Utrecht University

Electric vehicle adoption and its impact on 2035 German power demand

Master thesis

Tom Groeneweg
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Student number:
4168372
Supervisors:
Dr. W. van Sark - Utrecht University
Dr. I. Ellersdorfer - Uniper Global Commodities

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Abstract

Stringent emission regulation and consumer driven eco-friendly demand encourage automotive manufactures to reduce the Green House Gas-emissions of passenger vehicles. The introduction of battery electric vehicles reduce the average Green House Gas-emissions as they lack tail-pipe emissions, and as such have been deemed required to meet 2050 emission targets. This thesis forecasts electric vehicle adoption in Germany by 2035 and assesses the electric vehicle related power demand through the evaluation of three different power demand scenarios, i.e. charging scenarios, as this might cause transmission grid congestions.

By developing an electric vehicle adoption model, based on a general market diffusion of an ‘S-curve’ pattern, political targets, historical electric vehicle stock and total cost of ownership developments have led to a projection of 10,5 Million additional electric vehicles in Germany by 2035. The underlying assumptions are that total cost of ownership parity with internal combustion engine vehicles will be achieved between 2025 and 2030. Long-term political targets form the main driver for electric vehicle deployment up to total cost of ownership parity, and historical electric vehicle adoption are important for future developments.

The German electric vehicle stock is estimated to have an annual energy demand of roughly 26 TWh in 2035. This result is based on the average German mileage for passenger vehicles, specific energy consumption per kilometre and the projected electric vehicle stock.

The first power demand scenario is the ‘domestic charging’ scenario. The domestic charging scenario has an estimated 31 GW of power demand, resulting from a maximum power output of 3.7 kW per connection and a domestic charger per electric vehicle ratio of 0.8. The second scenario is the ‘public charging’ scenario, which had an estimated power demand of 41 GW. This resulted from the June 2016 German ‘Charging-mix’ containing an average maximum power output of 26 kW per connection and a public connection per electric vehicle ratio of 0.15. The third and last scenario is the ‘fast-charging’ scenario, resulting in a power demand of 37 GW based on the 2035 German electric vehicle stock forecast. For the ‘fast-charging’ scenario the average maximum power output was assumed to be 50 kW per connection with a connection to electric vehicle ratio of 0.07.

The presented results are based on worst case scenarios, whereby the likeliness of occurrence is aligned with the order of discussed scenarios. Starting with domestic charging, this is the most likely scenario to occur.

Further research is advised on the topic of public charger deployment and it is advised to update the electric vehicle model in the coming years.

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Definitions

Battery cell

The battery cell is comprised of all physical components which contribute to storing and (dis)charging electrical energy, this excludes software and electrical circuity to optimize charging, discharging and safety.

Battery pack

A battery pack consists of the arrangement of battery cells plus cooling system, hardware, software and an external protective casing make up a battery pack. The battery pack ensures a sufficient combined voltage and current level from the individual battery cells. A battery pack also ensures battery cycle life and by restricting sub-optimal utilization of the batteries (temperature, power in-/output, etc.)

Cycle life

The cycle life describes the amount of degradation a battery suffers from discharging and charging, cycle life describes the amount of full discharges (and chargers) a battery can take before a certain level of degradation of the battery cell is witnessed.

Energy capacity

The energy contained in the battery that is utilized for operation the electric vehicle, expressed in kilowatt-hours.

Energy demand

The energy demand relates to the energy content which is required for driving an EV for a certain range (i.e. energy contained within the battery) or the yearly consumption of energy (joule). The energy demand is expressed in (Tera/Giga/Mega/kilo-)Watt-hours, and can also expressed in (Tera/Giga/Mega/kilo-)Joule with the appropriate conversion factor (1 kWh = 3.6 MJ .

Electric Vehicle

The term Electric Vehicle (EV) translates to all highway legal passenger vehicles that contain an electric drivetrain, which can be powered by electricity obtained from charging the car by means of an electrical plug. Unless explicitly stated, the term EV is used for Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Range Extender Electric Vehicles (REEVs). The term EV excludes (mild) hybrid vehicles without an electrical plug.

Highway legal vehicles

The (electric) vehicles considered for this research are highway legal, this means that the vehicle is road legal by the standards of the respective national authorities and the vehicle can reach a speed of up to a minimum of 100km/h.

Light duty vehicle

The light duty vehicle relates to vehicles which are not intended for freight transport. The light duty vehicle is mainly a passenger transport vehicle used in the private sector.

Power demand

The power demand relates to the instantaneous energy transfer or consumption (joule per second), it can be used to divine how powerful a vehicle engine is, or how much energy can be transferred per second from or to the battery. The power demand is expressed in (Tera/Giga/Mega/kilo-)Watt.

Power in-/output

The amount of power that is supplied to or extracted from the electric vehicle in any given time, expressed in (Tera/Giga/Mega/kilo-)Watts.

Abbreviations

AC	Alternating Current
BEV	Battery Electric Vehicle
DC	Direct Current
DE	Germany
EV	Electric Vehicle
EVSE	Electric Vehicle Service Equipment
GHG	Green House Gas (emissions)
ICE	Internal Combustion Engine
LCO	Lithium Cobalt Oxide
LFP	Lithium iron Phosphate
Li-ion	Lithium-ion
LMO	Lithium Manganese Oxide spinel
NCA	lithium Nickel Cobalt Aluminium oxide
NMC	lithium Nickel Cobalt Manganese
NL	Netherlands
NO	Norway
PHEV	Plug-in Hybrid Electric Vehicle
REEV	Range-Extended Electric Vehicle
TCO	Total Cost of Ownership
SEC	Specific Energy Consumption
SoC	State of Charge
US	United States (of America)
YoY	Year on Year

1. Introduction

Stringent emission regulation and consumer driven eco-friendly demand encourage automotive manufactures to increasingly reduce the GHG-emissions (Green House Gas) of the passenger vehicle fleet. Even with the current estimations of yearly European ICE (Internal Combustion Engine) GHG-emissions reductions at 2.6%, around 8% (or 20 Million) of passenger vehicles will need to be electrified by 2021 to meet EU GHG-emissions targets for the transport sector (Eurostat, 2015a, 2016; ICCT, 2015; UBS, 2014b). For IEA's '*2DS scenario*[1]' around 75% (or 190 Million) of the EU passenger vehicles stock should be electrified by 2050 (IEA, 2013).

Introduction of the BEVs (Battery Electric Vehicles) could reduce the average GHG-emissions of the vehicle fleet. BEVs produce no tail-pipe GHG-emissions, in the contrary to ICE vehicles which were only incrementally improved to reduce GHG-emissions in order to meet regulation (ICCT, 2015). However, the BEV battery technology is still under development, it has significant potential for cost reductions and specific energy content (Bloomberg New Energy Finance, 2015c, 2015d; Matthey, 2014; UBS, 2014a, 2014b). To overcome early day BEV limitations, especially related to limited driving range per charge, the PHEV (Plug-in Hybrid Electric Vehicle) was developed. The PHEV serves as a compromise between the tail-pipe emission free BEVs limited in range and GHG-emitting ICEs with increased range.

At the global scale the EV passenger fleet, presented by BEVs and PHEVs, has risen from a several thousand in 2008 up to 1.3Million by the end of 2015[2]. Following the historical trend up to June 2016, the global EV fleet is expected to increase to a total of 2Million before the end of 2016. The historical trend represents a significant growth in the early EV adoption years where; The BEV and PHEV markets are still limited to a dozen of models (EVObsession.com, 2016), battery technologies for application in EVs are still in its infancy (Matthey, 2014) and EV TCO (Total Cost of Ownership) before incentives is not yet compatible for the majority of the mass-market car segments (UBS, 2014b).

North American, Chinese and European authorities support EV adoption by providing incentives to enforce competitiveness of EVs versus the conventional ICEs. In order to promote EV adoption, a variety of interventions has been witnessed, ranging from up-front tax-rebates for EV purchase (US), road-tax exemptions during vehicle ownership(DE) to the free use of public amenities such as parking and permittance to drive on bus lanes(NO).

The increase in EV stock brings along an increase in energy and power demand, as these vehicles are refuelled (i.e. charged) through an electrical plug. Every kilometre driven requires an average of 0.15 to 0.25kWh of electricity and every additional EV kilometre driven contributes to an increase of total energy demand. Thousands of EVs being charged at the same time induce an elevated power demand that can create congestions on distribution grids. This is especially the case for 'fast charging', associated with up to 120kW of power demand per single charge connection, a multitude of average house-hold power demand.

Presently EV market penetration is still relatively low with annual sales remaining under 1% of the global vehicle market (IEA, 2015, 2016). However, EVs are expected to have a lower unsubsidised TCO than ICEs between 2020 and 2030 (Bloomberg New Energy Finance, 2016; UBS, 2014a, 2014b). Even before TCO parity is achieved, consumers are already adopting the EVs. This is partly due to the institutional incentives to compensate for TCO losses, provided the institutions remain in favour if EV

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[1] The '*2DS scenario*' describes a scenario wherein GHG-emissions are limited to prevent average global temperature increases exceeding 2°C (IEA, 2013).

[2] *See chapter 2.2.2 Global EV stock history*.

adoption. Currently, the intuitional incentives are provided to boost EV adoption in order to achieve CO_2 emissions targets within the transport sector (IEA, 2013; UBS, 2014b). Overall, EVs are expected to be a major player in future vehicle markets, and with the adoption of EVs comes the power demand required to fuel these vehicles.

This master thesis report will provide an overview of the recent developments in electric vehicle technologies and aims to assess the impact of electric vehicle related power demand for Germany up to 2035. On the back of historical trends, global EV outlooks and German political targets and support schemes, a baseline EV adoption scenario will be created. This scenario will serve as a foundation to derive the German EV related energy and power demand. The EV related energy demand will then be investigated and translated into several EV power demand scenarios (i.e. charging scenarios), with each of these ‘charging-mix’ scenarios having a different impact on the power load demand. This master thesis will serve as an introduction to the topics of EV market penetration, EV technologies and developments, EV energy and power demand and will provide the host-organisation of Uniper Global Commodities with valuable insights for future decision making regarding the German energy markets. The research question answered in this thesis is as follows:

“*How will the increased stock of Electric Vehicles affect the German power demand up until 2035?”*

Within this research question, at least two (in)dependable variables can be identified;

- *“Stock of electric vehicles”*

The EV market penetration will be forecasted using a self-developed EV adoption model which maps the trend derived from the history of EV stock in cooperating global EV outlooks and German national targets (and support schemes). Moreover, the main technological drivers supporting EV competitiveness will be investigated to provide more in-depth picture. This in-depth knowledge should sever as an indicator of future EV adoption, as the automotive market is a global market with only a few large players (mainly large incumbent automotive companies) technological developments are researched on a global level.

- *“The German power demand”*

The German power demand is a dependant variable, which is affected by many factors. However, this thesis will only focus on the incremental power demand caused by the increase in EV stock. Based on charging standards, average distance travelled and other indicators a certain power demand can be calculated.

By translating the expected electric vehicle stock to energy and related power demand, three future power demand scenarios will be evaluated for the impacts on the 2035 German power demand. The results will contribute to the understanding of EV related power demand and could be utilized as a part of a broader energy outlook up to 2035. Additional EV power demand studies can be conducted based on these results.

The thesis will be structured as follows, it will start by addressing the current operational EV environment, ranging from available literature, political targets and support schemes to EV technologies, along with present-day German energy and power demand. The following part will analyse EV market penetration and the developed EV adoption forecasting model will be discussed. The underlying assumptions behind EV market penetration are discussed as input parameters and constraints. After which the theory behind EV energy and power demand is discussed. Lastly the reference German EV stock scenario with the three developed power demand (i.e. charging) scenarios, related to forecasted EV stock, will be discussed followed by the conclusion and discussion.

2. Theory

2.1. Literature review E-mobility

The theoretical background that formed the basis for this master thesis is divided into three parts.

Firstly, there are several studies that examine the expected EV market penetration from the perspective of TCO and cost reduction for technical developments (Bloomberg New Energy Finance, 2015c, 2015d, 2015e; McKinsey, 2014; UBS, 2014a, 2014b). These studies consider the share of EVs sold compared to the total share of passenger vehicles sold. However, they do not project EV stock. The reason might lie in the difficulties associated with the estimation of ICE vehicle replacement and/or EV lifetime. The problematic of the EV stock estimation is twofold: firstly, this topic is poorly covered in the literature and secondly, few recent researches that bring up estimations of stock numbers come to controversial results. These results will be examined and demonstrated in this thesis (Fraunhofer Institute, 2013).

Nonetheless, electric driving and related topics have been part of scientific research for many years now, not only due to the (renewed) interest related to sustainable energy generation and transportation emission reductions, but also because the concept of electric vehicles dates back to the early nineteenth century (PBS, 2009; Trigg et al., 2013). The technology for electric engines is quite mature (Ronanki, Hemasundar, & Parthiban, 2013), however the same does not hold for the battery providing the electric power to the engine.

The applied battery technologies in EVs represent the challenge for adoption of EVs and constitute the main reason for existing TCO gap between ICEs and EVs. Therefore, the batteries obtain a lot of the focus of EV TCO. The battery chemistries used in the current EVs are based on the lithium-ion chemistry. The lithium-ion chemistry for applications in EV is derived from Lithium Cobalt Oxide (LCO) chemistries used in many portable consumer electronics. However, battery requirements for EVs are far more demanding than those for consumer products. Lithium-ion batteries for application in EVs is just in its infancy as different chemistries are still to be improved and several chemistries are yet to be commercialized (Bloomberg New Energy Finance, 2015c). There are several sources dedicated to researching of the technological battery developments, battery price developments and novel battery chemistries. (Battery University, 2016b 2016c, Bloomberg New Energy Finance, 2015b, 2015c, 2015d; El Deed et al., 2014; IEA, 2016; Matthey, 2014; UBS, 2014; Young, Wang, Wang, & Strunz, 2013).

Secondly, there are several studies that focus either on psychological barriers such as perceived range anxiety, or on the analysis of operations costs such as comfort of charging - as another obstacle for adoption of EVs. (Dudenhöffer, Arora, Diverrez, Jochem, & Tücking, 2014; Fraunhofer Institute, 2013; IEA, 2013). However, what all these studies have in common is the acknowledgement for EV incentives, which is required to boost initial EV sales. To a great extent these studies are conducted on a continental or global level, rather than on a nation level with few exceptions. This is not out of the ordinary because technological developments for vehicles are usually carried out at a continental or global level: e.g. international exports make technological developments a 'liquid' product. Besides, in order to successfully position themselves at a new market automakers analyse carefully available vehicles in that market. For example, if the offered vehicle only has half the electrical driving range while being sold in the same price range, the decision for the majority of consumers would be heavily biased towards the larger range vehicle.

Lastly, there are several studies which address EV charging related power demand. These studies examine currently existing charging methods and the related power demand. They evaluate the charging patterns for different vehicle to grid scenarios. However, they rather focus on grid related power demand looking at the EVs from the perspective of their storage potential (Majidpour, Qiu, Chu, Pota, & Gadh, 2016). Furthermore, research literature has a limited coverage of the data related to charging profiles. In this regard some available studies provide probabilistic estimation of larger groups of EVs charging profiles using the grid (Majidpour et al., 2016; Tehrani & Wang, 2015). Furthermore a German case study was found which addresses the German vehicle to grid opportunities in 2030 (Hartmann & Özdemir, 2011), with additional grid studies from the Netherlands (Movares, 2013). and study covering almost an very board range of EV related topics was also found, evaluating the Norwegian EV developments. A study on the development of Norwegian EV market is covering almost every aspect of the EV problematic.

2.2. Global and German EV environment

At the end of 2015, about 1.3Million EVs were registered. With only a several thousand EVs on the road by 2008, this represents a significant growth in roughly 8 years of EV adoption. Although the global EV stock numbers, presented in *Table 2: Available EV stock data.*, cannot reveal the significance of the EV adoption against the market share of conventional ICE vehicles. Being a major mean to reduce GHG-emissions from the transport sector the adoption of the EVs that is observable until now is rather attributable to the incentives offered by the authorities.

2.2.1. Political targets and support schemes

For the European Union several countries have set EV adoption target, *Table 1* gives an overview of the European EV adoption targets. These targets are usually based on what is required to achieve proposed EU CO_2-reduction targets in the transport sector. For ease of reading, some targets have been summed up as they contained a share of PHEVs and EVs or were indicated solely as Zero-Emissions or Net-zero emission vehicles (biomass) in which case fuel cell electric vehicles are also included. Due to the relatively higher TCO of fuel cell electric vehicles, and the required electric drivetrain which is based on EVs, these vehicles are also accounted for in these targets as EVs.

