Are battery electric vehicles the future?

An uncertainty and robustness comparison with hydrogen fuel cell and internal combustion engine vehicles in Germany

vorgelegt von
M.Sc.
Alexander Wanitschke
ORCID: 0000-0001-9031-772X

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Promotionsausschuss:

Vorsitzender:	Prof. Dr. Thomas Brown
Gutachter:	Prof. Dr. Frank Behrendt
Gutachter:	Prof. Dr. Dr. Ortwin Renn

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I hereby declare that I have written the present work independently and I have not used any sources or resources other than those specified.

Berlin, June 11, 2021

Notes on language use

Conventions about acceptable style in academic writing differ across languages. For example, German academic writing routinely uses and prefers the passive voice, while English-speaking academics increasingly frown upon it and prefer the active voice and the first person, both singular and plural, as it results in more comprehensible language and encourages scientists to be explicit [1, 2]. For the sake of maximum clarity of thought and vigorous expression I use the active voice (i.e. first person in singular) where possible and the passive voice where appropriate. I also strive for specific but plain language for it is better to be clear and possibly wrong than to hide behind obscurity and not be understood at all. As Stuart Hampshire described Bertrand Russell's writing style (as cited in [3]): "It's a question of not obfuscating – of leaving no blurred edges; of the duty to be entirely clear, so that one's mistakes can be seen; of never being pompous or evasive. It's a question of never fudging the results, never using rhetoric to fill a gap, never using a phrase which conveniently straddles, as it were, two or three notes and leaves it ambiguous which one you're hitting."

Acknowledgments

What began with a ten-page exposé ends today - five years, two babies and 144 pages later. And even though words can hardly describe the range of my emotions I know that above all I feel enormous gratitude for all the support I have received over the years and along this journey.

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Abstract

The passenger vehicle sector in Germany is under increasing pressure to reduce its GHG emissions. As a scalable remedy three distinct technology options are available: (1) internal combustion engine vehicles (ICEV) supplied with non-fossil, hydrocarbon fuels, (2) fuel cell electric vehicles (FCEV) supplied with hydrogen, and (3) battery electric vehicles (BEV) supplied with electric energy. Public disagreement about the "best" option persist to this day. While uncertainty (i.e., lack of knowledge) arguably plays a major role in this disagreement, past research has touched only superficially on what we do and *do not* know in order to assess how robust the feasibility of any of the technology options is with regards to possible future states of the world.

In order to address this issue I conducted both a systematic uncertainty analysis and a consecutive robustness analysis. The results show that even though all three drive technology options are affected by a similar number and quality of uncertainties, the uncertainty landscape translates into significant differences of robustness regarding the different vehicle technology's total cost of ownership (TCO) and life cycle GHG emissions (LCE). According to a tipping point analysis none of the three technologies can be demonstrated to reliably outperform their competitors in all conceivable future states of the world. Each of the three technologies still has distinct vulnerabilities and associated risks. However, it can be argued that today's reality is closer to the point of clear superiority for BEV than for FCEV or ICEV. Broadly speaking my research contributes further arguments of why BEVs should be considered the most reliable option for decarbonizing passenger vehicles in Germany.

Zusammenfassung

Der deutsche PKW-Verkehr steht unter zunehmendem Druck, seine Treibhausgasemissionen zu reduzieren. Als skalierbare Lösung stehen drei unterschiedliche Technologieoptionen zur Verfügung: (1) verbrennungsmotorische PKW mit nicht-fossilen Kraftstoffen, (2) Brennstoffzellen-PKW mit Wasserstoff und (3) batterieelektrische PKW mit elektrischer Energie. Bis heute besteht Uneinigkeit über die Frage der "besten" Antriebsoption und obwohl Unsicherheit (d.h. das Fehlen von Wissen) dabei eine wichtige Rolle spielt, haben vorangegangene Forschungsarbeiten hierzu nur unzureichend herausgearbeitet, was *nicht* bekannt ist, um zu entscheiden wie robust die Güte der verschiedenen Antriebsoptionen bzgl. möglicher Entwicklungen der Zukunft ist.

Um diese Forschungslücke zu schließen, habe ich sowohl eine systematische Unsicherheitsanalyse als auch eine darauf aufbauende Robustheitsanalyse der drei Antriebsoptionen durchgeführt. Die Ergebnisse zeigen, dass, einerseits, alle Antriebsoptionen von einer ähnlichen Anzahl und Qualität von Unsicherheiten betroffen sind, und dass sich, andereseits, diese Unsicherheitslandschaft unterschiedlich stark auf die Robustheit der Antriebe bzgl. Ihrer total cost of ownership (TCO) und life cycle GHG emissions (LCE) auswirkt. Meine Ergebnisse liefern Argumente dafür, dass batterieelektrische PKW die robusteste Technologieoption sind, um den PKW-Verkehr in Deutschland zu dekarbonisieren.

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List of Acronyms and Symbols

AC	alternating current
batt	regarding the battery
BCE	battery cycle emissions
BEV	battery electric vehicle
CCS	combined charging system
CIE	carbon intensity of electricity
DC	direct current
FC	fuel cell
FCE	fuel cycle greenhouse gas emissions
FCEV	fuel cell electric vehicle
FE	fuel economy
GHG	greenhouse gas
HHV	higher heating value
HVAC	heating, ventilation and air conditioning
ICEV	internal combustion engine vehicle
ILUC	indirect land-use change
IQR	interquartile range
LCE	life cycle greenhouse gas emissions
LFP	lithium iron phosphate
LHS	latin hypercube sampling
LIB	lithium-ion battery
MCE	Monte Carlo experiment
NCA	nickel cobalt aluminum oxide

NMC	nickel manganese cobalt oxide
NPM	Nationale Plattform Zukunft der Mobilität (national platform future of mobility)
PHEV	plug-in hybrid electric vehicles
ref	reference value
SOW	(future) states of the world
TCO	total cost of ownership
VCE	vehicle cycle greenhouse gas emissions
VtG	Vehicle-to-grid
WTT	well-to-tank

α	threshold value for significance test
C	energy storage capacity
d	rank difference of an observation
D	annual driven distance
E	expectation
η	efficiency
I	model input
L	vehicle life time
μ	population mean
M_{scal}	scaling mass of a vehicle, i.e. vehicle mass excluding tires, fluids, battery and fuel cell system
n	population size
O	model output
p	price
P	power
R^2	coefficient of determination
r	discount rate
ρ	Spearman's rank correlation coefficient

σ	standard deviation
S	Spearman rank correlation
X_{1-14}	parameters of vehicle models for Monte Carlo simulation

Chapter 1

Introduction

"The more I learn, the more I realize how much I don't know."
— Albert Einstein

Germany, which is among the largest global emitters of greenhouse gas (GHG), ratified the Paris Agreement of 2015 in October 2016 and obligated itself to significantly reduce its GHG emissions [28]. More specifically, with its Climate Change Act of 2021 the German government set to achieve complete carbon neutrality by the year 2045 as well as a reduction of GHG emissions of 65 % by 2030 and 88 % by 2040 as compared to 1990 [29]. As part of this objective German transport is to reduce its GHG emissions by over 40 % by 2030 as compared to 2020 [30, 31].

Efforts to reduce Germany's carbon footprint have already led to a decrease of GHG emissions in most sectors of its economy. Only the transport sector has not achieved a relevant reduction of its carbon footprint but has been fluctuating around GHG emissions of some 160 Mt CO_2-eq. since 1990 [5]. Around 95 % of German transport's GHG emissions are caused by road-bound vehicles (59 % passenger cars and 35 % utility vehicles, see Fig. 1.1). Private cars' role in German transport cannot be overstated. Nearly 75 % of passenger kilometers in Germany are caused by motorized individual transport[1] [33]. As of today, German passenger cars almost completely (95 %) rely on fossil sources of energy and are responsible for 12 % of German GHG emissions and 24.5 % of German energy demand [5, 34].

[1]Motorized individual transport is defined as transport which individuals realize with private cars voluntarily in terms of time and distance [32]

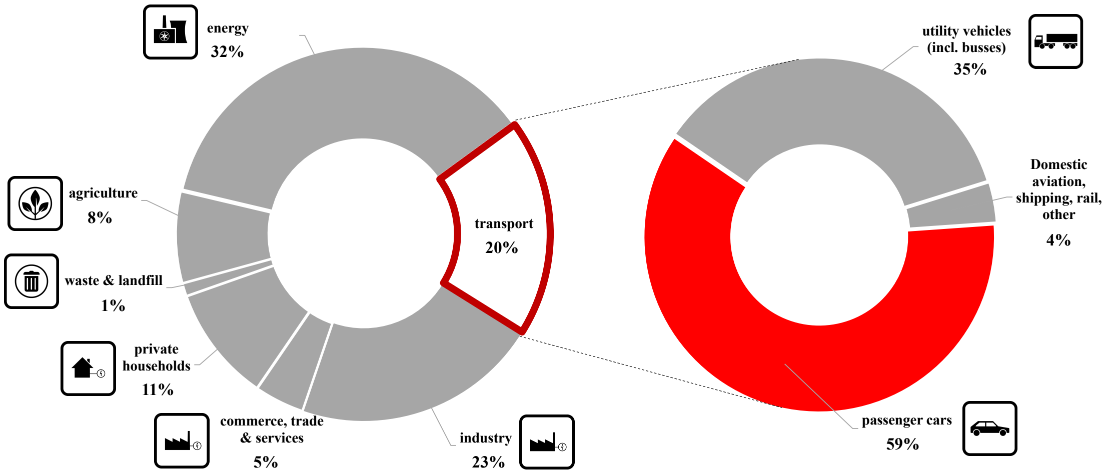


Figure 1.1: *Passenger cars as a major source of Germany's greenhouse gas emissions [4, 5]*

1.1 Alternative vehicle technologies

As a core transport sector, passenger vehicles have been the object of environmental scrutiny and the platform for technological innovation. For achieving the energy transition of transport, three different vehicle technology options have the potential to scalably decarbonize passenger vehicle transport: battery electric vehicles (BEVs), hydrogen-based fuel cell electric vehicles (FCEVs), and internal combustion engine vehicles (ICEVs) supplied with alternative hydrocarbon fuels [35]. Fig. 1.2 visualizes these options for decarbonizing passenger vehicles, based on a renewable energy supply.

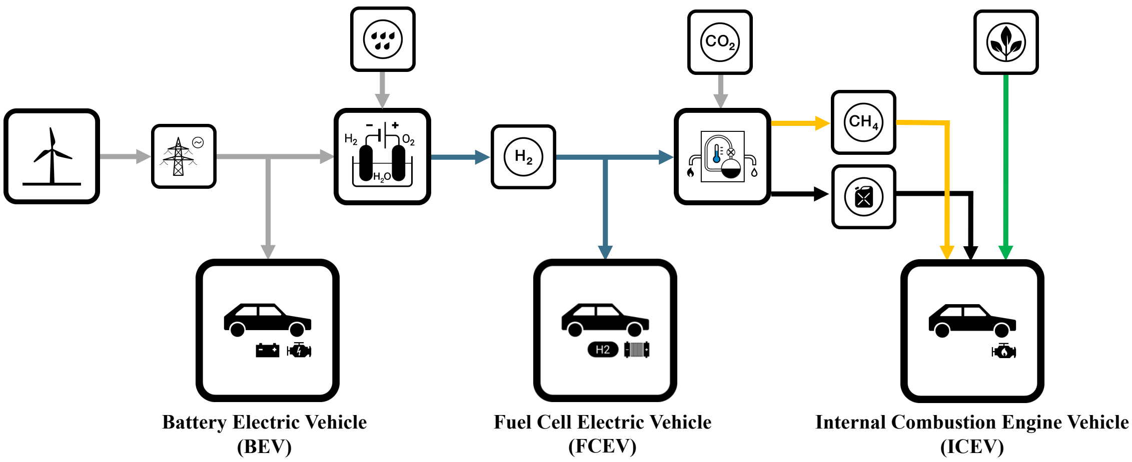


Figure 1.2: *Core technology options for low-carbon road transport*

Even though ICEVs are the most widely used type of vehicle today, the history of all three core technologies dates back to the 19th century [36]. One of the first electric vehicle is assumed to date back to the time between 1832 and 1839, built by

Scottish Engineer Robert Anderson in Aberdeen [37]. At the same time, in 1838 the German-Swiss chemist Christian Friedrich Schönbein discovered the principle of the fuel cell [38] (It took 128 years until General Motors built the first fuel cell electric vehicle in 1966 however). In 1876, Nikolaus Otto developed a new engine powered by gasoline, called *Otto Engine* [39] . A decade later in 1886, Gottlieb Daimler in Cannstadt and Carl Benz in Mannheim simultaneously but independently invented the first otto-engine-powered vehicle [40]. The "Benz Velo" was the first series-produced automobil in 1894 [40]. Simultaneously Ferdinand Porsche kept enhancing the electric automobile. By building a four-wheel drive, called Lohner-Porsche in 1900, Porsche invented the first popular electric car with four individual electric engines (see Fig. 1.3) [41]. Even though in 1905 electric cars made up more than a third of all cars in the United States of America further improvement of the internal combustion engine vehicle and inherent problems of the 19th century electric vehicle won the competition for the combustion engine and manifested ICEVs dominance in the 20th century [42]. A common explanation of BEVs historic inferiority is its limited range due to low energy density of its lead-acid batteries, however Gijs Mom finds that ICEVs early long range capability was only one of many perceived disadvantages of early 20th century battery electric vehicles [43]. Mom outlines how the historic combination of motor, battery and tire technology combined with crude road infrastructure and race-car-oriented societal expectations of a vehicle put the electric car on hold 100 years ago. More specifically, for instance lead-acid battery electric vehicles could only be maintained with expert knowledge (which initially made them popular for urban taxi fleets). Moreover, infrequent use of battery vehicles lead to buildup of sulfates within the cells which quickly eroded the wooden isolators. Wear and tear on rubber tires and suspensions was distinctly higher for heavier battery electric vehicles and underdeveloped, demanding roads too often had the sensitive lead plates of the battery break into pieces. Overall, the combustion engine vehicle was more resilient while gradually adopting and incorporating popular aspects of the electric vehicle such as front-wheel drive, electric starter as well as higher comfort through easier operability and quieter motors [43]. Increasingly available fossil fuels at decreasing prices finally gave the combustion engine vehicle the decisive advantage to become the dominating technology for road-based transport in the 20th century. Today, a century later, many technical challenges of the past have been overcome and modern BEV and FCEV as well as decarbonized fuels for ICEV technologies offer options to decarbonize passenger vehicles at scale. The following subsections describe the current technological state of the art and provide an overview of the three alternative vehicle technology options.

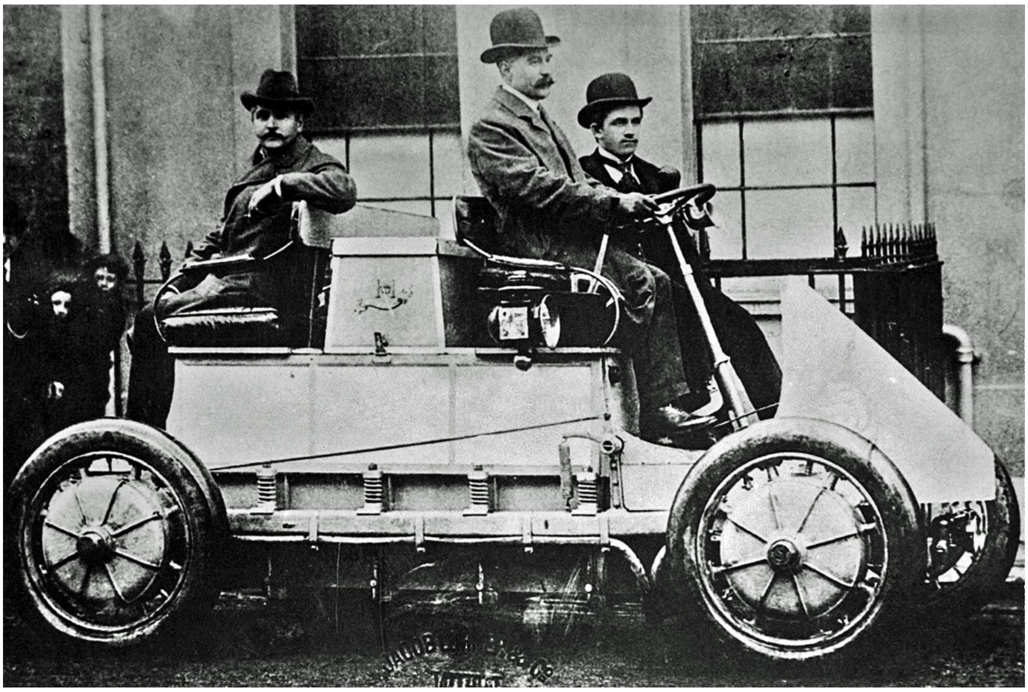


Figure 1.3: *Lohner-Porsche electromobile around 1900 [6]*

1.1.1 Internal combustion engine vehicles (ICEV)

Vehicle technology

The most established technology for passenger cars is that of internal combustion engine vehicles (ICEV). It is at its core a heat engine which generates mechanical energy from combustion of a liquid or gaseous fuel. Today's ICEV motors are based on the otto cycle or the diesel cycle which take in petrol or methane and diesel, respectively. The air-fuel-mixture is ignited by a spark from the spark plug. A diesel engine is commonly compression-ignited, rather than the spark-ignited systems used in a gasoline engine in which the fuel is injected into the combustion chamber and combined with air. Other basic components of an internal combustion engine vehicle are outline below (see also Fig. 1.4).

Fuel filler and tank: A nozzle from a fuel dispenser attaches to the receptacle of the vehicle to fill its tank which stores fuel on board for use in the engine.

Fuel line, pump and injection system: Via a metal tube or flexible hose the pump transfers fuel from the tank to the engine's fuel injection system which introduces the fuel into the engine's combustion chambers of ignition.

Transmission: The transmission forwards mechanical power from the engine to drive the wheels.

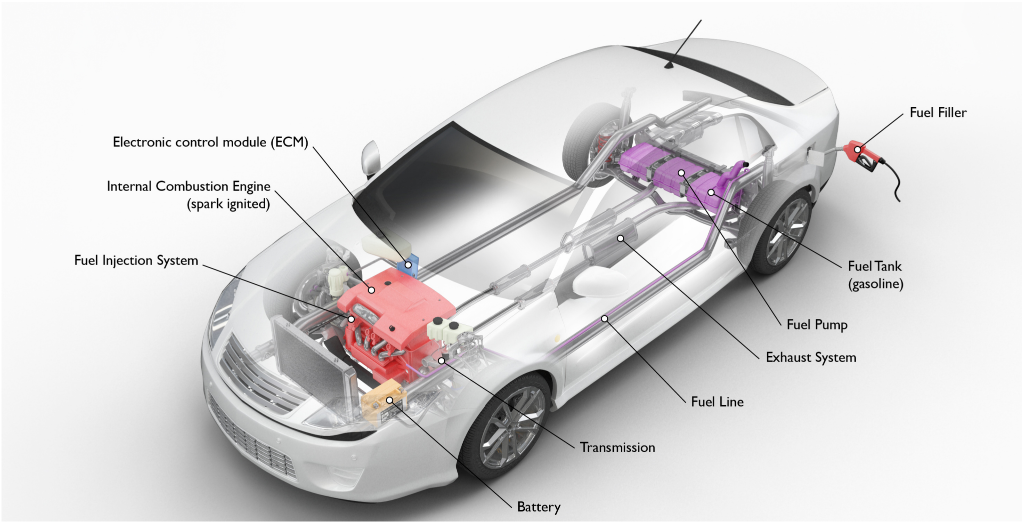


Figure 1.4: *Core components of a gasoline vehicle [7]*

Exhaust: The exhaust guides the product gases out from the engine through the tailpipe. A catalyst reduces engine emissions within the exhaust system.

Auxiliary battery The battery provides electric power to start-up the engine and power other vehicle electronics.

Electronic control module: The electronic control module monitors and controls the engine process (fuel mixture, ignition timing, and emissions system). It safeguards the engine from abuse, and detects and troubleshoots problems.

With over 40 million gasoline and diesel passenger vehicles in Germany and inventory shares of 65.2 % for gasoline and 31.2 % for diesel engine vehicles, ICEV technology is the dominating vehicle technology for passenger cars in Germany at the beginning of 2021 [44]. Including all hybrid powertrains as well as liquid petroleum and compressed natural gas powered vehicles, ICEV technology accounts for over 99 % of today's German passenger vehicle fleet.

Fuel infrastructure

As of July 2020 there were some 14,500 gas stations in Germany. The vast majority of fuel this infrastructure provides is still based on fossil resources [34]. A core criterion for the GHG neutrality of ICEV is the condition however that the production of its fuels is ultimately decarbonized. Different resources, processes and technologies are known today to achieve this. If compatibility with the existing infrastructure and vehicle technology is to be maintained however, only fuel syntheses providing liquid or gaseous hydrocarbon compounds can be used. Accordingly, alternative fuels are fuels which are produced with hydrogen and carbon. The main fuel process chains to achieve this are outlined in Fig. 1.5. The primary resources needed are water and electricity for hydrogen electrolysis as well as air or biomass to source carbon and additional hydrogen. Alternative fuel products are designed to replace fossil gasoline, diesel and methane. The details of intermediate process steps are not of importance in my research, as the fuel infrastructure for ICEV will be included on a macroeconomic scale. Due to multiple conversion steps, well-to-wheel efficiency[2] here is the lowest of all options (13-20 %) [45, 46]. In contrast, biofuels are produced on the basis of organic matter such as cultivated crops or organic waste products. In the past biofuels have been considered theoretically carbon neutral since they locally only emit the amount of carbon that has previously been bound by the plant (neglecting the energy input needed for plant production and conversion processes) [47].

[2]Well-to-wheel efficiency here is defined as regarding the energy chain starting with the supply of electric power and ending with the vehicle's propulsion.

