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Comparison of different CO_2 emission assessment methods of electric vehicles in selected European countries

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Abstract

With the establishment of e-mobility in the transport sector, the demand for electricity is also increasing and thus the CO_2 emissions generated by the power plants. Despite the theoretical approaches already introduced in the literature to calculate the emissions, it is difficult to establish and prove the actual CO_2 emissions generated for charging an electric car. This master thesis deals with implementing and evaluating emission assessment methods specifically applied to electric vehicles. First, an hourly charging profile of a single electric vehicle is modeled for an entire year, with operating costs minimized as the objective function. The model is composed of the available energy sources (energy from the grid, an installed photovoltaic system, and a photovoltaic battery storage system) applicable to charge the electric battery. With the charging profile as load and the electricity market data (generated energy, demand, electricity import and export, wholesale prices) for a selected country in Europe, a methodology is first developed which uses the merit order to determine the marginal power plants and marginal emissions. This method takes into account the effect of the additional load for charging the vehicle to the power plant operation and thus also the additional CO_2 emissions generated. In addition, the hourly and annually averaged CO_2 emission factors are determined from the annual electricity mix data and applied power plant types. The model for optimizing the load profile and the application of different emission evaluation methods is applied to the European reference countries Austria, Norway and Spain. Results show that the decision which emission assessment methods to apply is of significant importance as they can lead to different results. It also plays a major role under which circumstances the methods are applied. Determining emissions by electricity mix data is systematically simpler and more comprehensible, but not dynamic enough to describe the behavior of power plant operation. The methodology by determining the marginal emissions, describes the realistically occurring emissions on the basis of the applied type of power plant within the reference country or neighbor country. With this methodology, compared to the averaged emission methods, the emissions fall higher due to the consideration of the merit order. However the identification of the marginal power plant is complex. Hourly error-free electricity market data are needed to understand the relationship between the physical transport of electricity to or from neighboring countries.

Kurzfassung

Mit der Etablierung der E-Mobilität im Verkehrssektor steigt auch die Nachfrage nach Strom und damit die CO_2 durch die Kraftwerke. Trotz der in der Literatur bereits vorgestellten theoretischen Ansätze zur Berechnung der Emissionen ist es schwierig, die tatsächlichen CO_2-Emissionen, die beim Laden eines Elektroautos entstehen, zu ermitteln und nachzuweisen. Diese Masterarbeit befasst sich mit der Implementierung und Bewertung von Emissionsbewertungsmethoden speziell für Elektrofahrzeuge. Zunächst wird ein stündliches Ladeprofil eines einzelnen Elektrofahrzeugs für ein ganzes Jahr modelliert, wobei die Minimierung der Betriebskosten die Zielfunktion darstellt. Das Modell setzt sich aus den verfügbaren Energiequellen (Energie aus dem Netz, einer installierten Photovoltaikanlage und einem Photovoltaik-Batteriespeichersystem) zusammen, die zum Laden der elektrischen Batterie zur Verfügung stehen. Mit dem Ladeprofil als Last und den Strommarktdaten (erzeugte Energie, Nachfrage, Stromimport und -export, Großhandelspreise) für ein ausgewähltes Land in Europa wird zunächst eine Methode entwickelt, welche die Merit-Order nutzt, um die Grenzkraftwerke und die Grenzemissionen zu bestimmen. Diese Methode berücksichtigt die Auswirkung der zusätzlichen Last für das Aufladen des Fahrzeugs auf den Kraftwerkseinatz und damit auch die zusätzlich entstehenden CO_2-Emissionen. Darüber hinaus werden die stündlich und jährlich gemittelten CO_2-Emissionsfaktoren aus den jährlichen Strommixdaten und den eingesetzten Kraftwerkstypen ermittelt. Das Modell zur Optimierung des Lastprofils und die Anwendung verschiedener Emissionsbewertungsmethoden wird auf die europäischen Referenzländer Österreich, Norwegen und Spanien angewendet. Die Ergebnisse zeigen, dass die Entscheidung, welche Emissionsbewertungsmethoden angewendet werden sollen, von großer Bedeutung ist, da sie zu unterschiedlichen Ergebnissen führen können. Es spielt auch eine große Rolle, unter welchen Umständen die Methoden angewendet werden. Die Bestimmung der Emissionen anhand von Strommixdaten ist systematisch einfacher und verständlicher, aber nicht dynamisch genug, um das Verhalten des Kraftwerkseinsatzes. Die Methodik über die Bestimmung der Grenzemissionen beschreibt die realistisch auftretenden Emissionen auf der Basis des eingesetzten Kraftwerkstyps innerhalb des Referenzlandes oder Nachbarlandes. Bei dieser Methodik fallen die Emissionen im Vergleich zu den gemittelten Emissionsmethoden aufgrund der Berücksichtigung der Merit Order höher aus. Allerdings ist die Identifizierung des Grenzkraftwerks komplex. Stündliche, fehlerfreie Strommarktdaten sind erforderlich, um die Beziehung zwischen dem physischen Stromtransport in oder aus den Nachbarländern zu verstehen.

Contents

1 Introduction

1.1 Motivation

Measures are being gradually introduced to counteract climate change. By 2030 the climate and energy goals settled by the EU-policy are an improve in energy efficiency, an increased share of energy from renewable sources and a reduction of greenhouse gas emissions (European Commission, 2021). These targets are intended to reduce the consequences of climate change. Both the ecology with its melting ice caps and rising seas, radical weather fluctuations and the threatening endangerment of human and animal health as well as the economy through its resource shortage are extremely endangered by climate change.

The transport sector plays a significant role in the contribution of reaching the climate goals. In addition to the flight and cargo transportation, the focus is to change the private use of vehicles in order to help on protecting the environment. Electric cars are increasingly becoming visible on the road, replacing internal combustion engines.

In some countries, such as Norway the new registration of combustion engines will not be possible from 2025 onward. They are planning a full change to emission free vehicles (Stephansen, 2021). Other countries are following this approach. From an environmental point of view, when switching to e-mobility it is crucial that the electricity to charge the batteries of electric vehicles is supplied from renewable and CO_2-neutral energy sources.

However, this is not always possible now and in the near future. The question arises with the additional energy required for charging electric cars, taking into account the structural energy-economic conditions (portfolio of power plants in a country) and charging strategies (e.g. only drawing the charging current from grid, own photovoltaic system with or without stationary storage), how the carbon dioxide emissions balance changes.

1.2 Research question and method

In the beginning of this thesis, it is discussed how the loading behavior of an electric car is developed. An optimization model is programmed from the perspective of an individual vehicle owner. The model optimizes the minimal operating costs for charging the car battery considering different loading scenarios. The car battery is mainly charged from the energy supplied by the grid. In addition, scenarios are modeled where part of the energy is extracted from the installation of a photovoltaic system with or without a stationary storage. The loading costs are determined by the energy sources used.

The hourly charging profile of the electric vehicle, which has been optimized for minimal charging costs, is next linked to the hourly use of the power plant in the country of interest. First, the amount of energy generated and consumed every hour is determined. The next step is to analyze which power plants provide the capacity. It is important to differentiate between renewable and non-renewable power plants so that consumption can be used as a residual load. The amount of imported and exported energy from or in neighboring countries is also considered. The data is taken from the ENTSO-E (European association for the cooperation of transmission system operators for electricity) database. With the data filtered and completed for the use of this work, the hourly power plant usage is linked to the car's charging profile, taking into account the country's energy demand. The type of power plant that generates the additional energy required to charge the car battery is determined. This information is used to find the correct carbon dioxide emission factor for calculating the marginal emissions.

With the generated loading profile of the electric vehicle and determined power plant operations in the reference country and its neighboring countries the research question of comparing different carbon dioxide assessment methods such as marginal and average emissions is set up.

The implementation of the optimization model, the import of the power plant data, the determination of the power plant usage and, last but not least, the determination of the marginal and average emissions is developed with the programming language Python (PYTHON, 2021) and modeling package PuLP (PuLP, 2009).

1.3 Structure of the thesis

The state of the art in chapter two contains an overview of papers and projects that have dealt with emission assessment methods in connection with power plant operations. Additionally other works with a focus on electrical vehicles related to profile loads are addressed.

Chapter 3 discusses the methodology, with the first part focusing on the implementation of the charging behavior of an electric vehicle. An optimization model is introduces with the aid of a flowchart and mathematical formulations.

The second part of chapter 3 focuses on the determination of emissions applying different assessment methods. Also here, flowcharts are used to ease the understanding of the work.

Chapter 4 is used to summarize the results on the basis of various emission assessment methods in different reference countries.

The results are accompanied by the discussion in chapter 5. The focus is placed on summarizing important observations.

In chapter 6, special emphasis is placed on the outcome and statements are made on the research question. The thesis concludes with an outlook for further studies and research.

2 State of the art

In this part of the work, the already existing studies and works, which are related to the research question, are stated. These are divided into two main groups. First, there is the implementation of an optimization model for the charging behavior of an electric car based on incurred operating costs. The other is the actual resulting emissions with a focus on emission assessment methods. This chapter will then conclude with the citation of own contribution to this thesis.

2.1 Generation of electric vehicles charging profiles

With the trend of increasing the use of electric vehicles in the transport sector, the motivation to deal with studies related to electric vehicles has also increased. For instance, many modeling studies can be found with different objectives and problem statements. On the one hand the driving profiles of electrical vehicles are interesting, on the other hand the focus is on charging stations and batteries. However, the commonality of these works is the focus on charging profiles. Thus, different solution concepts are introduced.

A sophisticated method to model charging profiles of electric cars is introduced by (Brady and O'Mahony, 2016). They use stochastic simulations to develop a daily travel schedule and charging profile. The idea is to build a model driven by random data, since driving patterns in nature are usually stochastic as well. The approach is for the first driving day to set parameters which describe the number of driving sessions, the deposited distance and the time from which the driving starts. Next an iterative method of conditional distributions with a Bayesian inference is used to simulate the distance of individual journeys. Further, the journey time with the given distance and starting time is simulated and last but not least the parking time between the journeys is modeled. This process is then iterated for each other journey and day. Based on this, important data such as the electric vehicles battery state of charge when plugged in, the plugin behavior or charging point availability can be resulted. In this way a model is generated which corresponds more to reality and is less influenced by assumptions.

In his work at the Vienna University of Technology, (Litzlbauer, 2010) deals with the question of what influence the charging profiles will have on the network structure in terms of network load. He also uses a stochastic approach to model a load profile. Afterwards the bottom up methodology is used starting from a model of a single vehicle and working out to a total power demand of several electric cars. He builds a Matlab model and feeds it with a given driving profile describing the driving behavior. The model can create a route profile for an electric car by stochastically distributing the start times, the duration and distance of the routes, but also given charging conditions, and thus calculate the state of charge and charging power curve for this, taking into account the consumption and charging characteristics.

(Kaschub and Jochem, 2017) choose the empirical approach where they build a charging profile based on given data from electrical vehicle fleets in Germany. They deal with the question how a descriptive electrical vehicle charging profile can be generated from data of e-mobility, how the simulation is implemented and what are the characteristics of these simulated electrical vehicle charging profiles. For the realization, they use data from three electrical vehicle fleets with their statistical characteristic. Based on that, empirical load profiles for different scenarios are derived. As a preparation for the simulation, load projections are generated for a given time period from given data such as state of charge, battery management system, plug in time and much more. Using the data as input to the simulation model, the empirical density functions that span the time frame of the load projection are used. With the created simulation model, synthetic electrical vehicles load profiles can be generated and used for further analyses. In contrast to the stochastic method, the authors state that validation is somewhat difficult due to the different underlying data sources.

It should be mentioned that many other methods of implementation exist. They differ from each other slightly to very much, depending on the goal, effort and motivation behind the development. (Tu et al., 2020) for example uses a heuristic algorithm to design optimized charging schedules. (Zhang et al., 2020) create electric vehicle charging load profiles using probabilistic models and Monte Carlo algorithm. (Iversen and Henrik Madsen, 2014) relies on the stochastic approach to implement its optimization models for charging an electric vehicle.

2.2 Application of the emission evaluation methods

It is well known that the calculated emissions in different use cases can be different depending on the calculation methods chosen for this purpose. Since the application of existing emission assessment methods is essential for this work, some works related to emission calculations and the methods used for it are given below.

(Regett et al., 2021) from the FfE institute have, for example, compared the determination of emissions using mixed and marginal power plants. In their work, they apply formulas to find out which of the two methods gives a better statement regarding emissions. For the mixed power plant emission factor, they use a formula where the hourly emission factor is determined by taking into account all power plant inputs, their generation specific emission factor and fuel consumption, and then weighting them by the total hourly energy produced. For the determination of the marginal emission factors, the hourly change of the power plant energy is taken into account, whereby the marginal power plant is selected on the basis of electricity price and in case no allocation can be made, the marginal power plant with the next higher price is selected for the definition of the hourly marginal emission factor. Through a given scenario and model, they perform hourly calculations. In summary, both methods lead to different solutions with note to the merit order dilemma. The authors of this paper conclude that the choice of method depends strongly on the application. The mixed method is more suitable to represent existing systems and the effect of renewable power plants, while the marginal method should be used to identify system changes and marginal effects.

More e-mobility oriented, (Arvesen et al., 2021) deal with the impact of electric vehicle charging time on the emission generation in 2050 via a given model. In this quotation, the details and the outcome are not discussed, but rather it is pointed out that they also consider two types of electricity scenarios. One is the average and the other the marginal electricity generations. Their determination of the marginal effects is done by applying the power plant input over a given model (EMPS - power system optimization model to determine the hourly operation) twice. First, the model is run without the electric vehicle as a load, and then with the added electric vehicle. Then the different results are compared, highlighting the marginal effect. Their results also show that both scenarios lead to different results. For example, average calculated emissions fall lower since renewable sources are strongly emphasized in with method

In a seminar at the Massachusetts Institute of Technology, Magnus Korpås (MIT A+B Applied Energy Conference, 2019) also indicated and sought to apply how essential it is to choose the right calculation methods. He shows the determination of average CO_2 emissions by considering the annual generated energy with the annual generated demand and thereby generated CO_2 emissions. In addition, he introduces the marginal CO_2 factor where similar to the previously introduced works, the additional amount of energy applied for the additional demand generated is taken into account. Power market simulations are used to determine the actual power plants used. The results also lead to different emission factors whereby the marginal emissions fall higher.

Here is also to be noted that there are countless works that apply the emission determination methods such as the marginal or the mixed average methodology. Depending on the goals and motivations behind them, but also on the available sources and tools, these works vary little to a lot. (Bettle, Pout, and Hitchin, 2005) use the merit order approach to find the marginal emission factors. Another approach is chosen by (Clauß et al., 2019).

They determine the hourly averaged CO_2 factors with input-output models based on energy generation and demand balance within a country.

2.3 Own contribution

In this work, based on the research question, primarily the already theoretically existing emission assessment methods are implemented and applied to a given load. The load is represented by a high-resolution hourly load curve over a whole year, which has been optimized for minimum operating costs. Different scenarios are modeled that simulate the application of a photovoltaic system or an additional installation of a photovoltaic storage system. The model is also applied to three European countries to identify the impact of different environments and power plant resources. The emissions determined by the different methods will then be compared and a statement made as to what influence they have on the final result. The aim is to work with real data from existing electricity market databases in order to minimize assumptions and information deficiencies and to achieve realistic results. With this work, the reader is given an insight into how different charging scenarios affect the emissions generated when charging an electric vehicle, but also the importance of the correct selection and implementation of the emission assessment methodology.

