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„Are there Environmental Benefits from Driving Electric Vehicles in Germany? “

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List of abbreviations

BEV	Battery electric vehicle
CO_2	Carbon Dioxide
ENTSO-E	European Network of Transmission System Operators for Electricity
EPA	United States Environmental Protection Agency
HEV	Hybrid Electric Vehicle
HOV	High-occupancy vehicle lane
HP	Horse Power
KBA	Kraftfahrt Bundesamt
kW	Kilowatt
kWh	Kilowatt hours
mill.	million
MPG	Miles per Gallon
MW	Megawatts
NERC	North American Electric Reliability Corporation
NMVOC	Non-methane volatile organic compounds
NO_x	Nitrogen Oxide
ÖAAB	Austrian workers 'and workers' union
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulates Matter
SO_2	Sulphur dioxide
TWh	Terawatt hour
UBA	German Federal Environment Agency
VAT	Value-added tax
VOC	Volatile Organic Compounds
VW	Volkswagen

Introduction

The disaster of Fukushima in 2011 finally triggered the German government to initiate the transition process of moving away from nuclear energy towards renewable sources and to therefore establish a sustainable supply of electrical power. The German term for this transition is known as "Energiewende", which also became a buzzword for this development. At the same time, the advancing climate change also calls for a drastic reduction of fossil fuels like coal or gasoline, like it was almost globally agreed on in the Paris climate treaty in 2015.
For a country like Germany, that is worldwide known for its car manufacturers like Mercedes and Porsche, it meant a clear challenge, as abandoning both sources at the same time would either lead to a huge bottleneck in energy supply, or require vast investments in alternative sources and necessary infrastructure. Therefore, it became clear that new concepts and ideas for a more sustainable and environmentally friendly development were required, not just in Germany, but worldwide. One of the crucial future topics is electric mobility, which is naturally of special importance for Germany as location of industry and technology.

Regarding this challenge, Holland et. al. (2016) published a paper focusing on the environmental benefits of electric vehicles towards gasoline-powered ones, in which they especially examine the role of subsidies and the importance of local factors in the United States. They emphasize that the environmental gains of electric vehicles depend crucially on the sources of power generation and that comparing electric and gasoline-powered vehicles is in the majority of cases a comparison between exhaust emissions and those resulting from burning fossil fuels such as coal. The study criticizes the uniform federal purchase subsidy for electric vehicles, as the environmental benefits vary across the country, where some regions exhibit strong positive and others strong negative effects. The largest benefit was estimated for the city of Los Angeles, and the largest loss was determined for a non-urban region in North Dakota. According to Holland et. al. (2016), the environmental benefits are negative on American average, and therefore do not justify a purchase subsidy, but do instead require an additional tax in the status quo to compensate for the additional damage they cause.

These findings from the United States motivate to investigate the situation in Europe by transferring the mentioned study to Germany and expanding it in parts. It can be assumed, that subsidizing electric vehicles only makes sense where electricity is produced in such a way that it actually shows an environmental improvement in comparison to gasoline-powered vehicles.

Otherwise, an environmental change for worse is subsidized, which leads to an economic inefficiency and therefore losses in economic prosperity. Obviously, the power supply in most countries does not yet fulfil this requirement, for this reason investments into sustainable energy sources have to be made in order to boost this development.

In the first chapter, some background information on the electricity mix and the status quo of electric mobility in Germany is given to lay the necessary foundation for the topic.

Secondly, the theoretical discrete choice transportation model proposed by Holland et. al. (2016) is summarized in the next chapter that is intended to provide a sound framework for the analysis of environmental benefits and subsidies. In addition, the suggested model is enlarged by further factors to make the setting more realistic and include some contemporary considerations like the awareness of consumers for environmentally friendly technology.

The third chapter introduces the calculation method applied by Holland et. al. (2016) regarding the calculation of environmental benefits and explains how the procedure is transferred for data in Germany. Several adjustments are made to apply the procedure meaningfully.

Subsequently, chapter four presents the results of both the application of the theoretical choice model and the calculation of environmental benefits using data for Germany. Of course, those results are dependent on the underlying data basis which is why the assumptions are explained in detail in the foregoing chapters.

Finally, the fifth chapter presents a case study for the city of Stuttgart, which already has an air pollution problem for several years. The challenge is described in a nutshell and it is then elaborated how the results gained in the fourth chapter could be applied to combat the issue. The focus does not just lie on short-term solutions, but also how the results and the technological progress could be used to create a more sustainable environment.

In their paper, Holland et. al. (2016) focus on the comparison between electric vehicles and gasoline vehicles. This comparison is expanded by also looking at diesel vehicles, to account for the fact that both diesel and gasoline vehicles are widespread in Germany and diesel vehicles are often criticized for their dirtiness. The market for electric vehicles includes several types, including battery electric vehicles (BEV), fuel cell vehicles or hybrid electric vehicles (HEV). For simplicity, these are combined under the term electric vehicle and as a whole compared to gasoline and diesel vehicles.

1. Background information

To give an overview over the issue of electric vehicles and mobility, some background information regarding power and electricity mixtures and the state of the art of electric vehicles in different countries (especially Germany) is necessary. To do so, initially, an overview over the electricity mixture in Germany will be given, thereby concentrating on the composition of the mix including fossil fuels and renewable sources, such as the shares of those different sources as well as the historic development of alternative sources for instance.

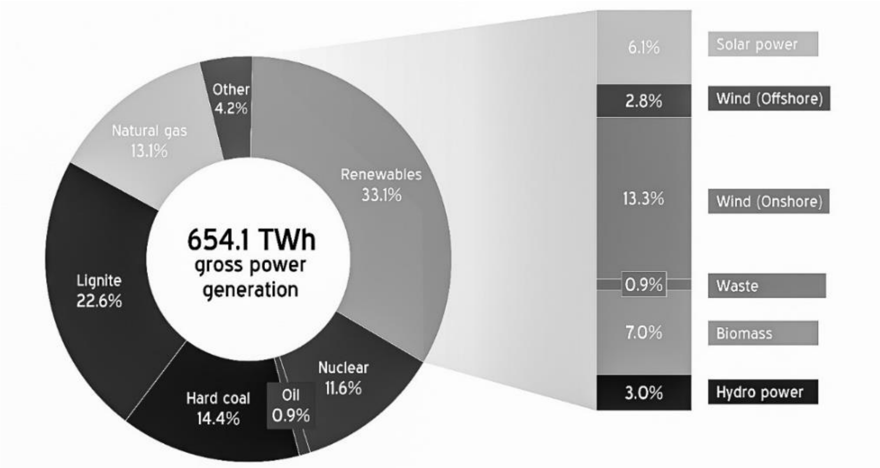
Secondly, as a next worthwhile aspect, the state of development of electric vehicles in different countries will be examined. This includes the share of electric vehicles (and hybrids) in total and historic development as well as incentives and subsidies for electric vehicles that are provided to enhance the change towards more electric mobility.

1.1. Electricity mixture in Germany

1.1.1. The overall situation

The German power generation mixture in 2017 (see figure 1.1.1) exhibits a balanced picture including not only fossil fuels, but also nuclear power and renewables.

Figure 1.1.1 Gross power generation mix in Germany 2017



Source: Morris (2018)

In 2017, the gross power generation added up to 654.1 TWh of which the majority of 55.3% was produced by conventional sources such as lignite (brown coal), hard coal (stone coal) or natural gas. At the same time, the power coming from renewables accounted for 33.1% and thus for about a third of the power generation mix. Although the German government initiated the Energiewende in 2011, and thereby announced the end of nuclear power production in Germany, nuclear energy still provides 11.6% of the mix (Morris, 2018). However, it must be mentioned that several power plants were already shut down in past years and more will follow in the coming years.

Taking a closer look at the sources included in the large share of the renewables shows, that almost half of the power generation is produced using wind power both onshore and offshore. Adding them up, they account for 15.1% of the mix which makes them the second largest source of power generation right after lignite that accounts for 22.6%. Apart from wind power, solar power (6.1%) and biomass (7.0%) also contribute an unneglectable part to the generation mix.

Table 1.1.2 Power generation in Germany (Gross performance of plants above 100 MW)

Type of plant	Total number of plants	Total electric power		Average (in MW)
		in MW	in %	
Fossil fuels	**217**	**76189.4**	**73.89%**	**351.1**
Lignite (Brown Coal)	40	21745.2	21.09%	543.6
Hard Coal (Stone Coal)	58	25499.3	24.73%	439.6
Natural Gas	85	22545.5	21.86%	265.2
Other gases	12	2031.7	1.97%	169.3
Fuel oil	10	2443.0	2.37%	244.3
Others	12	1924.7	1.87%	160.4
Nuclear Power	**7**	**10007.0**	**9.70%**	**1429.6**
Renewables	**85**	**16916.4**	**16.41%**	**199.0**
Hydro power	37	7164.5	**6.95%**	193.6
Wind power	44	9153.5	8.88%	208.0
Other renewables	4	598.4	0.58%	149.6
In total	**309**	**103112.8**	**100.0%**	**333.7**

Source: UBA (2018), own presentation

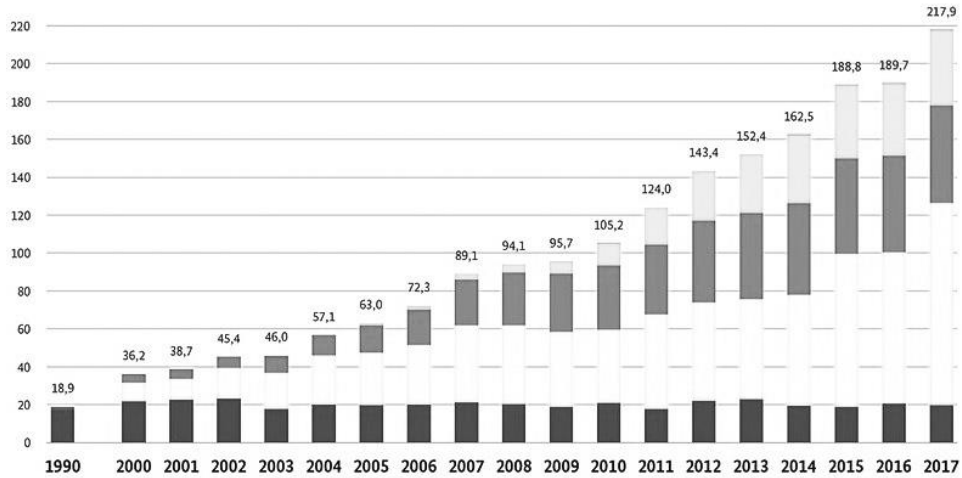
The gross performance of the largest power plants in Germany in 2017 shows that of the 309 power plants above 100 MW (see table 1.1.2), 85 power plants produced renewable energy (27.5%), while 217 were powered by fossil fuels (70.2%) and only 7 by nuclear power (2.3%). Despite this, renewables only accounted for about 16.4% of total electric power, while fossil fuels (73.9%) and nuclear energy (9.7%) both lie above their respective share in the number of power plants. The average performance of the power plants explains this unbalanced picture. While nuclear power plants had on average a performance of 1429.6 MW, fossil fuels with about 351.1 MW and renewables with 199.0 MW lie significantly below (UBA, 2018). Subsequently, to eventually replace all nuclear and fossil fuel powered power plants, many more and higher performing power plants using renewable sources are necessary to provide the current electricity supply.

1.1.2. Renewable energies in Germany

Although renewable energies are not very prevalent regarding the gross electrical performance of plants above 100 MW, they already constitute about one third of the German power generation mix. That is due to the fact that the importance and share of renewable sources of energy in the German power generation mix is increasing. However, the power generation coming from renewable energies in Germany was not that strong earlier and just developed intensely since 2000. In the last two decades, it experienced a strong progress by doubling since 2010 and even quadrupling since 2005 compared to 2017. Figure 1.1.3 below also shows that the growth mainly comes from the production volumes of wind power, biomass and solar energy, while hydro power remained unchanged since 2000. At the very beginning of the millennium, the share of hydro power in the power mix coming from renewables in Germany was about 56%, but fell to about 9.1% in 2017 (BMWi, 2018).

Figure 1.1.3 Power generation from renewable energies in Germany 2000 - 2017

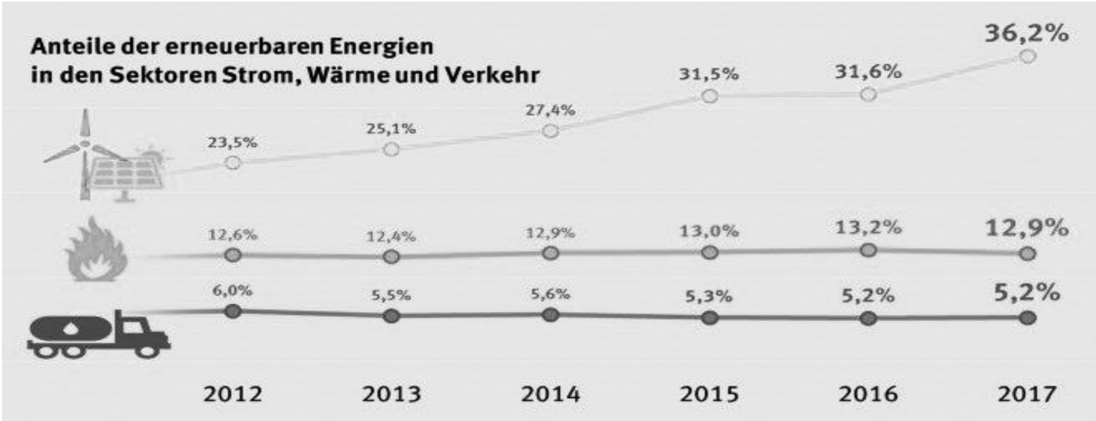
Gross electricity generation in billions of kilowatt hours



Source: BMWi (2018)

The power generation of renewable energy increased strongly since 2010 and doubled its performance since then. However, this development focused mainly on the electricity sector and did not affect the heat and transport sector. While the share of renewable energies in the electricity sector increased by 12.7 percentage points from 23.5% to 36.2%, the shares in the heat sector remained almost unchanged and the shares in the transport sector even decreased from 6.0% down to 5.2% (UBA, 2018). This development for the years 2012 – 2017 is presented in figure 1.1.4 below. All in all, electricity stemming from renewable sources is increasingly gaining importance, especially as the effects of the climate change are becoming more obvious.

Figure 1.1.4 Shares of renewable energies in different sectors 2012 - 2017



Source: UBA (2018)

1.1.3. Electricity production differentiated by region

In Germany, there are four large energy providers that supply the majority of the market (see table 1.1.5). These include EnBW, which solely covers Baden-Württemberg, EON, which is present in Bavaria, Hesse and North-West Germany, RWE, which covers Western Germany, and Vattenfall, which covers whole of Eastern Germany plus Berlin and Hamburg (UBA, 2018).

