Chair of Transportation Systems Engineering
Departement of Civil, Geo and Environmental Engineering
Technical University of Munich

# Impact of the Increasing Demand for eMobility on Power Consumption in Germany

## A scenario analysis examining increasing power demand in relation to projected electricity production capabilities

A study project presented in part fulfilment of the requirements of the Degree of Master of Environmental Engineering at the Department of Civil, Geo and Environmental Engineering, Technical University of Munich.

| | |
|---|---|
| **Supervisor** | Raoul Rothfeld<br>Chair of Transportation Systems Engineering |
| **Submitted by** | Jonas Schmid-Querg<br>Paradiesstraße 3<br>80538 München<br>Student ID: 03675585 |
| **Submitted on** | München, 08.02.2021 |

# Table of Contents

# List of Figures

# List of Tables

# Abbreviations

| **Abbreviation** | **Term** | **Description** |
|---|---|---|
| BEV | Battery electric vehicle | s. **chapter 3** |
| PHEV | Plug-In-Hybrid Electric Vehicle | s. **chapter 3** |
| EV | Electric Vehicle | s. **chapter 3** |
| kWh | Kilowatt hour | Energy amount |
| MWh | Megawatt hour | 1000 kWh |
| GWh | Gigawatt hour | 1000 MWh |
| TWh | Terawatt hour | 1000 GWh |
| NEP | Netzentwicklungsplan | Grid expansion plan |

# Abstract

The emerging eMobility trends in Germany invoke a series of technical and political questions. One of which is whether the electricity demand, which will undoubtably increase through eMobility, can be met by an increased power production and how the current official projections of production and demand correspond. This paper examines actual recent electricity data and attempts to answer said question for the year 2030. The employed method, a Monte Carlo simulation, shows that indeed, the power consumption in 2030 will likely exceed the national electricity production if the production capabilities will not be increased more than currently anticipated by official institutions and the government. Integrating a large number of electric vehicles into the German automobile fleet will amplify this effect.

# 1. Introduction

The past six years have continuously been the hottest years in the history of recorded temperatures and nine of the ten warmest years have occurred since 2005 (Climate.gov, 2020). The Paris Agreement therefore aims to keep the global temperature rise below two degrees Celsius above pre-industrial levels in order to minimize the impacts of climate change. It incorporates international collaboration, helping weaker economies and those countries especially affected. Further, it involves individual national plans, the nationally determined contributions, whose requirements the countries are encouraged to comply with and regularly report on.

Facing the ubiquitous threat of climate change and global warming, rethinking environmental sustainability has become more important than ever. In the wake of this need, various trends have been emerging claiming to do their part in reducing global emissions and saving the planet. Some business models truly are contributing to this goal, others are merely using it to create greater brand acceptance, playing on the societal credulity and the desire to purchase fair and sustainably produced goods.

One of the most prominent trends of recent times that has attached itself with the label of sustainability, is the electrification of vehicles, whether it is electric cars, scooters, or bikes, all of which have experienced a significantly greater demand in the past years. Without consulting sales figures of the respective companies, the trend is already visible especially in urban areas (Tagesspiegel, 2019). eScooter sharing fleets by Lime, Voi, Tier or Bird are shaping the urban image in German cities and one can observe many more electric cars on the streets than a few years ago.

The notion of sustainability pushes the demand for eMobility. On top of that, owning an electric car, particularly one from the luxury segment, has become somewhat of a status symbol. Furthermore, the German Government has made eMobility one of its top agendas as a component of the energy transition (*Energiewende*), subsidizing purchases of electric vehicles and charging infrastructure on a currently remarkable level (see **chapter 3.2**).

Accompanying the eMobility development is an increased demand for energy. It has been remarked numerous times that the current trend will result in imbalances of supply and demand, especially regarding the concurring plans to expand the share of fluctuating renewable energy sources whilst reducing fossil energy sources in the German electricity mix. This paper aims to analyze the compatibility of the additional power demand by eMobility with the production and grid capabilities. The analysis will be carried out through a Monte Carlo simulation encompassing official consumption and production projections modelled with various growth factors that are applied to the base year of 2019.

Though eMobility has multiple modes as mentioned above, the focus will lie on one specific mode, fully electric cars, as it has notably the greatest impact on the power demand compared to eScooter and eBikes as well as Plug-In-Hybrids.

eMobility leads to a strain on the electric grid of multiple grid levels. As charging stations are generally connected to the low and medium voltage network, the distribution system operators are crucial for the electrification of the transport sector by ensuring intelligent and appropriate power connections. The emerging problems of potential bottlenecks and solution approaches as well as the government’s current grid expansion plans will be a part of this paper. The following chapter serves to shed light on the structural logic of this research paper. It illustrates the employed methods and provides a first overview on the underlying literature

# 2. Methodology

## 2.1. Approach to the Research Question

As stated before, the central aim of this paper was to assess whether the increased power demand caused by eMobility can be satisfied by the future production of electricity and to establish a cause-and-effect relationship between the number of BEV's on German streets and possible energy production shortcomings. The core data needed for that was on the one hand actual quantitative data from the electricity production and demand in Germany and the current number of BEV's, on the other hand prognoses for the aforementioned for the future. The data used was secondary, to be found on official government portals and in studies carried out by professional associations and research institutes.

The overall approach to carry out the analyses of the research problem was to look at existing electricity data from the base year 2019 and then find production and consumption values for the target year 2030. These values naturally are assumptions. 2030 was chosen as the target year because it is the milestone year on the way to Germany's 2050 emission reduction plan. Therefore, concrete objectives regarding CO2 emission are set as well as plans for the energy budget. Namely, the government promises to reduce CO2 emissions by 55 percent until the year 2030 with 1990 being the reference year (Bundesministerium für Wirtschaft und Energie, n.d.). Considering these goals and the predictions of various sources, growth factors for the electricity demand and production for the base 2019 year were derived.

The validity of the actual production and consumption data is highly reliable, it is measured data provided on the SMARD portal for transparency in the electricity market by the *Federal Network Agency* (*Bundesnetzagentur*) (SMARD, n.d.). The data is checked for plausibility by various instances. However, the prognoses for the electricity demand and consumption trends should be regarded with caution as for example government sources tend to calculate with a much lower value of power consumption in the future as the independent research associations.

## 2.2. Methods of Analysis

The underlying data was found by an extensive literature research and consists of real values and future prognoses. Based on that, growth factors for the electricity production and consumption were derived. Details to the formation of the specific growth factors will be given in the following chapters.

The core of the paper is an analysis via statistical models carried out with the tools R Studio and Microsoft Excel to analyze the data. The first was used to perform a Monte Carlo simulation incorporating the base year (2019) electricity values and the growth factors with a defined range to model possible diversions from assumed pathways. To do so it employs selected ranges for parameters such as fuel consumption and annual mileage. The most important variable in the Monte Carlo simulation is the number of BEV's on German streets. That is why it is considered as a percentage of the overall number of automobiles in Germany and displayed in the graphical evaluation on the x-axis of the diagram. Excel was used to analyze the base year data and compare production and demand on a more granular level in order to find out when potential energy deficits occur respective to the time of the year and the time of the day.

The paper is thematically divided into three sections. Firstly, the literature research establishes the data foundation, presents background information, facts and figures on the augmenting electricity demand, illustrates the current BEV situation on German streets and addresses and evaluates future trends of eMobility. Based on the findings, calculations were carried out to determine the growth factors. The literature also provides an overview of the current power production and the energy market in Germany, explains the planned expansion of renewable energies, and identifies various bottlenecks in the developments of the electric grid in Germany on a local and regional level. Secondly, and serving as the core of the paper, is an analysis which compares energy production to energy consumption data and models possible pathways of the increased power demand by eMobility. Lastly, solution approaches to successfully implement the transport transition together with the energy transition will be proposed and examined.

# 3. Literature Research

This section of the research paper serves to establish the data fundament for the analysis as well as a basic understanding of the development of eMobility in Germany. Therefore, a few definitions must be set beforehand.

**Battery Electric Vehicle (BEV)**

*Fully electric vehicles without a gasoline engine. BEV's have high-capacity battery packs onboard which run the electric motor and the electronics. While in operation, BEV's do not emit emissions as combustion engines do, however, the emissions caused by the production of electricity used as fuel must be taken into account if one would want to carry out a comprehensive and holistic life cycle analysis* (EVgo.de, n.d.).

**Plug-In-Hybrid Electric Vehicle (PHEV)**

*PHEV's possess both, an electric and a combustion engine. They can charge their battery through regenerative breaking or through plugging in to charging infrastructure. The battery packs are usually much smaller than for BEV's so that the electric driving ranges is generally limited to around 30 kilometers* (EVgo.de, n.d.).

**Hybrid Electric Vehicle (HEV)**

*HEV's are able to run on regular gasoline as well as electric energy. The electric energy is solely produced by regenerative breaking, thus only very small electric driving ranges can be achieved. The electric energy is mostly used to start the motor and initially accelerate the car* (EVgo.de, n.d.).

This paper focuses on the battery electric vehicles as the HEV's do not have an impact on the energy demand and the impact of PHEV's is minor relative to BEV's as their battery capacity is very small. A calculation to prove this to back this claim can be found in the later chapters.

## 3.1. Development of Increasing Number of Battery Electric Vehicles in Germany

**Figure 1** shows a steady increase in the number of battery electric vehicles over the last decades. While vehicles with a combustion engine still hold the major share of 98 percent of all passenger cars, the exponential development is not to be disregarded. Since 2010 the number of battery electric vehicles has more than doubled every two years. In addition to the 136,617 BEV'S on January 1st, 2020, 102,175 PHEV's were admitted in Germany as well as 437,208 HEV's. All three categories experienced an increase of at least 52 percent with BEV's having the largest increase of more than 64 percent compared to the previous year on January 1st (Kraftfahrt-Bundesamt, 2020).

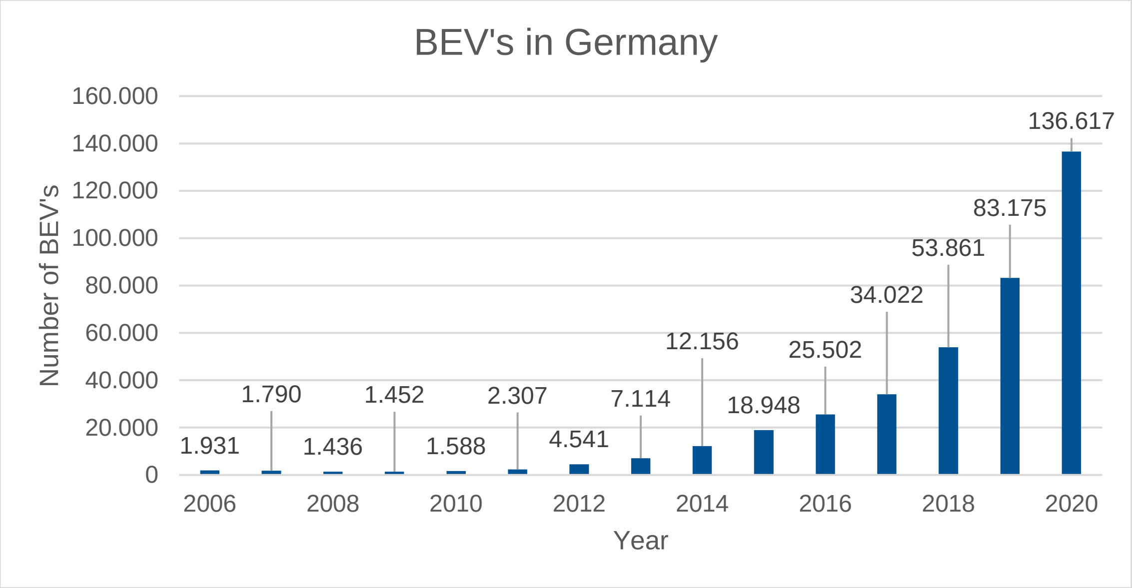


Figure 1 Development of admitted EV's in Germany
(Statista, 2020), own depiction

Likely impediments in the first years were socio-technical and economic barriers such as the minor level of awareness, the scarce offerings, the relatively high-cost price, the limited cruising range, the insufficient public charging infrastructure, and the battery charging time. New technologies without a long history of proven operational capability and standing political frameworks are generally looked upon skeptically by the broad society and technology enthusiasts are the first to adopt the new products (Egbue & Long, 2012). As will be discussed, all the aspects have improved significantly over the years.