Table 1: Known political EV targets [in Millions].
(Bevis, Smyth, & Walsh, 2013; Dudenhöffer et al., 2014; EV Fleetworld, 2016; Luo, Zhu, Wan, Zhang, & Li, 2016; Office for Low Emission Vehicles, 2015; Rijksoverheid, 2011; Swedish Energy Agency, 2015).

	2015	***2020***	***2025***	***2030***	***2050***
Germany		1		6	
France	0.45	2	4.5		
Netherlands		0.2	1		7.9 [100% stock]
Norway			*0.15* [sales *100%*]		3.1 [100% stock]
Sweden		0.6		5 [*100% stock*]	
United Kingdom		1.55			34.2 [100% stock]
Spain	1	2.5			
Czech republic		0.1			
Portugal		0.2			
Austria		0.2			
Denmark		0.08			

As can be concluded from the *Table 1*, some countries have set quite ambitious targets; e.g. Norway is planning to ban ICE sales by 2025 (EV Fleetworld, 2016*)* (Also The Netherlands has passed a parliamentary vote to look at the possibilities of banning ICE sales by 2025). Some of the targets like those set in Spain, Sweden and UK are rather not achievable. Spain will not achieve its 2020 target, mainly because of the lack of required support-schemes. Also, the Spanish 2020 target would be constrained by EV production capacities. Sweden intends to have a *100% fossil-free vehicle stock* by 2030. This shall limit the choice of combustion engines to those fuelled by biomass, hydrogen or electricity driven vehicles. However, current Swedish EV adoption scheme is far behind of that of other EU countries and there is no indication for a 100% fossil-free vehicles stock to be achieved anytime soon. For the UK the target of a 100% emission free stock by 2050 seems to be ambitious as well, since the size of the passenger vehicle fleet is rather big and it would need the right institutional interventions to make it obtainable.

For other countries the political targets are well within reach or are even likely to be overachieved by a to a large extend. For Norway the EV targets are substantial and with their aggressive support schemes not unobtainable. In March 2016 Norwegian EV sales, comprised of BEVs and PHEVs, rose to over 30% of the passenger vehicle market (GAS2, 2016; EVObsession, 2016).

Support schemes

The support schemes vary for different countries. Many of those schemes are focused on reducing costs, rather than solely providing perks for owners. The most aggressive incentivising can be seen in Norway (IEA, 2016), whereby financial incentives far exceed other vehicle markets and on top of that very attractive perks are offered, such as toll road exemption, use of bus lines in and around Oslo, use of ferries free of charge and exemption of parking fees in major cities (Figenbaum, Assum, & Kolbenstvedt, 2015; IEA, 2016; McKinsey, 2014).

While the Norwegian incentives are based on initial purchase cost reductions and perks throughout the ownership of the EV, the Dutch (Netherlands) EV support schemes are focussed more on tax exemptions and cost reductions throughout the ownership of EVs. Combining this with company lease contracts, these EVs can also be driven privately at reduced costs, they have a favourable 'bijtelling' based on the rated CO_2-emissions of the vehicle. This might be one of the reasons why the Dutch EV fleet consist of about 80% PHEVs(IEA, 2016), delivering long range driving distances during work hours and providing cheap private driving outside of office hours.

German support schemes

Germany had limited EV incentives, only excluding electric vehicle from road tax up to 10 years starting from the date of their first registration (European Automobile Manufacturers' Association, 2016), resulting in modest recurring savings of €150 (McKinsey, 2014). However, as of 2016 new incentives will be introduced for EV buyers (Bloomberg, 2016). EV and PHEV purchase costs will be reduced by €4000.- and respectively €3000.- up until €800M budget is spent. This represents financial support for 200,000-267,000 EVs. However, due to the late announcement, these new incentive was not incorporated into the model, it is expected that 2017 to 2020 numbers will be affected positively, however on the longer run this incentive is not likely to have an extended impact.

Additionally about €300M will be spent on implementation of charging infrastructure, translating to roughly to about 100,000 public level 2 chargers or 3,000 fast chargers or any linear combination between the two (Figenbaum et al., 2015). This information will be used to evaluate the different charging scenarios.

2.2.2. Global EV stock history

The global EV stock data indicated in Table 2 was obtained from multiple sources for all available countries. The historical data represented is only of an 8 year time series as mass production of electric vehicles only started in 2008, whereby the Tesla Roadster was considered as the first “mass produced”, highway legal, electric passenger vehicle.

Table 2: Available EV stock data.

	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Canada	-	-	-	-	2490	5642	10704	17058
China	5700	7030	8940	14510	19687	42016	94381	282489
Denmark	-	-	-	-	1388	-	2799	8100
Finland	-	-	-	-	271	-	-	2100
France	500	500	1830	6370	18885	30145	40939	75182
Germany	1450	1590	2310	4810	8103	15726	28325	53534
India	-	-	-	-	1428	-	2689	-
Italy	-	-	-	-	1643	-	7584	4700
Japan	1000	500	3000	18950	43294	72900.91	105722	128226
Portugal	-	-	-	-	1862	-	743	2100
Netherlands	70	70	398	1161	6423	28919	44094	88527
Norway	2780	2750	3350	5390	9910	20428	43033	78504
South Africa	-	-	-	-	-	-	48	260
Spain	-	-	-	-	787	-	3536	4700
Sweden	-	-	-	-	1198	2337	7275	16183
UK	1330	1450	1540	2610	6777	9550	23181	52230
United States	100	100	350	20924	73955	171309	286538	410470
R. of the world	0	500	1500	4000	13000	19000	39000	74000
Total	12930	14490	23220	76890	200624	407193.3	721759	1301063

As a multitude of sources were used to obtain these numbers, the sources are listed below in addition to the reference list;

- *IEA: (IEA, 2013, 2015, 2016)*
- *Eurostat: http://ec.europa.eu/eurostat/web/transport/data/database*
- *Research institute ZSW-BW: http://www.zsw-bw.de/en/support/press-releases/press-detail/number-of-electric-cars-worldwide-climbs-to-13-million.html*
- *RVO: http://www.rvo.nl/sites/default/files/2016/01/Special%20Analyse%20over%202015.pdf*
- *Hybridcars.com:*
  - *http://www.hybridcars.com/top-six-plug-in-vehicle-adopting-countries-2015/*
  - *http://www.hybridcars.com/2014s-top-10-global-best-selling-plug-in-cars/*
  - *http://www.hybridcars.com/top-6-plug-in-car-adopting-countries/*
  - *http://www.hybridcars.com/top-6-plug-in-vehicle-adopting-countries-2014/*
- *Appendix for ‘Fach- und Ideenkonferenz der bundesregierung am 6. und 7. Juni in Berlin’ (2016): http://www.vdivde-it.de/publikationen/201606_Sonderbeilage_DasElektroauto_Bundesregierung_HandelsblattundTagesspiegel.pdf*

Significant EV adoption markets

Major adopters of EV’s percentage-wise up until 2015 are Norway, followed by the Netherlands and California. For Norway a total market share of EVs **sales** hit 30% in March 2016 and in line with those numbers, Norway has, by far, witnessed the highest adoption rates percentage-wise of EVs in the world. This could be partly explained by aggressive tax exemptions and free use of public amenities, more on EV support schemes was discussed in *chapter 2.2.1 ‘Political targets and support schemes’*.

The Netherlands is, despite being only short of 17M inhabitants, the biggest EV adopter by absolute numbers in Europe. A significant share of the EVs is comprised of PHEVs and this might be linked to tax incentives which are favourable for EV adoption through a company vehicle, combining company driving with private use. Nonetheless, they are also one of the front runners in EV charging infrastructure, currently the highest amount of public chargers per EV. However, this charger to EV ratio is likely to decline at higher EV adoption rates and a matured EV charging infrastructure. More on charging and charging standards can be found under *chapter 2.3.3*.

The Californian EV market is promoted in order to achieve the states ambitions CO_2-reduction targets being one of the frontrunners in the area of the United States. As a result California is by far the largest EV player in the United States, subsidising not only EV sales but also subsiding EV manufactures, for example the EV intensive company of Tesla Motors. In terms of relative share the EV has not yet surpassed the 1% mark, and sales have seen a relative drop year on year over 2014-2015, reportedly due to reduced incentivising, lower oil-prices and in anticipation of a the new model X release by Tesla Motors.

Further significant markets are China and Japan, but unfortunately it seems likely that these EV stock numbers include EVs which do not classify as highway legal passenger vehicles such as micro-cars, bicycles, tricycles and light duty vehicles. Even though these markets are significant nonetheless, no exact representation can be given. What is known is that China is aggressively incentivising EV purchase and has witnessed the largest absolute growth worldwide over the previous year (2014-2015).

2.3. EV technologies

The EV propulsion technology differs from the ICE in two distinct ways, energy conversion and energy storage. The energy conversion of (B)EVs takes place by turning electricity into kinetic energy using an electrical motor. For the energy storage, a battery is used instead of a gasoline tank. The specific energy content of gasoline is much higher and for passenger vehicles, and transfer rates of energy exceed those of electrical charging (McKinsey, 2014).

2.3.1. Drivetrain Technology

The battery powered EVs, which can be charged using the electricity grid, currently come in three main variants; The Battery Electric Vehicle (BEV), Range-Extended Electric Vehicle (REEV), and the Plug-in Hybrid Electric Vehicle (PHEV). In this section the three drivetrain technologies will be discussed.

BEV

Starting with the Battery Electric Vehicle, it is a vehicle which only contains an electric drivetrain consisting of one or more electric motors to propel the car. The required power is solely provided by the electric battery and it can only be charged through electrical charging.

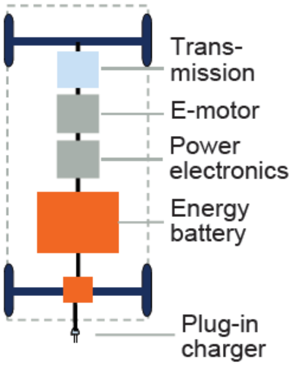

Figure 1: BEV drivetrain.
(Rathjens et al., 2014).

Battery electric vehicles do not wear as much as ICEs, due to the limited amount of operational (mechanical) components and the already relatively mature technology of electrical motors. The chemistry and size of the battery are key to achieve increased driving ranges, as relatively not much efficiency gains can be obtained elsewhere. The overall **Tank**-to-Wheel efficiency is above 60%, as compared to below 20% for an ICE vehicle (Bloomberg New Energy Finance, 2015a).

In 2016, the most expensive of BEVs (Tesla Model S 90P) can achieve rated ranges of up to 500km (New European Driving Cycle), whereas practical ranges achieved are up to 460km. The costs of BEV are expected to come down significantly, as currently the batteries are still quite expensive, with up to 33% of vehicle production costs.

REEV

The Range-Extended Electric Vehicle, has its drivetrain laid out based on the BEV principle, however battery sizes are usually smaller due to the fitting of an ICE which generates electricity whenever the battery is depleted. The REEV is a series PHEV, as it can only be driven directly through the use of an electric propulsion system.

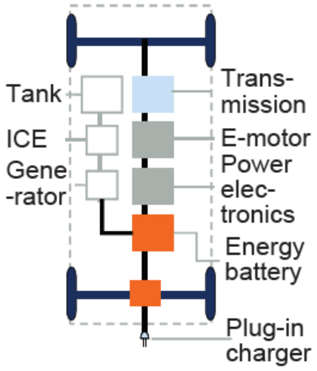

Figure 2: REEV drivetrain.
(Rathjens et al., 2014).

The REEV can provide fully electrical driving for average distances of up to 100km, while still being able to drive longer distances without the drawbacks of a smaller battery due to the ICE producing electricity.

The design of a REEV is somewhat more complicated, compared to a BEV as additional components are required. The additionally required components (for the ICE) are, amongst others, a tank, the ICE, a generator and an exhaust system. However, a pure REEV lacks a complicated gear box as the ICE is laid out to perform only under optimal conditions. For the ‘extended range’ the ICE only has to power a generator which creates the electricity. The management system for the propulsion is somewhat more complicated, as additional management for a steady state ICE are required. The potential reduction in battery size is offset somewhat against the offset of the ICE and related components.

PHEV

The Plug-in Hybrid Electric Vehicle has arguably the most complicated drivetrain as the propulsion can both occur via electricity or directly via the on-board ICE. The PHEV shown below is a parallel PHEV, as both engines can directly power the transmission. The series PHEV is discussed under the REEV (PHEV) vehicle.

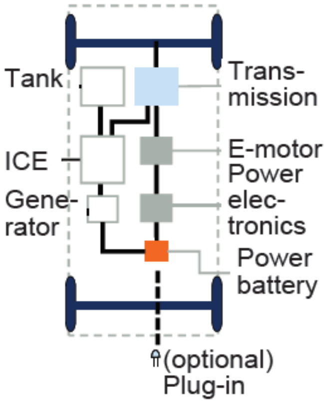

Figure 3: PHEV drivetrain. (Rathjens et al., 2014).

The PHEV can provide electrical propulsion for shorter ranges of up to 50km, however when longer ranges are required, the ICE is ready to be used as a conventional ICE vehicle. The PHEV tackles the range anxiety problem by switching to a standard size ICE engine whenever the battery runs out of energy.

Due to combination of propulsion systems, overall weight is usually higher and especially the transmission design is complicated to accommodate both the ICE and electric motor propulsion. Whereas the ICE conventionally has 5 or more gears, the ICE does not utilize this setup. The overall costs of a PHEV are most likely to remain higher than ICE's or BEV's as both technologies are applied in one vehicle and additional engine and transmission management systems are required.

Technological potential EV drivetrains

The technological improvements for drivetrains in electric vehicles leave relatively little room for improvement as overall drivetrain losses only account for an estimated 25% of loss from the battery (Bloomberg New Energy Finance, 2015a; Helms, Pehnt, Lambrecht, & Liebich, 2010). The rest of the energy is lost in aerodynamic resistance, rolling resistance and braking, and these components are not EV specific, these component improvements can also be applied to HEVs and ICE vehicles.

With current energy intensity per kilometre around 0.19kWh/km (Figenbaum et al., 2015), a theoretical minimum of 0.15kWh/km can be achieved for an average EV (Bloomberg New Energy Finance, 2015a). That disregards any theoretical limitations for the propulsion system and assumes zero losses, as can be deducted there is not a whole lot of room for significant improvement.

2.3.2. Battery technology

As battery developments are key for the overall TCO competitiveness with conventional ICE vehicles, this chapter discusses some key characteristics and issues related to battery formats, chemistry and development. EV battery life time is warranted ranging from 5, 8 to 10 years (Figenbaum et al., 2015). More on the EV TCO competitiveness can be found in chapter 3.2.2 'Determining EV sales'.

Formats

Different battery formats exist, whereas the cylindrical have been around for a while and technologies are more mature, the power to energy ratio[3] is lower than large format batteries consisting of pouch and prismatic cells (Bloomberg, 2014). The differences will shortly be discussed in this section.

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[3] However, when enough cylindrical cells are installed the obtained power is more than sufficient to power a (strong) engine. With energy capacity this 'saturation effect' is of course not achieved.

Cylindrical (18650 standard)

Most conventional consumer product batteries such as laptops, flash lights, remote controls, etc. use cylindrical battery formats. Although the cylindrical formats theoretically do not have the highest volumetric density being cylindrical, it is easier to arrange them in irregular cavities due to their relatively smaller standardized modular sizes. In vehicles, the wheel wells, axes, seats, trunk and hood all have their own specific 'irregular' dimensions and the cylindrical cells can be easily arranged maximise space utilization (Battery University, 2016b; Bloomberg, 2015).

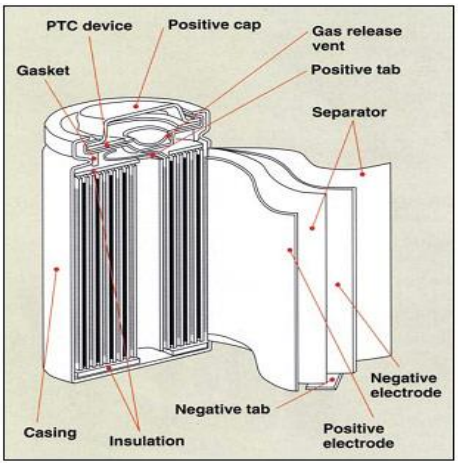


Figure 4: Cylindrical cell (Battery University, 2016).

Furthermore, the lower volumetric density of cylinders is beneficial for cooling capabilities. By utilizing the open cavities in between the batteries, natural or forced cooling is relatively easy as compared to pouch or prismatic formats where cell arrangements should accommodate cooling features.