Table 1.1.5 Electricity providers in Germany (Plants above 100MW)

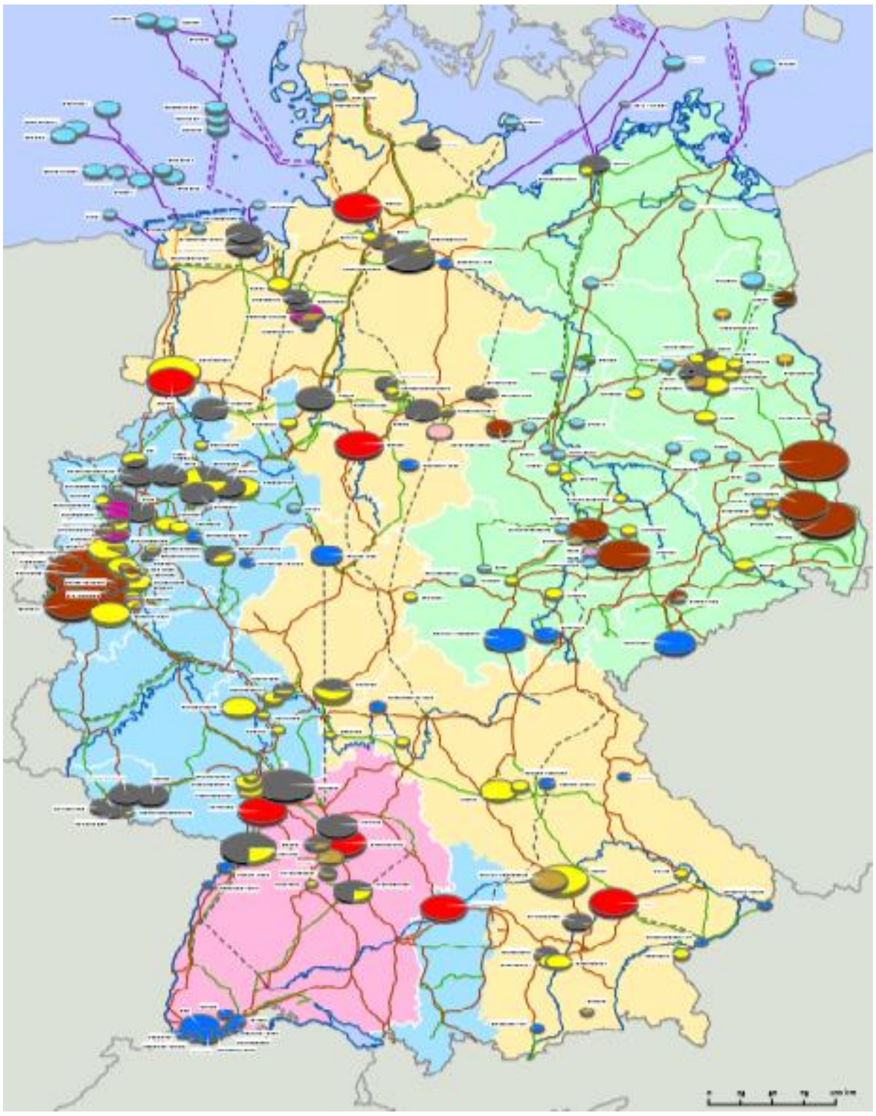
Provider	Bundesland	Total number	Share	Total power	Share
EnBW	BW	35	11.3%	12789,3	12.4%
E.ON	BY, HB, HE, NI, SH	96	31.1%	31662	30.7%
RWE	NW, RP, SL	89	28.8%	33805,3	32.8%
Vattenfall	BE, BB, MV, SN, ST, TH, HH	89	28.8%	24856,3	24.1%
In total		309	100.0%	103112,9	100.0%

Source: UBA (2018), own presentation

Figure 1.1.6, shows a map of the power plants and interconnected networks in Germany. Additionally, a list of power plants in Germany (from 100 megawatts of electrical power) differentiated by region can be found in Appendix A. Some regions have an historic focus on brown coal (brown circle), namely North-Rhine Westphalia in Western Germany and Saxony in the central East. Apart from those two regions, brown coal usage is rather rare, but several regions, especially in Western Germany, still have many power plants powered by stone coal (in grey circles). The nuclear power plants (in red circles), are located in Lower Saxony as well as in Bavaria and Baden-Württemberg. In the latter, the green party provides the regional prime minister since the elections in 2011, which took part just after the disaster of Fukushima in

March 2011. Nuclear power plants were already shut down, but as some French nuclear power plants are located right at the Germany border, France still supplies parts of Germany with this kind of energy across the border.

Figure 1.1.6. Power plants and interconnected networks in Germany



Source: UBA (2018)

Looking at renewable energies, there are many power plants producing electricity using wind power (in light blue circles) especially in Northern Germany and offshore on the North Sea and Baltic Sea. There are also several plants using hydro power (in dark blue circles), but those are not very widespread as the only larger facilities are located close to Freiburg at the Swiss border (in the South-West of Baden-Württemberg) and in Thuringia. Finally, natural gas-powered plants (in yellow circles), are widespread, but provide rather low amounts of electricity with only a few exceptions.

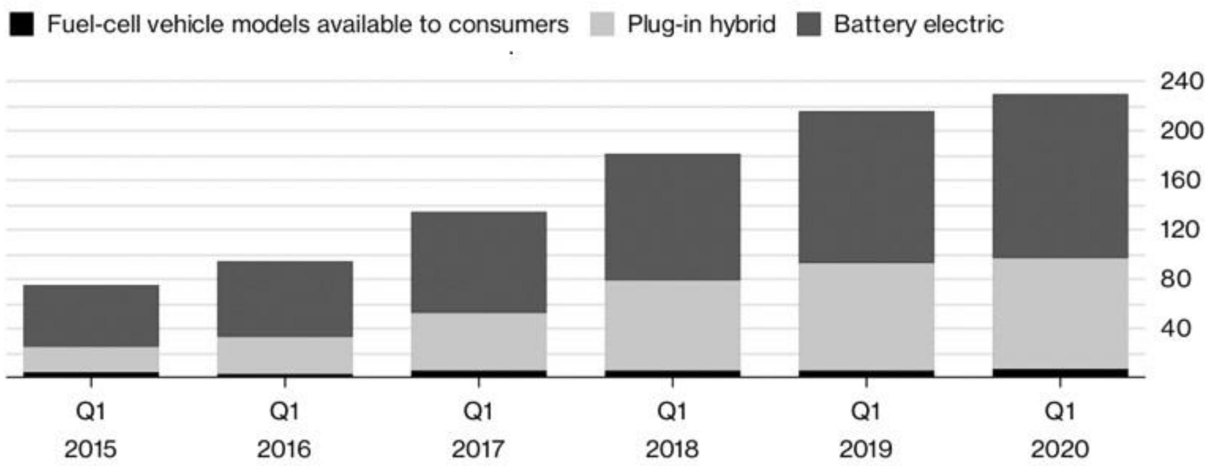
1.2. Current state of electric mobility

The further development of electric vehicles as successor of fuel combustion vehicles appears to be inevitable and rather a question of time than of feasibility. That is why it might be interesting to have a look at the current situation of electric mobility worldwide and the ways how electric vehicles are promoted worldwide by different countries and politicians.

1.2.1. Status quo and development of electric vehicles

In the daily news, electric vehicles and new record levels seem to be omnipresent. The available offer of electric vehicles increases steadily as more car manufacturers announce their market entry or new models. However, supply and demand of electric vehicle do seldom coincide, as the market share increases very slowly. According to an estimation of Naughton (2017, see figure 1.2.1), the market for electric vehicles will grow from currently roughly 180 models to about 230 models in the first quarter of 2020. This includes planned new vehicle launches of battery electric, plug-in hybrids and fuel-cell vehicle models.

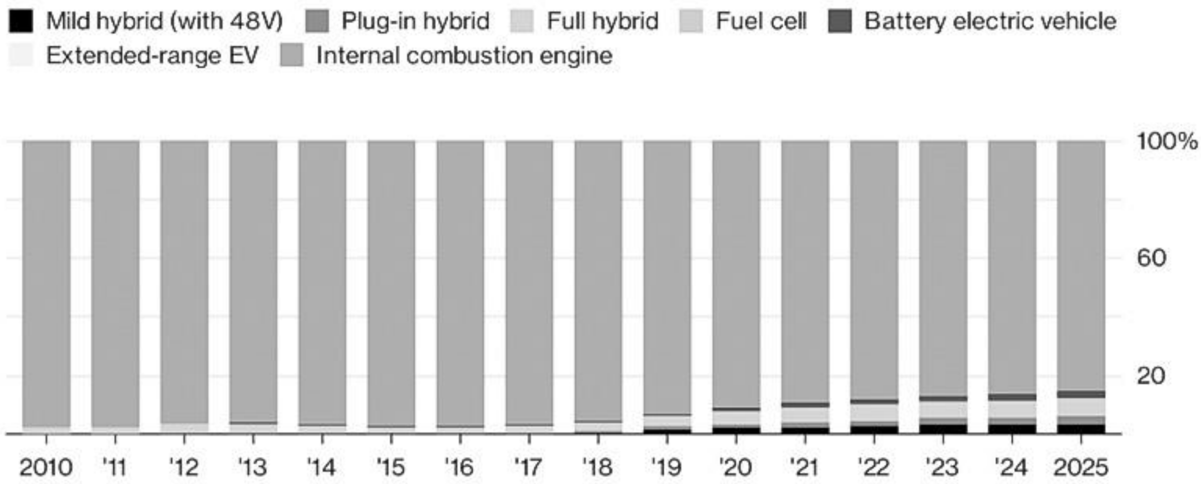
Figure 1.2.1 Planned new launches of electric cars by 2020



Source: Naughton (2017)

At the same time, a forecast of the development of the composition of the automotive market in the USA predicts a very slow increase of the share of electric vehicles of all kinds until 2025. Based on a prediction by Naughton (2017, see figure 1.2.2 below), internal combustion engine vehicles like diesel and gasoline are expected to still have a market share of approx. 85% in the US in 2025, while alternative engines including battery electric vehicles and fuel cells only add up to about 15% of market share.

Figure 1.2.2 Prediction of the composition of the automotive market in the USA until 2025



Source: Naughton (2017)

Of course, there are also examples of countries where the share of electric vehicles is already significant today, but those include rather small countries such as Norway, Iceland and Sweden. Additionally, the Scandinavian countries are also known to have a more forward-looking attitude to many things, where the focus on sustainable mobility is a good example for a progressive thinking in line with the challenges of scarce resources and threats like climate change. However, there are also larger countries that are in absolute terms very much engaged in the development of the market for E-Mobility. In 2017, "Norway, the Netherlands, France, the United Kingdom (UK), and Germany account[ed] for 82% of the cumulative sales of PEVs in Europe" (FleetCarma, 2017). As already addressed earlier, the situation was especially strong in Norway, where in 2017 "the market share for battery electric vehicles (BEVs) was 20.8 % and 18.4 % for plug-in hybrids (PHEVs) [which added up to] 39.2 % in total" (Norsk elbilforening, 2018), thereby making it the proportionately strongest market for electric mobility in Europe, but also worldwide.

1.2.2. Promotion of Electric Vehicles

To accelerate the development of e-mobility, many countries promote the electric vehicle sector by offering different kinds of incentives ranging from tax reductions or low electricity prices, to even directly providing purchase or replacement subsidies. While Norway is a pioneer in the field, already promoting electric mobility since 1990 and therefore having a broad range of incentives, other countries also offer a portfolio of incentives with the aim to drive the change.

1.2.2.1. Energy prices and charging infrastructure

Taking a look at energy pricing and charging infrastructure (table 1.2.3) shows that there exists a large variation of prices for electricity and gasoline and availability of charging infrastructure across the five considered countries (Norway, France, the Netherlands, the UK and Germany). Noticeable, Norway offers the best surrounding for electric vehicles with the lowest electricity prices, the highest density of charging stations per thousand registered vehicles and the highest prices for gasoline. The average price of about 12.9 cents per kWh is just half of the electricity price in Germany (25.9 cents), about 30 percent below the price level in the United Kingdom (17.8 cents) and slightly cheaper than the prices in France (14.5 cents) and the Netherlands (13.7 cents). At the same time, the average gasoline price is with 1.53€ per litre much higher than in the other four countries, where Germany (1.19€) and the UK (1.18€) charge the lowest prices on gasoline therefore being contrary to the electricity rates. Just looking at prices for electricity and gasoline gives a rather consistent picture featuring increasing electricity rates and decreasing gasoline prices from top to bottom (Norway to Germany) with only France deviating (Morland, 2017).

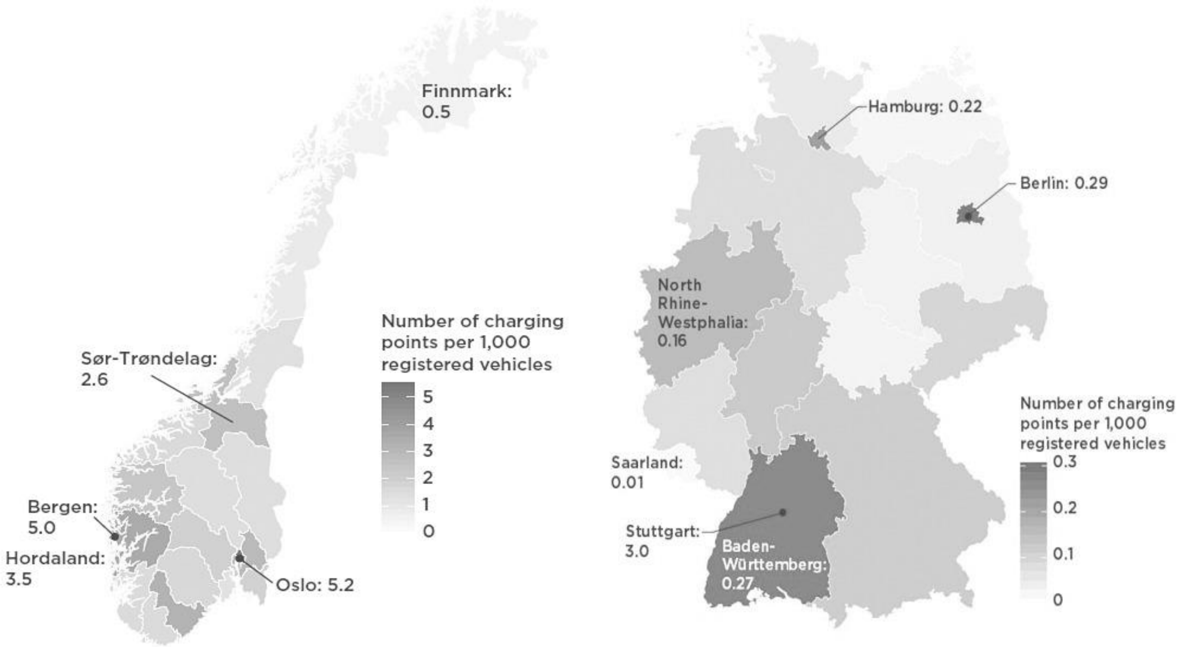
Table 1.2.3 Comparison of EVs in Europe: Energy Prices and Charging Infrastructure

Country	Energy pricing		Charging infrastructure
	Electricity rate	Gasoline price	
Norway	12.9 cents / kWh	1.53€ / litre	2.4 / 1000 vehicles
France	14.5 cents / kWh	1.23€ / litre	< 0.1 / 1000 vehicles
Netherlands	13.7 cents / kWh	1.36€ / litre	1.1 / 1000 vehicles
United Kingdom	17.8 cents / kWh	1.18€ / litre	0.31 / 1000 vehicles
Germany	25.9 cents / kWh	1.19€ / litre	0.19 / 1000 vehicles

Source: Morland (2017)

While electricity and gasoline prices are more or less consistent, the differences in charging infrastructure are far more impressive as figure 1.2.4 shows. At the top of the list, Norway offers a very dense network of charging infrastructure with an average of 2.4 charging points for every 1000 registered vehicles, with a maximum of 5.2 points in the capital Oslo and a minimum of 0.5 points in the far north. The comparison between Norway and Germany presented in figure 1.2.4 reveals that the minimum offer in Norway is still above the German average of 0.29 charging points per 1000 vehicles with only Stuttgart clearly standing out with an average of 3.0 charging points (Morland, 2017). It is very likely, that this comparably large offer is due to the fact that the city is home to two car manufacturers (Mercedes and Porsche), many technology companies (e.g. Bosch) and also governed by politicians coming from the Green Party both on city and state level. Furthermore, states in West Germany and in which Greens are (or were until recently) involved in the government tend to have a better developed availability of charging stations.