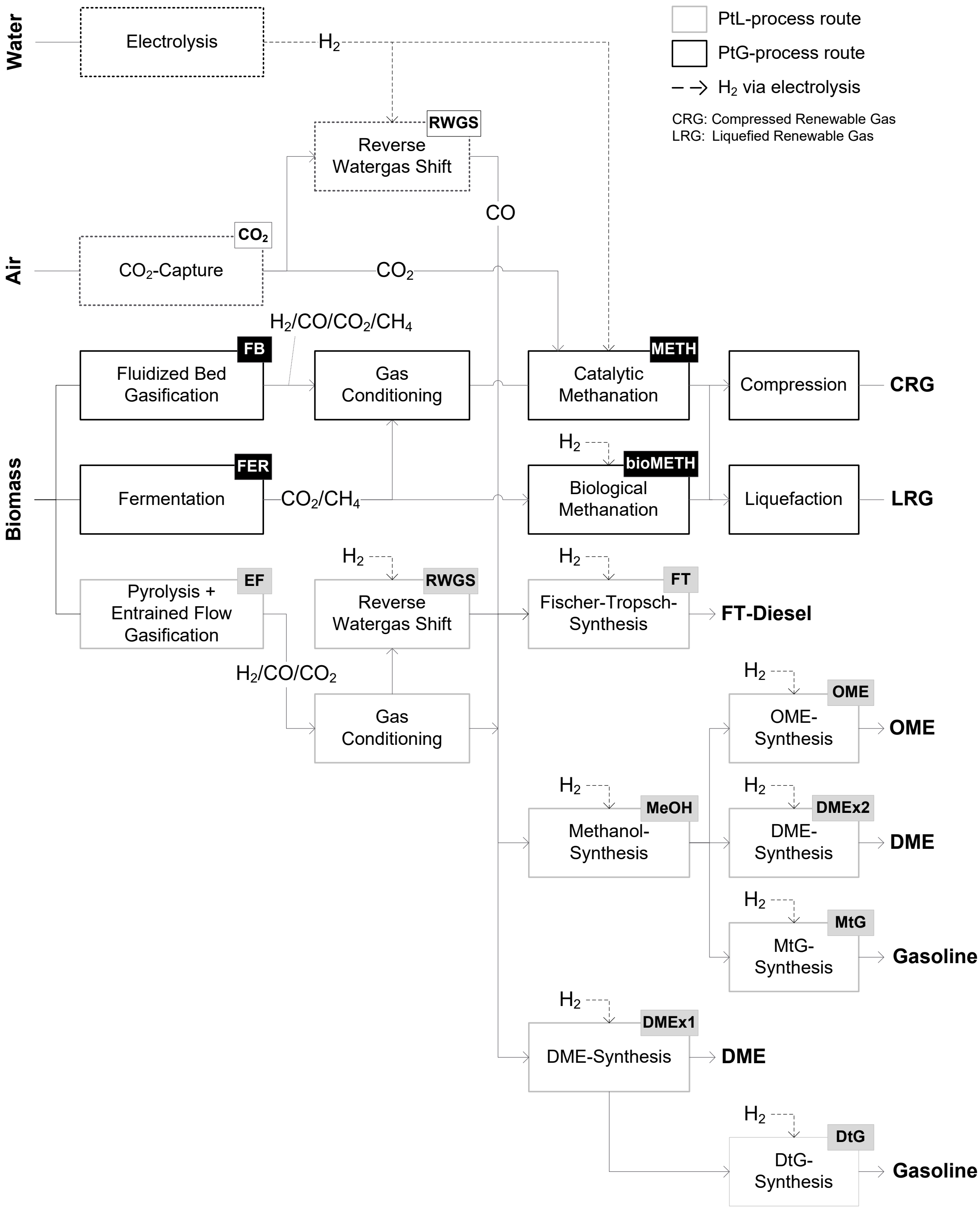


Figure 1.5: *Overview of alternative hydrocarbon fuel process chains [8]*

1.1.2 Battery electric vehicles (BEV)

Vehicle technology

Battery (all-)electric vehicles run on an electric traction motor instead of an internal combustion engine. A large traction battery pack powers the electric motor and is recharged when depleted. The traction battery functions as the main energy storage of the vehicle which powers the electric motor propulsion of the vehicle. As of 2020, the dominant battery cell technologies for electric vehicles are lithium-ion battery cells with graphite(-blend) anodes and different cathode chemistry, including nickel manganese cobalt oxide (NMC), nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP) [48]. Because the vehicle runs on electricity, it emits no exhaust from a tailpipe and does not need the typical liquid or gas fuel components, such as a fuel pump, fuel line, or fuel tank. Other auxiliary components of a battery electric vehicle are outline below (see also Fig. 1.6).

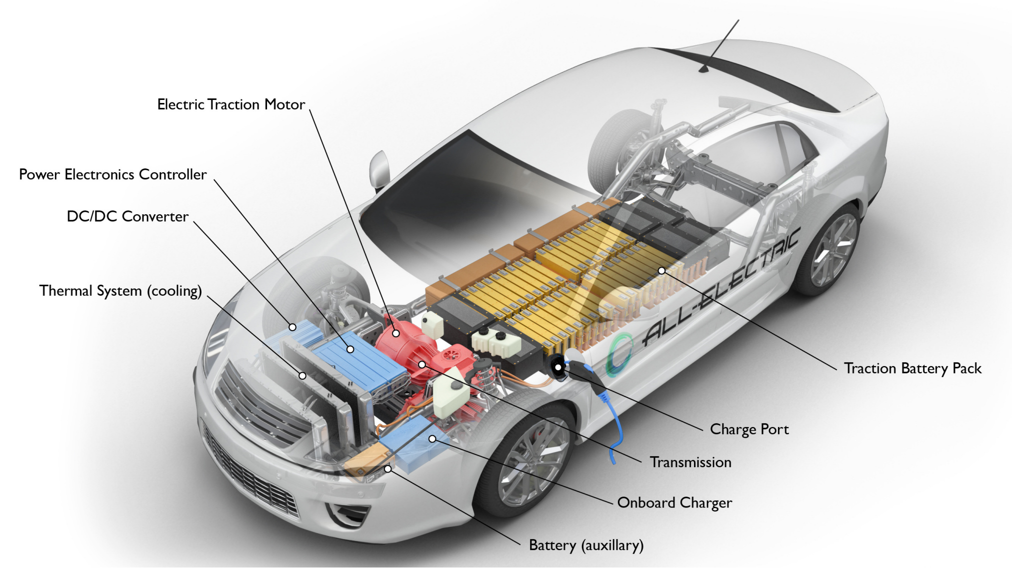


Figure 1.6: *Core components of a battery electric vehicle [9]*

Traction battery: The traction battery is the vehicle's main energy storage. Typical battery capacities of electric vehicles currently on the market range up to 100 kWh [49–51].

Auxiliary battery: Like in any vehicle the auxiliary battery provides electricity to power vehicle accessories.

Charge port and onboard charger: The charge port connects the vehicle to an external power supply for charging the traction battery. The onboard charger receives incoming alternating current (AC) or direct current (DC) supplied via the charge port and converts it to the DC for charging the traction battery. It also monitors the battery's voltage, current, temperature, and state of charge.

Power electronics controller: The power electronics controller administers the electrical power delivered by the traction battery, thus controlling the speed of the electric traction motor and the torque it applies to the wheels.

Electric transmission: The transmission channels mechanical power from the electric motor to the drive wheels.

DC/DC converter: The DC/DC converter takes higher-voltage DC power from the traction battery pack and converts it to the lower-voltage DC power which is needed to recharge the auxiliary battery and run vehicle accessories.

Thermal (cooling) system: The thermal system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components such as the battery pack.

In January of 2021 there were 309,083 passenger BEV as well as 279,861 plug-in hybrid electric vehicles (PHEV) on German roads [44]. This only makes one in a hundred passenger vehicles in Germany electric, however the market share of monthly registrations is steadily rising. In may 2021 some 12 % of new passenger vehicles were fully electric [52].

Fuel infrastructure

BEV's traction batteries can be recharged at public or private charging stations (also referred to as charging poles or charging stalls). Charging stations can consists of multiple charging points, each of which can only charge one vehicle at a time [53]. The German charging station regulation (German: Ladesäulenverordnung) differentiates charging points with regards to their power: normal charging points ($<$ 22 kW) and fast charging points ($\geq$ 22 kW). Outside of this categorization there are so called wall boxes which are usually privately owned, fused house outlet connections with a charging power no greater than 11 kW. While normal charging and some fast charging is supplied through alternating current, charging powers of around 50 kW and above are realized with direct current technology as the charger units onboard the vehicles are limited in their power intake. Today there are different types of charging plugs (see also Fig. 1.7):

Type 1 allows for AC single-phase charging of up to 7.4 kW. Due to its Asian origin, this standard is extremely rare in Germany.

Type 2 allows for AC triple-phase charging of up to 43 kW, although 22 kW and 11 kW are most common. It is considered to be the standard charging plug in Germany and Europe. Vehicles with type 2 inlets can also be charged with type 1 plugs.

Combined charging system (CCS) is an enhancement of the type 2 standard as it allows for both AC and DC charging due to two additional power contacts. CCS specification is comissioned for a charging power of up to 80 kW (CCS 1.0) and 350 kW (CCS 2.0).

Charge de move (CHAdeMO) was one of the first DC charging systems developed in Asia and originally allowed for a charging capacity of up to 150 kW (most commonly around 50 kW). Future version of CHAdeMO aim to increase this limit to 400 kW (CHAdeMO 2.0) and 500 kW (CHAdeMO 3.0) respectively.

Tesla Supercharger is a proprietary version of the type 2 standard, which was modified to allow for faster charging of *Tesla* vehicles.

In international comparison of charging infrastructure distribution Germany falls behind. Per 100 km of road Germany showed to have no more than 1.9 charging stations available [54]. At the same time the Netherlands had already achieved 29.3 public charging stations per 100 km of public road. In June of 2021 there were some 28,000 public charging stations in Germany (see Fig. 1.8). The majority of current public charging infrastructure in Germany allows for AC-charging (type 2) only. Only about 12 % of all charging stations are currently equipped with DC-charging technology (CCS, CHAdeMO or Tesla Supercharger).

Due to the high efficiency of the electric motor of up to 95 % and the possibility to partially recuperate the mechanical energy during breaking, BEVs exhibit the highest well-to-wheel efficiency of all considered technologies (around 70 %) [45, 55].

Figure 1.7: *Charging plug standards from left to right: type 1, type 2/Tesla supercharger, CCS, CHAdeMO [10]*

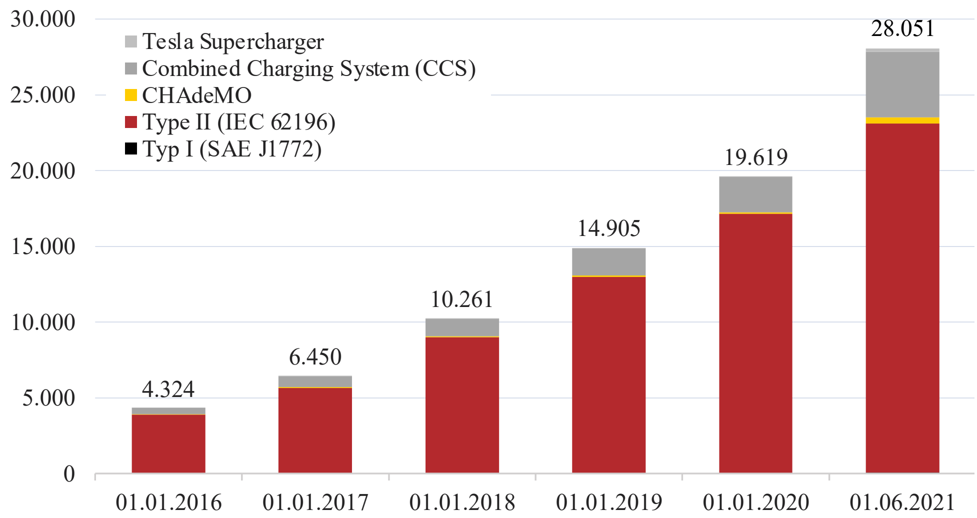


Figure 1.8: *Number of charging stations in Germany, based on [11, 12]*

1.1.3 Fuel cell electric vehicles (FCEV)

Vehicle technology

Like battery electric vehicles, fuel cell electric vehicles (FCEVs) use electric power to run a traction motor. In contrast to BEV, FCEVs produce electricity onboard via a hydrogen fuel cell in addition to a battery. Vehicle manufacturers set the power of the vehicle by the size of the electric motor, which in turn receives electricity from an appropriately sized fuel cell and battery combination. This is why FCEVs are by technical definition a hybrid technology. Car makers could include plug-in capabilities to charge the battery, but most FCEVs today use the battery solely for saving recuperated braking energy and for providing additional power during acceleration to smooth out the power delivered from the fuel cell as well as idling or switching off the fuel cell during low power needs. The amount of energy stored on board is determined by the size of the hydrogen fuel tank. Other core components of a FCEV are outline below (see also Fig. 1.4).

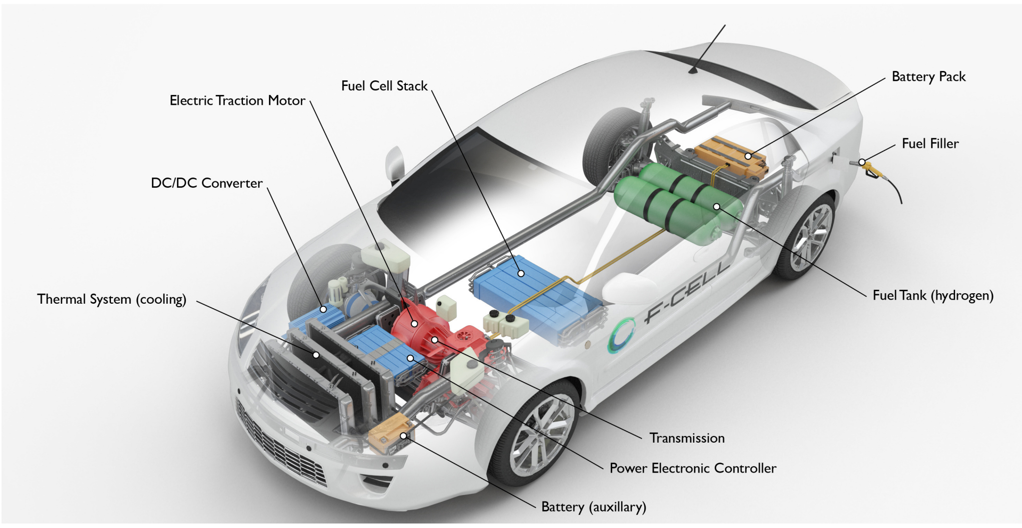


Figure 1.9: *Core components of a hydrogen fuel cell electric vehicle [13]*

Fuel filler: A nozzle from a high-pressure hydrogen dispenser attaches to the receptacle of the vehicle's hydrogen tank.

Hydrogen tank: The hydrogen tank stores hydrogen gas onboard until it is required by the fuel cell.

Fuel cell stack: The fuel cell stack gets its name from the assembly of individual membrane electrodes which use hydrogen and oxygen to produce electric energy and water.

Electric transmission: The transmission channels mechanical power from the electric motor to the drive wheels.

Power electronics controller: The power electronics controller administers the electrical power delivered by the fuel cell and the traction battery, controlling the power of the electric traction motor applied to the wheels.

Auxiliary battery: The auxiliary battery supplies electric power to start the car before the traction battery and the fuel cell are engaged and also powers vehicle accessories.

DC/DC converter: The DC/DC converter takes in higher-voltage DC power from the traction battery pack and outputs lower-voltage DC power to recharge the auxiliary battery.

Thermal (cooling) system: The thermal system monitors and controls the operating temperature range of the fuel cell, electric motor, power electronics, and other components.

As of January 2021 there were some 1,000 passenger FCEV registered in Germany [44]. Market shares of this vehicle technology are still negligible in 2021, with only a handful of vehicles registered every month.

Fuel infrastructure

One of FCEV technology's advantages is its ability to refuel in a matter of minutes. Accordingly, the required fuel infrastructure differs from that of BEV as it requires fewer and centrally located fuel stations much like ICEV's current fuel infrastructure. As of June 2021 there were 91 hydrogen stations in operation in Germany and some 16 stations being implemented (see Fig. 1.10).

Compared to BEV, the FCEV system contains an additional major conversion step, since electricity is utilized to first produce the energy carrier hydrogen through electrolysis, which then allows the on-board reconversion into electricity. Accordingly, the overall well-to-wheel efficiency is comparably lower but higher than that of ICEV (between 25-30 %) [45, 46].

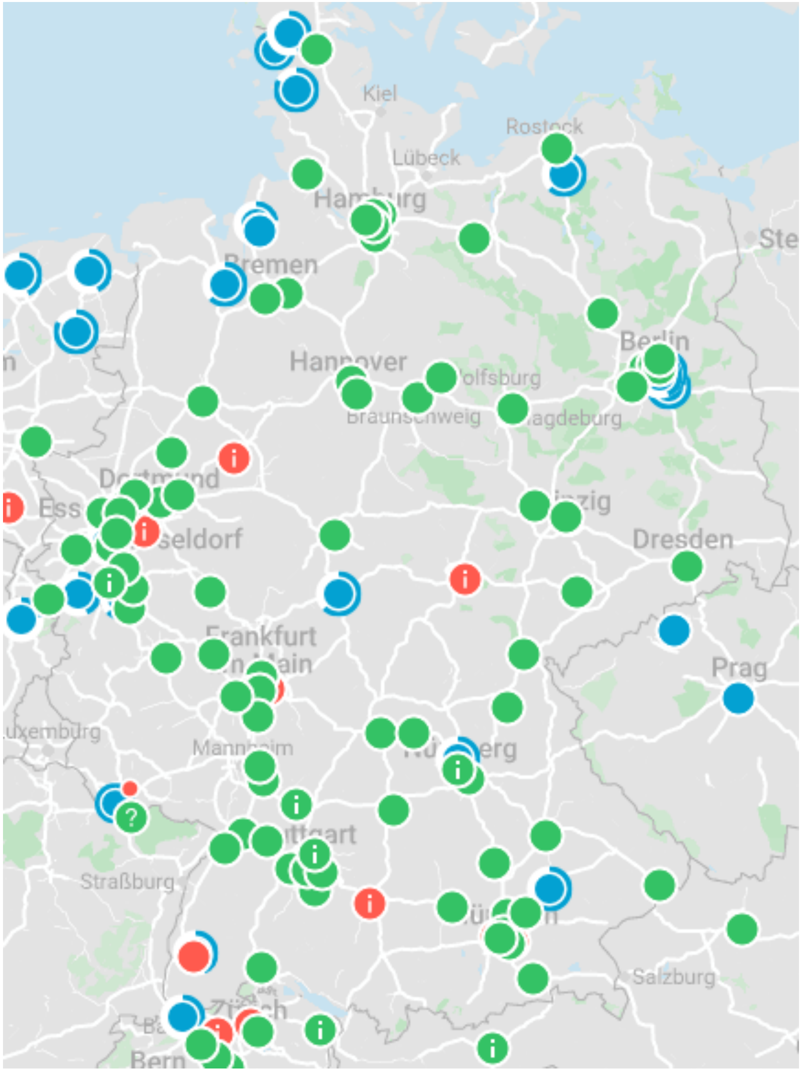


Figure 1.10: *Hydrogen fuel stations in Germany (green: in operation, red: currently out of operation, blue: implementation in progress [14]*

1.2 Public disagreement

While in theory today's status quo vehicle technology, the internal combustion engine vehicle (ICEV), could be decarbonized almost solely by decarbonizing its fuel system, a growing number of international government targets for phasing out sales of new ICEVs put increasing pressure on ICEV technology as a future option [56, 57]. The two alternative vehicle technologies of battery electric vehicles (BEV) and hydrogen-based fuel cell electric vehicles (FCEV) put increasing pressure on the status quo.

Ever since the US-american startup Tesla reintroduced the concept of battery electric vehicles at the beginning of the 20th century, more and more traditional car makers have adopted battery electrification as one of their strategic objectives for research and development. In 2019 Volkswagen's CEO Herbert Diess famously claimed that for Volkswagen “climate change mitigation will not be successful without the battery electric car”, adding however that hydrogen would *not* play a role for Volkswagen at least until the next decade [58]. In 2020, Volkswagen openly criticized the German Association of the Automotive Industry (German: Verband der Automobilindustrie e.V., VDA) for its demanding higher political targets for both hydrogen and alternative hydrocarbon fuels in Germany [59]. Similarly, Honda’s senior vice president Tom Gardner stated that Honda’s focus is on battery electrification and that hydrogen-based fuel cell vehicles are “a technology for the next era.” [60]. A similar statement was given by Martin Doppelbauer, professor at Karlsruhe Institute of Technology, whose strategy paper concludes that hydrogen-based fuel cell technology has no role to play in passenger cars and that battery electrification should be the focus of climate mitigation for car makers [61].

In the mean time Toyota emphasized that both BEV *and* FCEVs will be needed for passenger transport, both for economic and climate mitigation reasons [62]. Similarly, in its recent strategy “Ambition 2039” Daimler explicitly mentions hydrogen as a core technology pillar for its future vehicles. In the same way, PSA Group announced to launch a fleet of hydrogen vehicles for trade customers in 2021 [63]. At Handelsblatt’s automotive summit in November of 2020, ElringKlinger CEO Stefan Wolf went so far as to directly oppose Volkswagen’s and Tesla’s focus on battery electrification and claimed that fuel cell electric vehicles would be the most convincing passenger vehicle concept by as early as 2025 [64].

Notwithstanding the widespread pronouncement of electric vehicles and the growing number of international ICEV bans in cities and countries, public *as well as some scientific* voices in Germany do not shy away from forecasting a clean future for the combustion engine vehicle. In 2017, the Scientific Society of Automotive and Motor Technology (German: Wissenschaftliche Gesellschaft für Kraftfahrzeug- und Motorentechnik) went so far as to call BEV technology “a hype” [65] and spoke out for the future of ICEV technology. While this appears purely rhetorical at first, the past shows that hypes over different alternative vehicle technologies have, in fact, been observed before [66]. Three years later, in 2020 prominent industrial figures are persistent in their support for ICEV technology as a future option. Continental’s chief executive Elmar Degenhart maintained that electric vehicles were only a niche product and needed vast technological leaps in order to compete with ICEV technology. At the same time he pleaded for political technology openness with regards to the future of cars in Germany [67]. Similarly Carl Martin Weckler, president of the German Mechanical Engineering Industry Association (German: Verband

Deutscher Maschinen- und Anlagenbau, VDMA), claimed BEVs were incompetitive with ICEVs adding that BEV's "climate balance is far worse than commonly thought" [68]. In late 2020 Volkswagen's subsidiary Porsche announced its ambitions to further develop its ICEV technology based on "e-fuels" (i.e., hydrocarbon fuels produced with electric energy) [69].

Overall it has become apparent in recent years that even though the ambition to decarbonize road transport is unambiguous and many different technological remedies for the energy transition of passenger vehicles such as electric vehicles are available, public disagreement about the best option(s) persist to this day. This disagreement will persist as long as there is uncertainty (i.e., not knowing or sufficiently understanding) about the current and future feasibility of each vehicle technology. Filling the void of uncertainty with reliable and robust pieces of information is the responsibility of the scientific community and its epistemic discourse.

1.3 Research gap

The German national platform future of mobility (NPM), one of the leading German expert groups on sustainable mobility transition, published its second working group's assessments on the current technological state-of-the-art in transport and its probable future development, which lists the three key technology options for Germany to achieve its transport climate goals for 2030 and beyond: (1) electric vehicle concepts, (2) hydrogen and fuel cell as well as (3) decarbonized fuels for combustion engine vehicles [35]. NPM also states technology openness as one of their guiding principles for decarbonizing transport [70]. As a reason NPM's chairman Henning Kagermann listed the persistance of large model and parameter uncertainties regarding the future of transport as on of three core challenges for developing a sustainable mobility strategy for Germany (the other two challenges being profound, long lasting effect of political decisions and great time pressure to act) [70]. Despite uncertainty's central role for NPM's guiding strategy principles NPM has not produced a list of uncertainties which they regard as critical for future scientific analysis of the transport transition problem. Similarly, even though uncertainty has played a role in some recent research on the transport transition problem, results were only anecdotal or superficial, but never comprehensive and detailed. Much like NPM, the think tank Agora Verkehrswende stated openness to alternative technology pathways as one of their key transport policy paradigms and justified it with the existence of "a variety of persisting uncertainties" [17]. They did not, however, specify the uncertainties themselves. Similarly, in their analysis about future energy systems Fischedick et al. [71] discussed some path dependencies in transport, but did not explicitly list uncertainties. The research project RegMex produced a detailed list of uncertain and disruptive elements of the Germany energy transition as a whole. As of now, however, this list represents only a loose collection of assertions made by the experts involved and does not include any direct implications for the sustainable transport problem [72].

