing power plant i during time period Δt (in €)
S_{ti}^o	Total financial support for operating power plant i during time period Δt (in €)
S_{ti}^m	Total financial support for maintaining power plant i during time period Δt (in €)

The total financial support for building a new power plant comprises a flat rate a_{ti}^b, the sum of all supports k depending on the output of the power plant, the sum of all supports k depending on the construction costs, and the sum of all supports k depending on the emissions of CO_2 equivalent of the power plant; see Equation (5.4). It is assumed that all of the dependent support mechanisms are designed as rates of the factors, on which they depend. For example, the size of a specific power plant is multiplied by the factor b_{tik}^b to calculate the funding volume of support k at time t for power plant i. Support depending on emissions is modeled via the fraction of the funding rate and the emissions to realize the inverse connection between support and emissions. In the denominator, the additional +1 assures the full funding rate for power plants with zero emissions. The model suggests that the total of all supports is received once at the end of the construction period of the power plant.

$$S^b_{ti} = a^b_{ti} + \sum_{k=1}^{K} b^b_{tik} \cdot Size_{ti} + \sum_{k=1}^{K} c^b_{tik} \cdot C^b_{ti} + \sum_{k=1}^{K} \frac{d^b_{tik}}{E_{ti}+1} \tag{5.4}$$

a^b_{ti}	Flat rate support for building power plant i during Δt (in €)
b^b_{tik}	Funding rate of support k for building power plant i during Δt depending on the final output of the power plant (in €/MW)
c^b_{tik}	Funding rate of support k on the construction costs of power plant i during Δt ($\in \mathbb{R}^+_0$)
d^b_{tik}	Funding rate that maps the emissions of power plant i at time t inversely to the support (in €)
$Size_{ti}$	Installed capacity = total size of power plant i at time t (in MW)
E_{ti}	Emissions of power plant i during Δt (in tons of CO_2 per MWh)

Equation (5.5) describes the calculation of the funding rate of support k for building power plant i at time t depending on the final output of the power plant based on the algorithm used for calls of the RENEWFM [21] (see Section 2.4.1.3). In Equation (5.6)) the bidding prices (in € per MW) of each power plant are being transposed to the requested support per MWh by dividing the bidding price Pr^{MW}_{ik} by the full load hours FLH_i per year of power plant i. The mapping $\sigma(i)$ sorts all of the applications by the requested support per MWh in ascending order. In the case of equal requests, they are sorted by the time of application. In a second step, starting with the first application in the sorted list, the bidding price Pr^{MW}_{ik} is multiplied by the total size of the according power plant $Size_{ti}$. If the result doesn't exceed the total volume V^b_{tk} of the call, the bidding price Pr^{MW}_{ik} is granted. The second step is repeated and the results of each repetition are summed up until the the sum exceeds the total volume V^b_{tk} of the call. The first and all of the following applications, which cannot be covered by the funding volume are excluded from support.

$$b^b_{tik} = \begin{cases} Pr^{MW}_{ik} \cdot \delta^b_{jk} & , \text{ if } \sum\limits_{\iota:\sigma(\iota)\le\sigma(i)} Pr^{MW}_{\iota k} \cdot Size_{t\iota} \le V^b_{tk} \\ 0 & , \text{ else} \end{cases} \tag{5.5}$$

$\sigma(i) : I \to I$, such that

$$\forall i, \tilde{i} \in I, i \neq \tilde{i} : \sigma(i) < \sigma(\tilde{i}) :\Leftrightarrow \left(\frac{Pr^{MW}_{ik}}{FLH_i} < \frac{Pr^{MW}_{\tilde{i}k}}{FLH_{\tilde{i}}} \right) \vee \left(\frac{Pr^{MW}_{ik}}{FLH_i} = \frac{Pr^{MW}_{\tilde{i}k}}{FLH_{\tilde{i}}} \wedge \tau_{ik} < \tau_{\tilde{i}k} \right) \tag{5.6}$$

V^b_{tk}	Total funding volume of call k at time t (in €)
Pr^{MW}_{ik}	Bidding price of power plant i per MW for call k can be chosen by the applicant (in €/MW)
δ^b_{jk}	Indicator, if technology j is included in call k ($\in \{0,1\}$)
$Size_{ti}$	Total size of power plant i at time t (in MW)
FLH_{ti}	Full load hours of power plant i per year
$\sigma(i)$	Mapping of i, such that $\sigma(i)$ is the rank of power plant i depending on the size of the transposed price per MWh and, in the case of equal requests, on the time of application for support
τ_{ki}	Time of application of power plant i for funding call k (in JJJJ-MM-DD-hh-mm-ss)

Equation (5.7a) describes the calculation of the funding rate for the construction of a new power plant depending on the construction costs according to the EAG [2], which is described in Section 2.4.2.1. The procedure for selecting the projects to be funded starts with sorting the applications by the requested funding rate per MW. If applications request the same rate, they are sorted by the time of application in ascending order. $\sigma(i)$ represents this mapping as it has an argument i and returns the rank of the power plant i in the ordered list. In the next step, the requested funding rate for the first application in the sorted list ($c^b_{tik} : \sigma(i) = 1$) is multiplied by the eligible investment costs of the project ($C^b_{tik} : \sigma(i) = 1$) to obtain the funding volume in € of the first application in the sorted list. This procedure is repeated with the remaining applications in ascending order and the funding volumes are summed up. The first application that increases the sum of all funding volumes so that it exceeds the total funding volume of the call is still accepted if at most 50% of this application's funding volume exceeds the total funding volume of the call. The remaining applications are excluded from the call.

$$c^b_{tik} = \begin{cases} \tilde{c}^b_{tik} & \text{, if } \sum\limits_{\iota:\sigma(\iota)\leq\sigma(i)-1} c^b_{t\iota k} \cdot C^b_{t\iota} \leq V^b_{tk} + 0.5 \cdot \tilde{c}^b_{t\sigma(i)k} \cdot C^b_{ti} \\ 0 & \text{, else} \end{cases} \tag{5.7a}$$

$\tilde{c}^b_{tik}$	Requested funding rate of power plant i from funding call k at time t (in €)
V^b_{tk}	Total volume of funding call k at time t (in €)
$\sigma(i)$	Mapping of i, such that $\sigma(i)$ is the rank of power plant i depending on the height of the requested funding volume and, in the case of equal requests, on the time of application for support: $\sigma(i) : I \to I$ such that $\forall i, \tilde{i} \in I. i \neq \tilde{i} : \sigma(i) < \sigma(\tilde{i}) :\Leftrightarrow \left(\tilde{c}^b_{tik} < \tilde{c}^b_{t\tilde{i}k}\right) \vee \left(\tilde{c}^b_{tik} = \tilde{c}^b_{t\tilde{i}k} \wedge \tau_{ki} < \tau_{k\tilde{i}}\right)$
τ_{ki}	Time of application of power plant i for funding call k (in JJJJ-MM-DD-hh-mm-ss).

Equation (5.7b) describes another calculation of the funding rate for the construction of a new power plant depending on the construction costs based on the ERDF [29], which is described in 2.4.1.1. There are two options: Either all of the necessary conditions are met by the application or not. In the first case, the requested funding rate is granted, in the second case, the application is rejected. First of all, each application has to meet all of the 10 formal (k.o.) criteria in order to be approved for funding via the ERDF. This is implemented by multiplying the product of the scores (0 or 1) of each formal criterion with the rest of the term, so that the whole term becomes zero as soon as one of the formal criteria is not met (i.e., has score = 0). In a second step the content criteria are evaluated by calculating the percentage of the scores of the content criteria (0-3): As each criterion has a maximum of three points, the sum of all scores is divided by three times the number of criteria. In a third step the cross-divisional criteria are evaluated, which are divided into four parts that represent the possibility of additional percentage points of up to 1.5% each (i.e., 6% in total). If the result of the calculation exceeds 60%, the requested funding rate can be granted.

$$c_{tik}^{b} = \begin{cases} \tilde{c}_{tik}^{b} & \text{, if } \prod_{m=1}^{10} \kappa_{tikm} \cdot \left(\sum_{l=1}^{L_j} \frac{\xi_{tikl}}{3L} + \sum_{p=1}^{4} \frac{\nu_{tikp}}{\bar{\nu}_{kp}} \cdot 0.015 \right) \geq 0.6 \\ 0 & \text{, else} \end{cases} \tag{5.7b}$$

$\tilde{c}_{tik}^{b}$	Requested funding rate of power plant i from funding call k at time t
κ_{tikm}	Score of power plant i in the formal (k.o.) criterion m for funding project k at time t
ξ_{tikl}	Score of power plant i in the content criterion l for funding project k at time t
ν_{tikp}	Score of power plant i in the cross-divisional criterion p for funding project k at time t
$\bar{\nu}_{kp}$	Maximum score of cross-divisional criterion p for funding project k
L_j	Number of content criteria for power plant type j

Financial support for extending or improving an existing power plant comprises a flat rate, the sum of all supports depending on the difference in the output before and after the extension, the sum of all supports depending on the construction costs of the extension, and the sum of all supports depending on the reduction of CO_2 emissions, see Equation (5.8). The model suggests that all named supports are received at the end of the expansion phase, which takes $\bar{t}$ time steps. Also, construction costs are accounted for at the end of the construction phase. In the model, there is the possibility to calculate the funding rates for extending a power plant separately. However, it is common for the factors a_{ti}^{e}, b_{tik}^{e}, c_{tik}^{e}, and d_{tik}^{e} to be calculated identically to the factors for the construction of a new power plant.

$$S_{ti}^{e} = a_{ti}^{e} + \sum_{k=1}^{K} b_{tik}^{e} \cdot \Delta Size_{ti} + \sum_{k=1}^{K} c_{tik}^{e} \cdot C_{ti}^{e} + \sum_{k=1}^{K} d_{tik}^{e} \cdot (E_{(t-\bar{t})i} - E_{ti}) \tag{5.8}$$

a^e_{ti}	Flat rate support for extending or improving power plant i in period Δt (in €)
b^e_{tik}	Constant of support k for power plant i in period Δt depending on the size difference of the power plant before and after the extension (in € per MW)
c^e_{tik}	Constant of support k for power plant i in period Δt depending on the costs of the extension or improvement of the power plant ($\in \mathbb{R}^+_0$)
d^e_{tik}	Constant of support k for power plant i in period Δt depending on the emissions difference of the power plant before and after the extension
$\bar{t}$	Length of extending period ($\in \mathbb{N}$)
$\Delta Size_{ti}$	Difference between the size before and after the extension: $Size_{ti} - MW_{(t-\bar{t})i}$ (in MW)

Equation (5.9) describes the composition of the total support for operating power plant i at time t. It consists of a flat rate a^o_{ti}, the sum of all supports k depending on the actual output O_{ti}, and the sum of all supports k depending on the operating costs C^o_{ti}, which are calculated in Equation (5.14). Another term influencing the support for operating a power plant is designed to cover the difference between the costs per MW (i.e., the marginal costs) and the actual electricity price per MW, if the difference plus a constant d^o_t is positive (see Section 2.4.2.1). In theory, this cannot be the case, as the electricity price is given by the merit order system, which returns the highest marginal costs of all active power plants. However, in practice, there is the possibility that different market regulations affect the electricity price such that the described difference is negative. The last term, affecting the total support for operating a power plant, describes the inverse effect of emissions on certain support projects. In the denominator the constant 1 is added to the emissions E_{ti} to guarantee maximum support for power plants with zero emissions and to avoid division by zero.

$$S^o_{ti} = a^o_{ti} + \sum_{k=1}^{K} b^o_{tik} \cdot O_{ti} + \sum_{k=1}^{K} c^o_{tik} \cdot C^o_{ti} + \max\left(\frac{C^o_{ti}}{O_{ti}} + d^o_t - P^{el}_t, 0\right) + \sum_{k=1}^{K} e^o_{tik} \cdot \frac{1}{E_{ti}+1} \tag{5.9}$$

a^o_{ti}	Flat rate support for operating power plant i in period Δt (in €)
b^o_{tik}	Constant of support k for operating power plant i during Δt depending on the actual output of the power plant (in €/kWh)
c^o_{tik}	Constant of support k for operating power plant i during Δt depending on the operating costs of the power plant ($\in \mathbb{R}^+_0$)
d^o_t	Additive constant to regulate the support depending on difference between marginal costs and electricity price ($\in \mathbb{R}^+_0$)
e^o_{tik}	Constant of support k for operating power plant i during Δt depending on the emissions of the power plant (in €)

The model also offers the possibility to include support for maintaining power plant i at time t; see Equation (5.10). It consists of a flat rate a^m_{ti} and the sum of all supports k depending on the maintenance costs of the power plant. The maintenance costs are described in Equation (5.15) below.

$$S^m_{ti} = a^m_{ti} + \sum_{k=1}^{K} c^m_{tik} \cdot C^m_{ti} \tag{5.10}$$

a^m_{ti}	Flat rate support for maintaining power plant i in period Δt (in €)
c^m_{tik}	Constant of support k for maintaining power plant i during Δt depending on the maintenance costs of the power plant ($\in \mathbb{R}^+_0$)

5.1.2 Costs Functions

The costs of power plant i at time t can be split up into costs for building a power plant C^b_{ti}, the costs for extending a power plant C^e_{ti}, the costs for operating C^o_{ti}, and the maintenance costs C^m_{ti}:

$$C_{ti} = C^b_{ti} + C^e_{ti} + C^o_{ti} + C^m_{ti} \tag{5.11}$$

C^b_{ti}	Costs of building the power plant i at time t (in €)
C^e_{ti}	Costs of extending or improving the power plant i at time t (in €)
C^o_{ti}	Operating costs of power plant i at time t (in €)
C^m_{ti}	Maintenance costs of power plant i at time t (in €)