Conventional cylindrical cells typically have the highest energy density **per unit** and they can withstand internal pressure relatively well due to the cylindrical shape. In 2015, cylindrical cells were (still) cheaper to produce than the other larger formats of pouch and prismatic cells (Battery University, 2016b; Bloomberg, 2015).

The future developments for format regarding cylindrical cells is a bit uncertain as they have already been around for over a decade and are used in a wider range of consumer products. Format developments for EV purposes would possibly lie in increasing the size from the 18650 (18x65mm) standards towards an increase of both 10% height and diameter, based on claims made by Tesla's CEO Elon Musk during the Tesla 2014 Q2 earnings call. The increase in format size would lead to an increased energy density **per unit** mass.

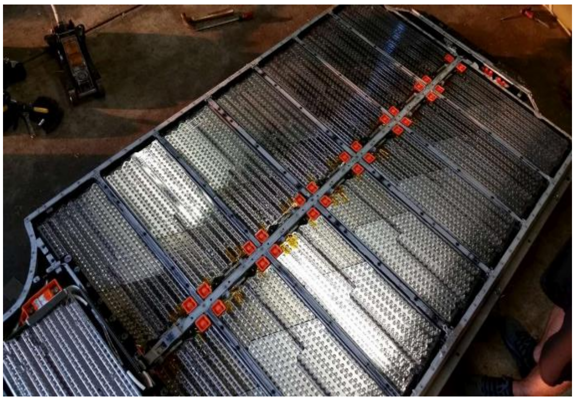


Figure 5: Cylindrical cell battery pack Tesla Model S 85. (Tesla Motors Club, 2014)

Currently Tesla is the largest automotive manufacturer using cylindrical battery cells for their EVs.

Pouch (large format cells)

The pouch format is a very flat battery cell, requiring no external casing per individual cell. The highest volumetric density can be achieved using pouch battery cells 90-95%, however the battery packs (stacked cells) should allow for expansion, as pouches tend to swell after a certain amount of cycles. In order to facilitate cooling and expansion, the pouch cells should receive some form of external support.

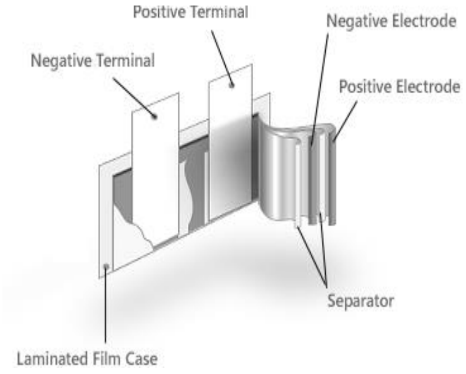


Figure 6: Pouch cell (SK Innovation Battery. 2013).

Even though the theoretical volumetric density of pouch cells is very high, the pouch cells will have to be cooled. To accommodate cooling, cavities have to be left for facilitate natural or forced cooling on top of the space required for the inherent swelling of pouch cells.

Pouch cells currently have a moderate energy density, roughly half of the energy density cylindrical on a weight basis but still higher then prismatic. As of yet there is no standardized size for pouch cells, with standardization increased energy yields are expected (Battery University, 2016b; Bloomberg, 2015).

Figure 7: Nissan Leaf Pouch cell battery pack (25kWh). (Cleantechnica, 2016)

Future developments for pouch cells lie in reducing the swelling caused by the battery cycles while thereby increasing reliability. These cells are series mounted, so if one cell fails the required amount of voltage will not be achieved. With economy of scales, the production costs gap with cylindrical cells will be narrowed, especially since these cells do not required individual cell casings. Currently the Nissan leaf, the most widely sold EV up to 2014 (Cheatsheet, 2015), uses pouch cells with battery packs of 25 kWh.

Prismatic (large format cells)

The prismatic format is a mix between the cylindrical and pouch formats, it has decent rectangular space utilization but that comes at the cost of hard to reach hot-spots in the middle of the prismatic format which can cause overheating as there is no effective adjunct cooling. Reliability for prismatic cells are key to the success of the battery pack. The prismatic battery packs are generally not very much able to cope with a loss of a cell as they are larger than the other formats and redundancy comes at higher spatial costs. Primatic cells are protected by a casing which can easily cope with internal pressure without deforming.

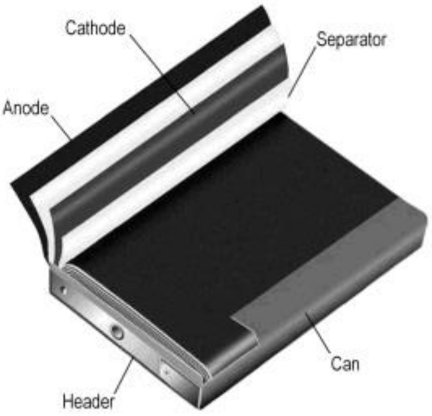


Figure 8: Prismatic cell (Battery University, 2016).

Currently prismatic cells have the lowest energy density, and the aim is to achieve energy densities equal to cylindrical cells. The packaging efficiency of these cells is the highest amongst the discussed battery formats. There are currently no standardizations in place for prismatic cells.

Future developments for prismatic cells are the increasing the of the energy density, up to the point of achieving energy density levels of cylindrical cells. The Volkswagen E-golf uses prismatic cells for its energy storage.

Figure 9: VW e-Golf Prismatic cell battery pack (kWh). (Cleantechnica,2016)

Chemistry

The battery chemistry can be divided into the cathode and anode chemistry along with the electrolyte, separator, foil and housing.. The cathode chemistry accounts for the largest material cost component of the batteries, and will be described in more detail. The anode and electrolyte play a larger role in technological developments and will be addressed under the respective header. The technological potential for the separator, foil and housing are rather limited, with present insights only some cost reductions are obtainable. In 2015 the cathode could account for up to 25% of battery cell cost or over 7% of total vehicle production cost (Bloomberg New Energy Finance, 2015b, 2015d; UBS, 2014a).

Cathode (Battery University, 2016c; Bloomberg New Energy Finance, 2015c; El Deed et al., 2014).

The cathode chemistry is the largest bottleneck in terms of battery development, it is here that improvements will have a significant impact on overall lithium-ion battery costs and performance. The cathode materials used today have a significantly lower gravimetric capacity than the anode materials, even though lithium itself has a very good energy density of almost 12,000 Wh/kg (110 to 210 Wh/kg is the average of currently applied Li-ion EV batteries), it cannot be used as an effective cathode as it does not favour reversible reactions. By introducing additional materials Lithium's energy density can be partly used while becoming much more favourable for application in EV batteries.

The battery chemistry used for EVs is derived from Lithium Cobalt Oxide (*LCO*) batteries in consumer products. The LCO batteries used in consumer products generally do have a high cyclability, and larger format LCO batteries have a high potential fire risk, therefore LCO is not used for EV applications

The battery chemistries discussed below are of standardized nature, blending between two or more combinations gives specific combined characteristics in terms of safety, capacity, power, cycle and calendar life. This is the reason why battery manufactures experiment with different chemistries and come up with their unique battery chemistry blends, depending on preferred characteristics. An overview of the pure chemistry types and their specific characteristic is given in *Table 3* at the end of the cathode section.

Lithium Manganese Oxide spinel (LMO) (Battery University, 2016c; Bloomberg New Energy Finance, 2015c; El Deed et al., 2014).

LMO is a battery formation which is of cubic nature, indicated by the spinel addition. Additionally the cubic structure applied makes the battery very safe, however due to the introduction of manganese to replace cobalt it only has a temperature tolerance up to 50°C. Above these temperature the manganese dissolves in the electrolyte, shortening the battery life. By introducing manganese cost reductions can be achieved as cobalt is more expensive than manganese chemistry, however energy capacity is reduced by roughly 20%. Currently it is one of the Li-ion technologies with the lowest specific energy capacity in mAh/g.

lithium Nickel Cobalt Aluminium oxide (NCA) (Battery University, 2016c; Bloomberg New Energy Finance, 2015c; El Deed et al., 2014).

The NCA chemistry is a derivative from Lithium Cobalt Oxide (*LCO*) chemistry used in consumer products. By replacing the cobalt by nickel a higher specific energy, power density and life span are obtained, while at reduced costs. However, the LNO composition would make the cathode unstable, by adding cobalt and aluminium, stability is improved again while retraining high capacity and voltage. So all in all Cobalt is replaced for a mixture of nickel, cobalt and aluminium to gain better battery capacities, higher battery voltage at reduced material costs. A drawback of NCA is that it has a quite low temperature tolerance.. A blend of NCA chemistry is currently used by Tesla Motors.

Lithium iron Phosphate (LFP) (Battery University, 2016c; Bloomberg New Energy Finance, 2015c)

LFP is currently the only commercialized Li-ion battery which is not a lithium metal oxide. LFP binds the oxygen atoms using phosphorous, which makes the battery very safe, even at elevated temperatures or when overcharged. LFP cells do not provide a high voltage, as a result more of them have to be fitted in order to achieve sufficient voltage levels, however the cells can accommodate higher currents to partly offset capacity losses as result of lower voltage. Despite lower raw costs, the production process requires an inert atmosphere and production is thus more expensive than other cells.

lithium Nickel Cobalt Manganese (NMC) (Battery University, 2016c; Bloomberg New Energy Finance, 2015c)

NMC shows the highest volumetric energy density and one of the highest gravimetric energy densities amongst the commercialized Li-ion battery chemistries, on top of the potential to become low cost. However, as the pure NMC blend was '*contemporaneously patented by Argonne National Laboratory and a partnership between 3m and Dalhousie University (Bloomberg New Energy Finance, 2015c, p.7)*', to date only NMC blends mixed with LMO are utilized in EV batteries. Companies including GM, BASF and LG Chem have been licensed for the pure NMC chemistry and it is likely that it will see its introduction into EVs within the next five years.

The NMC chemistry lends itself well to promote some battery chemistry characteristics over others, by changing the ratios of nickel, cobalt and manganese preferred characteristics of batteries can be promoted. More on the technological potential of NMC will follow below.

Technological potential of Li-ion batteries

The cathode chemistries are still in its infancy, however it is expected that the largest Li-ion cathode improvements will come from the NMC blend as it provides a platform for improvement above all others. Next to the cathode, anode as well as electrolyser developments.

NMC developments (Bloomberg New Energy Finance, 2015c)

Even though pure NMC chemistry is not applied in EV batteries yet, the platform of NMC combinations presents ample opportunity for improvement of preferred characteristics. By changing the ratio of Cobalt in order to reduce costs, Nickel and Manganese can be supplemented. Up to a minimum share of 10% Cobalt, the cobalt can be exchanged for Nickel or Manganese.

Anode developments (Bloomberg New Energy Finance, 2015c)

The anode chemistry makes up the lithium ions accepting side when charging, the anode is usually made out of carbon based materials (e.g. graphite). Presently the anode materials have a significantly higher gravimetric energy density than the cathodes. However, by improving anode chemistries, battery capacities could nonetheless be increased. Novel developments include the introduction of silicon into the carbon based materials, achieving 1,600mAh/g of capacity, twice that of the graphite anodes used to day.

Electrolyser developments (Bloomberg New Energy Finance, 2015c).

By replacing the liquid electrolyte by a solid inorganic electrolyte additional novel chemistries can be applied. The solid state cells and silicon based chemistries are discussed under 'technological potential' (Bloomberg New Energy Finance, 2015c).

Novel battery technologies

In this subsection the most important novel battery technologies will be discussed. These technologies are not expected for the near future, however after 2025-2030 they might represent significant improvements over today's Li-ion technology (Bloomberg New Energy Finance, 2015c).

All solid state (Bloomberg New Energy Finance, 2015c)

By replacing the liquid electrolyte used today for a solid material that would allow transfer of ions could provide opportunities to work with new chemistries. The inorganic electrolyte would also alow for a higher packing density that could allow batteries to achieve up to 400Wh/litre. Solid state batteries do come with some drawbacks, as they have an inherent joint resistance between the electrolyte and cathode, reducing the power density of the cell.

Lithium sulphur (Bloomberg New Energy Finance, 2015c)

Lithium sulphur batteries replace the carbon based cathode used in lithium-ion batteries for a sulphur based cathode. Instead of one ion, two ions will be released per reaction which allows for much higher energy densities. The aim is to achieve energy densities of up to 500Wh/kg, about three times that of commercialized Li-ion batteries. However, lithium sulphur has shown very short cycle life thus far and lithium sulphur batteries tend to swell up to twice its original volume when the cathode absorbs the lithium.

Lithium air (Bloomberg New Energy Finance, 2015c)

While showing the most promise, lithium air batteries are still hampered by electrolyte instability and slow reaction kinetics. Lithium air batteries have a commercially targeted energy density of 1,500 Wh/kg, and the absence of expensive materials such as cobalt would make lithium air a low cost battery. However, as was mentioned it still has to overcome hurdles before commercialization, and reportedly some large companies have pulled out of lithium air development projects.

Battery technologies differences between PHEV and BEV

The optimal battery characteristics of PHEVs and BEVs differ quite significantly. For PHEVs battery characteristics are optimized for maximum power output, at a lower total energy capacity. As battery size of a PHEV is smaller, the specific amount of power per energy content has to be much greater. In the contrary, for BEVs battery sizes are usually significantly larger, and it is way easier for a lot of cells to deliver the same of power as a limited amount of PHEV battery cells have to do. Inherently these battery characteristics and maximum power output over a low amount of integrated cells make not only the battery cells more expensive, but also the battery management system. The PHEV batteries are more prone to operate near their maximum operating limits. Large format cells are usually better to use in PHEVs battery packs as these have a higher specific power output per energy content, as opposed to the cylindrical battery cells(Bloomberg New Energy Finance, 2014, 2015c).

Comparison of battery chemistries

In *Table 3* a comparison matrix is given for the different battery chemistries.

Table 3: Comparison of (cathode) battery chemistries.
(Battery University, 2016c; Bloomberg New Energy Finance, 2015c; El Deed et al., 2014).

	LMO	**NCA**	**LFP**	**NMC**	**Lithium air**	**Lithium Sulphur**
Chemistry	$LiMn_2O_4$	$LiNiCoAlO_2$	$LiFePO_4$	$LiNiMnCoO_2$	LiO_2	LiS
Voltage (V vs Li/Li+)	3.7-3.8	3.6	3.2-3.4	3.6-3.7(3.9)	3.2	2.2
Specific capacity (mAh/g)	100-110	180-200	150-170	160-170 (200)	1700 (3350)	1000 (1670)
Volumetric energy density; Practical (and theoretical) (Wh/l)	280	250 (730)	130-200	350 (700)	700-1000 (3400)	300-800 (2800
Gravimetric energy density; Practical (and theoretical) (Wh/kg)	100-150 (280)	200-260 (280-300)	90-120 (219)	150-220 (290)	500-1000 (3500)	400-800 (2800)
Cycle life	300-1000	500*	1000-3000	1000-2000	1000	<1000
$/kWh averaged Costs of active materials in 2014	25	50	35	55 (30)	>25	-
Safety	🟩	🟥	🟩	🟩	🟩	🟥
Performance at hot and cold temperatures	🟥	🟥	🟨	🟨	🟨	🟨

* The cycle life of NCA is, next to other chemistries, related to depth of charge and temperatures. By introducing safety limits and temperature management, cycle life of NCA is preserved and can be considered as very good compared to other chemistries. Based on a PHEV charge cycle at 45°C (relatively limited capacity and high energy output, thus straining the battery as compared to BEV utilization) NCA can actually achieve up to three times higher cycle life, even achieving a higher overall capacity output in comparison to the other chemistries (Popp, Attia, Delcorso, & Trifonova, 2014)

2.3.3. Charging

In this subchapter an overview of electrical charger types will be given as well as insights into the common charging behaviour of Li-ion batteries. Currently several charging standards exist, with standardizations originating from Europe, the United States and Japan. As global legislation and standardization has been lacking thus far, several EV manufactures have either created their own type of charger or formed domestic/regional interest groups coming up and promoting own regional standards.

Nonetheless, safety regulations were incorporated for all electric vehicle charging standards, as they have to be 'paralyzed' while plugged in to protect the vehicle and charging point from accidental damage. This indicates that EV charging is always accompanied by some sort of data, either generated within the vehicle itself, receiving data from the charging point or most commonly, a combination of the two. Along with the 'drive-away' damage prevention, the (exchanged) data is used to protect the Li-ion battery and to determine optimal charging conditions at different intervals (Young et al., 2013). Lastly, for each EV different charging levels exists for domestic charging, public charging and fast charging (for some models). The charger type combined with the charging level determines the maximum charge rate of the batteries.