Some research in vehicle technology assessments of industry experts has shone some light on their disagreement and uncertainty. For instance, KPMG's yearly global automotive executive survey shows how conflicting and uncertain outlooks of car companies' executive levels have become. More specifically while the majority of the surveyed executives acknowledged the importance of drive train electrification, over 52 % of them found it likely to fail due to charging infrastructure challenges [73]. Another survey of electric vehicle media service electrive.net asked its readership whether the (above described) technology openness paradigm is helping or hindering sustainable transport transition. The survey's results show a strong disagreement among the experts regarding this core principle of decarbonizing German transport. Out of 512 respondents only three were undecided. The rest split into equal halves of opposing groups, specifically disagreeing whether battery electric vehicles can be the sole solution for passenger cars or not [74].

Various sensitivity analyses, a specific type of uncertainty analysis, can be found in the scientific literature, which touch on the vehicle technology problem. For instance in their article *the future cost of electrical energy storage based on experience rates* Schmidt et al. explored how different rates of future battery cost reduction influences the micro-economic competitiveness of BEV technology vs. fossil-fueled ICEV technology [24]. With their analysis the authors argued that cost-parity of those two technologies lies robustly in the 2020s, ignoring however the underlying uncertainty of some of their macro-economic assumptions such as resource availability. A macro-economic study on *Renewables in Transport 2050* was published by Ludwig Bölkow Systemtechnik (LBST), in which the authors showed how different scenarios based on some macro-economic uncertainties (e.g., transport demand, technology mix) produce different fuel demands in Germany [25]. While the use of macro-economic scenarios is a form sensitivity analysis (i.e., uncertainty analysis), the above study only employed a few scenarios in order to provide manageable narratives for the reader. While informative, single limited-scenario-based studies do not provide a comprehensive overview of uncertainties.

Some reviews of quantitative studies have implicitly touched on the underlying uncertainty of the corpus of transport studies. In his review on transport models, Creutzig [75] discovered a “discrepancy between epistemic communities and their models” and suggested ways to better integrate different modeling paradigms. Lennert and Schönduwe [76] demonstrated some underlying uncertainty of transport’s future by comparing 59 global business-as-usual transport scenarios, illustrating their diverging results. However, even though the scenarios’ results show a wide range of possible futures the authors did not systematically discuss any uncertainties or reasons for this discrepancy. Similarly, Runkel and Mahler [77] compared German transport scenarios from 14 studies but did not discuss any differences regarding the scenarios’ assumptions, much less identifying uncertain aspects. The practice of publishing non-critical meta-analyses is problematic because it can unconsciously (or deliberately) provoke a false sense of certainty about future developments as Dieckhoff discussed this in his proposal of epistemic meta-analysis [78]. He argued that a meta-analyses’ findings are especially questionable if uncertainty is large and the reference knowledge of the different scenarios diverge. Similarly, in their meta-analysis Annema and De Jong [79] identified a high inaccuracy of business-as-usual transport scenarios and suggested that the inherent future uncertainty of transport should always be reported to the policy maker. Likewise, in a systematic review of resilience concepts for transport Wan et al. [80] concluded that uncertainty analysis is underrepresented in transport research and that advanced uncertainty methods need to be introduced.

Overall, while uncertainty arguably plays a major role in the disagreement about the future of passenger vehicles in Germany, past research has touched only superficially on the difference between what we do and do not know on the transport problem. Furthermore the same is true for past robustness assessments of any of the technology options’ feasibility with regards to possible future states of the world. A thorough and systematic uncertainty assessment and robustness comparison of the three main vehicle technology options has yet to be conducted and published. This is where my work begins.

1.4 Research objective

My dissertation aims at bringing clarity to the public disagreement and scientific deficit on which alternative vehicle technology is “best” at decarbonizing passenger cars in Germany. With my work I strive to answering vehicle technology questions which have been the focus of public debates in the last years, for instance: Are battery electric vehicles a reliable alternative for achieving climate ambitions at reasonable cost? Is technology openness still a useful paradigm for Germany vehicle policy?

Based on the state-of-the-art I compare the three alternative vehicle technologies which would in theory allow for a deep and scalable decarbonization of road-bound transport in Germany: Battery electric vehicles, hydrogen-based fuel cell electric vehicles and internal combustion engine vehicles based on alternative hydrocarbon fuels. I limit my analysis to car-based road transport in Germany because it is largely characterized by regional or national systems with quasi-independent infrastructure, organization, and regulation which makes it a well-defined object for analysis.

Motivated by the aforementioned gap in previous research I aim at directly investigating the following core research questions:

Q1 How do the alternative vehicle technology options compare with regard to their underlying uncertainties?

Q2 Which of the three alternative vehicle technologies can be considered the most robust solution for decarbonizing passenger cars in Germany?

In order to converge on an answer for each of the two research questions I conduct two separate analyses. First, I identify and classify uncertainties for each vehicle technology in order to conduct a first comparison of all three technology options. Second, I employ the results of this uncertainty analysis to inform and conduct a robustness analysis of all the different vehicle technologies' total cost of ownership as well as their life cycle GHG emissions.

I begin by summarizing the current state of the art of sustainable vehicle technology options within a socio-technical theory of sustainable transport and by reviewing the theoretical frameworks of both uncertainty and robustness (Chap. 2). I proceed by outlining the methodology with which I analyze uncertainty and robustness of the different vehicle technologies (Chap. 3). The results are presented in Chap. 4, the first part of which systematically documents and structures the epistemic discourse and its arguments on the different vehicle technology options. The resulting argument map is scraped for implicit and explicit uncertainties which are then classified and clustered. Based on this uncertainty analysis the final part of the results chapter documents an economic and environmental robustness analysis which quantifies and compares each vehicle technology's robustness to possible future states of the world. Based on the robustness analysis the underlying uncertainties' are then compared and tipping points, at which one technology might robustly outperform another, are derived from the results. In Chap. 5 I will discuss the meaning and implications of my research results in reference to current and ongoing developments. Chap. 6 concludes my work by providing a summary, practical implications as well as an outlook.

My research specifically aims at an objective, which has been failed by all previous research on sustainable transport: The identification, classification and comparison of uncertainty as well as the consecutive analysis of technology options' robustness regarding the identified uncertainty range. This objective as well as my approach of explicitly addressing uncertainty (i.e., absence of knowledge) is novel in the field of transport transition but I claim it is better suited to address the public debates of "the better technology" than all other approaches before, because it can integrate and consolidate most (if not all) important arguments and highlight the relevant aspects for future discourses on decarbonizing vehicle technologies in Germany, including what we do not know yet about the technology options.

Chapter 2

Theory

> *"We know with confidence only when we know little; with knowledge doubt increases."*
> — Johann Wolfgang von Goethe

2.1 Sustainable transport

In order to embed my research within the broader context, it is important to capture the aspects of life which are affected by a sustainable transition of transport. As part of his historical case study of transport's transition from horse carriage to automobiles in the USA in the 19th and early 20th century, Frank Geels [15] partitioned the socio-technical system of transport into seven distinct elements: vehicle (as artefact), markets and user practices, production system and industry structure, maintenance and distribution network, regulations and policies, road infrastructure and traffic system, as well as culture and symbolic meaning (see Fig. 2.1). Geels' approach demonstrates the socio-technical dichotomoy of the sustainable transition problem as a whole. While my dissertation focuses on technology it is important to keep in mind that the social functions of the seven regimes also inform and influence their technological functions.

While a sustainable transition of transport can generally refer to a variety of objectives, such as clean air, noise reduction, traffic safety or equity of mobility, its core objective in this work is defined as the mitigation of GHG emissions. Based on this objective, an environmentally sustainable transition of transport is generally concerned with all socio-technical agents and artifacts which are involved in the multi-tiered interaction between the demand for mobility on the one side and its supply with primary energy on the other side. In between these two "forces"

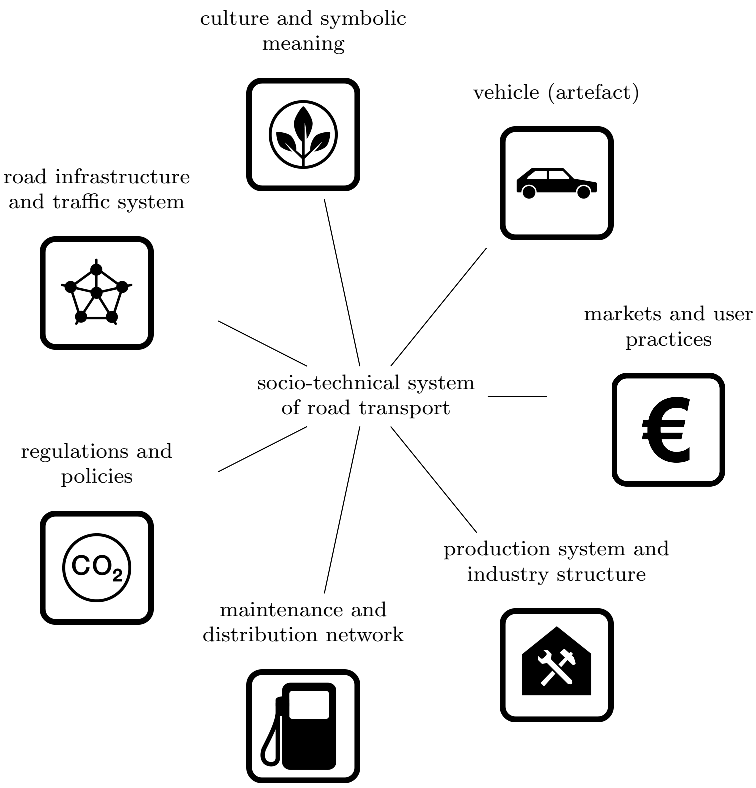


Figure 2.1: *Socio-technical regimes of road transport, based on [15]*

sustainable transport transition can be conceptually deconstructed with different levels of detail (see Fig. 2.2). Every approach to GHG mitigation in transport can generally be grouped into one of four concepts: reducing carbon intensity of fuels, increasing energy efficiency of vehicles, shifting to more efficient modes of transport, or reducing overall transport demand (while satisfying a constant or even growing demand for mobility) [16]. On a higher level the latter two are referred to as mobility transition, while the first two concern the energy transition of transport [17], in Germany also sometimes referred to as transition of the powertrain (German: Antriebswende). Other classifications of sustainable transition exist, however they are either less specific or not as integrative. For instance, Forschungszentrum Jülich's paradigm of avoidance, shift, and improvement (German: Vermeidung, Verlagerung, Verbesserung [81]) girds both pillars of the energy transition of transport in an unspecific notion of improvement. Likewise, the German National Platform Future of Mobility (NPM)'s proposed six areas of action for climate protection in transport which are specific but neither conceptually orthogonal nor coherent. NPM distinguishes between shift in powertrains, efficiency improvement of powertrains, renewable fuels, strengthening of rail, bus, and non-motorized modes of transport, strengthening of freight rail and inland waterway shipping as well as digitization [70].

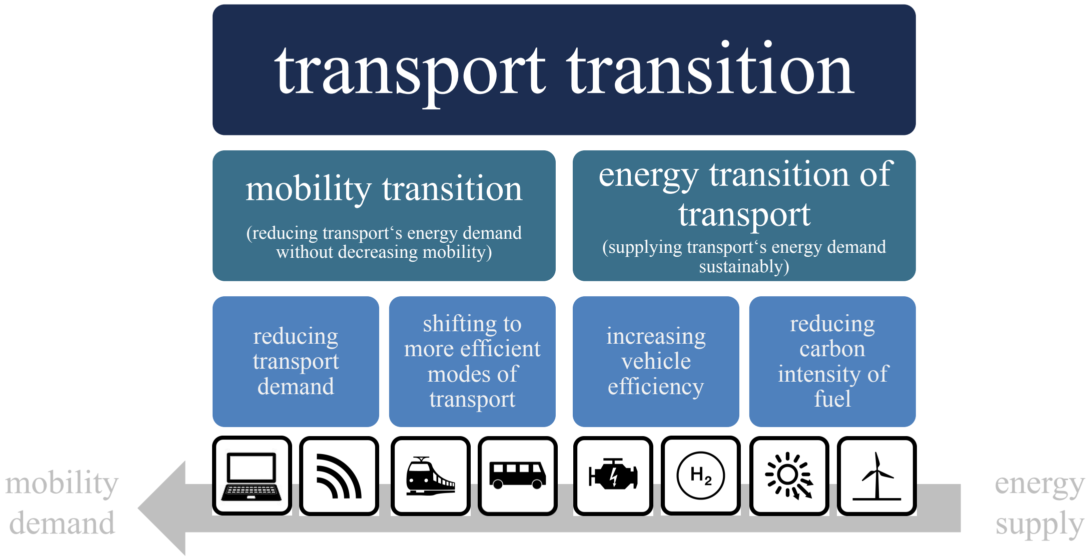


Figure 2.2: *Pillars of sustainable transport transition, adapted from [16, 17]*

Much like Geels' socio-technical regimes, the functions of both the mobility transition and the energy transition of transport are interconnected. For instance, Francis Sprei [82] comprehensively discussed transport's three main interdependent disruptions: electrification (as part of energy transition of transport) as well as shared mobility and automation (both part of mobility transition). Similarly, German carmaker Daimler AG abbreviates its forecasted disruptions of transport and mobility with the acronym C.A.S.E., an acronym for connected, autonomous, shared and electric [83].

Due to the focus my research questions my research will be mainly concerned with the first half of the transport transition: the energy transition of transport (right half of Fig. 2.2). However, as the theories above suggest, both pillars can be mutually dependent so my work will touch on aspects of the mobility transition wherever necessary or useful.

2.2 Uncertainty

The belief that systematic inquiry by mathematical and quantitative methods yields universal truth (referred to as positivism) has dominated science far into the 20th century and has since been criticized [84, 85]. Critical rationalism, for instance, states that scientific theories and claims to "positive" knowledge must be falsifiable in order to hold empirical value at all [86]. Social constructivism, on the other hand, claims the production of knowledge to be a process of social construction and negotiation [87]. Even though critical rationalism and social constructivism do not deny science the ability to produce some effective knowledge it has highlighted the role of uncertainty in science. After all "human knowledge is always incomplete and selective, and thus contingent upon certain assumptions, assertions and prediction" [88]. On the individual level, for instance, the Dunning-Kruger-effect describes how a person's ignorance can lead to an overestimation of her competence, and vice versa [89]. In other words, the more a subject knows the more he realizes how large his lack of knowledge (i.e., uncertainty) really is. Paradoxically, uncertainty on a given topic is best discovered by gathering as much knowledge on it as possible [90].

With modern real-world problems becoming increasingly complex, the concept of uncertainty has found its way into application, e.g. integrated assessment for policy analysis. However introducing uncertainty analysis into scientific practice is not merely about humbling the researcher but has effective advantages: assessment of uncertainty can improve communication of results to policymakers and other non-scientific stakeholders and thus increase trust in science and its results. Moreover identifying what is unknown and why it is unknown can improve the allocation of project resources [90]. Klinke and Renn [88] list scientific uncertainty as one of four key challenges for risk governance (along with seriousness, complexity, and interpretative and normative ambiguity). Renn [91] had previously proposed a similar concept with uncertainty, complexity and ambiguity as key challenges for risk management [91].

Uncertainty generally refers to the absence of knowledge [92]. More specifically it can refer to different depths of knowledge (or lack thereof) between determinism (i.e., absolute certainty or perfect knowledge) and total ignorance (i.e., unkown unknowns or impossible knowledge). In a technical sense uncertainty refers to all elements of a scientific discourse which are possible, some of which can be probable [78]. Researchers across different academic disciplines have suggested to disaggregate the broad notion of uncertainty into better operationalizable terms in order to systematically separate the reliable, certain aspects of their knowledge from the unreliable, uncertain ones. For instance, as a systemization of possibilities Gregor Betz suggested a two stage differentiation of possibilities with regard to their dichotomy of articulation and falsification (see Fig. 2.3).

As a measure of uncertainty however "mere possibilities are uninformative and useless (for, in the end anything is possible)" [18] which is why for uncertainty assessments quantification of possibilities (i.e., probabilities) through frequentist or bayesian approaches is more popular than mere possibility classification. One of the earliest uncertainty taxonomies which integrated possibilities and probabilities was

possibilities
- non-articulated ("unknown unknowns") .... **class 1**
- articulated
  - falsified (inconsistent with other knowledge) .... **class 2**
  - non-falsified
    - verified (consistent with other knowledge) .... **class 3**
    - merely articulated (neither verified nor falsified) .... **class 4**

Figure 2.3: *Classification of possibilities, according to [18]*

published by Frank Knight [93]. He proposed to distinguish between quantifiable (probabilistic) uncertainties which he called "risks" and unquantifiable (possibilistic) ones, which he referred to as "uncertainties".

Knight's classification has influenced many modern taxonomies of uncertainty. Arguably one of the most influential works of the 21st century on the practical application of uncertainty has been pubished by Marijolein van Asselt [94,95]. She opposed Knights approach criticizing that even though uncertainty and risk are "two sides of the same coin" they cannot be integrated on the same theoretical level. She initiated the notion to disaggregate uncertainty into multiple dimensions. Her ideas influenced the taxonomy of Walker and Kwakkel [19,90], which has been applied by many modelers and analysts of different disciplines. Based on van Asselt's original concept, Kwakkel's and Walker's taxonomy proposed that any uncertainty within a model of a problem can be classified along each of three dimensions:

1. location (*Where is the uncertainty found in the problem model?*), incl.
   - system boundary or context
   - conceptual model
   - mathematical model
   - input data or parameter assumptions
2. level (*How uncertain is it?*), incl.
   - knowing most alternatives and their probabilities (shallow uncertainty)
   - knowing most alternatives and their perceived relative likelihood-ranks (medium uncertainty)
   - knowing most alternatives without any likelihoods or plausibility (deep uncertainty)

- only knowing some alternatives and admitting the possibility of being surprised (recognized ignorance)

3. nature (*Why is it uncertain?*), incl.

    - imperfection of knowledge which may be reduced by more research and empirical efforts (epistemic uncertainty)
    - inherent, non-reducible variability, especially relevant with regards to human behavior and natural systems (variability, stochastic or ontic uncertainty)

Akin to this taxonomy Maier et al. suggested congruent dimensions of source, level and nature [96]. Similar to the concept of uncertainty nature Weinberg [97] stated that uncertainties are irreducible by science generally in four cases: (1) requiring impractically expensive, lengthy or impossible experiments, (2) referring to human behavior, (3) pertaining to the future, or (4) involving value judgment.

Another similar approach has been suggested by Ove Hansson [98] who marked the term "great uncertainty" for situations in which the decision maker lacks much of the information that is taken for granted in textbook cases. He proposed a four-dimensional classification:

1. uncertainty of demarcation: It is not well determined what the options are.
2. uncertainty of consequences: It is not known what the consequences of the options are.
3. uncertainty of reliance: It is not clear whether information from others (such as experts) can be relied on.
4. uncertainty of values: The values of decision makers or of relevant others are not well determined.

In summary, uncertainty can best be identified by first collecting and structuring knowledge as best as possible in order to then identify which aspects seem less certain with regards to what *does* seem certain. With the identified items of uncertainty at hand, different typologies and taxonomies of uncertainty can assist in clarifying the notion of uncertainty by mapping all relevant aspects onto a handful of principle components, most prominently the location, level and nature (or source) of uncertainty. Differences in typologies stem from the ambiguity with which this principle component analysis can be done. Oftentimes differences in suggested uncertainty taxonomies are motivated by the different reasons as to why uncertainty matters, e.g. objective model uncertainty analysis about what is uncertain versus subjective uncertainty analysis about who is uncertain and why.

Based on the reviewed theory I classify uncertainty along the three dimensions of location, level and nature of uncertainty. The location specifies where an uncertain aspect manifests itself in the decision problem. Many different location specifications have been proposed in uncertainty theory [19,88,90,95,99–104]. In this work I choose to distinguish between two general locations of uncertainty:

- **Conceptual uncertainty**: uncertainties regarding problem demarcation, decision objectives, and cause-effect relationships within the problem formulation
- **Parametric uncertainty**: uncertainties regarding external parameters which are largely independent of the problem itself

The second dimension, the level of uncertainty describes its degree, i.e. the depth of the lack of knowledge. It is aligned with the common understanding of knowledge lying between the extremes of deterministic (perfect) knowledge and total ignorance (complete absence of knowledge). Adapted from Kwakkel's [19] definition I use three distinct uncertainty levels (see Fig. 2.4):

- **Light uncertainty**: knowing all possible alternative events and associated plausible likelihoods
- **Medium uncertainty**: knowing all possible alternative events without any associated likelihood or plausibility
- **Recognized ignorance**: knowing only some of all possible alternative events while admitting the possibility of being surprised

Lastly, the nature of uncertainty represents the reason of uncertainty and builds on the traditional philosophical dichotomy of epistemic and ontic uncertainty. **Epistemic uncertainties** are all uncertainties which represent an imperfection of scientific knowledge and which are reducible through further research while **ontic uncertainties** are practically irreducible.

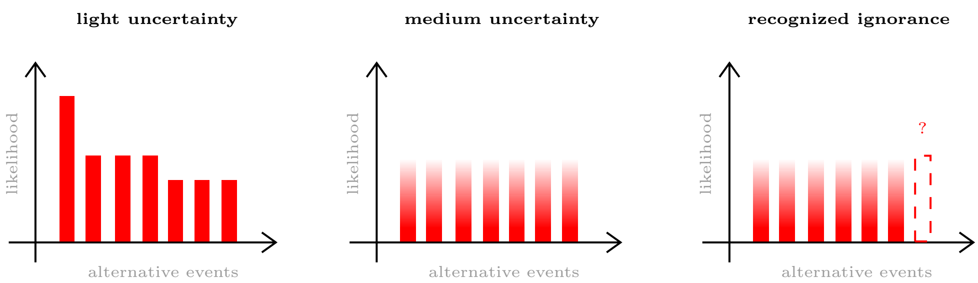


***Figure 2.4:** Levels of uncertainty, adapted from Kwakkel et al. [19]*

2.3 Robustness

Robustness generally refers to a system's ability to maintain a certain level of performance (as measured by one or more indicators) in the face of unforeseen events or changes to the system's environment, constraints or general landscape [105]. Robustness and resilience are closely related concepts, the later of which commonly regards more holistic and complex systems while robustness generally concerns a separate well-defined part of a global system [106]. Depending on the academic domain, there are different definitions of robustness and resilience with regards to transportation problems. The National Infrastructure Advisory Council (NIAC) defined an infrastructures system's resilience as its ability to predict, absorb, adapt to or quickly recover from a disruptive event or unforeseen changes [107]. In engineering a system's robustness has been defined as the ability to adjust its functionality in the face of unexpected changes [108].

Robustness as a concept has been gaining momentum and interest in science for policy [109], seemingly due to increasing uncertainty of political decision problems. A reason for this is that in science for practical decision-making "it is essential to stay within a corridor of admissable values" while it is "much less important to know the precise quantities of the relevant parameters" [110]. Accordingly Walker et al. state that "the ultimate goal [...] should be to reduce undesired impacts from surprises rather than hoping or expecting to eliminate them" [90]. In decision-making, robustness seeks to distinguish "the reliable from the unreliable" [111] and a robust choice is one that is often good enough but not maximized for any one performance indicator. The concept of robustness commonly consists of different sub-concepts, which can - depending on the author and discipline - be called different terms, but ultimately refer to two core approaches [96, 110]: static robustness (i.e., a system's ability to withstand external shocks while remaining unchanged) and dynamic robustness (i.e., a system's ability to being open and adaptable for future changes). Various concepts exist in the transportation literature which are related to or circumscribe the concept of robustness, including the following:

Reliability is the probability that a system remains operative during disruptive events [112, 113].

Adaptability or **flexibility** is the ability of a system to adjust itself during disruptive events or changes in order to achieve a new performant equilibrium [114–117]. As such, flexibility and adaptability are sometimes considered an alternative or complementary mechanism to robustness which focusses on enduring unforeseen changes first rather than adapting to them.