Figure 1.2.4 Charging infrastructure in Norway and Germany



Source: Morland (2017)

Also, when setting the exception of Stuttgart aside, the German offer is still dense in comparison to France, where the densest network in any region is just 0.1 points for 1000 vehicles. This is somewhat surprising, as France is home of large car manufacturers of which specifically Renault is already successful with electric vehicles (Renault Zoe), and also has relatively low electricity prices compared to Germany.

1.2.2.2. Subsidies and incentives

Norway is already promoting electric mobility since 1990 (Morland, 2017), despite of being one of the major oil producers worldwide, due to a special interest in preserving the local environment. That is why, the set of incentives for electric vehicle purchases is very broad and includes tax exemption as well as charging and parking without charge, and the usage of the bus and taxi lane for electric vehicle drivers. This whole package that was continuously enriched lead to a market share of electric vehicles of 39.4% as the benefits (and utility) of electric vehicles for consumers outperforms the utility of gasoline and diesel vehicles. Thus, the government of Norway intensely subsidizes the progress of electric mobility, despite of not having a large stake of the global automotive industry at hand like Germany, France or the United Kingdom do. This may be explained by either a higher contemporary societal environmental awareness or simply a weighting up of intergenerational utility which motivates a long-term planning horizon. They already started in 1990 with the abolishment of purchase and import taxes and continuously extended the list by other direct and indirect incentives like an exemption from toll roads fees and VAT. Table 1.2.5 below summarizes these subsidies as listed by Morland (2017).

Table 1.2.5 Electric Vehicle Incentives in Norway

Direct incentives	**Indirect incentives**
• 1990: No purchase/import taxes • 1996: Low annual road tax • 2000: 50% reduced company car tax • 2001: Exemption from 25% value added tax (VAT) on purchase • 2015: Exemption from 25% VAT on leasing	• 1997: No charges on toll roads • 1999: Free municipal parking • 2005: Access to bus lanes • 2009: No charges on ferries • high taxes on high emission vehicles

Source: Morland (2017)

The other four countries also offer different incentives for electric vehicles, although they are by far not as comprehensive like the ones offered in Norway. To give an overview of the situation in Europe, table 1.2.6 summarizes the most important features of subsidies and incentives in the four considered countries according to Morland (2017).

France has an incentive scheme that is fully based on purchase subsidies, including an environmental bonus for buying a zero-emission vehicle and a bonus for converting from a diesel vehicle to an electric vehicle. Adding those two incentives can result in a purchase subsidy of 10,000€. The Netherlands and the United Kingdom also have such direct purchase subsidies in different shapes, but additional exempt electric vehicles from the ownership tax and have special rules for the private use of company cars. Germany offers those kinds of incentives as well, but goes beyond in a direction that shows even more resemblance with the incentive scheme of Norway. Possibly, this is due to the large importance of the car manufacturing industry for the economy. These incentives include the access to restricted traffic areas, the use of the high-occupancy vehicle lane and free or preferential parking (Morland, 2017).

Table 1.2.6 Comparison of Electric Vehicles in Europe: Subsidies and incentives

Country	Direct incentives
France	• Environmental bonus or feebate - One-time tax that penalizes high CO_2 emitters and rewards low emitters. It can be as high as 27% of the list price to a maximum of 6,300 euros ($6,744 US) • Conversion bonus for diesel car owners who switch to a zero-emission vehicle – up to 3,700 euros ($3,961 US)
The Netherlands	• New car registration tax (based on the amount of CO_2 emissions) is zero for zero emission vehicles. This can save thousands of dollars compared to high CO_2 emitting vehicles. • Zero emission vehicles are exempted from ownership tax • Tax exemption on private use of company cars, which is significant because around 90% of plug-in electric vehicle (PEV) are registered to companies.
United Kingdom	• The Plug-in Car Grant—Covers 35% of the cost of a car (up to a maximum of £4,500 ($5,600 US) depending on the model) and 20% of the cost of a van, up to a maximum of £8,000 ($9,900 US). • Electric vehicles (with CO_2 emissions below 100g/km) are exempted from the annual circulation (ownership) tax. • Private use of company cars—Reduces the taxable income benefit based on CO_2
Germany	• 10-year exemption from ownership tax for BEVs registered before 2016 and a 5-year one for BEVs registered between 2016 and 2020. PHEVs pay the tax, which is lowered in proportion to their lower CO_2. • Grants - 4,000 euros ($4,950 US) for pure electric cars and 3,000 euros ($3,713 US) for hybrids. The grant applies only to cars up to a maximum list price of 60,000 euros ($74,250 US). • Private use of company cars—the tax on the taxable benefit to employee income is reduced by a formula involving the capacity of electric energy storage in the vehicle. • Preferential or free parking, access to high-occupancy vehicle lane (HOV) lanes, and restricted traffic zones for low emission vehicles

Source: Morland (2017)

2. Theoretical model

The model presented and explained below in chapter 2.1 is a summary of the discrete transportation decision model suggested by Holland et. al. (2016). For the interested reader, their paper "Are there environmental benefits from driving electric vehicles – The importance of local factors" provides a more detailed description of the model and methodology for environmental benefits calculation in the United States. The core model can be found on pages 3703 to 3708 in the American Economic Review of December 2016.

The proposed model captures the consumer choice on the market for new vehicles in a simplified matter, but could be enlarged by additional features. Therefore, it serves as underlying framework for an adjusted model that is set up in the following chapter 2.2. This adjusted model intends to enrich the setting with more realistic features like additional utility by caring about the environment and the contemporary threat of a ban on driving due to the increasing air pollution measured in several German cities.

Subsequently, the last subchapter 2.3 introduces environmental policy from the government's perspective. When choosing a vehicle, consumers do not care about possible external costs for society. They only care about their individual utility that does not include environmental awareness.

2.1. Benchmark model by Holland et. al. (2016)

The foundation for the comparison of environmental benefits is laid by setting up a theoretical model of discrete choice for the purchase decision of a new vehicle. The only two input factors that are relevant for the utility are the miles (here: kilometres) driven over the lifetime of the selected vehicle and a composite consumption good that captures everything else. Both inputs are assigned with a price. While the price of x is normalized to 1, the price of a mile specifies the price of a gasoline or electric mile, hence the fuel and electricity price, and taxes on these prices. Furthermore, the disposable income to maximize the utility from driving miles and consuming the composite good is defined as the difference between the income and the price of the chosen vehicle. Additionally, several policy variables are introduced that allow the government to steer the purchase decision of the consumer by taxing or subsidizing gasoline and electric vehicles. Obviously, the option of a purchase subsidy is primarily designed for electric vehicles, as fuel-powered gasoline vehicles are rather a temporary solution until electric vehicles will be fit for mass production and usage.

The key overview to the benchmark model by Holland et. al. (2016) can be found below in table 2.1. It includes all symbol categories, including inputs, prices, policy variables and others, a legend to the used symbols and a short description. Firstly, the indirect utility of purchasing a vehicle depends on the consumption of x and the number of miles driven over the lifetime of the vehicle. It is assumed that the disposable budget, the income minus the price of the car and maybe plus a purchase subsidy, is exhausted in order to maximize the indirect utility.

(2.1) Indirect utility of purchasing a gasoline vehicle

$$V_g = max_{x,g}\, x + f(g)\; such\; that\; x + (p_g + t_g)\, g = I - p_\psi$$

(2.2) Indirect utility of purchasing an electric vehicle

$$V_e = max_{x,e}\, x + f(e), such\; that\; x + (p_e + t_e)e = I - (p_\Omega - s)$$

Table 2.1. Legend to symbols for benchmark model by Holland et. al. (2016)

Category	**Symbol**	**Description**
Inputs	**x**	Composite consumption good, price normalized to one ($p_x = 1$)
	g	Miles driven with a gasoline vehicle over the whole lifetime of the vehicle
	e	Miles driven with an electric vehicle over the whole lifetime of the vehicle
Prices	$\mathbf{p_g}$	Price of a gasoline mile
	$\mathbf{p_e}$	Price of an electric mile
	$\mathbf{p_\Psi}$	Price of a gasoline vehicle
	$\mathbf{p_\Omega}$	Price of an electric vehicle
Income	**I**	Income of consumer
Policy variables	$\mathbf{t_g}$	Government tax on gasoline miles
	$\mathbf{t_e}$	Government tax on electric miles
	s	Purchase subsidy for electric vehicles
Utilities	$\mathbf{V_g}$	Indirect utility of purchasing a gasoline vehicle
	$\mathbf{V_e}$	Indirect utility of purchasing an electric vehicle
	$\mathbf{U_g}$	Expected utility if consumer selects a gasoline vehicle
	$\mathbf{U_e}$	Expected utility if consumer selects an electric vehicle
Error term	**ε**	Random variable that is i.i.d. with an expected value of zero and a standard deviation proportional to a parameter μ - $E[\varepsilon_g] = E[\varepsilon_e] = 0$

Source: Holland et. al. (2016)

Secondly, the direct utility of purchasing a vehicle is constituted of the sum of the indirect utility and an error term ε with expectation $E[\varepsilon_g] = E[\varepsilon_e] = 0$ and a standard deviation proportional to a parameter μ. Subsequently, the utilities are defined as follows:

(2.3) Expected utility of purchasing a gasoline vehicle

$$U_g = V_g + \varepsilon_g$$

(2.4) Expected utility of purchasing an electric vehicle

$$U_e = V_e + \varepsilon_e$$

Finally, whenever the expected utility from choosing a gasoline vehicle is larger than the expected utility from an electric vehicle, the first one is chosen. Therefore, selection probabilities are introduced and the expected utility from a new vehicle purchase is defined.

(2.5) Selection probability of gasoline vehicle, if $U_g > U_e$

$$\pi \equiv Probability(Ug > Ue) = \frac{exp(V_g)}{exp(V_g) + exp(V_e)}$$

(2.6) Expected utility of a new vehicle purchase is given by

$$E\left[max[U_e, U_g]\right] = \mu \, ln \, (exp(V_e) + exp(V_g))$$

By setting up this benchmark model, Holland et. al. (2016) provide a sound basis for the calculation of environmental benefits and purchase subsidies. However, to make the model more realistic and also include factors that reflect the current situation, the following subchapter extends the benchmark model by including and discussing additional features of the model.

2.2. Proposed extended model of consumer choice

The model proposed by Holland et. al. (2016) describes the consumer purchase decision on the market with gasoline-powered and electric vehicles in a simplistic and straight-forward way. It also introduces policy variables and thereby captures the influence of political decision making on the purchase decision. However, some more features should be added for a more realistic and broader picture. Of special importance are the following features that are discussed in detail below: utility drawn from environmental awareness, risks related to gasoline vehicles like a ban on driving or an air pollution tax, as well as risks related to electric vehicles like new technology and taxation risk.

To amend the model some risks for gasoline vehicles can be considered. Primarily, the risk of a ban on driving gasoline vehicles. The possible introduction of an additional tax on CO_2 or pollutants, is theoretically already included in government taxes on gasoline miles, but still are interesting to mention and discuss.

2.2.1. Environmental awareness

Over the last decades, mobility has become a basic need to take part in the society, but there still exist different perceptions regarding the means of transportation one is choosing. For example, driving a Porsche Carrera transmits a different wealth signal than using public transportation. Similarly, the decision between an electric and a gasoline vehicle shows for many people a different attitude towards environmental awareness and can therefore be translated into an additional utility from driving an electric vehicle. This awareness factor has no direct impact on the utility maximization of the consumer for consumption and driving, but influences the choice of the vehicle type as it affects the direct utility. Therefore, an environmental awareness for the gasoline vehicle of $A_g = 1$ and for the electric vehicle of $A_e > 1$, is assumed. Thus, a gasoline vehicle does not deliver an additional utility as it represents the market average, while the electric vehicle provides additional utility as it stands for an above average awareness.

2.2.2. Ban on driving

In several German cities like Stuttgart or Hamburg, a ban on driving for certain types of vehicles has already been applied several times due to smog warnings (Die Welt, 2017). Additionally, several car manufacturers had to call back their models in the course of the diesel emissions scandal for cheating and had to adjust their software and thereby caused inconvenience and value losses to vehicle owners. As the tracing of environmental protection targets set by the international community is increasingly gaining importance, the deviation from the rules will be harsher punished and thresholds will be tightened.

That means that the decision for a gasoline and especially diesel vehicle theoretically might result in the exclusion from certain metropolitan areas and thus the possibility of a ban on driving as a barrier should be included into the analysis. To account for this risk, a factor B for a possible ban on driving will be introduced. It is multiplied by the indirect utility of driving and consumption and thereby directly influences the utility drawn from a certain choice. Assume $B_e = 1$, meaning that no ban is expected, and $0 < B_g < 1$, hence that the expected utility from driving a gasoline vehicle decreases. Of course, the eventuality of engineering an absolutely clean fossil-fuel powered vehicle cannot be excluded, but fossil fuels are scarce and, currently, the technological break-through for such a vehicle seems rather unrealistic. For further information, the case study in chapter 5 “Particulates alert in Stuttgart” provides a description of the situation in the city, including a proposal how the situation could be improved in the short-term and solved in the long-term.

2.2.3. Air pollution tax

To counterbalance the negative externalities caused by driving gasoline vehicles, a Pigouvian tax could be used to internalize these costs on society. Indeed, a large share of the gasoline price is due to the petroleum tax and VAT, but since 1987, the use of the funds in Austria is not earmarked anymore for any specific purpose. Earlier it was assigned for infrastructure investments to maintain and extend the network of infrastructure facilities, but today it directly goes to the federal treasury as one of the most important sources of income (ÖAAB, 2016).

Technically, the broad definition of government taxes used by Holland et. al. (2016) leaves space for the extension by an environmental pollution tax, like the carbon tax or air pollution tax. Hence, no direct adjustment is necessary, but the discussion on government taxes can be enriched in this framework by mentioning the option of introducing a Pigouvian tax to fight the negative externalities. However, the most obvious solution would be to earmark parts of the already existing government taxes to fight the negative externalities caused by driving gasoline vehicles, instead of using it for other government expenses.

2.2.4. New technology risk

Although electric vehicles are a rather new phenomenon, the underlying electric engine already exists for some time. However, purchasers of such vehicles still need to be considered as pioneers that take an additional risk that must be recompensed. This risk-taking is less due to the technological risk of the engine, but to the surrounding technology including batteries, charging infrastructure and so on. The purchase subsidy offered by the government can be regarded as such a reward, although it is controvertible how this can be implemented. For example, it raises the question whether countries without any direct stake in the car manufacturing should advance the development of an industry that benefits especially countries like Germany and France. And within these countries regions that do not directly profit from the success of the automotive industry.

2.2.5. Taxation risk

Directly connected to the new technology risk described above, the second risk that might be relevant in the nearer future is the introduction of electricity taxes as equivalent to gasoline taxes for the government to finance expenses. Currently, the government is still setting incentives to motivate the development of the electric vehicle market. However, as soon as the share of electric vehicles will be on a similar level like gasoline vehicles, the government may get interested in taxing them as well in order to substitute the missing tax income that would otherwise be generated by gasoline vehicle driving.

However, taxes and prices in general are already included in the proposed theoretical model, so it will not change the calculation, but just increase the amount of taxes and therefore the costs of driving an electric kilometre.

2.2.6. Summary of extended theoretical model

The features discussed above and the initially proposed model by Holland et. Al. together yield an adjusted model that captures a more realistic purchase decision for the consumer. However, it is important to mention that only environmental awareness A and a risk of a ban on driving B are directly visible in the adjusted model. The reward for the new technology risk (M) is captured within the purchase subsidy of the government. Then, the risk of an air pollution tax and the taxation risk are additional factors to be considered in the future that affect the prices of electric and gasoline kilometres. These also influence the utility maximization of the consumer.