As of June 2020, 60 models of electric vehicles by German car manufacturers were available on the market (BMWi, n.d.). A diverse supply is currently available and is important for technological and price competition, however, compared to other nations, Germany is not considered to be at the top of the list. In China, 630.000 electric cars were sold in 2019. This is surely due to the country's large population; however, the market share of 6.3 percent indicates a clear margin compared to Germany. In Norway, the share of new registrations is currently at 56 percent and in Sweden around 30 percent (EFahrer.com, 2020). Scandinavia appears to be very innovative when it comes to eMobility. The differing values of market share generally correlate with a country's wealth but within wealthy countries, the government initiatives are a major factor in driving technology as well as the number of purchases of electric cars.

## 3.2. Reasons for Augmenting Demand

The reasons for the augmenting market of eMobility are manifold. As previously mentioned, political, social, and technical aspects all play important roles. The German government has invested around three billion Euros into research and development of eMobility (BMWi, n.d.). The aim is to assert a pole position of German car manufacturers within this emerging sector as it is believed to be the future of traffic and transport. The investment's focus lies in various fields such as electrical drive technology, battery, and energy research, improving the value chain, digitalization, grid integration and intelligent billing with charging infrastructure as well as driving down production costs especially for the battery. A threshold value for battery costs is 100 Euros per kilowatt hour, which is supposed to be accomplished in 2023 (Heise, 2020). This figure relates to average values for the entire sector, specific suppliers may have individual cost advantages.

A major driver for the purchase decision for electric vehicles is the so called *Umweltbonus* (eng. "*Environment Bonus*"). It is a subsidy for people wanting to buy electric cars and a joint effort of the German government and the car manufacturers. Existing already for several years in varying scales, the federal share has been enhanced, namely doubled, during the COVID-19 pandemic as an innovation bonus. BEV's with a list price below 40,000 Euro are subsidized with 9,000 Euros, Plug-In-Hybrids with 6,750 Euro. Vehicles that are more expensive are subsidized with 7,500 Euros in case they are fully electric, Plug-In-Hybrids with 5,625 Euros. The current status of subventions is vowed to last until 31.12.2021 (Die Bundesregierung, n.d.). In addition to that, electric car owners enjoy several other benefits. They are not obligated to pay the motor vehicle tax for ten years, after this period the tax amounts to 50 percent of the regular rate for combustion engines. Depending on the type of car that might implicate a reduction of 500.00 € per year. Especially as a company car, the purchase of a BEV has recently become more financially attractive. Employees pay only 0.25 percent taxes for the non-cash benefit in case the gross list price of the BEV is below 60,000 € (Einkommensteuergesetz § 6). For non-electric vehicles, the rate is one percent. Furthermore, the fixed rate per kilometer between home and workplace for BEV's and Hybrid cars is 0,015 percent instead of 0,03 percent. Regarding a mid-range car of 45,000 € gross list price that amounts to a monthly difference of around 425 € compared to a regular car.

In addition to subsidizing the EV's itself, the acquisition of charging infrastructure can be supported as well. Previously, regional municipal utilities or other companies involved in the energy business have financially supported customers by taking over a part of their private charging infrastructure. The government started out financing public charging infrastructure back in 2017 within the framework of the *Förderrichtlinie Ladeinfrastruktur für Elektrofahrzeuge*, partly financing the investment costs (Bundesministerium für Verkehr und digitale Infrastruktur, n.d.). Only recently a subsidy for private charging infrastructure like wall boxes has been implemented. From the end of November 2020, the investment cost and installation can be supported with 900 Euros from the government program (Bundesministerium für Verkehr und digitale Infrastruktur, 2020).

In terms of social aspects regarding car purchase decisions, it is interesting to note that an electric car has become a sort of status symbol. Sustainability aside, it is simply deemed fashionable to own a BEV or PHEV. Studies show that the target group is generally very well-funded. Ten percent of the most affluent households in Germany pose 70 percent of EV customers. In many cases of this specific target group, the EV is a secondary vehicle next to regular cars with extensive horsepower numbers (Sickel, 2020). Many of the more powerful EV's are likely not bought by people because they want to do something good for the environment (the sustainability of EV's, BEV or PHEV, diminishes with the size of the EV) but because they want to have a powerful electric car just to possess it. Those cars like the Porsche Taycan, the BMW i8, the Audi eTron or Tesla Model X experience a very large sales market. The Porsche Taycan was sold 20.000 times in 2020 alone (Handelsblatt, 2021).

Last but not least the technical aspects and benefits of the eMobility development are worth noting. Over the past years the driving range has significantly increased, making BEV's more attractive for longer travel distances as well. Depending on the model distances of up to 632 km per full battery load can be achieved (Tesla Model S 100D), however, more common are ranges of 200 to 300 km per battery load (The Mobility House, 2020). Along with the cost of acquisition and the tax situation, the maintenance and usage costs are crucial for consumers. To make a comparison for the latter, one should calculate the cost of the respective fuel for 100 km. The amount depends on the driving behavior, the weight of the car and whether additional gadgets such as heating or cooling system is turned on. However, it is reasonable to make use of average consumption values for BEV's and combustors.

| | **BEV** | **Combustor (Petrol)** |
|---|---|---|
| **Consumption per 100 kilometer** | 15 kWh (E.ON, 2020) | 7.8 litres (Statista, 2020) |
| **Cost per unit of fuel** | 31,94 Ct (Statista, 2020)<br>(Avg. price per kWh for private households in 2019 in Germany) | 1.30 € (Statista, 2020) |
| **Cost per 100 kilometer** | 4.79 € | 12.48 € |
| **Cost per annual mileage (15,000 kilometers)** | 718.50 € | 1,872.00 € |

Table 1 Cost of usage for BEV's and Combustors

The public charging infrastructure has improved as well, currently almost 16,400 public charging points exist in Germany, whereof 12,200 are normal and 2,200 are fast charging points (Bundesnetzagentur, 2020). Prices and pricing models vary significantly (a deficiency that many EV owners rightly complain about), nevertheless, a well-established infrastructure generally supports the development of eMobility. Initiatives such as maps of publicly available charging infrastructures (Bundesnetzagentur, 2020) on official portals such as the *Federal Network Agency* (*Bundesnetzagentur*) make it more convenient for customers to plan their trips with their electric vehicles and alleviates the fear of running out of electricity on the road.

In terms of eMobility in general, apart from electric automobiles, several promoting measures for eBikes and eScooter have been implemented as well. The development will only briefly be mentioned and not discussed in further detail. On a nationwide level, subsidies for eBikes and eScooters are available by the *KfW Bankengruppe* as well es by the *Federal Office for Economics and Export Control* (*Bundesamt für Wirtschaft und Ausfuhrkontrolle, BAFA*). Several other subsidies are available from the respective federal states or local companies (co2online, 2020). Sharing concepts widely implemented in urban areas for vehicles like electric kick scooters or eBikes often provide market-based incentives for their customer to make use of. The initial contact for the customer acquisition and their retention is often realized with particularly cheap usage offers. The eScooter provider Emmy, which is active in Munich and other cities, for example demands a ten Euro registration fee but the price includes 50 charge free minutes (emmy-sharing.de, n.d.).

## 3.3. Future Trends for EV‘s

The governments initial goal of one million electric vehicles on German streets in 2020 was too ambitious. At the beginning of the year there were only almost 240,000 EV’s (including BEV’s and PHEV’s, not HEV’s) (Kraftfahrt-Bundesamt, 2020) which is why the goal was pushed back two years to 2022. The goal for 2030 was set to seven to ten million EV’s (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, 2020) along with one million public charging points. The latter is planned to be realized with an investment of 300 million Euros (BMWi, n.d.). While these numbers sound optimistic, the recent actuals give reason for a positive outlook.

In September 2020 alone 21,188 BEV’s were admitted which is more than 260 percent more than in the same month of the previous year. For PHEV’s the number was even higher: 54,036 admissions in September 2020 and 185 percent more than in the same month of 2019. That makes up for eight, respectively 20.4 percent of all new admissions, making almost every third new admission an electric vehicle. The development suggest that electric vehicles could have a market share of 30 to 40 percent by 2030 (EnBW, 2020). As of January 1st 2020, the entire automobile fleet in Germany counted 47,715,977 cars which was a plus of 1.3 percent compared to the previous year (Kraftfahrt-Bundesamt, 2020). The market share above would indicate 14 to 19 million EV’s in Germany by 2030.

As mentioned before the analysis shows the impact of BEV’s on the power demand in Germany and possible shortcomings on the production side. The number of BEV’s in 2030 is therefore the most essential variable and depicted on the x-axis in percent of the entire German automobile fleet in the graphical simulation results. That allows for a classical “what happens if”-analysis. An accurate prediction for this variable in 2030 is difficult, however, the total number of BEV’s is assumed to lie between five and 10 million.

## 3.4. Power Demand of BEV’s

For the power demand in Germany, the consumption of electricity by BEV’s will play a vital role in the future. Therefore, in the simulation values for a single BEV over the course of a year need to be assumed.

An average value that can be found in multiple sources states of 15 kWh/100 kilometers (E.ON, 2020). Since a precise value is unrealistic, the Monte Carlo simulation uses a range of ± 20 percent or 12 to 18 kWh/100 kilometers. An average value for the annual mileage in Germany is 15,000 kilometers (Statista, 2020). The assumed range in the simulation is again ± 20 percent or 12,000 to 18,000 kilometers for the annual mileage of a car.

By multiplying these two numbers, one can easily derive the annual electricity consumption for one BEV. To put the consumption of a single BEV in perspective, with 15 kWh/100 km and 15,000 km, the annual consumption would amount to 2250 kWh, which is comparable to a three-person household in a residential row house building.

To quickly prove the previous statement, that transport modes such as eScooter, eKick-Scooter and Pedelecs have an insignificant enough impact on the power demand to not be regarded in this analysis, the following calculation provides a quick insight:

eKick-Scooters consume less than 1 kWh/100 kilometers (Verivox, 2020).

Larger eScooters (model Niu N1 S as a reference) consume approximately 3,5 kWh/100 kilometers including charging losses (ADAC, n.d.).

Assuming an eBike has a driving range of 100 kilometers with one battery charge and the battery capacity averages 0.5 kWh would add up to a consumption to 0.5 kWh/100 kilometers (Stromliste, 2019).