Vulnerability is the degree of a system's susceptibility to perturbation and degradation during unforeseen changes [118]. It is somewhat of an inverse concept of robustness as higher vulnerability weakens a system's ability to endure unforeseen events.

Redundancy measures the ability of a system's components to take over each others functions if one or more of them fail, while maintaining the systems overall performance [119, 120]. Higher redundancy generally increases robustness.

Further robustness-related concepts in transportation in essence repeat or reframe the above terms. These include recoverability and survivability [121], preparedness [122], resourcefulness [123], responsiveness [124] as well as rapidity [125].

In robustness analysis robust properties or entities tend to be (1) more easily detectable, (2) less subject to illusion or artifact, (3) more explanatorily fruitful, and (4) predictively richer than nonrobust properties or entities [111]. For operationalizing robustness different approaches have been suggested to systematically approach and analyze robustness. They generally include at least two steps: (1) identifying what's uncertain in order to (2) model and analyze how the system reacts to the uncertainties. In addition some approaches suggest complementing robustness analysis with adaptive strategies for potential vulnerable (i.e., non-robust) aspects [126, 127]. At the core, robustness analysis attempts to "triangulate on the existance and character of a common phenomenon, object or result by "using different assumptions, models, or axiomizations to derive the same results" [111]. For quantitative robustness analysis different robustness approaches have been suggested but they all generally fall into one of three families of robustness metrics [127, 128]:

1. **regret**: comparing a given option's performance in a specific possible scenario and the performance of the best performing option in that same scenario

2. **statistical**: analyzing the distributional character of the outcomes of interest
3. **satisficing**: maximizing the number of scenarios which meet a minimum performance threshold

For my robustness analysis I employ a numeric simulation model of the problem space through a Monte-Carlo simulation, which falls into the "exploratory modeling" category. For exploratory modeling, robustness can been quantified through one of the following:

- the first order derivative of the objective function [129]
- acceptably performant aspects over a wide range of plausible futures [130]
- relatively performant aspects, based on regret [102]
- improved sensitivity to violated assumptions by sacrificing performance on at least one metric [130]

The first option, calculating the first order derivative of the objective function is not possible in my case, as the model is of numeric nature and thus does not lend itself to such analytical methods. Moreover, as my model does not include constraints I will not be able to analyze robustness with help of the last of the four listed approaches. Finally, as my robustness analysis focuses on comparing different technology options, I will focus on identifying acceptably performant aspects over a wide range of plausible futures (based on the identified uncertainties) as well as discussing relatively performant aspects, based on regret between the different options.

Chapter 3

Methods

"How can we remember our ignorance, which our growth requires, when we are using our knowledge all the time?"
— Henry David Thoreau

3.1 Uncertainty analysis

In order to compare the different vehicle technology options with regard to their uncertainties, I conducted two sequential steps: (1) argument mapping for identifying uncertain aspects and (2) classification of the identified uncertainties as the basis of comparison.

Based on the reviewed theory uncertainty can be best identified by collecting and structuring knowledge as best as possible. In order to coherently document and analyze the knowledge on Germany's energy transition of road transport I employ a dialectic argument mapping method which is a tool for organizing knowledge and supporting decision-making commonly used in the field of humanities, particularly in philosophy [131]. By applying the argument analysis method and creating an argument map I aim to provide a comprehensive interdisciplinary overview of the epistemological discourse involving the arguments supporting and objecting the the three vehicle technologies of interest.

The argument analysis consists of two central steps: argument reconstruction and argument mapping. Argument reconstruction refers to the practice of identifying arguments within a debate and describing their core statements in the clearest way possible. An argument by definition is composed of a set of statements, which can function as premises or conclusions to the argument, while always representing a sentence that can either be true or false [132]. Since this composition of statements is usually not clearly identifiable within a given text or debate, a reconstruction of the arguments is required. The main goal in this process is to achieve a high degree of explicitness, precision and transparency in the formulation of the arguments, reducing both rhetorical force and ambiguity of a statement as much as possible [131]. The subsequent step, argument mapping, visually connects the debate's arguments and their interrelations by linking statements with arrows of support (in green) or attack (in red).

Argument maps are not intended to provide a single decision recommendation or direct solution to a certain problem or discussion. On the contrary, the neutrality of the entire argument analysis is of major importance to allow for different evaluations. Thus, an argument map aims at documenting a debate as complete and dialectically coherent as possible without biasing the reader's perception [133]. Accordingly the argument map allows to model a knowledge space larger than that of a single person or group and thus enables proponents within a debate to arrive at well-considered and reflected positions after considering all relevant descriptive and normative premises of their respective arguments. It thus provides a common ground for conflicting positions and interests by outlining descriptive premises which can be objectively accepted by all proponents. It thus allows for the integration of knowledge from different disciplines and perspectives into one coherent knowledge model.

To reconstruct the debate of the German energy transition in transport the following steps were conducted:

1. Scope definition Setting of the geographical context of the analysis (Germany), selecting the reference year 2050 for guiding the expert interviews regarding the energy transition of the German road transport sector towards quasi-decarbonization as stated in the German climate protection plan [134].

2. Expert guidance Exploratory and open exchange with 13 experts from the transport field with different background knowledge of the problem dimensions (social science, engineering, economics, environmental science, political science, philosophy, geography), see table A in the appendix. The experts were individually asked for their outlook on the different drive technologies for decarbonizing German passenger cars by 2050. The subsequent discussion was searched for indicators of new descriptive and analytical arguments guiding the subsequent review of the literature.

3. Literature review Based on the arguments and information provided by the experts, peer-reviewed as well as grey literature of scientific authorities was identified to reference the current state of knowledge regarding the vehicle technologies under consideration.

4. Argument reconstruction and map development Based on the arguments provided by the experts as well as additional details provided by the literature, the argument map was continuously modified and extended. Starting from a first draft of the map, different versions of the map were developed, each representing a specific stage in the overall process of the argument analysis. The practical development and formatting of the argument map were realized with the following software: First versions with Argunet 2.0 and yEd Graph Editor [135,136] and a final version with Kialo.com [20].

Step two, three and four are a circular process (see Fig. 3.1) in which the last state of argument reconstruction is used to guide the subsequent expert exchange by following up on fundamentally new and incomplete arguments within the map.

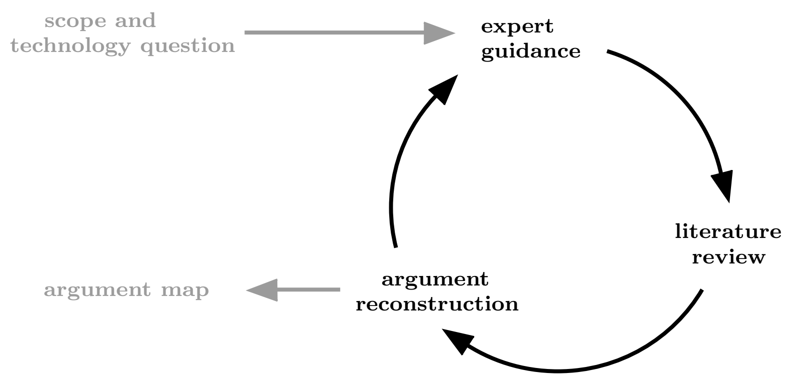


Figure 3.1: *Argument mapping process*

With the argument map in place I identified and extracted uncertainties about the different vehicle technologies in two different ways: (1) explicit statements of uncertainty within the map supported by other arguments and (2) implicit uncertainty which is indicated by controversies (contradicting arguments) within the map. Based on the reviewed theory of uncertainty (see section 2.2) I classified the identified uncertain aspects of the argument map along the three dimensions of location, level and nature of uncertainty. I determined each uncertainty's location, level and nature according to its network context in the argument map and the background information provided by the literature.

3.2 Robustness analysis

I conducted the robustness analysis with four different steps: (1) modeling the different vehicle technologies and (2) simulating their performance against the identified uncertainties. With the produced data set I went on to (3) analyzing the different vehicle technologies' robustness and (4) discriminating influential uncertainties (i.e. vulnerabilities) from irrelevant ones (see also Fig. 3.2).

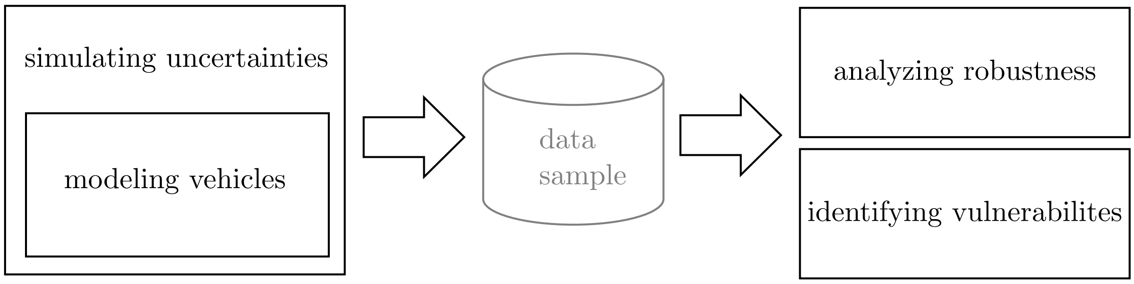


Figure 3.2: *Robustness analysis methodology*

3.2.1 Vehicle modeling

In order to test how future uncertainty about the vehicle technologies could manifest itself, I employed the vehicle models from *OVEmAT* [137], a tool which builds on the vehicle models employed in the Carboncounter application by Miotti et al. [26]. The model assesses different vehicle technologies' economic and environmental performance by determining their total cost of ownership (TCO in EUR/km) as well as life cycle greenhouse gas emissions (LCE in g CO_2-eq./km). This two-dimensional evaluation space is not weighted or commensurated into one dimension so as to keep and visualize the irreducible political uncertainty as part of landscape developments as discussed in section 4.1. TCO refers to the objective of minimizing economic cost while LCE offers a measure of maximizing environmental benefit (i.e. minimizing environmental cost). Visualizing different technologies' "goodness" in this two-dimensional space will draw a geographical-like map which Richard Levins said to be a good way of avoiding "too high a magnification" on the model results because what matters most about a map are not the individual details but the fact that "contiguity on the map implies contiguity in reality, relative distance on the map correspond to relative distances in reality" [138]. In addition to the three technology options of BEV, FCEV and ICEV a fourth option is modeled: A serial plug-in hybrid electric vehicle is also considered in order to analyze hybridization's role in the robustness of a technology. BEVs with an effective driving range below 500 km are filtered out from the final modeling results as to not compare vehicle options with incompatible usability. 500 km of effective driving range is used as the threshold because it can be generally considered sufficient for the vast majority of personal vehicle use cases [139, 140]. Equations 3.1 and 3.5 describe the core evaluation functions of the model. For scalable execution the mathematical model was implemented with the Python programming language (version 3.7) [141]. The code base and along with its documentation and manual is publicly available at Github.com [137].

Life cycle greenhouse gas emissions

$$\mathrm{LCE} = \frac{\mathrm{VCE}}{L \cdot D} + \mathrm{FCE} \tag{3.1}$$

Vehicle cycle greenhouse gas emissions

$$\begin{aligned} \mathrm{VCE} = X_2 + X_3 \cdot \mathrm{CIE}_{\mathrm{vce}} + M_{\mathrm{scal}} &\cdot (X_4 + X_5 \cdot \mathrm{CIE}_{\mathrm{vce}}) \\ &+ C_{\mathrm{batt}} \cdot (X_{10} + X_{11} \cdot \mathrm{CIE}_{\mathrm{bce}}) \\ &+ P_{\mathrm{fc}} \cdot (X_{13} + X_{14} \cdot \mathrm{CIE}_{\mathrm{vce}}) \end{aligned} \tag{3.2}$$

$$\begin{aligned} M_{\mathrm{scal}} = M_{\mathrm{curb}} &- X_1 \\ &- X_9 \cdot C_{\mathrm{batt,ref}} \\ &- X_{12} \cdot P_{\mathrm{fc,ref}} \end{aligned} \tag{3.3}$$

Fuel cycle greenhouse gas emissions

$$\mathrm{FCE} = \mathrm{CIE}_{\mathrm{fce}} \cdot \eta_{\mathrm{wtt}} \cdot \mathrm{HHV}_{\mathrm{fuel}} \cdot \mathrm{FE}_{\mathrm{vehicle}} \tag{3.4}$$

Total cost of ownership

$$\mathrm{TCO} = \frac{\mathrm{CAPEX}}{L \cdot D} + \mathrm{OPEX} \tag{3.5}$$

Capital expenditure

$$\begin{aligned} \mathrm{CAPEX} = p_{\mathrm{vehicle,ref}} &- p_{\mathrm{batt,ref}} \cdot C_{\mathrm{batt}} \\ &+ p_{\mathrm{batt}} \cdot C_{\mathrm{batt,ref}} \\ &- p_{\mathrm{fc,ref}} \cdot P_{\mathrm{fc,ref}} \\ &+ p_{\mathrm{fc}} \cdot P_{\mathrm{fc}} \end{aligned} \tag{3.6}$$

Operational expenditure

$$\mathrm{OPEX} = \sum_{y=1}^{L} \frac{p_{\mathrm{fuel}} \cdot \mathrm{FE}_{\mathrm{vehicle}} + p_{\mathrm{maintenance}}}{(1+r)^{y-1}} \tag{3.7}$$

Reference vehicle values (e.g. vehicle price $p_{\mathrm{vehicle,ref}}$, battery size $C_{\mathrm{batt,ref}}$ and fuel cell power $P_{\mathrm{fc,ref}}$) are derived from data of currently available vehicle models. To minimize imbalance between vehicle technologies, vehicle model pairs were chosen, meaning same model but different technologies (e.g. Ford Focus and Ford Focus electric, see table B.1 in the appendix).

3.2.2 Uncertainty simulation

The identified uncertainties approximate the space of future alternative states of the world (SOW) against which a vehicle technology's robustness is assessed. An exhaustive simulation of all combinations of all possible SOWs computationally infeasible, so a reasonable approximation was made which could be realized in due time. A simple but dependable approach for this was to conduct a Monte Carlo experiment (MCE) in which a set of random permutations of SOWs was realized for evaluating the vehicle models. In order to fully but efficiently sweep the SOW space, the MCE was conducted using the latin hypercube sampling (LHS) method [142]. Unlike pseudo-random sampling the LHS method efficiently searches a multidimensional space by ensuring samples are randomly but equally distributed along each uncertainty (model input) range.

3.2.3 Robustness quantification

Various methods exist for quantifying robustness. Since both TCO and LCE of vehicle technologies are expected to be generally within a certain range of values but can show extreme negative cases the possibility of a poisson distribution for either performance indicator can not be reasonably excluded. As this might introduce skewness (asymmetry) into the distribution of model output I used the following metrics:

- median value
- interquartile range (IQR): It is not affected by extreme values and quantifies how spread out the middle 50 % of the data is.

- Convex hull in the two dimensional space of TCO and LCE in order to visualize and identify extreme (regret) cases.

Median and IQR will be integrated within a box plot analysis.

3.2.4 Uncertainty comparison

In order to discriminate those (input I) uncertainties which most influence the resulting (output O) paremeters TCO, LCE or their priors CAPEX, OPEX, VCE, and FCE I identified associations between model input and output using Spearman's rank correlation coefficient ρ [143]. It determines the common Pearson correlation coefficient [144], however not for the raw scores but instead their converted rank variables. This is necessary because I can expect my experimental data set to not comply to at least two prerequisites for the standard Pearson correlation. Firstly, not all (if any) variables are normally distributed. As a matter of fact at least all model input variables are uniformally distributed by design. Secondly, correlations can not be assumed to be exclusively linear, e.g. annual distance and TCO are by definition of equation 3.5 hyperbolically related. Accordingly the correlation coefficient used for further analysis is defined as

$$\rho_S = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{3.8}$$

where n is the number of observations and d is the difference between the two ranks of each observation.

$$d = rg(I) - rg(O) \tag{3.9}$$

Correlation as a measure of uncertainty interdependence is more insightful than for instance covariance as measures both the direction and the strength of a variable pair relationship and is independent of the scale of the variables themselves. Its measure is normalized between negative one and one which makes comparison of uncertainties possible. Ultimately the proportion of shared variance between input and output uncertainties is realized with the coefficient of determination R^2. Its interpretation is superior to that of a correlation coefficient as its quantification is a direct measure of determination, e.g. $R^2 = 0.8$ means an input-output-relation accounts for 80 % of total variation. The determination coefficient is approximated with a derivation from Spearman's rank correlation coefficient [145] :

$$R^2 = \rho_S^2 \tag{3.10}$$

Due to computational resource restrictions the limited population size might produce correlations with low statistical significance where the “signal-to-noise”-ratio is high. Accordingly, correlation coefficients with $\alpha > 0.05$ were not reviewed further. The above statistical analysis is realized with the stats package within the R programming language [146].

Chapter 4

Results

"Our truth is the intersection of independent lies."
— Richard Levins

4.1 Uncertainty analysis

The basis for my uncertainty analysis is the argument map. It consists of some 330 arguments and as many logical inferences, grouped into 34 argument groups, clustered into distinct topics within the debate on energy transition in transport. The complete version is publicly available at rl-institut.de [147] as well as kialo.com [20]. Extended documentation of the map's synthesis was provided by Simon Hoffmann [148]. Linking arrows indicate how arguments relate to one another and if they support (solid green) or oppose (dashed red) one another. Fig. 4.1 visualizes this topology in a pseudo rose diagram. Overall, 48 % of arguments refer in one way or another to BEV, 20 % to FCEV and the rest to ICEV (20 % to synthesized hydrocarbon fuels and 12 % to bio fuels).

From the final argument map's structure I extracted a set of 23 general uncertainties (see table 4.1). Each of the three drive technologies is affected by a similar number of general uncertainties (BEV: 12, FCEV 15, ICEV: 12). Based on the background knowledge and arguments associated with an uncertainty, I categorized it according to the taxonomy outlined above. For instance the uncertain price development of lithium battery technology cells is considered light (level), because its downward trajectory can plausibly be assumed based on multiple arguments. Its uncertainty location is parametric as price is a quantifiable index with clear parametric meaning to the problem. And finally, as price development concerns the future it must be characterized as irreducible (nature), according to my proposed taxonomy. All

Figure 4.1: *Argument map topology with pro (green) and contra (red) argument structure [20]*

uncertainties and their characterizations are listed in table 4.1 along with the technologies they affect. Based on the categorization each general uncertainty can be clustered into one of five distinct uncertainty clusters as outlined in Fig. 4.2: economic developments, technological developments, security of supply, greenhouse gas balancing, and mobility transition. Each of the technology options is affected by all five uncertainty clusters. The individual uncertainties within each cluster and their allocation within the uncertainty taxonomy are explained in the following subsections.

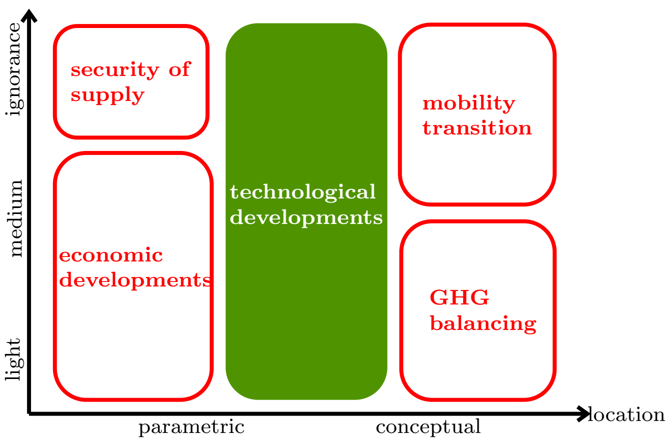


Figure 4.2: *Clusters of uncertainties affecting low-carbon drive technologies, clustered according to level, location, and nature (framed red: irreducible, shaded green: reducible)*

Table 4.1: *Uncertainties with their location (I-parametric, II-conceptual), level (1-light uncertainty, 2-medium uncertainty, 3-recognized ignorance) and nature (A-reducible, B-irreducible) as well as respective technologies (✓-affected, ✗-not affected)*

Cluster	Uncertainty	BEV	FCEV	ICEV	loc.	lev.	nat.
econ. developments	price developments of el. power	✓	✓	✓	I	1	B
	price development of LIB cells	✓	✓	✗	I	1	B
	LIB lifetime	✓	✓	✗	I	1	B
	price development of hydrogen	✗	✓	✓	I	2	B
	price development of fuel cells	✗	✓	✗	I	1	B
	price development of synthetic fuels	✗	✗	✓	I	2	B
	domestic value and labor effects	✓	✓	✓	I	3	B
techn. developments	battery technology	✓	✓	✗	I	1	A
	hydrogen storage technology	✗	✓	✗	I	3	A
	carbon capture technology	✗	✗	✓	I	3	A
	algae oil technology	✗	✗	✓	I	3	A
	EV-auxiliary technologies	✓	✗	✗	II	3	A
	charging infrastructure	✓	✗	✗	II	1	A
	hydrogen infrastructure	✗	✓	✗	II	1	A
security of supply	LIB	✓	✓	✗	I	3	B
	platinum	✗	✓	✗	I	3	B
	synthetic fuels	✗	✗	✓	I	3	B
GHG balancing	BEV	✓	✗	✗	II	1	B
	hydrogen and synthetic fuel	✗	✓	✓	II	2	B
	biofuels	✗	✗	✓	II	1	B
mobility transition	niche innovations	✓	✓	✓	II	3	B
	regime trajectories	✓	✓	✓	II	3	B
	landscape developments	✓	✓	✓	II	2	B

4.1.1 Economic developments

Even though each drive technology is affected by some irreducible uncertainty of economic development, those that affect BEV are generally of a lower level than those of both FCEV and ICEV. This can be attributed to multiple reasons which are outlined in the following paragraphs.

BEV Currently BEVs' retail prices correlate strongly with the size of their batteries (see fig. 4.3). Due to rapidly falling battery cell prices and low cost of operation, battery electric vehicles are expected to be robustly cost-competitive regarding total cost of ownership (TCO) with fossil ICEVs sometime in the 2020s [24, 149, 150]. Beyond that, by 2030 they could become even "cheaper to make than ICEV cars"

[151]. This is especially relevant as customers only offset a car's purchase costs for the first five years of operation [152]. Yet, even though the economic perspective is largely positive, there remain some uncertainties.