3 Methodology

3.1 Modeling the electricity demand of an electrical vehicle

In order to evaluate the different valuation methods of emission determination, the demand that contributes to the emissions is depicted with the yearly consume of an individual electric vehicle (EV). The EV is modeled based on an average every day car driver. This approach makes the comparison with common combustion engine drives easier and is a comprehensible method to understand the evaluated amount of emissions. The assumptions of the loading and driving behavior but also charging specifications on different scenarios are based on Austrian statistics and facts. When executing the model on other reference countries, the assumptions are partly adapted.

3.1.1 Reference values and assumptions

For the vehicle parameters within the model, the technical specifications of a Tesla Model 3 are used. However this should not restrict the fact that any other electrical vehicle can be used to model the yearly energy consumption. Table 3.1 shows the specifications of the EV.

Table 3.1: Vehicle specifications (EV Database - Tesla, 2021)

Model		Tesla Model 3 Standard Range Plus
Energy source		electricity
Power	P	239 kW
Driving range	r	$\sim$ 320 km
Battery capacity	C_{bat}	52 kWh
Consumption	E	0.153 $^{kWh}/_{km}$
Charging port		Type 2

Driving behavior

In this work, it is assumed that the EV-owner uses the vehicle for daily rides to the working location and occasionally for doing different activities. On the weekends sporadic car trips are assumed. In average, a normal vehicle user drives about $r_{yearly} = 10000$ km per year (eurostat, 2021).That results about 27 km per day. This assumption will be used as an average consumption. Outgoing from the vehicle specification and the driving distance deposited, the total energy consumed in one year W_{total} of the EV is approximately 1530 kWh:

$$W_{total} = E \cdot r_{yearly} = 0.153\,{}^{\mathrm{kWh}}/_{\mathrm{km}} \cdot 10000\,\mathrm{km} = 1530\,\mathrm{kWh} \tag{3.1}$$

Loading behavior

Regarding Tesla's manuals for the Model 3, it is recommended to not operate the battery of the EV below 20 % of the maximum capacity. Part of the remaining capacity is used for necessary electrical functions and a backup energy for the self discharging effect of the battery when the vehicle is in idle mode (Tesla, 2021).

With a consumption of 0.153 ${}^{\mathrm{kWh}}/_{\mathrm{km}}$, a battery capacity of 52 kWh and an assumed daily driving distance of $r_{daily} = 27$ ${}^{\mathrm{km}}/_{\mathrm{d}}$, the EV-battery is discharged from 100 % to 20 % in about 10 days.

$$I_{charge} = \frac{C_{bat} \cdot 0.8}{E \cdot r_{daily}} = \frac{52\,\mathrm{kWh} \cdot 0.8}{0.153\,{}^{\mathrm{kWh}}/_{\mathrm{km}} \cdot 27\,{}^{\mathrm{km}}/_{\mathrm{d}}} = 10\,d \tag{3.2}$$

Whereby the factor 0.8 is the percentage that describes the amount of recommended energy to be consumed.

3.1.2 Loading scenarios

The EV owner has the freedom to charge the EV battery in any suitable station. For model purposes, it is assumed that the owner only charges the car at home using the privately installed EV Tesla charger, the Wall Connector. Here again, there are no restrictions on what loading device is used. It only must be suitable for the EV model and its technical specifications permitted for an installation at home.

As stated in the EV specifications, the Tesla vehicle is plugged with a Type 2 charging port to the power connection. To achieve fast charging, it is assumed that in combination with the wall charger, a 16 A three-phase connection is available. At this rate, up to 10 kWp of charging power can be provided via the Type 2 port, thus charging the EV from 0 to 100 % in about 5.25 hours (EV Database - Tesla, 2021).

3.1.2.1 Energy source from grid

For charging the battery, the charging device uses the available energy source that is delivered from the grid. The maximal amount of power that the grid can deliver is assumed to be 10 kW. This amount of power ensures that enough energy is available to charge the car but also to operate the house at the same time, without any safety fuse switches being activated in the event of overload.

Since the optimization model minimizes the charging costs of the EV-battery, information of the energy price in €/kWh is needed. Because Austria is used as the reference country, the prices for electricity costs are set by the Austrian energy market. For a normal household with up to 5000 kWh/a in 2019, the price for electricity supply was about 0.201 €/kWh (E-CONTROL, 2021).

The energy price changes when calculating the optimization model for another country. For other such as Norway the price was about 0.18 €/kWh and for Spain about 0.24 €/kWh (eurostat Database, 2021).

3.1.2.2 Additional source from a photovoltaic system and battery storage

In order to understand what effect a photovoltaic (PV) system as an energy source has on the CO2-Emissions factor of the EV, in this thesis the energy supply from a PV system is also modeled. Based on the PV specifications, the module types and panel size, in a detached house usually a PV system installation with a peak power of 5 kW is assumed. In order to reproduce the energy curve of the PV plant, actual data from the renewables.ninja (Pfenninger and Staffell, 2021) database is used.

According to a study by the Fraunhofer Institute, the Levelized Cost of Energy (LCOE) of a small PV system in Germany, without an external battery, are around 0.073 €/kWh (Kost, 2018).

PV systems for private use are gradually being installed in combination with battery storage systems (PV-B). The excess sustainable energy of the PV system is stored in order to use it at a later point of time. In a household with a PV system of 5 kWp and an average consumption of 5000 kWh/a, a PV-B with up to 5 kWh can be assumed. The loading curve of the PV-B is modeled later on in chapter 3.1.3. For the process of storing the solar energy on the PV-B, an efficiency of 90 % is assumed (Institute for Applied Ecology, 2018).

Considering the installed capacity, the LCOE of a PV-B are around 0.08 €/kWh (Kost, 2018).

Since the focus is on determining marginal emissions by identifying the power plants used, the difference in prices among different countries is less important. Important is that the model differentiates the power plants by making electricity from the grid the most expensive option. The most favorable option is the PV plant. The energy from the battery costs more, but less expensive than the supply from the grid. Therefore, the researched values can also be used for other countries.

3.1.3 Optimization model

To identify the influence of the energy source to the marginal emissions, three different scenarios are modeled. The EV charger installed in the house, can extract the energy from the grid, a photovoltaic system and the battery storage of the PV system. In the following an optimization model is introduced to ensure the use of the least expensive energy source to charge the electrical vehicle. The costs are based on the price of the source power in €/kWh.

Table 3.2 summarizes the possible energy source combinations.

Table 3.2: Scenario circumstances of the loading curve

	Grid	Photovoltaic System	Battery Storage
Scenario 1	•		
Scenario 2	•	•	
Scenario 3	•	•	•

3.1.3.1 Flowchart

The flowchart in the figure 3.1 shows the sequences of the optimization model execution. It starts with the data preparation and ends with a finished set of loading profiles. The model calculates the minimal charging costs for each hour during a whole year.

In the following, the explanation of the procedure is given, whereby the numbering in brackets can be identified with the numbering on the flowchart.

The program starts by defining a loading scenario (1) as introduced in section 3.1.2.

In order for the model to execute the optimization without any corrupt data, it has to be ensured that the datasets (2) are available and correct for each hour. In this thesis, datasets of the year 2019 were used.

Regarding the power delivery from the PV system, a list is imported that contains the loading profile for each hour over the year. It describes the maximum amount of available power in kW. The data is extracted from the online database introduced in section 3.1.1 where it simulates the PV loading profile of an installation in Vienna.

The maximum power from the grid is a constant over the year since a permanent availability is assumed. Alternatively a grid power profile can be imported.

The PV-B is not depicted with a loading profile. Within the model, the residual energy of the PV system is used to charge the PV external battery. The efficiency of the battery also falls into the model.

In order to avoid an ideal amount of available energy source for the charger and to better simulate reality, the energy consumption of the household is also integrated into the calculation. The actual consumption values, which are determined by means of load profile meters, are available on a database for synthetic load profiles (APCS, 2020) where the hourly consume of an average household in Austria is ready to be extracted.

The next step is to prepare the data (3). All the data's are converted into legible lists. This opportunity is used to do the conversion of the units. The model calculates in kW for each hour. Euros € are used as a currency for the costs.

For the optimization model the constraints and the objective function as described in section 3.1.3.2 are modeled (4). Within this step the amount of available energy from the data is used to set the constraints on each hour. The model execution and with it the calculation of the objective function will be carried out in the next step.

The state of charge (SoC) of the EV-B is modeled online (5). First the specifications of the EV are used to set consumption rate of the car. It is assumed that at the beginning of the year, the car will have full battery capacity. On every new day, the car is discharged with 4,16 kWh. When it reaches the 20% of SoC a plugin to the charger occurs. While charging, the optimization model defines which power source is used on every hour. The SoC is also checked iteratively. When it reaches 100% a plug-out occurs. The discharging continues on a daily rate. In one year about 36 charging cycles occur.

After iterating over every hour of the year the model stops and delivers the results (6). A validation calculation is also implemented that compares the total amount of the extracted energy $\mathrm{E_{out,a}}$ with the total demand $E_{in,a}$. If the difference $E_{\triangle}$ between these values equals zero, the model execution was successful (7).

$$E_{\triangle} = E_{out,a} - E_{in,a} \tag{3.3}$$

$E_{\triangle}$	difference between imported and consumed energy	kWh
$E_{out,a}$	total imported energy from grid, PV and PV storage	kWh
$E_{in,a}$	total consumed energy from the EV and household	kWh

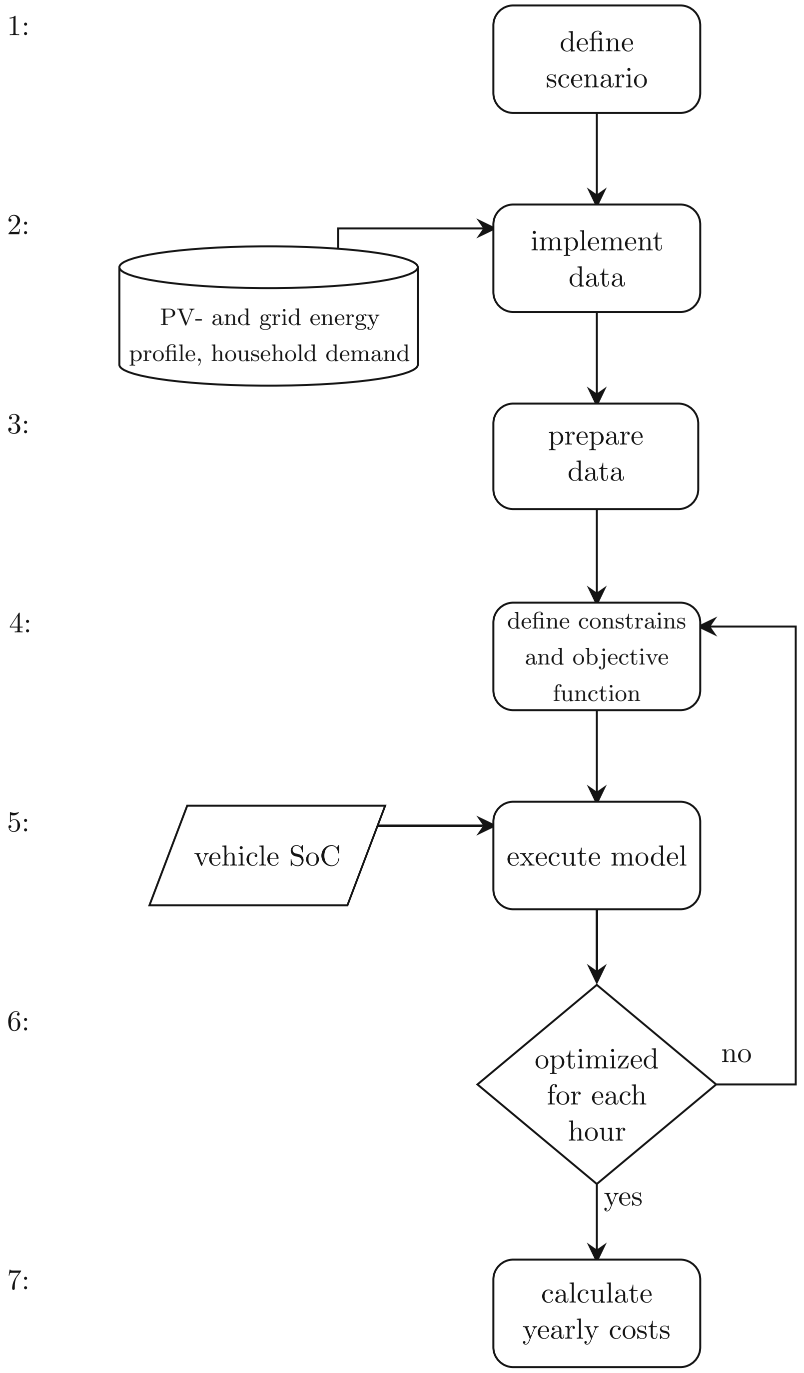


Figure 3.1: Flowchart- Creating the optimization model

3.1.3.2 Mathematical definition

In the following, the formulation of the optimization model is discussed. The objectives and constraints for charging the EV with the energy sources are declared. In addition, the operation of the PV battery is explained in detail.

To understand the context of the formulation, the following parameters are necessary:

Nomenclature

General

i	time index	–
e	yearly energy costs	€/a
$y_{ev,i}$	demand of the electrical vehicle	kWh
$y_{h,i}$	demand of the house consumption	kWh

Grid

$x_{grid,i}$	decision variable of grid supply	kWh
p_{grid}	energy price of grid supply	€/kWh
$c_{grid,i}$	maximum grid supply	kWh

Photovoltaic system

$x_{pv,i}$	decision variable of photovoltaic energy	kWh
p_{pv}	operating costs of photovoltaic energy	€/kWh
$c_{pv,i}$	maximum energy generation from photovoltaic supply	kWh

PV - external storage (battery)

$SoC_{pv,bat,min}$	minimal battery capacity	kWh
$SoC_{pv,bat,max}$	maximal battery capacity	kWh
$SoC_{pv,bat,i}$	battery capacity in hour i	kWh
$x^{in}_{pv,bat,i}$	power to charge the battery in hour i	kW
$x^{out}_{pv,bat,i}$	power to discharge the battery in hour i	kW
$c_{pv,bat}$	maximal power to charge/discharge the battery	kW
η	efficiency of the battery	–

Formulation

The scope of the optimization model is to reduce the total consumption costs of the EV. The minimization model is a sum function of decision variables for each plants multiplied by its energy costs. The total sum iterates over a year for every hour. The iteration parameter is marked with i and is rated from 0 to 8760. The constant 8760 describes the amount of hours in a calendar year. The objective function is formulated with:

$$\min_{x_{grid,i}, x_{pv,i}, x^{out}_{pv,bat,i}} e = \sum_{i=0}^{8760} x_{grid,i} \cdot p_{grid} + x_{pv,i} \cdot p_{pv} + x^{out}_{pv,bat,i} \cdot p_{pv,bat} \tag{3.4}$$

If the objective function 3.4 is analyzed on a single hour $i = 0$, the costs at e_0 consist out of the energy supply from the grid at $x_{grid,0}$ multiplied by the average end user costs p_{grid} of the grid supply. The amount of energy that is taken from the PV system $x_{pv,0}$ is also multiplied by the operating costs p_{pv} and added to the total costs. Similar to the PV system the energy from the battery storage $x^{out}_{pv,bat,i}$ is seen as a cost component $p_{pv,bat}$ and thus contributes to the hourly costs. The objective function $\min(x_{grid,i}, x_{pv,i}, x^{out}_{pv,bat,i})$ ensures minimal energy costs in every hour by using the power supply source with the least costs while meeting the constraints. The result of the sum function over the year provides the minimized total consumption costs of an electric vehicle.