The costs for building a power plant are calculated by a linear function and consist of fixed costs x^b_{ti} and variable costs $y^b_{tj} \cdot Size_{ti}$; see Equation (5.12). It is important to notice that the fixed costs x^b_{ti} depend on time t and on the specific power plant i, but the factor y^b_{tj} depends on time t and the technology/type j of the power plant. This reflects the idea that every power plant has specific fixed costs due to different locations, network accessibility, land-costs, etc. However, the installation process can be modeled linearly depending on the size and the type j of the power plant:

$$C^b_{ti} = x^b_{ti} + y^b_{tj} \cdot Size_{ti} \tag{5.12}$$

x^b_{ti}	Fixed costs for building power plant i at time t (in €)
y^b_{tj}	Factor to calculate costs depending on the size of power plants of technology j at time t (in €/MW)

The costs for extending or improving power plant i at time t are modeled similarly to the construction costs. However, the variable costs do not depend on the total installed size, but on the size difference $(Size_{ti} - Size_{(t-\bar{t})i})$ which was achieved by the extension process:

$$C^e_{ti} = x^e_{ti} + y^e_{tj} \cdot (Size_{ti} - Size_{(t-\bar{t})i}) \tag{5.13}$$

x^e_{ti}	Fixed costs for extending or improving power plant i (in €)
y^e_{tj}	Factor to calculate costs depending on output for power plants of technology j in (€/MW)
$\bar{t}$	Length of the extending period ($\in \mathbb{N}$)

Costs for operating power plant i at time t can be split up into four parts: Costs for resources, costs for emissions via taxes and CO_2 certificates, costs for wages, and ramping costs. The costs depending on the emissions of a power plant are modeled according to the Austrian emissions tax system and the European Union emissions trading system (see Sections 2.2 and 2.3). The term concerning the costs for wages is designed by multiplying the wages by the square root of the size to reflect the diminishing marginal labor cost with respect to size. Furthermore, those costs are multiplied by a term that ensures that only half of the wages have to be paid, if the power plant is not active. The last term describes the ramping costs, which occur only, if the power plant is active at time t and was inactive at time $t-1$.

$$
\begin{aligned}
C^{o}_{ti} = P^{res}_{tj} \cdot Res_{ti} \cdot O_{ti} \\
+ \left(tax_t + P^{cert}_t\right) \cdot E_{ti} \cdot O_{ti} \\
+ \left(W_{ti} \cdot \sqrt{\frac{Size_{ti}}{2}}\right) \cdot (0.5 + 0.5 \cdot \mathrm{OnOff}_{ti}) \\
+ C^{start}_{ti}
\end{aligned}
\tag{5.14}
$$

Res_i	Amount of resource needed by the power plant i per MWh
P^{res}_{tj}	Price of resource j at time t (in €/unit of resource j)
P^{cert}_t	Price of a CO_2 certificate at time t (in € per ton of CO_2)
tax_t	Taxes on CO_2 emissions at time t (in € per ton of CO_2)
W_{ti}	Total wages of all employees of the power plant i at time t (in €)
$\tilde{C}^{start}_{ti}$	Possible ramping costs for power plant i at time t (in €)
OnOff_{ti}	Indicates whether power plant i is active at time t or not ($\in \{0,1\}$)

$$
\mathrm{OnOff}_{ti} = \begin{cases} 1 \Leftrightarrow O_{ti} > 0 \\ 0, \text{ else} \end{cases}
$$

$C^{start}_{ti} =$ $(\tilde{C}^{start}_{ti} \cdot \mathrm{OnOff}_{ti}) \cdot (1 - \mathrm{OnOff}_{(t-1)i})$ Actual ramping costs for power plant i at time t (in €)

Maintenance costs consist of fixed costs x^m_{ti} for each power plant i at time t and variable costs depending on the age and the size of the power plant. The variable costs consist of a factor y^m_{tj} depending on the type j of the power plant, multiplied by the age and the square root of the size of power plant i at time t. The square root of the size reflects the diminishing marginal maintenance costs with respect to size. The total maintenance costs are multiplied by the variable OnOff_{ti} to make sure that the maintenance costs only occur if the power plant is active at time t.

$$
C^{m}_{ti} = \left(x^m_{ti} + y^m_{tj} \cdot age_{ti} \cdot \sqrt{\frac{Size_{ti}}{2}}\right) \cdot \mathrm{OnOff}_{ti}
\tag{5.15}
$$

x^m_{ti}	Fixed costs for maintaining power plant i at time t (in €)
y^m_{tj}	Factor to calculate costs depending on size and age for power plants of technology j at time t (in €/MW)
age_{ti}	Age of power plant i at time t

5.2 Constraints

5.2.1 Power Plants

Range of Output: Every power plant has a minimum and a maximum load. Therefore, each power plant has a certain range of output within which it can deliver electricity:

$$\forall i \in I, \forall t \in \mathbb{N} : \text{MWh}_{ti}^{min} \leq O_{ti} \leq \text{MWh}_{ti}^{max} \tag{5.16}$$

MWh_{ti}^{min}	Minimum output of power plant i at time t (in MWh)
MWh_{ti}^{max}	Maximum output of power plant i at time t (in MWh)

Output meets Demand: At any time t the total output $\sum_{i \in I} O_{ti}$ has to meet the demand D_t:

$$\forall t \in \mathbb{N} : \sum_{i \in I} O_{ti} = D_t \tag{5.17}$$

Constant Output: As there are power plants which cannot guarantee a certain amount of power at any time, there need to be power plants with as much constant output as the demand can be at maximum:

$$\forall t : \sum_{i \in I_c} \alpha_i \cdot \text{MWh}_{ti}^{max} \geq D_{max} \tag{5.18}$$

I_c	Set of all types of power plants that can deliver a constant rate of electricity
α_i	Factor indicating the fraction of the installed capacity that can be guaranteed at any time $\in (0, 1)$
D_{max}	Maximum possible demand of the country (in MWh)

Ramping Times: In times of sudden power shortage, it is necessary to have power plants that are able to start producing electricity in a short time. For example, water and natural gas power plants are suitable for this case, as they can deliver electricity at all times and have a short so-called ramping time:

$$\forall t : \sum_{i \in I_{ramp}} O_{ti} \geq D_{max}^{ramp} \tag{5.19}$$

I^{ramp}	Set of power plants types that have sufficiently short ramping times
D_{max}^{ramp}	Maximum demand for short term additional electricity (in MWh)

5.2.2 Financial Support Constraints

Total financial support for a project must not exceed a certain limit.

$$\begin{aligned} S^b_{ti} &\leq s^{max}_{ti} \cdot C^b_{ti} \\ S^e_{ti} &\leq s^{max}_{ti} \cdot C^e_{ti} \\ S^o_{ti} &\leq s^{max}_{ti} \cdot C^o_{ti} \\ S^m_{ti} &\leq s^{max}_{ti} \cdot C^m_{ti} \end{aligned} \tag{5.20}$$

s^{max}_{ti} Maximal funding rate for power plant i during Δt ($\in (0,1)$)

5.2.3 Geographical and Ecological Conditions

Geographical conditions impose the possibility of different types of power plants. Storage or pumped-storage power plants can only be installed in mountainous areas, whereas river power plants can only be installed in rivers that are big enough. Another type of power plant that depends on the geographical conditions is a solar power plant, as high and steep mountains cause too much shadow for a profitable PV power plant. All of the other types of power plants could at least in theory be built anywhere. The geographical conditions are respected indirectly as a power plant that is not economically profitable (e.g., a solar power plant in the shadow) will not be part of the optimal solution.

5.2.4 Power Grid

Inside the Country: To model the power grid in a simple way, one needs to respect several components:

- Power plants (see Section 5.2.1)
- Transformation stations between high, middle and low voltage networks
- Networks for high, middle and low voltage
- Electricity recipients for high, middle and low voltage

Power plants have a certain maximum but also minimum level of output, and also every transformation station has a range of capacity which has to be taken into account. Networks have a certain capacity depending on their type (high, middle or low).
The Austrian power grid was divided into areas by the size of the electricity lines (220 kV or 380 kV; see Figure 4.1). Each area is capable of supplying and demanding electricity. When defining a power plant i it is necessary to give the information, in which area the power plant is located. In Table 5.1 the areas of the Austrian power grid are listed.

Another set of regions are foreign countries, that can also supply and demand electricity via electricity lines of different capacities; see Table 5.2.

In Equation (5.21) the continuity equation is regarded. The sum of all energy sources in each area has to equal the sum of all energy sinks:

$$\forall t \in \mathbb{N}, \forall x \in X^{AUT} : \mathrm{MWh}^{x^s}_t + \mathrm{MWh}^{x^{in}}_t = \mathrm{MWh}^{x^d}_t + \mathrm{MWh}^{x^{out}}_t \tag{5.21}$$

Area	Shortcut	Power line	Max. capacity of line
Western Tyrol and Vorarlberg	TyV	220 kV & 380 kV	3.2 GW
Central Tyrol	Tyr	220 kV	0.8 GW
Tauern	Tau	380 kV	2.4 GW
Salzburg	Sal	220 kV	0.8 GW
Carinthia	Car	220 kV	0.8 GW
Southern Styria and Burgenland	StB	380 kV	2.4 GW
Northern Styria	NSt	220 kV	0.8 GW
Upper Austria	UpA	220 kV & 380 kV	3.2 GW
Lower Austria	LoA	220 kV & 380 kV	3.2 GW
Vienna	VIE	220 kV & 380 kV	3.2 GW

Tab. 5.1: Areas of the Austrian Power Grid

Area	Shortcut	Power line (kV)	Max. capacity of line
Germany-Upper Austria	GU	380 & 220	3.2 GW
Germany-Vorarlberg	GV	220	0.8 GW
Germany-Tyrol	GT	380 & 220	3.2 GW
Switzerland-Tyrol	ST	380	2.4 GW
Italy-Tyrol	IT	220	0.8 GW
Italy-Carinthia	IC	220	0.8 GW
Slovenia-Carinthia	SC	220	0.8 GW
Slovenia-Styria	SS	380	2.4 GW
Hungary-Burgenland	HB	380 & 220	3.2 GW
Czech Republic-Lower Austria	CL	380 & 220	3.2 GW

Tab. 5.2: Neighboring areas of the Austria Power Grid

As each electricity line has a maximum capacity, it is necessary to constraint the maximum flow through every area; see Equation (5.22):

$$\forall t \in \mathbb{N}, \forall x \in X^{AUT} : \mathrm{MWh}_t^{x^s} + \mathrm{MWh}_t^{x^{in}} \leq MW_x^{line} \tag{5.22}$$

At any time, the total demand for electricity in each area x has to be covered by total supply of this area plus the total amount of electricity flowing into the area; see Equation (5.23)):

$$\forall t \in \mathbb{N}, \forall x \in X^{AUT} : \mathrm{MWh}_t^{x^s} + \mathrm{MWh}_t^{x^{in}} \geq \mathrm{MWh}_t^{x^d} \tag{5.23}$$

$\mathrm{MWh}_t^{x^s}$	Total supply of electricity in region x at time t $= \sum_{i \in \text{ region } x} O_{ti}$
$\mathrm{MWh}_t^{x^d}$	Total demand of electricity in region x at time t
$\mathrm{MWh}_t^{x^{in}}$	Total amount of electricity flowing into region x at time t
$\mathrm{MWh}_t^{x^{out}}$	Total amount of electricity flowing out of region x at time t
MW_x^{line}	Maximum capacity of the electricity line in region x
X^{AUT}	Set of all Austrian areas
X^{NBR}	Set of all areas in Austrian neighboring states

5.2.5 Merit Order Principle

Equation (5.24) describes the principle of merit order. The price of electricity equals the marginal costs of the the last power plant of the sorted list, which is needed to meet the demand D_t at time t. The list is sorted by the marginal costs C_{ti}^{marg} in ascending order; see Equation (5.25).

$$\forall t \in \mathbb{N}, \forall i \in I : P_t^{el} = C_{ti}^{marg} \Leftrightarrow \left(\sum_{\iota:\sigma(\iota)<\sigma(i)} O_{t\iota} < D_t \wedge \sum_{\iota:\sigma(\iota)\leq\sigma(i)} O_{t\iota} \geq D_t \right) \tag{5.24}$$

$$\begin{aligned} &\sigma(i) : I \to I \text{ , such that} \\ &\qquad \forall i, \tilde{i} \in I : \sigma(i) \leq \sigma(\tilde{i}) \Leftrightarrow C_{ti}^{marg} \leq C_{t\tilde{i}}^{marg} \end{aligned} \tag{5.25}$$

C_{ti}^{marg}	Marginal costs of power plant i at time t (in €/MWh)
D_t	Total demand of electricity during time period Δt (in MWh)

Chapter 6

Code

6.1 Implementation Process

The initial idea was to create a linear model with the output of power plants as variables. I decided to use the optimization software ”General Algebraic Modeling System” (GAMS) to implement my model. However, after successfully coding the structure of the problem in a basic way, the free version of GAMS was not able to handle the desired amount of variables and I did not have access to the full version. After a bit of research I found a library linking GAMS and Python called ”gamspy”. This gave me the possibility to code in GAMS syntax inside a larger Python code. The advantages were, that the definition of functions, which were not included in the optimization process, and above all plots were easier to code in Python. The problem concerning the license for GAMS was in the gamspy library the same and therefore I had to find a different way. My next step was to find libraries in Python that could solve optimization problems. The first choice was the library ”scipy”, but after some attempts I realized that this library was not suitable for implementing my problem. The next library ”pulp” was promising as I could implement a basic version of my optimization problem, but when I decided to include the price of electricity in my model, the problem was no longer linear, which made a library necessary that was capable of solving non-linear problems; see Equation (5.2). At first I tried ”pyscipopt” but this library could only solve simple bilinear problems. Finally I found the library ”pyomo”, which had all the desired features, and I could implement the model properly. Yet it had some issues with feasibility when I changed the values of certain parameters. The solving process has two steps: first, the non-linear parts are converted to linear parts by adding constraints, and second, the linear solver solves the problem. After intense inspection of my model and the code, I found out that the default linear solver ”glpk” (GNU Linear Programming Kit) was not capable of solving a problem of the given size. I tried to substitute ”glpk” with ”cplex”, but I had troubles getting a license for the cplex solver. Finally I found the solver ”gurobi”, which can solve the problem in the given size and provides a free full version for academic users.