If there were five million vehicles of all three modes, which is a very unlikely high outcome even in the future, and if eKick-Scooters had an annual mileage of 1000 kilometers, eScooters of 3000 kilometers and eBikes of 2000 kilometers, that would amount to the following electricity consumption:

$$\left(\frac{1\,kWh}{100\,km}\times 1000\,km+\frac{3.5\,kWh}{100\,km}\times 3000\,km+\frac{0.5\,kWh}{100\,km}\times 2000\,km\right)\times 5\times 10^{6}$$
$$= 0.625\,TWh$$

Based on an overall electricity consumption of 500 TWh per year, these modes would only make up for 0.125 percent and are thus fairly insignificant. The numbers are approximations and assumptions and only serve to put the demand of the three vehicle modes into perspective and explain why this paper only focuses on BEV's.

Plug-In-Hybrids mostly have a battery range of only 30 kilometers and do not go into full electric mode often, after the 30 kilometers they run on regular fuel if not charged again. That means for any longer trips, they emit the full amount of $CO_2$, yet they are still eligible for the *Umweltbonus* at purchase and receive many tax advantages and serve the car manufacturers to artificially lower their fleet $CO_2$ value in order to comply with the regulations. Even though it is clear, that PHEV's have a much higher CO2 emission than on the paper (Süddeutsche Zeitung, 2020). If one assumes there were 5 million PHEV's, that they would have the same annual driving range as BEV's and drive 30 percent on a purely electric basis (Fraunhofer ISI, 2020), the result would be the following:

$$\frac{15\,kWh}{100\,km}\times 15{,}000\,km\times 0{,}3\times 5\times 10^{6} = 3.375\,TWh$$

Based on an overall electricity consumption of 500 TWh per year, that would only make up for 0.675 percent. That is 30 percent of what the same amount of purely electric BEV's would need and therefore already worth mentioning. However, and this is an important point for the understanding of the logic of this paper:

The seven to ten million electric vehicles that the government plans to have on German streets by 2030 already account for BEV's and PHEV's. The analysis, however, assumes that the entire electric fleet consists of BEV's, resulting in a higher power demand. Therefore, consumption-wise, it is kind of an “extreme case” scenario when it comes to the question of what the ratio of BEV's and PHEV's will be in the future. From a standpoint of sustainability that would be the ideal scenario.

## 3.5. Power Production in Germany – Excursus

The power production in Germany has experienced an overall increase since the 1990ies due to an augmenting demand of industry and households. There are exceptions from the trend, most notably the year of 2009 when the economic downturn caused the economy to shrink. Ever since 2003 more electricity was generated than consumed leading to a net electricity export. The upward trend ended in 2017, since then the net production shrunk by approximately five percent due to the abandonment of conventional powerplants, especially the nuclear powerplants of which the last one is obligated to be shut down in the near future, in 2022 to be exact, due to the phase-out law *Atomgesetz* (*AtG*) from 2002 (Umweltbundesamt, 2020).

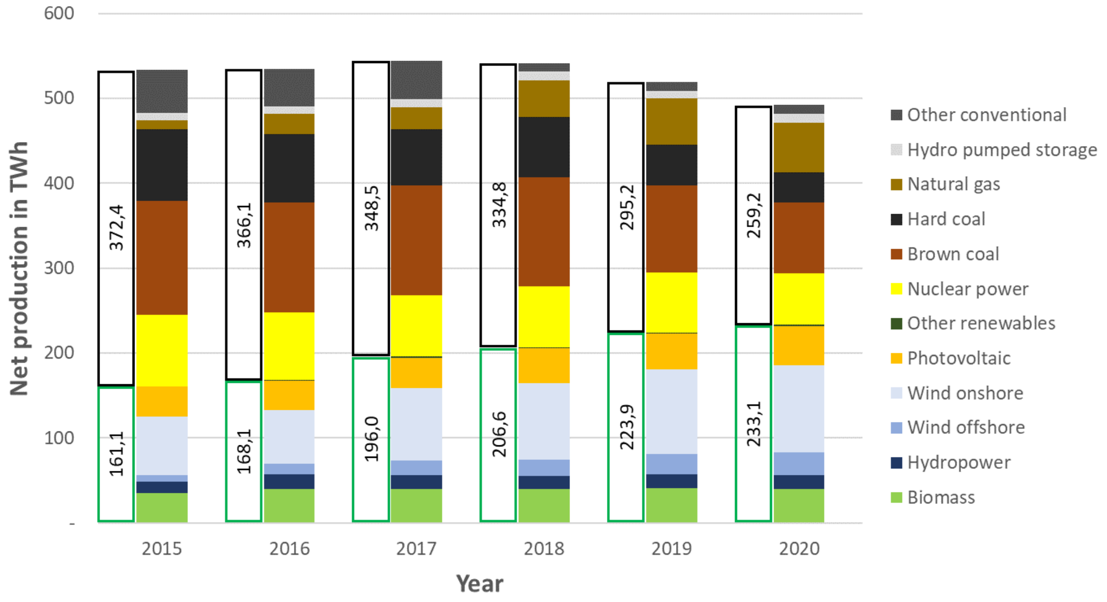


Figure 2 Net electricity production from 2015 to 2019
(SMARD, n.d.), own depiction

The table above shows the net electricity production from 2015 to 2019. The combined net production of renewables is marked by the bar on the left outlined in green and the conventional energies production is marked by the bar outlined in black. It is clearly visible that the renewable energy sources have increased their share within these five years significantly. In 2015 the renewable net production share amounted to 30.2 percent, in 2019 it was 43.1 percent with the largest increase from 2018 to 2019 with 5 percent (SMARD, n.d.). While onshore wind production has by far the largest absolute value in 2019 among the renewable sources, the increase was the highest for offshore wind production: almost by 300 percent.

The use of hard coal has recently declined because of the increased production of natural gas. This is due to decreasing spot prices of natural gas and increasing prices for emission allowances leading to natural gas being before hard coal in the merit order model (ewi, 2020).

By 2030 the government plans to achieve a share of 65 percent of renewable in the gross electricity consumption. An ambitious plan, which, according to studies, will most likely fail to be implemented (ewi, 2020). The EWI expects a share of 46 percent renewables in 2030.

## 3.6. Input Data for Production and Consumption in 2030

As mentioned before, the ensuing simulation uses base values from 2019 for each energy source and derives growth factor ranges to derive a corridor for the production of each energy source in 2030 as well as for the consumption. The base values are actual net production or consumption values from 2019 in Germany and can be found in Table **1** in chapter **4.2.2**. The source for these values is the official information portal for electricity markets and data *SMARD* by the *Federal Network Agency* (*Bundesnetzagentur, BNetzA*) and the Department of Commerce *(Wirtschaftsministerium, BMWi*) (SMARD, n.d.) where the data is freely accessible. SMARD was implemented to further the energy market's transparency, it provides real time date of the power market.

To derive the production and consumption growth factors, the latest grid expansion plan *(Netzentwicklungsplan Strom 2030, NEP)* was consulted. The NEP considers the scenarios of the BNetzA for the future energy production including the integration of renewable energy sources and describes the need for the grid expansion in order to reach the scenario goals. Being the middle ground between scenarios *A 2030* and *C 2030*, the scenario *B 2030* was chosen for this purpose, representing an energy transition with increasingly flexible production and consumption, capped carbon dioxide emissions in powerplants and a moderate expansion of renewable energy sources.

In the NEP installed production capacities in Gigawatt of the various energy sources are given for the reference year 2017 and predicted for the year 2030. The assumption is that the ratio between installed capacity of each individual energy source and its actual production is the same for base year and target year. To transfer the developments to the reference year 2019 and the net production in TWh the following steps are necessary:

1. Calculate the average growth rate from 2017 to 2030 for the installed capacities ($Cap$) of each energy source (n = 13 stands for the year 2030).

$$\rho = \left(\frac{Cap_{2030}}{Cap_{2017}}\right)^{\frac{1}{n}}$$

2. Calculate the installed capacities for 2019, which is two years from the reference year 2017.

$$Cap_{2019} = Cap_{2017} * \rho^2$$

3. Calculate the growth factors for each energy source from 2019 to 2030.

$$growthfactor = (Cap_{2030} \div Cap_{2019}) - 1$$

4. As a definite value prediction is unlikely, it is preferable to have a corridor in which the actual value could lie. Therefore, the decision was made to add and respectively substract 15 percent of the growth factor value to receive a minimum and maximum border.

$$growthfactor = (Cap_{2030} \div Cap_{2019}) \pm (Cap_{2030} \div Cap_{2019}) \times 0.15 - 1$$

An exception in this is nuclear power, the growth factor is simply negative one, as by 2030 no nuclear power plants will be in use. The last one will be taken off the grid in 2022 (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit, n.d.).

The consumption growth factor was derived similarly. The aforementioned NEP does have a prediction for the net electricity consumption in 2030 (543,9 TWh). This prediction is most likely overestimating the savings by energy efficiency measures. Studies vary in their propositions for the energy consumption in 2030. An EWI analysis predicts 748 TWh (Energiewirtschaftliches Institut an der Universität Köln, 2020), stating that amongst others, eMobility and heat pumps will push the consumption values. The *Deutsche Energie-Agentur Gmbh (dena)*, a federally owned, yet proclaimed independent company that renders services, shapes projects, and conducts studies in the context of the climate change and the energy transition, quantifies the consumption in 2030 at 670 to 840 TWh, depending on the scenario (dena-Leitstudie Integrierte Energiewende, 2018). Another scenario by the *Bundesverband Erneuerbare Energie e.V. (BEE)* estimates a consumption of 740 TWh and also states that the share of eMobility in this scenario will be 68 TWh.

However, the conservative consumption prediction by the NEP was chosen to derive the growth factor for three reasons. Number one being that having production and consumption values from the same source ensures consistency. Secondly, the estimates for the consumption by the NEP is very conservative compared to the other study results mentioned above. This implicates, should the results still show an overall power deficit over the year, the hypothesis, that Germany will have a power gap in the future if the expansion of the renewable energy sources is not pushed much more than it is now, is true with a high likelihood. And thirdly, because employing all assumptions from the government plan serves to question their estimates and perhaps reveal possible weaknesses. As before for the production and consumption growth factors, to conduct the Monte Carlo simulation, a corridor of plus and minus 15 percent was chosen to represent possible deviations from the actual future value.

It is important to note that the eMobility electricity demand is already incorporated in the consumption values from 2019 and 2030 from the literature. Therefore, the known number of electric vehicles in 2019 multiplied by their average yearly consumption is subtracted from the net consumption in 2019 in the input data for the modeling. For 2030, the NEP assumes six million EV’s, which was also multiplied by the average yearly consumption of one EV and subtracted by the estimated overall consumption. These resulting values for base and target year were employed to derive the growth factor and the growth factor range, respectively.

# 4. Scenarios – Compatibility of eMobility Trends with the Future Electricity Production

This chapter makes use of the previously collected data and trends and employs the gathered knowledge in order to examine how compatible the future electricity production is with the increased demand caused by an augmenting number of BEV'S in Germany.

## 4.1. Simulation Possibilities

In order to show the compatibility and sufficiency of the power production and the power consumption, various approaches can be taken. The most sophisticated being a holistic agent-based simulation which focuses on the separate components of a system. In the case of the power grid, the grid would essentially be recreated virtually, containing all relevant consumers, producers as agents, their load behavior as dynamic actions and all grid capacities in the respective locations as well as the infrastructure between the agents. Small electrical loads such as households, car charging stations, heat pumps as well as industrial users would be modelled with their specific load profile. Similarly, the various energy generating sources, conventional and renewables alike, would be part of the simulation. This kind of simulation is referred to as a bottom-up approach, starting with the individual agents working up to the complex interactions with the structure connecting them (Sameera, Theodoropoulos, Lemarinier, & O'Hare, 2016).