Constraints are used to feed the objective function with the correct decisions variables that meet the conditions 3.5 to 3.9. Constraint 3.5 indicates that the demand from the household $y_{h,i}$ but also for charging the EV $y_{ev,i}$ must be covered at every hour. The energy for covering the demand is supplied by one or a combination of the three energy sources $x_{grid,i}$, $x_{pv,i}$ or $x^{out}_{pv,bat,i}$.

$$x_{grid,i} + x_{pv,i} + x^{out}_{pv,bat,i} = y_{ev,i} + y_{h,i} \tag{3.5}$$

For the specification of the maximum deliverable power from the grid network, the constraint 3.6 is set. The decision variable $x_{grid,i}$ can take values between zero and the maximum grid supply $c_{grid,i}$

$$0 \leq x_{grid,i} \leq c_{grid,i} \tag{3.6}$$

Similar conditions need to be met by the decision variable of the PV system. Constraint 3.7 also describes that the power supply $x_{pv,i}$ depending on the availability, can preserve values between zero and the maximum energy generated by the PV system $c_{pv,i}$

$$0 \leq x_{pv,i} \leq c_{pv,i} \tag{3.7}$$

When it comes to using the capacity stored inside the PV-B, the constraints become complex since a charging and discharging of the battery occurs. The state of charge $SoC_{pv,bat,i}$ describes the amount of capacity stored in the PV-B. Depending on the demand and the residual energy of the PV, the battery can be charged or discharged.

The variable $x^{in}_{pv,bat,i}$ describes the power to charge the PV-B. This is determined from the residual energy of the PV system and is limited by the maximum charging power. If the PV system generates more energy than what is consumed, the remaining energy is stored inside the PV-B. Constraint 3.8 shows the conditions that need to be met.

$$x^{in}_{pv,bat,i} = \min(c_{pv,i} - x_{pv,i}, C_{pv,bat}) \tag{3.8}$$

The parameter $x^{out}_{pv,bat,i}$ is the actual decision variable that describes how much power can be drawn from the battery to cover the demand. The variable can fluctuate between zero and the amount of capacity $SoC_{pv,bat,i-1}$ stored inside the PV-B. Whereas the charging power is limited by the maximal power to charge $C_{pv,bat}$. Constraints 3.9 shows the mathematical formulation of the conditions to be met.

$$0 \leq x^{out}_{pv,bat,i} \leq \min(SoC_{pv,bat,i-1}, C_{pv,bat}) \tag{3.9}$$

As mentioned in chapter 3.1.1 the charging and discharging of the battery is not ideal. The residual energy of the PV system is not stored completely since the battery has an efficiency of η and thus part of the energy is converted into losses. This loss share is taken into account when calculating the capacity in 3.10.

$$SoC_{pv,bat,i} = SoC_{pv,bat,i-1} + x^{in}_{pv,bat,i} \cdot \eta - x^{out}_{pv,bat,i}/\eta \tag{3.10}$$

Depending on whether the battery is being charged or discharged, a new amount of energy is either added or removed from the capacity of the last hour, taking into account the constraints set in 3.8 and 3.9.

The battery capacity $SoC_{pv,bat,i}$ is limited by a minimal and a maximal capacity:

$$SoC_{pv,bat,min} \leq SoC_{pv,bat,i} \leq SoC_{pv,bat,max} \tag{3.11}$$

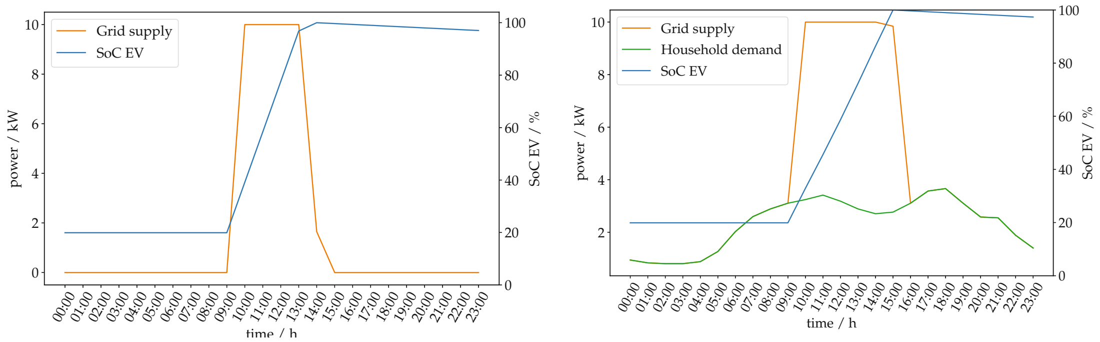
3.1.3.3 Demonstration of the functionality of the model

Scenario - Grid as an energy supply

In this scenario the charger uses the maximum available power from the grid to charge the EV. Since in this thesis it is assumed that the grid delivers up to 10 kW, on the graph 3.2 it is visible how the EV demand is covered with the grid supply. The battery capacity of the electrical vehicle rises from 20% to 100% in approximately five to six hours. This charging time is given by the maximum battery capacity of 52 kWh and a charging rate of 10 kW. This shows that a charge device connector with Supercharging[1] feature that can supply up to 170 kW (EV Database - Tesla, 2021) of loading power and charge the EV-B in about 20 minutes, if the circumstances[2] are given. The Plug-in time has no effect at the final results since the available grid energy is constant over the day.

Adding the household share to the total demand, as it is in picture 3.2 visible, the charging process takes longer. This effect occurs since the model prioritizes the coverage of the household demand.

Figure 3.2: Demand covered by electricity from grid



(a) EV as a demand

(b) EV and household consumption as a demand

Scenario - PV as an energy supply

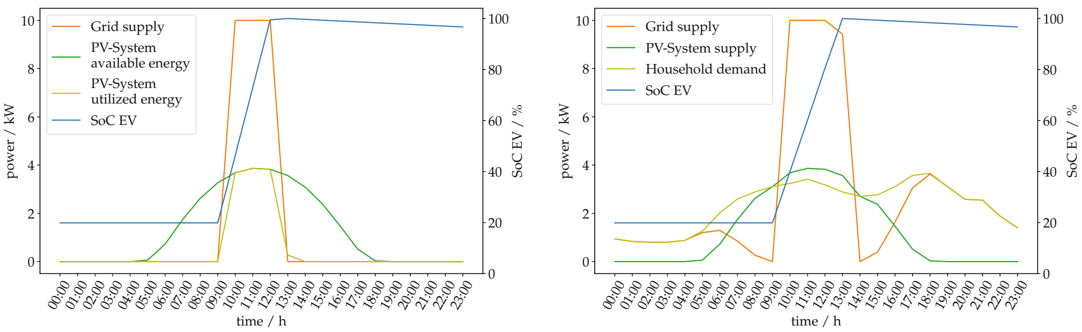
By adding the PV system to the power source, a shorter charging time can be achieved. Figure 3.3 shows the existing capacity of the PV system as well as the capacity that is actually used. The PV-system is inactive until the Plug In. After the connection, the

[1]Teslas charger to supply an EV-B in a short time of period by using a high charging rate
[2]Limited by the max. charging power of the vehicle

PV-system is fully utilized for several hours. In addition to the renewable energy, the charger uses the maximum available power from the grid.

By adding the household demand, the PV system is fully utilized throughout the day. Similar to the scenario without a renewable source, the model prioritizes the delivery of energy to the household. It leads to a longer charging time for the electric vehicle. Figure 3.3 shows the energy curves when considering household demand.

Figure 3.3: Demand covered by electricity from grid and PV-System



(a) EV as a demand (b) EV and household consumption as a demand

In this scenario, the Plug-in time can not be neglected. The photovoltaic energy curve which has the peak at noon is used by the model to find out when is the best time to connect the charger. The code was extended with a function that simulates all possible connection scenarios which can occur from 1 am to midnight to determine the most favorable time to connect the EV to the charger during the day. The total costs over the year for each Plug-in time are observed. The most favorable variant for charging the car serves as a decision criterion. As can be seen in figure 3.4, the renewable energy from the PV system can be best utilized with a Plug-in at around 10 a.m., since the costs at the end of the year will thus be the smallest.

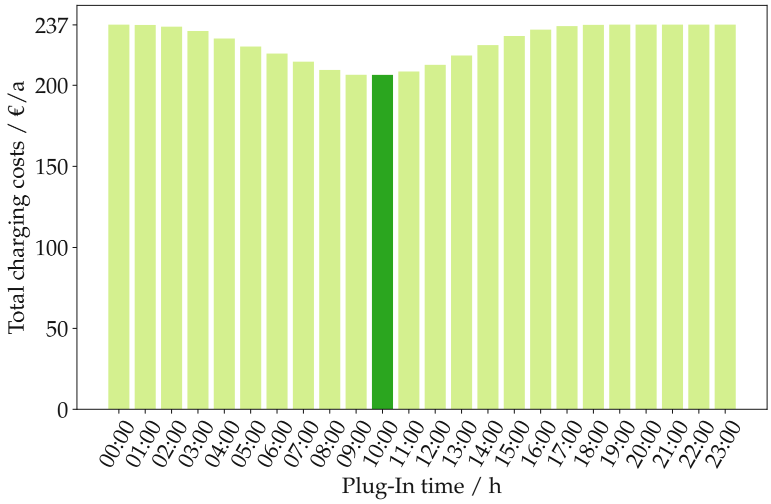


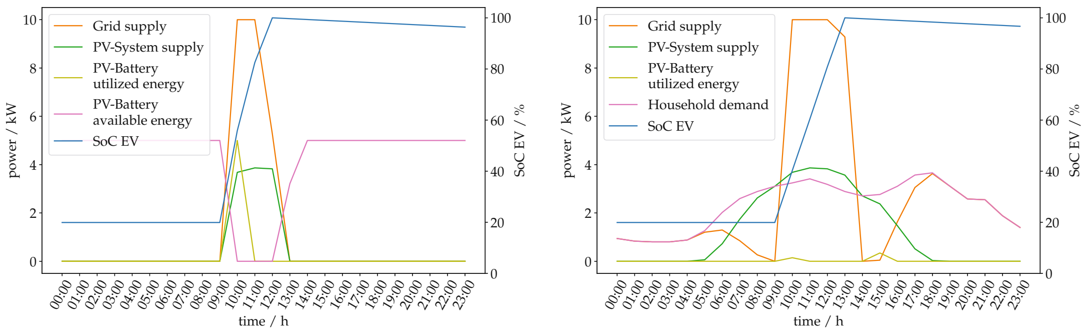
Figure 3.4: Yearly charging costs at different Plug-In times.

Scenario - PV and a battery storage as an energy supply

The storage is charged with the surplus energy from the PV system. At the time of charging, the PV system is primarily used. Furthermore, since the charger takes the maximum available energy from the three options, the PV storage is also used immediately. Afterwards, the grid is used. During the charging process, the battery storage is used up in a few hours. However, an even faster charging time is achieved with a cost-effective and renewable energy source. Once the car is fully charged, additional surplus of PV energy is used to charge the PV-B.

Considering the demand of the household as shown in figure 3.5, it can be observed that the PV system is mostly used for the own demand of the household and therefore little surplus is left for charging the storage. The same effect is seen when using energy from the PV-Storage. The model prioritizes the household which leads to little amount of energy left for charging the car. It can be clearly stated that the battery contributes little or hardly to the charging of the EV if the household demand is high.

Figure 3.5: Demand covered by electricity from grid, PV-System and a PV-Battery storage



(a) EV as a demand

(b) EV and householdconsumption as a demand

3.2 Introduction to marginal power plants

In order to correlate the hourly load profiles with the use of power plants, it is necessary to take a close look at their structure. In the following chapters, the classification of power plants, its function and the emission profile will be briefly addressed. The discussion is followed by a conclusion on how the power plants in the country are used to meet the total demand based on the merit order curve. Their order on the merit order curve is essential for determining the marginal power plants that come into operation when charging the EV.

3.2.1 Power plants and their contribution to emissions

As mentioned earlier, there are two main types of power plant parks that are used to generate energy. On the one hand, these can be conventional, which mainly produce energy from combustible raw materials, and on the other hand, those that transform energy from renewable sources.

In Austria, conventional power plant parks include mainly coal and natural gas power plants. Since this thesis also takes into account imported energy from neighboring countries, other conventional power plants, besides those installed in Austria, are also briefly discussed. These include lignite-fired power plants and other mixed power plants. Additionally, nuclear power plants are still operated in Europe. Although they do not directly combust resources and create CO_2 emissions, they are still counted among conventional energy generators. Wind turbines, hydroelectric power plants, hydro pump storage plants, solar plants, biomass plants and geothermal plants are counted among the renewable energy producers. The individual types of power units are briefly addressed below.

3.2.1.1 Conventional power plants

Lignite fired power plants

Lignite-fired power plants are coal powered and use steam for energy production. They provide large power outputs and are mainly used to supply the base demand. Due to the fuel quality, the efficiency of lignite powered plants is low. In addition, lignite is one of the most CO_2-generating resources. Although operating these plants is cost convenient, the investment costs are very high (Paschotta, 2020). In contrast to the border countries, Austria has no installed lignite-fired power plants (Umweltbundesamt, 2018).

Hard coal power plants

Coal-fired power plants are used for medium- and peak-load coverage due to better controllability. With a lower CO_2 emission factor and a better efficiency compared to lignite-fired power plants, coal-fired power plants are more expensive in terms of operating costs (Paschotta, 2020). Austria has about 598 MW of installed capacity in 2019 (ENTSO-E, 2019).
The Environment Agency Austria, E-Control, provides the value 882 g/kWh as a guideline for CO_2 generation using coal as a recource (E-CONTROL, 2012).

Natural gas power plants

With an installed capacity of 4463 MW, natural gas power plants in Austria are among the most energy producing power plants (ENTSO-E, 2019). In contrast to coal-fired power plants, gas-fired power plants are highly flexible, which makes them easy to use for base load as well as medium and peak load. Despite the high marginal costs, the lower CO_2 emissions and also the low investment costs also contribute to a high utilization. The emission factor of the energy production is about 440 g/kWh (E-CONTROL, 2012).

Oil power plants

An oil-fired power plant is a thermal power plant operated with a petroleum-based fuel. Due to the comparatively high fuel costs, oil-fired power plants are rarely used in Europe and are practically only used for peak loads.A large oil-fired power plant can be based on a steam turbine, a gas turbine or a combination of both (Paschotta, 2020). The installed oil-fired power plants in Austria provide 178 MW.
The Environment Agency Austria prescribes a CO_2 reference value of 645 g/kWh by using oil-fired power plants (ENTSO-E, 2019).

Nuclear power plants

Nuclear power plants use the theory of nuclear fission[3] to generate electricity. They are very slow in energy regulation and need long powering on and off times. Nuclear power plants are mainly used to cover the base load. In contrast to Austria, in some European countries, nuclear power plants are still operated. Because of the high investment costs and their difficulty on handling the final storage, nuclear power plants are slowly being phased out in other countries as well. In Germany for example they are steadily being shut down since 2011. By 2022 the nuclear power plants will be completely deactivated

[3] A process where atoms are splitted and nuclei are produced. The reaction of this process releases energy (lumen, 2021).

(Germany, 2021).
Besides the final deposit of radioactive waste, which indirectly contributes to environmental pollution, nuclear power plants are among the CO_2 emission-free power plants during the energy generation (E-CONTROL, 2012).

Mixed and other conventional power plants

In addition to the types of power plants listed so far, which are mainly used to cover the base load, other technologies are also used in Europe. Their operation mainly supports the coverage of peak loads (Strommarktdaten, 2021) :

- Gas derived from coal
- Fossil peat
- Mineral oil
- Blast furnace gas
- Refinery gas
- Gas with high hydrogen content
- Other residues from production (e.g. steel and coke production)
- Mixture of several fuels
- Waste

In total, these power plants provide about 173 MW in Austria (ENTSO-E, 2019). According to the Federal Environment Agency of Austria (E-CONTROL, 2012), mixed conventional power plants generate about 650 g/kWh of CO_2. Since the focus of this thesis is to only identify the power plant types in operation, the mixed conventional power plants will not be further discussed.