(2.7) Adjusted indirect utility of purchasing a gasoline vehicle

$$V_g = max_{x,g}\, x + f(g) \;\; such\, that\; x + (p_g + t_g)\, g = I - p_\psi$$

(2.8) Adjusted indirect utility of purchasing an electric vehicle

$$V_e = max_{x,e}\, x + f(e) \;\; such\, that\; x + (p_e + t_e)e = I - (p_\Omega - s_e)$$

(2.9) Direct adjusted utility of purchasing a gasoline vehicle

$$U_g = \left(V_g + \varepsilon_g\right) * B_g$$

(2.10) Direct adjusted utility of purchasing an electric vehicle

$$U_e = (V_e + \varepsilon_e) * A_e$$

Table 2.2. Legend to symbols for adjusted model

Environmental Awareness	**A_g**	Environmental awareness of driving a gasoline vehicle, with $A_g = 0$
	A_e	Environmental awareness of driving an electric vehicle, with $A_e > 0$
Risk of a Ban on driving	**B_g**	“Ban on driving”- risk for gasoline vehicle, with $0 < B_g < 1$
	B_e	“Ban on driving”- risk for electric vehicle, with $B_e = 1$
Maintenance costs	**M_g**	Maintenance costs for driving a gasoline vehicle, with $M_g = 0$
	M_e	Maintenance costs for driving an electric vehicle, with $M_e > 0$

Source: Own work

The model presented here and summarized in table 2.2 above is used later for the calculations of consumer purchase decisions on the market for new vehicles. The underlying data and parameters used for the calculations will also be explained at the beginning of the fourth chapter, to clarify the assumptions made.

2.3. Environmental policy and welfare

While the consumer's decision for driving either a gasoline or an electric vehicle is solely based on the expected utility, this decision also leads to negative externalities for the environment, including nature, people and infrastructure. These externalities are fully ignored by the consumers in their decision process. However, the model further assumes that the local and central government take into consideration these damages and choose purchase subsidies in such a way that it maximizes the welfare (function) for society as a whole.

The basic ingredients of this set-up are explained in the following. Firstly, it allows for different locations to differentiate between damages occurring not only at the offspring, but also at all other locations. Thus, it distinguishes between local (or native) damages and global (or exported) damages. Secondly, two different types of regulation are introduced to account for the fact that each local government might decide independently or that a central government might apply a uniform subsidy. An additional feature is that governments could care about all damages occurring or just the native damages, thereby ignoring the exported damages. To account for this fact, the differentiation between both types is important. Subsequently, environmental benefits will be defined and the application in the next parts of the paper will be explained.

2.3.1. Introducing location and damages

Initially, the realistic assumption is introduced that damages resulting from driving in one location might be both local and global. Therefore, to distinguish and determine local and global pollution, Holland et. al. (2016) allow for multiple locations, where m denotes the number of locations and α_i denotes the proportion of the total population of new vehicle buyers that resides in location i.

Then, three types of damages that are introduced for analysis purposes need to be distinguished. *Full damages* are defined as "the sum across all locations of local damages plus the global damages […] due to driving in location i" (Holland et. al. (2016): p. 3705). These can be split into *native damages*, damages appearing solely in i, and *exported damages* appearing in all locations. For this work, it is assumed throughout the whole calculations that governments care about full damages, but they could also have other approaches.

For simplicity, Holland et. al. (2016) assume that both local and global damage functions are linear and full damages can be characterized with a single variable for each type of vehicle. Hence, this results in δ_{gi} as the marginal full damages from driving a gasoline vehicle in location i and δ_{ei} as the marginal full damages from driving an electric vehicle in location i (both in $ per mile). The legend to symbols presented below in table 2.3 summarizes the relevant information.

Table 2.3. Legend to symbols for introduction of location, damages and regulation

m	Total number of locations
i	Location
$\boldsymbol{\alpha_i}$	Proportion of the total population of new vehicle buyers that resides in location i
$\boldsymbol{\delta_{gi}}$	Marginal full damages from driving a gasoline vehicle in location i (in $ per mile)
$\boldsymbol{\delta_{ei}}$	Marginal full damages from driving an electric vehicle in location i (in $ per mile)
$\mathbf{W_i}$	Welfare
$\mathbf{R_i}$	Expected government revenues generated by the purchase of a new vehicle in location i

Source: Holland et. al. (2016), p. 3705

2.3.2. Governments and regulation

Two different kinds of regulation for welfare maximizing purchase subsidies are assumed. Either a uniform regulation where a central government decides for homogenous purchase subsidies in all locations, or a differentiated regulation where each local government decides about purchase subsidies on its own. For the latter case it is possible that the government in location i cares about all damages caused by driving in the same location (full damages), or solely cares about damages occurring in the own location (local damages). With the second option, they would ignore damages exported to all other locations. This may strongly depend on the attitudes and goals of political decision makers. Either, one solely cares about damage done to his own location and ignores the rest of the world, or one also takes into consideration what consequences the own actions have in total. Herein, subsidies are labelled as the second-best policy, as the economically best policy would be Pigouvian taxes.

It is assumed that the local governments care about full damages and choose location-specific purchase subsidies s_i in such a way that they maximize the respective welfare function W_i. The welfare function presented below as (2.7) is the sum of expectations for utilities, government revenue R_i and pollution damages.

(2.7) Welfare under differentiated regulation

$$W_i = \mu\,(\ln(\exp(V_{ei}) + \exp\big(V_{gi}\big) + R_i - (\delta_{gi}\pi_i g_i + \delta_{ei}(1-\pi_{i)} e_i)$$

(2.8) Second-best location specific purchase subsidy

$$s_i^* = (\delta_{gi} g_{i-} \delta_{ei} e_i)$$

Optimizing implies that the second-best location specific purchase subsidy is defined as the difference of full damages over the whole driving lifetime between driving a gasoline and an electric vehicle (see 2.8). If we assume that the distance driven by both vehicles is equal and consumers do not vary their driving behaviour depending on the chosen vehicle, we can cancel e and g on both sides of the equation and define (marginal) environmental benefits as:

(2.9) Environmental benefits of driving an Electric vehicle instead of a gasoline vehicle

$$s_i^* = \delta_{gi} - \delta_{ei}$$

However, it might still be that full damages from driving electric vehicles are higher than those from gasoline vehicles, although the marginal damage may be lower, because the relative benefit is offset by driving more than before. Subsequently, a purchase subsidy must be calculated based on the assumption that consumer stick to the same driving behaviour for both vehicles. Otherwise, despite replacing a gasoline with an electric vehicle, society as a whole might even be worse off if the driven distance is increased at the same time. Holland et. al. (2016) also present the results for uniform regulation in their paper and the purchase subsidies for the case that local governments do simply care about native damages. However, due to the simplicity of the work at hand, these calculations do not deliver any additional information and are therefore not presented here. Of course, they can be found in the motivating paper of Holland et. al. (2016).

2.3.3. Native vs. Exported Damages

Another important feature is that the full damages can be broken down into native or local damages that occur directly at the same location and exported damages that occur in all locations except the location of origin. This differentiation is of special importance as gasoline vehicles emit pollution directly on the spot via their tailpipe. In comparison, the pollution caused by electric vehicles at the location of the supplying power plant often occurs at a much higher altitude due to the height of their smokestacks. Consequently, gasoline vehicles produce proportionally much more local pollution, while electric vehicles cause a higher proportion of global pollution.

In a different way from Holland et. al. (2016), this study will not differentiate between native and exported damages, but it will focus on the calculation of full damages and will use this characteristic later in the case study about Stuttgart to present possible sample applications of this differentiation.

2.3.4. Defining Environmental Benefits

In the paper of Holland et. al. (2016), environmental benefits are defined as the marginal difference per mile between the damage caused by a gasoline and an electric vehicle. Thus, the environmental benefit of an electric vehicle is the environmental improvement it effectuates by replacing a gasoline vehicle. This comprehensible result is coming from optimizing the welfare function under both uniform and differentiated regulation. It suggests that a justifiable government purchase subsidy per mile or kilometre for electric vehicles is equal to the environmental benefit that is caused by replacing a gasoline vehicle.

For the calculation of the subsidy, Holland et. al. (2016) assume a lifetime performance of 160,000 miles which is equal to about 257,000 kilometres. Subsequently, a vehicle that provides an environmental benefit of 1 cent per kilometre would be eligible for a subsidy of 2,570 Euro. However, such a purchase subsidy could also be negative, if an electric vehicle causes a negative environmental benefit. This methodology will also be used in the calculation of environmental benefits and subsidies for Germany, but with the assumption of a lifetime performance of 200,000km instead. Theoretically speaking, the purchase subsidy for an electric vehicle should be dependent on the expected environmental benefit over the whole lifetime and chosen accordingly by the government. The implementation of the purchase subsidy than affects the utility maximization of the consumer on the market of new vehicles.

3. Conceptual framework

In the first subchapter, the method of environmental benefits calculation applied by the underlying paper of Holland et. al. (2016) for data from the US is described. It differentiates between emissions caused by driving either gasoline or electric vehicles and calculates emissions per mile for each type of vehicle, secondly emissions are mapped into damages. Similarly, to the set-up of the theoretical model, the framework for the calculation is based on the work of Holland et. al. (2016) In the paper, the approach description can be found on pages 3708 to 3712.

This serves as benchmark for the further calculation of results in the work at hand, and are matched to the requirements of the particular conditions of the available data. To do so, the second subchapter explains the handling of certain assumptions and issues that are necessary to mention for the implementation of a similar approach to data of Germany. Please note that the environmental benefits for Germany will be calculated per kilometre.

3.1. Description of the papers methodology

To describe the papers proceedings, it is important to first recall the definition of environmental benefits that is encompassed in the theoretical model. Afterwards, the methodology is applied by first calculating the emissions per mile for both types of vehicles and by then mapping these marginal emissions into damages, using an estimate for external costs. In doing so the marginal damages of driving for both types of vehicles can be estimated and consequently the respective environmental benefits can be calculated on the basis of these results. Please note that the basic unit of location used are the 3,144 counties of the continental US (excluding Alaska and Hawaii).

3.1.1. Defining environmental benefits

The coherent result for solving the theoretical model (see calculations and results of Holland et. Al. 2016) is that environmental benefits are defined as the difference of marginal damages per mile between gasoline and electric vehicles. In order to estimate environmental benefits and justifiable subsidies, marginal damages per mile for both types of vehicles have to be estimated. The subsidy of an electric vehicle is defined as the environmental benefit provoked by the car multiplied with the expected lifetime distance. Holland et. Al. assume 160,000 miles (approximately 257,495 kilometres) as this lifetime distance.

3.1.2. Calculating emissions per mile

In the first step, the emissions per mile for electric and gasoline vehicles are calculated. For gasoline vehicles, the procedure is done by integrating different data sources, including data from the US Environmental Protection Agency (EPA). As a result of the data integration, the emissions per mile differ only across urban and non-urban counties, hence they differentiate between traffic in the city (urban traffic) and on the countryside (non-urban traffic), but not between the different counties.

For electric vehicles, the approach is more complicated and requires more steps than the calculation for gasoline vehicles. Initially, the electricity consumption in kWh per mile as a measure for miles per gallon (MPG) equivalent are estimated and adjusted to the temperature profile in each county. Then, an econometric model is used to estimate the marginal emission factors for each pollutant at each of the power plants due to an increase in the regional electricity load. Those estimates are then combined with an assumed daily charging profile of electric vehicles to determine emissions per mile at each power plant when charging an electric vehicle in a given county. The result of this procedure is that emissions for electric vehicles may differ not only across urban and non-urban regions, but also across any two counties.

3.1.3. Mapping of emissions into damages

In the second step, the emissions of both types of vehicles are mapped into damages to account for the fact that both emissions and damages may differ by location. Hence, these emissions must be attached to estimates for external costs to measure the damages different vehicles are causing to the environment. This step is crucial, as the linking of pollutants to certain cost factors allows to differentiate between the damages that different types of vehicles and power plants are causing.

This explanation is intended to give a brief overview of the methodology applied. For a more detailed description, please see Holland et. al. (2016).

3.2. Calculation of environmental benefits

To explain the applied method for the calculation of environmental benefits, the next part explains how the papers methodology of Holland et. Al. (2016) was translated into the thesis at hand. Afterwards, the basic approach for the calculation is explained before turning to the results of the thesis in the fourth chapter.

3.2.1. Conversion of the papers methodology

To convert the procedure applied by Holland et. al. (2016) to Germany, some adjustments must be made, in order to account for geographic differences between the US and Germany and to simplify the methodology. It will be discussed how the approach was translated and how issues were dealt with. The aim was to stick as close as possible to the suggested approach, but also to apply a simple and straight-forward method that is easily comprehensible. Therefore, the following sections focus on the translation to this paper with regard to the basic unit of location, the set of vehicles, the pollutants, the temperature profiles, the power plants and the control regions.

3.2.1.1. Basic unit of location

The study is focused on continental US, thus excluding Alaska and Hawaii. The 48 states are grouped into 3,144 counties in total, which is used by the authors as basic unit of location. Correspondingly, Germany consists of 401 rural districts and urban municipalities. As table 3.1 demonstrates, there are eleven metropolitan areas in Germany that are inhabited by about two third of the total population of 82.5 million people (Statista, 2018). Unlike Holland et. al. (2016), the study at hand will not consider the county or districts as basic unit of location, but will solely focus on the differentiation of urban and non-urban areas in Germany, hence accounting for the fact that the fuel and electricity consumption might differ depending on the surrounding. Obviously, densely populated regions like Rhine-Ruhr which includes many large cities like Cologne, Dusseldorf and Dortmund on a relatively small area, differ from regions like Nuremberg that are larger in size, but less populated. Furthermore, there might exist differences in the stage of development depending on the economic performance of the region as well as geographic and historic backgrounds which may influence the availability of infrastructure and the sources of energy. However, this study will only focus on the difference between urban and non-urban areas and disregard further details for the sake of simplicity.

Table 3.1 Metropolitan Areas in Germany

Metropolitan Area	Population	
	In Mio.	**In %**
Rhine-Ruhr	11.6	14.06
Berlin/Brandenburg	6.0	7.27
Munich	6.0	7.27
Rhine-Main/Frankfurt	5.7	6.91
Stuttgart	5.4	6.55
Hamburg	5.3	6.42
Hanover-Brunswick –Göttingen-Wolfsburg	3.8	4.61
Nuremberg	3.5	4.24
Bremen-Oldenburg	2.7	3.27
Central Germany	2.5	3.03
Rhine-Neckar	2.4	2.91
Metropolitan Areas in total	**54.9**	**66.55**
Germany	**82.5**	**100**

Source: firmendb (2018), Statista (2018)

3.2.1.2. Set of vehicles

The set of vehicles used by Holland et. al. (2016) includes all 11 purely electric vehicles in the EPA data bank of 2014 and its closest substitutes. However, checking for the 10 most popular electric cars in Germany discloses that only three cars identically exist on both lists. Those include the Smart For two, the Tesla Model S and the Nissan Leaf. Looking at the sales figures demonstrates that the Nissan Leaf, which is the best-selling electric car in the world, experienced only a slight increase in annual purchase numbers from 2014 to 2017 and is located in tenth place of the 10 most popular vehicles list in Germany (Schneider, 2018). On the other hand, the Renault Zoe as the best-selling electric car in Europe and in Germany, is not present at all in the set of vehicles considered for the United States.