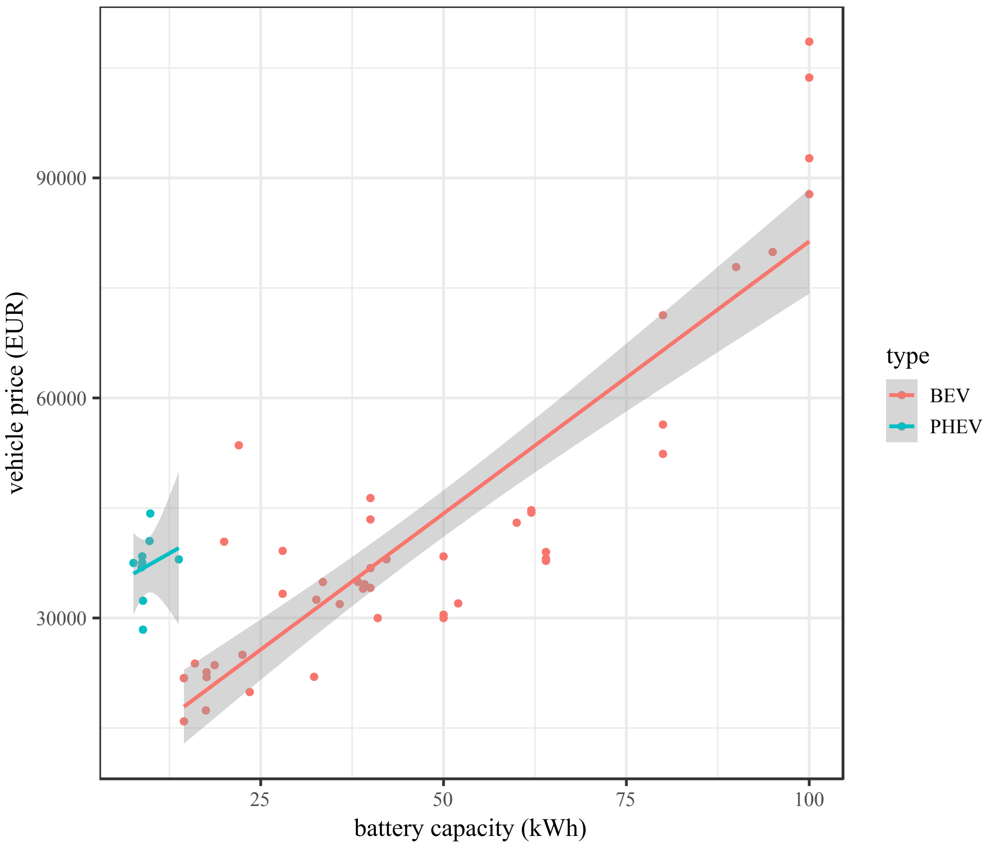


Figure 4.3: *Around 77 % of BEV's price variation can be explained by variations in battery size, data based on [21]*

First, there is uncertainty regarding future German electricity prices. Some experts' expectations about wholesale electricity price developments in Germany are pessimistic. In a survey over 70 % of experts expected strong price increases, only less than 10 % expected the opposite [153]. Other studies are generally optimistic on price developments [154, 155]. Independently, a reduced tax income from decreasing fossil fuel use could potentially require a higher taxation of other energy carriers including electricity [71], which could in turn put increasing pressure on the economic feasibility of electricity-based vehicles options.

Second, while lithium-ion battery (LIB) cell prices are expected to fall well below 100 EUR/kWh between 2020 and 2030 [22, 24], uncertainty remains as to how quickly and how low prices will actually fall because LIB cell prices depend on cell chemistry, size and geometry, production capacity uptake (economics of scale and cumulated production), material- and process innovations to decrease specific material use, as well as material- and process innovations to close the cost margin between cell and material cost [22]. Based on learning curves Schmidt et al. [24] quantified both the cost uncertainty associated with cumulated production as well as the uncertainty of the speed of the production uptake. Their analysis demonstrates that despite the overall uncertainty the cost-parity prospect still lies robustly in the 2020s. Ultimately, however, the cost floor depends on the material price, which depends on the availability of resources, which is itself uncertain as will be discussed below.

Another economic uncertainty of financing and operating a BEV lies in the lifetime of the battery, which is influenced by both the calendric as well as the cyclic degradation which depend on ambient conditions as well as individual charging and driving behavior. Latest Tesla capacity and driving distance data shows that on average Model S battery degradation would allow for more than 500,000 km driven before the state of charge reaches 80 % (first-life threshold), however, the data variance is high (with outliers lying as low as 84 % state of health at just under 30,000 km) [156]. Tesla, like most other BEV manufacturers provides a battery warranty for less than ten years which leaves uncertainty as to how much the calendric lifetime of the battery can jeopardize economic feasibility [157]. After all, around 25 % of German vehicle kilometers are driven in cars older than ten years [158].

Another explicit economic uncertainty regarding the overall feasibility of BEV technology regards the German domestic value chain and labor market. About 840,000 jobs in Germany depend in some way on the production and operation of conventional ICEV technology, with a fourth directly associated with the production of the powertrain [159]. A shift towards electric powertrains can put the current industry structures at risk. A recent study by Fraunhofer IAO shows how through powertrain electrification Germany could lose 75,000 jobs by 2030 [159]. This number already includes about 25,000 new jobs for production of new components such as batteries and power electronics. A reason why domestic labour effects are uncertain is the fact that BEVs need fewer parts than ICEVs. Engine parts like pistons, fuel injection or spark plugs will no longer be needed. Moreover, the vast majority (96 %) of current global LIB cell production is located in China, Japan and South Korea [160]. 43 % of today's BEVs are already produced in China [161]. Even if battery production could be shifted towards Germany, the production of LIB cells is highly automated and would require comparatively less human labor than current structures [162]. Ultimately however, it remains unknown how strong the effect of electrification of the powertrain on the German labor market will be compared to other landscape trends such as digitization and automation [163].

FCEV Much like BEV, hydrogen FCEV technology's TCO is expected to decrease. With further system and process optimization the fuel cell system cost could be decreased by another 80 % [164]. However, there remains uncertainty.

Historic product cost analysis has shown that electrolyzer and fuel cell as core technologies of the hydrogen transport system show similar or even higher experience rates[1] than LIB technology [24], indicating the downward price developments could show the same trajectory if production uptake took place. This means however that price uncertainty is directly coupled to the uncertainty of the speed of cumulated production of that technology [165]. A non-modular technology such as hydrogen FCEV is disadvantaged in this regard. There are research and development ventures to produce smaller, more modular electrolyzer systems in order to decrease cost by cross-utilizing components from automotive industry [166]. Comparison of current quantifications of the price uncertainty of core BEV and FCEV components support the notion that even though both are qualitatively only lightly uncertain the economic feasibility of the FCEV pathway is quantitatively more uncertain than that of BEV (see Fig. 4.4).

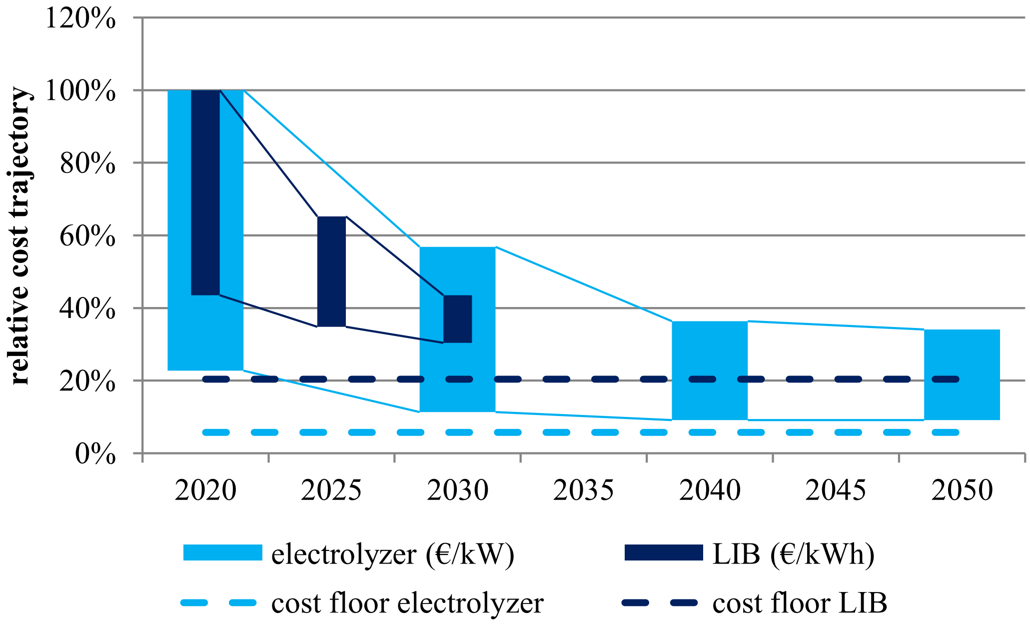


Figure 4.4: *Cost trajectories' uncertainty comparison of LIB cells [22] and electrolyzer [23] based on meta-studies, each normalized with upper 2020 value; material cost floors validate feasibility of quantification [24]*

While under current regulatory conditions the production of hydrogen in Germany is not economically feasible [167] the development of a hydrogen supportive electricity and gas market can be economically feasible [168]. Inter-sectoral use of hydrogen

[1] Experience rate depicts a product's price development as a function of increased cumulative production [24].

infrastructure can influence the price positively through better utilization of production facilities and overall larger scales of production [169]. However, it could lead to competition from other sectors such as rail, flight, heat and chemical, especially while renewable production capacity is limited [46]. Even though installation costs have been halved in the last ten years, hydrogen infrastructure has a higher risk for sunk cost than charging infrastructure [71], because of its non-modular expansion and its lower flexibility with regards to uncertain local demand. Robinius et al. [170] showed how hydrogen infrastructure operation can however become cost competitive with charging infrastructure at large vehicle market volumes, starting at at around 10 million vehicles.

Macro-economically there are arguments why domestic value and labor market uncertainty of a shift towards hydrogen based transportation would be less grave compared to those explained for BEV above. First of all, a fuel cell vehicle contains other parts in addition to a battery and electric motor (hydrogen tank, balance-of-plant-components such as humidifier, pumps, valves and compressors, as well as the fuel cell stack itself). Second, Germany is better equipped with the industrial know-how of these components: every part of the value chain of FCEV production is covered by at least one German industry partner [171].

Lastly, as with BEVs final cost floor, the ultimate product price of fuel cells remains uncertain as the security of international platinum supply remains controversial, as explained below.

ICEV As post-products of hydrogen, synthetic fuel's price developments generally suffer from the same controversy and uncertainty as hydrogen. Long-term price projections of synthetic fuel are consistently higher than their fossil fuel equivalents [46, 172]. Accordingly, there is little doubt that synthetic hydrocarbon fuels do not offer an economically feasible short- to midterm solution for large-scale decarbonization of transport. However, there still seems room for economic optimization. Just recently process efficiency improvement was achieved by coupling high-temperature electrolysis with methanation [173]. Further incremental efficiency improvements are currently being researched.

4.1.2 Technological developments

As with economic developments, the uncertainties affecting BEV's technological development are generally of lower level than those regarding the other two drive technologies. Unlike ICEV, which can rely on already existing fueling infrastructure, both BEV and FCEV suffer from some conceptual uncertainty regarding the setup of new fuel infrastructure.

BEV In comparison to the other alternatives BEVs are characterized by the most advanced technological development [150, 151]. They are currently underway of leaving their niche and establishing themselves within the German passenger car market [174]. Nonetheless there remain some technological uncertainties regarding BEV's full-scale potential.

Energy density of LIB cells has been increasing at about 5-7 % per year [151]. It is projected to hit its maximum potential within the next decade. Estimates range from 260 to 350 Wh/kg and 600 to 1000 Wh/L [22]. The uncertainties regarding this potential are founded in technological conflicts. Firstly, today's active material's energy performance is intentionally reduced for safety reasons. Ongoing research and development is aimed at high energy active materials for electrodes without jeopardizing cell safety. Secondly, power requirements lead to a battery design which is suboptimal regarding overall energy density [175]. Thirdly, since the longevity of the battery cells depends on ambient conditions, cooling requirements lead to an overall increase of pack mass per energy stored. Lastly, adoption speed of new cell technologies depends on existing and binding supply contract durations of auto companies. In addition, persisting energy density differences exist due to format (cylindrical, prismatic, pouch) but are expected to dissolve within the next decade [22].

In accordance with ongoing improvements, there is technological opportunity (f, uncertainty) in new battery technologies, e.g. solid-electrolyte battery technologies. Such technologies could improve safety as well as volumetric (but not significant gravimetric) energy density due to thinner electrolyte and anode layers as well as fewer passive components, which could bring the module level closer to cell level performance. Nonetheless, the development of solid-state batteries is uncertain and requires "research efforts towards feasible electrolyte materials, overall material design and production processes" [22]. Market diffusion is not expected before 2030 [22]. Many joint efforts (including established car manufacturers) are currently researching and developing this new generation of batteries [176, 177].

In addition to the expected technological improvements of BEV, there are still other anticipated technological uncertainties which could strengthen BEV's status, especially in the heavy duty passenger and freight transport sectors, which might have implications for passenger cars as well. The research project *E-Road Arlanda* is developing and testing conductive technology which aims at enabling electric cars, buses and trucks to be recharged while driven [178]. Another Swedish-German project aims at developing overhead wire conductive and inductive systems for the same purpose [179]. Similarly, China is currently planning a 161 km solar highway, which would allow electric vehicles to charge inductively while driving [180]. It remains unclear how much a successful introduction of these auxiliary technologies could extend BEV's functionality to a relevant degree.

Another technological uncertainty of BEV is the grid compatibility of large BEV fleets. Generally, the additional electric energy demand of deep BEV penetration does not pose a risk. The current German power generation surplus alone could supply around 20 million electric vehicles [181]. Uncertainty rather lies in temporal and topological constrains. While at least a few million BEVs can be integrated into the existing power grid, especially in urban areas, the effects of very high shares on the different grid levels is still largely unknown [170, 182–184]. The current situation in which most charging happens in the distribution grid with high temporal simultaneity [185] means that higher shares of BEV would increase local power demand. A widely discussed remedy to this problem is vehicle-to-grid(VtG)-technology in which cars' batteries support the infrastructure through ancillary services [186]. However, insufficient legal framework as well as missing business models makes this option uncertain. At moderate BEV uptake a parallel and successive extension of the power grid could avoid grid problems [187]. Load management on the other hand could allow for a BEV penetration of up to 80 % without having to strengthen the power grid [188]. However, as with VtG-applications overhead expenses might exceed the sensible limit [189]. After all, massive and unsupervised shift of charging demand into times of low power price can have feedback effects on the power price itself [190]. Randomized charging can also sufficiently mitigate stress on the grid, but would lower vehicles' availability [184].

Similar to the grid-level uncertainty is that of the charging infrastructure uptake. While Germany already counts for 20,000 public charging stations, the official goal was 100,000 for 2020 [191]. After all the European commission directive suggests a BEV-to-charging-point-ratio of ten to one [192]. It remains further uncertain what role high power charging will play in the future. Current projects such as Mega-E and CEUC are installing and testing over 400 ultra-fast chargers (350 kW) in Germany and other European countries [193, 194]. While high power charging can decrease the overall required number of charging stations and improve ranges of BEVs its technological viability is controversial. The need for larger batteries, system cooling, increased infrastructure cost and decreased efficiency might pose practical limits [175, 195].

FCEV In contrast to BEV technology, generation of hydrogen fuel can be temporarily and geographically decoupled from transport demand and thus does not pose an infrastructure risk but rather an opportunity to support the transition towards renewable electricity generation [196, 197]. Electrolyzer technology is technologically mature [24]. However, storing and distributing hydrogen at high pressure or low temperature necessitates the installation of an entirely new infrastructure. A remedy could bring the storage of hydrogen via liquid organic hydrogen carriers (LOHC) which might allow for the same kind of transportation, storage and safety as with fossil liquid fuels today [198]. First prototypes for trains are currently being developed but are not expected before the following decade [199].

ICEV As a core technology of today's road transport ICEVs are tried and tested. Its uncertainties therefore lie not on the vehicle but on the fuel level.

Large scale production of synthetic hydrocarbon fuels requires capturing carbon dioxide from industrial processes and directly from the air. While some parts of carbon capture systems have been demonstrated at commercial scale, large uncertainty remains regarding the viability of direct air capture. Its low technology readiness level between three and five (out of nine) clearly indicates a vast research and development need [200].

A new and scalable alternative substitute to fossil fuel is the production of a biofuel via industrial algae oil harvesting. After an optimistic research and development phase as well as many business ventures, the current outlook is more pessimistic. Real productivity is a fraction of the one expected. The biofuel production efficiency from culture of algae in pilot-scale systems is at levels similar to that of terrestrial plants [201]. It remains unknown if and how emerging technologies of genetic modification might advance algae biofuel in the future [202].

4.1.3 Security of supply

Security of supply uncertainties affect all three drive technologies. However, while for BEV and FCEV they concern the vehicle level, ICEV faces uncertainty regarding its overall fuel supply.

BEV & FCEV LIB systems which are part of both BEV and FCEV are subject to supply uncertainties for two reasons. First, the supply of resources necessary for producing LIB cells is not trivial. While the future demand from EV uptake does not exceed the global reserves of crude material [203, 204] there is uncertainty due to potential geopolitical dependencies resulting in the risk of supply shortages and high price volatilities [205,206]. Three quarters of the world's reserves of lithium are located in China and Chile and global cobalt production comes mainly from regions within the Democratic Republic of Congo [207]. It remains uncertain how much cobalt will actually be required in the future as cobalt material shares in LIB systems are still successfully being reduced in considerable quantities without compromising quality of the battery [208]. Similar effects, for instance, had been observed in the past with the development of new generations of electric motors as a reaction to a shortage of noble earths [209]. Second, in addition to the material supply uncertainty there is a product supply uncertainty due to the need for massive uptake of global battery production capacity. If global production of battery cells cannot follow product demand there is a risk of production bottle necks [206, 210] as was the case in 2017 with a global shortage of cylindrical cells due to problems with Tesla's Gigafactory [211]. Additional supply risk stems from the anticipated gap between European battery demand and production (global 28 % and 12 % respectively) in 2025 [22, 151].

In addition to the battery's supply uncertainties, sufficient fuel cell's supply seems to be at least controversial. More specifically it concerns the supply of platinum as a crucial material for fuel cell stacks. While current ICEV technology already relies on platinum as a catalyst for exhaust fume treatment, platinum loading per vehicle is much higher for FCEVs. Overall global reserves are sufficient for potential future uptake of FCEVs [203, 204]. Nonetheless there is doubt as to how fast global platinum production could follow demand growth. Current global platinum production is comparably low at 200 t/a with 70 % being produced in South Africa [212]. Assuming an average platinum load of 20g/vehicle only some 10 million FCEVs could be produced per year with the current global platinum supply. A fast expansion of the supply base is unlikely due to limited investment potential and non-platinum solutions are currently still in the fundamental research stage with prototypes a decade away [164, 213].

ICEV While security of supply does not pose a risk to ICEV on the vehicle level, supply uncertainty lies within the decarbonized fuel production and distribution.

Even though established distribution and fueling infrastructure in Germany could be utilized, the necessary synthetic or biogenic fuels could not be produced exclusively within Germany because of land use insufficiency and social acceptance issues regarding the required expansion of renewable energy generation in Germany [197, 214] as well as carbon capture facilities [215]. Import of fuels or electric power would become necessary imposing geopolitical dependencies. In addition to land use and social acceptance issues, synthetic fuels are expected to be produced most economically in global regions outside of Germany and Europe, specifically in North Africa [46].

4.1.4 Greenhouse gas balancing

While all three drive technologies are affected by conceptual and irreducible uncertainties regarding their greenhouse gas balancing, BEV's uncertain GHG balancing is of a lower level than that of both FCEV and ICEV.

BEV With the carbon intensity of the current German power mix, operation of BEVs is already associated with, on average, similar to lower GHG emissions than fossil counterparts [216, 217]. However, there remains some risk which could jeopardize climate mitigation potential of BEV technology.

First, Schill et al. demonstrated how uncontrolled charging of large BEV fleets might lead to higher overall emissions of the power generation mix if carbon intensive power plants such as coal are not pro-actively faded out in parallel to the uptake of BEV [218]. Second, due to energy intensive battery production a larger part of BEV's life cycle greenhouse gas emissions is allocated to the production phase than is the case for FCEVs or ICEVs [216,219,220]. Accordingly, production emissions of a BEV must be redeemed by sufficient fossil fuel substitution during the operation phase. Thus, potentially insufficient vehicle use and the current trend towards larger batteries for range and high power charging can intensify this risk. Quantification about the actual extent of GHG intensity of battery capacity is itself still controversial, with numbers varying by a factor of five [220]. End-of-life emissions add further uncertainty, with possibilities ranging from opportunities such as stationary second-life-usage of the batteries to GHG intensification due to energy intensive recycling of the battery [221]. Both options are currently still under research and industrial investigation, exemplified by Daimler who is involved in stationary storage applications as well as research and development of modular battery architectures for efficient recycling and reuse [222].

FCEV & ICEV GHG balancing of hydrogen for FCEV and synthetic fuels for ICEV is uncertain due to more complicated cause-effect-mechanisms in the energy chain.

While FCEVs and ICEVs require about three (and six times) as much energy to realize the the same driven distance than BEVs, their associated GHG emissions might not correlate linearly in the short-term due to temporal decoupling of generation and use of hydrogen fuel. For instance, Robinius et al. argue that if hydrogen generation can be realized with renewable power which would otherwise be curtailed, zero GHG emissions can be accounted already today [170]. However, long term reliance on this mechanism is not justified as grid extension can avoid curtailment and cancel this out this effect in at instant. After all, producing hydrogen solely from excess renewable energy is not economically feasible [23, 223].

While biofuels have been used for many decades, their environmental risks of indirect land-use change (ILUC) have only been acknowledged for about a decade [224, 225]. Analysis by the European Commission states that there is "a real risk that ILUC could undermine the environmental viability of biofuels." [226]. It warns of non-linear ILUC-related risks regarding biofuel volumes and behavioral parameters. Overall, there remains large uncertainty about the overall climate change mitigation potential of biofuels [227].

4.1.5 Mobility transition

The remaining uncertainties concern the realm of mobility transition (i.e., shifting modes of transport and reducing overall demand). However, as will be seen, they also affect the energy transition of road transport. Since the following uncertainties affect all three drive technologies equally I discuss them along the three transition layers as proposed by Frank Geels [228, 229]: Niche, Regime, and Landscape.

Niche innovations The successful diffusion of new low-carbon technologies in transport heavily depends on how service and product demand within the passenger transport regime will develop. Currently, consumers' acceptance of BEV and FCEV is generally considered to be lower than that of ICEV due to current technological discrepancies (e.g., lower range and higher range uncertainty due to volatile ambient conditions as well as misleading range indications by manufacturers, higher frequency and longer duration of refueling process, deficient charging infrastructure) [230–233]. However, as knowledge of electric vehicle technology's advantages (e.g., higher driving comfort and lower noise, lower service and maintenance costs, new potential product services such as home storage [186]) increases, the existing consumer regime might "stretch and transform" to adjust to and adopt the new functionality and thus accelerate market diffusion [234]. In fact, user acceptance of alternative mobility options has been paramount to the recent deployment of electric vehicles in Germany [235]. Ultimately, electric vehicle technology itself can help leverage other niche innovations such as lighter, single-person vehicles which offer a lower-price alternative to cars while maintaining comfort of transport. After all, former niche solutions such as electric bikes or scooters are early examples of strong-growing e-mobility products [236, 237].

Regime trajectories The transition towards low-carbon technologies might not only substitute fossil fuels but can also alter current transport regime structures by essentially redefining the role of a vehicle. The individual comfort and freedom of mobility which historically came with *owning* a car could in theory be replaced by the ease and independence which comes with on-demand-access to new mobility services such as private and public shared transportation [238–241]. The traditional private multipurpose vehicle could be substituted by a public multipurpose (digital) platform providing diverse mobility services. A general shift away from purchasing long-term car ownership to purchasing temporary transport services could potentially devalue the importance of individual vehicle performance, which could in turn accelerate BEV's acceptance and increase its demand. The ultimate goal of such a service-based multi-modal transport system would be to decrease the overall energy demand by leveraging more efficient modes where possible. In fact, car sharing has shown to decrease overall vehicle transport demand [242]. Ongoing urbanization can further decrease passenger transport demand by shortening average routes, and further leveraging more efficient modes of transport.

While niche innovations can leverage a mobility transition towards lower energy demand of passenger car transport, some current regime trajectories push an opposite development. First, general transport demand has been increasing steadily over the last decade due to increasing mobility demand [243]. Second, even though car ownership rates have recently dropped there is a trend among remaining car owners to purchase heavier vehicles with higher overall engine power and energy demand [158]. Lastly, while automation of vehicles can help improve access to shared modes of transport, it can potentially increase overall transport demand as full automation enables vehicles to operate (and use energy) without transporting any passengers.