A sophisticated agent-based simulation has the possibility to analyze production and consumption in a temporal and regional, even local manner, given the required data is provided. This means, energy deficits can be simulated fairly accurately, and countermeasures might be undertaken. The greatest difficulty, however, is, besides the availability of data and complexity of programming, the unpredictability of fluctuating energy sources like wind and solar energy. As they are dependent on weather conditions, they cannot be accurately predicted for a large time horizon.

Several programs for the described simulation already exist and are usually part of a larger research project.

*GridSim* is a simulation model by the *Forschungsstelle für Energiewirtschaft e.V (FfE)*, an independent research center for energy efficiency, renewable energy, digitalization, and integrated energy systems. The model serves a detailed reflection of the distribution grid and aims to analyze the implications of various decentralized production and consumption systems on the distribution grid (Forschungstelle für Energiewirtschaft e.V., 2020). GridSim is capable of modelling many scenarios such as grid loads due to eMobility by differing market penetrations, decentralized production usability for future consumers or the impact of energy storage on integrating fluctuating renewable energy sources into the energy mix.

As agent-based simulations for the power grid would be exceedingly complicated regarding data acquisition, programming, and behavioral predictions of agents, in this context it is feasible to make use of a simpler approach to show the impact of increasing eMobility demand in Germany. This paper will examine an alignment of production and consumption values while assuming different numbers of electric vehicles as an additional load.

## 4.2. Chosen Simulation

As the agent-based approach is too complex for a small research project such as this one, a simpler approach was chosen. The goal was to identify whether an energy deficit may occur in the future, namely in 2030. The previous research concerned the base year 2019 and the underlying trends and assumptions for the year 2030. In order to find out how likely and severe these potential power deficits will be due to eMobility, an approach employing an analysis via statistical models using the tools R and Microsoft Excel has been chosen. The simulation in R serves to model whether the production surpasses the consumption over the course of a year and the simulation in Excel serves to find the most critical energy deltas on a temporal level.

### 4.2.1. Simulation with R

The simulation uses actual electricity production and consumption data from 2019 and makes use of estimated growth factors to predict the values in the year 2030. The basic equation of the simulation is the simple difference (delta) between Production and Consumption:

$$\Delta PC_{2030} = P_{2030} - C_{2030}$$

| | |
|---|---|
| P | Production |
| C | Consumption |

The production in turn consists of the shares of the individual energy sources:

$$P_{2030} = \sum_i ProductionEnergySource2030_i$$
$$= BM + HP + WOf + WOn + PV + OR + NE + BC + HC + G + PHS + OCE$$

The variables represent the production by the various types of energy sources:

| | | | |
|---|---|---|---|
| BM | Biomass | HP | Hydro power |
| WOf | Wind offshore | WOn | Wind onshore |
| PV | Photovoltaic | OR | Other renewables |
| NE | Nuclear energy | BC | Brown coal |
| HC | Hard coal | G | Natural gas |
| PHS | Pumped hydro storage | OCE | Other conventional energy |

The summands in ***P*** in turn consist of a base value for each energy source in 2019 multiplied by one plus a respective growth factor to simulate the production of each energy source in the target year.

$$ProductionEnergySource2030_i$$
$$= ProductionEnergySource2019_i * (1 + ProductionGrowthFactor_i)$$

For example:

$$BM = BM_{19} * (1 + PoductionGrowthFactor_{BM})$$

The formula for the consumption in the target year 2030 is as follows

$$C_{2030} = C_{2019} * (1 + GrowthFactorC) + CeM$$

$$CeM = X * AM * \frac{EKm}{100}$$

| | |
|---|---|
| $C_{2019}$ | Energy consumption in 2019 without emobility |
| CeM | additional energy consumption by eMobility |
| X | Number of electric Cars |
| AM | Annual mileage |
| EKm | Energy per 100 km |

Each growth factor and yet unknown variables like the number of electric cars, their annual mileage and the energy per 100 km is actually represented by a corridor of possible assumptions between a minimum and maximum value. The simulation uses the Monte-Carlo-Method with 20,000 iterations to create these values.

### 4.2.2. Input Data R

Power production:

| Description | Value in MWh | Growth factors |
|---|---|---|
| Biomass | 41,030,981.75 | -0.3041, -0.0585 |
| Hydro power | 15,843,344.75 | -0.15, 0.15 |
| Wind Offshore | 24,185,404.00 | 0.2744, 0.7242 |
| Wind Onshore | 99,634,865.00 | 1.2431, 2.0348 |
| Photovoltaic | 41,915,997.00 | 0.6266, 1.2007 |
| Other renewables | 1,317,000.50 | 2.5446, 3.7956 |
| Nuclear energy | 71,044,587.00 | -1, -1 |
| Brown coal | 102,732,654.75 | -0.5767, -0.4273 |
| Hard coal | 47,819,697.00 | -0.6152, -0.4793 |
| Natural gas | 54,624,090.00 | -0.0158, 0.3316 |
| Pumped hydro storage | 8,954,958.00 | 0.0065, 0.3617 |
| Other conventional energy | 10,051,213.00 | -0.2303, 0.0414 |

Table 2 Power production base values 2019 and growth factor ranges
(SMARD, n.d.), own depiction

Power consumption:

| **Description** | **Value** |
|---|---|
| Consumption 2019 without eMobility | 490,292,889 MWh |
| Consumption growth factor | -0.0805, 0.2441 |
| Number of electric cars<br>(50 million representing the entire German car fleet in 2030) | 0, 50,000,000 |
| Annual mileage | 12,000, 18000 km |
| Energy per 100 Km | 12, 18 kWh |

Table 3 Power consumption base values, growth factor range

### 4.2.3. Excel Analysis of the Timely Variation of the Power Deficits

The Excel analysis is a separate analysis from the Monte Carlo simulation. They are not connected mathematically but thematically because a deeper understanding of possible eMobility consumption problems is revealed in both.

With this analysis, a comparison of production and consumption data from 2019 is carried out to find times when consumption outgrew the production, the so-called power deficits. Therefore, the aim was to break down the production data from 2019 to a more granular basis. The load profiles of consumption and production from this year were once again obtained from the electricity portal *SMARD*. It is to be noted that this does not examine the timely occurrence and distribution of power gaps in 2030 or the future in general. How the energy is produced, centralized or decentralized by many small power plants, might differ greatly from the current time.

The goal of finding the most critical times of power deficits, when the consumption value exceeds the production, was realized by directly comparing the actual data. The simple subtraction of production and consumption for every 15 minutes throughout all of 2019 provides an overview when these power gaps occur because the timestamp is always given. The simple Excel analysis makes use of the time stamp and shows the number of negative intervals and their accumulated energy in GWh over the course of the year as well as on a monthly level. Then the timely distribution is analyzed and compared with consumption behavior.

## 4.3. Analysis Results and Discussion

### 4.3.1. Monte Carlo Simulation

In **Figure 3**, the simulation was run without any consumption growth from 2019 to 2030. On the x-axis the percentage of BEV's of the overall carpool is provided, which is assumed to be 50 million in 2030. As of 2020, it was 47.1 million and it experienced a slow but steady increase each year for the past years (Statista, 2020). On the y-axis the difference between production and consumption is displayed.

To put the numbers into perspective: the production will be around 500 TWh in 2030, thus, 50 TWh as a power deficit would be roughly ten percent of the production.

The thick blue line is a fitted line through the point cloud to allow for a better overview. The two thinner blue lines show the quartiles of the statistical distribution, meaning that 50 percent of the data points lie within the two thin blue lines, and 25 percent of the data points lie each above and below them. The red lines show the planned share of BEV's in 2030, namely ten to twenty percent or five to ten million.

Interestingly enough, even if the growth factor for the regular consumption is assumed to be zero, meaning that the base consumption from 2019 will not increase, the simulation shows that a small number of BEV on German streets will raise the consumption over the production dimensions. The figure shows that somewhere between five and seven million electric cars, a power deficit between the annual national production and consumption will become very likely. The result implies that the gap can only be filled by electricity imports from neighboring countries, as it is not a temporal or local but an absolute deficit of electricity. By simple market mechanisms, imports from other countries generally mean higher energy prices than for nationally produced electricity.

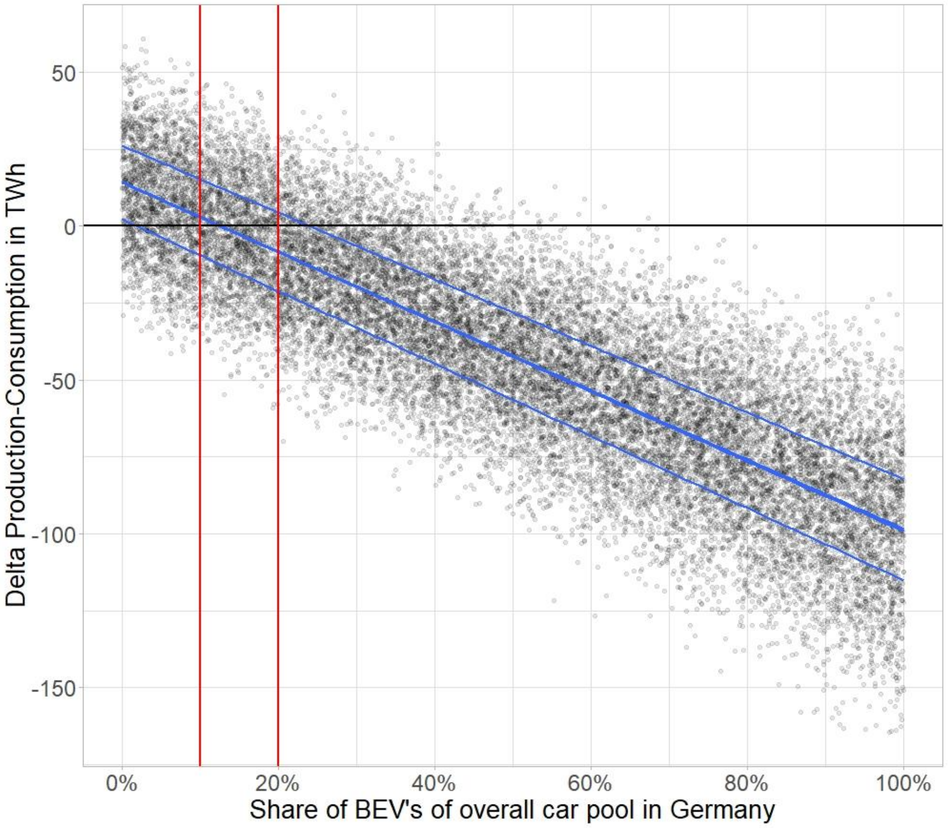


Figure 3 Monte Carlo Simulation with a consistent base consumption from 2019 to 2030

In **Figure 4**, the regular consumption growth is considered and the result shows that overall power deficits are much more likely. The median lies below a net zero already at a share of zero percent BEV’s. At a ten percent share, or five million BEV’s of the 2030 carpool, even the upper quartile crosses the net zero line, implying that there is only a 25 percent chance that the power production exceeds the consumption in 2030 given the used data and assumptions. Considering the goal of five to ten million BEV’s in the target year the analysis result implies that the power deficit will likely amount to 40 to 50 TWh based on the current predictions of installed capacities.