Coulomb's Charging rate

As a large range of different battery capacities have been and can be developed, a uniform charging rate applicable for all batteries regardless of maximum battery capacity been developed. The Coulomb's charging rate (C-rate) describes the amount of hours it takes for a full battery charge under ideal circumstances. For example, a C-rate of 1C gives a charging time of 1 hour, 0.5C means only 50% of the battery is charged in an hour, so the complete charging of the battery will ideally take 2 hours etcetera. *Table 4* gives an indication of common C-rates (Battery University, 2016c).

Table 4: Common C-rates.
(Battery University, 2016c).

C-rate	***Time required to charge a fully depleted battery***
2C	30 minutes
1C	1 hour
0.5C	2 hours
0.2C	5 hours
0.1C	10 hours
0.05C	20 hours

However, the above mentioned C-rates only act as a temporarily maximum charging rate, at peak battery charging conditions. Charging a fully depleted battery always requires more time than indicated by the C-rates (Young et al., 2013). Example; So for a 2C charging rate, the initial 70 to 80% can be achieved within 19 to 24 minutes, but the remaining 20 to 30% will take additional time, anywhere up to 24 minutes of additional charging. Thus, charging a battery from fully depleted to fully charged can take up to 50 minutes with a charging rate of 2C. Keep in mind that these values are example values, a more detailed description of

Currently the highest theoretical C-rates provided are those charging points that can charge 40kW or more, for very small battery packs which can accept the high currents and voltages associated with this charging level. However, if we take the example of Tesla, the highest theoretical C-rate is achieved when charging at a Tesla Supercharger (120kW) with the smallest battery pack available on the model S (60kWh). This gives a theoretical C-rate of 2. The above example indicates that C-rates on itself are quite tricky to mention, if no further details are provided. More on Li-ion charging behaviour and available charging levels can be found in the respective headers.

Charging behaviour of Li-ion batteries

The optimal charging process for Lithium-ion batteries does not follow a linear pattern. Between the cut-off levels (used to prevent battery damage and preserve optimal battery life), the Li-ion battery ideally obtains a combination two methods of charging. During the initial stage charging current is kept constant and voltage is increased slowly. When a battery voltage (SOC – State of Charge) threshold is reached, a threshold depending on battery chemistry, voltage is kept constant and current is slowly reduced until the SOC has reached 100%. *Figure 10* shows the battery charging pattern, however this figure includes the pre-charging method, which is applied before the battery is ready to use in the EV.

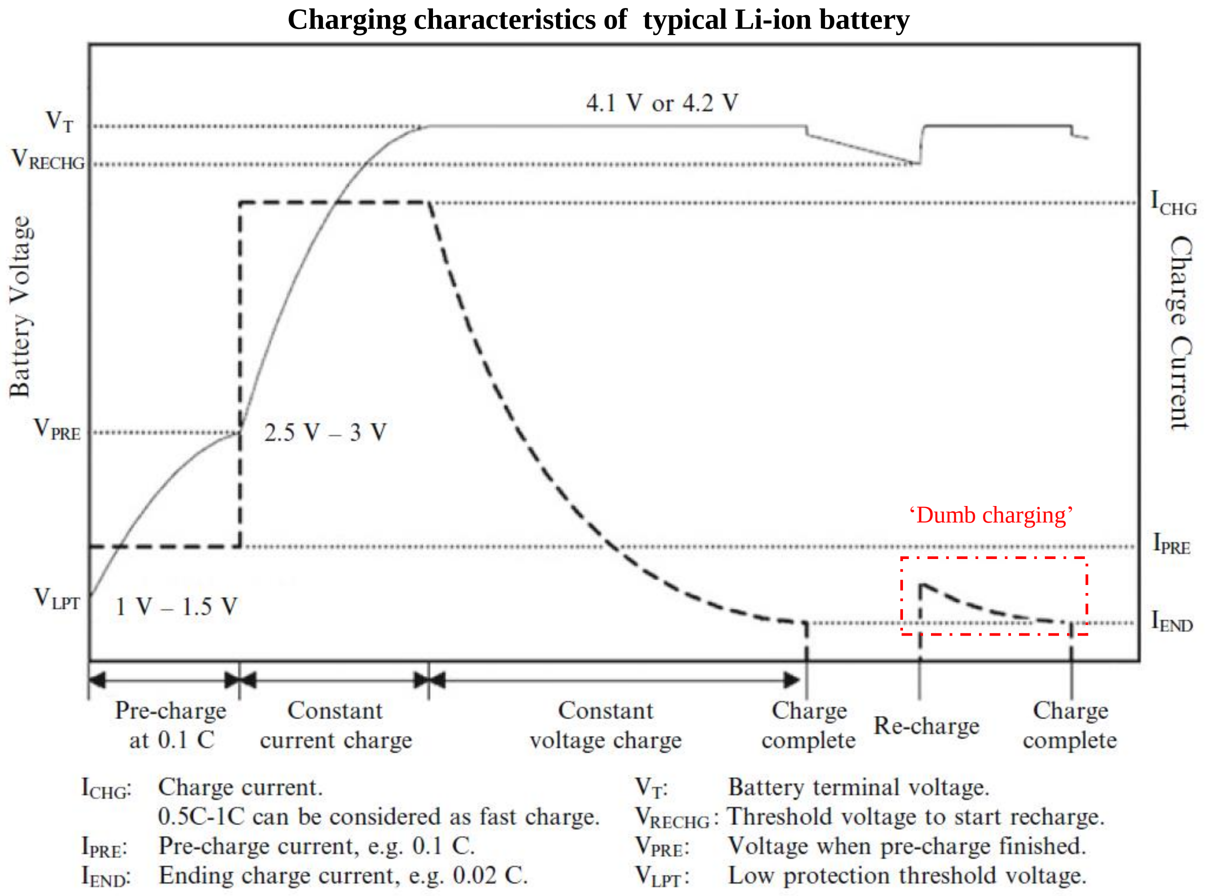


Figure 10: Charging characteristics of typical Li-ion battery.
(Young et al., 2013)

For the charging scenario of 'Dumb charging', the charging profile indicated by the red box in *Figure 10* would occur. This indicates that the current of charging is rather low, whilst voltage is maintained at a steady level. This 'topping up' the battery would take significantly longer than the C-rates obtained at constant current charging or in the beginning of constant voltage charging.

Nonetheless, around 60% of the German vehicle owners owns a garages or private parking spot, making overnight charging a viable option (Fraunhofer Institute, 2013). By incorporating overnight charging with the 'Dumb charging' scenario, peak demands would be rather low. Of course with more 'intelligent charging' scenarios, peak demand could be reduced even further.

Specific values of charging power depend on the converter size incorporated with the vehicle, currently 3.3kW is employed by most vehicle manufactures (EVObsession.com, 2015). However, this seems likely to increase in the future, with battery sizes and growing battery behaviour experience.

Charging levels

Different charging levels are have been established, resulting either from national standards (US with ≈110V grid output), to electrical fuse standards (16 Amps), to convenient charging rates for fast charging (as fast charging usually does not exceed 1C charging rates). Furthermore the charging levels are divided by Alternating Current*(AC)* and Direct Current*(DC)* charging. AC connections usually provide a significant lower charging rate within the same charging level as the vehicle has to internally convert the AC into DC. Furthermore, with DC connections, usually the charging stations provide more optimal power is supply as DC connections are purpose build to charge EVs with different voltage and current levels during the charging cycle. *Table 5* shows the different charging standards and connectors including theoretical maximum charging power, and when applicable the maximum operational power levels have been indicated between brackets.

Table 5: Overview charging levels.
(Alternative Fuels Data Center, 2016; Battery University, 2016a; Hybridcars.com, 2015)

Level	***Charging Location***	***Type***	***Power***	***Voltage***	***Amps***	***Standards***
1	Private	AC	<1.92kW	120V	≤16	1.5 kW NEMA 5-15 1.8 kW NEMA 5-20 1.92kW SEA J1772 charge port
	Public	DC	<36kW (<40kW)	200-450V	≤80	40kW SEA J1772 Combo Charging System - *CCS*
2	Private/ Public	AC	<19.2kW	200-240V	≤80	10 kW NEMA 14-50 19.2kW SEA J1772 charge port
	Public (Fast)	DC	<90kW (<100kW)	200-450V	≤200	62.5 kW CHAmeDo (50kW) 100 kW SEA J1772 CCS (50kW)
3	Public (Fast)	AC	>19.2kW	≥200-≤600V	≥80-≤400	-
		DC	<240kW	200-600V	≤400	120 kW Tesla Supercharger

Domestic charging

Domestic charging, or in other words private charging, is dominated by level 1 and 2 AC charging standards. Level 1 AC charging is predominately developed for home charging within the United States and applied for distribution grids with a similar voltage of 110-120V AC. The charging level 1 for the US is rather slow as power output is very limited at 1.5 to a theoretical maximum of 1.92kW charging power. For common smaller BEV batteries at 25kWh capacity this translated to a C-rate for charging of <0.06C or for the largest of BEV batteries at 90kWh to well below 0.02C. Translated in the hours this is a range of between 16 hours and respectively 60 hours of charging to top up a fully depleted battery. As these are theoretical values, operational values will always be lower due to grid resistances and battery charging behaviour as explained the previous section *'Charging behaviour of Li-ion batteries'*.

In order to supply level 2 AC charging in private US residences, a wall-mounted charger module has to be installed, usually along with the electrical wiring required for 3 phased 220V (US) and also in order to support a maximum of up to 80 Amps of current in Europe. By installing a wall-mounted or stand-alone charging module, also a communication system interacting with the battery management system is included. The exchanged data is used to optimize power output, as current and voltage vary during the charging cycle to optimize the charging process. As they do more than just simply charging, these charging devices are called Electric Vehicle Service Equipment (EVSE). Costs for the installation and EVSE device itself are in the region of $700 to $1000 for the US market and at a minimum of around €800 was found for the Dutch market before incentives (ANWB, 2016). By utilizing EVSEs maximum C-rates can be obtained of 0.77 and 0.44C respectively.

Public charging

Public charging, consisting level 1 DC and level 2 AC are assumed to be publicly available, excluding privately owned parking spots and/or ESVEs, and they must have a maximum charging power output of >3.7kW. Based on level 1 DC charging a maximum charging output of <40kW can be achieved when using these types of EVSEs. This translates to maximum public C-rates smaller BEV batteries (25 kWh) of 0.63C but more likely in the region of 0.50-0.55C under operational conditions. For the largest BEV batteries currently available (90kWh) this translates to a maximum C-rate of 0.44, or around 0.35-0.40C under real world conditions.

Public charging EVSEs installed cost were found for Norway, generally coming in at an average cost of 2.500 €/charge point, with a minimum of €500 and a maximum of up to 4.000 €/charge point excluding VAT (Figenbaum et al., 2015). Public charging points are seldom installed for a single charger, however the amount of charging connectors usually varies between 2 and 8.

Fast charging

Fast charging is dominated by level 2 and level 3 DC chargers, however as these power outputs sometimes exceed battery park limits, not all electric vehicles can accept power outputs as high as is allowed by the level 2 DC standard. For level 2 DC chargers, the operational values are around 50kW, while the standardized values allow charging of up to 100kW. With operational CCS combo and CHAdeMO outputs of 50kW, a 90kWh battery would achieve up to 0.55C. Smaller battery size are unlike to be able to accept these higher power outputs and thus C-rates of >3C are not applicable (Young et al., 2013).

Level 3 DC charging is currently only offered by Tesla and applicable only for Tesla vehicles. A theoretical maximum power output of 120kW is currently the fastest charging method available. For a 60kWh Tesla Model S this translates to a theoretical C-rate of 2C and for the 90kWH version to a C-rate of 1.33C.

Public fast charger costs were found to range between 62.000 to 125.000 €/charge point in Norway for the CHAdeMo standard, however (a lot of) these installed charging points might require distribution grid expansions upstream which are not accounted for (Figenbaum et al., 2015). As planning, permits (and labor costs) are becoming more of an issue rather than material costs, usually more connectors are installed per charging point, up to an average of 6.4 per Tesla supercharger charging point.

2.4. German energy and power demand

In order evaluate the impact of EV related energy and power demand, it is important to gain insights into the current German energy and power demand. The energy demand is based on yearly final electricity consumption (excluding grid losses), whilst the power demand is described along the daily power load shapes with maximums during peak hours, either in winter or in summer.

2.4.1. German energy demand

The final electricity consumption in German is, over the years 2005 to 2014, averaging out just over of 525 TWh/a, coming in at 512 TWh for 2014 (Eurostat, 2015b). A decline in energy demand can be witnessed from the annual Eurostat data, whereby energy demand has declined by almost 10% over the shown period. Furthermore, German final electricity consumption is expected to decline even further, to about 75% in 2050 as compared to 2008 levels (German Energy Transition, 2015). The historical decline was largely driven by energy efficiency gains and these are expected to drive further declines.

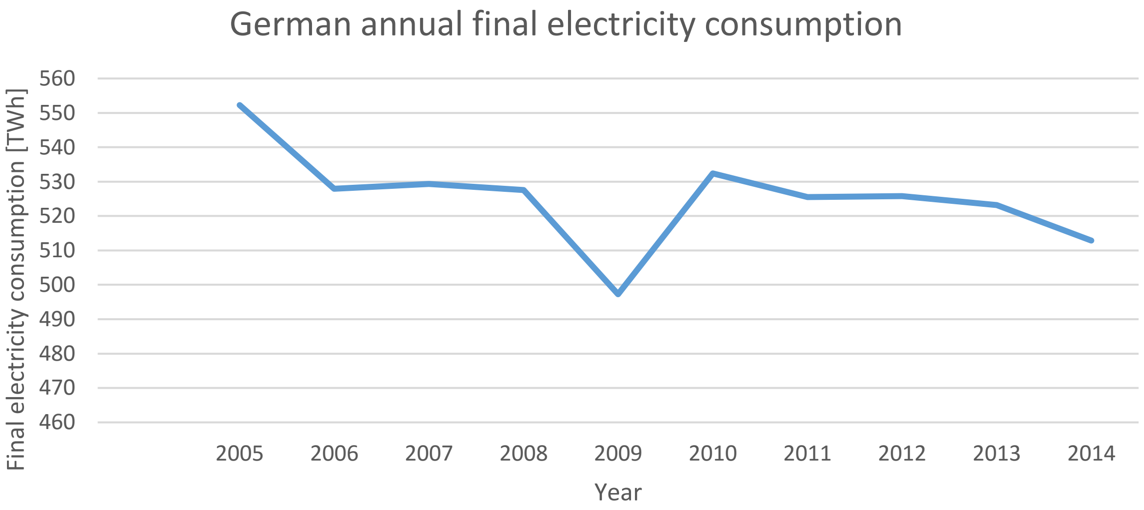


Figure 11: German annual energy demand.
(Eurostat, 2015b)

Energy demand developments

The efficiency gains responsible for the decline of annual final electricity consumption are expected to account for up to 17.5% reduction in energy demand or 92TWh as of 2035 based on 2008's consumption. This would roughly translate to an final energy consumption of 435TWh in 2035. The efficiency gains are part of political (emission) targets, and are presumed a likely scenario based on the shown historic data from Eurostat.

2.4.2. German power demand

The German power demand and power load profiles will be affected by the power demand originating from EVs, the significance of EV power demand depends on the ratio between additional EV related power demand and the current power load profiles in Germany. To evaluate the impact of EV-mobility a winter day and a summer day in Germany were taken as reference case power load profiles (ENTSO-E, 2016). The winter day was taken at the third Wednesday of January, i.e. January 20th, 2016 (with an avg. temperature of -1° C with historical averages between -3 and 2° C (AccuWeather.com, 2016), this is in accordance with ENTSO-E peak demand guidelines (ENTSO-E, 2015).