It remains largely unknown however, as to how fast and how much the automation of transport will take place [244].

Events in which transport demand and energy use increase by introducing more efficient technologies of transport are known as rebound-effects. More formally, ”rebound effects refer to [adverse] behavioral or other systemic responses after the implementation of new technologies or other measures to reduce energy consumption” [245]. While the strength of a rebound-effect depends on the price-elasticity of a commodity [246], there are rebound-effects associated with all general mitigation strategies of sustainable transport (including drive train electrification) which will lead to at least an offsetting of expected savings in energy use and GHG emissions in the transport sector [245]. There are different types of rebound-effects some of which have been shown to apply to alternative drive technologies as well. For instance, Sophia Becker showed how an increase in efficiency of a vehicle can trigger individual behavior which increases energy demand [73]. She identified three different types:

1. purchase rebound: customer buys a more efficient but larger and more powerful vehicle,
2. mileage rebound: customer buys a more efficient car but drives more miles than before, and
3. driving style rebound: customer buys a more efficient car but drives more aggressively and energy intensive than before.

Even though Becker’s work originally referred to combustion engine vehicles there is little reason to assume that these rebound effects will not affect battery and fuel cell electric vehicles the same way, especially as their efficiency effect is much larger than historic combustion engine efficiency improvements.

in their meta-analysis Schmidt et al. [25] show how different expert analyses for passenger and freight road transport anticipate different developments of transport demand in Germany, quantifying the uncertainty outlined above. Fig. 4.5 shows how freight transport demand could double or half by the year 2050. Passenger transport uncertainty is relatively smaller with long-term scenarios lying between 50 and 100 %.

Landscape developments Because socio-technical landscape developments “comprise slow-changing trends over which regime actors have little to no influence [...]

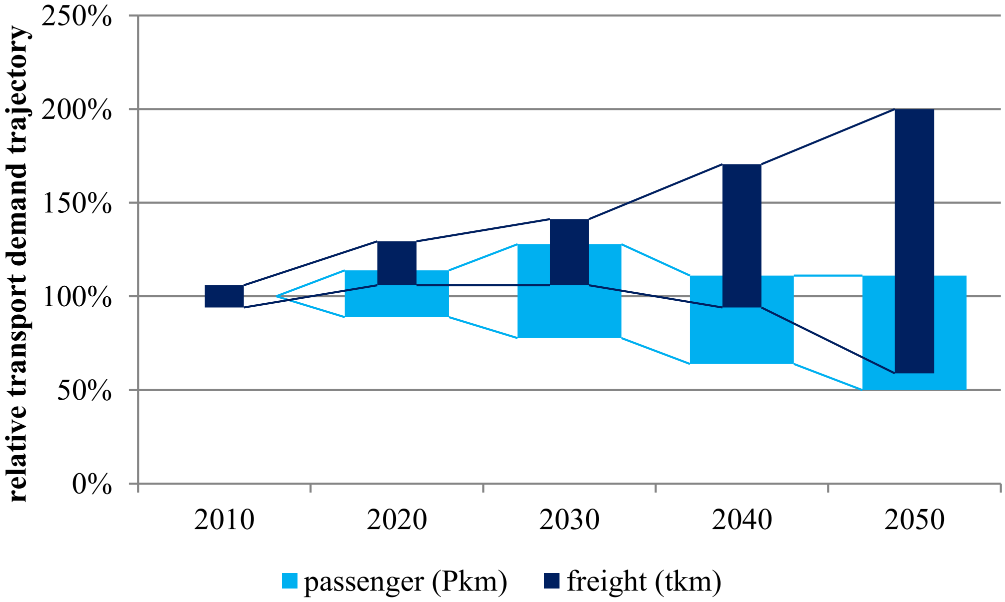


Figure 4.5: *Demand trajectory uncertainties for passenger and freight road transport in Germany, adapted from [25], all values normalized with 2010 values*

(e.g., ideology)" [247], I allocate the identified political uncertainties to this layer. Strategic objectives and constraints of passenger vehicle transport's overall transition reveal themselves through both implicit and explicit root premises in the argument map. They can be subsumed as follows: minimization of economic cost, maximization of environmental benefit as well as maximization of overall system resilience, all while reliably supplying transport demand and maintaining technical feasibility (e.g., infrastructure, electrical grid). As far as these objectives and constraints are in conflict with each other they introduce political uncertainty, necessitating societal discourse, compromises and introducing some irreducible trade-offs. This is congruent with the defined objective space of the German national platform future of mobility (NPM), which states that both economic and environmental cost are both central in assessing and comparing alternative drive technologies [35].

4.1.6 Quantification of parameter uncertainties

Based on the above qualitative uncertainty analysis and in preparation of the robustness analysis an additional literature review was conducted specifically for quantifiable (parameter) uncertainties. For each of the three vehicle technology options literature values for general parameters such as well-to-tank-efficiency, fuel consumption, fuel price, vehicle lifetime, annual distance driven as well as technology specific parameters such as battery capacities, battery and fuel cell pack prices, and energy consumption of battery pack production were identified. A comprehensive list of

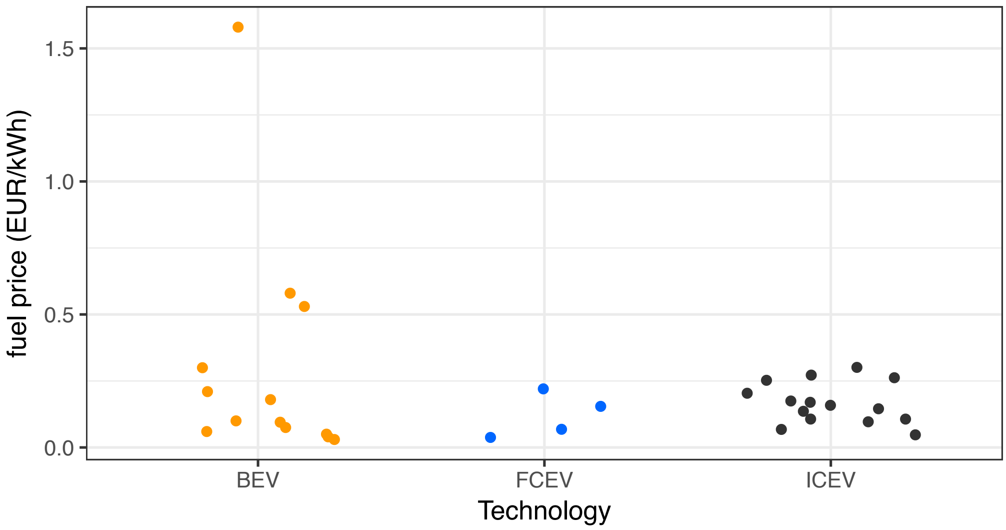


Figure 4.6: *Range of literature values for fuel prices of different vehicle technologies, based on tables C.1 - C.3*

review findings can be found in tables C.1 - C.3 in the appendix. The following two examples outline the extent and reasoning behind parameter uncertainties.

Fig. 4.6 shows possible (wholesale) fuel prices as found in the literature. The comparison illustrates how the fuel price for charging BEVs seems comparatively more volatile. More specifically, fast charging and other additional utility services might increase charging prices far above standard utility prices [248, 249].

Fig. 4.7 illustrates another example of quantifiable differences of parameter uncertainty. It shows how the spread of fuel consumption values for midsize passenger cars vary among the different technology options. More specifically, it suggests that expected fuel consumption of ICEV technology is comparatively more uncertain than that of electrified vehicle technologies. Multiple arguments support this. Firstly, potential fuel consumption of the ICEV could theoretically be some 60 % lower than current levels through motor downsizing as well as change of driving style as compared to today [55]. Secondly, some research has shown how real-life fuel consumption of ICEV was 24 % and 40 % higher than official type-approval levels in 2015 and 2017, respectively [250, 251]. In contrast neither BEV nor FCEV show comparable uncertainty of overall fuel consumption, independent of motor size and driving style [35, 45, 49, 55, 252–256].

The resulting value ranges to inform the Monte Carlo experiment for the robustness analysis can be found in table B.3 in the appendix.

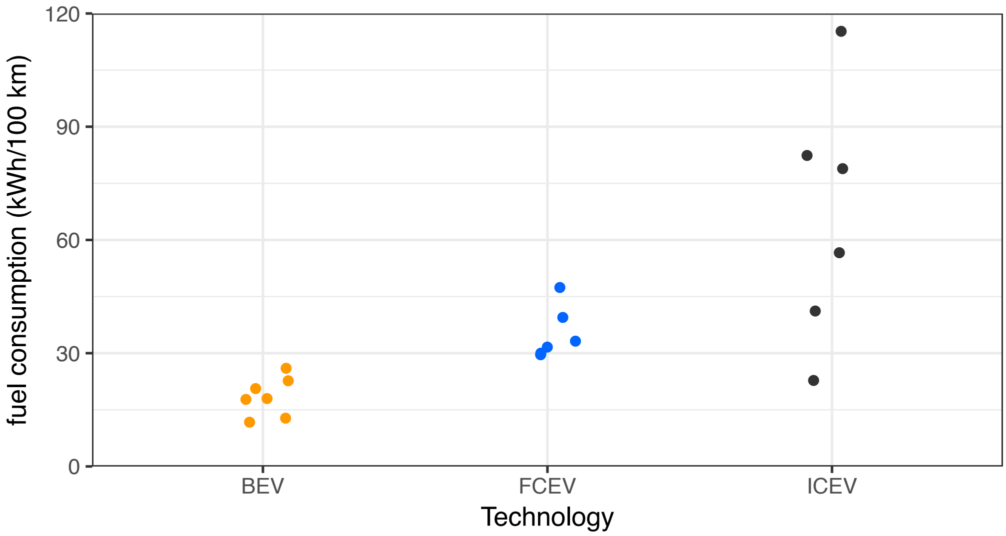


Figure 4.7: Range of literature values for fuel consumption of different vehicle technologies, based on tables C.1 - C.3

4.2 Robustness analysis

In this section I first compare the different vehicle technologies (including plug-in hybrid electric vehicles, PHEV as a hedging option) regarding their robustness regarding both total cost of ownership (TCO) and lifecycle greenhouse gas emissions (LCE). “ICEV” technology here denotes only synthesized hydrocarbon fuels based on electric power. Common biomass based fuels are not included as they do not constitute a fully scalable and theoretically unconstrained technology solution for Germany. I then identify for each technology which how influential their input uncertainties are regarding the overall uncertainty of both TCO and LCE. The computational experiment for producing the underlying data set was realized in a Python 3.7 runtime environment without parallelization on a 2.66 GHz Intel Core 2 Duo processor with a total computation time of 23 hours and 46 minutes.

4.2.1 Technology comparison

In order to introduce the Monte Carlo simulation’s overall results, its data set is summarized via a kernel density estimate with a rule-of-thumb bandwidth [257]. Fig. 4.8 shows the two-dimensional density plot (scaled to maximum of 1) as well as the population’s median value regarding both TCO and LCE for each technology.

Some distinct observations can be made. First of all, based in the experiment BEV exhibits the densest population around its median value of all four technologies. BEV’s results also show the lowest median values for both TCO and LCE (see table 4.2). Whether this is an indication for overall superior robustness against its uncertainties will be seen in further analysis. The subsequent order of two-dimensional robustness for the remaining three technologies is not clear. While ICEV shows the second best median and density for TCO, its performance regarding LCE is worst among all technologies. The inverse is true for FCEV. While its median for LCE and overall robustness is better than that of ICEV, FCEV's median TCO is highest among all technologies with the least dense population around the cost median. PHEV shows a more complex distribution. While its median for LCE as well as its density lies in between those of BEV and ICEV, its TCO performance is worse than both of its root technologies (regarding both median and robustness). This initial picture of the experiment's results will be further broken down for the subvariables of operational expenditure (OPEX) and capital expenditure (CAPEX) as well as vehicle cycle emissions (VCE) and fuel cycle emissions (FCE).

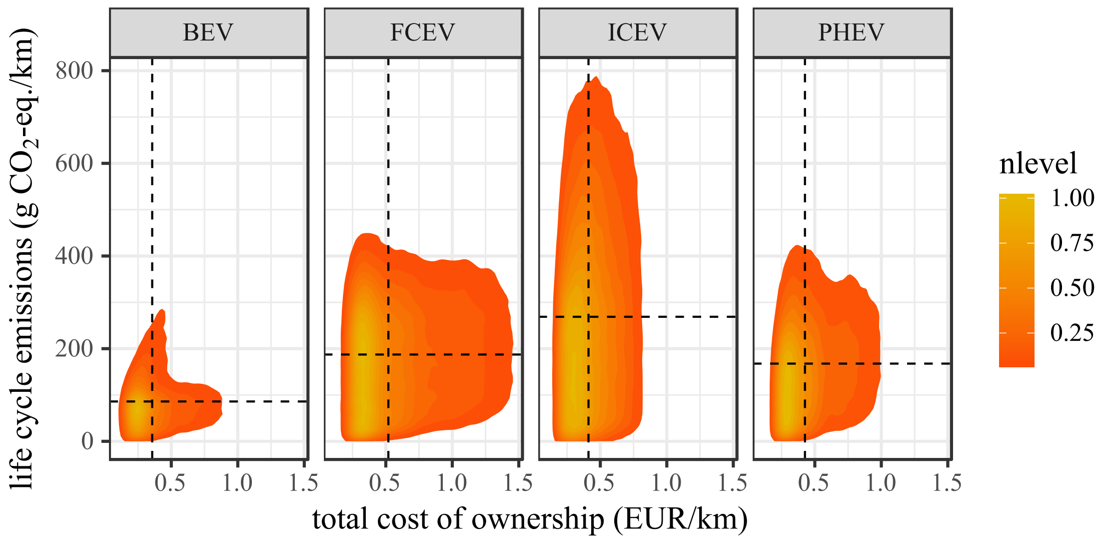


Figure 4.8: *Two-dimensional density plot and median for each technology*

Table 4.2: *Overall median values*

	technology	LCE	TCO
1	BEV	86.01	0.36
2	FCEV	187.36	0.52
3	PHEV	167.74	0.43
4	ICEV	268.83	0.41

While the density plot conveyed an impression of overall robustness, extreme cases within the experiment's data set are visualized by w convex hull plot of each technology's LCE-TCO-scatter in Fig. 4.9. Additionally, the Fig. includes marginal density plots for both TCO as well as LCE as a decomposition of Fig. 4.8. Extreme cases put the above density results into a different context, in that BEV loses its apparent superiority. First of all, BEV's worst case TCO values exceed those of ICEV. Similarly, BEV's worst case LCE values exceed those of FCEV and PHEV. Both observations indicate some of BEV's distinct vulnerabilities which will be be discovered through more in-depth-analysis later in this chapter. The convex hull analysis also shows that BEV's overall behavior is different than that of the other three technologies, in that its convex hull does not represent a rectangular-like shape. More specifically, there are no extreme cases of low cost and high emissions. For FCEV, ICEV and PHEV extreme case analysis shows a picture much like that of the density analysis above: FCEV exhibits much higher vulnerability cost-wise than the other two, while ICEV and PHEV exhibit extreme cases of high LCE. Notably the extreme best cases are very similar among all technologies. By design of the experiment, all four technologies must allow for a quasi-zero LCE. On the other hand, BEV shows minimum possible TCO among all technologies in this experiment, closely followed by ICE and then FCEV and PHEV. Despite the minute differences, minimum TCO can be considered similarly low over all technologies, ranging from 8.5 to 13.3 EUR-Ct/km for BEV and FCEV, respectively.

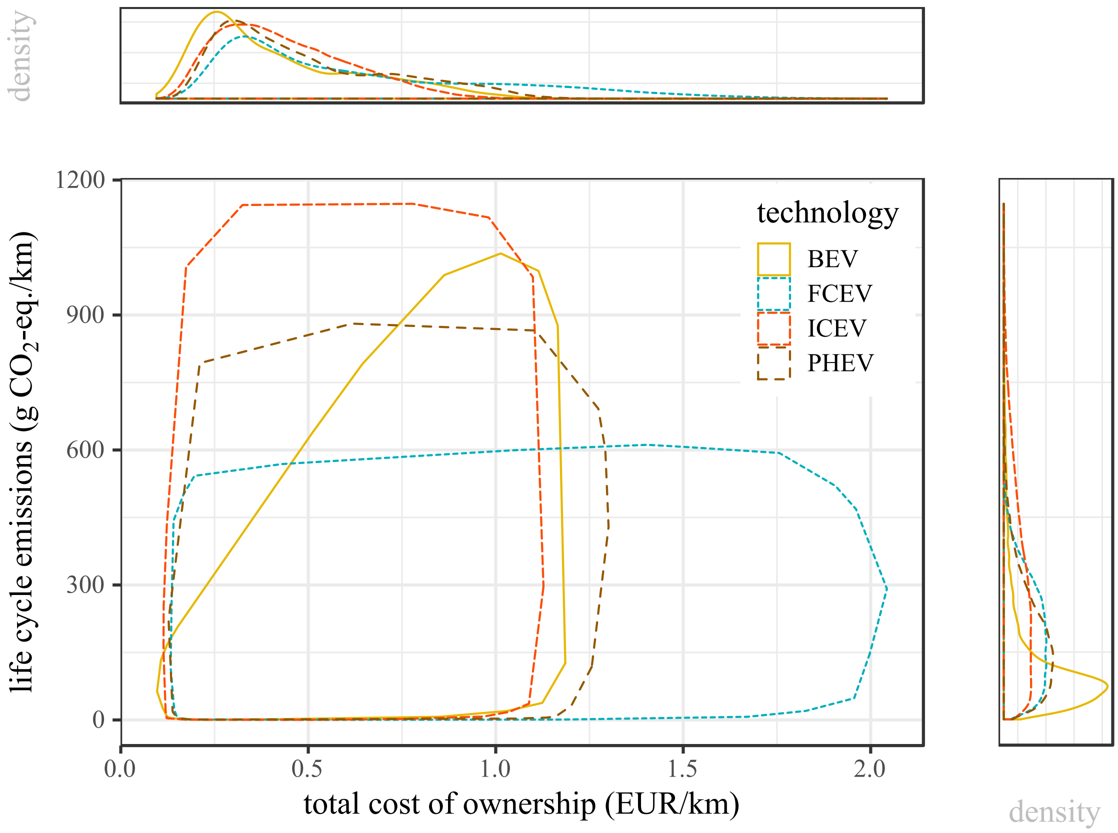


Figure 4.9: *Convex hull plots of each technologies scatter for TCO and LCE*

Total cost of ownership

In order to better understand the reasons behind overall results above, a deeper analysis of individual variables is necessary. Due to the hyperbolic causal relationship between both TCO and LCE and annual distance driven (see equations 3.5 and 3.1), the violin plots of the following analysis are faceted for the different annual distances as used in the experiment: 5,000;10,000; 20,000; and 40,000 km/a.

Fig. 4.10 shows a combined violin- and box plot (referred to as violin plot from this point forward) of each technology's TCO for different annual distances. It shows how both median and robustness (by measure of interquartile range) of TCO improves significantly with increasing driving distance for all four technologies, most notably for FCEV. Only robustness of ICEV does not improve markedly. Here too, BEV show superior performance. With the exception of very low driving distances of around 5000 km/a, BEV exhibits the lowest median TCO with comparable or better robustness than that of all other technologies. In order to understand better the reasons for this behavior, a similar violin plot for each CAPEX and OPEX is visualized in Fig. 4.11 and 4.12.

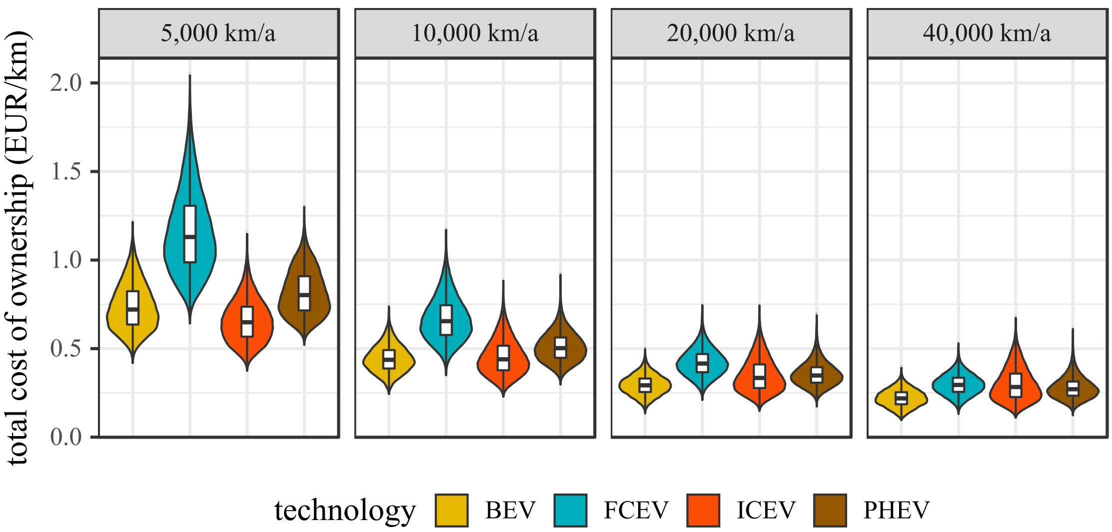


Figure 4.10: *Violin plots for each technology's TCO, faceted for annual distances*

CAPEX uncertainty within the experiment shows that FCEV's high TCO is dominated by high median CAPEX with comparably low robustness (see Fig. 4.11). However, it is apparent that worst case CAPEX for FCEV refers to current vehicle prices (compare with tables B.1 and B.2), thus its CAPEX uncertainty is to be considered an opportunity for further price and cost reductions. Superior CAPEX valuation lies robustly with ICEV, as there are no included uncertainties by design of this experiment. BEV's and PHEV's median and interquartile range lie in between those of ICEV and FCEV.

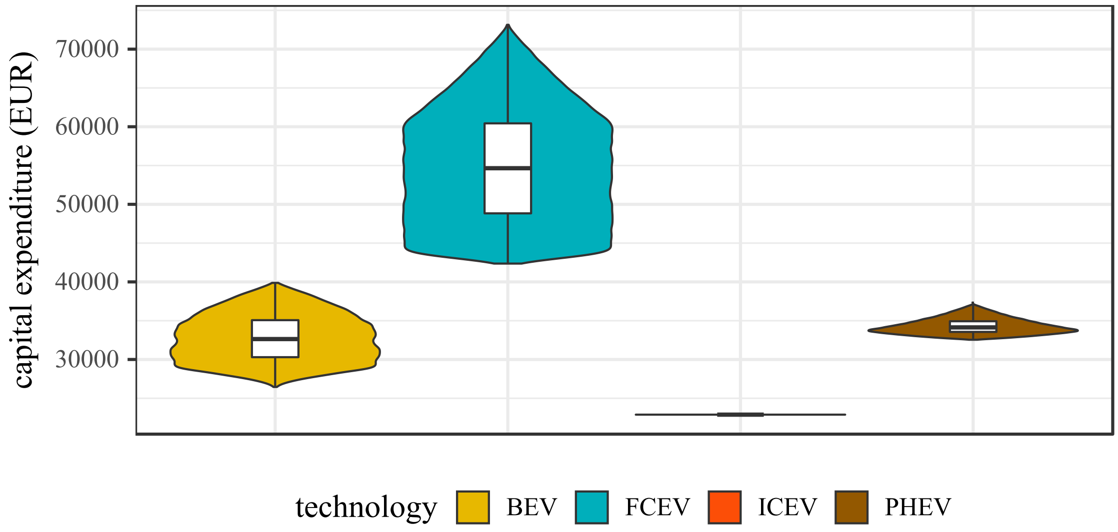


Figure 4.11: *Violin plots for each technology's CAPEX*

Other than CAPEX, the different technologies' OPEX valuation is not disparate 4.12, with the exception of ICEV. Both its median and interquartile range are distinctly inferior to the other technologies, especially FCEV and BEV. Overall BEV again shows best performance regarding its median OPEX, with an interquartile range similar to that of both FCEV and PHEV.