Holland et. al. (2016) choose for many of their results the Ford Focus, as there also exists an equivalent electric version that allows a good comparison. In line with that, this study will focus on the VW Golf, which is available as an electric, gasoline and diesel version. Hence, the set of vehicles is reduced to only one vehicle, but additionally the difference between gasoline and diesel vehicles will be taken into consideration. For more information about the chosen vehicles, please see “4.1.2. Characteristics of chosen vehicles” in the next chapter.

Table 3.2 The 10 most popular electric cars in Germany, annual purchases

#	Car type	2017	2014	Note
1	Renault Zoe	4,322	1,498	Europe's most popular electric car.
2	VW Golf	3,026	1,040	Best-selling gasoline car in Europe.
3	**Smart For two**	2,987	1,589	Daimler subsidiary Car2go, has the electric For two in in use for car sharing
4	Kia Soul	2,933	-	
5	BMW i3	2,791	1,242	
6	**Tesla Model S**	2,036	815	Used to be not eligible for purchase subsidy funding in Germany.
7	Tesla Model X	1,090	-	Not eligible for purchase subsidy funding in Germany.
8	VW Up	1,078	919	
9	Hyundai Ioniq	881	-	
10	**Nissan Leaf**	841	812	Best-selling electric car in the world.

Source: KBA (2018), Schneider (2018)

3.2.1.3. Pollutants

The original study includes five pollutants (CO_2, VOCs, $PM_{2.5}$, SO_2, NO_x) that are in the focus of the public debate according to the authors. The same pollutants will be analysed in the present study, although it should be mentioned that data in Germany focuses rather on the particulate PM_{10} and does not investigate such small particulates such as $PM_{2.5}$ yet.

3.2.1.4. Temperature profiles

As there exist large differences in the climate of different regions of the US, Holland et. al. (2016) adjust the electricity consumption to temperature profiles in each county to account for the prevalent conditions of the considered county. However, as Germany is much smaller, there are smaller differences in temperature profiles and it is therefore assumed that there are no substantial differences that may intensely influence the electricity and gasoline consumption.

3.2.1.5. Power plants

For the calculation of emissions, 1,486 power plants in the US are considered, which extend over all 3,144 US counties. This implies a power plant coverage of 47.3% of all counties if it is assumed that there is maximally one plant per county. For comparison, there are 309 power plants of different kinds with a power of above 100 megawatts in Germany. These are explained in the section on background information in chapter 1.

3.2.1.6. ENTSO-E control regions

Within the United States there are three main interconnections which can be divided according to Holland et. Al. into 9 distinct NERC (North American Electric Reliability Corporation) regions to define spatial scale for measuring emissions per kWh.
In comparison to that, Germany can be divided into four different regions or ENTSO-E (European Network of Transmission System Operators for Electricity) control areas: Amprion (Western Germany), TransnetBW (Baden-Württemberg), 50Hertz (Eastern Germany and Hamburg) and TenneT (North-western, Middle and South-eastern Germany). Please see figure 1.1.6. Power plants and interconnected networks in Germany (UBA, 2018). The regions vary much regarding the composition of the electricity mix, but due to the close interconnectedness of the German and European electricity grid it will not be differentiated between the regions. Therefore, it is assumed that the marginal power plant for an electric vehicle in Baden-Württemberg might theoretically also be a brown coal-fired power plant in Saxony or an offshore power plant in the North Sea. Thus, in this study is only differentiated between metropolitan areas and the countryside.

3.2.2. Adjusted calculation approach

Following Holland et. al. (2016), this study calculates the environmental benefits in a two-step approach. It is distinguished between electric and gasoline as well as diesel vehicles. For gasoline or diesel vehicles, the first step is executed with the determination of emissions per kilometre by integrating several data sources on pollution data (including data from UBA, Deutsche Umwelthilfe and Deutscher Bundestag). For electric vehicles, firstly, the marginal emissions of prototypes of the different power plants per kWh is estimated and then the emissions per kilometre are calculated by taking the average electricity consumption per kilometre of the considered electric vehicle. Secondly, an estimate of external costs by the German Ministry of the Environment (UBA) for the considered pollutants is used to map the emissions into damages. Therefore, the marginal damages per kilometre are calculated by weighting the marginal emissions with the cost estimates.

The environmental benefits of electric vehicles are then defined as environmental enhancement of driving an electric vehicle instead of a gasoline vehicle for a kilometre. When using the assumption of a lifetime performance per vehicle of 200,000 kilometres, a justified subsidy as a product of the marginal environmental benefit and the expected lifetime performance can be calculated.

4. Results

The presented set-up consists of a theoretical model, which leads to the result that subsidies should be equal to the environmental benefit they provide, and furthermore the calculation of environmental benefits based on data for the case of Germany. Firstly, the basic assumptions used for the calculations will be explained, before looking at the results of theoretical model and the environmental benefits calculation.

For a clear arrangement, chapter 4.1 explains the assumptions for the calculations regarding the theoretical model and chapter 4.2 presents the results of the model. Then, chapter 4.3 explains the underlying data used for the calculation of environmental benefits, while 4.4 presents the results looking at different scenarios.

4.1. Basis for calculations for the theoretical model

4.1.1. General assumptions

According to the German Federal Office for Motor Traffic (KBA) there were about 46.5 million passenger cars registered in Germany in total with a mean age of 9.6 years at the beginning of 2018 and out of these about 3.44 million newly registered passenger vehicles (KBA, 2018). For simplicity, the study will therefore assume evenly distributed car purchases every 12 years so that the purchase decision of 3.5 million consumers per year for consumers that can decide between a gasoline, diesel or electric vehicle is considered. Additionally, the theoretical fourth option of not buying a new car is excluded, although offers like car sharing are getting increasingly popular and especially inhabitants of metropolitan areas do often enjoy good public transportation.

The average annual number of kilometres driven per driver amounted to approx. 14,000 km in 2016 (KBA, 2018) According to a survey conducted by Statista for the same year, the vast majority of passenger vehicles (75%) drove less than 15,000 kilometres per year (Statista, 2018), which corresponds to less than 40km per day. It can be assumed that the distances driven per day are rather minor, which might be a good fit for an electric vehicle. Most types of electric vehicles are quite limited regarding the distance they are capable to drive without having to be recharged. This means that they are not well suited for a long holiday trip on the same day. On the other hand, such occasions are very seldom and most trips are done in the short distance like for example shopping or commuting to work. Hence, it could therefore be assumed that gasoline or diesel cars that are being replaced by electric vehicles are anyway driven by consumers that tend to drive less than average, on the other side, driving an electric vehicle is much cheaper than driving a gasoline vehicle and most of the time a maximum of 200 km suffices without problems for an average day. Therefore, the same number of gasoline and electric kilometres is assumed unless stated differently. Additionally, the introduced prices and costs stay constant over the whole lifetime of the vehicle, thus guaranteeing price stability for the purchase decision.

4.1.2. Characteristics of chosen vehicles

4.1.2.1. Price of vehicles

The currently available electric Golf can be purchased in Germany and other countries like Austria at different prices. While the price begins at 35,900€ in Germany, for example in Austria it starts from 39,300€. However, there are also differences in prices concerning both the selected gasoline and diesel model. For comparability, models are chosen that match the electric Golf as best as possible on basis of kilowatt and horsepower. Regarding the consumption of fuel and electricity, the electric Golf consumes about 12.7 kWh per 100 kilometres on average, according to the official catalogue of Volkswagen.

Table 4.1.1 Comparison of characteristics of chosen vehicles

Properties	VW E-Golf	VW Golf 1.5 TSI ACT	VW Golf 2.0 TDI
Engine	Electric	Gasoline	Diesel
Kilowatt (kW)	100 kW	96 kW	110 kW
Horsepower (HP)	136 HP	130 HP	150 HP
Consumption	12.7kWh/100km	4.9l/100km	4.3l/100km
CO_2-Emissions	0g/km	113g/km	111g/km
Price in Germany	From 35,900€	From 25,800€	From 29,200€
Price in Austria	From 39,390€	From 26,640€	From 29,730€

Source: Volkswagen (2018)

As vehicle price the recommended retail price for the base model suggested by Volkswagen in their current pricing catalogue is used. This is explained and summarized among other details in table 4.1.1 above. The prices for a new VW in Germany and Austria differ which influences the purchase decision of the consumer. The electric Golf has properties of 100 kW and 136 HP and therefore the VW Golf Highline 1.5 TSI ACT Blue motion can be assumed as comparable vehicle which is specified with 96 kW and 130 HP. This gasoline version is available from 25,800€ in Germany and from 26,640€ in Austria. The diesel version is more expensive with a base price of 29,200€ for 110 kW and 150 HP in Germany and 29,730€ in Austria.

4.1.2.2. Electric vehicle subsidies

The available purchase subsidies for pure electric vehicles in Germany and Austria currently amounts to 4000€ for selected vehicles that do not exceed in the base model 50.000€ in its gross price. In Germany the subsidy is provided in equal parts by the federal government and the automotive industry. Therefore, the chosen VW Electric Golf with a net list price of 35.900€ in Germany and 39.390€ in Austria are entitled for the purchase subsidies in both countries. Unless otherwise stated, $s_e = 4000$ (€) is kept fixed.

4.1.3. Cost of driving

While the price of the composite consumption good is normalized to one, the price of driving a kilometre needs to be determined by including the most important cost factors. For the thesis, the costs of fuel and electricity, the loss of value over the whole lifetime of the chosen vehicle, the maintenance costs, as well as costs of insurance and motor-vehicle taxes will be taken into consideration.

4.1.3.1. Costs of fuel and electricity

The first obvious factor to estimate are the costs arising from fuel or electricity consumption of driving the vehicle. Therefore, the manufacturer’s data for estimated average consumption per 100 kilometres is multiplied by the average price of gasoline, diesel and electricity and then divided by 100 to get the costs per kilometre. While the average consumption should be similar, the fuel and especially electricity price vary strongly across Europe. In 2016, the average price per kWh in the European Union was 20.5 cents, thereby varying between 11.3 cents in Hungary and 30.8 cents in Denmark. Germany is right behind Denmark at second place with 29.8 cents per kWh, while Austria is with 20.1 cents even below European average (Eurostat, 2017).

4.1.3.2. Loss of value

To determine the loss of value per kilometre driven, it is assumed that the selected vehicle is driven for the whole lifetime of 12 years with a residual value of 0€ at the end. Therefore, the cost per kilometre coming from loss of value can be directly estimated by dividing the purchase price of the vehicle by the number of kilometres driven over the whole lifetime. For example, a vehicle that is purchased at the price of 20,000€ and is driven 200,000km over its lifetime has a loss of value per kilometre of 0.10€. The assumption of a constant loss of value is due to simplicity in favour of straight forward calculations. Including the loss of value per kilometre is one option how to include the vehicle price into the calculation. The second is by just including the price of the vehicle and subtract the costs from the available budget.

4.1.3.3. Maintenance costs

Every vehicle needs to get checked annually as it should be in a good condition over the whole lifetime to reduce risks and higher costs for more severe repair. However, as mechanical parts wear off more easily in gasoline or diesel vehicles than in electric vehicles, higher maintenance costs for drivers of conventional vehicles than for those of electric vehicles can be assumed. Thus, maintenance costs of 500€ per year for gasoline and diesel vehicles and 100€ a year for electric vehicles are assumed. All independent from the kilometres driven per year.

4.1.3.4. Insurance costs

Another important cost factor are insurance costs for vehicles that can vary strongly based on the driver’s history and the type of the vehicle. To keep it simple, equal insurance costs for both gasoline and electric vehicles in the amount of 500€ per year are assumed and the possibility of severe accidents resulting in additional costs is ignored.

4.1.3.5. Motor-vehicle tax

This annual tax depends on the first registration date, the emission class, the type of fuel and for newer models, there is also a penalty tax for each gram, which lays above the threshold value of CO_2 being emitted. The mentioned tax is much higher for diesel vehicles than for gasoline vehicles. According to the German Ministry of Finance, there is a vehicle tax of 70€ for the gasoline car and 220€ for the diesel version (Bundesfinanzministerium, 2018) As an additional incentive, electric vehicles are exempted from the motor-vehicle tax for 10 years in

Germany (Maas, 2017). This tax exemption is assumed for simplicity for the whole lifetime of the vehicle, as it is not clear yet how electric vehicles will develop in the next decade.

4.1.3.6. Other costs

Of course, there might also be other costs, like for example road taxes, parking fees or parking tickets, but since these are either negligible, we will exclude such costs at this point.

4.1.4. Disposable income

The assumption is that a purchased vehicle will be driven over its whole lifetime of 12 years. After that the residual value is zero and the consumer can decide again which vehicle he would like to purchase. Of course, the decision is made at current prices and state of technology. As default value of disposal income, the annual median income in Germany for the year 2015 is assumed which was 20,053€ and thus 1,671€ per month (DIW, 2017). With an interest rate of r = 3 percent and T = 12, an annuity factor of approximately 9.02 is calculated and thus the annual decision instead of the whole lifetime of the vehicle is considered.

4.2. Results for the theoretical consumer purchase decision in Germany

In chapter 2.2.4., the adjusted theoretical model was presented that will be used for the following calculations of consumer choice according to the theoretical model. In principle, the suggested model by Holland et. al. (2016) was extended by an additional term for environmental awareness for the purchase of an electric vehicle and a term that captures the possibility of a ban of driving for gasoline and diesel vehicles. Therefore, consumers can decide which vehicle to choose based on the expected indirect and direct utility coming from any of the three types of vehicles. Please see - for a short recap - the formulas presented in the theoretical part:

The adjusted indirect utility of purchasing a gasoline vehicle (2.7) is given as:

$$V_g = x + (p_g + t_g)\, g = I - p_\psi$$

While the direct adjusted utility of a gasoline vehicle purchase (2.9) is the following:

$$U_g = \left(V_g + \varepsilon_g\right) * B_g$$

Secondly, the adjusted indirect utility of purchasing an electric vehicle (2.8) is given as

$$V_e = x + (p_e + t_e)e = I - (p_\Omega - s_e)$$

With the direct adjusted utility of an electric vehicle purchase (2.10) as the following:

$$U_e = (V_e + \varepsilon_e) * A_e$$

Based on these functions, first the consumer utility under some standard assumptions is calculated and then the variations with regard to driving behaviour is checked. A special interest also lies in the differentiation between the three above mentioned scenarios.

4.2.1. Standard model

For the default model, we assume an average distance per year of 14,000 kilometres, an annual income of 20,053€, the recent catalogue prices of new VWs in Germany, an electric vehicle subsidy of 4000€, and a price per kilometre driven that is set together by including the costs of fuel or electricity, maintenance, insurance and car taxes. The exact description why these values are chosen is discussed in the previous subchapter 4.1 and the used values can be found below in tables 4.2.1 and 4.2.2.

Table 4.2.1 Basic assumptions for the standard model calculation

Engine	**x**	**g / e**	**p**	**I**	P_T	P_t	s_T	s_t
	Consumption Good	**Distance in km**	**Price in € per km**	**Income (in €)**	**Vehicle Price (in €) in total**	**Vehicle Price (in €) annually**	**Subsidy (in €) in total**	**Subsidy (in €) annually**
Gasoline	15156.7	14000	0.1454	20053	25800	2860.3	0	0
Diesel	14587.7	14000	0.1591	20053	29200	3237.3	0	0
Electric	15402.6	14000	0.0796	20053	35900	3980.0	4000	443.5

Table 4.2.2 Basic assumptions for the costs of driving

Engine	**Costs of driving per km**	**Fuel costs**	**Maintenance costs**		**Insurance costs**		**Car taxes**	
			per year	**per km**	**per year**	**per km**	**per year**	**per km**
Gasoline	**0.145**	**0.0690**	500	**0.0357**	500	**0.036**	70	**0.0050**
Diesel	**0.159**	**0.0720**	500	**0.0357**	500	**0.036**	220	**0.0157**
Electric	**0.080**	**0.0367**	100	**0.0071**	500	**0.036**	0	**0.0000**

The application of the set-up for the standard model, results in an indirect utility that is largest for the purchase of an electric vehicle and lowest for a diesel vehicle, even without adding the additional features of a risk of a ban on driving or environmental awareness. Correspondingly, the direct utility of an electric vehicle is even larger, when including the added features. Table 4.2.3 below shows these results.