To implement the model, assumptions had to be made. First, the types of power plants were reduced to the six main technologies in Austria:

- Hydropower: Pumped storage power plant
- Natural gas: Open cycle gas turbine
- Oil: Heavy fuel steam turbine
- Wind: Onshore wind power plant
- Solar: Photovoltaic power plant
- Biomass: Direct combustion (steam turbine)

The total number of power plants was reduced to 23 to demonstrate the dynamics of the model, but still achieve proper runtimes. Another simplification is, that the power grid is not taken into account. Therefore, the grid accessibility, grid capacity or transfer costs are not included in the problem. For each of the power plant types, various data is necessary to run the model. Due to numerous factors influencing the data of power plants (for example economic crisis, political insecurities or just the style of data generation), all of the used data have been researched in the first place (see chapter 3) and all of the data were adapted in a second step to receive results that demonstrate how the model works. The following table 6.1 shows the most important data of the power plants:

Item	**Hydro**	**Gas**	**Oil**	**Wind**	**Solar**	**Biomass**
Size (MW)	200-700	300-900	90-120	15-100	2-6	10-20
Max output (MWh/size/month)	300	400	250	200	150	400
Min output (% of size)	10	30	50	0	0	40
Starting costs (€)	200	500	1000	0	0	300
Full load (/month)	250	200	300	175	150	600
Resource per MWh	/	8 mmBtu	250 liters	/	/	1000 kg
Emissions (g CO_2 /MWh)	10[1]	500	900	15[1]	40[1]	70
Wages (€/MW)	1000	2500	3500	800	500	2000
Fixed costs constr. (Mio€)	50	20	30	5	2	30
Var. costs constr. (Mio€/MW)	2	0.5	1.5	1.2	0.5	2.5
Fixed costs maint. (€)	250 000	125 000	170 000	42 000	25 000	208 000
Var. costs maint. (€/MW)	8300	4200	6700	2500	1600	8300
Price of resource (€)	0	3/mmBtu	0.45/liter	0	0	0.08/kg

Tab. 6.1: Data used for implementation and calculation; taken from Chapters 2 and 3

6.2 Optimization Part

6.2.1 Objective Function

The objective function consists of a sum of the revenues minus costs over all points in time and all of the power plants that are in service at that time. The revenues comprise the product of the output $model.O[t,i]$ by the electricity price $model.P\_el[t]$ plus the total support $S(model,t,i)$ for power plant i at time t. The product of the output by the electricity is the reason, why the model is nonlinear, as both of the factors are variables. Additionally, $P\_el[t]$ depends on the output of all power plants at time t. The support $S(model,t,i)$ and the Costs $C(model,t,i)$ are also variables as there are special factors representing the support and the costs depending on the actual output (see Sections 6.2.3 and 6.2.4). For the solving process, the solver "ipopt" was used to transform the non-linear terms to linear terms by using additional constraints. The solver "gurobi" was chosen to solve the final linear problem.

[1] Wind, solar, and hydropower are not entirely emission-free due to emissions generated during the construction and decommissioning of facilities and components.

Program Code 6.1: Objective Function

```
def obj_rule(model):
    return sum((model.O[t,i]*model.P_el[t] + S(model, t, i) - C(model, t,
        i)) for t in range(T+1) for i in range(NumPPl[t]))
model.obj = Objective(rule=obj_rule, sense=maximize)

solver = SolverFactory('mindtpy')
results = solver.solve(
    model,
    mip_solver='gurobi',
    nlp_solver='ipopt'
)
```

6.2.2 Definition of Variables and Constraints

In the following part of the Code (6.2) the variables and the constraints of the optimization model are defined. The most important variables are the output $O[t,i]$ at each time step t for every power plant i. As the price for electricity $P\_el[t]$ for every time step t depends on the output of all power plants in a noncontinuous way (see Section 5.2.5), $P\_el[t]$ was defined as a variable, too, as four additional constraints were necessary to implement the link between output and price for electricity. The electricity price has no index i as it is the same for all power plants. Variables $p[t,i]$ and $max[t,i]$ are used to calculate the electricity price at time t according to the merit order system. The binary variable OnOff$[t,i]$ indicates, whether or not power plant i has output > 0 at time t and is used for special constraints.

Program Code 6.2: Definition of Variables

```
model = ConcreteModel("Power Plant Optimization")

#Decision Variables:
model.O = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    bounds=(0, None), initialize=0)
model.OnOff = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    within=Binary, initialize=0)
model.P_el = Var(range(T+1), bounds=(C_marg_min[t], C_marg_max[t]),
    initialize=C_marg_min[t])
model.p = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    bounds=(0, C_marg_max[t]), initialize=0)
model.max = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    within=Binary, initialize=0)
```

6.2.2.1 General Constraints

Listing 6.3 shows the most important constraints of the optimization model:

- The first constraint guarantees, that the total output of all power plants at time t meets the total demand $D[t]$.
- The $maxout\_rule(model, t, i)$ and the $minout\_rule(model, t, i)$ represent the constraint, that the actual output $O[t, i]$ stays within the bounds of each power plant. These bounds may vary over time, as a power plant can be extended or modified.
- The "BigM constraints" link $O[t, i]$ and $\mathrm{OnOff}[t, i]$ such that the binary variable $\mathrm{OnOff}[t, i]$ indicates whether power plant i is active (i.e., $O[t, i] > 0$) at time t. $BigM$ represents a large number and $epsilon$ is a very small number ϵ. As this constraint is designed with an approximation, there occurs a small rounding error ($\mathrm{OnOff}[t, i] = 0$ while $O[t, i] \leq \epsilon \neq 0$).

6.2.2.2 Constraints to Implement the Merit Order System

- To model the merit order system, four sets of constraints where necessary:
  - The $merit\_list\_rule$ forces the variable $p[t, i]$ to equal the marginal costs $C\_marg[t][i]$ if power plant i is active at time t and to be zero if not. This constraint creates therefore a list of all marginal costs of active power plants.
  - The one_max_rule restricts the sum of all binary variables $max[t, i]$ to equal 1. This ensures that at every time t there is exactly one index i for which $max[t, i] = 1$. In combination with the $upper\_bound\_rule$ and the optimization sense "maximum", the variable $max[t, i]$ equals 1 if and only if C_marg[t][i] is the maximum among all power plants i which are active at time t.
  - The $upper\_bound\_rule$ forces $P\_el[t]$ to be less or equal to all of the marginal costs of the active power plants (stored in $p[t, i]$) plus the product of $BigM$ by $(1 - max[t, i])$. This ensures that the electricity price is lower than a very large number for all of the indices i except for the one, where $max[t, i] = 1$. In this case the term with BigM is canceled and $P\_el[t]$ is less than the maximum marginal costs of all active power plants.
  - The $lower\_bound\_rule$ forces $P\_el[t]$ to be at least as high as the maximum marginal costs of all active power plants. From the right hand side $C\_marg[t][i] \cdot OnOff[t, i]$ the small number $epsilon$ is subtracted to ensure feasibility for the solver.

Program Code 6.3: Definition of Constraints

```
# Constraint: Demand coverage
def demand_rule(model, t):
    return sum(model.O[t,i] for i in range(NumPPl[t])) <= D[t]
model.demand = Constraint(range(T+1), rule=demand_rule)

# Constraint: Maximum output per plant
def maxout_rule(model, t, i):
    return model.O[t,i] <= MaxOut[t][i]
model.maxout_constraint = Constraint(((t, i) for t in range(T+1) for i in
    range(NumPPl[t])), rule=maxout_rule)

# Constraint: Minimum output per plant
def minout_rule(model, t, i):
    return model.O[t,i] >= MinOut[t][i] * model.OnOff[t,i]
model.minout_constraint = Constraint(((t, i) for t in range(T+1) for i in
    range(NumPPl[t])), rule=minout_rule)

# Constraint: Big-M constraint 1 (ensures that O is positive only if the
    plant is running)
def bigM1_rule(model, t, i):
    return model.O[t,i] <= BigM * model.OnOff[t,i]
model.bigM1 = Constraint(((t, i) for t in range(T+1) for i in
    range(NumPPl[t])), rule=bigM1_rule)

# Constraint: Big-M constraint 2 (ensures that O is greater than epsilon
    only if the plant is running)
def bigM2_rule(model, t, i):
    return model.O[t,i] >= epsilon * model.OnOff[t,i]
model.bigM2 = Constraint(((t, i) for t in range(T+1) for i in
    range(NumPPl[t])), rule=bigM2_rule)


########### Merit Order Constraints ######################################

# Constraint: create list C_marg of all active power plants
def merit_list_rule(model, t, i):
    return model.p[t,i] == C_marg[t][i] * model.OnOff[t,i]
model.merit_list = Constraint(((t, i) for t in range(T+1) for i in
    range(NumPPl[t])), rule=merit_list_rule)

# Constraint: used to find the maximum C_arg among active power plants
def one_max_rule(model, t):
    return sum(model.max[t, i] for i in range(NumPPl[t])) == 1
model.one_max_constraint = Constraint((t for t in range(T+1)),
    rule=one_max_rule)

```

```
# Constraint: P_el must be at most C_marg of the most expensive active
    power plant
def upper_bound_rule(model, t, i):
    return model.P_el[t] <= model.p[t, i] + BigM * (1 - model.max[t, i])
model.upper_bound_constraint = Constraint(((t, i) for t in range(T+1) for
    i in range(NumPPl[t])), rule=upper_bound_rule)

# Constraint: P_el must be at least C_marg of the most expensive active
    power plant
def lower_bound_rule(model, t, i):
    return model.P_el[t] >= C_marg[t][i] * model.OnOff[t,i] - epsilon
model.lower_bound_constraint = Constraint(((t, i) for t in range(T+1) for
    i in range(NumPPl[t])), rule=lower_bound_rule)
```

6.2.3 Cost Functions

Listing 6.4 shows the lines to calculate the cost function which is split up into three components:

- $C\_b(t, i)$ calculates the costs for building or extending a power plant. The linear function exists of fixed costs $x\_b(t, i)$ plus the variable costs times the size difference of the power plant $(y\_b(t, i) \cdot size\_diff)$.The whole linear function is multiplied by the binary parameter $build(t, i)$, which indicates whether power plant i was built or extended during time period t. Before the function returns the calculation, it has to be checked, whether $t = 0$ or if power plant i existed before time t to avoid indexing errors.
- $C\_o(model, t, i)$ calculates the costs for operating power plant i at time t. The operating costs consist of four terms:
  - The costs for the resource times the amount of needed resource times the binary variable $\mathrm{OnOff}[t, i]$, to avoid resource costs for inactive power plants.
  - The costs for CO_2 certificates and taxes depending on the emissions $Emiss(t, i)$, again multiplied by the binary variable $\mathrm{OnOff}[t, i]$, to avoid taxes for inactive power plants.
  - The costs for wages are calculated by the wages per size $wages(t, i)$ times the square root of half of the capacity $\sqrt{\frac{Size(t,i)}{2}}$. This term is multiplied by the term $(0.5 + 0.5 \cdot \mathrm{OnOff}[t, i])$ to decrease the wages by 50% if the power plant is not active.
  - The costs for starting up are fixed, but it has to be checked if $t = 0$ or if the power plant was active at time $t - 1$ to add the starting costs only if power plant i starts (again) at time t.
- $C\_m(model, t, i)$ calculates the costs for maintaining power plant i at time t. To do so, a linear function is used: Fixed costs $x_m(t, i)$ plus variable costs times the size and the age $y_m(t, i) \cdot Size(t, i) \cdot age(t, i)$. The maintenance costs are multiplied by the binary variable $\mathrm{OnOff}[t, i]$ to set the maintenance costs to zero if power plant is not working at time t.

Program Code 6.4: Calculation of Costs for every power plant

```
def C_b(t, i):
    if t == 0:
        size_diff = Size(t, i)
    else:
        if i < NumPPl[t-1]:
            prev_size = Size(t-1, i)
            if np.isnan(prev_size):
                size_diff = Size(t, i)
            else:
                size_diff = Size(t, i) - prev_size
        else:
            size_diff = Size(t, i)
    return (x_b(t,i) + y_b(t,i) * size_diff) * build(t, i)

def C_o(model, t, i):
    j = TechnIndex(t, i)
    res = P_res(t, j)*ResAmount(t,i)*model.O[t,i]
    tax = Co2Cert*(1+EmisTax)*Emiss(t, i)*model.O[t,i]
    wag = (wages(t, i)*np.sqrt(Size(t, i)/2))*(0.5+0.5*model.OnOff[t,i])
        # if ppl is off -> half of the wages
    if t == 0:
        start = StartCost[t][i]*model.OnOff[t,i]
    else:
        if i < NumPPl[t-1]: # Check if plant existed in previous period
            start = (StartCost[t][i] * model.OnOff[t,i]) * (1 -
                model.OnOff[t-1,i])
        else:
            start = StartCost[t][i] * model.OnOff[t,i] # Treat as new plant
    return res + tax + start + wag


def C_m(model, t, i):
    return (x_m(t, i) + y_m(t,i)*Size(t,i)*age(t,i))*model.OnOff[t,i]

def C(model, t, i):
    return C_b(t, i) + C_o(model, t, i) + C_m(model, t, i)
```

6.2.4 Support Functions

The calculations of the support for every power plant consists of the three main parts:

- Support for building or extending power plant i at time t
- Support for operating power plant i at time t
- Support for maintaining power plant i at time t

In reality, most of the funding is granted for building or extending a power plant. As the support mechanism for constructing and for extending a power plant are very similar, both of them are calculated in the part of building a power plant. The calculation 6.5 is based on the idea of section 6.2.4. For all of the parameters a_b, b_b, c_b0, and c_b1 the code checks if

- Technology j of power plant i is approved for funding at time t. The function $delta(t, j, k)$ gets the information from the parameter table $dataSup[t]$.
- Support k has a positive funding volume at time t.
- Funding call k depends on building costs (c_b0 and c_b1), emissions reduction (b_b), or has an independent funding volume (a_b) for any power plant during the construction process.
- Power plant i is built or extended at time t.