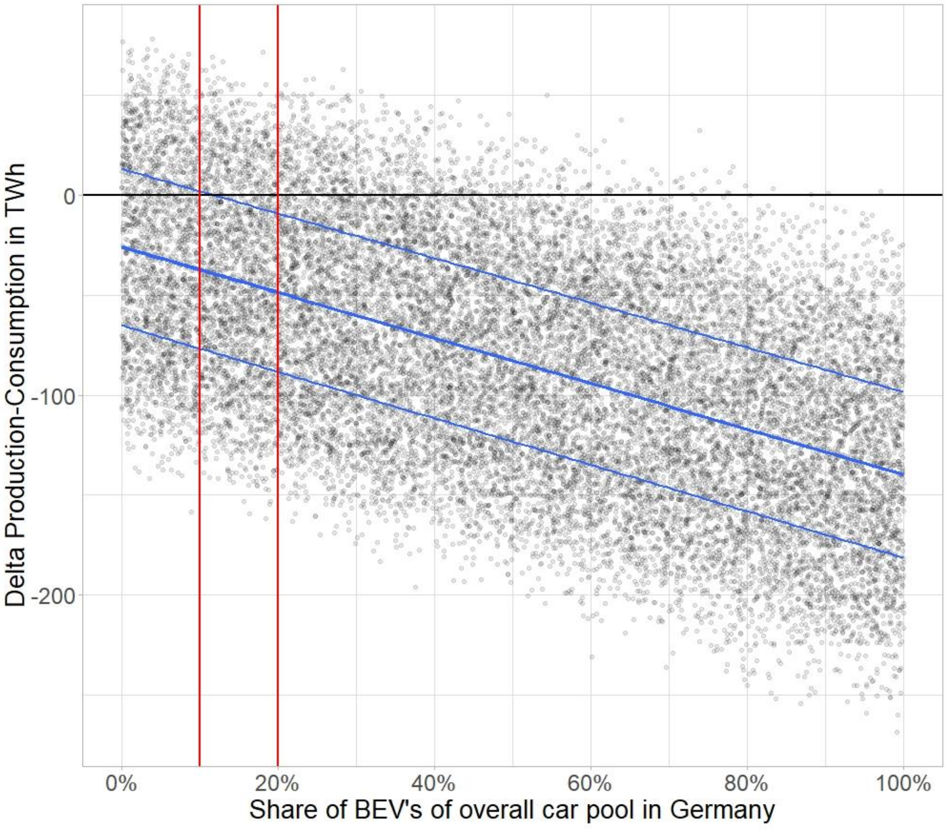


Figure 4 Monte Carlo Simulation from 2019 to 2030

### 4.3.2. Temporal Power Deficit Analysis

The analysis in Microsoft Excel aimed to get a better understanding of the temporal occurrence of negative energy gaps throughout the year and throughout a day. The analysis is separate from the previous simulation but is thematically connected as will be evident after the result's discussion.

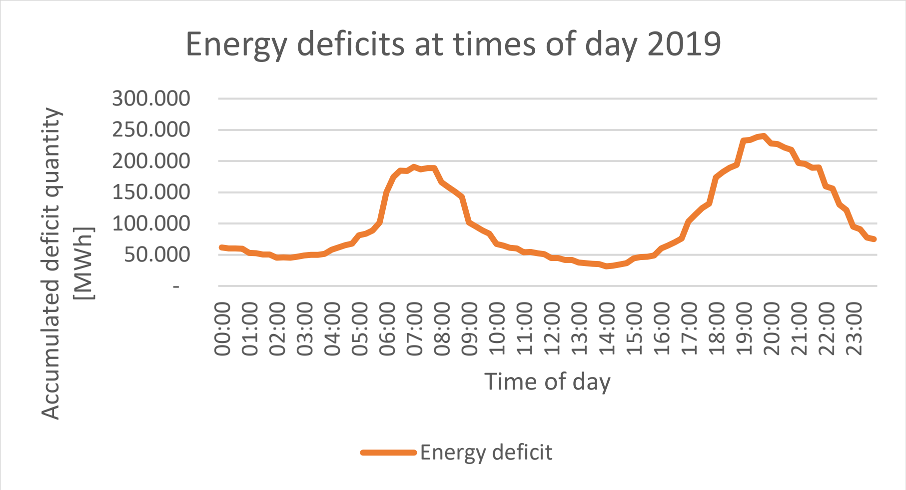
The underlying data is comprised of the 15-minute interval profiles of production and consumption. Again the difference of both was calculated, this time for every 15-minute interval.

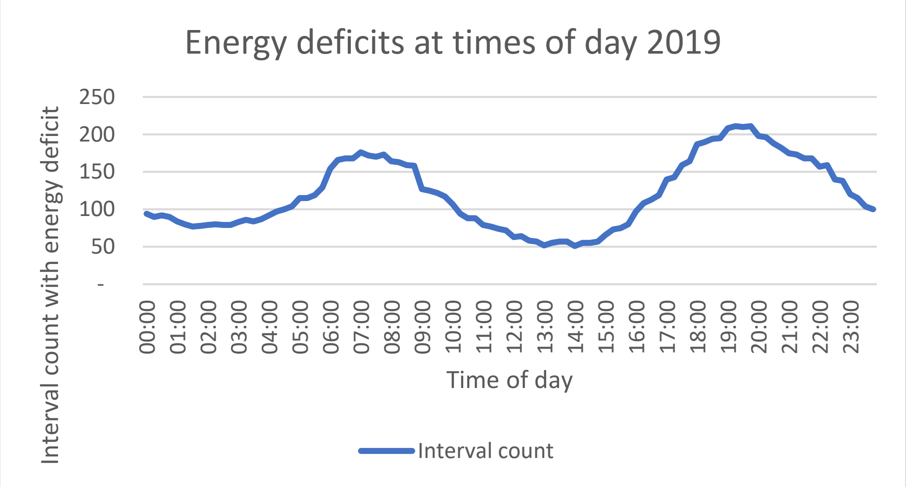
By comparing the production and consumption data, the following results became evident:

1. Over the course of 2019, the consumption outgrew the production in 11,479 15-minutes intervals. This represents 32.76 percent of all intervals.

2. While the overall surplus of production amounts to 28,674.8 GWh, the energy quantity of all negative intervals amounts to 9,980.1 GWh.
3. The average negative interval has a shortcoming of 801.1 MWh.
4. The largest deficit amounted to 3,689.75 MWh and occurred at 6:30 in the morning on the 28th of May.
5. The most and laragest negative intervals occur from 5:45 to 9:15 in the morning and from 17:00 to 22:45 in the evening with 19:45 being the most critical time.
6. On average, the electricity prices (**Figure 7**) correlate with the phenomenon of the energy deficits. The average hourly peak prices occur at 8:00 in the morning with an average price of 45.36 €/MWh and at 19:00 in the evening with an average price of 48.76 €/MWh.

**Figure 5** and **Figure 6** show the course of the accumulated number of energy deficits over a day (blue line) and the accumulated quantity of energy in MWh (orange line) in the respective time intervals over the year 2019. Looking at the shape of the plot, one can quickly notice the similarity to a standard H0 load profile of a household over a day with the significant morning and evening peaks. Clearly, a correlation to the consumption in an average household can be drawn, as it is common knowledge that household consume the most energy when people are at home and go after their daily routines of watching TV, running the dishwasher, or doing the laundry.





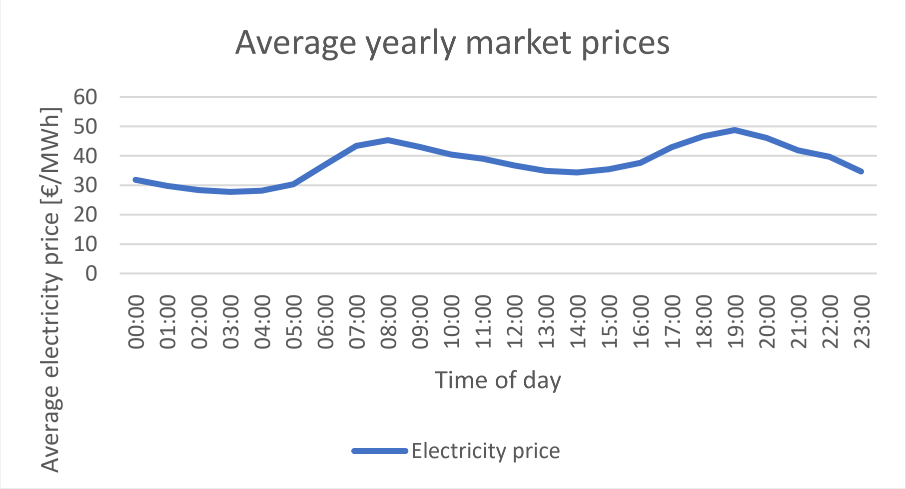


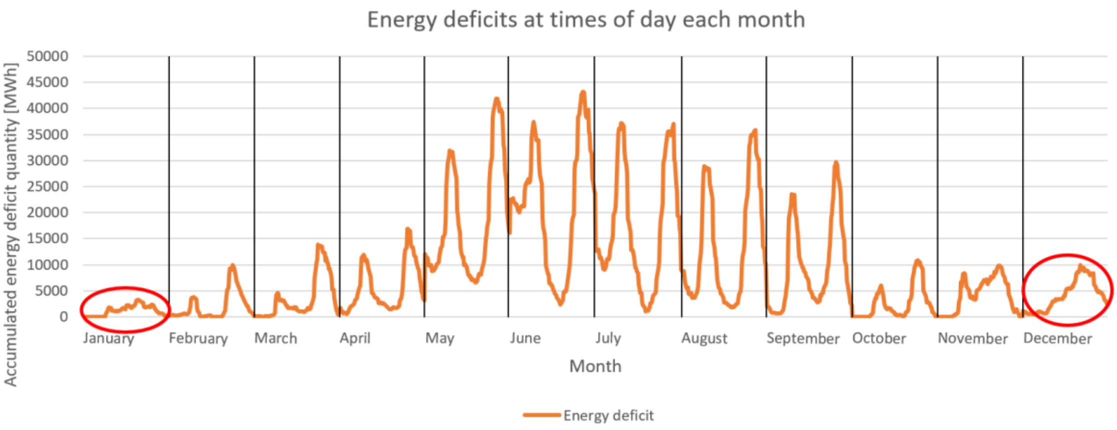
Figure 5 Accumulated deficit quantity at times of day

Figure 6 Deficit interval count at times of day

Figure 7 Average yearly market prices at the EEX Stock exchange for Germany in 2019

(SMARD, n.d.), own depiction

When wanting to transfer this analysis to a more granular level, such as months, to see how energy deficits occur over the year, the data shows that they occur mostly in summertime in the warmer season (see **Figure 8** and **Figure 9**). All months are displayed in one diagram in order to better understand the proportions and have one scale.