Table 4.2.3 Results of the standard model calculation

Engine	**Indirect utility**	**Risk of Ban on Driving**		**Environmental Awareness**		**Direct utility**
Gasoline	29156.7	$B_g < 1$	0.99	$A_g = 1$	1	28865.1
Diesel	28587.7	$B_d < 1$	0.99	$A_d = 1$	1	28301.9
Electric	**29402.6**	$B_e = 1$	1	$A_e > 1$	1.01	**29696.6**

Of course, there are several incentives provided by the government to boost sales of electric mobility, and without those the situation might change, as the benefit coming from electric vehicles is just slightly larger than the one of gasoline vehicles.

If the promotions are removed, already the abolishment of the direct purchase subsidy results in a change in relative indirect utility as can be seen below in table 4.2.4. Without the subsidy, the electric vehicle would only be the second-best choice for the consumer regarding indirect utility behind the gasoline vehicle, but including the factors of a possible ban on driving and environmental awareness, it still is the best choice for the consumer.

Table 4.2.4 Results of the standard model calculation without purchase subsidy

Engine	Indirect utility	Risk of Ban on Driving		Environmental Awareness		Direct utility
Gasoline	**29156.7**	$B_g < 1$	0.99	$A_g = 1$	1	28865.1
Diesel	28587.7	$B_d < 1$	0.99	$A_d = 1$	1	28301.9
Electric	28959.2	$B_e = 1$	1	$A_e > 1$	1.01	**29248.7**

Apart from the purchase subsidy, there are also other incentives to boost electric vehicle purchases, like for example relatively low electricity prices, an exemption from car taxes and low expected maintenance costs. For the scenario, where electric vehicles had to pay the same car tax as gasoline vehicles (70€ per year), had the same expected cost of maintenance (500€ per year) and electricity prices doubled, electric vehicles would be the worst choice regarding indirect utility and even direct utility as table 4.2.5 shows.

Table 4.2.5 Results of the standard model calculation without promotions

Engine	Indirect utility	Risk of Ban on Driving		Environmental Awareness		Direct utility
Gasoline	**29156.7**	$B_g < 1$	0.99	$A_g = 1$	1	**28865.1**
Diesel	28587.7	$B_d < 1$	0.99	$A_d = 1$	1	28301.9
Electric	27975.4	$B_e = 1$	1	$A_e > 1$	1.01	28255.1

For the same scenario, where prices of electric vehicles drop to 30,000€, they again would be the best-choice regarding direct utility. See therefore Appendix B.

4.2.2. Decision with regard to driving behaviour

Until now, an annual driven distance of 14,000 kilometres was assumed, which is approximately the average of drivers in Germany and equal to about 38 kilometres a day assuming a uniform distribution of kilometres driven annually. Of course, there are also other types of drivers like for example vehicle owners that are living in the city and use their vehicle only on the weekend for shopping or short trips. Furthermore, there are also commuters or business people that drive much more due to the work-related necessity. To take this driving behaviour in account, the utility for different types of vehicles is checked by varying the distance driven and keep all other initial assumptions from the standard model constant.

For this, the same procedure is applied like before. First of all, the standard situation is considered, where all current incentives are included, hence both purchase subsidy as well as other incentives. In the second step, the purchase subsidy is removed, and finally also the remaining incentives. This leads to three different scenarios, with both the indirect and direct utility case. As most electric vehicles just have a maximum range of 200 kilometres before they have to be recharged, the annual maximum distance to be driven for an electric vehicle is assumed to be 73,000 kilometres (200km every day of the year). Table 4.2.6 below summarizes the results.

Scenario (1): Standard case including all incentives

Under the current conditions for an electric vehicle purchase, it is a customer's best-choice regarding the indirect utility if he is driving annually above approximately 6,400 kilometres, below that the gasoline vehicle is the best-choice. Also including the factors of a possible ban and environmental awareness leads to the case that electric vehicles are the best choice if more than zero kilometres are driven. For both cases, electric vehicles are also preferred to diesel vehicles.

Scenario (2): Without purchase subsidy

When removing the purchase subsidy, purchasing an electric vehicle gets less attractive. However, if more than 20,000 kilometres are driven, it is worth buying the electric vehicle in terms of indirect utility. Below 20,000 kilometres, the gasoline vehicle would be the best-choice. Additionally, below a driven distance of 3,500km, the diesel vehicle would be preferred to the electric vehicle. Regarding direct utility, the situation is comparable to the standard case in terms of indirect utility. The electric vehicle is always better than the diesel vehicle, and the best-choice for an annual driven distance of above 6,500km.

Scenario (3): Without any incentive

For the case, when all incentives are removed, the electric vehicle stops being attractive to buy in the light of indirect utility, always being the worst-choice, even in comparison to the diesel vehicle. Regarding direct utility, the electric vehicle is preferred to diesel for an annual distance of more than 16,500 kilometres and the best-choice in general for more than 57,000 kilometres. Below that, the gasoline vehicle would be worth the most for the consumer.

Table 4.2.6 Decision with regard to driving behaviour

Scenario	Indirect utility		Direct utility	
(1) Standard with all incentives	**km < 6,400**	GV best-choice	**km > 0**	EV best-choice
	km > 6,400	EV best-choice		
(2) Without purchase subsidy	**km < 20,000**	GV best-choice	**km > 0**	EV > DV
	km > 20,000	EV best-choice	**km < 6500**	GV best-choice
	km > 3,500	EV > DV	**km > 6500**	EV best-choice
(3) Without any incentive	**km > 0**	GV best-choice	**km < 16,500**	EV < DV < GV
	km > 0	EV worst-choice	**km > 16,500**	GV > EV > DV
			km > 57,000	EV > GV > DV
GV = gasoline vehicle, DV = diesel vehicle, EV = electric vehicle				

In summary, the electric vehicle is a purchase that is profitable for the consumer, but currently solely due to the comprehensive set of incentives. Moreover, the additionally included factors of a ban on driving and environmental awareness constitute a strong influence on the purchase decision in favour of electric vehicles. Including those factors and all incentives leads to the electric vehicle as best-choice, while when excluding all incentives and additional factors, the electric vehicle is always the worst-choice. Without the purchase subsidy but including the other incentives, the electric vehicles would be preferred regarding indirect utility for a distance of more than 20,000 kilometres (≈ 55 kilometres per day), which is a case that is imaginable in the light of commuters that live about 30 kilometres away from their workplace and drive to work every day. In the third scenario direct utility case, the electric vehicle would be the best choice for an annual distance of 57,000 km (≈ 156 km per day). This is a rather unlikely distance for an electric vehicle to be driven per day, unless it is used commercially for intra-urban transports or deliveries.

4.3. Basis for the calculations of environmental benefits

As outlined in the theoretical model, the environmental benefits that an electric vehicle delivers are defined as the marginal damage per kilometre saved by replacing a gasoline vehicle with an electric vehicle. It needs to be mentioned that the calculations are solely aimed at the pure comparison of the damages created due to driving, and the production process is not taken into consideration, although this is an important point of criticism and still a challenge for engineers. However, just as Holland et. al. (2016) this study will consider the effect isolated from other influences.

The crucial feature for the calculation is the underlying data and the assumptions made. Therefore, the basis for further results is explained to make clear where the applied numbers are coming from. First, the marginal emissions per kilometre of the selected vehicles have to be determined. However, most sources in the public debate focus mainly on carbon dioxide while other pollutants are also often mentioned, but rarely supported by data. That is why it was challenging to collect consistent data on all fuels and sources of energy, but by integrating data from different sources, especially the German Ministry of the Environment, a meaningful set of data was compiled. Secondly, the pricing of the marginal emissions is done by using estimates by the UBA that are based on several studies.

4.3.1. Marginal emissions per kilometre

Many of the estimates for emissions of vehicles powered by gasoline or diesel are already provided as a measure for kilometre, but those for electric vehicles are mainly given as per kWh estimate. For the electric VW Golf, an initial electricity consumption of 12.7 kWh for 100 kilometres is assumed. Thus, a marginal consumption per kilometre 0.127 kWh which is the basis for the calculation of the benefits (Volkswagen, 2018).

4.3.1.1. From driving fossil-fuel powered vehicles

Deutsche Umwelthilfe (2016, German Environmental Aid Association) conducted independent tests of 39 vehicles on CO_2 and NO_x emissions in real life operation method and found that the results deviated in parts considerably from the officially presented emissions by the car manufacturers. For the VW Golf VII 1.6 TDI, 134 g/km were measured for the CO_2 emissions of the Diesel version, while VW specifies the emissions per km with 106-109g, which is about 24.7% more if calculating with the average. UBA (2018) states that the emissions of gasoline version are on a comparable level and hence this value is also used for the gasoline-powered Golf.

Concerning NO_x, the threshold for Diesel is set by Euro 6 to 80 mg/km (UBA, 2018). However, Deutsche Umwelthilfe found an actual value of 228 mg/km for the VW Golf VII 1.6 TDI, hence a violation of the limit by factor 2.9. It must be mentioned, that most of the considered vehicles surpassed the limit significantly and VW was no exception. In comparison, the gasoline-powered Golf has a much lower emission of NO_x only accounting to about 12 mg / km according to a test conducted by a sports magazine specialized on vehicles (Auto, Motor und Sport, 2017). Nevertheless, the Euro 6 emission standard of 60 mg / km will be used instead, as there are also several other vehicles that do surpass the limit.

While the emissions for sulphur dioxide and methane are negligible according to Seilnacht (2018), we assume a particulates matter of 4.5 mg / km for both types of vehicles. However, gasoline-powered vehicles exhibit a much larger emission for non-methane volatile organic compound according to UBA (2018) and Seilnacht (2018) than diesel-powered vehicles. Table 4.3.1. summarizes the specific emission factors.

Table 4.3.1. Specific emission factors for chosen gasoline and diesel vehicles

Pollutant	Gasoline (VW Golf)	Diesel (VW Golf)
Carbon dioxide (CO_2)[1]	134 g / km	134 g / km
Sulfur dioxide (SO_2)[2]	-	-
Nitrogen dioxide (NO_x)[1,3]	60 mg / km	228 mg / km
Particulates matter (PM_{10})[3]	4.5 mg / km	4.5 mg / km
Non-methane volatile organic compound (NMVOC)[3]	68 mg / km	19 mg / km
Methane[2]	-	-

Sources: 1) Deutsche Umwelthilfe (2016), 2) Seilnacht (2018), 3) UBA (2018)

4.3.1.2. From driving electric vehicles

The electricity from driving electric vehicles is coming from the German electricity mix that consists of different sources of energy and is experiencing a change from fossil fuels towards renewable energies. According to UBA (2016) the specific emission factors for the whole German electricity mix are presented in the table 4.3.2. As they are given in emissions per kWh, again an electricity consumption per kilometre of 0.127 kWh is assumed and numbers are calculated that allow the comparison of driving of an electric vehicle with the emissions caused by a fossil-fuel powered vehicle.

Table 4.3.2 Specific emission factors for the German electricity mix

Pollutant	Emissions per kWh	Emissions per km
Carbon dioxide (CO_2)	516 g / kWh	65.5 g / km
Sulphur dioxide (SO_2)	290 mg / kWh	36.8 mg / km
Nitrogen dioxide (NO_x)	440 mg / kWh	55.9 mg / km
Non-methane volatile organic compound (NMVOC)	17 mg / kWh	2.2 mg / km
Methane	184 mg / kWh	23.4mg / km
Particulates matter (PM_{10})	15 mg / kWh	1.9 mg / km

Source: UBA (2016)

While the data for the whole electricity mix reveals a mixed picture of pollutants coming from the different sources of energy, it is even more interesting to have a closer look at the average emissions of the different types of power plants, especially brown coal (lignite), stone coal (hard coal) and natural gas which is used in a combined cycle power plant. These are summarized in table 4.3.3 and are relevant when distinguishing for the marginal unit of electricity.

Table 4.3.3 Average emissions from different types of electric power plants

Source	CO_2	SO_2	NO_x	NMVOC	Methane	PM_{10}
Brown coal	1105g 1)	606mg 2)	671mg 2)	17mg 3)	92mg 3)	27.9mg 2)
Stone coal	935g 1)	414mg 2)	469mg 2)	17mg 3)	92mg 3)	27.8mg 2)
Natural gas	420g 1)	-	120mg	17mg 3)	920mg 3)	-

Source: 1) Bundestag (2007), 2) UBA (2017), 3) UBA (2017)

4.3.1.3. Comparison between urban and non-urban areas

The above stated average emission factors for gasoline or diesel-powered vehicles can be assumed for an average combined fuel consumption of about 5 litres per 100 kilometres (Volkswagen, 2018). For driving outside of cities and with a higher speed, a lower consumption can be considered and consequently also a lower emission of the above stated pollutants. However, driving within a metropolitan area often means driving slower, due to more traffic and stricter speed limits, which results in a higher consumption of fuel and thereby higher emissions.

For simplicity, a lower fuel consumption of 4.5 litres for 100 kilometres in non-urban areas and a higher fuel consumption of 6 litres for 100 kilometres in urban areas will be assumed. This allows to differentiate between metropolitan and non-metropolitan areas, where the emissions in urban areas are assumed to be 20% higher and 10% lower in non-urban areas.

Just as fossil-fuel-powered vehicles, there are also differences for the electricity consumption of electric vehicles depending on the location where they are driving. Most models that are currently available have an expected driving range of about 250 kilometres depending on the quality of the battery and a specified consumption of about 12 - 20 kWh per 100 kilometres. However, tests found that the consumption under real-life driving conditions is regularly much higher than stated by the car manufacturer, and also the driving range decreases drastically when driving in another driving mode than within metropolitan area traffic with low speed (Olschewski, 2017).

To account for the fact that electric vehicles are worse suited for non-urban traffic, we assume for non-metropolitan areas an electricity consumption of about 19 kWh for 100 kilometres, which is an increase of about 50 percent. Regarding urban traffic, the assumed consumption of 12.7 kWh that is stated by VW is reduced by approximately 20 percent to 10 kWh, although many vehicles deviate much more upwards for real-life testing and this consumption appears to be at the lower level of estimates. These additional assumptions allow to not only calculate environmental benefits on the basis of average conditions and emissions, but also to distinguish between urban and non-urban areas, to investigate how the different conditions, influence the marginal environmental benefit and a possible purchase subsidy for electric vehicles.

4.3.2. External costs of pollutants

One of the crucial assumptions is the pricing of the pollution caused by driving. As basis the estimates of environmental costs in the energy and transport sector by the UBA (2014) is used that were published in 2014. Regarding climate costs caused by CO_2 the study suggests several values, including different scenarios and periods. Following the recommendation, we assume a base cost of 80€ per ton of CO_2. Table 4.3.4 below presents the different forecasts.

Table 4.3.4 UBA recommendation on the climate costs

	Climate costs in EUR 2010 / t CO_2		
	Short-term 2010	**Medium-term 2030**	**Long-term 2050**
Lower value	40	70	130
Mean value	**80**	145	260
Upper value	120	215	390

Source: UBA (2014)

Furthermore, the UBA also presents estimates for average environmental costs of air pollution from energy production in Germany coming from different pollutants. As presented in table 4.5 below, the total costs consist to a large part of the damage caused to health, while the damages to crops, material and biodiversity are comparably low.