The Python function $b\_b(t, i, k)$ calculates the funding rates depending on the size for a specific funding project. If none of the conditions equals 0, the power plant t is approved for the support application process. The implementation of the application process is realized by constructing a new list $lst["Product"]$ that contains the ascending sorted bidding prices of the power plants at time t times the size of the power plant. In the next step, the described products are summed up over all power plants in correct order as long as there is funding volume left to be distributed. If the volume is exhausted, the remaining power plants are excluded from this call.

The function $c\_b0(t, i, k)$ is similar to $b\_b(t, i, k)$. However, the calculated funding rate depends now on the installation costs of the power plant. Again, a locally existing list is used to sort the requested funding rates in ascending order and grant support for all power plants as long as the funding volume is positive. This time it is possible that the last grant can exceed the funding volume by 50%. The remaining applications are excluded from this call.

The function c_b1 also calculates the funding rate depending on the installation costs, but in another way (for another funding project). In this function, the results of different criteria are summed up and if the application exceeds 60% of all possible points, the requested funding rate is granted.

The function $S\_b(t, i)$ returns the sum of all of the granted funding volumes of all funding calls for building power plant i at time t.

Program Code 6.5: Calculation of Support for every power plant

```python

def a_b(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or dataSup[t]['a_b'].iloc[k]
        == 0 or build(t,i) ==0:
        return 0
    else:
        return dataSup[t]['a_b'].iloc[k]

def b_b(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or dataSup[t]['b_b'].iloc[k]
        == 0 or build(t,i) ==0:
        return 0
```

```
    else:
        lst = dataPPl[t].copy()
        lst['Bid/FLH'] = lst["Biddingprice"] / (lst["FLH"]+epsilon)
        lst = lst.sort_values(by='Bid/FLH',
            ascending=True).reset_index(drop=True)
        lst["Product"] = lst["Biddingprice"] * lst["Size"]
        row_index = lst[lst['Number'] == i].index[0]
        cumsum = lst["Product"].iloc[:row_index].sum()
        if cumsum <= V_b(t, k):
            return lst["Biddingprice"].iloc[row_index]
        else:
            return 0

def c_b0(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or
        dataSup[t]['c_b0'].iloc[k] == 0 or build(t,i) ==0:
        return 0
    else:
        lst = dataPPl[t].copy()
        lst["InvCost"] = [C_b(t, i) for i in range(NumPPl[t])]
        lst = lst.sort_values(by=f"RequestFund{k}",
            ascending=True).reset_index(drop=True)
        lst["Product"] = lst[f"RequestFund{k}"] * lst["InvCost"]
        row_index = lst[lst['Number'] == i].index[0]
        cumsum = lst["Product"].iloc[:row_index].sum()
        if cumsum <= V_b(t, k) - 0.5 * C_b(t, i) * RequestFund(t, i, k):
            return RequestFund(t, i, k)
        else:
            return 0

def c_b1(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or
        dataSup[t]['c_b1'].iloc[k] == 0 or build(t,i) ==0:
        return 0
    else:
        if CritForm(t, i) * (CritCont(t, i) + CritCros(t, i) * 0.015) >=
            0.6:
            return RequestFund(t, i, 1)
        else:
            return 0

def S_b(t, i):
    a = sum(a_b(t, i, k) for k in range(NumSup[t]))
    b = sum(b_b(t, i, k) * dataSup[t]['b_b'].iloc[k] for k in
        range(NumSup[t])) * Size(t, i)
    c0 = sum(c_b0(t, i, k) * dataSup[t]['c_b0'].iloc[k] for k in
        range(NumSup[t]))
```

```
    c1 = sum(c_b1(t, i, k) * dataSup[t]['c_b1'].iloc[k] for k in
        range(NumSup[t]))
    c = (c0 + c1) * C_b(t, i)
    if a + b + c <= C_b(t, i) * MaxFundFact:
        return a + b + c
    else:
        return C_b(t, i) * MaxFundFact
```

Listing 6.6 shows the implementation of the calculations of support for operating power plant i at time t. Similar to the support for building a power plant, the calculation is split up into several parts that check at first, if funding is possible:

- $a\_o(t, i, k)$ describes the funding volume of call k for power plant i at time t that is granted independently for every active power plant.
- $b\_o(t, i, k)$ describes the funding rate of call k depending on the actual output of power plant i at time t.
- $c\_o(t, i, k)$ describes the funding rate of call k depending on the operating costs of power plant i at time t.
- $d\_o(t, i, k)$ describes the funding rate of call k negatively depending on the emissions caused by power plant i at time t.

Program Code 6.6: Calculation of Support for operating a power plant

```

def a_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['a_o'].iloc[k]
        == 0:
        return 0
    else:
        return dataSup[t]['a_o'].iloc[k]

def b_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['b_o'].iloc[k]
        == 0:
        return 0
    else:
        return dataSup[t]['b_o'].iloc[k]

def c_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['c_o'].iloc[k]
        == 0:
        return 0
    else:
```

```
        return dataSup[t]['c_o'].iloc[k]

def d_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['d_o'].iloc[k]
        == 0:
        return 0
    else:
        return dataSup[t]['d_o'].iloc[k]

def S_o(model, t, i):
    a = sum(a_o(t, i, k) for k in range(NumSup[t]))
    b = sum(b_o(t, i, k) * model.O[t, i] for k in range(NumSup[t]))
    c = sum(c_o(t, i, k) * C_o(model, t, i) for k in range(NumSup[t]))
    d = sum(d_o(t, i, k) * 1/(Emiss(t, i) + 1) for k in range(NumSup[t]))
    return (a + b + c + d) * model.OnOff[t,i]
```

In a similar way to the support for building and for operating a power plant, the support for maintaining a power plant was implemented. As this kind of support only depends on the maintenance costs, a simple linear function was chosen.

Program Code 6.7: Calculation of Support for maintaining a power plant

```

def a_m(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_m(t, k) == 0 or dataSup[t]['a_m'].iloc[k]
        == 0:
        return 0
    else:
        return dataSup[t]['a_m'].iloc[k]

def b_m(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_m(t, k) == 0 or dataSup[t]['b_m'].iloc[k]
        == 0:
        return 0
    else:
        return dataSup[t]['b_m'].iloc[k]

def S_m(t, i):
    a = sum(a_m(t, i, k) for k in range(NumSup[t]))
    b = sum(b_m(t, i, k) * C_m(t, i) for k in range(NumSup[t]))
    return a + b
```

Chapter 7

Results and Conclusion

In this chapter the behavior and the sensitivity of the model will be discussed. The data that were used for the calculations is taken from Chapters 2 and 3. Due to numerous factors influencing the data of different sources, it is not possible to work with the data without proper rescaling and adaption. Some of the factors are:

- Economic crises of the last 10 years
- Instable political situations
- Resulting volatile interest rates, prices for resources, plant parts, wages, etc.

As the data were adapted to gain knowledge about the way the model works, the results must not be taken as absolute values but should rather be used to see connections and relative dependencies.

Time Horizon	12 Months
Demand	6000 MWh
Maximum Possible Demand	7330 MWh
Prices:	
CO_2 Certificates	€ 80/ton of CO_2
CO_2 Taxes	€ 55/ton of CO_2
Natural Gas	€ 0.5/mmBtu
Oil	€ 0.5/liter
Biomass	€ 0.08/kg
Wind, Solar, Water	0

Name	Vol_b	Vol_o	Vol_m	a_b	b_b	c_b0	c_b1	a_o	b_o	c_o	d_o	a_m	b_m
EAG	10 000 000	300 000	0	300 000	0	1	0	0	0.1	0	0	0	0
ERDF	1 000 000	100 000	10 000	0	0	0	1	0	0	0.3	0	200	0.1
Horizon	2 000 000	200 000	0	0	0	0	0	0	0	0.3	2000	0	0
RENEWFM	3 000 000	300 000	0	200 000	1	0	0	0	0	0	0	0	0

Tab. 7.1: Support projects and their characteristic parameters

Runtime

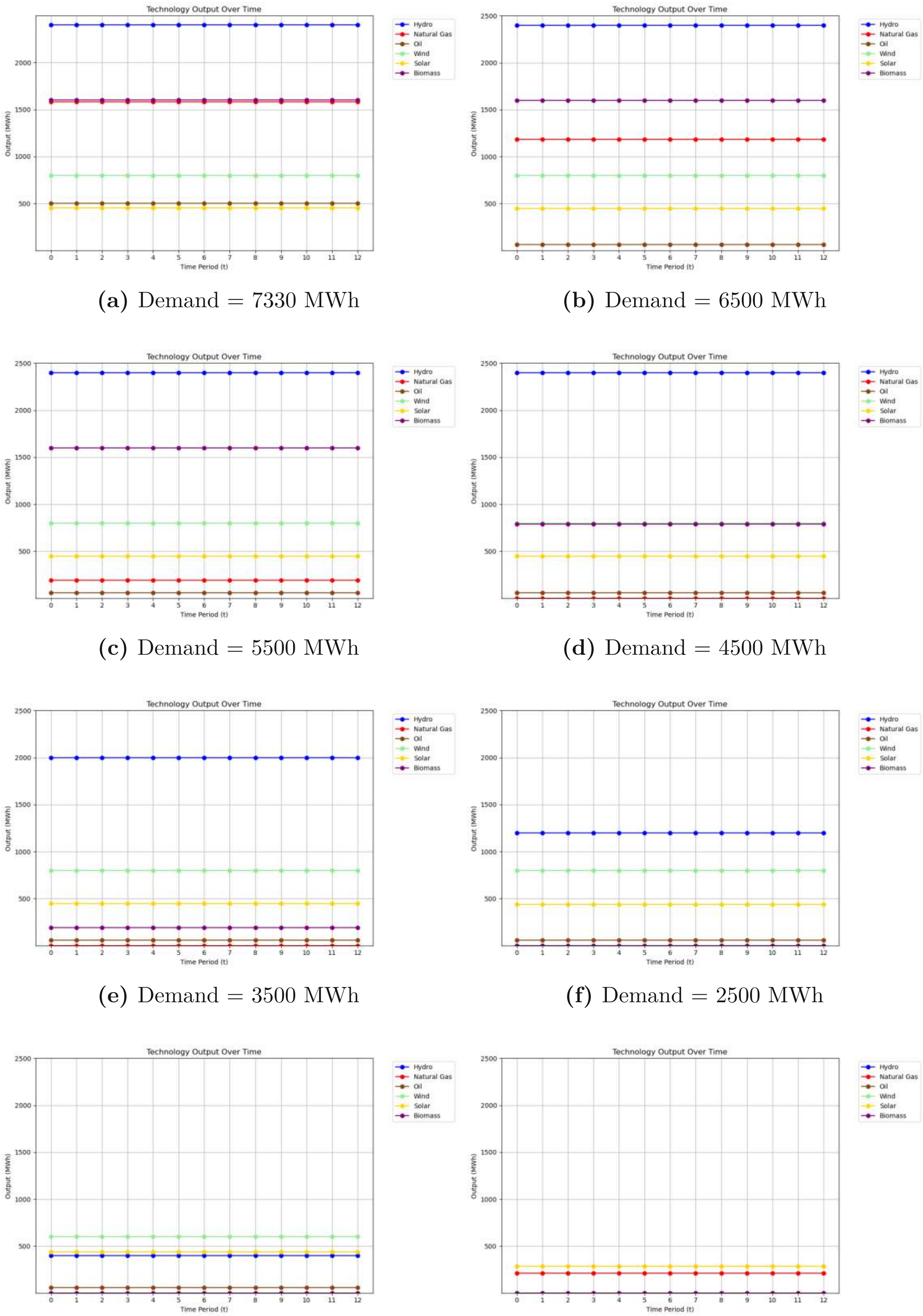
There is a variation in the runtime of each calculation because of the nonlinear solver. That means that even with identical input the program does not run equally long. For 12 time steps ($T = 12$) the runtime varies roughly between 30 and 40 seconds. The less time steps need to be calculated, the shorter is the runtime. For six time steps ($T = 6$) the runtime is about 11 to 13 seconds long, for four time steps ($T = 3$) the runtime is between 7 and 8 seconds.

7.1 Impact of Demand

Figure 7.1 shows in eight separate plots the dynamics of the output by technology over time for different values of demand. The Price for CO_2 certificates is € 80, and the emission taxes are fixed at € 55 for all plots in Figure 7.1. Moreover, the 100% of support is granted (factor for support = 1). In every plot the optimization was conducted over 13 time steps. One can observe that for constant demand, the output for each technology and therefore the composition of technologies is constant. If the full capacity of the sum of all power plants (7330 MWh) is demanded, all power plants produce their maximum output (see Figure 7.1a). By stepwisely decreasing demand (7330, 6500, 5500, 4500, . . . , 500), output decreases first for oil power plants (7.1b), followed by gas power plants (7.1b, 7.1c), and biomass power plants (7.1c, 7.1d). This behavior can be explained by the design of the support schemes and the CO_2 certificates and emission taxes, as support is granted only for "green" power plants (i.e., hydro, wind, solar, biomass), and the CO_2 certificates and emission taxes mainly occur for CO_2 emitters (oil, gas, and biomass). It is remarkable that output for oil power plants starts decreasing as the first of all power plants, but never reaches 0 output, except for the very low demand of 500 MWh. This is caused by the calculation of the price for electricity by the merit order system. To maximize the total profit of all power plants, the highest possible price for electricity is needed. Therefore, the power plant with the highest marginal costs (an oil power plant) stays active at the minimum level of output to push the electricity price upwards for all power plants. At very low demand it is not optimal to keep an oil power plant active, as the costs are too high, which however activates the group of power plants with the second highest marginal costs: gas power plants (see Figure 7.1h).