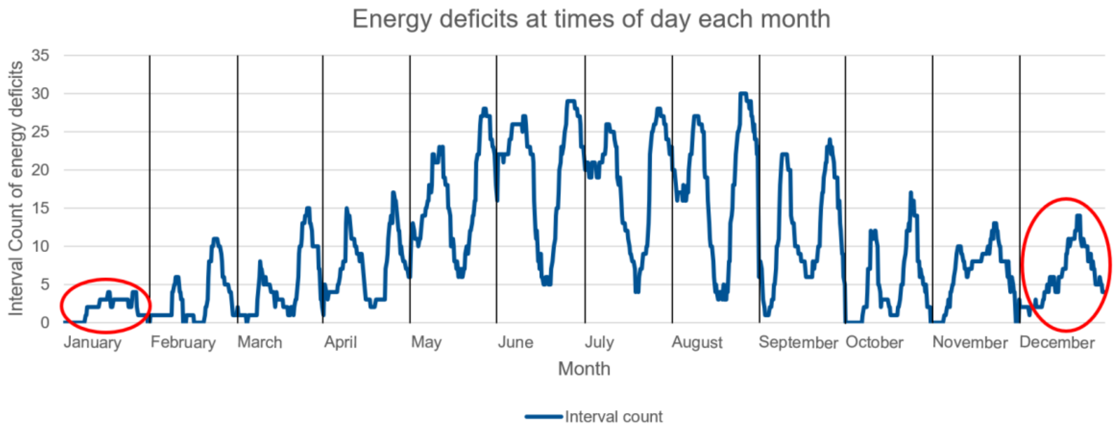


Figure 8 Accumulated deficit quantity at times of day according to each month

Figure 9 Deficit interval count at times of day according to each month

(SMARD, n.d.), own depiction

It appears that the energy deficit amount is around five to ten times higher in the summer months than in the winter months and the deficit count is also much higher during that time.

The question arises whether this phenomenon is due to less production in summer compared to winter or due to more consumption in summer compared to winter. Data shows that both is less in summer, however, electricity production shrinks more relatively. The key factor on the production side are two energy sources, namely onshore wind and hard coal. While photovoltaic naturally produces more energy in the summer months, it does not compensate the lesser production of onshore wind and hard coal during the summer months (SMARD, n.d.).

Especially graph plots of December and January are of peculiar shape. One cannot discern the typical shape of the standard load profile of a household with its two characteristic peaks in the morning and evening. The evening peak is notably earlier than in the other months, namely two hours at 16.00. The differing shape of the plots might be explained by divergent behavior of the average consumer with less days at work due to the Christmas holidays and thus no need to rise early for work. However, the modes of operation of the big industrial electrical consumers might also factor into this phenomenon. Further research would have to be conducted to properly analyze the anomaly.

The following assertions can be drawn from the data:

1. In January, 166 a total of energy deficits occurred, which is 1.4 percent of the total number. Their accumulated amount makes up for 1.1 percent of the overall energy deficit amount.

2. In February, 305 a total of energy deficits occurred, which is 2.7 percent of the total number. Their accumulated amount makes up for 2.0 percent of the overall energy deficit amount.

3. In March, 470 a total of energy deficits occurred, which is 4.1 percent of the total number. Their accumulated amount makes up for 3.4 percent of the overall energy deficit amount.

4. In April, 702 a total of energy deficits occurred, which is 6.1 percent of the total number. Their accumulated amount makes up for 5.3 percent of the overall energy deficit amount.

5. In May, 1577 a total of energy deficits occurred, which is 13.7 percent of the total number. Their accumulated amount makes up for 18.1 percent of the overall energy deficit amount.

6. In June, 1932 a total of energy deficits occurred, which is 16.8 percent of the total number. Their accumulated amount makes up for 20.8 percent of the overall energy deficit amount.

7. In July, 1784 a total of energy deficits occurred, which is 15.5 percent of the total number. Their accumulated amount makes up for 16.5 percent of the overall energy deficit amount.

8. In August, 1768 a total of energy deficits occurred, which is 15.4 percent of the total number. Their accumulated amount makes for 13.0 percent of the overall energy deficit amount.

9. In September, 1131 a total of energy deficits occurred, which is 9.9 percent of the total number. Their accumulated amount makes up for 9.4 percent of the overall energy deficit amount.

10. In October, 468 a total of energy deficits occurred, which is 4.1 percent of the total number. Their accumulated amount makes up for 2.5 percent of the overall energy deficit amount.

11. In November, 601 a total of energy deficits occurred, which is 5.1 percent of the total number. Their accumulated amount makes up for 3.9 percent of the overall energy deficit amount.

12. In December, 575 a total of energy deficits occurred, which is 5.0 percent of the total number. Their accumulated amount makes up for 4.0 percent of the overall energy deficit amount.

13. The highest average deficit occurs in May and amounts to 1146.1 MWh. The lowest average deficit occurs in October and amounts to 524.6 MWh.

The data reveals that the consecutive summer months of May to August are the ones where on average the single power gaps are the largest. This can be derived from calculating the quotient of the accumulated energy deficit and the number of power gaps according to month and time of day.

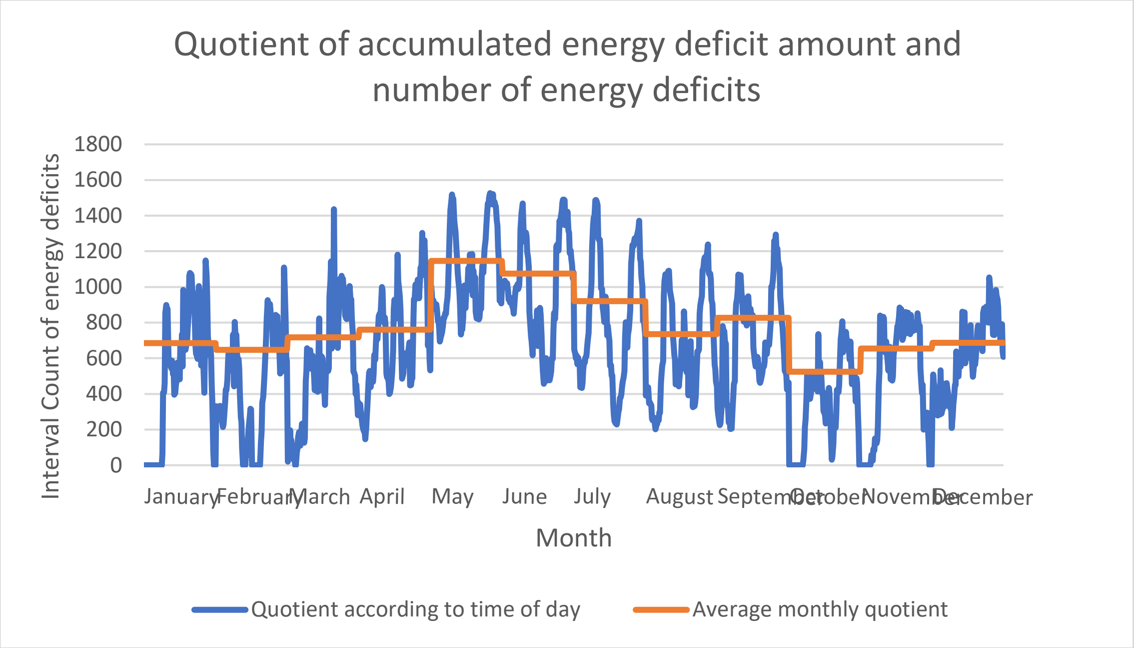


Figure 10 Deficit interval count at times of day according to each month

(SMARD, n.d.), own depiction

This implicates a bigger stress on the electricity grid in those months and higher market prices for electricity as Germany imports the missing energy from other countries. Electromobility might amplify this effect in the future if the number of BEV's rises quickly and the production side of energy does not correspondingly.

As can be seen in **Figure 5** and **Figure 6**, the most critical hours when power deficit occur are the evening hours from 17.00 to 22.00. These are also the time frames when the energy demand of eMobility will pose the most critical challenges in the future. Especially in the evening, when the average person comes home from work and plugs in their electric car to charge for the next day. The vast majority of German employees finishes their work between 16.00 and 18.00 (WirtschaftsWoche, 2016). 80 percent of all charging processes take place in the evening at home (eon, 2019). Assuming that after finishing work, the average person takes 30 minutes from the workplace to their home, they will most likely plug in their electric car and start the charging process between 16.30 and 18.30. As of now, eMobility does not have a significant effect on the power consumption since the number of BEV's and PHEV's is fairly small. But that will change in the future, likely especially increasing the amplitudes of power deficits in the already critical evening hours. That will likely lead to a higher overall deficit as well as more stress on the local grid, wherever many BEV's charge simultaneously during the times when the average household consumption is already on a peak.

## 4.4. Discussion of the Model’s Significance

As explained in section **4.1**, the chosen model is a simple approach compared to other complex simulations and is diagnostically less conclusive when it comes to very detailed propositions. However, it is able to predict a likely negative difference in power production and demand on a national level and thus energy shortcomings based the current prediction for power generation in 2030 according to the current plan rubber-stamped by the government. It can also indicate the likely times of an average day, when the difference of production and demand is the greatest. The fact that negative differences exist on a national level can be translated into existing shortcomings on a local level on an even more severe scale. The model proves, that scaling up and changing the power production is definitely needed, though, it cannot advise on how it is done in a most efficient way.

Questions that cannot be answered by the employed model are amongst others:

- How many BEV’s can be integrated into an existing power network on a local scale?
    - That most likely depends on the miscellaneous grid load by households and co-generation plants as well as the wattage with which the cars are loaded.

- When and where do capacity bottlenecks occur on a local scale?
    - More affluent people are more likely to by a BEV, thus, solvent neighborhoods are more likely to reach a high eMobility rate sooner than poorer neighborhoods. Income disparities and residential structures can only be factored in by an agent-based simulation. However, the Excel analysis suggests, that overall power deficits occur in the morning and in the evening. If one assumes that working people all charge their BEV after work, it is likely that that is when bottlenecks also occur on a regional scale.

- Quantitative statements on how to prepare local power networks for eMobility

These questions must be answered with agent-based models with probabilistic load simulations that are able to incorporate standard load profiles of households as well as those for BEV charging stations and decentralized photovoltaic installations.

# 5. Grid Expansion Plan for the Renewable Energy Development

While reading about eMobility and its future challenges, one frequently hears about the fear that the augmented electricity demand my cause large black outs in Germany. Some studies suggest that already an eMobility rate of 30 percent, which will likely be reached between 2025 and 2040 will overstress the low voltage grid in case regulatory requirements will not change and the grid infrastructure will not be improved (Oliver Wyman, 2018).

However, the electricity grid does have certain security measures in place. One of which is the *(N-1)-Criterion*. It implies that with the failing of one component, the shutdown of the system is prevented by redundancies, thus, securing grid stability. This means, in case a component like a transformer fails, the amount of electricity routed via other components is not allowed to surpass a certain threshold to prevent overloads. Therefore, components within the grid are normally loaded with half the maximum electricity to cover for a potential failing of one component and pose reserve capacities (Next Kraftwerke, n.d.). As disruptions in higher grid levels like the transmission network usually have more severe impacts, sometimes more strict safety standards are upheld like for example *(N-2)-Criterion*.

Nevertheless, the changing composition of energy sources toward renewables demands action on behalf of the grid operators, to ensure a capable electricity network. Energy needs to be transported to the major consumer centers. Wind energy mostly produced in the northern parts of Germany needs to be brought to the south. Transport bottlenecks occur also on lower grid levels like the distribution grid and must be counteracted by grid expansion measures.

## 5.1. Expansion Measures

The Federal Network Agency (*BNetzA*) describes the grid expansion as a five-step process. Firstly, a scenario framework is to be developed by the transmission grid operators incorporating future compositions of energy sources and predictions of consumer demands. On that basis, the transmission grid operators calculate the need of expansion in form of a grid development plan, which is to be approved by the *BNetzA* and to be discussed by other state entities and the people of Germany. Together with the concomitant environmental inspection of the measures, this plan makes up the binding requirement plan. The transmission grid operators then propose a corridor for the power line to be built in and finally after another examination, the exact course is determined (Bundesnetzagentur, n.d.).