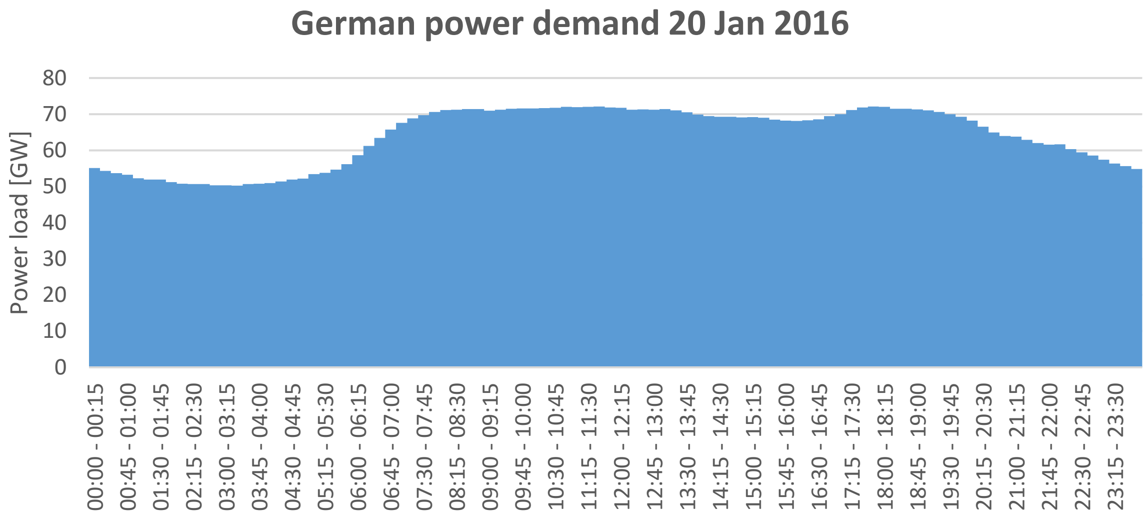


Figure 12: Winter day load shape January 20th, 2016. (ENTSO-E, 2016).

For the summer day load profile, the third Wednesday of June 2016, June 15th, was taken. The temperature on this day was 20° C with historical averages between 13 and 22° C (AccuWeather.com, (2016), this is not fully in accordance with ENTSO-E peak demand guidelines, as the third Wednesday of July is not yet available the guideline, in this case a monthly reference point one month ahead was used.

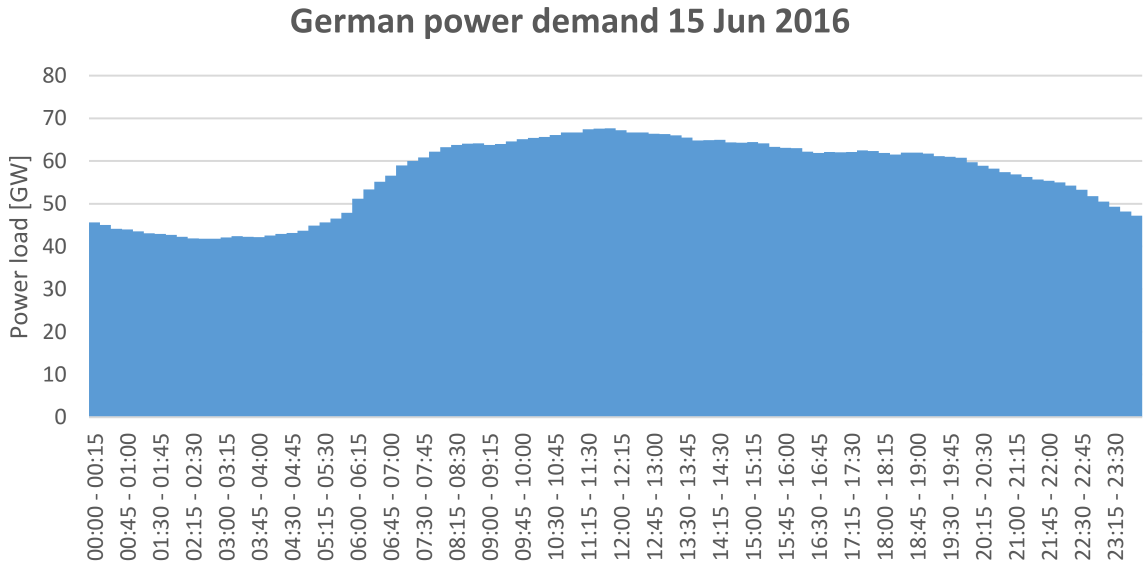


Figure 13: Summer day load shape June 15th, 2016. (ENTRO-E ,2016).

As can be deducted from *Figure 12* and *Figure 13*, the power load shape for the winter day exceeds that of the summer day. Coming in at just over 72GW during evening peak hours in the winter, this value will be used to relate EV charging scenarios on top of existing power load profiles.

Power demand developments

The ENTSO-E stated in their ‘*2015 scenario and adequacy forecast*’ that no significant changes in German power demand have been witnessed in recent years. And even though overall power demand for the European Union is expected to rise by 8,5% until 2025, they expect that no rise in energy demand in Germany will occur at least up until 2025. Furthermore, they expect that 2016 peak demand will remain slightly higher than peak demand in 2020 and 2025. These assumptions are in accordance with current projects in Germany and the National Grid Development Plan. Underlying assumptions indicate that efficiency gains and heat generation gains will offset the E-mobility related power demand and thus keep power demand at stable levels at least up to 2025 (ENTSO-E, 2015).

As no clear indications are given for the gains due to efficiency and reduced heating load, it is not possible to evaluate their outlook on EV related power demand. However, in the scenario analysis, several EV charging scenarios will be discussed and their significance related to the 2016 power load shapes. The significance will be related to the 2016 snapshot of German power demand, as no further increase in power demand is foreseen by ENTSO-E.

3. Methodology

In this section the processes which led to the results are described. Starting with the EV adoption characteristics, model description and as well as how the input parameters are determined which will lead to the scenario results. Additionally the translation to German EV adoption and its impact discussed, followed by insights which justify the chosen input parameters for the model and lastly the power demand related to EV adoption is discussed.

3.1. Market penetration characteristics of EVs

The characteristics of EV market penetration are expected to follow a pattern of consumer product market penetration (Grünig, Witte, Marcellino, Selig, & Van Essen, 2011). At first EV market has to evolve as a niche market of the passenger vehicle market. In other words, the prerequisite for market penetration is a demand for EVs per se. Furthermore, in contract to the ICE vehicles, which have their refuelling infrastructure (gas stations) laid out for them (gasoline stations) and action radius is in excess of 400 km per tank for most models, the market attractiveness of BEVs is affected by the lack of specific infrastructure. Therefore, especially at the early stage of its development, the BEV technology will face difficulties to compete with the established technology of ICE vehicles.

Pattern of product market penetration

Novel consumer products usually follow a market penetration pattern called 'S-curve'. The initial sales are low but increasing, followed by a steep increase in sales and lastly – towards the point of market saturation – sales show a slowdown (Rogers, 2003). The market share development is illustrated in *Figure 14*.

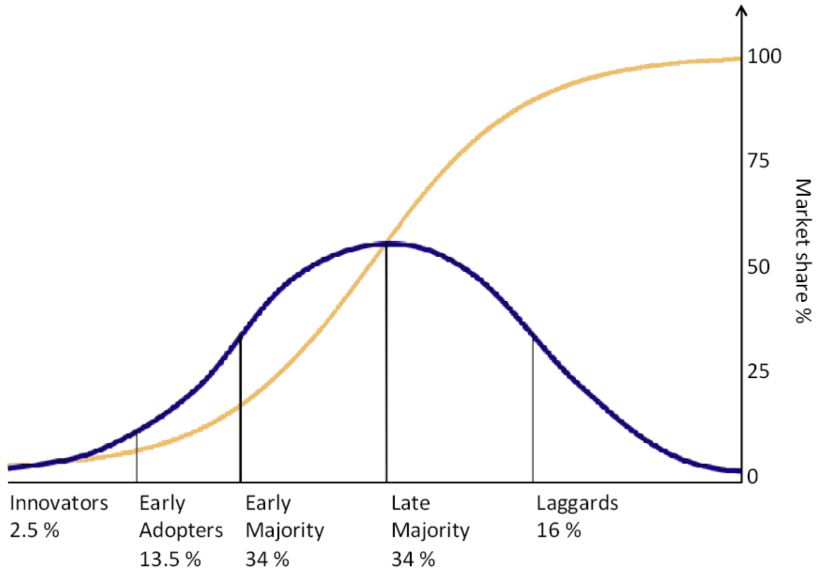


Figure 14: Market penetration 'S-curve' (Movares, 2013)

Initial sales/Innovators

The market penetration for EVs is likely to follow a similar 'S-curve' pattern. The reason for this lies in the high initial purchase costs compared to ICE vehicles. Further factors such as limited EV production capacity, incompatibility of conventional infrastructure for charging EVs, technological immaturity of EV batteries - limited action radius between charges -, and early (perceived) range anxieties have not been refuted for the majority of potential adopters. The early market penetration is a key to the overall success of EV adoption.

The initial sales depend on the innovator consumer group and are supported by incentivising EV adoption. Production growth remains limited by small economies of scale and required capital intensive ramp up investments. Over the past 8 years a total of only 1.2 million EVs has been produced with the cost of a production facility for 500,000 vehicles/year are estimated at $1-2Billion. and if batteries are manufacturer made an additional $5Billion is estimated to serve 500000 vehicles with their batteries (UBS, 2014a). The cost developments of EVs are discussed subchapters *3.2.2 Determining EV sales - 'Total cost of Ownership'*.

Early adopters/majority

Amongst the early adopters/majority are the 'early' mass-market consumers, which are still likely to benefit from (potential financial) incentives to adopt an EV. During this rapid growth period a *'critical mass'* will be reached, which suggests that *"the innovation's further rate of adoption becomes self-sustaining…"* (P. 344; Rogers, 2003); Once sufficient EV market penetration has been achieved, the production of EVs and expansion of charging infrastructure is expected to become a self-sustaining business. Further developments and market penetration will be self-induced with decreasing prices due to increased economies of scale, improved technologies and exposure.

More information regarding the charging and charging infrastructure was described in *chapter 2.3.3*.

Late majority/laggards

The late majority but especially the laggards will transition to the new innovation after the innovation has achieved a dominant share in the market. The late majority/laggards can enjoy advanced technological developments and market competitive pricing. However, among the laggards some might be force into buying an EV as some countries already consider regulations to ban ICE vehicle sales. The Netherlands and Norway are investigating to implement such measures as soon as 2025.

More information on '*Political targets and support schemes*' and '*EV drivetrain technologies*' can be found under the respective headers in chapter 2 '*Theory*'.

3.2. EV adoption model

While the EV market penetration is likely to follow an 'S-curve' (See chapter 3.1 '*Market penetration characteristics EV*'), the Gumpertz function was used to illustrate an S-curve growth development. The model has been set up utilizing the regression analysis method of minimizing the sum of square residuals, or Root Mean Square Error (*RMSE*) (Trappey & Wu, 2008). Initially the model was run for the EU28 countries in order to calibrate and evaluate the differences between the results. The results for EU28 can be found in the model accompanying this master thesis but only the German results will be reported in this thesis.

As the EV market penetration follows an 'S-curve', it represents a non-linear function. For non-linear functions the minimised sum of square residuals (optimal solution) has to be found irrelatively, in other words, the model is set to search for the best-fit 'S-curve' function taking into account all values set by the user. The input values are comprised of the historical EV adoption data, global EV outlooks and political targets. The 'S-curve' function determines the (German) EV stock, while the global EV outlooks used gave percentage of sales as their forecast. However, the annual sales were derived from the stock. The annual sales are based on the stock growth, this provides the opportunity to relate the results to the global EV outlooks. More information on the model characteristics will be discussed in *chapter 3.2.1 'Modelling market penetration'*.

Several adjustments have been applied to create a baseline scenario for EV adoption. Global outlooks on EV adoption have been compared and the differences were evaluated, European political targets have been taken into account and lastly historical EV adoption also plays an important role in EV adoption, especially in combination with EV incentives. The EV outlooks from (Bloomberg New Energy Finance, 2016; IEA, 2013; UBS, 2014b) have been used as reference outlooks. These outlooks estimate EV market penetration in terms of percentage EVs sold compared to total annual vehicle sales.

Together with this information a model was developed to estimate market penetration of EVs. The model is of modular nature and is set for use beyond its initial purpose as part of this master thesis. E.g. the assumptions used for the purpose of this analysis can be amended and extended (e.g. political targets, historical data, assumptions regarding market in question.

3.2.1. Modelling market penetration

In order to forecast the market penetration along an 'S-curve' profile, the Gompertz function introduced by Benjamin Gompertz can be utilized (Trappey & Wu, 2008). The Gompertz function is a relatively simple mathematical formula describing a 'S-curve' profile which can be used to match growth (i.e. market adoption rate), displacement along the x-axis (i.e. adoption lag) and an upper limit in the form of an asymptote (i.e. addressable market). As only a small change in total vehicle stocks (<<10%) in Germany is expected over the years up to 2035, vehicle stock is assumed to be stable over the time series. Therefore mathematical formula of extended logistic model was not chosen (Trappey & Wu, 2008). The Gumpertz function is as following;

$$y(t) = ae^{-be^{-ct}} \tag{1}$$

Whereby (see *Figure 15*) ;

- *a* describes the asymptotic upper limit or addressable market, because the '*power to'* can only achieve a maximum of zero, than *a* is the result, illustrated in *Figure 15* as the black line;

$$\lim_{t \to \infty} ae^{-be^{-ct}} = ae^{0} = 1a \tag{2}$$

- *b* describes the displacement along the x-axis or the adoption lag, illustrated in *Figure 15* in blue;
- *c* describes the growth or adoption rate (steepness of the curve) over the time series ,illustrated in *Figure 15* as the red line.

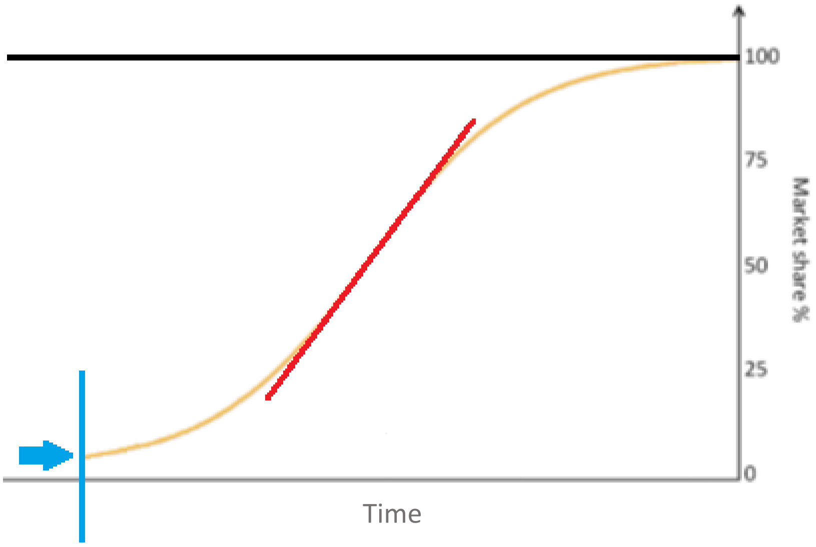


Figure 15: Gumpertz function illustration.

As described in the (Trappey & Wu, 2008) article, the upper bound, or (upper) asymptotic limit, should always be estimated before estimating the other parameters. The total amount of vehicles present in a country is assumed to be stable over time, and was estimated for the end of the time series. Present-day vehicle stocks do not present a limitation for EV adoption just yet, as they currently do not have a significant market share. More on the estimation of addressable vehicle stock will be discussed under in this subchapter.

As for the variables, in the infinite future, year $\lim_{t \to \infty} t$, variable a describes the upper limit, or total addressable market/total vehicle stock, based on the assumption that a certain saturation limit of vehicle ownership per inhabitant per country is achieved. If we combine that figure with the expected amount of inhabitants of the targeted geographical area (country) in year t, than an estimated vehicle stock adoption can be calculated per country.

To describe a certain initial delay in teams of electric vehicle deployment, i.e. adoption lag, b describes the 'offset' on the x-axis. This simply translates to a delay in adoption along the time series by the amount of b (in this case years). To ensure a better match of the historical data and the related growth, the back-cast projection of the 'first year' of significant EV adoption (sales of >500), b is used.

The growth rate, i.e. the rate of EV market penetration, is described by c. By constraining the EV growth to a maximum yearly growth, which is based on a 100% percentage of current yearly vehicle sales, the growth c is limited to represent a maximum of yearly sales in a region. Total sales can of course still achieve higher than 100%, but for EV adoption this 100% is a limiting factor as a guide-line. Estimation of addressable vehicle stock

For the estimation of total market capacity for vehicles, and thus for EVs, the estimated German population in 2050 was used. The model results are only shown up until 2035, but for a correct market penetration development 2050 was chosen as end-date for the model to run to. This has to do with both political target set at 2050 as well as a sufficient delta of 15 years after the presented 2035 results. The last 15 years near the asymptotic limit and have therefore a smaller overall impact. The population expectations were previously divined within the thesis host-organisation of Uniper Global Commodites (Germany) at 79.9Million, whereas Shell's estimations of German population are slightly lower, at 77Million in 2040 (Shell, 2014).