Figure 7.2 shows the output per technology as functions of the demand. The price for CO_2 certificates is € 80 and the emission taxes are fixed at € 55. Again, the 100% of support is granted (factor for support = 1). For each size of demand, the optimization model was run for three time steps with constant demand for each run of the program. The corresponding values for output are taken from the second time step to avoid distortion by ramping costs. The results are in line with the ones presented in Figure 7.1.

In Figure 7.3 the optimization model was run once with 12 time steps but varying demand over time. This demonstrates the overall optimal solution for the period of one year, if demand increases (7.3a) or decreases 7.3b) per month.



(a) Demand = 7330 MWh
(b) Demand = 6500 MWh
(c) Demand = 5500 MWh
(d) Demand = 4500 MWh
(e) Demand = 3500 MWh
(f) Demand = 2500 MWh
(g) Demand = 1500 MWh
(h) Demand = 500 MWh

Fig. 7.1: Output per technology as function time t in months with constant demand for electricity. Demand is constant at different levels per subplot. Price for CO_2 certificates = € 80; Emission taxes = € 55; Support factor = 1.

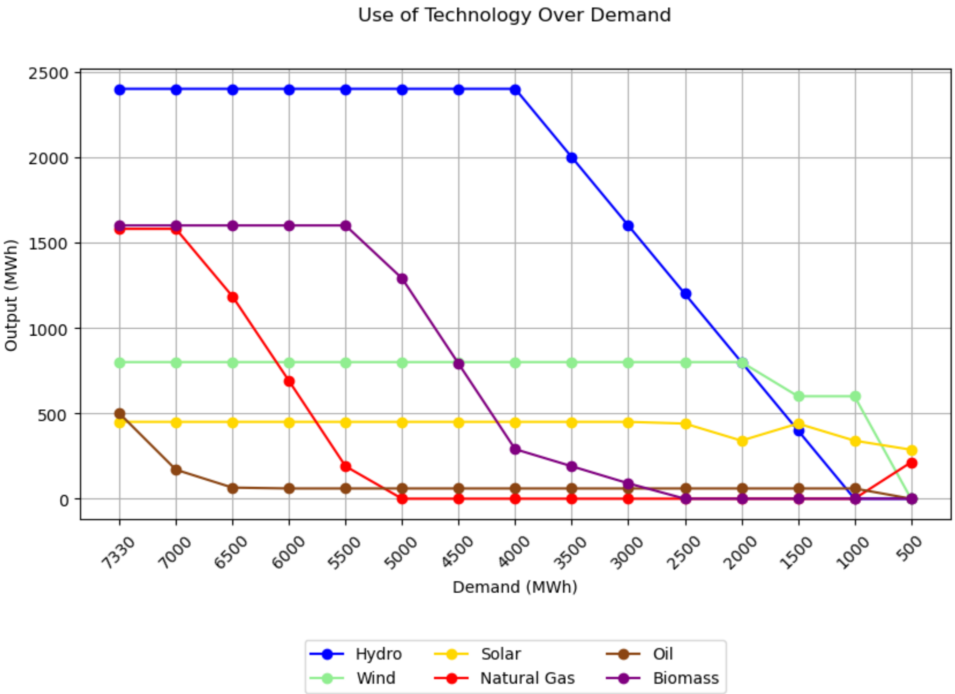
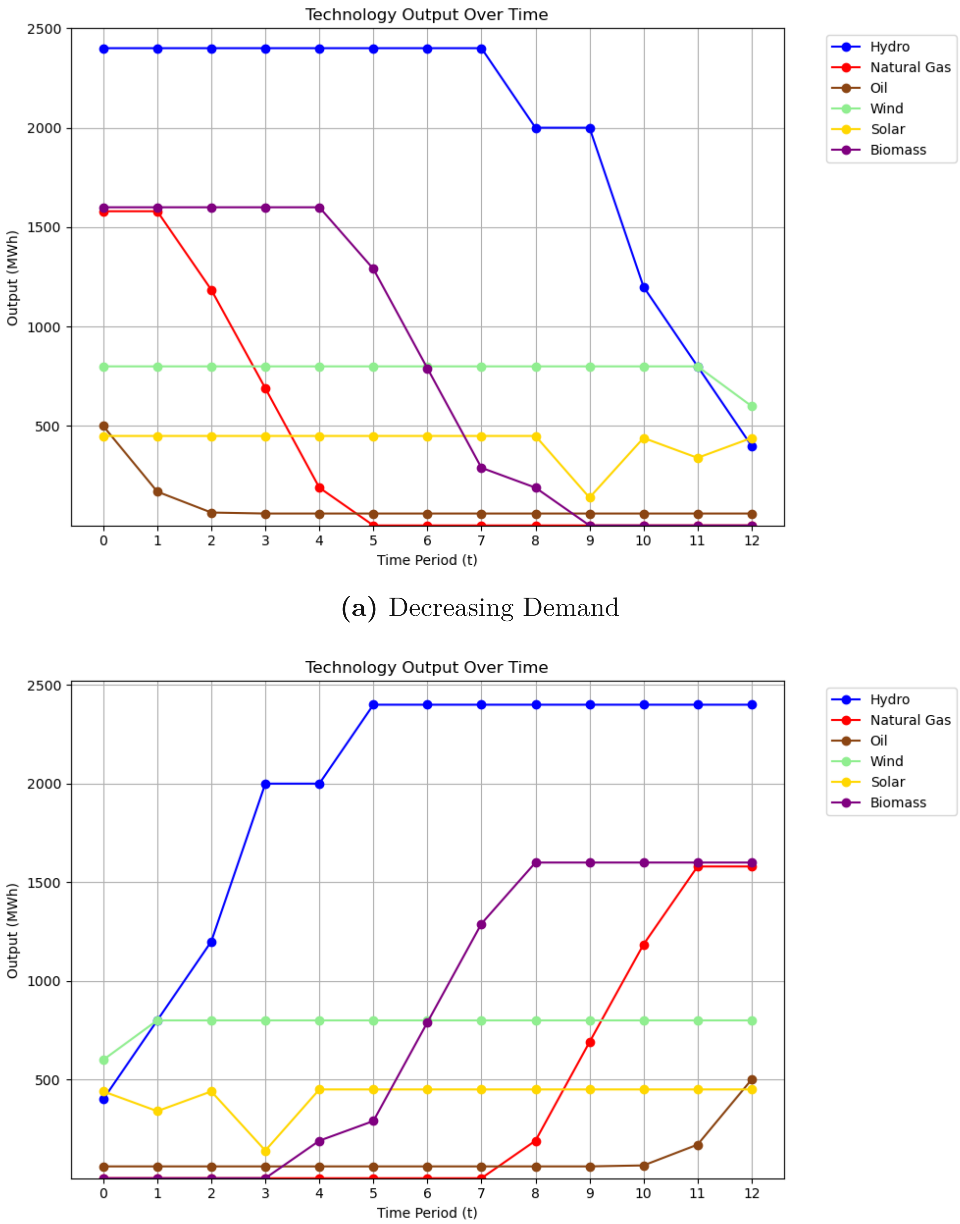


Fig. 7.2: Output per technology as functions of the demand for electricity. One optimization run per demand size with 3 time steps each. Price for CO_2 certificates = € 80; Emission taxes = € 55; Support factor = 1.



(a) Decreasing Demand

(b) Increasing Demand

Fig. 7.3: Output per technology as functions of the demand for electricity. One optimization run with 12 time steps. Price for CO_2 certificates = € 80; Emission taxes = € 55; Support factor = 1.

7.2 Construction and Shutdown of Power Plants

If a new power plant is constructed or power plants are shut down, the outputs change according to the new maximum output per technology. Figure 7.4 shows the output per technology over the time of 13 months, where at time step 3 both of the existing oil power plants are shut down and at the same time, one hydropower plant is built. The maximum output of the oil power plants was 250 MWh per month each, whereas the maximum output of the new hydropower plant has a maximum output of 400 MWh per month. As there is more capacity from hydropower available with a constant demand, the additional capacity is used and the use of gas power plants is reduced. The shut down of the oil power plants can be seen, as the output drops to zero at the time of the shut down. Figure 7.4 shows also that the change of output due to construction and shut down of power plants does not depend on the number of time steps used for the optimization. As both of the oil power plants are shut down, the electricity price for all power plants decreases, because the oil power plants have the highest marginal costs. Therefore, the profit per time step is lower after building the hydropower plant and shutting down the oil power plants. However, it is not optimal to construct a new fossil power plant, as their construction costs are not supported at all. Furthermore, an additional fossil power plant will never be part of the optimal solution as long as there are still other power plants with capacity left. This can bee seen in Figure 7.6, where the construction of an oil power plant at time t = 2 was modeled, but the new plant was never activated, which leads to constant output per technology over time.

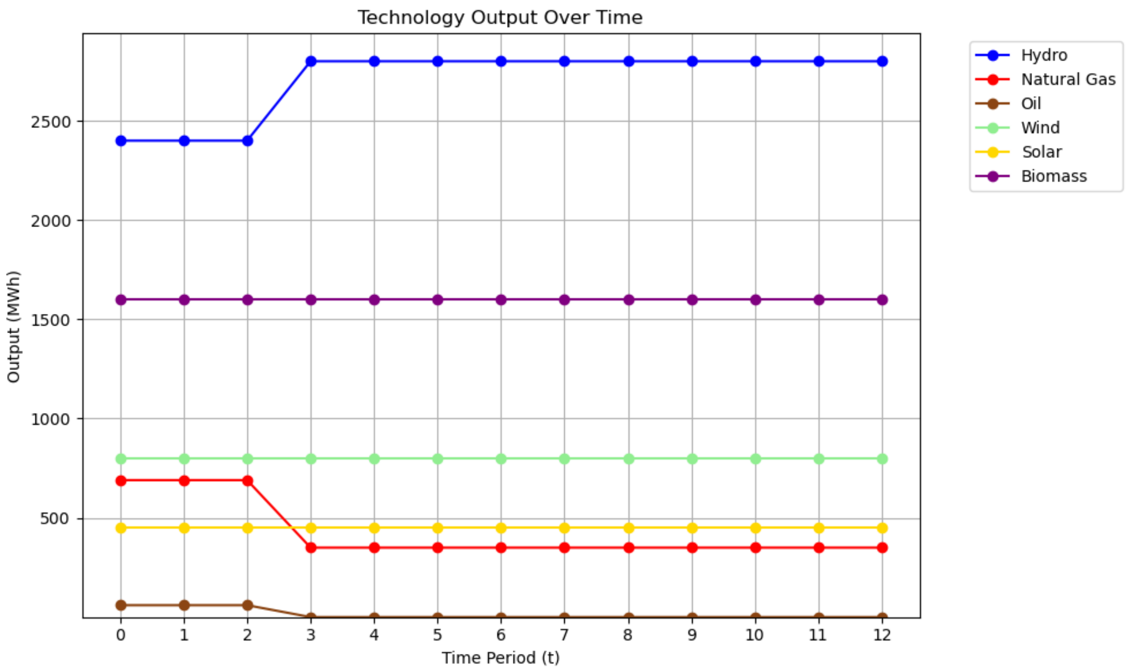
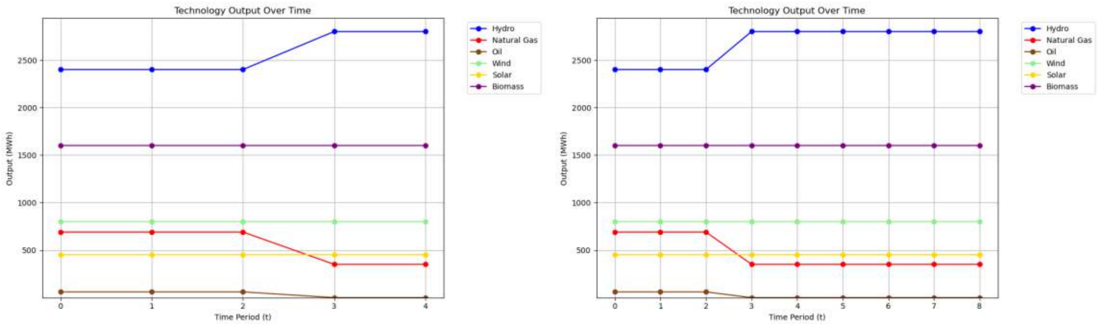


Fig. 7.4: Output per technology over time t for 12 time steps. Construction of a new hydropower plant and shutdown of both oil power plants at time $t = 3$. Constant demand of 6000 MWh, price for CO_2 certificates = € 80; Emission taxes = € 55; Support factor = 1.



(a) 4 time steps **(b)** 8 time steps

Fig. 7.5: Output per technology over time t for less than 12 time steps. Construction of a new hydropower plant and shutdown of both oil power plants at time $t = 3$. Constant demand of 6000 MWh, price for CO_2 certificates = € 80; Emission taxes = € 55; Support factor = 1.