### 5.1.1. Concrete Measures

The most prominent powerline that will be built is *SuedLink*, connecting the north with the south. A novum is that the big powerlines now will be highest voltage direct current transmission lines instead of alternating current (BMWi, n.d.). In addition to that it will be an underground cable, implicating a much higher cost, but also greater acceptance among the population.

The Federal Government wants to assert a twofold strategy in order to save cost with the grid expansion. They aim to expedite approval procedures for constructional measures on the one side and also implement new technologies to optimize the existing grid networks and use their capacity to a higher degree. The latter will save cost portions until the grid is fully developed (Aktionsplan Stromnetz, 2018).

### 5.1.2. Facts and Costs

As of now, the transmission grid has a length of 37,000 kilometer and the grid operators estimate that an investment of 50 billion euros will be necessary until the year 2030. The high voltage grid has a length of 94,000 kilometers, the medium voltage grid 520,000 kilometers and the the low voltage network has a length of 1.2 million kilometers, distributing the energy to the final consumers (BMWi, n.d.).

## 5.2. Technical Grid Codes Regarding BEV’s for Local House Grids

Regular households are generally connected to the low voltage grid of 230 volt. Regular sockets are secured at 16 amperes, which means the maximum load that can be withdrawn amounts to 230 V * 16 A = 3.68 kW. As many BEV’s have the ability to be charged with more than 3,7 kW, this study aims to provide a brief overview of the technical connection conditions for eMobility.

Two types of charging can be differentiated, alternating current (AC) and direct current (DC) charging. The battery of a BEV can only be charged with direct current, thus the alternating current from the power grid has to be rectified. If that process takes place within the charging infrastructure, it is called DC, if it happens within the charger in the BEV, it is called AC (EnBW, 2020).

The type of charging can also be divided in fast- and normal charging. Normal charging is considered to be every process up to 22 kW and above that the charging process is called fast charging (EU-Richtlinie 2014 / 94 / EU, 2014). AC charging ranges from 2.3 kW to 44 kW and DC charging ranges from 10 kW to 400 kW.

Even only one BEV being charged via the home grid connection can be too much wattage extraction. Thus, it might be necessary to reinforce the connection point in close agreement with the distribution net operator. In case the charging station is aimed to be greater than 12 kW, it is obligatory to include a control element, so that the distribution net operator can regulate the power inflow in times of energy scarcity or excessive load peaks (Der Technische Leitfaden - Ladeinfrastruktur Elektromobilität, 2020).

# 6. Solution Approaches

The study has shown that shortcomings in the energy production are to be expected with the current projections. This result can be backed by a study of Oliver Wyman, according to which extensive blackouts are likely to happen at a BEV share of 30 percent of the German carpool (Oliver Wyman, 2018). This would be around 15 million BEV's. In order to prevent that and to prevent a dependency on expensive power imports from neighboring countries, several measures need to be undertaken and considered. Namely, there are two different problems: an overall power deficit as the demand will likely exceed the electricity production in 2030 and local and time dependent load peaks due to concurrent demand especially in the evening times. The latter will especially be amplified by eMobility once it reaches a high market penetration. The following solution approaches address both of the problems above.

1. **Increase energy production**
   1. *Amount of production*

      The overall energy production needs to be increased by 2030, the study has shown that even without BEV's, we are very likely to consume more energy than will be produced with the currently planned installed capacity of energy sources. Especially the renewables need to be expanded in order to fulfill Germany's commitment to reduce 95 percent $CO_2$ by 2050.
   2. *Decentralization of production*

      By investing in decentral power plants, the costs for the grid expansion could be drastically reduced. Smaller PV projects on individual houses especially in connection with energy storages will flexibilize the availability of decentral produced electricity. There are already initiatives by individual states that PV is mandatory on roofs of new construction. Hamburg for example has implemented an obligation for PV on new buildings from 2023 (PV Magazine, 2021)

2. **Invest in grid expansion**

   After making sure that enough energy is produced in Germany to satisfy the demand, it is necessary to distribute it throughout the country to avoid regional and local bottlenecks. Wherever a high density of EV's will be apparent, the grid will be especially stressed in the evening hours due to the inherent temporal use of charging stations of EV's in private homes.

### 3. Decrease dependency on cars

Avoiding traffic is favorable over electrifying as many cars as possible in Germany. Kilometers not driven are the most sustainable kilometers. Advancing and expanding sharing concepts with eMobility will help on this task as well as making public transport more attractive by for example pricing mechanisms.

### 4. Interruptible electrical consumer units (IECU)

Interruptible electrical consumer units are electric meters, in this case integrated in eMobility charging infrastructure, whose power supply can be directed by the distribution network operator. That means that when an EV is connected to the wall box at home, the grid operator is allowed to cut the electricity supply for a certain time each day and thus ensure grid stability. According to the *Energiewirtschaftsgesetz §14a (EnWG)*, an IECU must include (Energiewirtschaftsgesetz, 2005)

- A grid usage contract between distribution net operator and energy supplier or end-consumer
- The technical capability to curtail or to completely interrupt the power supply during defined time windows
- An electrical meter separate from the house meter.

The time windows where the power supply can be regulated vary in length day frequency per day with the distribution net operator. In the case of *bayernwerk*, a distribution net operator in the state of Bavaria, the times are from 16.30 to 20.30 (bayernwerk, 2020) and thus lie within the hours of regular maximum power demands in households.

For the purpose of intelligent flexibilization of charging processes, the distribution network operator is allowed cut off the power supply to BEV charging stations in times when energy is scarce and needed more in other locations. If 50 percent of BEV owners would commit to this practice an eMobility share of 50 percent of all cars could be integrated into the low voltage grid (Oliver Wyman, 2018). The cost for flexibility lies well below those of a large grid expansion.

The thought of having to wait until the car charges naturally does not please the car owners, however, incentives by benefiting electricity tariffs for charging stations could help spread acceptance of IECU’s as well as implementing a “manual override” of the power cut for a fixed fee.

It is already common practice to incentivize private BEV owners for committing to this practice by favorable electricity tariffs. More specifically, the grid fee, paid for every kWh is reduced. It makes sense because the grid fee is to compensate the grid operators for their cost of grid expansion. When less load peaks occur due to controllable charging processes, the cost is reduced and thus this benefit is passed on to the customer who helped achieve it.

Example:
In 2021 the German distribution net operator *Bayernwerk* charges 6.19 ct/kWh grid fee in regular tariffs. For interruptible electrical consumer units this fee amounts to a gross value of only 3.00 ct/kWh (bayernwerk, 2020). With 15,000 kilometers per year and 15 kWh/100 km, this would result in a saving of slightly over 70 Euros a year.

## 5. Bidirectional Charging

There are two possibilities of bidirectional charging: *Vehicle to Grid* (V2G) and *Vehicle to Home* (V2H). For the first one, the car serves as an energy storage for control energy. The distribution network operator can unload and retrieve energy whenever the BEV is connected to the charging station or load the car when there is too much energy in the grid. The more cars are connected to a so-called swarm storage, the better the fluctuations due to wind and solar energy can be balanced out. The owner of the car will be compensated for delivering the control energy. The latter concept takes place on a very local scale and will be more interesting in the future, when cars are charged by solar energy from the own roof and time variable electricity tariffs will become reality.

As of now, bidirectional charging is still in a very preliminary stage and only tested in specific research projects. Only few models like the Nissan Leaf, some Mitsubishi models, the C-Zero Citröen and Peugot iOn (both based on Mitsubishi technology) and the Sion from the Munich start up Sono Motors have the ability to do bidirectional charging (SmarterFahren, 2020). Apparently, the Tesla models are also equipped with the technology already (Elektroauto-News, 2020).

## 6. Driving range amelioration

The driving range of many medium-cost BEV’s lies within 150 to 250 kilometers. Logically, these cars have to be charged frequently and the distance might only be sufficient for 3-4 days, covering the way to work and the everyday trips like grocery shopping. Frequent charging processes result in frequent load peaks in the power grid. The better the driving range of the average BEV, the better the charging processes would be distributed over time and concurrency could be minimized.

## 7. Industrial energy storages

According to the *Federal Network Agency (Bundesnetzagentur),* energy storages can play a role in flattening load curves in the grid, though their potential is widely overestimated. Large industrial energy storages are occasionally operated by subsidiary firms of distribution net operators. By law, this practice is currently not viewed as fully legal, however, it mostly stays without consequences (Bundesnetzagentur, 2020). At this point a financially worthwhile operating is difficult but could become more viable when larger shares of the production are covered by volatile energy sources. Industrial firms with many short but high load peaks may see a business case in large energy storages by covering those peaks with energy from the storage and thus omitting grid fees. A substantial part of the energy cost for large customers is calculated based solely on single highest load peak of the year.

# 7. Conclusion

In consideration of the ongoing climate change and fossil fuels reserves tightening, new mobility concepts will soon be inevitable and eMobility will be a vital part of this development. The federal German government has asserted its influence on the eMobility market to make BEV's more attractive to the customer and the rising numbers of new BEV registrations show that there will soon be many electric vehicles on German streets. Perhaps the governments prognosis of seven to ten million in 2030 will even come true. Alongside this development come several challenges, one of them being to integrate eMobility in the German power grid and to satisfy the augmented demand of electricity.

The different analyses have shown two problems that exist already on their own but will be amplified by a large share of eMobility:

1. With the current plan for expanding the energy production and installed capacities for each energy source in 2030, the power production will likely be exceeded by the power demand. The analysis took very conservative values for the demand prognosis and came up with this result, making the likelihood of this problem becoming reality very high.

2. Bottleneck situations in the energy supply are very likely to happen on a local and temporal scale. The analysis showed that the gravest power deficits correspond with the H0 household load profile and occur in the evening when the demand is highest between 17.00 and 22.00. eMobility will likely amplify these bottlenecks due to the temporal charging behavior of people.

Having more than ten million BEV's in Germany will most definitely lead to a surpass of the consumption of energy over the production, amplifying problem one and two. Due to likely charging behavior, eMobility will especially create demand in the already critical hours in the evening. There are several solution approaches as discussed in the previous chapter.

Regarding the eMobility development, while it is welcomed to have an increasing number of BEV's in Germany from a sustainability point of view, traffic avoidance is still to be prioritized over having all cars electrified and maintaining the average annual mileage. Changing transportation and mobility habits towards less usage of cars saves energy and alleviates the power grid, thus saving money for the grid expansion. Furthermore, it reduces carbon dioxide emissions and traffic congestions especially in urban environments.

While it is undoubtedly true that the government plan of expanding energy production needs to be adapted to a higher production, one question will be whether it is more viable to invest in a simple grid expansion or focus on grid flexibilization. As mentioned before, peak loads can be shifted by a more decentralized manner of energy production, reducing the stress on the grid.

There is no point in compensating coal power plants for going off the grid in the 2030ies, using the money to invest in PV and wind energy and let the market do the rest to make coal power plants unattractive from an economic point of view would be much more efficient and cheaper.

Furthermore, the BEV fleet could be used more efficiently to serve as small, decentralized energy storages. This would enable owners to earn at least a small amount of money by providing control energy and aid the power grid stabilization.

As it is obvious, that not only the timing of the energy supply must be managed in a smart and flexible way, but the general amount of energy produced over a year needs to be increased, Germany must increase its goals in installing more renewable energy plants to cover the increased demand. The current goals in the NEP are not ambitious enough to cover the augmenting eMobility in the country.