Table 4.3.5 Average environmental costs of air pollution from energy production in Germany

Emission (in €2010 per t)	**Cost rates for emissions in Germany**				
	Health damage	**Loss of biodiversity**	**Crop damage**	**Material damage**	**In total**
$PM_{2.5}$	55,400	0	0	0	55,400
PM_{10}	39,700	0	0	0	**39,700**
NO_x	12,600	2,200	500	100	**15,400**
SO_2	11,900	800	-100	500	**13,200**
NMVOC	1,600	-300	300	0	**1,600**

Source: UBA (2014)

These environmental costs serve as basis for the calculation of environmental benefits. There is no estimate given for methane, but different sources assess the damage about twenty times worse than CO_2, that is why we assume the same external cost for methane like for NMVOC and hence about 1,600€ per ton.

Of course, different interest groups assess the risks and costs differently, depending on for example their occupation or geographic background. Additionally, such estimates tend to increase over time as science emerges and events such as natural disasters become more frequent. Therefore, the estimates by UBA can be considered as rather conservative and likely to increase as well over time.

4.4. Calculating Environmental Benefits

After introducing the procedure and the underlying data, the environmental benefits for Germany can be calculated. Basically, there are three options that will be considered. First, the marginal environmental benefit of driving (one vehicle for one kilometre) and thus comparing between the electric vehicle and the fossil fuel-powered vehicles. This marginal benefit than serves as basis for the absolute environmental benefit calculated over the whole lifetime of the vehicle. Holland et. al. (2016) consider this value as fair subsidy an electric vehicle is eligible to receive. Finally, the total environmental benefit for society is calculated. This is the sum of benefits that a theoretic number of new vehicle purchases provides when replacing the same number of fossil fuel-powered vehicles.

4.4.1. Results under standard assumptions

Initially, environmental benefits are calculated under the standard assumption of average fuel and electricity consumption. As lifetime performance for any vehicle a distance of 200,000 km is assumed and the absolute damages are calculated for one and one million vehicles.

4.4.1.1. Benefits given the electricity mix

For the given data, a marginal damage of driving of 1.19 cents for gasoline vehicles, 1.44 cents for diesel vehicles and 0.67 cents for electric vehicles can be calculated, if the emission factors of the whole electricity mix are assumed. Summing up the marginal damage for the whole expected distance driven over the vehicles lifetime (assuming a lifetime performance of 200,000 kilometres), results in absolute damages of 2,386€ for gasoline, 2,888€ for diesel and 1,341€ for electric vehicles. See table 4.4.1 for those results.

Table 4.4.1 Marginal and absolute environmental damages (electricity mix, average)

Choosen vehicle	Total marginal damage	Kilometers driven	Absolute damage for 1 vehicle	Absolute damage for 1 mill. vehicles
Gasoline	€ 0.0119	200000	€ 2 386	€ 2 386 290 000
Diesel	€ 0.0144	200000	€ 2 888	€ 2 888 050 000
Electricity mix	€ 0.0067	200000	€ 1 341	€ 1 341 147 940

Hence, the marginal environmental benefit of electric vehicles (presented in table 4.4.2) is 0.52 cents towards the gasoline vehicle and 0.77 cents towards a diesel vehicle. Over the whole lifetime, the vehicle would be eligible to a subsidy of 1,045€ if replacing or chosen over a gasoline version and 1,547€ if chosen over a diesel version. If a million electric vehicles were replacing the same number of gasoline or diesel vehicles, this would lead to a total benefit for society of 1.045 billion Euro towards gasoline and 1,55 billion Euro towards diesel vehicles.

Table 4.4.2 Marginal environmental damages of driving (electricity mix, average)

Electricity source	**Compared to**	**Marginal benefit**	**(Purchase) subsidy**	**Total benefits for 1 vehicle**	**Total benefits for 1 mill. vehicles**
Electricity mix	**Gasoline**	€ 0.0052	€ 1 045.1	€ 1 045	€ 1 045 142 060
	Diesel	€ 0.0077	€ 1 546.9	€ 1 547	€ 1 546 902 060

In this scenario, electric vehicles constitute an environmental benefit compared to both gasoline and diesel vehicles, although the calculated justified subsidy lies much below the purchase subsidy provided by the German government which adds up to 4000€.

If it was therefore assumed that the marginal kWh was coming from renewable sources like water or wind, this could theoretically reduce the marginal environmental damage to zero. Thus, the environmental benefit of electric vehicles would be exactly equal to the negative marginal damage coming from gasoline (1.19 cents) and diesel (1.44 cents) vehicles and hence lead to a subsidy of 2,386€ for gasoline vehicles and 2,888€ for diesel vehicles. Subsequently, even in this extreme case, the purchase subsidy for electric vehicles that is provided by the German government would not be fully justified under the aspect of environmental benefits.

However, the marginal power plant that is providing the marginal kWh must be one that is very flexible and can be adjusted to additional demand at short notice. Therefore, renewable energies cannot be considered, as their power is already exhausted and an additional kWh has to be available quickly. That is why, the marginal power plant is in the majority of cases either lignite, hard coal or natural gas. Depending on the energy supplier, the environmental benefits of electric vehicles in comparison to conventional vehicles may either go up or down. In the best case, the marginal power plant is a power plant using natural gas, in the worst case, it is one using brown coal (Elsen, R., Körber, T. and Kulik, L., 2012).

4.4.1.2. Best-case vs. worst-case scenario

Thus, the marginal power plant cannot be coming from renewable or nuclear energy, but from some fossil fuel instead. As the electricity grid in Germany is highly interconnected, it was assumed that the marginal kWh for an electric vehicle in Southern Germany might also come from a power plant in Saxony using brown coal. The benefits therefore solely depend on the source of energy that produces the marginal unit electricity for the electric vehicle. Table 4.4.3 presents the comparison of marginal and absolute damages of all considered vehicles and table 4.4.4 summarizes the environmental benefits and subsidies of all relevant sources of electricity in comparison to diesel and gasoline vehicles.

In the best case, the electricity is produced by a power plant using natural gas, which causes a total marginal damage of just 0.47 cents and lies with this about 0.2 cents below the marginal damage caused by the electricity mix on average. Therefore, it lies almost one cent (0.97 cents) below diesel and 0.72 cents below the gasoline vehicles.

Altogether, the absolute damage of an electric vehicle driving with natural gas-powered electricity is just € 938 (€ 938 458 880 for one million vehicles) over its whole lifetime. With this, it would justify a subsidy of € 1 448 for replacing a gasoline vehicle, € 1 950 for replacing a diesel vehicle, and thereby causes total benefits of 1.45 billion (gasoline) and 1.95 billion (diesel) Euro regarding one million vehicles.

Table 4.4.3 Comparison of marginal and absolute damages (average)

Choosen vehicle	Total marginal damage	Kilometers driven	Absolute damage for 1 vehicle	Absolute damage for 1 mill. Vehicles
Gasoline	€ 0.0119	200000	€ 2 386	€ 2 386 290 000
Diesel	€ 0.0144	200000	€ 2 888	€ 2 888 050 000
Brown coal	€ 0.0137	200000	€ 2 744	€ 2 743 571 602
Stone coal	€ 0.0113	200000	€ 2 255	€ 2 254 642 684
Natural Gas	€ 0.0047	200000	€ 938	€ 938 458 880
Electricity mix	€ 0.0067	200000	€ 1 341	€ 1 341 147 940

However, if brown coal was the marginal producer of electricity, this would be the worst-case scenario for electric vehicles, as it exhibits a much larger marginal damage of 1.37 cents. This value lies well above the marginal damage of gasoline (1.19 cents), but still below the damage of a diesel vehicle (1.44 cents) resulting in marginal benefits of - € 0.18 (compared to gasoline) and €0.07 (compared to diesel).

Now calculating the eligible subsidy for an electric vehicle driving with brown coal-produced electricity, results in a negative benefit of - € 357 for the comparison with gasoline vehicles, which means that an additional tax would be considered necessary, given the surplus damage it causes. Looking at the overall picture with a million vehicles, this replacement resulted in a total loss for society of 357 million Euro. In comparison to diesel vehicles, the electric vehicle still constitutes a marginal environmental benefit, but it is relatively small and therefore justifies a subsidy of just € 144 over the whole lifetime. For one million vehicles, the total benefit is about 144.5 million.

Table 4.4.4 Comparison of environmental benefits and subsidies (average)

Electricity source	**Compared to**	**Marginal benefit**	**(Purchase) subsidy**	**Total benefits for 1 vehicle**	**Total benefits for 1 mill. vehicles**
Brown coal	Gasoline	**- € 0.0018**	**- € 357.3**	**- € 357**	**- € 357 281 602**
	Diesel	**€ 0.0007**	**€ 144.5**	**€ 144**	€ 144 478 398
Stone coal	Gasoline	**€ 0.0007**	**€ 131.6**	**€ 132**	€ 131 647 316
	Diesel	**€ 0.0032**	**€ 633.4**	**€ 633**	€ 633 407 316
Natural Gas	Gasoline	**€ 0.0072**	**€ 1 447.8**	**€ 1 448**	€ 1 447 831 120
	Diesel	**€ 0.0097**	**€ 1 949.6**	**€ 1 950**	€ 1 949 591 120
Electricity mix	Gasoline	**€ 0.0052**	**€ 1 045.1**	**€ 1 045**	€ 1 045 142 060
	Diesel	**€ 0.0077**	**€ 1 546.9**	**€ 1 547**	€ 1 546 902 060

4.4.2. Distinction by location of driving

Until now, the presented calculations were based on average fuel and electricity consumption. However, it is also interesting to determine the differences regarding the location of driving, as the consumption also goes along with the extent of emissions that are caused.

Firstly, the environmental benefits in urban traffic are calculated. The traffic in urban areas can generally be characterized as being prone to traffic jams and stop-and-go traffic. Thus, the speed is rather slow and it is important to start up regularly. Electric vehicles tend to better accommodate to these conditions and are assumed to have a lower electricity consumption. On the contrary, gasoline and diesel vehicles tend to have a higher consumption under such conditions. Secondly, the situation changes with regard to overland or non-urban traffic, where the speed generally is higher and driving is more constant than in the city. To account for this fact, the electric vehicles are assumed to have a much higher consumption, while diesel and gasoline vehicle have a lower than average consumption. Appendix C presents the emission tables for all three cases (average, urban and non-urban) that constitute the basis for the calculations at hand.

4.4.2.1. In urban traffic

For the case of urban traffic, the marginal damages of fuel and electricity shift apart. The damage of natural gas drops to 0.38 cents and the one of diesel rises to 1.73 cents, resulting in an environmental marginal benefit of 1.36 cents for this comparison. Under these assumptions, the marginal damage of brown coal (1.1 cents) lies again below the one of gasoline (1.43 cents) which leads to an environmental benefit of 0.33 cents. These benefits lead to subsidies in the amount of €2,715 (natural gas to diesel) and €2,113 (natural gas to gasoline) and €1,271 (brown coal to diesel) and €669 (brown coal to gasoline). See tables 4.4.5 and 4.4.6 below for results.

Table 4.4.5 Comparison of marginal and absolute damages in urban traffic

Choosen vehicle	Total marginal damage	Kilometers driven	Absolute damage for 1 vehicle	Absolute damage for 1 mill. vehicles
Gasoline	€ 0.0143	200000	€ 2,864	€ 2,863,548,000
Diesel	€ 0.0173	200000	€ 3,466	€ 3,465,660,000
Brown coal	€ 0.0110	200000	€ 2,195	€ 2,194,857,282
Natural Gas	€ 0.0038	200000	€ 751	€ 750,767,104

In the extreme case, this delivers total environmental benefits of 2.7 billion Euro when replacing a million diesel-powered vehicles by electric vehicles running on electricity that is produced by natural gas. Subsequently, the calculated subsidies again lie well below the offered purchase subsidy of 4,000€ when just considering the environmental benefit.

Table 4.4.6 Comparison of environmental benefits and subsidies in urban traffic

Electricity source	Compared to	Marginal benefit	(Purchase) subsidy	Total benefits for 1 vehicle	Total benefits for 1 mill. vehicles
Brown coal	Gasoline	**€ 0.0033**	**€ 668.7**	**€ 669**	€ 668,690,718
	Diesel	**€ 0.0064**	**€ 1,270.8**	**€ 1,271**	€ 1,270,802,718
Natural Gas	Gasoline	**€ 0.0106**	**€ 2,112.8**	**€ 2,113**	€ 2,112,780,896
	Diesel	**€ 0.0136**	**€ 2,714.9**	**€ 2,715**	€ 2,714,892,896

4.4.2.2. In overland traffic

When looking at overland traffic, the utilization of electric vehicles is getting far dirtier, as the electricity consumption outside of urban areas increases significantly. Under these assumptions, the marginal damage of diesel (1.3 cents) and gasoline (1.07 cents) vehicles decreases, while the damage of natural gas (0.7 cents) and brown coal (2.06 cents) increases. For the environmental benefits this results in reduced benefits of natural gas compared to diesel (0.6 cents) and gasoline (0.37 cents) and now significant environmental losses when comparing brown coal with gasoline (- 0.98 cents) and diesel (- 0.76 cents). See tables 4.4.7 and 4.4.8 below for results.

Table 4.4.7 Comparison of marginal and absolute damages in overland traffic

Choosen vehicle	Total marginal damage	Kilometers driven	Absolute damage for 1 vehicle	Absolute damage for 1 mill. vehicles
Gasoline	€ 0.0107	200000	€ 2,148	€ 2,147,661,000
Diesel	€ 0.0130	200000	€ 2,599	€ 2,599,245,000
Brown coal	€ 0.0206	200000	€ 4,115	€ 4,115,357,403
Natural Gas	€ 0.0070	200000	€ 1,408	€ 3,381,964,026

Now, the subsidy for electric vehicles that are powered by brown coal-produced electricity turns into environmental taxes of € 1,968 (gasoline to brown coal) and 1,516 (diesel to brown coal). For natural gas, the subsidy is significantly lower than before, but still positive. Regarding the total benefits, the electric vehicles deliver a large loss for brown coal produced electricity.

Table 4.4.8 Comparison of environmental benefits and subsidies in overland traffic

Electricity source	Compared to	Marginal benefit	Purchase subsidy	Total benefits for 1 vehicle	Total benefits for 1 mill. vehicles
Brown coal	Gasoline	**- € 0.0098**	**- € 1,967.7**	**- € 1,968**	- € 1,967,696,403
	Diesel	**- € 0.0076**	**- € 1,516.1**	**- € 1,516**	- € 1,516,112,403
Natural Gas	Gasoline	**€ 0.0037**	**€ 740.0**	**€ 740**	€ 739,972,680
	Diesel	**€ 0.0060**	**€ 1,191.6**	**€ 1,192**	€ 1,191,556,680

4.4.3. Comparison of expectations and reality

In public debate, the benefits of electric vehicles are often overestimated, as not just politicians, but also advertisements promote electric vehicles as emission free. In reality, this claim must be identified as half-truth, as the sole act of driving is indeed emission free, but neither the production for electricity, nor the vehicle production is. However, as previously mentioned, the car and battery manufacturing are not considered in this work.

Summing up, the driving of electric vehicles under average conditions can indeed deliver significant environmental benefits compared to gasoline and especially diesel vehicles, but the extent crucially depends on the producer of the marginal unit of electricity. On the one hand, for the comparison of gasoline vehicles and electric vehicles powered by electricity coming from brown coal, the replacement even results in an environmental loss and should not be subsidized. But, if the electricity is on the other hand produced by the use of natural gas, this delivers large environmental benefits for society and thereby justifies a subsidy.