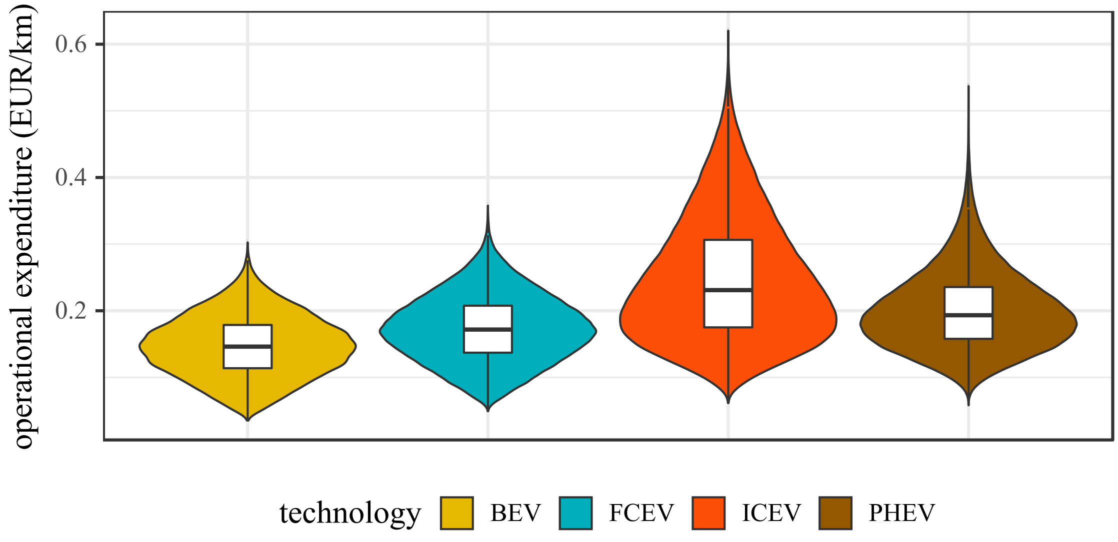


Figure 4.12: *Violin plots for each technology's OPEX*

Life cycle greenhouse gas emissions

In analogy to TCO, analysis of LCE can be broken down into its three principle components: annual driven distance (Fig. 4.13), vehicle cycle emissions (VCE, Fig. 4.14) as well as fuel cycle emissions (FCE, Fig. 4.15).

Other than TCO, LCE median and robustness does not strongly depend on annual distance for any of the technologies with the exception of BEV. Its LCE shows improvement over increasing annual distance, mostly regarding its robustness. BEV's median LCE is distinctly lower than all other technologies for all annual distances. For very low driving (below 10,000 km/a) distances its interquartile range is inferior to that of FCEV and PHEV and comparable to that of ICEV. For moderate and high driving distances above 20,000 km/a BEV technology shows robustly low LCE, despite all uncertainties used in this experiment.

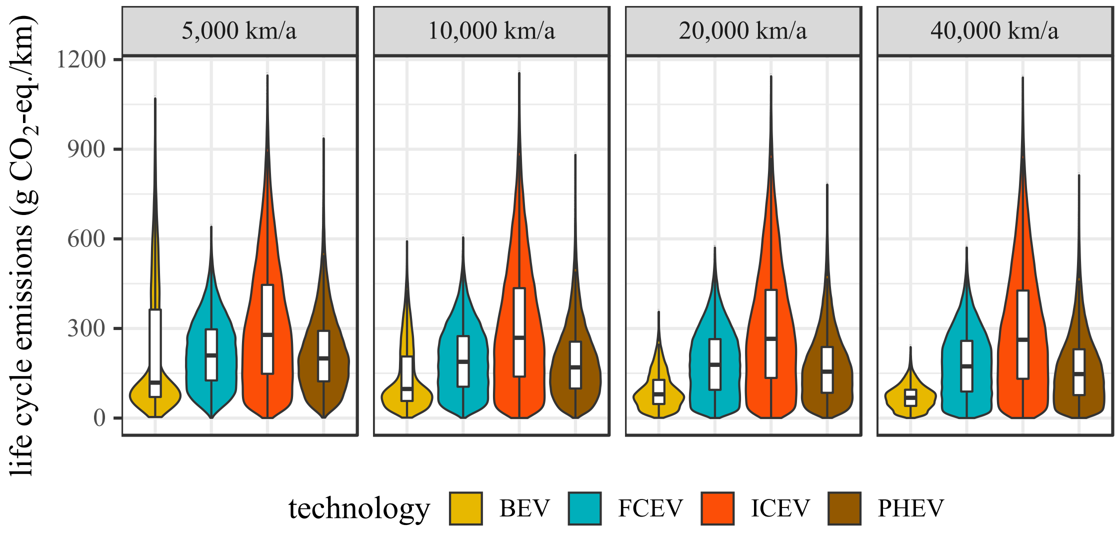


Figure 4.13: *Violin plots for each technology's LCE, faceted for annual distances*

Analysis of VCE and FCE illustrates why BEV is the only technology which ran reduce its LCE (and the uncertainty thereof) with increasing driving distances. BEV's VCE, although low on median, is largely more uncertain than those of all other technologies, its interquartile range stretches over two orders of magnitude. Similar, but dampened behavior can be seen with PHEV's VCE, which indicates the battery's role in this uncertainty. FCEV's and ICEV's VCE lies robustly below 5 t CO_2-eq. per vehicle.

Analysis of FCE shows an inverse picture to that of VCE, in that BEV is distinctly superior in FCE median and robustness than all other technologies, its operation-based emissions lie robustly under the median of the other three technologies, which

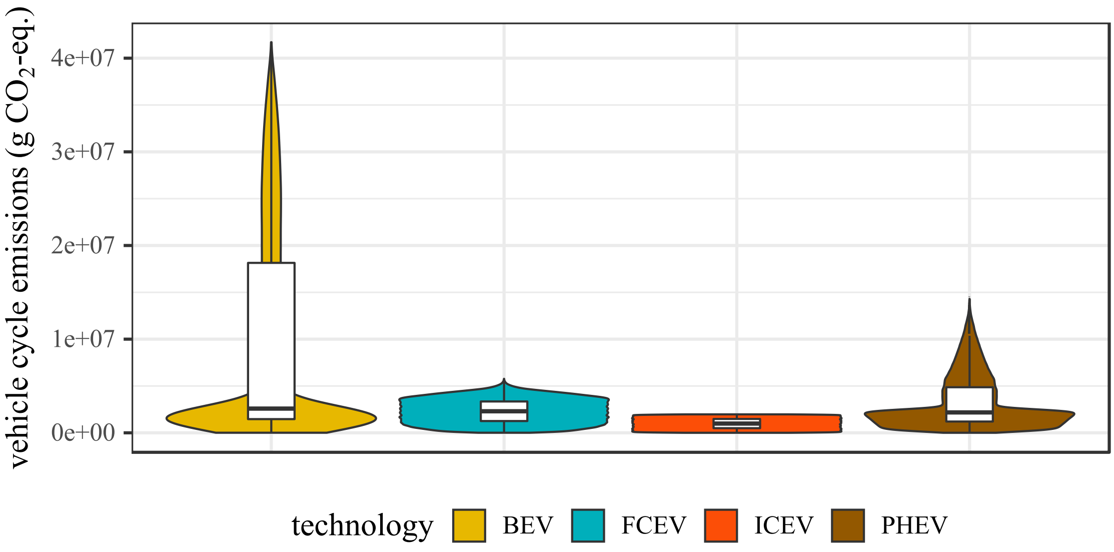


Figure 4.14: *Violin plots for each technology's VCE*

all show vulnerability towards extreme levels of fuel cycle emissions - ICEV's FCE reach as high as 1 kg CO_2-eq./ km.

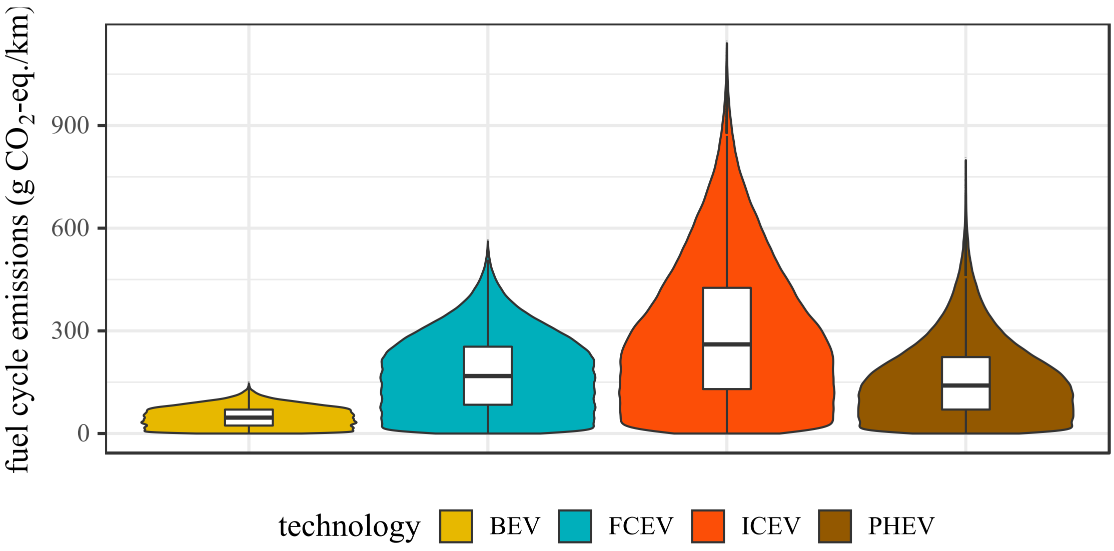


Figure 4.15: *Violin plots for each technology's FCE*

4.2.2 Uncertainty comparison

In order to gain a better understanding about the nature of each technology's robustness and its vulnerabilities, the following analysis infers from the evaluation space of TCO and LCE back into the model input space, in order to ultimately discriminate the dominating from the non-dominating uncertainties. This is visualized by stacking the proportions of shared variance between each TCO and LCE and their correlated input uncertainties. This does not depict how for instance a single TCO value depends on model input variables but rather how TCO's overall uncertainty depends on the uncertainty of different model input uncertainties. This way an abstraction above single value levels can be made and more general effects become visible. All proportions of shared variance are listed in appendix D.

Battery electric vehicles

Table D.1 in the appendix lists the spearman rank correlation coefficients of core input and output variables of based on the Monte Carlo simulations' results for BEV. It includes some collinearities of known independent variables (e.g. CAPEX and VCE), however since the causal relationships of the model are known a priori, a multicollinearity test is not necessary for further analysis. Overall, the correlation analysis shows how TCO's uncertainty is much more correlated with that of OPEX than that of CAPEX. LCE's uncertainty depends on both FCE's and VCE's uncertainty to approximately equal parts.

In order to get an overview of the different uncertainties and their role in determining BEV's TCO uncertainty, Fig. 4.16 stacks the proportion of shared variance between TCO and correlated model input uncertainties, again distinguished for the different annual driving distances. It shows that lifetime is a strong predictor for overall TCO, especially when a BEV is only used for small annual driving distances. With increasing driving distance OPEX-related uncertainties dominate TCOs uncertainty, notably fuel price as well as the price for maintaining the vehicle. Other factors such as capacity and price of the battery as well as fuel use efficiency of the vehicle are less determining in the uncertainty of BEV's TCO, which is true for moderate to high driving distances.

Compared to TCO, LCE's uncertainty is much less determined by the uncertainty of the lifetime of a BEV. Shared variance analysis shows that the two most influential uncertainties are those of energy intensity of battery production ("X11") and carbon intensity of the power required to charge a BEV. Uncertainties of carbon intensity of the power for battery and vehicle production are comparably of lesser influence, which is further decreasing with annual driving distance. Fuel use and battery capacity uncertainties qualitatively swap importance with increasing annual driving distance, however both are less important uncertainties compared to energy intensity of battery production and carbon intensity of electric power for charging a BEV. All proportions of shared variance for LCE of BEV are shown in Fig. 4.17.

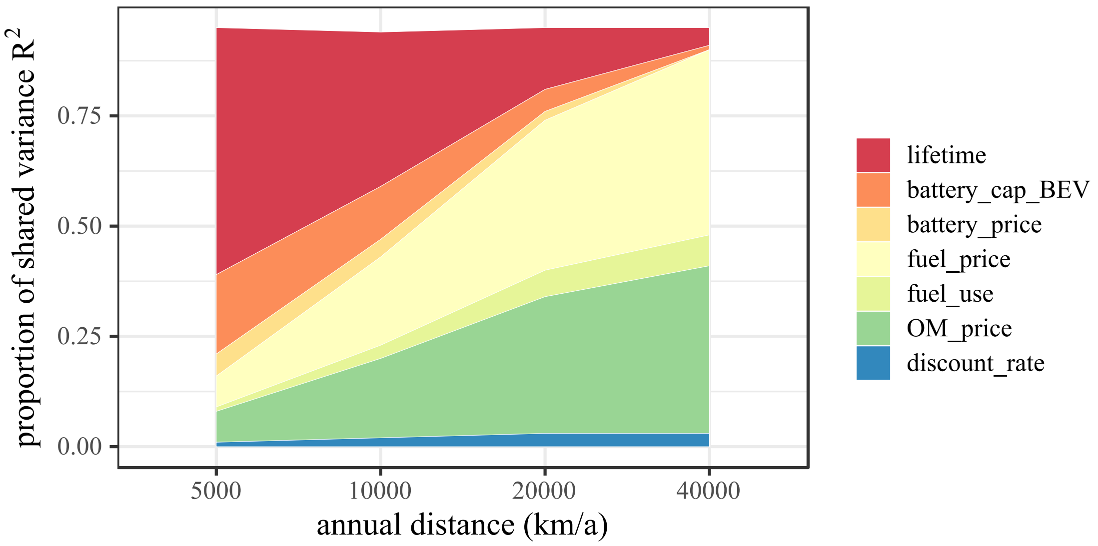


Figure 4.16: *Proportions of shared variance between input uncertainties and TCO of BEV*

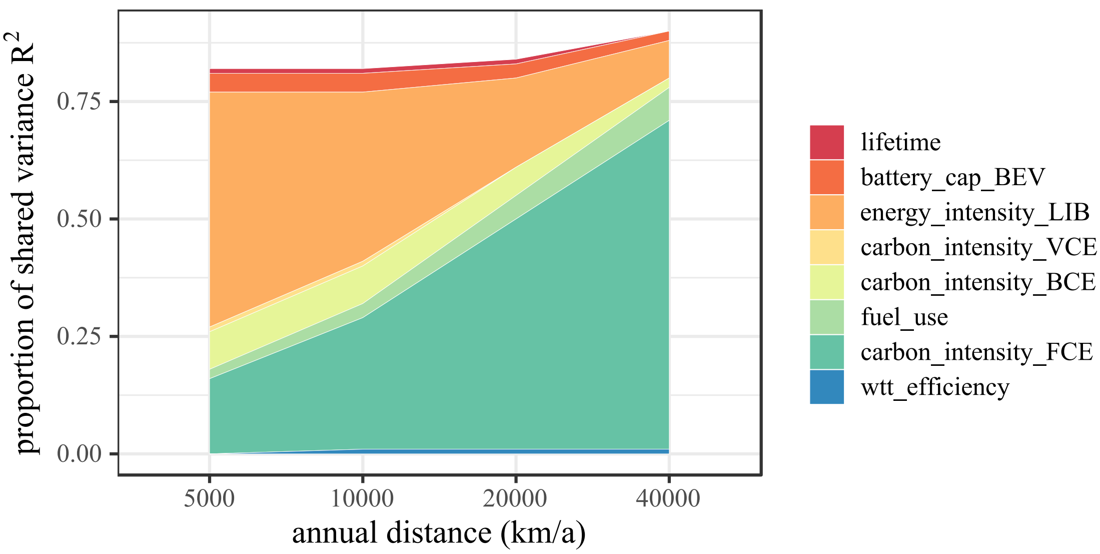


Figure 4.17: *Proportions of shared variance between input uncertainties and LCE of BEV*

Fuel cell electric vehicles

Table D.2 in the appendix lists all correlations between input and output uncertainties of the FCEV model. It shows that FCEV's overall TCO uncertainty is determined both by CAPEX and OPEX's uncertainties to similar proportions. For the uncertainty of LCE, FCEV is significantly determined by the uncertainty of its FCEs, with a very high proportion of shared variance.

More detailed analysis of TCO's dependencies (Fig. 4.18) shows that much like BEV, a major vulnerability to FCEV's TCO is the lifetime of the vehicle, especially for a low annual distance. Another important uncertainty is that of fuel cell price (but not fuel cell power). For low annual driving distances, lifetime and fuel cell price are practically the only vulnerabilities for FCEV's TCO, however with increasing annual driving distance OPEX-associated uncertainties, such as hydrogen price and maintenance gain importance. Fuel use (i.e., propulsion efficiency) is a negligible uncertainty for any driving distance.

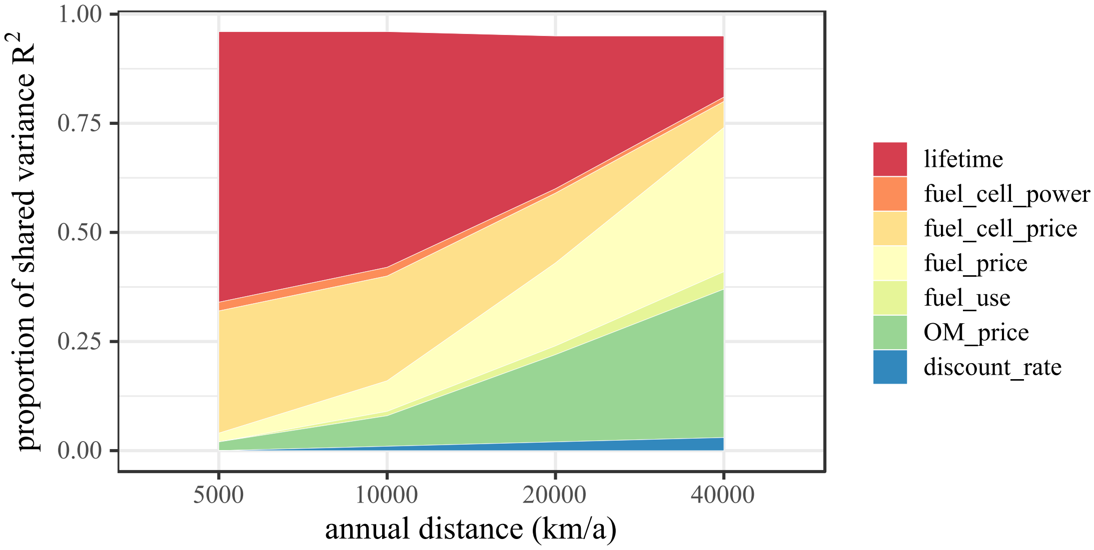


Figure 4.18: *Proportions of shared variance between input uncertainties and TCO of FCEV*

Detailed analysis of the reasons for uncertainty of FCEV's LCE (Fig. 4.19 reveals a single most important uncertainty: the carbon intensity of the electric power for FCEV's fuel cycle. Across all driving distances it is by far the most important vulnerability of LCE. Well-to-tank efficiency and fuel use can help mitigate the risk of high root emissions for producing hydrogen fuel, however not to a significant degree. Uncertainty about upfront emissions of producing a FCEV is comparably very low: lifetime, battery and vehicle emissions play almost no role across different driving distances when compared to the carbon emissions allocated to the fuel cycle.

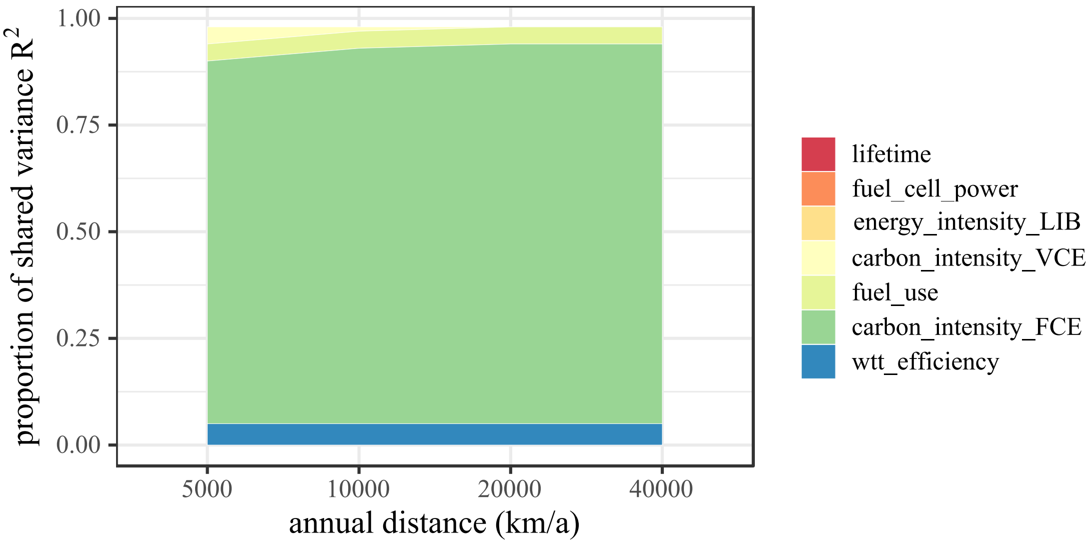


Figure 4.19: *Proportions of shared variance between input uncertainties and LCE of FCEV*

Internal combustion engine vehicle

Table D.3 in the appendix lists all correlations between input and output uncertainties of the ICEV model. It shows that ICEV's overall TCO uncertainty is almost entirely dependent on OPEX's uncertainties. This is by design, as there are no CAPEX-related uncertainties implemented in the experiment's underlying model. Much like for FCEV, the uncertainty of ICEV's LCE is practically only determined by the uncertainty of emissions associated with the fuel cycle of the operation phase.

Fig. 4.20 shows why OPEX's uncertainty is such a strong factor in determining TCO's variance. It is vastly dominated by the large uncertainties of the future price of synthetic fuels as well as the average fuel use of ICEVs, so much so that the influence of lifetime uncertainty is significantly lower here than is the case for BEV and FCEV, especially for moderate and high annual distances. Similarly the importance of maintenance price uncertainty is suppressed for ICEV.