Combined with the Eurostat data on passenger vehicles per 1000 inhabitants, which currently sit at around 0.53 vehicles per inhabitant for Germany, this gives an estimated 42.3M German vehicle stock in 2050. Now of course this is a simplified calculation method, and is comprised out of the total vehicle stock (all propulsion technologies combined).

To account for the uncertainty regarding the 42.3M vehicles in 2050, a certain degree of freedom have been given to the model input, whereby the model was said to target only to 80% EV market stock in 2050 with 25% degrees of freedom on either side (achieving a maximum of 42.3M vehicles a minimum of 25.4M vehicles in 2050). Justification on such a significant market share will be discussed throughout this chapter but some main arguments are;

- Lower TCO for EVs is estimated to be achieved before 2030;
- European Commission CO_2-reduction targets in the transport sector require 8% vehicle stock to be electrified;
- Political EV adoption targets are in-line, especially in a later stages of the time series;
- Some European countries are already looking at banning sales of ICEs by 2025, whereby the Netherlands and Sweden are actively discussing the possibilities in parliament. Regarding EV targets, Western-European have in the past shown a correlation between E-mobility targets.

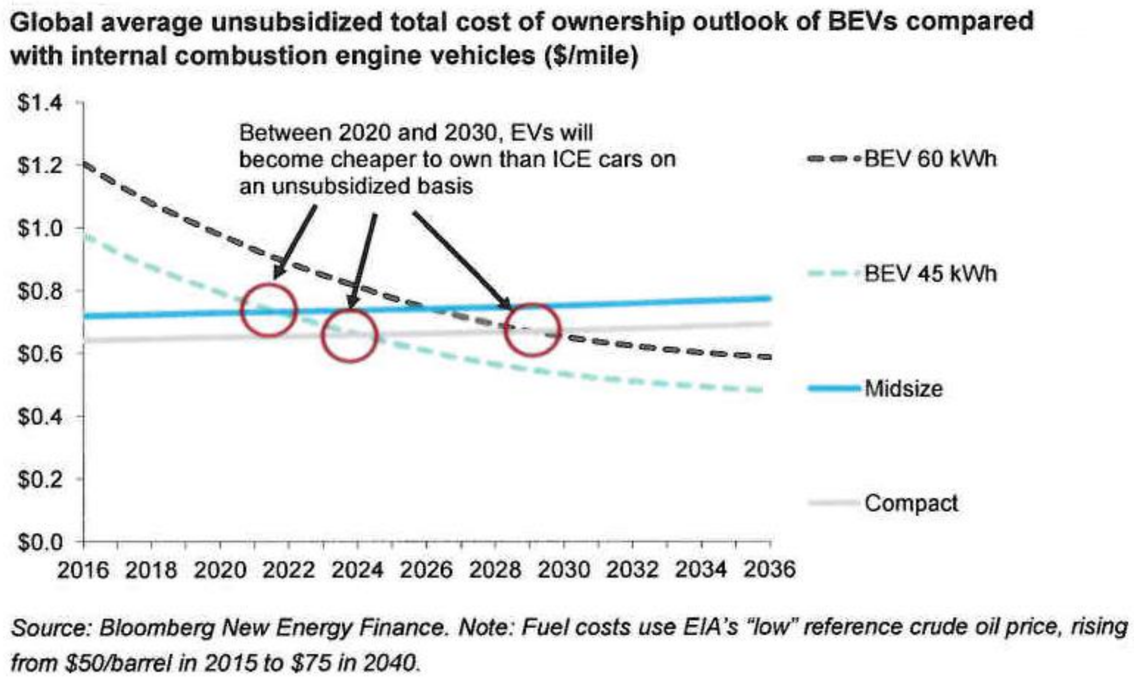
3.2.2. Determining EV sales

As multiple sources used to not provide EV stock numbers, but rather EV sales numbers (on a yearly basis) it is important to distinguish stock from sales in order to be able to compare inputs and outputs. Year on Year(YoY) EV stock growth comprises of both new additions to the stock for new adopters, but in due years it will also comprise of the EVs that will be replaced by end of life EVs. This is something that is important to take into account looking at EV sales over an time series of 10 to 50 years. For now, 'EV to EV replacement' (based on sales in year $t - t_{replace}$) has been set to 10 years to match battery calendar life, however this is more than likely to change with battery developments and/or battery replacement schemes (and this value can also easily be changed within the model).

Explained in more detail, if year *t* would be 2035, the projected 'S-curve' growth of year 2034 to 2035 would give for example 1M vehicles, however in year $t - t_{replace}$, *giving 2035 – 10 = 2025* or *t-10,* EV stock growth 2024-2025 stood at 100k vehicles. By subtracting *t-(t-10)* stock growth*,* it is derived that actual new additions of EVs are 900k vehicles, instead of the 1M vehicles sold in the year 2034-2035. Now this will happen again for 2045 and 2055, etc. These replacement-waves have been modelled (up to 5 times) in order to account for new sales and replacement sales. Eventually EV sales will saturate and close to a 100% of EVs sold will be a replacing an EV, as the addressable market is already saturated. The justification for EV market saturation follows from the general consensus that electric vehicles will be most cost efficient in achieving GHG-emission reduction targets, and TCO will become less than conventional ICE somewhere between 2020 and 2030.

Total cost of ownership

The total cost of ownership of a BEV is expected to be competitive with ICE vehicles by 2022 for the first models as indicated by the below *Figure 16* of (Bloomberg New Energy Finance, 2016). What divines the offset of BEV TCO vs. ICE is the drivetrain. The majority of the vehicle is relatively comparable in terms of cost and design, so any competitiveness gained implicitly means evaluating the cost of ICE and it's components against the cost of an electric drivetrain and its battery.


Global average unsubsidized total cost of ownership outlook of BEVs compared with internal combustion engine vehicles ($/mile)

Source: Bloomberg New Energy Finance. Note: Fuel costs use EIA's "low" reference crude oil price, rising from $50/barrel in 2015 to $75 in 2040.

Figure 16: TCO competiveness of BEV vs ICE.
(Bloomberg New Energy Finance, 2016)

Cost components of TCO

The total cost of ownership is made out of several cost components during the lifetime of an vehicle. These include the initial purchase price, maintenance during vehicle lifetime, fuel costs and road taxes and/or other taxes levied.

Purchase price

The purchase prices comprises of initial purchase and a certain set interest rate for financing the purchase, comprising the down payment cost and depreciation costs. These are translated to a yearly cost, as maintenance, fuel cost and road tax are all yearly costs(UBS, 2014a).

However what is often not mentioned is that the production costs of ICEs will rise, due to stringent GHG-emission regulation the production costs of conventional ICEs are expected to rise. In order to meet 2020 GHG reduction targets, i.e. to cut emissions by roughly 35%, around €1000 in additional production costs are anticipated, to achieve the next 15% GHG reduction for targets beyond 2020 an additional €1000 production costs are anticipated (Mohr, D; Muller, N; Krieg, A; Gao, P; Kaas, H W; Krieger, A; Hensley, 2013). Especially in smaller-mass market vehicles these amounts are a significant burden on the initial purchase price, accounting for respectively 20 and 40% of drivetrain related production costs (UBS, 2014a).

Maintenance

Maintenance for BEVs is often perceived as lower, due to the fact that there only a limited amount of mechanical parts that move during vehicle operation. However, maintenance for PHEV is likely to be higher than ICEs, as they have a more complicated drivetrain combining both of an ICE and electric engine and battery. UBS indicates that maintenance of a BEV could be half the cost of that of an ICE vehicle (UBS, 2014a).

Fuel cost

The fuel costs varies from country to country and TCO varies with fuel costs. The absolute level of fuel costs are not so much as important, but the relative difference between gasoline and/or diesel and the amount of electricity obtained is of importance. For example, if US gasoline prices vs. electricity prices are compared to German prices, it is clear that US prices are about 20% (medio June) more favourable, while taking into account energetic losses within the vehicles[4]. Meaning that in the US TCO parity between ICE and BEVs will be achieved earlier than in Germany.

Road tax

Road tax is also an important parameter, when (partly) based on rated CO_2-emission this provides an advantage to BEVs and PHEVs. However, when no connection is made with CO_2-emissions, the road tax before incentives is not relevant for TCO competitiveness and can even be negative when based on vehicle weight, as PHEV and BEVs are usually heavier than their ICE counterparts.

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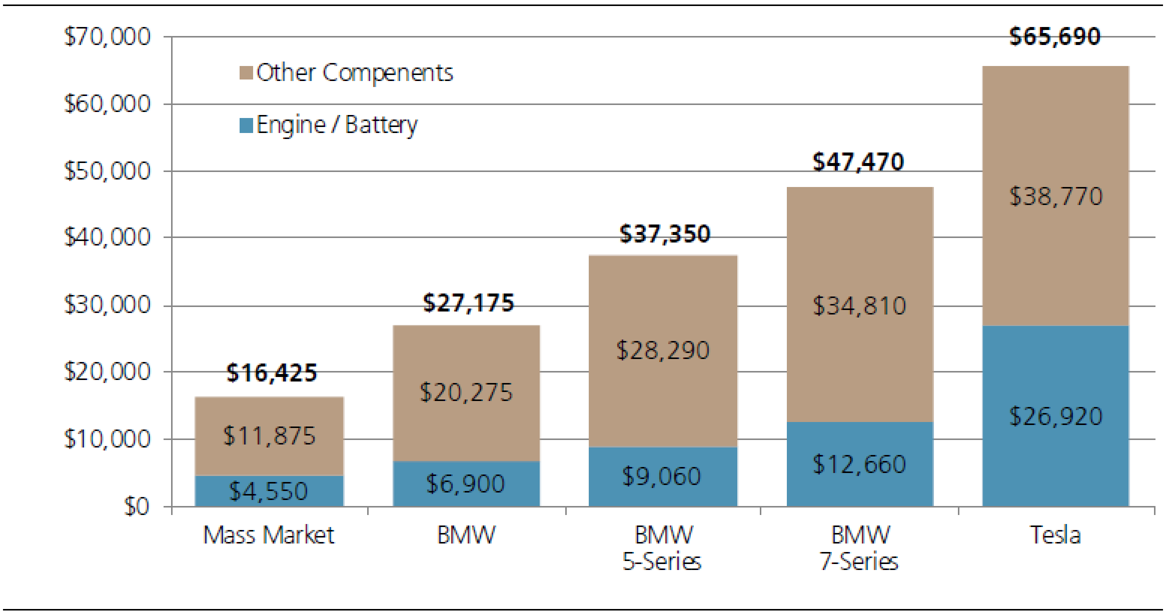
[4] Based on US 0.55 €/litre and 0.10 €/kWh vs. DE 1,35 €/L and 0.30 €/kWh For extended calculation see the EV adoption model.

Electric vs. ICE drivetrain costs

The battery costs of an EV make up the lion-share of production costs on a component level. Based on a 2014 study conducted by UBS up to 41% ($26,920 of the $65,690) of the costs in the production of the he luxury EV Tesla model S are estimated to be associated with an 80 kWh battery pack and its electrical engine (UBS, 2014a). In comparison, an ICE in the same class, in this case the BMW 7-series, was estimated to have around $12,660 of variable cost for the ICE. This means that in 2014 the drivetrain offset was $14,260 for a Tesla model S compared to a BMW 7-series, whereas other component cost differences were found to be quite limited (UBS, 2014a). In *Figure 17* estimated costs of several vehicles is shown.



Source: Company reports, UBS estimates

Figure 17: Electric vs. ICE drivetrain costs luxury segment.
(UBS, 2014a)

Battery price development

Emerging energy technologies have a tendency to see a certain decline in production costs over each cumulative doubling of production numbers. The specific decline in cost per doubling can be described (in the long term) by the experience curve. Especially the cost of energy technologies have the tendency to be somewhat predictable over longer periods (IEA, 2000).

Due to the relatively high raw material costs, only a certain level of price reduction can be achieved. The cost reduction of conventional lithium-ion batteries is assumed to be a function of economies of scale, but affected by safety trade-offs, battery management, and replacement costs etc. The sources used to reference battery price developments make use of battery price forecast models such as BatPac, i.e. (Bloomberg New Energy Finance, 2015e).

Following the end 2015 battery price survey of Bloomberg New Energy Finance, **average** BEV battery pack prices dropped from $495/kWh in H2 2014 to around $340/kWh in H2 2015 (Bloomberg New Energy Finance, 2015b). This represents a staggering 30% year on year drop off battery costs, these results were believed to be caused by three main reasons. First off, the technological developments drove battery cost down, about 6% for each previous year(Bloomberg New Energy Finance, 2014). Secondly, increasing economies of scale of new built battery production plants are driving down battery prices. Lastly, the drop in price could be the result of aggressive pricing by the larger battery manufacturers as there is currently a severe overcapacity in battery production capacities (Bloomberg New Energy Finance, 2015b).

Taking into account the 30% year on year cost reduction, the UBS electric drivetrain cost estimate of 2014 would translate to around $18.884 costs in 2015. This reduction is not taking into account that the electrical motor forms part of the EV drivetrain cost, however the estimation is based on **avarage** battery prices. For bigger companies, battery prices are likely to lower than avarage. In terms of reduction, this translates to a year on year reduction of approximately $8000 euro of drivetrain costs and would only leave a further cost offset of ICE vs. Electric drivetrain of around $6000 in 2015.

However, historically spoken and excluding 2015 reduction hike of 30%, cost reductions of around 6% on a year on year basis where previously achieved (Bloomberg New Energy Finance, 2014). Thus requiring about 6 to 7 more years of historical cost reductions to achieve drivetrain cost competitiveness, creating a cost competitiveness in 2021 or 2022 for luxury BEVs. However, giving the scaling of range with size, lower segment BEVs with higher battery capacities would not have a competitive TCO by 2022, as indicated in *Figure 16*.

These results assume there is enough theoretical room for improvement of EV battery chemistry, assembly and without a significant increase in material costs. More on technological developments can be found in the next subchapter ‘*technological developments*’.

PHEV TCO vs BEV

Currently PHEV batteries are about 30% more expensive than BEV batteries, and they will always remain more expensive as requirements for power output against energy capacity are far higher than BEV batteries. However, because battery sizes of PHEVs are smaller than 10kWh, the total costs of the battery pack remains lower than BEVs. For most TCO calculations the BEV battery pack is shown, as PHEV battery packs can vary in size and their impact is less important due to the combination with the ICE drivetrain (Bloomberg New Energy Finance, 2015b).

3.2.1. Setting targets

In order to give the ‘S-curve’ it’s projection, a certain set of inputs is required. The inputs create the basis on which the best-fit ‘S-curve’ will be found using the RMSE method in combination with the Gumpertz function. The input targets for the model are comprised of historical EV adoption data, global EV outlooks and the political targets.

Additional constrains can be given as desired, presently constrains are set for an absolute cap on yearly vehicle sales. The cap for yearly EV sales was set to match 100% of 2015’s 3.2M German vehicle sales (Best-selling-cars.com, 2016).

Because of the relatively low significance of early day EV adoption characteristics, an additional weight factor had to be assigned to the data which is not targeted by the model as asymptote. In other words, to increase the relevance of numbers in comparison with the targeted market saturation, additional weight had to be assigned to these numbers. In order to do so, the difference between the furthers most target and the number in question has been ‘squared’ to give a more equal weighting. This ensure that the model will attempt to match historical data, whereas these small numbers would otherwise have been completely insignificant, thus not providing an accurate start of EV adoption.

3.3. Calculating energy demand

The energy demand resulting from electric driving is calculated according to current passenger car driving profiles. Calculating the final electricity consumption, or energy demand, is relatively straight forward. Electric vehicle 'fuel consumption' is measured in [kWh/km]. With a given annual mileage, annual energy demand can be calculated by a simple multiplication of average Specific Energy Consumption (SEC) per kilometre times mileage per annum;

$$Average\ SEC \left[\frac{kWh}{km}\right] \times \text{annual milage} \left[\frac{\text{km}}{a}\right] = \text{Energy demand}[\frac{\text{kWh}}{\text{a}}] \tag{3}$$

The SEC is comprised of both PHEV and BEV electric kilometres driven. The factors to determine the average SEC are the ratio of PHEV vs BEV, and for PHEVs, the ratio of electric kilometres driven vs. 'combustion' kilometres driven;

$$Average\ SEC \left[\frac{kWh}{km}\right] = SEC\ PHEV \left[\frac{kWh}{km}\right] * PHEV\ Share[\%] + SEC\ BEV \left[\frac{kWh}{km}\right] * \ BEV\ Share[\%] \tag{4}$$

With;

$$SEC\ PHEV\ \left[\frac{kWh}{km}\right] = SEC\ \left[\frac{kWh}{km}\right] * \ electric\ km's\ share\ [\%] \tag{5}$$

The energy demand will represent an annual average, based on average driven profiles. Different scenario assumptions are linear in relative impact, as can be deduced from the above formulas.