What needs to be mentioned additionally, is that the cost of natural gas is much higher than the one of coal, and that is why it is far less attractive for producers to use natural gas as the marginal unit instead of coal. Thus, it might be that the marginal electricity for a single vehicle is coming from natural gas, but for many vehicles it is not considered economical and therefore coal is used instead which leads to a much higher damage than natural gas as shown above.

However, regarding this issue, political incentives need to be set to steer the further development. For example, a tax could be implemented that is specifically designed to cover the external costs of fossil fuels, thereby making the utilization of coal as marginal power plant less attractive.

5. Case Study: Particulates alarm in Stuttgart

The story of Stuttgart is an interesting example of the challenges that mankind is faced in the light of environmental pollution, the climate change and globalisation. The city is the capital and largest city of Baden-Württemberg and inhabits about 610.000 people. Primarily, it is known as hometown of world-famous technology firms such as Bosch, Mercedes or Porsche, which export their products into the whole world. Secondly, both the regional prime minister and the city's major are members of the Green Party, being successfully engaged in the combination of the region's economic prosperity and environmental awareness.

Nevertheless, the city is also known to have huge problems with air pollution, which is not just due to their large industry, but also the geographic location. The location is often described as a "boiler" as the city is surrounded by hills in three directions which makes natural air circulation difficult and therefore keeps pollutants longer in the city than elsewhere. That is why, a particulates alarm was already announced several times, including the call for commuters to use public transportation at a reduced price (which is normally quite expensive) or ride sharing, but also a ban of driving for certain types of diesel vehicles.

Naturally, many politicians in the region support the promotion of electric vehicles and other forms of sustainable mobility to combat these issues not only in Stuttgart, but also in other places of the world. Therefore, the question could be raised, how electric vehicles might help fighting the air pollution problem in the short-term, and how the issue could be solved in the future? By using the results of Holland et. al. (2016), pollution can be divided into local and global pollution, and therefore different results for native and exported damages are calculated. The difference between driving an electric and a gasoline vehicle is not just the extent of the caused pollution, but also the location at which pollution occurs. While gasoline and diesel vehicles emit the caused pollution directly in place, the pollution caused by driving electric vehicles is emitted at the place where the electricity is produced and therefore in many cases not in the same place where the vehicle is driven. For cities such as Stuttgart, the substitution of gasoline and diesel vehicles through electric vehicles offers the short-term solution to reduce the pollution in place and export it out of the city. Of course, this option is only possible as long as the electric power plant is not situated within the metropolitan area, but for example on the country side, where less people are directly affected.

If it is now assumed, that there is no uniform subsidy and instead a differentiated purchase subsidy for electric vehicles, the governments of metropolitan areas such as Stuttgart could be very interested in subsidizing electric vehicles and therefore crowding out the pollution from the city and export it to the countryside. According to the city of Stuttgart, 377 of every 1000 inhabitants owned a private vehicle in 2015 (Statistisches Amt, 2018). Assuming a population of 610,000 people would therefore result in a total of 230,000 vehicles just including locals. Additionally, assuming that about a third of the 250,000 commuters (Statistik BW, 2017) arrives by car, results in about 300,000 vehicles that are driving in Stuttgart on a regular basis.

Table 5.1 Possible environmental benefits through electric vehicles (average)

Choosen vehicle	Total marginal damage	Kilometers driven	Number of Vehicles	Absolute damage	(Local) Environmental benefit
Gasoline	€ 0.0119	200000	150000	€ 357,943,500	
Diesel	€ 0.0144	200000	150000	€ 433,207,500	
Sum of absolute damages				**€ 791,151,000**	**€ 791,151,000**
Brown coal	€ 0.0137	200000	300000	€ 823,071,481	**- € 31,920,481**
Natural Gas	€ 0.0047	200000	300000	€ 281,537,664	**€ 509,613,336**

Using the assumptions that half of the vehicles are gasoline-powered and the other half diesel-powered, would result in absolute damages of 790 million Euro over the whole lifetime of the considered vehicles. If all those vehicles were replaced by electric vehicles, this could lead to three different extreme cases:

Firstly, if the whole electricity was produced somewhere else, this would reduce the local damage to zero and therefore could lead to local environmental benefits in the full amount of 790 million Euro. Of course, those damages then occurred somewhere else. Secondly, for the case that the electricity was produced entirely by brown-coal within the city territory, this would lead to absolute damages of 823 million Euro and thus environmental losses of about 32 million Euro. The pollution would even be worse than before. Finally, the absolute damages could be reduced from 790 million down to 280 million Euro, if the whole electricity was coming from power plants using natural gas, as well within the city borders.

Consequently, electric vehicles in combination with the right electricity supply could offer a way out for the city to drastically reduce its local pollution. However, this probably just offers a short-term relieve, and has to be considered as intermediate stage on the way towards a sustainable mobility on the basis of renewable sources of energy and new technologies.

Conclusion

In summary, the research question whether there are environmental benefits from driving electric vehicles in Germany cannot be answered explicitly. It crucially depends on the source of energy that is utilized for the production of electricity. For example, if gasoline and diesel vehicles are replaced by electric vehicles using electricity from natural gas, this results in a large environmental benefit for society, under each of the considered cases. However, if the replacing vehicle is powered using brown coal, the society is only then slightly better off, if the replaced vehicle was a diesel-powered one or the driving in urban-conditions is considered. Otherwise, the electric vehicle leads to significant environmental losses.

Regarding the justified subsidies to incentivize the purchase of electric vehicles, the results find that the current purchase subsidy is significantly higher than it should be, given the environmental benefits that an electric vehicle provides even under the most optimistic assumptions. Furthermore, it needs to be considered that the subsidies for electric vehicles do not just include the direct purchase subsidy, but also the indirect subsidies by exempting electric vehicles from the motor-vehicle tax or charging a lower tax on electricity. Subsequently, the calculated subsidy that an electric vehicle might be eligible to receive should cover for the whole package of incentives and not just the purchase subsidy.

Consequently, the development of electric vehicles is one that is a step in the right direction under environmental aspects, but the purpose of purchase subsidies without a large-scale erection and extension of the necessary infrastructure is questionable. Currently, electric vehicles only then deliver a higher utility for the consumer as long as the direct and indirect incentives are given, but without them the benefit for the consumer is gone. Furthermore, there are also other issues like battery range, charging infrastructure and relatively high electricity prices that have to be addressed by politicians, businessmen and engineers.

Thus, governments should instead invest in the establishment of a sustainable mobility concept, that includes the availability of clean and renewable energies, the enhancement of charging infrastructure both in urban and rural areas, the extension of environmentally friendly means of transportation like public transport and trains, and the strengthening of share economy ideas like car sharing. If energy sources would be taxed according to their real costs, hence including external costs, the utilization of fossil fuels was much less attractive and sustainable sources became economically reasonable in the long-term planning. Forcing the market to radically rethink and incentivizing the development of sustainable technologies is the best investment in the future that a government can make.

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Appendix

Appendix A: Power plants in Germany (from 100 megawatts of electrical power)

Bundesland	Abbr.	Total number	Total power	Average	Basic Provider
Baden-Württemberg	BW	35	12789.3	365.4	EnBW
Bavaria	BY	25	9611.5	384.5	E.ON
Bremen	HB	5	1462.0	292.4	E.ON
Hamburg	HH	4	2001.0	500.3	Vattenfall
Hesse	HE	11	2693.7	244.9	E.ON
Lower Saxony	NI	29	10195.2	351.6	E.ON
North Rhine-Westphalia	NW	79	29917.3	378.7	RWE
Rhineland-Palatinate	RP	5	1786.0	357.2	RWE
Saarland	SL	5	2102.0	420.4	RWE
Schleswig Holstein	SH	10	3098.2	309.8	E.ON
Offshore (North Sea)		16	4601.4	287.6	E.ON
West Germany		**224**	**80257.6**		
Berlin	BE	13	2432.0	187.1	Vattenfall
Brandenburg	BB	26	7999.7	307.7	Vattenfall
Mecklenburg-Vorpommern	MV	3	808.0	269.3	Vattenfall
Saxony	SN	15	6043.2	402.9	Vattenfall
Saxony-Anhalt	ST	17	2996.8	173.3	Vattenfall
Thuringia	TH	9	1937.6	215.3	Vattenfall
Offshore (Baltic Sea)		2	638.0	319.0	Vattenfall
East Germany (incl. Berlin)		**83**	**22217.3**		Vattenfall
in total		**309**	**103112.8**	**333.7**	

Source: UBA (2018), own presentation

Appendix B: Results of standard model calculation without promotions, with P_{Te} = 30,000€

Engine	Indirect utility	Risk of Ban on Driving		Environmental Awareness		Direct utility
Gasoline	**29156.7**	$B_g < 1$	0.99	$A_g = 1$	1	28865.1
Diesel	28587.7	$B_d < 1$	0.99	$A_d = 1$	1	28301.9
Electric	28629.5	$B_e = 1$	1	$A_e > 1$	1.01	**28915.8**

Appendix C: Overview (for consumption per km = 0.127 kWh)

Source of Energy / Unit		Pollutant					
		CO_2	**SO_2**	**NO_x**	**NMVOC**	**Methane**	**PM_{10}**
Gasoline	**t / km**	**1.34E-04**	**-**	**6.00E-08**	**6.80E-08**	**-**	**4.50E-09**
Diesel	**t / km**	**1.34E-04**	**-**	**2.28E-07**	**1.90E-08**	**-**	**4.50E-09**
Brown Coal	**(m)g/kWh**	1105g	606mg	671mg	17mg	92mg	27.9mg
	t / kWh	1.11E-03	6.06E-07	6.71E-07	1.70E-08	9.20E-08	2.79E-08
	t / km	**1.40E-04**	**7.70E-08**	**8.52E-08**	**2.16E-09**	**1.17E-08**	**3.54E-09**
	(m)g/km	140.3g	76.7mg	85.2mg	2.16mg	11.7mg	3.5mg
Stone Coal	**(m)g/kWh**	935g	414mg	469mg	17mg	92mg	27.8mg
	t / kWh	9.35E-04	4.14E-07	4.69E-07	1.70E-08	9.20E-08	2.78E-08
	t / km	**1.19E-04**	**5.26E-08**	**5.96E-08**	**2.16E-09**	**1.17E-08**	**3.53E-09**
	(m)g/km	118.7mg	52.6mg	59.6mg	2.16mg	11.7mg	3.5mg
Natural Gas	**(m)g/kWh**	420g	-	120mg	17mg	920mg	-
	t / kWh	4.20E-04	-	1.20E-07	1.70E-08	9.20E-07	-
	t / km	**5.33E-05**	**-**	**1.52E-08**	**2.16E-09**	**1.17E-07**	**-**
	(m)g/km	53.34g	-	15.24mg	2.16mg	116.8mg	-
Electricity Mix	**(m)g/kWh**	516g	290mg	440mg	17mg	184mg	15mg
	t / kWh	5.16E-04	2.90E-07	4.40E-07	1.70E-08	1.84E-07	1.50E-08
	t / km	**6.55E-05**	**3.68E-08**	**5.59E-08**	**2.16E-09**	**2.34E-08**	**1.91E-09**
	(m)g/km	65.53g	36.83mg	55.88mg	2.16mg	23.368mg	1.91mg

Source: UBA (2016 & 2018), Seilnacht (2018), own presentation

Appendix D: Average marginal damage per pollutant

Source of Energy / Unit		(1) Average marginal damage per pollutant (average conditions)						Total marginal damage (in €)
		CO_2	SO_2	NO_x	NMVOC	Methane	PM_{10}	
Gasoline	**€ / km**	0.0107200	-	0.0009240	0.0001088	-	0.0001787	0.0119
Diesel	**€ / km**	0.0107200	-	0.0035112	0.0000304	-	0.0001787	0.0144
Brown coal	**€ / km**	0.0112268	0.0010159	0.0013123	0.0000035	0.0000187	0.0001407	0.0137
Stone coal	**€ / km**	0.0094996	0.0006940	0.0009173	0.0000035	0.0000187	0.0001402	0.0113
Natural Gas	**€ / km**	0.0042672	-	0.0002347	0.0000035	0.0001869	-	0.0047
Electricity mix	**€ / km**	0.0052426	0.0004862	0.0008606	0.0000035	0.0000374	0.0000756	0.0067

Source of Energy / Unit		(2) Average marginal damage per pollutant (in urban traffic)						Total marginal damage (in €)
		CO_2	SO_2	NO_x	NMVOC	Methane	PM_{10}	
Gasoline	**€ / km**	0.0128640	-	0.0011088	0.0001306	-	0.0002144	0.0143
Diesel	**€ / km**	0.0128640	-	0.0042134	0.0000365	-	0.0002144	0.0173
Brown coal	**€ / km**	0.0089814	0.0008127	0.0010499	0.0000028	0.0000150	0.0001125	0.0110
Stone coal	**€ / km**	0.0075997	0.0005552	0.0007338	0.0000028	0.0000150	0.0001121	0.0090
Natural Gas	**€ / km**	0.0034138	-	0.0001878	0.0000028	0.0001496	-	0.0038
Electricity mix	**€ / km**	0.0041940	0.0003889	0.0006884	0.0000028	0.0000299	0.0000605	0.0054

Source of Energy / Unit		(3) Average marginal damage per pollutant (in non-urban traffic)						Total marginal damage (in €)
		CO_2	SO_2	NO_x	NMVOC	Methane	PM_{10}	
Gasoline	**€ / km**	0.0096480	-	0.0008316	0.0000979	-	0.0001608	0.0107
Diesel	**€ / km**	0.0096480	-	0.0031601	0.0000274	-	0.0001608	0.0130
Brown coal	**€ / km**	0.0168402	0.0015238	0.0019685	0.0000052	0.0000280	0.0002110	0.0206
Stone coal	**€ / km**	0.0142494	0.0010410	0.0013759	0.0000052	0.0000280	0.0002102	0.0169
Natural Gas	**€ / km**	0.0064008	-	0.0003520	0.0000052	0.0002804	-	0.0070
Electricity mix	**€ / km**	0.0078638	0.0007292	0.0012908	0.0000052	0.0000561	0.0001134	0.0101

Source: UBA (2016 & 2018), Seilnacht (2018), own presentation

Abstract

In this master thesis, the research question whether there are environmental benefits from driving electric vehicles in Germany is addressed by adapting and enlarging the approach used by Holland et. al. (2016). By the use of a discrete choice transportation model and the variation of policy variables, the consumer purchase decision is simulated for different scenarios. Furthermore, environmental benefits of electric vehicles in comparison to diesel and gasoline vehicles are calculated for data of the German electricity and vehicle market. The aim is to contribute to the discussion of future mobility in line with renewable energies and by the use of new technologies, to deal with the challenges of the climate change, environmental pollution and scarcity of fossil resources.

Zusammenfassung

In dieser Masterarbeit wird die Forschungsfrage gestellt, ob das Fahren von Elektroautos in Deutschland zu Umweltvorteilen gegenüber Benzin- und Dieselfahrzeugen führt. Dafür wird die Vorgehensweise von Holland et. al. (2016) übernommen und erweitert. Zuerst wird in einem diskreten Modell die Kaufentscheidung der Konsumenten unter Variierung verschiedener Variablen simuliert. Zum Zweiten werden auf Basis von Verschmutzungsdaten und Schätzungen für externe Kosten Berechnungen für Umweltvorteile von Elektroautos gegenüber Benzin- und Dieselfahrzeugen aufgestellt. Ziel ist es einen Beitrag zur Diskussion um zukünftige Mobilität zu leisten und zu untersuchen wie die Herausforderungen des Klimawandels, der Umweltverschmutzung und der Ressourcenknappheit durch die Integration Erneuerbarer Energien und neuer Technologien gemeistert werden können.