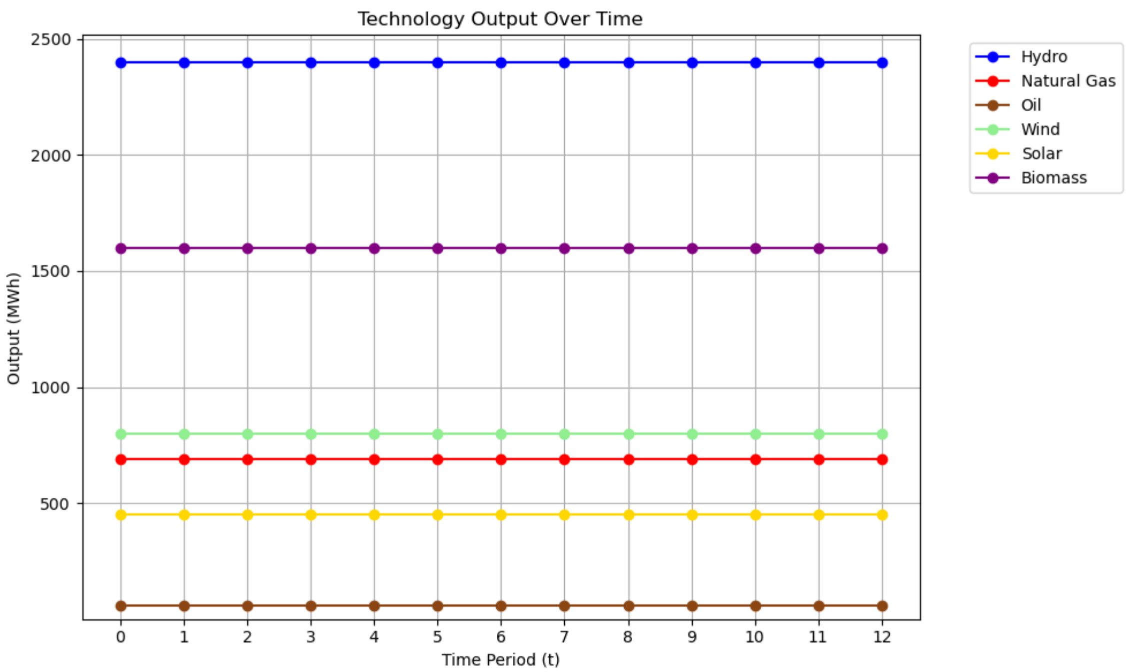


Fig. 7.6: Output per technology over time t for 12 time steps. Construction of a new oil power plant at time $t = 2$. Constant demand of 6000 MWh, price for CO_2 certificates = € 80; Emission taxes = € 55; support factor = 1.

7.3 Impact of CO_2 Certificates

Figure 7.7 shows the impact of the price of CO_2 certificates on the output per technology and the price for electricity. As the price for electricity is determined by the marginal costs of the active power plants (according to the merit order system), the price for CO_2 certificates affects the price for electricity, because the expenses for CO_2 certificates are taken into account when the marginal costs are calculated. For very low CO_2 prices, the oil power plants are not part of the optimal solution, and therefore the price for electricity is rather low. As soon as the first oil power plant is activated, the electricity price starts increasing. At a certain CO_2 price, the electricity price drops to a lower level, because the oil power plant with the highest marginal costs has too high overall costs, that in the optimal solution power plants with the second highest marginal costs are activated instead. If the CO_2 price rises further, the price for electricity rises again, until it is again more profitable to trade a lower electricity price for the deactivation of the most expensive still active power plant. At this second drop of the electricity price, both of the oil power plants are deactivated and the price-setting power plant is a gas power plant. As there are only two oil power plants, one can see a small change in the electricity generation by oil at the first drop of the electricity price and the total deactivation of all oil power plants at the second drop. The very small change of output from oil power plants at the first drop of the electricity price (price for CO_2 certificate = € 150) occurs, because the most expensive oil power plant has a slightly higher minimum output than the second most expensive power plant, and most of the time only one oil power plant is activated at the minimum output level to push the electricity price for all power plants.

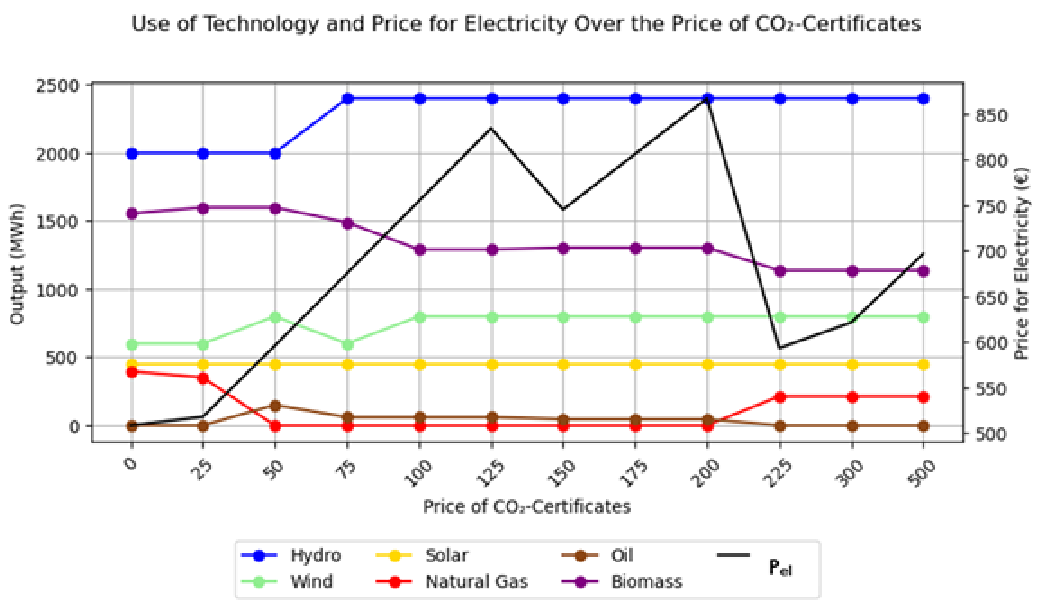


Fig. 7.7: Technology Output and Price of Electricity as Functions of the Price for CO_2 Certificates. Constant demand of 5000 MWh; Emission taxes = € 0; Support factor = 1.

The subfigures of Figure 7.8 show the technology output and the profit as functions of the price of CO_2 certificates with a constant demand of 5000 MWh. The difference between the sub-figures is the factor, by which the total support is multiplied to model different dynamics due to different support sizes. In all of the subfigures, the axis of the CO_2 prices can be separated into three parts: low, medium, and high CO_2 prices. For the originally designed size of the support

(7.8a) one can observe that for low CO_2 prices the output of gas power plants is reduced in favor of hydroelectric plants with increasing prices. For medium CO_2 prices, small price-changes do not affect the composition of technologies, and high CO_2 prices reduce biomass production in favor of gas power plants, while hydroelectric plants produce electricity at the maximum of their capacity. The change from biomass to gas is caused by the deactivation of oil power plants at a certain height of CO_2 certificate price, which forces the power plant with the next highest marginal costs (a gas power plant) to be activated in order to push the electricity price and with it the total profit to the maximum. It is remarkable that for very low prices of CO_2 certificates, oil power plants are not activated at all. After a peak between low and medium CO_2 prices, the output of oil power plants stays roughly constant until the CO_2 prices reach a high level, where the oil output is driven to zero again.

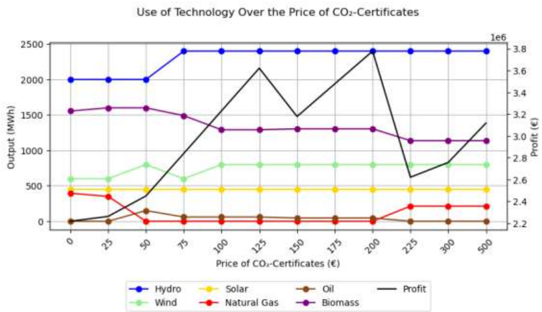
The black line represents the summed up profit of all power plants for each CO_2 certificate price. One can observe that the profit increases with increasing CO_2 prices, but it has two local minima. Those jumps are caused by the deactivation of the most expensive power plant, leading to a reduced electricity price for all power plants and therefore to less profit. The first drop (at € 150 per CO_2 certificate) is caused by switching from the most expensive oil power plant to the second most expensive one. The second jump is caused by deactivating the second (and last) oil power plant, which makes one of the gas power plants the most expensive active power plant, as gas power plants are activated at this price of CO_2 certificates.

If the support for the operation and maintenance of power plants is doubled (7.8b), the part of a nearly constant composition of technologies starts with lower CO_2 prices, but ends at the same as with the support factor = 1. One main difference between support factors 1 and 2 is the size of the hydropower and biomass production, since with higher support, hydropower starts at a higher level and declines to a lower level for medium CO_2 prices, then reaches a local maximum for high CO_2 prices and declines again for highest CO_2 prices. The output of biomass power plants appears inversely to the output of hydropower as the support is high enough for biomass power plants to compete with hydropower plants. For doubled support, the small peak in the output of oil power plants between low and medium CO_2 costs does not appear.

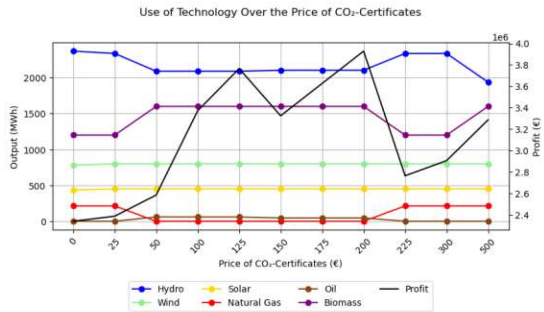
If the support is cut in half (7.8c), parts of the hydropower generation are substituted by gas power plants for low prices for CO_2 certificates. With rising CO_2 prices, the output of hydroelectric plants increases and the gas power plants generate less electricity. The interval of CO_2 certificate prices, that do not affect the composition of technologies starts at a higher price and is therefore shorter compared to a scenario with support factor = 1. For highest CO_2 prices, there is no difference in the output of technologies compared to the support factor = 1.

Figure 7.8d shows a scenario of very low support for the operation and maintenance of power plants (1% of the original support volume). One can observe that the dynamics of 7.8c are continued and intensified. Hydropower plants start at an even lower level of output than gas power plants for very low prices for CO_2 certificates. To reach a composition in which all of the sustainable power plant types generate electricity at their maximum level and fossil power plants are only used to cover remaining demand, very high CO_2 prices are necessary. If support is low and CO_2 prices are high, the output of biomass power plants decreases in contrast to high support and high CO_2 prices.

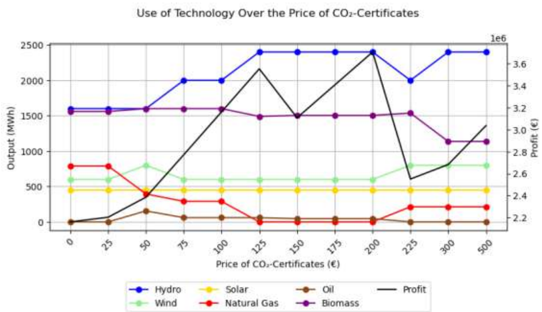
The total profit of all power plants is very similar for all four different support factors. The reason for this is that the vast majority of subsidies are aimed at the construction of new power plants and not at their operation. However, the quantity of profit increases with increasing support, which is not surprising. Also it is remarkable that between the local inner maxima of the profit curve, the price of CO_2 certificates has hardly any effect on the size and the composition of output of the different technologies, but affects the total profit of all power plants. In general, raising the prices of CO_2 certificates causes higher profits apart from certain jumping points.



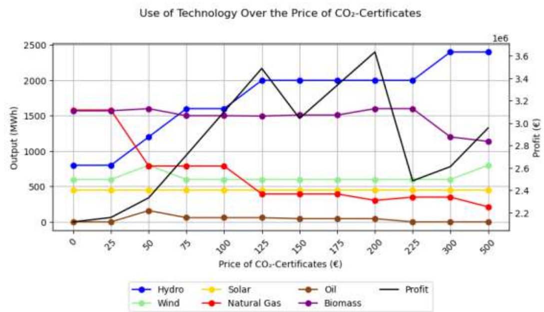
(a) Support Factor = 1



(b) Support Factor = 2



(c) Support Factor = 0.5



(d) Support Factor = 0.01

Fig. 7.8: Technology Output and Profit as Functions of the Price of CO_2 Certificates for different support factors. Constant demand of 5000 MWh; Emission tax = € 0.

As for all support factors the global maximum of total profit for all of the power plants occured at the price for CO_2 certificates of € 200 (see 7.8), in figure 7.9 the output per technology and the total profit are plotted as functions of the support factor for constant demand of 5000 MWh and a CO_2 certificate price of € 200. With decreasing support, the total profit of all power plants decreases, too. It is interesting that the reduction of the support factor from 1 to 0.5 does not lead to additional electricity generation by fossil power plants. However, it causes a shift from wind energy to biomass power plants and a loss of profit. Only if the support is too low, gas power plants are activated instead of parts of the hydropower plants.

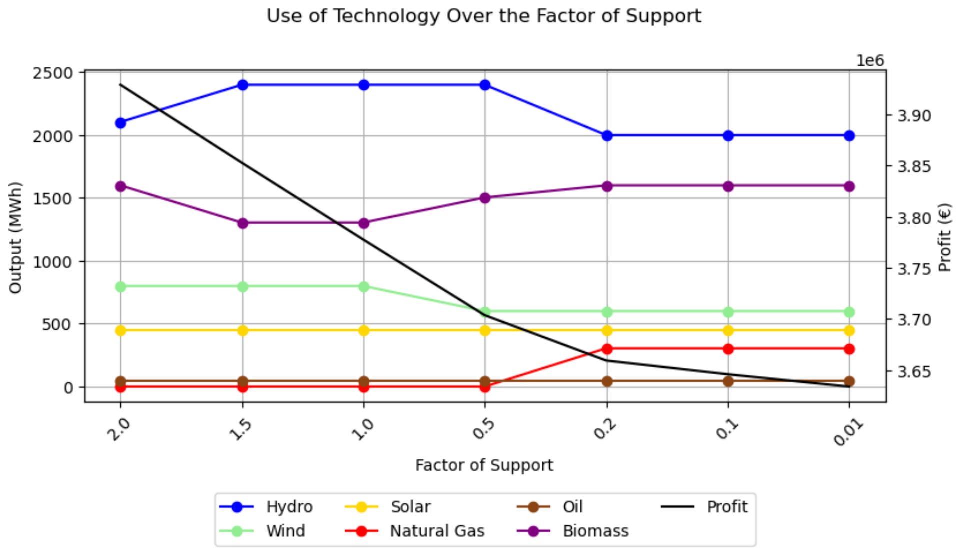


Fig. 7.9: Technology Output and Profit As functions of the Support Factor. Constant demand of 5000 MWh; Price of CO_2 certificate = € 200; Emission tax = € 0.