3.4. Calculating power demand

The power demand calculated for Germany is based on maximum charging standards, and currently publically installed chargers which represent a certain ‘charging-mix’. Additional scenarios will be discussed in the scenario analysis. The power demand will be calculated for worst case scenarios as actual power demand during battery charging is not linear, it depends on battery characteristics, on-board battery management systems and level of battery depletion, see *‘Charging behaviour of Lithium-ion batteries’* under *chapter 2.3.3*. First domestic or private charging will be discussed, followed by public chargers (including fast-chargers), based on the current ‘charging-mix’ and lastly an extreme scenario of fast chargers only.

For domestic charging the maximum power output of type 2 AC chargers is 3.7kW, based on 230V and up to 16 Amperes (see *‘Charging levels’* under *chapter 2.3.3*). However, a large share of models can currently only accept up to 3.3kW charging power input (EVObsession.com, 2015). This results in a maximum power output of 3.3 to 3.7kW for domestic charging.

For public charging the actual German ‘charging-mix’ was derived and averaged out to give an average maximum power output of 26kW. See *Table 6* for the composition of charging standards available at charging stations in German (as of June 2016). The ‘Avg. Max. power’ was derived from the maximum power output per standard, as these may vary depending on the instalment, see Appendix 1 installed capacities per standard.

Table 6: EV chargers in Germany.
(Going Electric, 2016)

	Avg. Max. power (kW)	***No. chargers***	***Total installed power (kW)***
CHAdeMo	34.9	307	10700
CCS	38.7	397	15350
Type 3	22.0	6	132
Type 2	19.3	8472	163605
CEE Rot[5]	15.8	900	14256
Tesla superchargers	120.0	369	44280
Tesla destination chargers	19.2	16	307
Total		9561	248630

For fast-charging the CHAdeMO’s maximum operation power output of 50kW was used, however the Tesla superchargers have a far higher power output at 120kW and are installed at 60 locations with a combined power output of 44MW. But of course the downside is that these can only be used by Tesla owners, and when translating these numbers to an estimated German EV stock of 10.5 Million in 2035, it is highly unlikely that these will all be Tesla’s. Furthermore, Tesla’s are able to charge at CHAdeMO charging points using an adaptor.

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[5] Including 1 CEE + charger with an maximum power output of 7.2kW.

4. German EV scenarios

Key takeaways

- In Germany 1M EVs have an average annual energy demand of roughly 2.4TWh, based on an average annual (German) mileage of 13,500km, a specific energy consumption of 0.19kWh/km driven and a (German) PHEV share of 22% with an 78% share of electric mileage;
- Simultaneous charging of 1M EVs requires 3.5 to 3.7 GW of power for domestic charging and could require up to 26GW for public charging in a worst case scenario (see next bullet).
- Simultaneous fast charging of 1M EVs would *currently* require up to 50GW (or 120GW in Tesla's case) in a worst scenario; I.e. if all EVs have exactly the same battery characteristics, size and management system, all started charging within a 10 to 15 minute timeframe, and with equal battery depletion levels, somewhere below 30% of total battery capacity. It can be concluded that this is a very unlikely scenario.

Major Assumptions

- Political targets are assumed to be one of the leading indicators of EV penetration and EVSE deployment up to 2035, along with TCO parity with ICEs after 2025.
- Current ratios of chargers are likely to drop, as EV infrastructure is currently well represented vs. the amount of EVs in German.
- No economic crisis or (global) events will disrupt EV adoption up to 2035.

For Germany EV adoption up until 2015 has been rather slow, coming in at just over 53,500 registered EVs. The initial adoption of EVs was not very extensive, perhaps because incentivising has not been comparable with countries that have seen relatively higher EV adoption (McKinsey, 2014). However, with the recently introduced incentives to boost EV sales (Bloomberg, 2016), perhaps adoption rates will increase. The EV scenarios below are focussed on energy demand than on EV stock demand, as the changing the reference scenario of EV adoption will be straightforward in translating of annual energy demand and power demand.

4.1. EV adoption Scenarios

Using the developed EV adoption model, the German EV market penetration, the results based on political targets, TCO, yearly sales, addressable market and historical data will be presented in this section.

4.1.1. German EV market penetration

First off, to relate the German EV numbers, the total amount of registered German passenger vehicles was believed to be 45,071,209 at the start of 2016, whereas German passenger vehicle sales came in at 3203042 for the year 2015 (Best-selling-cars.com, 2016b, respectively 2016a). Over the past few years annual sales have been relatively stable sales levels, however total German vehicle stock is increasing slightly. As overall population is expected to decline (Shell, 2014), it is likely vehicle ownership will also see a decline in the years up to 2050.

Table 7: German vehicle sales and stock.

	2010	***2011***	***2012***	***2013***	***2014***	***2015***
Vehicle sales	2,916,260	3,173,634	3,082,504	2,952,431	3,036,773	3,203,042
Vehicle stock	42,301,563	42,927,647	43,431,124	43,851,230	44,403,124	45,071,209

As for EV adoption forecast, the model results are summarized in Table 8. Annual EV adoption data, underlying subsequent *Figure 18* can be found in appendix II. For the year of 2015, historical German data was used, and this number represents the 'data edge'. As it is historical data, the same number can be found for Germany in '*chapter 2.2.2 Global EV stock history*'.

Table 8: Key numbers for EV adoption.

	2015	***2020***	***2025***	***2030***	***2035***
EV stock	53,534	459,034	1,992,882	5,372,870	10,499,327
EV sales	25,209	141,740	439,985	833,210	1,129,615
EV replacement	-	-	13,500	105,028	380,734

When relating this to the political targets set by the German national government, at 1 Million EVs by 2020 and 6M EVs by 2030, some discrepancies exist. The 2020 target will be missed by a long shot, coming in at only at an estimated 45.9% (or 459,034) of the targeted EV stocks. However, 2030 targets are likely to be met for 90% of the targeted EV stock number according to the model.

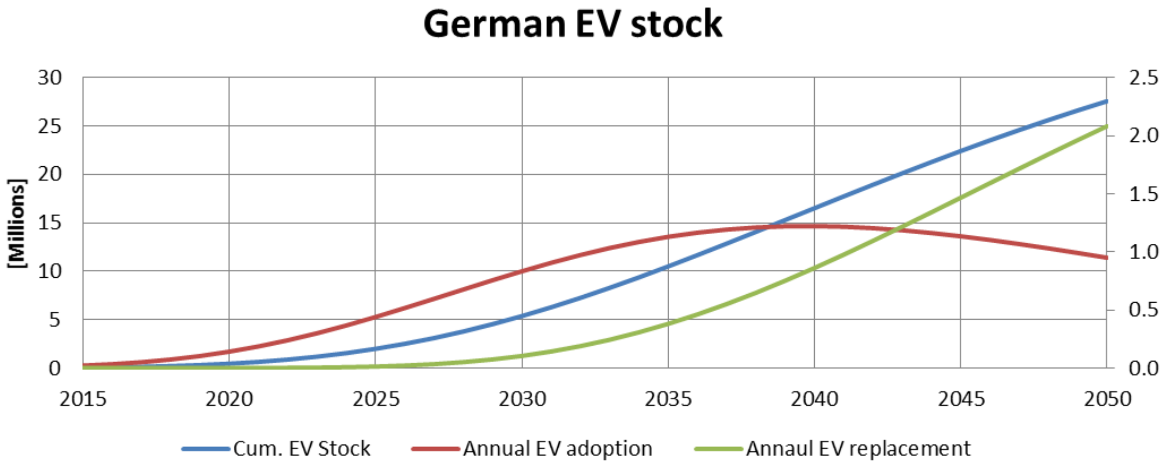

Figure 18: German EV market penetration.

EVs are expected to surpass a 10% vehicle stock in the year 2028-2029, by 2035 23% of all German passenger vehicles is expected to be an EV. In the year 2032-2033 the highest EV adoption growth for EVs can be witnessed at an increase of 789,784 additions to German EV stock YoY. After 2033, the end of life EVs[6] being replaced by EVs reduce the new additions to EV stock.

Given that EV TCO is expected to be comparable to ICE vehicles by 2025-2030 (Bloomberg New Energy Finance, 2016; UBS, 2014b), the model incorporates this turn-over point as EV sales are picking up rapidly, with 2030 sales almost doubling 2025 EV sales.

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[6] An EV lifetime of 10 years is assumed based on battery calendar life, battery replacement has not been taken into account and could have a significant impact on replacement of the vehicle.

4.1.2. German EV Energy demand

The energy demand for EVs is an estimated 2.44 TWh per Million EVs, following from an average milage of 13,500 km/a (Kalinowska & Kuhfeld, 2006), average SEC of 0.19 kWh/km (Dudenhöffer et al., 2014; Figenbaum et al., 2015). Of course, for PHEV the mileage is not directly related to electricity consumption and an average SEC has to be calculated. To calculate the average SEC a PHEV share of 22% was assumed (Insideevs.com, 2014) and on average about 78% kilometres driven by PHEV drivers was electric (Fraunhofer Institute, 2013). Using *equations 3 through 5*, the average annual energy demand resulting from EVs (based on current driving profiles) is an average of 2440,85 kWh per EV.

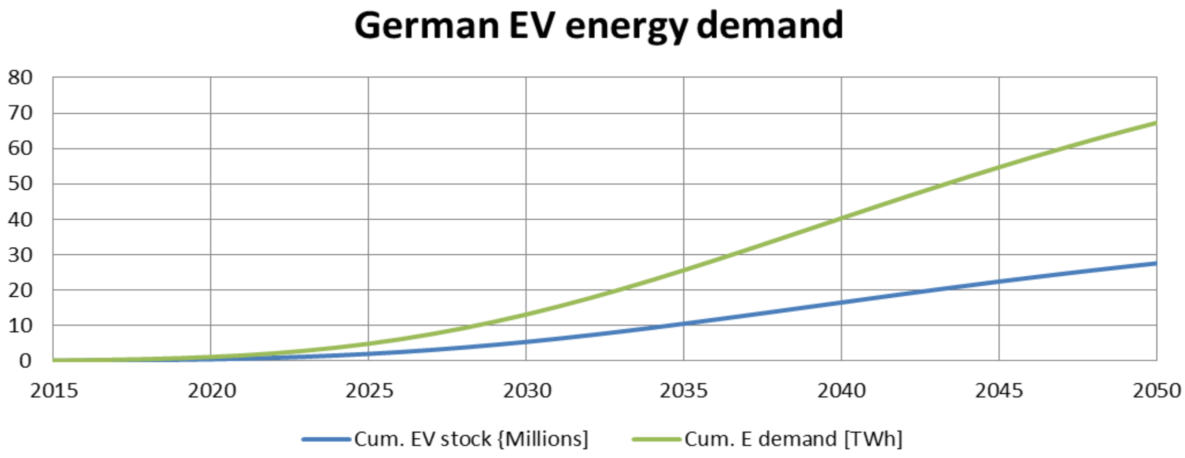

Figure 19: German EV related energy demand.

4.1.3. Validation of the results

The obtained results of the model have been validated with the Fraunhofer institute (*Patrick Plötz, Karlsruhe, May 2016*), which have performed extended EV studies, including German EV penetration studies up to 2020 (Fraunhofer Institute, 2013). Furthermore, although partly based on global EV outlooks (Bloomberg New Energy Finance, 2016; IEA, 2013; UBS, 2014b), the developed EV adoption model has shown relatively similar results for Germany, especially for EV adoption in early forecast years 2015-2020. Whenever applicable the model predicted slightly higher growth rates, which is due to more recent data input. There is also a tendency for the covered reports to underestimate initial EV uptake, something that is not witnessed in the developed EV adoption model. However, as of late may the German authorities reached agreement on implementation of an additional support scheme, this has not been taken into account. This new support scheme is discussed in *chapter 2.2.1* and is likely to hasten EV adoptions up until 2018.

For the energy demand calculations there is limited room for errors, given the variables resulting from different literature sources and the linear relation to EV adoption. Most sources are in range of 2-3 TWh, the lower is attributed to smaller driving range, thus limiting annual mileage. The higher estimates are linked to a different vehicle utilization, with shared driving profiles and/or relatively lower cost per km.

4.1.4. Sensitivity

The sensitivity for input parameters have been addressed for EV stock. By changing inputs the adoption model by +/- 10% the EV stock results presented in Table 9 were obtained. The inputs altered can be found in *equation 1* (*chapter 3.2.1).*

Table 9: Sensitivity Analysis EV adoption.

		2020	**2025**	**2030**	**2035**	**2035 Energy demand [TWh]**
	Base	459,034	1,992,882	5,372,870	10,499,327	25.63
Addressable market (a)	*-10%*	413,131	1,793,594	4,835,583	9,449,394	23.06
	+10%	504,937	2,192,171	5,910,157	11,549,259	28.19
Adoption lag (b)	*-10%*	291,975	1,468,068	4,370,622	9,132,590	22.29
	+10%	721,679	2,705,311	6,604,947	12,070,603	29.46
Adoption rate (c)	*-10%*	317,294	1,360,509	3,783,268	7,760,791	18.94
	+10%	645,840	2,798,052	7,251,397	13,459,808	32.85

As can be concluded from Table 9, the model is most sensitive to changes in adoption rate. This is in line with expectations. Assuming that adoption lag would only displace EV uptake by a year (=10%). Furthermore, the addressable market, representing a 100% is a saturation level, will scale S-curve along it's whole length. For Adoption rates, the steepness of the S-curve is directly affected and affects growth on an annual basis.

4.2. Power demand scenarios

For the power demand three different scenarios have been developed. A scenario for domestic, public and fast-charging. These scenarios are based on maximum power outputs by standard and deployment ratios of the respective charging method. Annual numbers can be found in Appendix II.

4.2.1. Domestic charging

Domestic charging currently accounts for up to 95% of annual EV energy demand (EVObsession.com, 2015). With domestic charging, charging power does not exceed 3,68 kW per EV for AC charging. This leads to a relatively straight forward domestic charging power demand of 3,7 TWh per million EVs under worst case conditions. However, for the overall 2035 power demand a ratio of 0.8 domestic chargers per EV was taken as baseline, based on German national targets (Dudenhöffer et al., 2014).

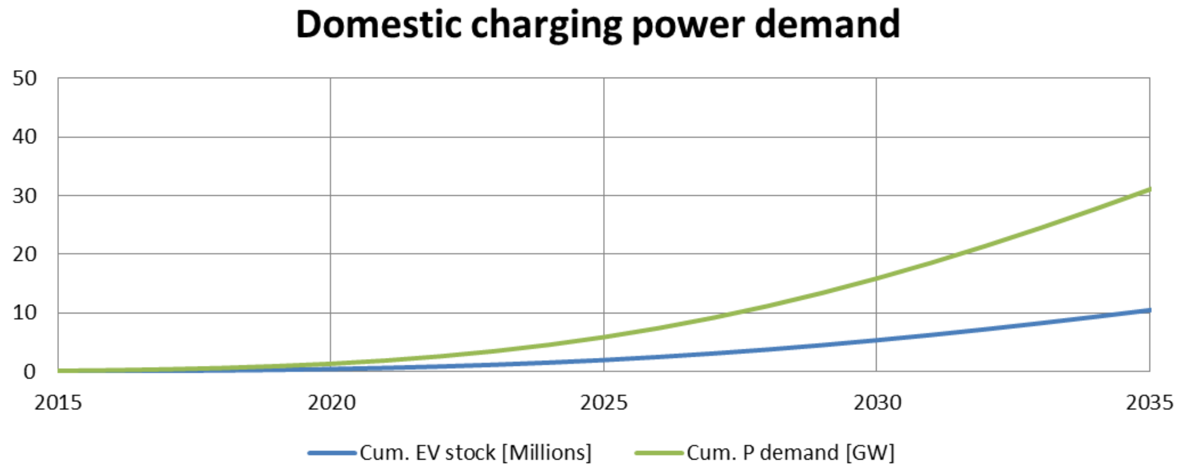

Figure 20: Domestric charging power demand.

This scenario is not unlikely to occur, given that no load shedding 'smart-charging' technologies will be developed. The charging power of different EV models ranges from 3.3kW upwards, and is expected to increase in the future. By limiting charging power to 3.3kW, even for the smaller PHEV batteries a charging time of 2 hours is more or less the minimum (E-vision, 2016).