3.2.1.2 Renewable energy

Wind turbines

Wind turbines mechanically convert wind energy into electrical energy via a generator. Due to the energy resource, they belong to the renewable energy power plants. Wind turbines can be installed either on land (Onshore) or at sea (Offshore), where the high wind currents are harnessed. Wind power plants have high investment costs, but no additional costs for fuel or CO_2 certificates.The disadvantage of these plants is that they are very dependent on weather conditions and therefore operate volatile (Stoeckmann, 2014).
Since renewable energy is directly converted to electricity the CO_2 emission generation value is 0 kWh.

Hydroelectric power plants

With water as an energy resource, hydro power plants generate no emissions. Water propulsion converts potential energy into electrical energy. They can be operated either directly on flowing water (Run-of-river hydro power) or in combination with dams where water can be stored as energy or reused at any time to generate electricity (Storage hydro power). Another construction type is where pumps are installed between an upper and a lower water reservoir (Pumped storage hydro power). Depending on the construction, hydroelectric power plants can be operated either for base load or peak load coverage (Association, 2020).
In Austria, a total of 5558 MW Run-of-river hydro power, 2440 MW Storage hydro power, and 3120 MW Pumped storage hydro power are installed (ENTSO-E, 2019).

Photovoltaic plants

Solar power plants use solar radiation to produce energy. Similar to wind power plants, their operation is also weather-dependent and thus the electricity fed into the grid is volatile. The use of light as an energy resource also eliminates CO_2 certificate and fuel costs. Solar plants also belong to power plants that entail high investment costs (Stoeckmann, 2014).
The installed power output of PV systems in Austria is approx. 1193 MW (ENTSO-E, 2019).

Biomass plants

Two types are used in the use of biomass to generate electrical energy. Bio gas plants, in which biomass is fermented and the resulting gas is converted into electricity in a combined heat and wood chip plants, in which bio solid mass is burned directly and used to generate electricity. The advantage of the technology lies in the temporally flexible, weather-independent generation of electricity. It is therefore well suited as a regulating energy when wind and PV collapse in their production. (Stoeckmann, 2014).
Biomass plants installed in Austria provide about 500 MW (ENTSO-E, 2019).

Geothermal plants

Water and steam serve as carriers of the earth's geothermal energy. The transported emission free thermal energy is converted into electrical energy. With the main advantage of not depending on weather conditions, they are mainly used to cover the base load.
In Austria, their installation provide about 1 MW (ENTSO-E, 2019).

Other renewable power plants

Renewable energies also include other installed capacities, which will not be discussed further in this paper (Strommarktdaten, 2021):

- Marine
- Landfill gas
- Sewage gas
- Mine gas

In Austria, the remaining installed capacity of renewable power plants is about 42 MW (ENTSO-E, 2019).

3.2.2 Energy demand coverage

Electricity balance in Austria

In 2019, the domestic electricity consumption in Austria was 71763 GWh. 92.4% was used for final consumption, the rest for own use of the power plants and system losses in the transport of energy to end customers. Table 3.3 shows a tabular representation of consumption in Austria. The figures were taken from a statistical report by E-CONTROL (E-CONTROL Key statistics, 2020).

Table 3.3: Shares of total domestic electrical consumption in Austria (2019)

	Shares in GWh	**Shares in %**
Consumer	66366	92.4
Grid losses	3305	4.6
Subsistence	2092	3.0
Total domestic el. consumption	71763	

While 14.6% of the output is used by medium-sized industries, large-scale industries represent about 27.6% of the total demand. 24.5% of energy sales are delivered to households. The remaining share of sales is used to cover other small consumers. Table 3.4 summarizes the shares in electricity demand (E-CONTROL Key statistics, 2020).

Table 3.4: Austrian consumer structure in 2019

	Shares in %
Large-sized industry	27.6
Mid-sized industry	14.6
Household	24.5
Other end customers	33.3

The demand is either covered by the power plants within Austria or electricity is purchased from neighboring countries. Austria imported about 26.2% of physical electricity in 2019. Table 3.5 shows the composition of the produced in electricity in Austria which represent 73.8% of the demand coverage (E-CONTROL Key statistics, 2020).

During the production of electricity, scenarios can arise where consumption decreases or more energy is produced than necessary, e.g. by wind power plants. This leads to surplus energy which has to be treated. Instead of shutting down these power plants, surplus energy is either stored or sold abroad. In 2019, Austria exported about 23% (E-CONTROL Key statistics, 2020) of the total generated electricity.

Table 3.5: Austrian energy generation components in 2019 - Gross power mix

	Shares in %
Hydropower	60.2
Hard coal	2.0
Natural gas	15.5
Other conventional	4.8
Wind	10.1
Photovoltaic	1.2
Biomass	6.1
Other sources	0.1

Figure 3.6 shows a time diagram of the power generating facilities in Austria supplying the demand. The data is taken from the (ENTSO-E, 2019) database, with hourly outputs plotted over 14 days starting from Monday. This interval was chosen at a random time in spring with the aim of displaying the influence of all power plants.

It is easy to observe that hydro powered plants offer the highest input. Biomass and waste provide constant energy and renewable power plants such as wind farms and photovoltaic plants depend on natural sources. On weekends, the demand sinks visibly. With a lower demand, wind power plants are shut down. The conventional power plants contribute less to total energy production.

Nevertheless, the use of the power plants is regulated and the application is based on certain decision criteria. The wholesale price and the level of demand are the most important factors in deciding which energy producers are applied. The merit order curve can be used to represent the deployment of power plants.

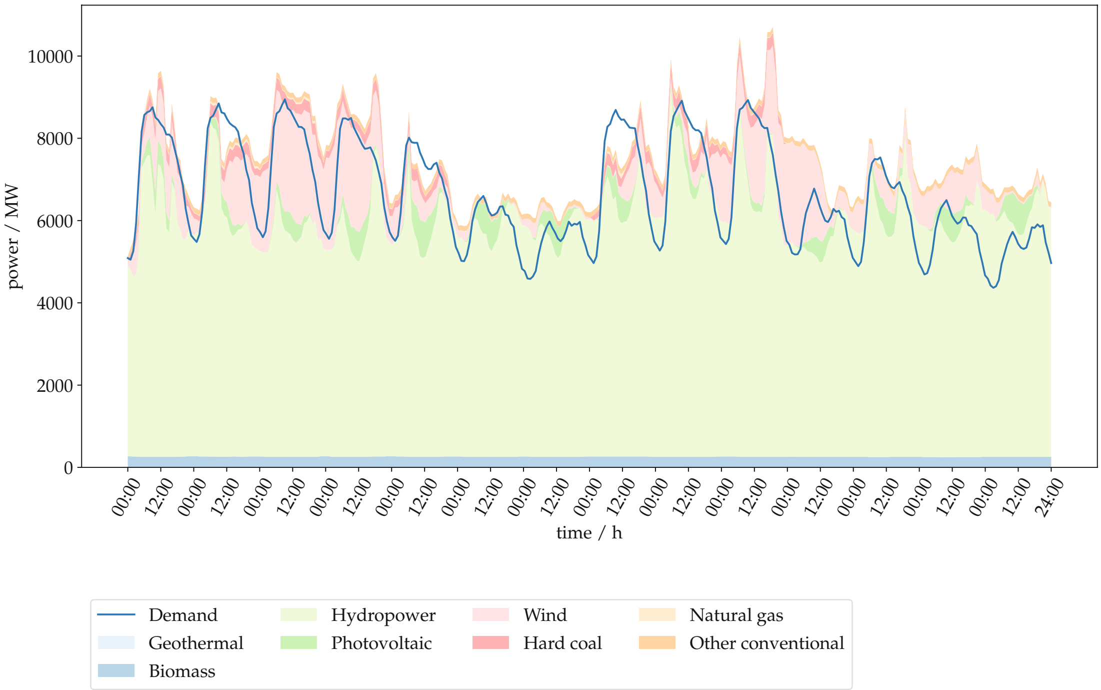


Figure 3.6: Generated power plotted over 14 days. Graph according to own creation based on (ENTSO-E, 2019) data.

3.2.3 Marginal power plants

A marginal power plant is the power plant that is operated last after the major demand has been supplied by other power plants. The merit order curve is a method that shows the operating order of power plants staggered from left to right according to the level of marginal costs. The least expensive power plants are at the left part of the merit order curve, the more expensive ones are at the right. This order is necessary to determine how the demand in the market must be served. The cheapest power plants are therefore guaranteed to be used. Since the renewable energy plants with the low variable costs belong to the most favorable power plant parks, these are always used, according to merit order, to cover the base load. The remaining demand to be covered is referred to as residual load and is covered by the next most price favorable power plant. For example, in countries where nuclear power plants are still active, they are the next to be switched on, as they are among the cheapest conventional power plants in terms of marginal costs. As demand increases, other power plants, such as those powered by coal or natural oil, are switched on in series. The marginal price of the marginal power plant sets the ”market clearing price”.

Since the low-cost renewable power plant suppliers are usually permanently in operation, they benefit from the increased market clearing price. This results in an additional profit for the low-cost suppliers. The price difference between the marginal costs and the market clearing price is the profit that the energy suppliers achieve. Figure 3.7 late on shows a schematic representation of a merit order sequence from left to right with rising marginal costs.

In this work it is essential to identify the hourly power plant input. With the detected marginal power plant, the emission factor for determining the hourly marginal emissions can be defined.

From the database of the electricity market (ENTSO-E, 2019), in addition to the producer and consumer data, the wholesale prices can also be extracted. Theoretically, the wholesale price should correlate with the consumption and the supply delivered by individual power plants. In the actual electricity market, however, the relationship is more complicated, since the wholesale price is established in advance of the actual use of the power plant and is based only on forecast data and contracts between providers and consumers. On the physical side of the power purchase scenarios takes place where the supplier is forced to sell the power partly cheaper than the production costs actually are. This occurs, for example, when shutting down the plant is less profitable than selling the power below the lucrative price.

In conclusion, the merit order curve is difficult to be defined purely based of the wholesale price and the demand. In order to identify the sequential use of the power plants an approach with the marginal costs is drawn.

3.2.4 Marginal costs

In the electricity industry, marginal costs are the costs arising to the energy provider per additional produced unit of capacity. The Research Center for Energy Economics (FfE, 2010) has dealt with marginal cost calculation of power plants and introduced the formula 3.12.

$$K_{marginal} = \frac{k_{fuel}}{\eta} + K_{certificate} \cdot \frac{m_{CO_2 spez}}{\eta} + k_{var} \tag{3.12}$$

Nomenclature

The marginal costs consist of the variable operating costs of the plant, the costs of the CO_2 certificates depending on the emission generation, but also the fuel costs per generated amount of energy which occur at a certain efficiency of the power plant. The calculated marginal costs are expressed in €/MWh.

$K_{marginal}$	Marginal costs per power plant	€/MWh
k_{fuel}	Specific fuel price per energy source	€/MWh
η	Efficiency per power plant	–
$K_{certificate}$	Certificate price	€/MWh
$m_{CO_2 spez}$	Specific emissions per energy source	T/MWh
k_{var}	Variable operating costs per power plant	€/MWh

The marginal costs calculation can be applied to each individual power plant. The power plants can then be plotted on the merit order curve with ascending marginal costs. However, since the scope of this thesis is not to determine the marginal costs of the individual power plant types, the existing literature is used to extract already calculated costs and draw conclusions on the merit order.

The Institute for Energy Economics at the University of Cologne has published a Merit Order Tool in the course of a study. The EWI Merit Order tool represents the merit order of the conventional power plant fleet in Germany for 2020. The tool uses assumptions, fuel prices, emission certificates, emission factors and other variable parameters such as costs. This work uses the tool to its advantage and includes the results in the thesis. However, it should be noted that this calculation was performed for power plants in Germany. Since the goal is to develop a standardized model for all countries, it is assumed that the merit order curve remains the same for each other country in Europe.

Figure 3.7 shows the calculation of the merit order curve based on data and assumptions given in the documentation of the tool (EWI, Merit-Order Tool, Doc, 2021).

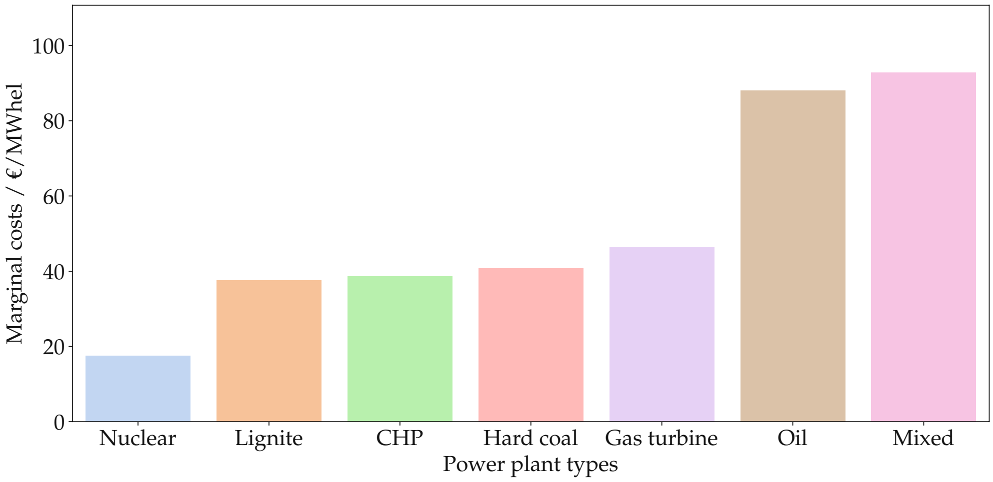


Figure 3.7: Marginal costs of power plant input in Germany, 2020. Graph is from own creation and adaption using the merit order tool results (EWI, 2021).

As previously mentioned, renewable generators are always used for base load coverage. Therefore, the graph only gives the merit order of conventional power plants that covers the residual load. In 3.13 the mathematical declaration of the residual load follows, whereas the index $(i|i \in \mathbb{N}, i \leq 8760)$ indicates the hourly progression during one year.

$$P_{i,Residual} = P_{i,Load,tot} - P_{i,Renewables} \tag{3.13}$$

Nomenclature

$P_{i,Residual}$	Residual Load	MW
$P_{i,Load,tot}$	Total demand in the reference country	MW
$P_{i,Renewables}$	Produced power by renewable power plants	MW

3.2.5 Marginal emissions

Now that the merit order has been established with the help of the marginal costs and the marginal power plant can be identified, the calculation of the marginal emissions can be realized. Marginal emissions are the emissions generated by the operation of the marginal power plant. They differ from the average emissions, however, by determining the marginal emissions the actual power plant used for the amount of energy to be evaluated is considered. A calculation of the emissions by marginal power plant data gives results that come closer to reality.

3.3 Methodology to determine the marginal carbon dioxide emissions

With the information, which power plants are in use at which capacity, as well as the previously defined merit order, furthermore the level of demand in the country and the import and export share, a connection with the charging profile of the electric vehicle can now be created. Besides the function of determining the marginal emission values, it is also the aim of this work to develop and program methods that are easily adaptable for different countries assuming that all the data of the reference country, where the actual EV charging takes place, and those of the neighboring countries, are available. The methodology that follows is therefore suitable for different countries.

Before the data is used to determine the marginal power plants, the power plant types are summarized with their CO_2-emission factor on table 3.6.