7.4 Conclusion

Taking into account the results and the design of the model one can draw several conclusions. First of all, the results verify that the height of CO_2 taxes or CO_2 certificate prices and the volume of financial support are both effective political instruments to reduce the emission of greenhouse gases in the sector of electricity generation. Both of those instruments can be implemented independently from each other and have the possibility to shift the electricity generation from fossil power plants to renewable power plants. The data used for optimization suggest that there is an interval of prices for CO_2 certificates/emission taxes in which the composition of technologies does not change. If the price for CO_2 certificates is in this interval, it is effective for political decision makers to adjust the financial support in order to achieve the desired composition of technologies for generating electricity. As support is granted only for renewable power plants and the CO_2 certificates and taxes affect only the fossil power plants, the model suggests that it is not rational to construct a new fossil power plant. However, in reality there are numerous other factors influencing the decision of building a new power plant. Some of those factors are:

- High demand for electricity in areas with low possibilities of installing hydropower or wind power plants.
- Network capacity to transport electricity from big power plants to areas with high demand.
- Grid accessibility.
- Need for power plants with short ramping times to cover short term power shortages.

All of the factors mentioned above are respected in the theoretical model (Chapter 5). With the data used for the optimization problem, another conclusion is possible: Even without support, by raising the price for CO_2 certificates it is possible to reach a composition of technologies for electricity generation where green power plants generate electricity at their maximum output level, the oil power plants are deactivated at all, and gas is only used to cover the remaining demand. In addition, even for such a scenario, the total profit of all power plants is still positive.

One may interpret this result with caution, as the data were adapted in order to receive a feasible and qualitative solution rather than quantitative results.

Further work can be done by including more factors influencing the construction or shut down of power plants to the model. To gain the possibility of interpreting the solutions quantitatively, an intense research and generation of necessary data is necessary. Another extension of the problem can be realized by constructing another optimization model to find the optimal sizes of support and of the CO_2 certificate price.

Bibliography

[1] greenmatch AG. *How to Calculate the Levelized Cost of Energy (LCOE)?* 2024. URL: https://www.greenmatch.ch/en/knowledge-center/how-to-calculate-the-levelized-cost-of-energy-lcoe/ (visited on 12/04/2024).

[2] Austrian National Council. *Gesamte Rechtsvorschrift für Erneuerbaren-Ausbau-Gesetz*. Version of 2025-01-24. 2021. URL: https://www.ris.bka.gv.at/GeltendeFassung/Bundesnormen/20011619/EAG%2c%20Fassung%20vom%2024.01.2025.pdf.

[3] Austrian Power Grid. *Stromnetz*. 2024. URL: https://www.apg.at/stromnetz/stromnetz-oesterreich/ (visited on 02/18/2025).

[4] Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. *Investitionsförderungsrichtlinien 2022 für die Umweltförderung im Inland*. 2022. URL: https://www.umweltfoerderung.at/fileadmin/user_upload/umweltfoerderung/uebergeordnete_dokumente/IFRL_UFI.pdf (visited on 02/11/2025).

[5] Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie. *Klimafonds-Jahresprogramm: Innovationen für den Klimaschutz*. 2024. URL: https://www.bmk.gv.at/service/presse/gewessler/2024/0130_klima-und-energiefonds-2024.html (visited on 01/26/2025).

[6] G. W. Crabtree and N. S. Lewis. "Solar energy conversion". In: *Physics Today* 60.3 (Mar. 2007), pp. 37–42. ISSN: 0031-9228. DOI: 10.1063/1.2718755. URL: https://doi.org/10.1063/1.2718755 (visited on 05/05/2025).

[7] EAG-Förderabwicklungsstelle. *Statistik*. 2024. URL: https://www.eag-abwicklungsstelle.at/statistik (visited on 01/25/2025).

[8] Energy Institute. *Statistical Review of World Energy*. Energy Institute, 2024.

[9] European Commission. "Commission Decision (EU) 2020/1722 of 16 November 2020 on the Union-wide quantity of allowances to be issued under the EU Emissions Trading System for 2021". In: *Official Journal of the European Union* 63 (2020), pp. 26–27.

[10] European Commission. "Commission Decision (EU) 2023/1575 of 27 July 2023 on the Union-wide quantity of allowances to be issued under the EU Emissions Trading System for 2024". In: *Official Journal of the European Union* 66 (2023), pp. 30–31.

[11] European Commission. "Commission Delegated Regulation (EU) 2019/856 of 26 February 2019 Supplementing Directive 2003/87/EC of the European Parliament and of the Council with Regard to the Operation of the Innovation Fund". In: *Official Journal of the European Union* 62 (2019), pp. 6–17.

[12] European Commission. *Connecting Europe Facility*. 2025. URL: https://cinea.ec.europa.eu/programmes/connecting-europe-facility_en (visited on 01/22/2025).

[13] European Commission. *EU Emission Trading System (EU ETS)*. 2024. URL: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en (visited on 11/30/2024).

[14] European Commission. *Horizon Europe*. 2025. URL: `https://cinea.ec.europa.eu/programmes/horizon-europe_en` (visited on 01/17/2025).

[15] European Commission. *Horizon Europe. The EU Research and Innovation Programme 2021 - 27*. 2021. URL: `https://research-and-innovation.ec.europa.eu/document/download/9224c3b4-f529-4b48-b21b-879c442002a2_en?filename=ec_rtd_he-investing-to-shape-our-future.pdf` (visited on 04/25/2025).

[16] European Commission. *Life Programme*. 2025. URL: `https://cinea.ec.europa.eu/programmes/life_en` (visited on 01/17/2025).

[17] European Commission. "Regulation (EU) 2021/1056 of the European Parliament and of the council of 24 June 2021 establishing the Just Transition Fund". In: *Official Journal of the European Union* 64 (2021), pp. 1–20.

[18] European Commission. "Regulation (EU) 2021/1060 of the European parliament and of the council of 24 June 2021 laying down common provisions on the European Regional Development Fund, the European Social Fund Plus, the Cohesion Fund, the Just Transition Fund and the European Maritime, Fisheries and Aquaculture Fund and financial rules for those and for the Asylum, Migration and Integration Fund, the Internal Security Fund and the Instrument for Financial Support for Border Management and Visa Policy". In: *Official Journal of the European Union* 64 (2021), pp. 159–251.

[19] European Commission. *Renewable Energy Financing Mechanisms Multi Technology. Topic Conditions and Documents*. 2025. URL: `https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/renewfm-2025-invest-multi` (visited on 02/14/2025).

[20] European Commission. *Union Renewable Energy Financing Mechanism (RENEWFM)*. 2025. URL: `https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/programmes/renewfm` (visited on 01/17/2025).

[21] European Commission. *Union Renewable Energy Financing Mechanism (RENEWFM) Call for Proposals*. July 30, 2024. URL: `https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/renewfm/wp-call/2025/call-fiche_renewfm-2025-invest-multi_en.pdf` (visited on 02/14/2025).

[22] European Investment Bank. *EIB Energy Lending Policy. Supporting the Energy Transformation*. European Investment Bank, 2023.

[23] FFG Forschung wirkt. *Horizon Europe*. URL: `https://www.ffg.at/Europa/Horizon-Europe` (visited on 02/12/2025).

[24] Fördermittel Vergleich. *EU-LIFE – Förderprogramm für die Umwelt und Klimapolitik (2021–2027)*. 2025. URL: `https://www.xn--frdermittel-vergleich-hec.de/europa/eu-life/` (visited on 01/21/2025).

[25] M. B. Hayat, D. Ali, K. C. Monyake, L. Alagha, and N. Ahmed. "Solar energy—A look into power generation, challenges, and a solar-powered future". In: *International Journal of Energy Research* 43.3 (2019), pp. 1049–1067.

[26] International Energy Agency. *Where does Austria get its electricity?* 2023. URL: `https://www.iea.org/countries/austria/electricity` (visited on 03/02/2025).

[27] IRENA. *Renewable Energy Statistics 2024*. Abu Dhabi: International Renewable Energy Agency, 2024. ISBN: 978-92-9260-614-5.

[28] IRENA. *Renewable Power Generation Costs in 2023*. Abu Dhabi: International Renewable Energy Agency, 2024. ISBN: 978-92-9260-621-3.

[29] IWB/EFRE Verwaltungsbehörde. *Investitionen in Beschäftigung und Wachstum Österreich 2021-2027 (EFRE & JTF) – Methodik und Kriterien für die Projektselektion.* Version 2. Formal criteria and funding eligibility for projects under EFRE & JTF Austria. May 2023. URL: https://www.umweltfoerderung.at/fileadmin/user_upload/umweltfoerderung/efre/EFRE21-27_Auswahlverfahren_Projektmassnahmen.pdf (visited on 02/04/2025).

[30] M. Kelter. *Großkraftwerke Kohle, Gas, Öl und Kombikraftwerk.* June 12, 2020. URL: https://kelter-energie.de/grosskraftwerke-kohle-gas-oel-und-kombikraftwerk/ (visited on 03/03/2025).

[31] C. Kost, P. Müller, J. S. Schweiger, F. Verena, and J. Thomsen. *Stromgestehungskosten Erneuerbare Energien.* Aug. 2024. URL: https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/studie-stromgestehungskosten-erneuerbare-energien.html (visited on 02/20/2025).

[32] M. Kotz, A. Levermann, and L. Wenz. "The economic commitment of climate change". In: *Nature* 628.8008 (2024), pp. 551–557.

[33] C. Kousky. "Informing climate adaptation: A review of the economic costs of natural disasters". In: *Energy Economics* 46 (2014), pp. 576–592.

[34] M. McDowell. *EU Förderung für regionale Entwicklung.* Ed. by Geschäftsstelle der Österreichischen Raumordnungskonferenz (ÖROK). Vienna, Austria, 2022. URL: https://www.efre.gv.at/fileadmin/user_upload/2021-2027/downloadcenter/Programm/EFRE-JTF-broschuere-web-barrierefrei.pdf (visited on 02/11/2025).

[35] NRW Bank. *EU-Innovationsfonds.* 2025. URL: https://www.nrwbank.de/de/foerderung/foerderprodukte/16046/eu-innovationsfonds.html (visited on 01/22/2025).

[36] Oeko-Institut e.V. *How Supply and Demand Determine Electricity Prices: The Merit Order Principle.* 2025. URL: https://www.flickr.com/photos/oekoinstitut/40334509872/in/album-72157634042349017 (visited on 05/06/2025).

[37] OeMAG. *OeMAG Abwicklungsstelle für Ökostrom AG.* 2025. URL: https://www.oem-ag.at/de/home/ (visited on 01/24/2025).

[38] Parlamentsdirektion der Republik Österreich. *Analyse des Budgetdienstes. Analyse der ökosozialen Steuerreform 2022.* Parlamentsdirektion der Republik Österreich, Jan. 10, 2022, pp. 46–50.

[39] R. Paschotta. *RP-Energie-Lexikon. Ölkraftwerk.* Aug. 23, 2023. URL: https://www.energie-lexikon.info/oelkraftwerk.html (visited on 02/28/2025).

[40] F. Sandau, S. Timme, C. Baumgarten, and R. Beckers. "Daten und Fakten zu Braun- und Steinkohlen. Stand und Perspektiven 2021". In: *TEXTE* 28 (2021).

[41] S. Shimura, R. Herrero, M. K. Zuffo, and J. A. B. Grimoni. "Production costs estimation in photovoltaic power plants using reliability". In: *Solar Energy* 133 (2016), pp. 294–304.