# References

*ADAC*. (n.d.). Retrieved December 04, 2020, from https://www.adac.de/rund-ums-fahrzeug/tests/elektromobilitaet/e-roller/details/4103/niu-n1-s/

(2018). *Aktionsplan Stromnetz.*

bayernwerk. (2020). *bayernwerk.* Retrieved January 12, 2021, from https://www.bayernwerk-netz.de/content/dam/revu-global/bayernwerk-netz/files/netz/netzzugang/netzentgeltestrom/20201006-bayernwerk-preisblaetter-strom-2021gesamt.pdf

*BMWi*. (n.d.). Retrieved October 20, 2020, from https://www.bmwi.de/Redaktion/DE/Dossier/netze-und-netzausbau.html

*BMWi*. (n.d.). Retrieved October 17, 2020, from https://www.bmwi.de/Redaktion/DE/Dossier/elektromobilitaet.html

*Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit*. (n.d.). Retrieved November 10, 2020, from BMU: https://www.bmu.de/media/atomkraftwerke-in-deutschland-abschaltung-der-noch-betriebenen-reaktoren-gemaess-atomgesetz-atg/

*Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit*. (2020). Retrieved November 12, 2020, from https://www.bmu.de/themen/luft-laerm-verkehr/verkehr/elektromobilitaet/foerderung/

*Bundesministerium für Verkehr und digitale Infrastruktur*. (n.d.). Retrieved December 27, 2020, from https://www.bmvi.de/SharedDocs/DE/Artikel/G/foerderrichtlinie-ladeinfrastruktur-elektrofahrzeuge.html

*Bundesministerium für Verkehr und digitale Infrastruktur*. (2020). Retrieved December 15, 2020, from https://www.bmvi.de/SharedDocs/DE/Pressemitteilungen/2020/065-scheuer-startschuss-fuer-wallbox-foerderung.html

*Bundesministerium für Wirtschaft und Energie*. (n.d.). Retrieved October 13, 2020, from BMWi: https://www.bmwi.de/Redaktion/DE/Artikel/Industrie/klimaschutz-klimaschutzplan-2050.html

*Bundesnetzagentur*. (n.d.). Retrieved January 10, 2021, from https://www.netzausbau.de/5schritte/de.html;jsessionid=E5A4432CE03D50770A293A3A3F2FA6FD

*Bundesnetzagentur*. (2020). Retrieved December 02, 2020, from https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/HandelundVertrieb/Ladesaeulenkarte/Ladesaeulenkarte_node.html

Bundesnetzagentur. (2020, November 5). Ladesäulenkarte.

Bundesnetzagentur. (2020). *Regelungen zu Stromspeichern im deutschen Strommarkt.*

*Climate.gov*. (2020, August 14). Retrieved October 10, 2020, from National Oceanic and Atmospheric Administration: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

*co2online*. (2020). Retrieved November 18, 2020, from https://www.co2online.de/foerdermittel/liste/elektroroller/

(2018). *dena-Leitstudie Integrierte Energiewende.* Deutsche Energie-Agentur GmbH (dena). Retrieved from https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

*Der Technische Leitfaden - Ladeinfrastruktur Elektromobilität.* (2020). VDE.

*Die Bundesregierung*. (n.d.). Retrieved December 27, 2020, from https://www.bundesregierung.de/breg-de/themen/energiewende/kaufpraemie-fuer-elektroautos-erhoeht-369482

*E.ON*. (2020). Retrieved November 21, 2020, from https://www.eon.de/frag-eon/themen/e-mobility/fragen-und-antworten/der-stromverbrauch-bei-elektroautos-wieviel-verbraucht-ein-e/

*EFahrer.com*. (2020, 03 09). Retrieved October 15, 2020, from https://efahrer.chip.de/news/die-10-fuehrenden-elektroauto-nationen-deutschland-deutlich-abgeschlagen_102051

Egbue, O., & Long, s. (2012, June 27). Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. *Energy Policy*, pp. 717-729.

Einkommensteuergesetz § 6. (n.d.). Deutschland: Bundesministerium der Justiz und Verbraucherschutz.

*Elektroauto-News*. (2020, May 21). Retrieved January 12, 2021, from https://www.elektroauto-news.net/2020/tesla-oeffnet-sich-bidirektionalem-laden-hardware-verbaut

*emmy-sharing.de*. (n.d.). Retrieved December 10, 2020, from https://emmy-sharing.de/preise/

*EnBW*. (2020, November 9). Retrieved December 03, 2020, from https://www.enbw.com/blog/elektromobilitaet/trends/elektrisch-in-die-zukunft-verkaufszahlen-der-elektroautos/

*EnBW*. (2020, Januar 3). Retrieved January 21, 2021, from https://www.enbw.com/blog/elektromobilitaet/laden/grundwissen-was-ist-der-unterschied-zwischen-ac-und-dc-laden/

*Energiewirtschaftliches Institut an der Universität Köln*. (2020, January 6). Retrieved November 15, 2020, from https://www.ewi.uni-koeln.de/de/news/ee-ziel-2030/

Energiewirtschaftsgesetz. (2005). *§ 14Aufgaben der Betreiber von Elektrizitätsverteilernetzen*.

*eon*. (2019). Retrieved January 15, 2021, from https://www.eon.de/de/eonerleben/laden-von-elektroautos.html

EU-Richtlinie 2014 / 94 / EU. (2014, October 10). *Aufbau der Infrastruktur für alternative Kraftstoffe*. Retrieved from https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32014L0094&from=DE

*EVgo.de*. (n.d.). Retrieved November 01, 2020, from https://www.evgo.com/why-evs/types-of-electric-vehicles/

*ewi*. (2020). Retrieved December 16, 2020, from https://www.ewi.uni-koeln.de/en/news/ewi-merit-order-tool-2020-weniger-kohle-mehr-gas-im-einsatz/

*ewi*. (2020, January 06). Retrieved December 16, 2020, from https://www.ewi.uni-koeln.de/de/news/ee-ziel-2030/

*Forschungstelle für Energiewirtschaft e.V.* (2020). Retrieved November 28, 2020, from https://www.ffe.de/themen-und-methoden/modelle-und-tools/641-das-ffe-netz-simulationsmodell-gridsim

*Fraunhofer ISI.* (2020, September). Retrieved December 10, 2020, from https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2020/PHEV_ICCT_FraunhoferISI_Policy_Brief_DE.pdf

*Handelsblatt*. (2021, January 12). Retrieved January 20, 2021, from https://www.handelsblatt.com/unternehmen/industrie/autoindustrie-elektro-porsche-taycan-knackt-im-corona-jahr-die-20-000er-marke/26788390.html?ticket=ST-7656112-bCDxjeqZP2euoyAv75Gs-ap5

*Heise*. (2020, December 20). Retrieved December 27, 2020, from https://www.heise.de/newsticker/meldung/Kosten-fuer-E-Auto-Akkus-100-Dollar-pro-Kilowattstunde-in-Reichweite-4620218.html

*Kraftfahrt-Bundesamt*. (2020). Retrieved October 15, 2020, from https://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/Jahresbilanz/fz_b_jahresbilanz_archiv/2020/2020_b_barometer.html?nn=2601598

*Kraftfahrt-Bundesamt.* (2020, Juni). Retrieved October 30, 2020, from https://www.kba.de/SharedDocs/Pressemitteilungen/DE/2020/pm_06_19_bestand_01_20_pdf.pdf;jsessionid=8D8C37701E5DEE8D0070BC1A61BC1D5E.live21304?__blob=publicationFile&v=3

*Next Kraftwerke*. (n.d.). Retrieved December 20, 2020, from https://www.next-kraftwerke.de/wissen/n-1-kriterium

Oliver Wyman. (2018). *Blackout - E-Mobilität setzt Netzbetreiber unter Druck.*

*PV Magazine*. (2021, January 5). Retrieved January 29, 2021, from https://www.pv-magazine.de/2021/01/05/hamburg-beschliesst-photovoltaik-pflicht-ab-2023/

Sameera, A., Theodoropoulos, G. K., Lemarinier, P., & O'Hare, G. M. (2016, July 24). Agent Based Modelling and Simulation tools: A review of the state-of-the-art software. *Computer Science Review*.

Sickel, F. (2020, July 3). *acxiom.* Retrieved December 20, 2020, from https://www.acxiom.de/elektroautofahrer-in-deutschland-eine-sehr-exklusive-zielgruppe/

*SMARD*. (n.d.). Retrieved October 13, 2020, from https://www.smard.de/home

*SmarterFahren*. (2020). Retrieved January 12, 2021, from https://www.smarter-fahren.de/bidirektional-laden/

*Statista*. (2020, December 09). Retrieved from https://de.statista.com/statistik/daten/studie/12131/umfrage/pkw-bestand-in-deutschland/

*Statista*. (2020, 09 29). Retrieved October 15, 2020, from https://de.statista.com/statistik/daten/studie/265995/umfrage/anzahl-der-elektroautos-in-deutschland/

*Statista*. (2020, November 2). Retrieved November 29, 2020, from https://de.statista.com/statistik/daten/studie/484054/umfrage/durchschnittsverbrauch-pkw-in-privaten-haushalten-in-deutschland/

*Statista*. (2020, November 11). Retrieved November 29, 2020, from https://de.statista.com/statistik/daten/studie/776/umfrage/durchschnittspreis-fuer-superbenzin-seit-dem-jahr-1972/

*Statista*. (2020, November 25). Retrieved November 29, 2020, from https://de.statista.com/statistik/daten/studie/154908/umfrage/strompreise-fuer-haushaltskunden-seit-2006/

*Statista*. (2020, March 23). Retrieved November 23, 2020, from https://de.statista.com/statistik/daten/studie/246069/umfrage/laufleistung-privater-pkw-in-deutschland/

*Stromliste*. (2019). Retrieved December 04, 2020, from https://stromliste.at/nuetzliche-infos/e-bike-pedelec-strom

*Süddeutsche Zeitung*. (2020, November 21). Retrieved December 12, 2020, from https://www.sueddeutsche.de/wirtschaft/hybridmotoren-elektroantrieb-oezdemir-1.5122460

*Tagesspiegel*. (2019, December 28). Retrieved October 12, 2020, from https://www.tagesspiegel.de/berlin/flut-der-e-scooter-verkehrssenatorin-fordert-parkplaetze-fuer-e-roller/25371564.html

*The Mobility House.* (2020). Retrieved December 20, 2020, from https://www.mobilityhouse.com/de_de/ratgeber/ladezeitenuebersicht-fuer-elektroautos

*Umweltbundesamt*. (2020, November 12). Retrieved December 14, 2020, from https://www.umweltbundesamt.de/daten/energie/erneuerbare-konventionelle-stromerzeugung#bruttostromerzeugung-nach-energietragern-

*Verivox*. (2020). Retrieved December 04, 2020, from https://www.verivox.de/elektromobilitaet/themen/e-scooter-stromverbrauch/

*WirtschaftsWoche*. (2016, April 08). Retrieved January 15, 2021, from https://www.wiwo.de/erfolg/beruf/arbeitszeit-freitags-machen-alle-frueher-feierabend-oder/13420774.html

# Declaration

I hereby confirm that the presented thesis work has been done independently and using only the sources and resources as are listed. This thesis has not previously been submitted elsewhere for purposes of assessment.

Munich, 08.02.2021

Place, Date, Signature