Table 3.6: CO_2-emission factors of power plants based on (E-CONTROL, 2012) and (IASS, 2019)

Power plants	g/kWh
Renewables	0
Nuclear	0
Lignite	1161
Hard coal	882
Gas	411
Oil	645
Mixed and other conventional	650

3.3.1 Methodology to identify the marginal power plant

In the course of this work, a system was developed to identify which power plants cover the residual load, whereas the merit order is taken into account. In addition to the residual load, the share of exported energy as well as the consumption modeled for charging the EV battery have to be considered. In formula 3.14 the total hourly demand is declared, whereas $(i|i \in \mathbb{N}, i \leq 8760)$ applies.

$$P_{i,Demand} = P_{i,Residual} + P_{i,Exported} + P_{i,M,Demand} \tag{3.14}$$

Nomenclature

$P_{i,Demand}$	(Corrected) total demand	MW
$P_{i,Residual}$	Residual Load	MW
$P_{i,Exported}$	Exported amount of energy	MW
$P_{i,M,Demand}$	Modeled EV-demand	MW

3.3.1.1 Marginal plants inside the reference country

The determination of the marginal power plant occurs in the form of a token matrix as shown in table 3.7. The columns of the matrix contain the power plant types, whereby the order from left to right must correspond to the merit order. Additionally there is the column "*Imported*" reserved for the imported energy. The matrix has the quantity of rows corresponding to the yearly hours (8760 rows). Alternatively, the row can correspond to the amount of hours under examination.

A program sequence, which takes the hourly demand and subtracts the hourly capacity covered by the power plants was developed. This is performed with the first power plant from left to right in order to correspond to the reality , where the residual load is covered

Table 3.7: Token Matrix to protocol the marginal power plants

	Power plant types							
Time index	*Renewables*	*Nuclear*	*Lignite*	*Hard coal*	*Gas*	*Oil*	*Mixed*	*Imported*
1	0	0	0	0	0	0	1	0
2	0	0	0	0	1	0	0	0
3	1	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
8760	0	0	0	0	1	0	0	0

with the lowest priced power plant possible. If the power plant does not cover the load, i.e. $R_{i,Demand}$ does not equal 0, then a so-called token with the value "0" is written in the matrix, indicating the power plant not being the marginal power plant. The remaining demand is covered by the next most favorable operator. This procedure is repeated until the load is completely supplied. The last power plant applied to supply the remaining demand, is reserved in the matrix with the token "1" indicating the marginal power plant. After the loop has been executed, a row with tokens of value 0 or 1 is created.This sequence is repeated for the next hour.

3.3.1.2 Marginal plants within neighbor countries

The scenario, where the power plants do not produce enough energy to meet the demand can occur. This not supplied energy share is imported from neighboring countries. The matrix identifies it with a "1" in column "*Imported*".

A solution must be introduced, which determines the actual marginal power plant abroad. In general, there are different ways to estimate an approximate emission factor for the imported energy.

The solution method that corresponds to reality is to create a separate token matrix for the neighboring country. The load that must then be covered is the residual load in the own country in addition to the exported share. This method will then give a more accurate indication of the marginal power plant, but will not be useful if the neighboring country still has to import energy to cover its own load. If this effect occurs, a token matrix of a further neighboring country must be built. This chain effect is then continued until the demand has been supplied. Here, as well, the least expensive neighboring country is used to import the energy from. In conclusion, it is difficult to implement this method, since each country must be considered. A network structure considering Kirchhoff's law would then have to be programmed with the function to analyze all countries within Europe. In addition, it must be ensured that all datasets are available.

Therefore the solution that best corresponds to reality and is also feasible in this work is to import the electricity from the cheapest neighboring country. Whereas for this country, a separate token matrix is developed. The energy share that the neighboring country cannot cover is imported from the next cheapest neighboring country. This procedure continues until all the necessary energy has been imported or all neighboring countries have been considered. The marginal power plant is the power plant abroad, which has covered the last portion of the load. If the energy cannot be covered by all neighboring countries, then it is assumed that the remaining share is supported by mixed conventional power plants. With the ulterior motive that the neighboring countries export the most expensive power supplier.

With this method a token matrix is generated for each neighboring country. A programmed function updates the token matrix of the reference country with the now determined marginal power plant type from the foreign country.

How this method is prepared and implemented in the calculations of the CO_2 emissions is described in the following chapter.

3.3.2 Flowchart

A flowchart in figure 3.8 is again used to discuss the process steps used to determine the marginal power plants and emissions. During the discussion a numbering in brackets can be identified with the process steps on the flowchart.

The program starts by preparing the datasets (1). As already mentioned in the introduction, the data is extracted from the ENTSO-E database (ENTSO-E, 2019). All possible power plant data of several countries are downloaded.

After this step, a data set for each country inside Europe with the following hourly information is ready to be used:

- Power plant generation in kWh
- Demand in kWh
- Export- and import capacity in kWh to or from border countries
- Wholesale price €$/kWh$

Next, the reference country is declared with their neighboring countries (2). The large data collection is thus minimized down to the countries of interest.

The preparation also includes the implementation of the modeled hourly network utilization from chapter 3.1.3 (3). It contains the information of used energy from the grid that were necessary to charge the electrical car.

Once all the necessary data have been gathered, the actual determination of the marginal power plants can now be executed (4). The determination of the marginal power plants is carried out with the token matrix method as introduced in chapter 3.3.1.1. Thereby a file is generated, which contains information about the share of energy imported from abroad.

This data is used to complete the token matrix through the neighboring countries (5). For the neighboring country, equal to the reference country, the method of the token matrix is executed.

The next action is to ensure that all neighboring countries have completed the token matrix (6). Additionally the reference countries token matrix is updated with the identified marginal plant from the foreign country.

A file in the form of a matrix is exported (7), which is then used to determine the marginal emissions (8) as described in the following chapter 3.3.3.

The process steps just described were and the methodology of generating the token matrix were realized by the programming language Python (PYTHON, 2021).

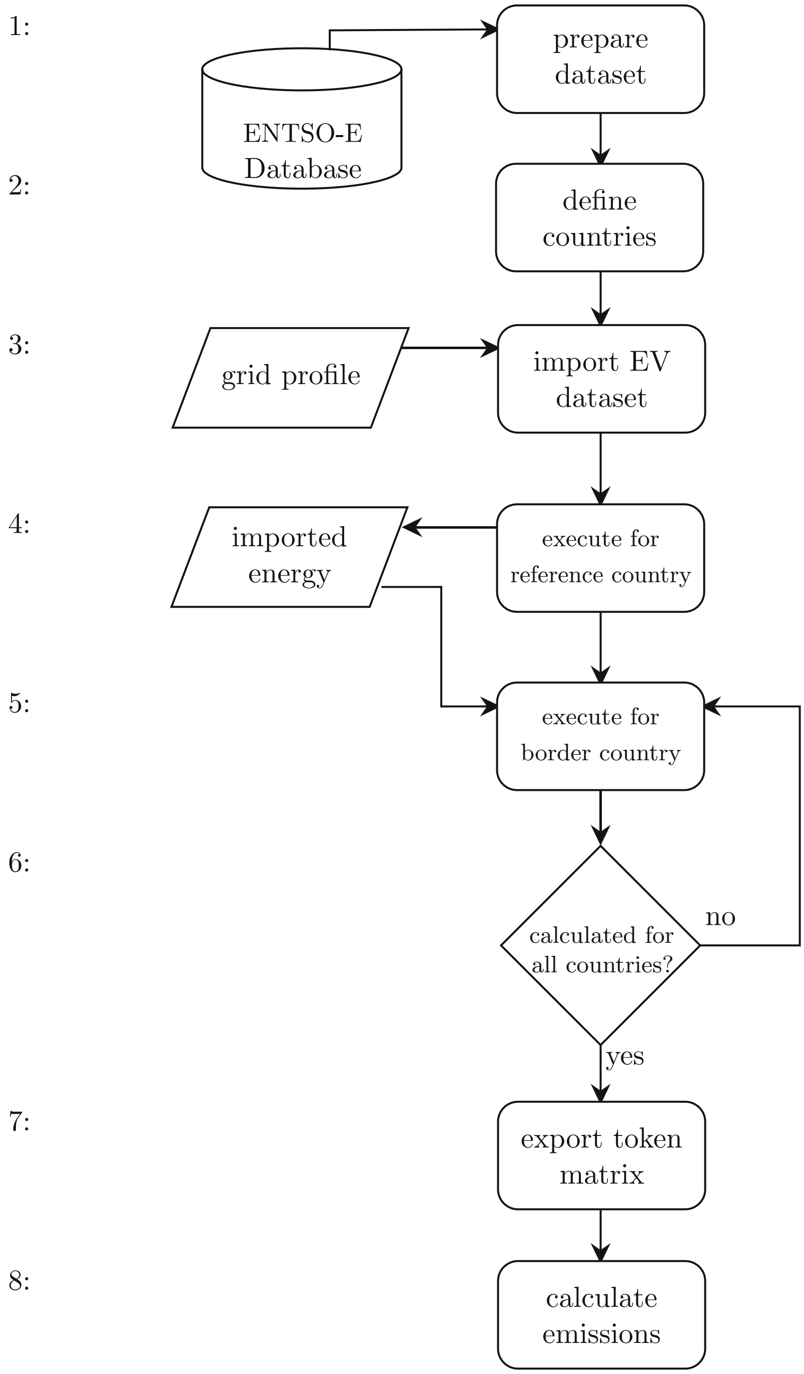


Figure 3.8: Flowchart - Compiling the token matrix

3.3.3 Calculation of the marginal emissions

With the researched emission factors of the generator types, the modeled amount of energy from the grid for charging the EV and the determined marginal power plant with the token system, the formula (3.15) that calculates the annual marginal emissions for charging the EV can be introduced.

$$f_{y,marg,CO_2} = \sum_{i=1}^{8760} P_{i,EV\,Load} \cdot (\sum_{k=1}^{7} f_{k,PP} \cdot t_{i,k,PP}) \tag{3.15}$$

whereas the index i describes the hourly progression ($i | i \in \mathbb{N}, i \leq 8760$) and k identifies the power plant type:

Table 3.8: Plant identification by the index k

Index k	Power plant type
1	Renewables
2	Nuclear
3	Lignite
4	Hard coal
5	Gas turbine
6	Oil
7	Mixed

Nomenclature

$f_{y,marg,CO_2}$	Yearly accumulated marginal emissions	kg/a
$P_{i,M,Demand}$	Hourly modeled EV-Demand	kWh
$f_{i,k,PP}$	Emission factor of plant k	kg/kWh
$t_{i,k,PP}$	Token of plant k	

The token factor $t_{i,k,PP}$ of the plant k is a constant and contains the value "0" or "1" based on the token matrix. The emission factors $f_{i,k,PP}$ contain the values summarized in chapter 3.3.

By calculating this formula, for each hour, the decisive marginal emission values can be determined. To realize this, the results of the token matrix are implemented in the formulation where for each individual power plant, the associated emission factor is multiplied by the token. This term is then summed up to cover all the plants, whereby the emission factors apart from that of the marginal power plant ($t_{i,k,PP} = 1$) are multiplied by a zero ($t_{i,k,PP} = 0$) and are thus omitted. A single emission factor is left which is multiplied by the electrical demand used for charging the EV. In order to obtain the annual emission factor, this calculation is carried out for each additional hour of the year and subjected to summation. The expressed emission factor f_{marg,CO_2} as calculated in 3.16 describes the average marginal emissions for charging an EV.

$$f_{marg,CO_2} = \frac{f_{y,marg,CO_2}}{\sum_{i=1}^{8760} P_{i,EV\,Load}} \tag{3.16}$$

3.4 Methodology to determine the averaged emission factors from power mix

In order to have a reference point to the conventional emission assessment methods in the discussion, the common methods quoted in chapter 2 are applied for calculating the yearly emissions. A similar approach is taken as in the work of Regett et al. The load is based on the EV load curve. The generation power mix data are taken from ENTSO-E database.

3.4.1 Annual average method

First of all, the methodology is given where the annual load of the EV is multiplied by the annual emission factor resulting from the electricity mix. This emission factor is calculated from the sum of the emissions generated by the individual power plants divided by the sum of the accumulated total energy in the reference country. Formula 3.17 provides the mathematical composition,

$$f_{y,yAvg,CO_2} = P_{total,EV} \cdot \left(\frac{\sum_{k=1}^{n} P_{k,total} \cdot f_{k,CO_2}}{\sum_{k=1}^{n} P_{k,total}} \right) \tag{3.17}$$

Nomenclature

$f_{y,yAvg,CO_2}$	Yearly annual averaged emissions	kg/a
$P_{total,EV}$	Total charged EV capacity	kWh/a
$P_{k,total}$	Total generated energy by power plant k	kWh/a
f_{k,CO_2}	Emission factor of power plant k	kg/kWh

whereas k indexes the applied power plant types and the emission factors f_{k,CO_2} contain the values summarized in chapter 3.3.

3.4.2 Hourly average method

This calculation method takes into account the influence of time. Thus, the emission results become more accurate due to the flexible data. For each individual hour, the electricity mix of the generated energy and its emission factor are taken into account where hourly averaged emission factor is multiplied by the EV load to obtain the hourly emissions. The hourly results are then summed up for the year. Formula 3.18 shows the mathematical definition of this methodology,

$$f_{y,hAvg,CO_2} = \sum_{i=0}^{8760} \left(P_{i,EV} \cdot \frac{\sum_{k=1}^{n} P_{k,i} \cdot f_{k,CO_2}}{\sum_{k=1}^{n} P_{k,i}} \right) \tag{3.18}$$

Nomenclature

$f_{y,hAvg,CO_2}$	Hourly annual averaged emissions	kg/a
$P_{i,EV}$	Charged EV capacity at hour i	kWh/a
$P_{k,i}$	Generated energy by power plant k at hour i	kWh/a
f_{k,CO_2}	Emission factor of power plant k	kg/kWh

whereas the index i describes the hourly progression $(i|i \in \mathbb{N}, i \leq 8760)$ and k identifies the power plant type.

4 Results

The implementation of the recently introduced methodology for the determination of the marginal power plants and the annual marginal emissions follows below. Austria was chosen as an interesting reference country due to the high use of renewable energy as well as the numerous conventional power plants used. The various import and export countries are also of interest.

Furthermore, Norway was also considered as a reference example, with the aim of analyzing the influence of 97.7 % produced renewable energy on the emission share (Statistics Norway, 2019).

Finally, to show the influence of importing energy from abroad, Spain and its two neighbors, Portugal and France, have also been chosen as a reference (ENTSO-E, 2019).

4.1 Marginal emissions - With Austria as reference country and comprehension of the results

As mentioned in the introduction, Austria serves as one of the reference countries. Due to the import and export of the electricity, the concerned neighboring countries Germany, Czech Republic, Hungary, Slovenia, Italy and Switzerland are also considered (ENTSO-E, 2019).

In this section, the marginal emissions for charging the car within Austria are determined. This chapter also aims to review the results for plausibility. In this context, the values determined in the scenario where the electricity is supplied by the grid, are combined with statistical data and it is evaluated whether a correlation arises.

4.1.1 Comprehension of the marginal emission assessment method

Before the methodology is applied on the loading profiles, the power plant operations in Austria are analyzed over a whole year for comprehension purposes. The marginal power plants are observed without considering the charging of the EV. This ensures a neutral representation of the marginal power plants.

Figure 4.1: Europe map illustration (EU-Map, 2021) - Austria with neighboring countries

For the following table 4.1, the token matrix for Austria was set up over a whole year and summarized in which countries the marginal power plants are located.