Appendix A

Full Code

```
from pyomo.environ import ConcreteModel, Var, Objective, SolverFactory,
    Binary, Constraint, maximize, TerminationCondition, value
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

T = 12
dataPPl = {}
dataSup = {}
dataPrice = {}
NumPPl = {}
NumSup = {}

for t in range(T+1):
    h=-11
    dataPPl[t] = pd.read_excel(f'data{t+h}.xlsx', sheet_name='PPl',
        decimal=",").drop(columns=["Name", "Technology"])
    dataSup[t] = pd.read_excel(f'data{t+h}.xlsx', sheet_name='Support',
        decimal=",")
    dataPrice[t] = pd.read_excel(f'data{t+h}.xlsx',
        sheet_name='Pricelist', decimal=",")
    NumPPl[t] = len(dataPPl[t])
    NumSup[t] = len(dataSup[t])

# Data / Parameters:
VAT = 0.2
D = {t: 6000 for t in range(T+1)}
Co2Cert = {t: 80 for t in range(T+1)}
EmisTax = {t: 55 for t in range(T+1)}
BigM = 1e4
epsilon = 1e-4
MaxFundFact = 0.5
RampFact = 0.1
xo = 1
SupFact = 0

Size_arr = {}
MaxOut = {}
```

```python
MinOut = {}
C_marg = {}
StartCost = {}

for t in range(T+1):
    Size_arr[t] = np.array(dataPPl[t]["Size"])
    MaxOut[t] = np.array(dataPPl[t]["MaxOut"])
    MinOut[t] = np.array(dataPPl[t]["MinOut"])
    C_marg[t] = [0]*NumPPl[t]
    StartCost[t] = np.array(dataPPl[t]["StartCost"])

###########################################################################
# Functions
###########################################################################

def TechnIndex(t, i):
    return dataPPl[t].loc[i, "TechnIndex"]

def RequestFund(t, i, k):
    return dataPPl[t].loc[i, f"RequestFund{k}"]

def CritForm(t, i):
    return dataPPl[t].loc[i, "CritForm"]

def CritCont(t, i):
    return dataPPl[t].loc[i, "CritCont"]

def CritCros(t, i):
    return dataPPl[t].loc[i, "CritCros"]

def Size(t, i):
    return dataPPl[t].loc[i, "Size"]

def age(t,i):
    return dataPPl[t].loc[i, "Age"]

def Emiss(t, i):
    return xo*dataPPl[t].loc[i, "Emissions"]

def ResAmount(t, i):
    return dataPPl[t].loc[i, "ResAmount"]

def wages(t,i):
    return dataPPl[t].loc[i, "Wages"]

def P_res(t,j):
    return dataPrice[t].loc[j, "ResPrice"]

def x_b(t, i):
```

```
    return dataPPl[t].loc[i, "x_b"]

def y_b(t, i):
    return dataPPl[t].loc[i, "y_b"]

def x_m(t, i):
    return dataPPl[t].loc[i, "x_m"]

def y_m(t, i):
    return dataPPl[t].loc[i, "y_m"]

def build(t, i):
    return dataPPl[t].loc[i, "build"]

hydro_indices = [[i for i in range(NumPPl[t]) if TechnIndex(t, i) == 0]
    for t in range(T+1)]
gas_indices = [[i for i in range(NumPPl[t]) if TechnIndex(t, i) == 1] for
    t in range(T+1)]
oil_indices = [[i for i in range(NumPPl[t]) if TechnIndex(t, i) == 2] for
    t in range(T+1)]
wind_indices = [[i for i in range(NumPPl[t]) if TechnIndex(t, i) == 3]
    for t in range(T+1)]
solar_indices = [[i for i in range(NumPPl[t]) if TechnIndex(t, i) == 4]
    for t in range(T+1)]
bio_indices = [[i for i in range(NumPPl[t]) if TechnIndex(t, i) == 5] for
    t in range(T+1)]

def sum_out(t):
    return sum(MaxOut[t][i] for i in range(NumPPl[t]))

def sum_out_hydro(t):
    return sum(MaxOut[t][i] for i in hydro_indices[t])

def sum_out_gas(t):
    return sum(MaxOut[t][i] for i in gas_indices[t])

def sum_out_oil(t):
    return sum(MaxOut[t][i] for i in oil_indices[t])

def sum_out_wind(t):
    return sum(MaxOut[t][i] for i in wind_indices[t])

def sum_out_solar(t):
    return sum(MaxOut[t][i] for i in solar_indices[t])

def sum_out_bio(t):
    return sum(MaxOut[t][i] for i in bio_indices[t])

##########################################################################
```

```
# COST-functions
#########################################################################

def C_b(t, i):
    if t == 0:
        size_diff = Size(t, i)
    else:
        if i < NumPPl[t-1]:
            prev_size = Size(t-1, i)
            if np.isnan(prev_size):
                size_diff = Size(t, i)
            else:
                size_diff = Size(t, i) - prev_size
        else:
            size_diff = Size(t, i)
    return (x_b(t,i) + y_b(t,i) * size_diff) * build(t, i)

def C_o(model, t, i):
    j = TechnIndex(t, i)
    res = P_res(t, j)*ResAmount(t,i)*model.O[t,i]
    tax = (Co2Cert[t]+EmisTax[t])*Emiss(t, i)*model.O[t,i]
    wag = (wages(t, i)*np.sqrt(Size(t, i)/2))*(0.5+0.5*model.OnOff[t,i])
        # if ppl is off -> half of the wages
    if t == 0:
        start = StartCost[t][i]*model.OnOff[t,i]
    else:
        if i < NumPPl[t-1]:
            start = (StartCost[t][i] * model.OnOff[t,i]) * (1 -
                model.OnOff[t-1,i])
        else:
            start = StartCost[t][i] * model.OnOff[t,i]
    return res + tax + wag + start

def C_m(model, t, i):
    return (x_m(t, i) +
        y_m(t,i)*np.sqrt(Size(t,i)/2)*age(t,i))*model.OnOff[t,i]

def C(model, t, i):
    return C_b(t, i) + C_o(model, t, i) + C_m(model, t, i)

#########################################################################
# SUPPORT-Functions
#########################################################################

def V_b(t, k):
    return dataSup[t]['Vol_b'].iloc[k]

def V_o(t,k):
    return dataSup[t]['Vol_o'].iloc[k]
```

```

def V_m(t,k):
    return dataSup[t]['Vol_m'].iloc[k]

def delta(t, j, k):
    return dataSup[t].iloc[k, 2+j]

def a_b(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or dataSup[t]['a_b'].iloc[k]
        == 0 or build(t,i) ==0:
        return 0
    else:
        return dataSup[t]['a_b'].iloc[k]

def b_b(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or dataSup[t]['b_b'].iloc[k]
        == 0 or build(t,i) ==0:
        return 0
    else:
        lst = dataPPl[t].copy()
        lst['Bid/FLH'] = lst["Biddingprice"] / (lst["FLH"]+1)
        lst = lst.sort_values(by='Bid/FLH',
            ascending=True).reset_index(drop=True)
        lst["Product"] = lst["Biddingprice"] * lst["Size"]
        row_index = lst[lst['Number'] == i].index[0]
        cumsum = lst["Product"].iloc[:row_index].sum()
        if cumsum <= V_b(t, k):
            return lst["Biddingprice"].iloc[row_index]
        else:
            return 0

def c_b0(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or
        dataSup[t]['c_b0'].iloc[k] == 0 or build(t,i) ==0:
        return 0
    else:
        lst = dataPPl[t].copy()
        lst["InvCost"] = [C_b(t, i) for i in range(NumPPl[t])]
        for i in range(NumPPl[t]):
            lst.loc[dataPPl[t]["build"] == 0, f"RequestFund{k}"] = BigM
        lst = lst.sort_values(by=f"RequestFund{k}",
            ascending=True).reset_index(drop=True)
        lst["Product"] = lst[f"RequestFund{k}"] * lst["InvCost"]
        #print(lst["Product"])
        row_index = lst[lst['Number'] == i].index[0]
        #print(row_index)
```

```
        cumsum = lst["Product"].iloc[:row_index+1].sum()
        #print(cumsum)
        if cumsum <= V_b(t, k) + 0.5 * C_b(t, i) * RequestFund(t, i, k):
            return RequestFund(t, i, k)
        else:
            return 0

def c_b1(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_b(t, k) == 0 or dataSup[t]['c_b1'].iloc[k] == 0 or build(t,i) ==0:
        return 0
    else:
        if CritForm(t, i) * (CritCont(t, i) + CritCros(t, i) * 0.015) >= 0.6:
            return RequestFund(t, i, 1)
        else:
            return 0

def S_b(t, i):
    a = sum(a_b(t, i, k) for k in range(NumSup[t]))
    b = sum(b_b(t, i, k) * dataSup[t]['b_b'].iloc[k] for k in range(NumSup[t])) * Size(t, i)
    c0 = sum(c_b0(t, i, k) * dataSup[t]['c_b0'].iloc[k] for k in range(NumSup[t]))
    c1 = sum(c_b1(t, i, k) * dataSup[t]['c_b1'].iloc[k] for k in range(NumSup[t]))
    c = (c0 + c1) * C_b(t, i)
    if a + b + c <= C_b(t, i) * MaxFundFact:
        return a + b + c
    else:
        return C_b(t, i) * MaxFundFact

def a_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['a_o'].iloc[k] == 0:
        return 0
    else:
        return dataSup[t]['a_o'].iloc[k]

def b_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['b_o'].iloc[k] == 0:
        return 0
    else:
        return dataSup[t]['b_o'].iloc[k]
```

```
def c_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['c_o'].iloc[k] == 0:
        return 0
    else:
        return dataSup[t]['c_o'].iloc[k]

def d_o(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_o(t, k) == 0 or dataSup[t]['d_o'].iloc[k] == 0:
        return 0
    else:
        return dataSup[t]['d_o'].iloc[k]

def S_o(model, t, i):
    a = sum(a_o(t, i, k) for k in range(NumSup[t]))
    b = sum(b_o(t, i, k) * model.O[t, i] for k in range(NumSup[t]))
    c = sum(c_o(t, i, k) * C_o(model, t, i) for k in range(NumSup[t]))
    d = sum(d_o(t, i, k) * 1/(Emiss(t, i) + 1) for k in range(NumSup[t]))
    return (a + b + c + d) * model.OnOff[t,i]

def a_m(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_m(t, k) == 0 or dataSup[t]['a_m'].iloc[k] == 0:
        return 0
    else:
        return dataSup[t]['a_m'].iloc[k]

def b_m(t, i, k):
    j = TechnIndex(t, i)
    if delta(t, j, k) == 0 or V_m(t, k) == 0 or dataSup[t]['b_m'].iloc[k] == 0:
        return 0
    else:
        return dataSup[t]['b_m'].iloc[k]

def S_m(t, i):
    a = sum(a_m(t, i, k) for k in range(NumSup[t]))
    b = sum(b_m(t, i, k) * C_m(model,t, i) for k in range(NumSup[t]))
    return a + b

def S(model, t, i):
    return SupFact*(S_b(t, i) + S_o(model, t, i) + S_m(t, i))

##########################################################################
# C_marg[t][i]
```

```
##########################################################################

for t in range(T+1):
    for i in range(NumPPl[t]):
        j = TechnIndex(t, i)
        res = P_res(t, j)*ResAmount(t,i)*MinOut[t][i]
        tax = (Co2Cert[t]+EmisTax[t])*Emiss(t, i)/xo*MinOut[t][i]
        wag = wages(t, i)*np.sqrt(Size(t, i)/2)
        C_o_marg = res + tax + wag
        C_m_marg = x_m(t, i) + y_m(t,i)*Size(t,i)*age(t,i)

        a = sum(a_o(t, i, k) for k in range(NumSup[t]))
        b = sum(b_o(t, i, k) * MinOut[t][i] for k in range(NumSup[t]))
        c = sum(c_o(t, i, k) * C_o_marg for k in range(NumSup[t]))
        d = sum(d_o(t, i, k) * 1/(1000*Emiss(t, i) + 1) for k in
            range(NumSup[t]))
        S_o_marg = (a + b + c + d)
        a = sum(a_m(t, i, k) for k in range(NumSup[t]))
        b = sum(b_m(t, i, k) * C_m_marg for k in range(NumSup[t]))
        S_m_marg = a + b

        C_marg[t][i] = ((C_o_marg - S_o_marg)*(795))/45000

##########################################################################
# MODEL
##########################################################################

model = ConcreteModel("Power Plant Optimization")

##### Decision Variables:
model.O = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    bounds=(0, BigM), initialize=50)
model.OnOff = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    within=Binary, initialize=1)
model.P_el = Var(range(T+1), bounds=(0, 900), initialize=720)
model.p = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    bounds=(0, BigM), initialize=50)
model.max = Var(((t, i) for t in range(T+1) for i in range(NumPPl[t])),
    within=Binary)

##########################################################################
# Constraints
##########################################################################

# Constraint: Demand coverage
def demand_rule(model, t):
    return sum(model.O[t,i] for i in range(NumPPl[t])) == D[t]
model.demand = Constraint(range(T+1), rule=demand_rule)
```

```python
# Constraint: Maximum output per plant
def maxout_rule(model, t, i):
    return model.O[t,i] <= MaxOut[t][i]
model.maxout_constraint = Constraint(((t, i) for t in range(T+1) for i in range(NumPPl[t])), rule=maxout_rule)

# Constraint: Minimum output per plant
def minout_rule(model, t, i):
    return model.O[t,i] >= MinOut[t][i] * model.OnOff[t,i]
model.minout_constraint = Constraint(((t, i) for t in range(T+1) for i in range(NumPPl[t])), rule=minout_rule)

# Constraint: Big-M constraint 1 (ensures that O is positive only if the plant is running)
def bigM1_rule(model, t, i):
    return model.O[t,i] <= BigM * model.OnOff[t,i]
model.bigM1 = Constraint(((t, i) for t in range(T+1) for i in range(NumPPl[t])), rule=bigM1_rule)

# Constraint: Big-M constraint 2 (ensures that O is greater than epsilon only if the plant is running)
def bigM2_rule(model, t, i):
    return model.O[t,i] >= epsilon * model.OnOff[t,i]
model.bigM2 = Constraint(((t, i) for t in range(T+1) for i in range(NumPPl[t])), rule=bigM2_rule)

########### Merit Order Constraints ####################################

# Constraint: create list C_marg of all active power plants
def merit_list_rule(model, t, i):
    return model.p[t,i] == C_marg[t][i] * model.OnOff[t,i]
model.merit_list = Constraint(((t, i) for t in range(T+1) for i in range(NumPPl[t])), rule=merit_list_rule)

# Constraint: used to find the maximum C_arg among active power plants
def one_max_rule(model, t):
    return sum(model.max[t, i] for i in range(NumPPl[t])) == 1
model.one_max_constraint = Constraint((t for t in range(T+1)), rule=one_max_rule)

# Constraint: P_el must be at most C_marg of the most expensive active power plant
def upper_bound_rule(model, t, i):
    return model.P_el[t] <= model.p[t, i] + BigM * (1 - model.max[t, i])
model.upper_bound_constraint = Constraint(((t, i) for t in range(T+1) for i in range(NumPPl[t])), rule=upper_bound_rule)

# Constraint: P_el must be at least C_marg of the most expensive active power plant
```

```
def lower_bound_rule(model, t, i):
    return model.P_el[t] >= C_marg[t][i] * model.OnOff[t,i] - epsilon
model.lower_bound_constraint = Constraint(((t, i) for t in range(T+1) for
    i in range(NumPPl[t])), rule=lower_bound_rule)

##########################################################################
# Objective
##########################################################################

def obj_rule(model):
    return sum((model.O[t,i]*model.P_el[t] + S(model, t, i) - C(model, t,
        i)) for t in range(T+1) for i in range(NumPPl[t]))
model.obj = Objective(rule=obj_rule, sense=maximize)

##########################################################################
# Solving Model
##########################################################################

solver = SolverFactory('mindtpy')
results = solver.solve(
    model,
    mip_solver='gurobi',
    nlp_solver='ipopt',
)
```