4.2.2. Public charging

In Germany the charging infrastructure is quite biased towards the Type 2 chargers, making up almost 90% of the total amount of public chargers (see *Table 6*). The current German charging mix (June 2016) has served as a basis for this scenario, with an average maximum charging output of 26 GW per 1 million EVs. However, the overall ratio for installed public chargers is assumed to be 0.15 per EV which is in line with German public charger deployment targets (Dudenhöffer et al., 2014).

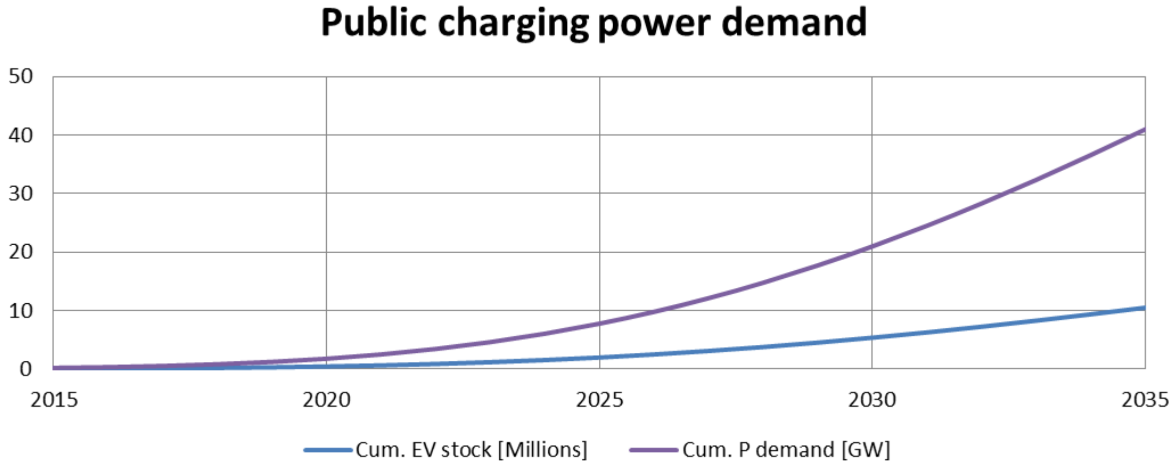

Figure 21: Public charging power demand.

The scenario of public charging and maximum power output is less likely to occur than the Domestic charging scenario due to several reasons. First of all, not all EVs are capable of accepting charging power of up to 26GW (average), let alone 50 or 120kW which were also taken into account in the June 2016 German 'charging-mix' (Going electric, 2016; E-vision, 2016). Furthermore, current PHEV batteries consist of batteries up to 10kWh (E-vision, 2016), even in 2035 scenarios it questionable if PHEVs would be able to accept C-rates up to 2.5 since they can rely on refuelling combustibles for longer trips where faster charging would be most convenient.

4.2.3. Fast charging

The fast-charging power demand scenario relies on a current operational maximum power output of 50kW, shared by CHAdeMo and CCS standards, discarding Tesla's 120kW fast-charging as only Tesla's can currently accept this amount of charging power and the overall charging stations only represent around 10% of fast-charging public chargers. A ratio of 0.07 fast-chargers per EV greatly limit overall impact (Dudenhöffer et al., 2014).

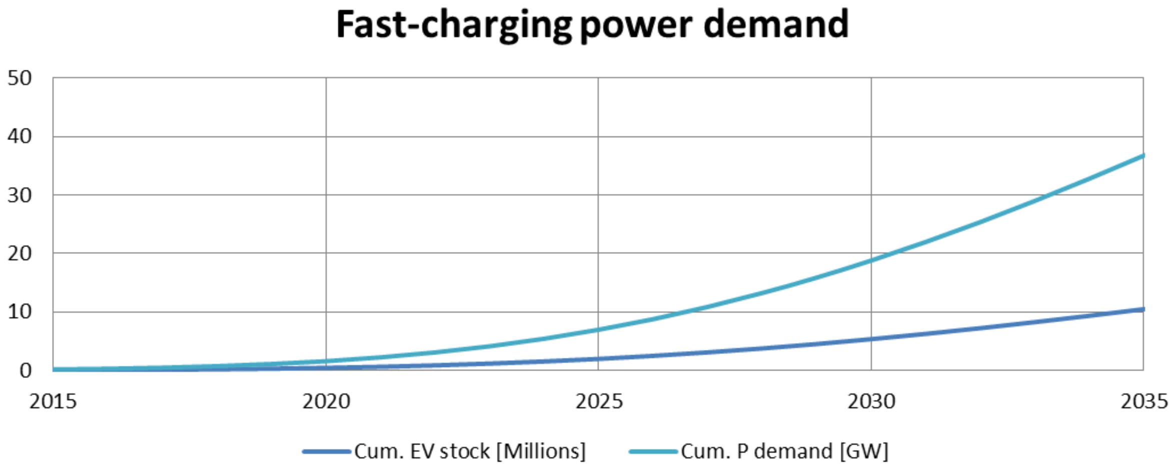

Figure 22: Fast-charging power demand.

The scenario of fast-charging is the least likely scenario to occur, given the very specific conditions of charging cycles with such higher powered charging connections. In order for this scenario to be achieved, the vehicle group would have to meet the following requirements;

- All vehicles must be able to accept fast-charging connections, current very few vehicles can accept direct DC-charging, and the only model which can accept 50kW or higher are the Tesla EVs (Ecomento, n.d.);
- The EVs would have to have the same battery chemistry, characteristics and size;
- The EVs would have to be at equal remaining battery capacities, below 30%;
- And lastly and most importantly, the EVs would have to be plugged in within the same timeframe, about 10 to 15 minutes.

It can be concluded that this scenario is very unlikely, however as higher charging levels are within the scope of automotive companies, this scenario might grow in overall German power demand impact.

4.2.4. Scenario results overview

The results of all the German power scenarios are shown in *Table 10*, with a cumulative EV stock of 10.5 Million in 2035, with an estimated energy demand of 25.63 TWh.

Table 10: Overview German EV power scenarios.

	Avg. maximum power output (kW)	**Assumed charger deployment ratio**	**Power load (GW)**
Domestic charging	3.7	0.8	31.08
Public charging	26	0.15	40.95
Fast-charging	50	0.07	36.75

As can be deducted from *Table 10*, all power scenarios are relatively comparable when it comes to impact. Especially the domestic charging scenario is likely to occur, given no ‘smart-charging’ is introduced. The domestic charging scenario is not limited by operational values, whereas both the public charging and fast-charging scenarios are.

4.2.5. Sensitivity

The sensitivity for the power scenarios are all of linear nature, by changing the avg. maximum power output, the total power demand increases or decreases in a one to one relationship. The sensitivity for EV stock has been discussed in *chapter 4.1.4*.

5. Discussion & Conclusion

In this section, the results will be discussed, and the research question will be answered.

5.1. Discussion

The results shown in *chapter 4.2.4* show that between 30 and 40 GW of additional power demand could be required for the evaluated scenarios by 2035. This is when no interventions for charging are introduced, which seems unlikely as currently peak and off hour tariffs for electricity are already available. However these scenarios are all based on worst case scenarios, wherein the maximum power output is taken for granted, discarding the specific charging behaviour of Li-ion batteries as discussed in *chapter 2.3.3.* Nonetheless, the scenarios indicate a worst case scenario and as such they serve the purpose of indicating the extreme situations that could possibly occur if no intervention is introduced.

By providing ratios of deployment for different charging standards based on political targets, the scenarios are more likely to occur. However, the deployment ratios are only a target, and currently a domestic charging connection ratio of almost 1:1 is witnessed (IEA, 2016), indicating that as of now, the targets are overachieved. As EV penetration is still limited, the 1:1 ratio is likely to drop, but it could well remain above the political target of 0.8:1 (Dudenhöffer et al., 2014).

The same does not hold for public and fast-charging, currently the ratios of deployment fall short of political targets, and a €300 Million incentive should boost public charger deployment (Bloomberg, 2016). Public chargers are currently present in a ratio of 1:10, and fast-charging in a ratio of 1:62.5(IEA, 2016), as opposed to the political targets of respective 1:6.7 and 1:14 (Dudenhöffer et al., 2014).

Furthermore, no specific deployment model of charger connectors, or EVSEs, has been developed. This might provide additional insights in power demand related to EV charging.

Regarding energy demand, results seem to be reliable as compared to other similar studies, this is perhaps caused by the relative ease of calculating energy demand per EV. As for EV stock development, this is of course a more unreliable estimation as there are many factors impacting EV sales and adoption. The sensitives presented in *chapter 4.1.4* show that only a slight adjustment to input parameters has a significant consequence for EV market penetration. As EV markets are still in its infancy it is recommended to follow the latest developments and to update the EV adoption model over the course of the next years.

The underlying input parameters for the EV adoption model are sensitive to future developments, such as the TCO parity and incentives to boost EV sales. The TCO developments are a well estimated guess, depending on a variety of factors, including fuel and electricity prices, raw material costs and tax and incentive schemes. As nobody can write the future, best guestimates is all that is available to make the best of predications, given certain constrains and assumptions. The validity of the results depends on current insights and knowledge, but those might change over the next 20 years.

This study focussed on German as case study, however results can be translated to additional Western European countries, given some discrepancies, e.g. political targets and TCO, are addressed.

5.2. Conclusion

This report aimed to assess the future EV penetration in Germany and its related impact on German power demand by answering the following research question;

"*How will the increased stock of Electric Vehicles affect the German power demand up until 2035?"*

In order to predict "*the increased stock of electric vehicles*", an EV adoption model was developed targeted at forecasting the German EV stock. The EV market penetration is based on general diffusion characteristics of consumer products, following a pattern called 'S-curve'. The forecast is, amongst others, based on inputs and constrains consisting of political targets, global EV outlooks, technological developments and historical EV adoption. The developed EV adoption model is based on the Gumpertz function and is of modular nature, set for use beyond its initial purpose as part of this master thesis.

Given the input and constraints, the EV adoption model forecasts a German EV stock up to 10.5 Million by 2035, while naturally showing most sensitivity to the growth-rates of EV stock. The results of the EV adoption model contribute to the scientific literature by forecasting German 2035 EV stock numbers. In addition, the model can derive annual EV sales and derive the amount of EVs being replaced by EVs at end of life, the replacement EVs are not amounting to absolute EV stock growth.

Following the German EV stock, the results for 2035 the '*German power demand*' caused by EV usage was calculated. The additional power demand resulting from EV usage was calculated for the scenarios of domestic EV charging, public EV charging according to the current 'charging-mix' and EV fast-charging.

In 2035, the maximum additional power demand resulting from domestic EV charging will rise to 3.50 GW per 1 Milllion EVs or, in worst case, 31.08 GW when simultaneously charging 80% of the entire 2035 German EV stock[7].

For public charging the June 2016 'charging-mix' would translate to an averaged maximum power output of 26 GW per 1 Million public charging connectors[8]. However, for public charging maximum power to occur is less likely, due to the implementation of optimal charging patterns for different battery sizes, chemistries and management systems. Applying a 0.15 deployment ratio of public chargers per EV, based on the total German 2035 EV stock, the public charging scenario would require up to 40.95 GW of additional power demand in a worst case scenario.

Lastly, fast-charging would currently impose an additional power load of 50 GW per 1 Million EVs. With Tesla's supercharger this could increase up to 120 GW, and manufacturers such as Porsche and Audi are aiming to increase charging power even further. At the start of 2016, about a 1,000 Fast-chargers are operational in Germany and these numbers are very unlikely to develop up to a Million as these fast-chargers are only used for long distance range-extenders, something similar to today's gas stations. Taking into account a deployment ratio of 0.07 fast-chargers per EV, an additional power demand of 36.75 GW could be required 2035 in a worst case scenario, which is most unlikely.

Concluding; Given the forecasted stock of 10.5 Million EVs by 2035, the German EV related power demand will increase by 31.08 GW caused by domestic charging, up to 40.95 GW by public charging and up to 36.75 GW by fast-charging in worst-case scenarios.

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[7] All EVs would have to have a (domestic) charging connector available, current ratios of German domestic EV connectors per EV are currently still close to 1:1 (IEA, 2016).

[8] Current ratios for public charging *connectors* per EV are around 1:10 (IEA, 2016), originally targeted to achieve 1:6.7 public charging *stations* by 2020 (Dudenhöffer et al., 2014).

5.2.1. Future research

As EV markets are quite volatile it is suggested to keep updating the forecast model in order to account for new technological developments and/or new incentivising schemes. Price reductions are currently quite steep and in-depth insights would prove useful to calculate TCO parity between ICE and EV more accurate. An update in 3 or 4 years is recommended after the first cheap, long range EVs have shown their impacts, such as the Chevrolet Bolt and more importantly the Tesla Model 3. These models are likely to hasten EV adoption significantly and to set the bar for future EV (cost) developments.

What has not been addressed in this study is the vehicle ownership development, how this will evolve over the coming years. In a scenario where private vehicle ownership would become less and a more utilization based approach for vehicle ownership was introduced, this could have a significant impact on EV stock development, reducing the amount of vehicles sold but could increas the need for 'faster'-charging.

Furthermore, EVSE developments have not been addressed in depth. Significant cost reductions and ease of obtaining permits could hasten EVSE deployment, thereby increasing EV mobility. Additionally, automotive companies such as Porche and Audi have announced even greater charging levels than the current 120kW prodived by Tesla superchargers, technological developments in this regard could have a great impact for German power demand, especially when standardization is improved across different continents.

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Appendix I

More detailed specification of publicly available charging stations in Germany (>7.4kW);

Table 11: Detailed overview of public 'Charging-mix' Germany, June 2016.

	120 kW	50 kW	43 kW	22 kW	20 kW	11 kW	7.4 kW	*3.7 kW*
CEE Rot			22	366		524		
CEE Blau								*1190*
CHAdeMO		157			155			
CCS		150			267			
Schuko								*6236*
Tesla Supercharger	369							
Type 3				6				*1*
Type 2			152	5976		2292	52	*727*
Type 1								*52*

Appendix II

Table 12: Detailed results of EV adoption model.

	EV Stock [-]	Energy demand [TWh]	Domestic charging [GW]	Public Charging [GW]	Fast-charging [GW]
2010	2310	0.01	0.01	0.01	0.01
2011	4810	0.01	0.01	0.02	0.02
2012	8103	0.02	0.02	0.03	0.03
2013	15726	0.04	0.05	0.06	0.06
2014	28325	0.07	0.08	0.11	0.10
2015	53534	0.13	0.16	0.21	0.19
2016	86579	0.21	0.26	0.34	0.30
2017	138152	0.34	0.41	0.54	0.48
2018	212808	0.52	0.63	0.83	0.74
2019	317294	0.77	0.94	1.24	1.11
2020	459034	1.12	1.36	1.79	1.61
2021	645840	1.58	1.91	2.52	2.26
2022	885555	2.16	2.62	3.45	3.10
2023	1185664	2.89	3.51	4.62	4.15
2024	1552898	3.79	4.60	6.06	5.44
2025	1992882	4.86	5.90	7.77	6.98
2026	2509835	6.13	7.43	9.79	8.78
2027	3106348	7.58	9.19	12.11	10.87
2028	3783268	9.23	11.20	14.75	13.24
2029	4539660	11.08	13.44	17.70	15.89
2030	5372870	13.11	15.90	20.95	18.81
2031	6278658	15.33	18.58	24.49	21.98
2032	7251397	17.70	21.46	28.28	25.38
2033	8284305	20.22	24.52	32.31	29.00
2034	9369711	22.87	27.73	36.54	32.79
2035	10499327	25.63	31.08	40.95	36.75
2036	11664504	28.47	34.53	45.49	40.83
2037	12856482	31.38	38.06	50.14	45.00
2038	14066607	34.33	41.64	54.86	49.23
2039	15286516	37.31	45.25	59.62	53.50
2040	16508290	40.29	48.86	64.38	57.78
2041	17724572	43.26	52.46	69.13	62.04
2042	18928652	46.20	56.03	73.82	66.25
2043	20114519	49.10	59.54	78.45	70.40
2044	21276892	51.93	62.98	82.98	74.47
2045	22411226	54.70	66.34	87.40	78.44
2046	23513691	57.39	69.60	91.70	82.30
2047	24581154	60.00	72.76	95.87	86.03
2048	25611129	62.51	75.81	99.88	89.64
2049	26601737	64.93	78.74	103.75	93.11
2050	27551647	67.25	81.55	107.45	96.43