Table 4.1: Summary of the neighboring countries and the reference country in which the marginal power plants are located

	%
Germany	38.5
Austria	30.5
Czech Republic	21.85
Switzerland	8.81
Slovenia	0.91
Hungary	0.02
Italy	0

Germany leads with 38.5 % as it is also one of the main suppliers for Austria. Austria accounts for 30.5 % of the marginal power plants. The high share is mainly found in high summer since the generation increases with the renewables and thus enough energy is produced for the own country (ENTSO-E, 2019). The higher prices from the Czech Republic compared to Germany can also be seen with 21 % share, since mostly Czech Republic is the second choice when Germany can not export enough. The remaining shares are distributed among the remaining neighboring countries, whereby none of the marginal plants are located in Italy. This is to be concluded from the low import (ENTSO-E, 2019).

The shares in table 4.1 correlate very well with the prices, given that Austria would buy from the cheapest supplier first. To refute this, table 4.2 summarizes the average prices for the respective countries from ENTSO-E (ENTSO-E, 2019) for the year 2019. The total share in imported Energy from the neighboring countries to supply the domestic load within Austria is also introduced. This also indicates a correlation with the neighboring countries in which the marginal power plants are located. Since the most energy is imported from Germany, the probability of the marginal power plant being located in Germany is high. According to the results, this is the case. After Germany, Czech Republic leads as a neighboring country in which the marginal power plants are located. As per imported amount of energy and wholesale prices, the Czech republic is also a secondary energy supplier. This correlation applies analogously to the other countries.

Table 4.2: Mean wholesale prices and import share from neighboring countries according to (ENTSO-E, 2019)

	Mean wholesales price [€/MWh]	Share of total imported energy [%]
Germany	37.7	86.0
Czech Republic	40.2	8.0
Switzerland	40.9	4.0
Slovenia	48.6	1.0
Hungary	50.4	~ 0.0
Italy	51.2	~ 0.0

It is interesting to note that according to (E-CONTROL Key statistics, 2020), approximately 26% of the demand in Austria cannot be covered by the domestic market and therefore has to be imported, but nevertheless only 30.5% of the marginal power plant is located in Austria. Hourly, Austria covers the main part of the demand. However, up to 69,5% of the time electricity has to be imported from abroad in order to cover the remaining marginal demand. This leads to a situation where the marginal power plant then ends up in a foreign country.

Knowing where each of the marginal power plants are located, the types can be investigated. Pie chart 4.2 illustrates the distribution of marginal power plants, whereas the renewable and conventional power plants are summarized as introduced in chapter 3.2.1.

The more expensive marginal power plants, as defined in chapter 3.2.1.1, can be identified by a high utilization, whereas the share of oil-fired power plants has fallen very low. This can be explained by the low installed capacity. The hard coal and nuclear share, which originated purely from abroad, can also be noticed. The high use of renewables, especially during the summer, also has an effect. Here it can already be concluded that only 13.1% of the marginal power plants Austria are emission-free.

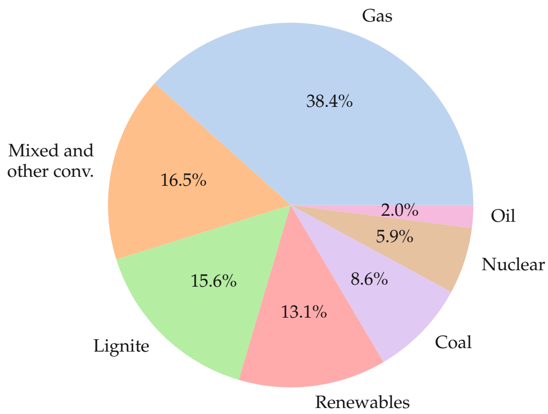


Figure 4.2: Share of marginal power plants in Austria - Scenario: Grid

Since the use of marginal power plants correlates very well with the merit order and those in the importing countries with the wholesale prices but also with the import and export shares, it can be concluded that the developed method for determining the marginal power plants is reliable.

4.1.2 Marginal emissions of a single charging cycle

Before summarizing the results, a calculation of the marginal emissions, as discussed in chapter 3.3.3, of a single charge is presented. The charging cycle itself is randomly selected during a time in winter where the domestic demand in Austria is high.

Before the implementation, a brief summary to the demand as stated in chapter 3.1.1 follows:

The EV with a maximum battery capacity of 52 kWh is charged from 20 to 100%. The 80% (41.6 kWh) are charged with wall connector which extracts the maximum grid power of 10 kW. For the results, at first the token matrix is developed and set up in table 4.3 where early results already indicate that the marginal power plants are located in foreign countries since the token on "*Imported*" contains the values "1" . The charging also occurs between 10:00 and 14:00.

Table 4.3: Token Matrix of a single random charging cycle

	Power plant types							
Time index	*Renewables*	*Nuclear*	*Lignite*	*Hard coal*	*Gas*	*Oil*	*Mixed*	*Imported*
1	0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
10	0	0	0	1	0	0	0	1
11	0	0	1	0	0	0	0	1
12	0	0	0	1	0	0	1	1
13	0	0	1	0	0	0	1	1
14	0	0	1	0	0	0	0	1
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
24	0	0	0	0	0	0	0	0

With the matrix in place, the known emission factor from chapter 3.6 and the defined formula 3.15 can be used to determine the marginal emissions for a single charge cycle, whereas $(i|i \in \mathbb{N}, i \leq 24)$ applies. In the following, the marginal emissions formula is used, whereby only a single hour$(i = 10)$ is mathematically presented in order to maintain a clear overview. The remaining hours are calculated analogously and are indexed by dots $(\ldots)$.

$$f_{cycle,marg,CO_2} = \sum_{i=1}^{24} P_{i,EV\,Load} \cdot (\sum_{k=1}^{7} f_{k,PP} \cdot t_{i,k,PP}) =$$

$$= \cdots + P_{10,EV\,Load} \cdot (f_{5,PP} \cdot t_{10,5,PP}) + \cdots =$$

$$= \cdots + 10\,\mathrm{kWh} \cdot (0.882\,\mathrm{kg/kWh} \cdot 1) + \cdots = 42.8\,\mathrm{kg}$$

The calculated emissions associated with power from the grid system are displayed in graph 4.3. The curve for the emissions is indexed with the hourly marginal power plants and their location. In total, 42.8 kg of emissions were produced during this single cycle. Since the charging was carried out from 20 to 100% battery capacity and thus approximately 41.6 kWh of was stored, it can be concluded that this charging process produced 1.03 kg/kWh of CO_2 emissions.

$$f_{CO_2} = \frac{f_{cycle,marg,CO_2}}{P_{EV\,Load}} = \frac{42.8\,\mathrm{kg}}{41.6\,\mathrm{kWh}} = 1.03\,\mathrm{kg/kWh}$$

As a reference, the same calculation was performed for a cycle in summer. The emission curve is represented in figure 4.4. For the summer, the emissions sink significantly due to renewable marginal power plants and thus emission-poor charging occurs. This charging process produces about 8.82 kg of emissions. In this case, a much lower CO_2 emission factor of 0.212 kg/kWh is achieved.

$$f_{CO_2} = \frac{f_{cycle,marg,CO_2}}{P_{EV\,Load}} = \frac{8.82\,\mathrm{kg}}{41.6\,\mathrm{kWh}} = 0.212\,\mathrm{kg/kWh}$$

In both time periods, the charging costs remains the same since the costs of electricity are assumed to be equal during the year. The loading of a single charge costs the owner 8.37 €.

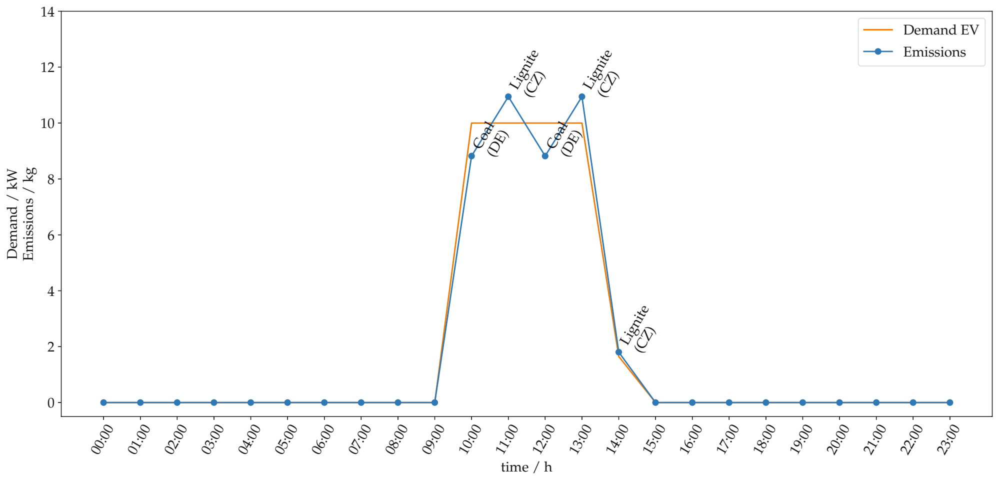


Figure 4.3: Marginal emissions and power plants during a single charging cycle in winter

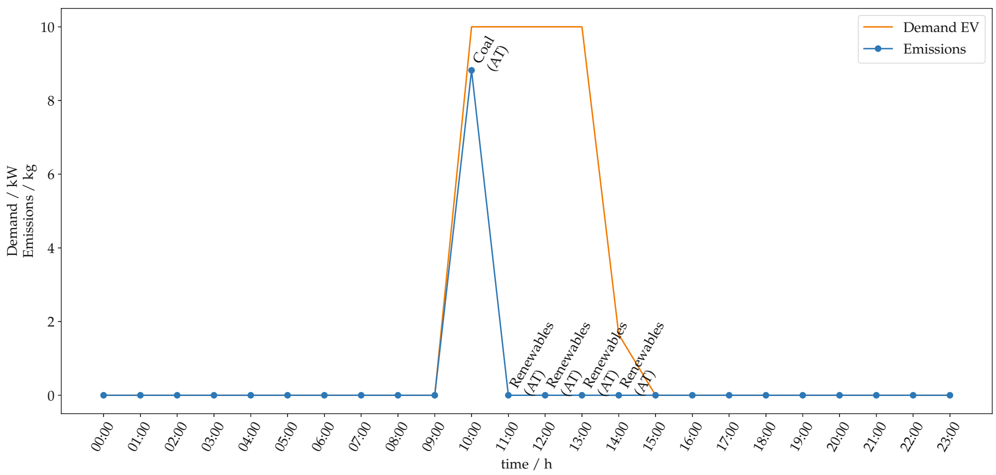


Figure 4.4: Marginal emissions and power plants during a single charging cycle in summer

4.1.3 Yearly marginal emissions

The following results show the emission values for the whole year. A total of 36 charging cycles were performed over the entire year. In total, 1347.4 kWh were required for the charging cycles. In these results, the scenario in which only the grid power is available applies.

Table 4.4 shows the total emissions over a whole year. In addition, the summer and the winter are given, since these seasons offer different resource shares in terms of production.

As expected, the emissions for the charging process in summer fall lower compared to winter, while the capacity remains the same. This can be explained by the increased share of renewable energy during summer.

Table 4.4: Summarized emission characteristics of a charge directly from the grid

		Whole year	Summer	Winter
Capacity	[kWh]	1374.4	343.6	343.6
Marginal emissions	[kg]	842	190	213.8
Marginal emission factor	[g/kWh]	612.6	552	622.4

Next the influence of additional power source installations and demands are introduced.

4.1.3.1 Influence of additional power sources and loads

PV-system and PV-B as an additional power source

In this section the effect of the PV installation at home and the PV-B storage are treated. For each season the utilization of the individual power sources is compared and observed what influence it has on the marginal emissions. Table 4.5 displays the yearly accumulated emissions on different scenarios. The emission characteristics over the whole year can be clearly distinguished under the different scenarios. Although the costs per charge cycle do not change much for the EV owner, the emission factor increases drastically when the PV system or PV storage is switched on.

Table 4.5: Comparison of scenarios - Accumulated emission characteristics over a year - Austria

		Scenario 1	Scenario 2	Scenario 3
Capacity - Grid	[kWh/a]	1374.4	1070	945.7
Capacity - PV	[kWh/a]	0	304.4	263.6
Capacity - PV-B	[kWh/a]	0	0	165
Marginal emissions	[kg/a]	842.8	659	585.2
Marginal emission factor	[g/kWh]	612.6	479.8	425.8
Charging costs	[€/a]	276.3	237.3	222.5
Average price for a single charging cycle	[€/charge]	8.4	7.2	6.7

Influence of additional demand

Next, the emissions are determined where the EV charging curve was affected by household demand. Again, all three scenarios are compared whereas table 4.6 merely shows the emission factors compared with the previously determined results without the household demand. It is clear that the PV system and the battery are heavily used by the household. This leaves little renewable capacity for the electric car, which leads to low CO_2 factor differences compared to those without household load influence.

Table 4.6: Comparison of scenarios with and without additional load - Marginal emission factors

		Scenario 1	Scenario 2	Scenario 3
f_{marg,CO_2} without household demand	[g/kWh]	612.2	479.8	425.8
f_{marg,CO_2} with household demand	[g/kWh]	601.5	588.4	585.2

To illustrate the strong influence of the household, a randomly chosen single charging cycle of scenario 1 is graphically depicted in figure 4.5. Since the model prioritizes supplying the household and a maximum of 10kW can be supplied from the grid, the charging process takes longer. This leads to more marginal power plants that have to be taken into account and thus have an impact on the marginal emissions.

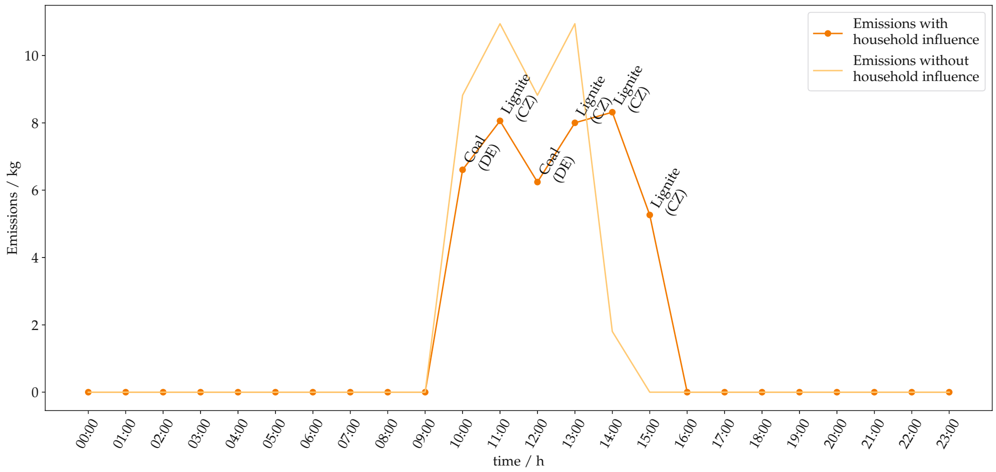


Figure 4.5: Household influence to the marginal emissions

4.2 Marginal emissions - With Norway as reference country

As Norway is the country in Europe with the highest use of hydroelectric power plants, and also has the highest drive to convert use of conventional vehicles to electrical vehicles, the marginal emissions for this country are also interesting to consider.

Norway's importing countries include Sweden, Finland, Denmark and the Netherlands.

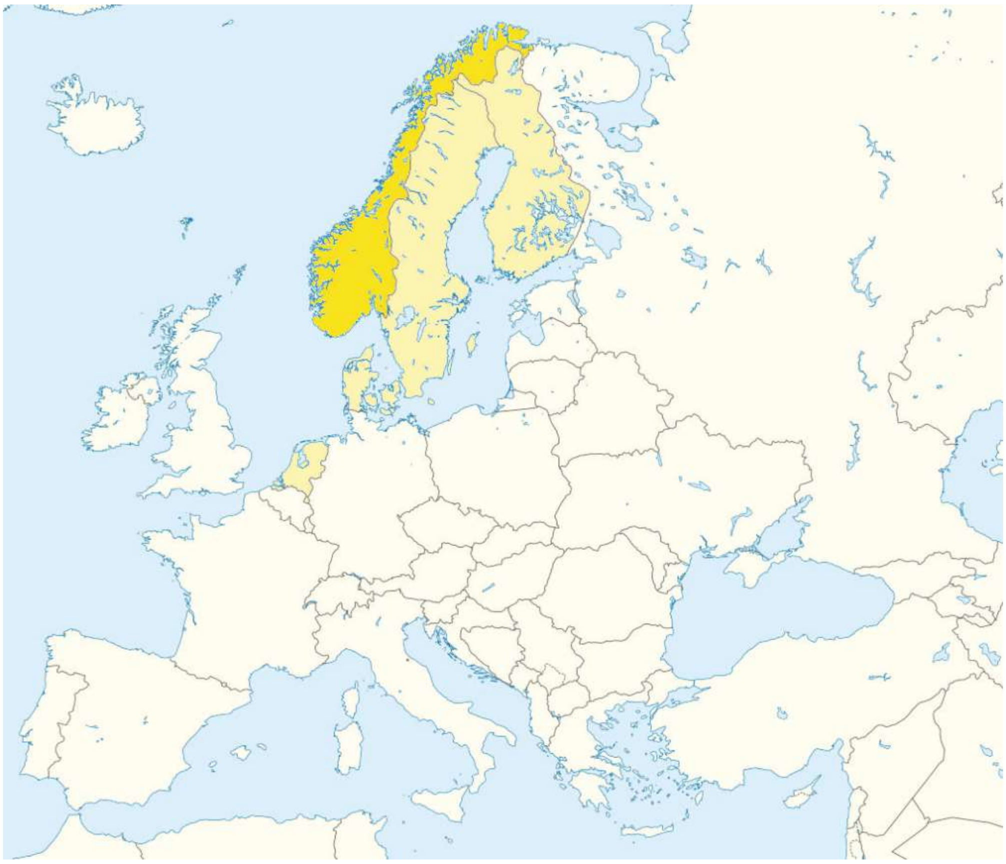


Figure 4.6: Europe map illustration (EU-Map, 2021) - Norway with neighboring countries

Figure 4.7 graphically illustrates the power plant usage within Norway. The time line consists of data over two weeks from spring. It can be noticed that, according to (ENTSO-E, 2019), Norway produces predominantly renewable energy. Only a minimal amount of energy is derived from wind, gas or other conventionally operated power plants.

Similar to the reference country Austria, the hourly token matrix over a year was generated to determine the marginal emissions, regardless of whether an EV is attached

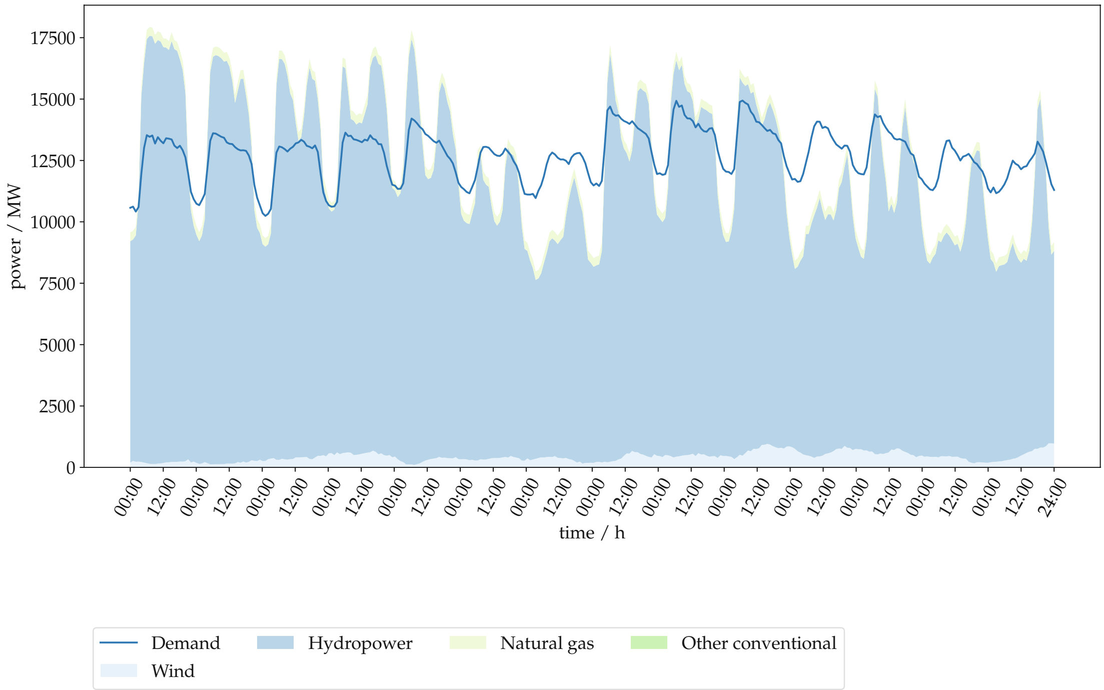


Figure 4.7: Energy generation over two weeks during spring in Norway (ENTSO-E, 2019).

to the load. Figure 4.8 shows the shares in which countries they are located and figure 4.9 the types that applied.

Since Norway already produces a very high proportion of energy and this is usually sufficient to cover its own consumption, this means that half of the time the marginal power plants are actually located in Norway. The occurring marginal power plants in the neighboring countries correlate with the import volumes. This behavior is also indirectly noticeable in the marginal power plant types, as the hydro power plants in Norway in combination with the imported renewables account for the highest share. Mixed energy power plant shares located in neighboring countries also appear. Nuclear driven energy mainly from Sweden also has a very strong effect.

A deeper analysis shows that 6% of the marginal power plants could not be allocated to Norway or its neighboring countries because the demand was higher than the production. Such situation arises when a country sells energy to the reference country but cannot provide it. These non-assignable power plants are categorized under "Mixed and other conventional" to determine the emissions. Chapter 3.3.1 explains these assumptions in detail

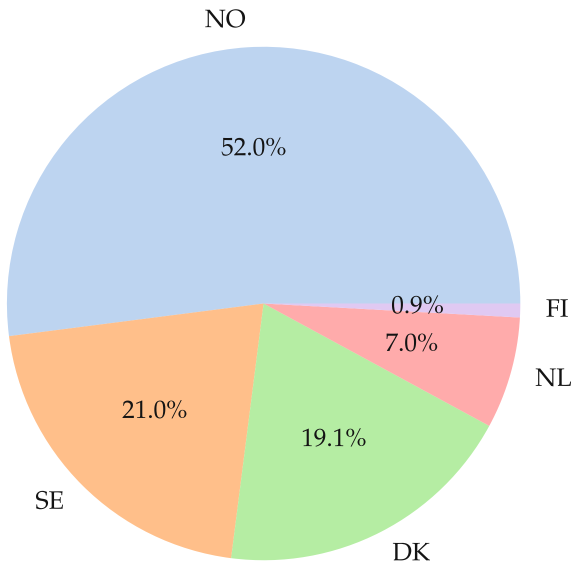


Figure 4.8: Summary of marginal power plant location within Norway and its neighboring countries

4.2.1 Yearly marginal emissions

Based on this breakdown, it can be said in advance that the emissions will fall very low due to the renewable and nuclear share. Table 4.7 summarizes the emission results of charging the EV in Norway. The scenarios determine the charging strategies as introduced in section 3.1.3 whereas for the PV system a charging profile was used which simulates an installation in Oslo.

Table 4.7: Comparison of scenarios - Accumulated emission characteristics over a year - Norway

		Scenario 1	Scenario 2	Scenario 3
Capacity - Grid	[kWh/a]	1374.4	1145	1004.9
Capacity - PV	[kWh/a]	0	229.4	204.5
Capacity - PV-B	[kWh/a]	0	0	165
Marginal emissions	[kg/a]	350.2	291	252.5
Marginal emission factor	[g/kWh]	254.8	212	183.7
Charging costs	[€/a]	247.4	206.1	180.9
Average price for a single charging cycle	[€/charge]	7.5	6.2	5.5

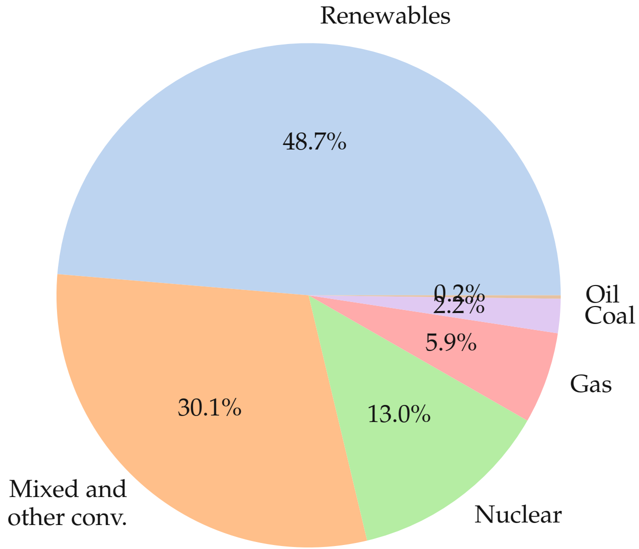


Figure 4.9: Share of marginal power plants in Norway

4.3 Marginal emissions - With Spain as reference country

Spain has also been chosen as a reference country with the aim to analyze the impact of the high import from the foreign countries France and Portugal.

Figure 4.10: Europe map illustration (EU-Map, 2021) - Spain with neighboring countries

First of all, it is illustrated which power plants within the country, Spain uses for supplying its own consumption. For reasons of clarity in figure 4.11, a time chart over two weeks during spring is shown. Again, for this country the marginal power plant types and its locations in general are determined.

Based on figure 4.12 it is hinted that France is the main supplier of energy for Spain. This leads naturally to an increased probability of the marginal power plants being located up to 48% in France. Portugal also represents a strong position in terms of power plant use.

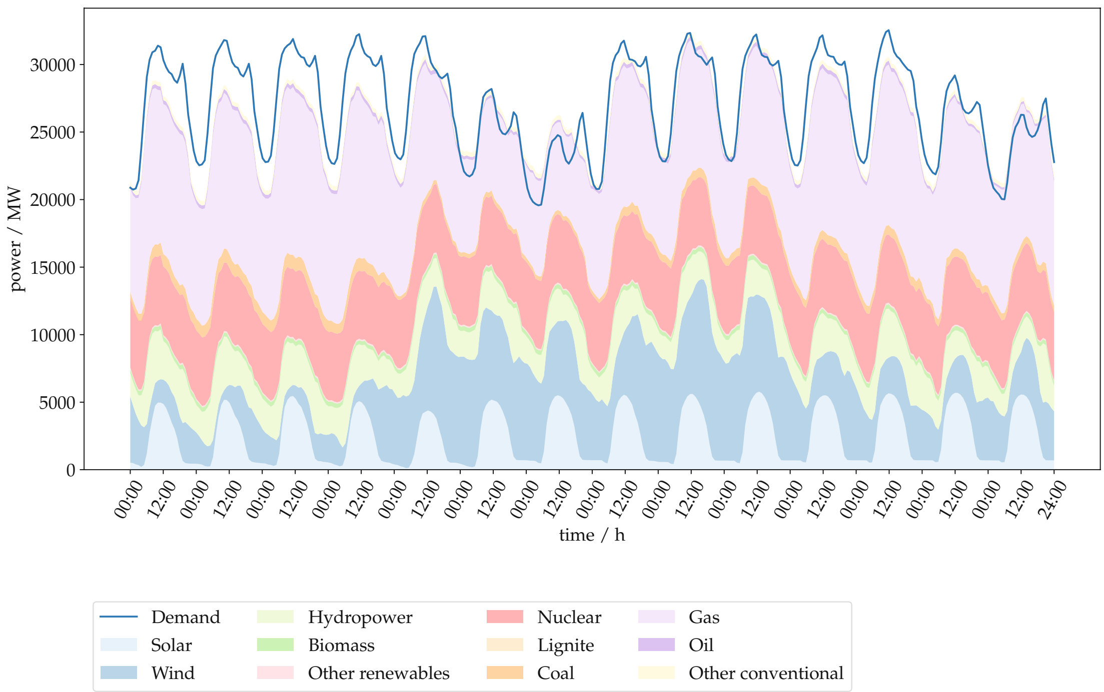


Figure 4.11: Energy generation over two weeks during spring in Spain (ENTSO-E, 2019).

As can be seen, the gas powered plants, which are mainly used in Spain and Portugal, and the nuclear energy from France and partially from Spain dominate in terms of marginal power plants. It is interesting to note that despite the high installation of renewable power plants in Spain, but also in Portugal, they appear less frequently as marginal power plants due to the high demand within Spain. Figure 4.13 shows the proportions in a pie chart.

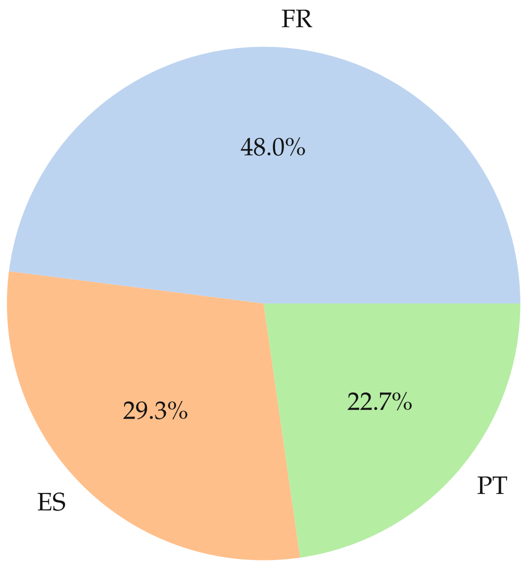


Figure 4.12: Summary of marginal power plant location within Spain and its neighboring countries

4.3.1 Yearly marginal emissions

In order to get an overview of the influence of the scenarios in Spain, the results of the emission share statistics of an EV are presented on table 4.8. The amount of energy used for the whole year is shown with the resulting marginal emissions. From this, the emission factor can also be derived. The PV profile curve for an installation in Madrid was assumed. The further assumptions remain as described in chapter 3.1.1.

Table 4.8: Comparison of scenarios - Accumulated emission characteristics over a year - Spain

		Scenario 1	Scenario 2	Scenario 3
Capacity - Grid	[kWh/a]	1374.4	1009.3	868.9
Capacity - PV	[kWh/a]	0	365.1	340.5
Capacity - PV-B	[kWh/a]	0	0	165
Marginal emissions	[kg/a]	436	340.7	301.2
Marginal emission factor	[g/kWh]	317.2	247.8	219.1
Charging costs	[€/a]	329.8	242.2	208.5
Average price for a single charging cycle	[€/charge]	10	7.3	6.3

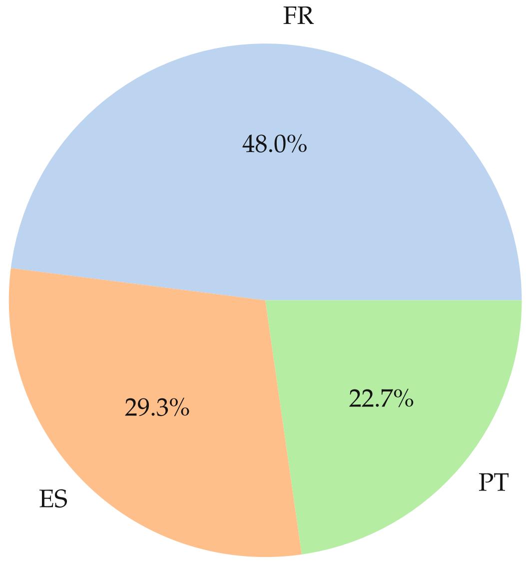


Figure 4.13: Share of marginal power plants in Spain

4.4 Emission assessment with conventional determination methods

The results of the accumulated emissions follow, which were determined using emission factors based on the electricity mix. The load used corresponds to the annual amount of energy drawn from the grid that was necessary to charge the EV.

4.4.1 Annual average emissions

Formula 3.17 was used to determine the average annual emission factors. In the following table 4.9 the results are presented for each reference country, whereas Scenario 1 was set as a loading strategy.

Table 4.9: Accumulated emission characteristics over a year based on annual average

		Austria	Norway	Spain
Capacity - Grid	[kWh/a]	1374.4	1374.4	1374.4
Annual emissions	[kg/a]	133.8	10	250.2
Yearly annual averaged emission factor	[g/kWh]	97.4	13.8	182

In figure 4.14, within Austria the emission curve is shown based on a single charge cycle. For each individual hour, the emission is calculated here using an average marginal factor.

4.4.2 Hourly average emissions

In order to calculate the hourly averaged emission factor of the EV, the modeled load was applied to the formula 3.18 and the results determined for each reference country were presented on table 4.10. Also in this case, only scenario 1 was applied to demonstrate the application of the emission method.

Table 4.10: Accumulated emission characteristics over a year based on hourly average

		Austria	Norway	Spain
Capacity - Grid	[kWh/a]	1374.4	1374.4	1374.4
Annual emissions	[kg/a]	162.9	14,12	225
Hourly annual averaged emission factor	[g/kWh]	118.5	10.3	163.7

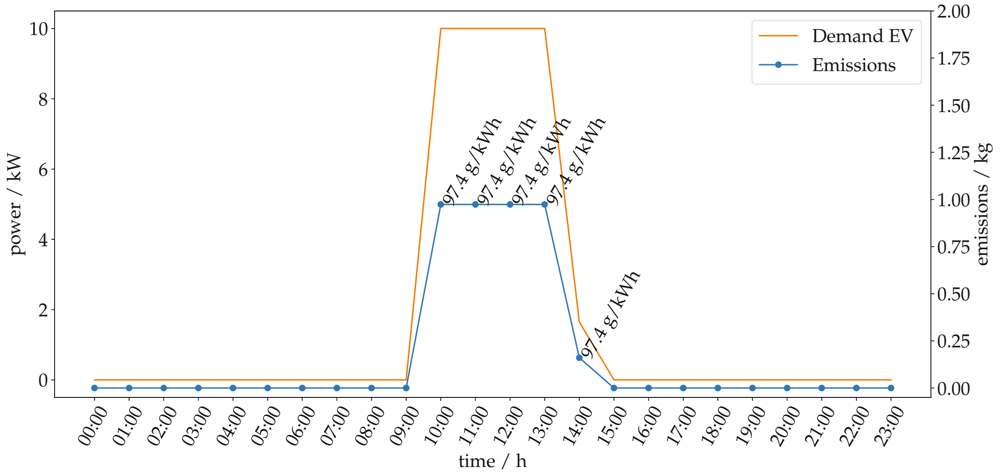


Figure 4.14: CO_2 emissions over a single charging cycle determined with the annual average method in Austria

Figure 4.15 shows how the electricity mix for Austria sets up the hourly emissions. Compared to the previous figure, the dynamic development of emissions and power plant capacities can be seen. The single charging cycle is randomly selected during winter and does not resemble other single emissions trends.

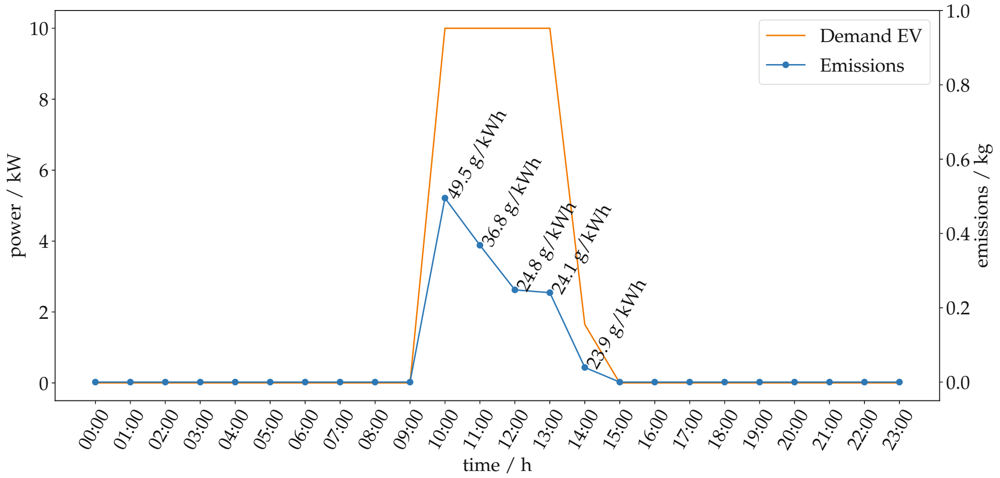


Figure 4.15: CO_2 emissions over a single charging cycle determined with the hourly average method in Austria

5 Discussion

5.1 Marginal emissions in different countries

This chapter deals with a more profound discussion of the results presented above. The determined marginal emission values under different reference countries are compared and the effects of the various power plant applications are investigated. The influence of the charging scenario with a PV system as an additional power source is also considered.

Table 5.1 summarizes the emission characteristics of individual reference countries, with exclusively grid electricity as the energy source.

Table 5.1: Comparison of reference countries - Accumulated emission characteristics over a year

		Austria	Norway	Spain
Capacity - Grid	[kWh/a]	1374,4	1374,4	1374,4
Marginal emissions	[kg/a]	842,8	350,2	436
Marginal emission factor	[g/kWh]	612,6	254,8	317,2

The charging of electric cars in Austria is the least environmentally friendly. This is due to the 86.9% of conventional marginal power plants as shown in figure 4.2. Although Austria produces up to 60.2% (E-CONTROL Key statistics, 2020) of renewable energy in its own country, the influence of conventional energy is high enough on account of the imported amount of energy in order that the emission contribution falls higher than in Norway or Spain.

Spain benefits from the high share of nuclear marginal power plants (0 g/kWh (E-CONTROL, 2012)) from France. With the additional 1.3% of renewable marginal power plants, the charging of electric cars in Spain becomes up to 33.6% emission free. The gas share also contributes to keeping the emission levels low, as the marginal emission factor of gas-powered energy is only 411 g/kWh (E-CONTROL, 2012) on average.

Norway offers the most attractive emissions profile for charging an EV. This is mainly due to the high share of hydropower plants in the reference country. It is interesting to note, that despite 97.7% of the hydroelectric power plants used to generate the energy, only 48.7 % of the marginal emissions are renewable. Thus, it can be concluded that even Norway does not offer a fully emission-free charging. However, it is clear that the renewable shares together with the nuclear imports predominate and thus the charging in Norway mainly takes place with low emissions. With regard to guarantees of origin, the share of renewable energy use is to be viewed critical. Magnus Korpås pointed out that with Norway being part of the guarantees of origin program, the hydro power energy producers sell their guaranteed renewable energy to European countries. As a result to this program the electricity purchases in Norway are only 19 % guaranteed of origin (hydro power energy). From data of Norwegian Water Resources and Energy Directorate (nve.no, 2021), it is established that the energy without guarantees of origin sold to the end consumer consists of about 9% renewable energy, 39% from nuclear sources and the rest from thermal conventional power plants. With taking into account that the hydro power is sold with guaranteed of origin to other countries, the energy consumption sold in Norway ends up accumulating to 530 g/kWh (MIT A+B Applied Energy Conference, 2019).

Next, a comparison is made of how marginal emissions occur when a PV system is installed at the charging location. Table 5.2 provides a summary of all three reference countries.

Table 5.2: Comparison of reference countries with additional PV source installed- Accumulated emission characteristics over a year

		Austria	Norway	Spain
Capacity - Grid	[kWh/a]	1070.0	1145	1009.3
Capacity - PV	[kWh/a]	304.4	229.4	365.1
Marginal emissions	[kg/a]	659	291	340.7
Marginal Emission factor	[g/kWh]	479.8	212	247.8

The use of PV systems does not directly cause a change in the marginal power plant unit in the reference country, however, the amount of energy that is drawn from the grid decreases. This then leads to low accumulated emissions. For example, due to the high share of solar radiation in Madrid (Spain), the accumulated capacity from the grid drops from 1374.4 kWh to 1009 kWh. This saves about 95.3 kg of emissions. The PV installation from Vienna (Austria) also has a positive effect on emission generation, as the emission factor drops by about 132.8 g/kWh. In Oslo (Norway), however, it was only possible to save about 59 kg in emissions, since the cold weather conditions in Scandinavian Europe usually have a negative impact on the PV installation, e.g.: decreasing efficiency or insufficient solar radiation.

5.2 Conventionally determined emissions in different countries

In order to be able to compare the emission assessment methods with each other, the results of the marginal emissions from chapter 4.1 to chapter 4.3 are compared with those determined in chapter 4.4 by conventional methods.

Annual average method

If the annual average method is applied, the emissions will be lower than the marginal emissions 4.9. This is due to the annual evaluation of the power plants used. For example, the 77.6 % of renewable produced energy in Austria, which does not produce any emissions, is predominant. The emissions therefore result from the remaining (conventional) power plants. Imports were not taken into account in this methodology. Also for Spain and Norway the emissions are very low with this calculation method. Once again, the reason for this is that the annual renewable input has a strong influence on the result. It is interesting to note here that Spain now produces more emissions than Austria with the same loading EV profile. This is mainly explained by the higher renewable production in Austria and the fact that the nuclear share from France to Spain no longer affects the final result.

This method is simple to implement and easy to follow. Although it gives a benchmark for comparison between different countries and scenarios, the results are far from the actual marginal emissions, indicating inaccuracy.

Hourly average method

This inaccuracy can be improved by implementing time flexibility. In the application with the methodology of hourly calculation, analog to the previous method, the capacity generated in the country and the emission factor are applied directly, taking into account the hourly evolution. With this method the actual hourly generated capacity forms the emissions. In general, the hourly averaged emissions are higher than the annually averaged emissions since the renewable energy sources are more volatile and its effect can be best shown when viewing as a yearly result and less as a hourly result. For Austria and Norway, the emissions compared to annual averaged are higher. For Spain, however, they decrease. After a profound investigation, it was found that in Spain, as is well known, a lot of solar energy can be generated and this benefits the EV charging emissions, since the charging process is modeled always at midday. In this method, the time of the charging connection is essential.

This method also gives a good benchmark in terms of comparison between scenarios and reference countries. Despite temporal flexibility, this methodology does not give exact emission values. In contrast to the marginal emissions, the actual imported energy and the power plant used are not taken into account.

At this stage, since the marginal emissions fall higher then the conventionally mixed ones, it is important to refer, as in the study of Regett et al., to the merit order dilemma. With a demand largely covered by renewables, a small share remains which must be covered conventionally. The emission factor from the electricity mix thus falls low because of this combination. The emission determined from the marginal power plants falls very high, since the emission to be taken into account is determined solely by conventional power plants such as coal-fired power plants with its low marginal costs but high emission factor. In contrast, the emission factor from the electricity mix falls higher when the demand is very high, because several conventional power plant types have to be added. For the same scenario, marginally considered, the emissions fall more favorably, since here, for example, gas-fired power plants with their high marginal costs determine the emission factor. As is well known, gas-fired power plants have a lower emission factor compared to coal-fired power plants.

6 Conclusion

In this thesis, different emission assessment methods are compared and evaluated. An EV charging profile minimized to operating costs, from the perspective of a single car owner, serves as the load.The model is shaped with different scenarios. Grid connection, PV system and PV storage serve as energy sources. The modeling is constructed on an hourly basis for the entire year 2019. Based on the amount of energy drawn from the grid necessary for charging, emission factors are set up that reflect the emission profile of the EV. The methods used to determine the emission factor are based on the average annual electricity mix, the average hourly electricity mix and the marginal power plants.

Results show that the setup of which installed energy sources (grid, PV, PV-battery storage) are available when charging the EV plays an important role. Apart from the fact that the use of PV or PV-battery storage makes the charging of an EV more cost-effective, the consumer side already ensures that the emission profile of an EV is low-emission. Another important factor is the availability of energy sources. For example, the charging connection plays an important role in the best use of solar energy. Likewise, household demand influences the availability of PV storage, as at the time of charging there are occasions when the energy capacity of PV-battery storage has been used up by household demand. It is also important to consider in which country the EV charging takes place. When applying the model in different European countries, the costs and emissions for charging the EV vary due to electricity prices and PV power availability.

When determining the emission factors, the emission assessment methods lead to different results. The application of the annual averaged methodology delivers inflexible results and is rigid with regard to hourly resolution. The handling is simple, but only the capacity shares of the power plant types are taken into account. Imported and exported energy quantities are neglected and the actual domestic demand is also not taken into account. Although this methodology is suitable for comparing charging scenarios in different countries, it is to be judged critically when it comes to establishing the actual accumulated emissions. Time-flexible results are provided by the hourly average method. This method takes into account the charging connection and the charging time, which enables a comparison of the scenarios. Despite the time flexibility, this method only takes into account the hourly generated capacities and hardly the actual power plant use.

Marginal power plants are taken into account when determining marginal emissions. This methodology allows to identify the actual hourly type of power plant used to cover the additional amount of energy needed to charge the EV. The marginal emissions are defined by the marginal power plants. With this methodology, in addition to the total energy demand in the reference country, the wholesale prices, the import and export shares and the installed power plant types are taken into account in this work. Although a complex model must be programmed for this emission assessment methodology, which is fed with error-free electricity market data, the marginal power plants within the reference country and in neighbouring countries are taken into account. An exact and comprehensible comparison of the reference countries becomes possible. The scenarios are also optimally reflected. Through this methodology, realistic emission factors for charging an EV are identified. Compared to the annual and hourly averaged emission factors, the results can sometimes be controversial. This is due to the merit order dilemma.

In summary, the right choice of emission assessment methodology is an important criterion. Depending on the objective, motivation and available data, the choice has to be treated critically. Annual or hourly averaged emissions are easy to implement, but are undynamic and only take into account the capacity shares of the power plants. Marginal emissions lead to comprehensible emission quantities and take the electricity market data into account, but they are complex to determine.

As an outlook for this work, the existing optimization model can be extended to an EV fleet. With the trend of increasing e-mobility, the modeled EV fleet can be applied to the marginal power plant methodology. It can then be indicated whether the use of EV in large quantities triggers new marginal power plants and what consequences these have in terms of emissions. Based on this work, the future shift from conventional to renewable power plants can also be simulated and conclusions drawn on how the emissions for charging an EV will fall in the future.

Appendix

List of Figures

List of Tables

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Eidesstattliche Erklärung

Hiermit erkläre ich, dass ich die vorliegende Arbeit gemäß dem Code of Conduct – Regeln zur Sicherung guter wissenschaftlicher Praxis, insbesondere ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel, angefertigt wurde. Die aus anderen Quellen direkt oder indirekt übernommenen Daten und Konzepte sind unter Angabe der Quelle gekennzeichnet. Die Arbeit wurde bisher weder im In- noch im Ausland in gleicher oder in ähnlicher Form in anderen Prüfungsverfahren vorgelegt.

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