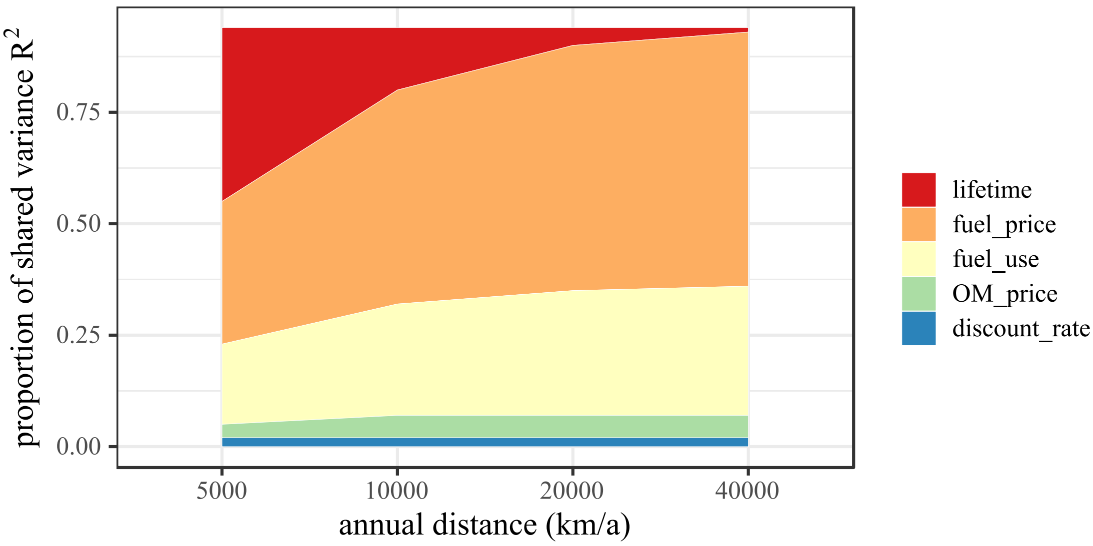


Figure 4.20: *Proportions of shared variance between input uncertainties and TCO of ICEV*

Much like FCEV, ICEV's LCE uncertainty is almost entirely caused by the uncertainty of carbon intensity of the fuel mix, i.e. the carbon intensity of the power used for producing synthetic hydrocarbon fuels (see Fig. 4.21). Congruently, vehicle lifetime and vehicle cycle emissions play practically no role in the vulnerability of LCE. Fuel use and well-to-tank-efficiency play some role across all driving distances but are of less importance than the uncertainty of whether synthetic fuel is produced with low-carbon electric power or not. By and large, carbon intensity and not efficiency of synthetic fuel production is most relevant for climate mitigation potential of internal combustion engines. Similarly, uncertainty of fuel use plays a secondary role.

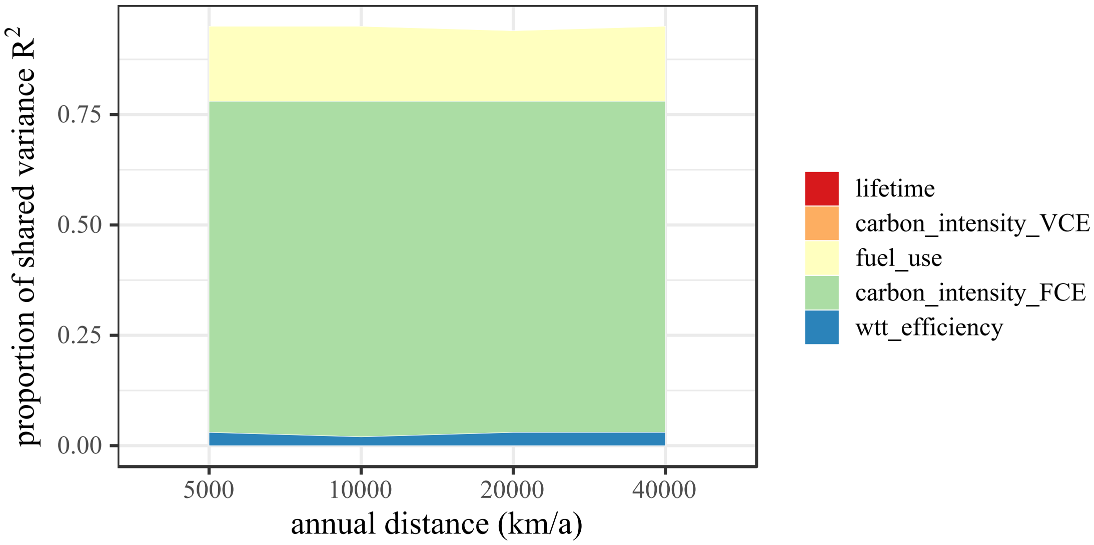


Figure 4.21: *Proportions of shared variance between input uncertainties and LCE of ICEV*

Plug-in hybrid electric vehicles

Table D.4 in the appendix lists all correlations between input and output uncertainties of the PHEV model. It shows that, like ICEV, PHEV's overall TCO uncertainty is largely dependent on OPEX's uncertainties. CAPEX uncertainty plays almost no role. In accordance, LCE uncertainty of PHEV is also strongly connected to the uncertainty of FCEs, and to a lesser extend to the uncerainty of VCEs.

Much like BEV and FCEV, uncertainty of PHEV's TCO is strongly introduced by lifetime uncertainty for low driving distances (see Fig. 4.22). In comparison, battery related uncertainties are overall practically irrelevant. With increasing driving distance OPEX-related uncertainties become more important in explaining what makes TCO of PHEV uncertain. Firstly, uncertainty of fuel prices of both electric power and synthetic fuel are cost vulnerabilities for higher driving distances. Similarly, maintenance price, synthetic fuel use efficiency as well as the share between electric and non-electric mode (charge depleting mode) all become more important vulnerabilities with increasing driving distance. Only fuel use uncertainty of the electric motor plays almost no role when compared to the above listed uncertainties.

More detailed analysis of PHEV's LCE uncertainty reveals a hybrid picture between the LCE uncertainty of BEV and those of ICEV. On the one hand, the energy intensity as well as the carbon intensity of battery production are visible uncertainties for low driving distances. On the other hand, however, these two BEV-typical uncertainties are quickly overshadowed by ICEV-related uncertainties, most prominently carbon intensity of the synthetic fuel cycle as well as the uncertainty of fuel use efficiency of the combustion engine. Notably the ICEV-related uncertainties are much more determining for the overall LCE uncertainty of PHEV than the battery related ones. This is true even independent of annual distances as well as charge depleting modes shares.

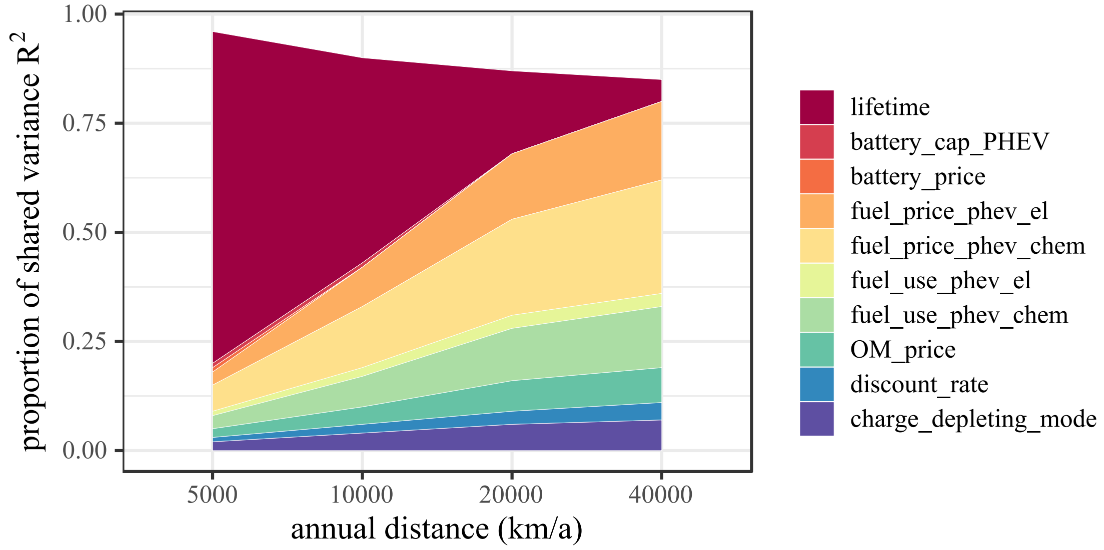


Figure 4.22: *Proportions of shared variance between input uncertainties and TCO of PHEV*

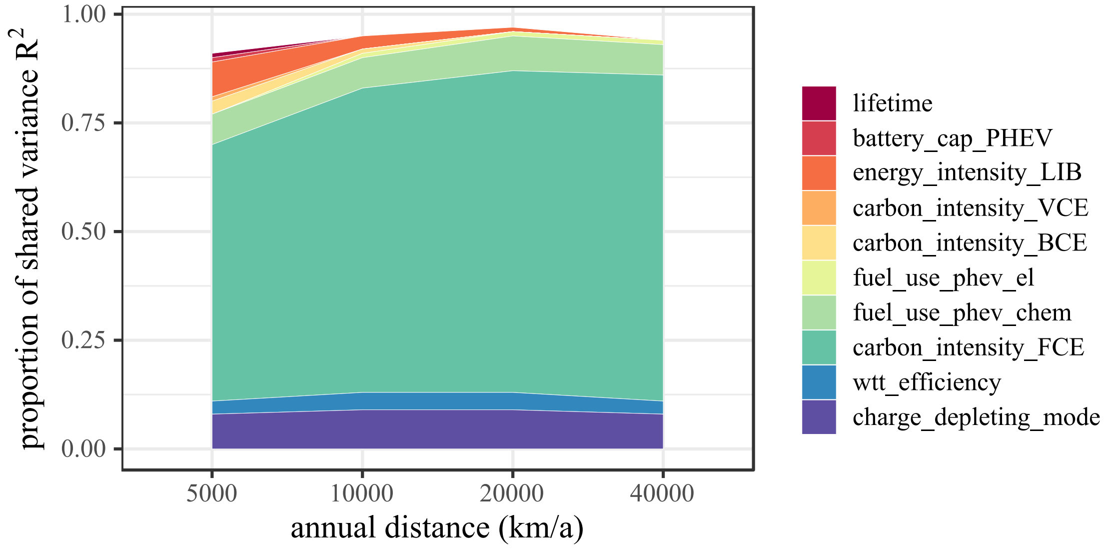


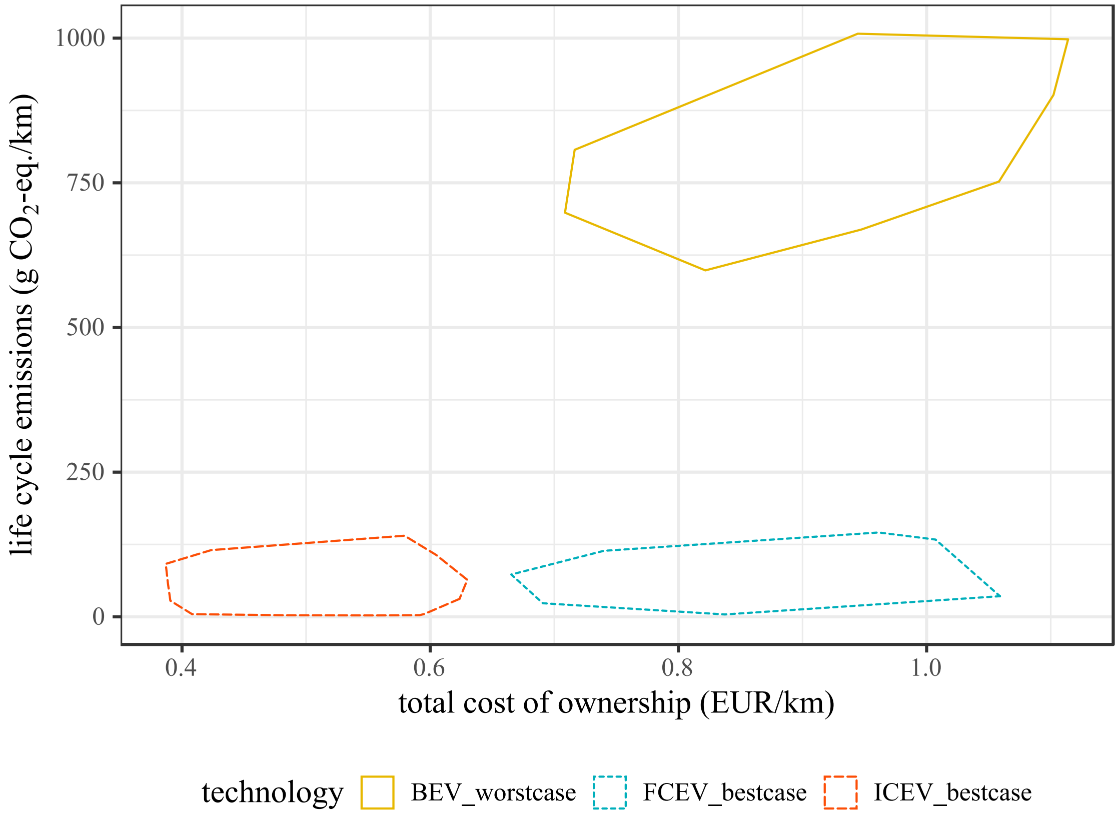
Figure 4.23: *Proportions of shared variance between input uncertainties and LCE of PHEV*

4.2.3 Tipping points

As the above analysis of uncertainty dominance shows there is not one single uncertainty which makes a technology vulnerable but instead multiple uncertainties. In order to identify a narrative about tipping points, some important uncertainty parameters were manually iterated on in order to identify single states of the world at which one technology suddenly and clearly outperforms another. Table 4.3 lists one state of the world for each BEV, FCEV and ICEV. These points approximate the threshold between different state ranges of the world at which both FCEV and ICE show a clear advantage over BEV and vice versa. Fig. 4.24 show the different technology options' TCO and LCE for those states of the world which are robustly unfavorable for BEVs and favorable for ICEV and FCEV. More precisely, BEVs with very large batteries (> 80 kWh) produced with comparatively high energy and carbon intensity(400 kWh_{el}/kWh_{cap} at > 800 g CO_2-eq./kWh_{cap}), a short vehicle lifetime of under ten years, high charging prices over 0.3 EUR/kWh as well as higher carbon intensity of electric power for the fuel cycle than that of ICEV and FCEV, can be robustly said to be "worse" than their ICEV and FCEV competitors each with very favorable conditions according to table 4.3, even at very high annual driven distances. Inversely however, if BEV technology can successfully manage to stay below these parameter thresholds while ICEV's and FCEV's fuel use remains above 5 L/100 km (at above 1 EUR/L), and 1 kg/100 km (at above 3 EUR/kg) respectively, BEV's economic and greenhouse gas advantage can be robustly assumed, independent of the annual driving distance (see Fig. 4.25). In other words, if fuel use efficiency and fuel price, as well as carbon intensity of power for fuel cycle don't considerably improve for both ICEV and FCEV, neither technology will show a clear TCO or LCE advantage even over unsubsidized long-range BEV (i.e., with battery capacities up to 80 kWh, charging at up to 0.3 EUR/kWh).

Table 4.3: *Tipping points for narrating superior and inferior cases of FCEV and ICEV over BEV*

uncertainty	BEV	FCEV	ICEV
lifetime (a)	10	10	10
fuel price	0.3 EUR/kWh	3 EUR/kg	1 EUR/L
carbon intensity of power for fuel cycle (g CO_2-eq./kWh)	100	100	100
fuel use		1 kg/100 km	5 L/ 100 km
carbon intensity of power for LIB production (g CO_2-eq./kWh)	800		
el. energy intensity of LIB production "X11" (kWh/kWh)	10 vs. 400		
battery capacity (kWh)	80		



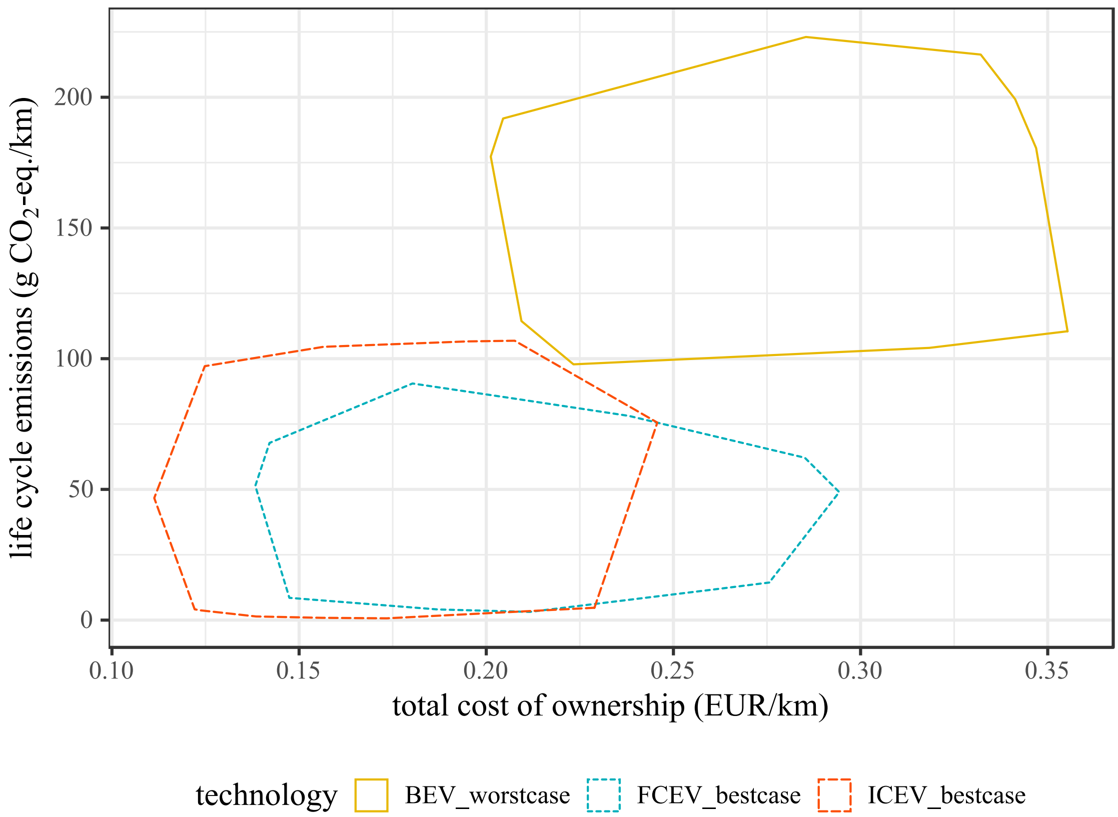


Figure 4.24: *Case comparison in favor of ICEV and FCEV according to identified tipping points, for 5000 (top) and 40,000 km/a (bottom)*

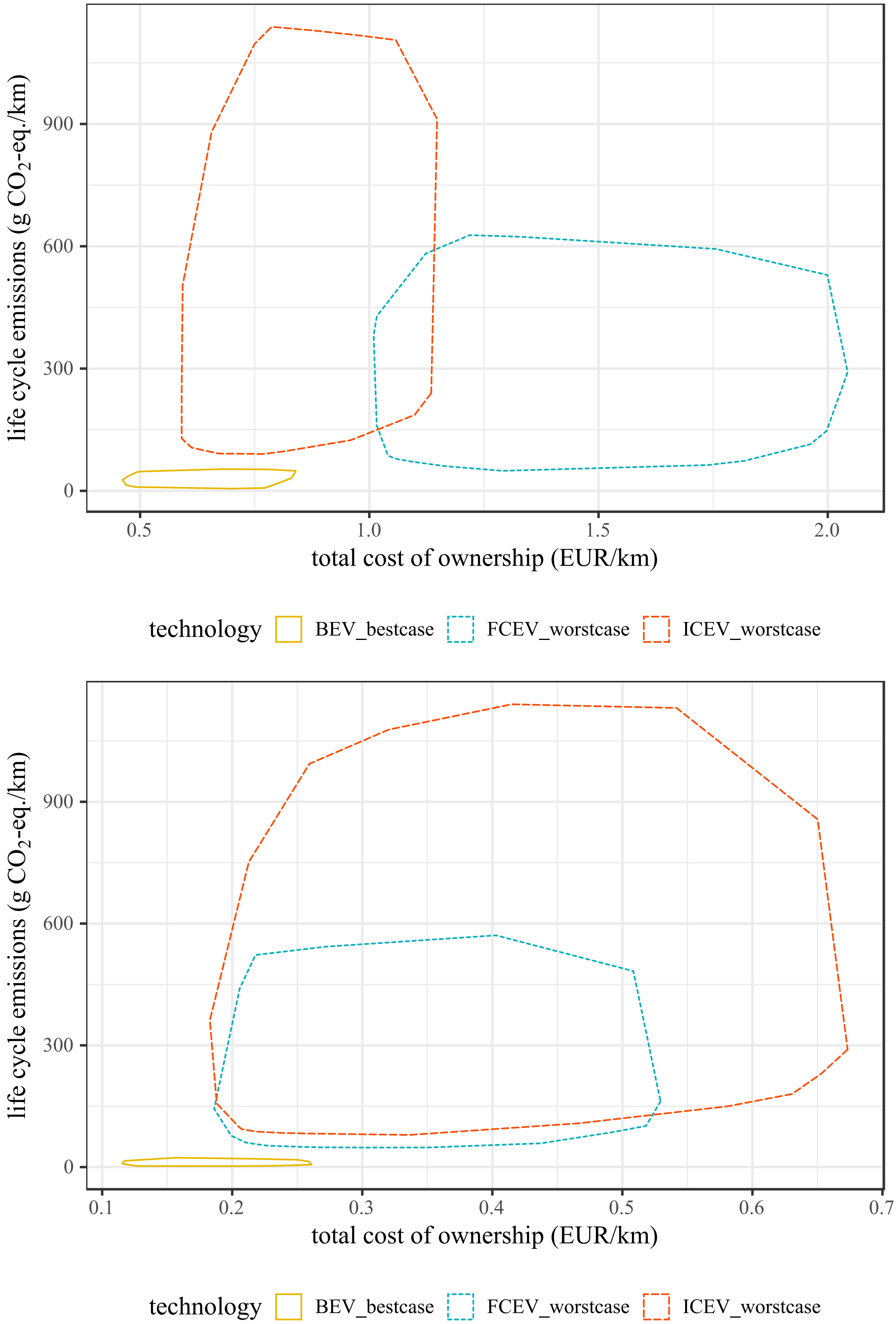


Figure 4.25: *Case comparison in favor of BEV according to identified tipping points, for 5000 (top) and 40,000 km/a (bottom)*

Chapter 5

Discussion

"The demand for scientific objectivity makes it inevitable that every scientific statement must remain tentative for ever."
— Karl Popper

5.1 Uncertainty and robustness

I was able to show that each of the three drive technology options is affected by a similar number of uncertainties with similar characteristics as part of five uncertainty clusters: security of supply, economic developments, technological developments, GHG balancing and overall mobility transition. This means that based on the knowledge space that was captured in an extensive argument map there is not one single technology option for Germany's energy transition of road transport which does not face irreducible, conceptual, and ignorance-affected uncertainties, including combustion engine vehicles. Solely based on this observation one could argue in support of the persistent German political paradigm of technology openness [70].

A closer look at the results of the uncertainty analysis however reveals that a technology comparison merely based on uncertainties (i.e., lack of knowledge) is not sufficient for deriving strategic or political paradigms. For instance, while all vehicle technology options are affected by the uncertainties of mobility transition (niche innovations, regime trajectories, landscape developments) it can be argued that these uncertainties ultimately affect the different vehicle technologies differently. More specifically, while the core practical advantages of both FCEV and ICEV (fast refueling, high energy storage density) speak to the user behavior and socio-technical transport patterns of the past, it can be argued that potential future developments towards different mobility patterns such as shared and automated vehicles is more compatible with a lean battery-electric drive train [82, 83], thus turning the same uncertainty into a risk for ICEV and to some degree FCEV, and into an opportunity for BEV. An additional reason why a comparison of only the technologies' uncertainties is ultimately not sufficient is demonstrated by the uncertainty quantification. It showed that without further context, a comparison of, for instance, fuel prices is misleading as fuel price itself is not an appropriate metric of comparing vehicle options' performance. The same is true for the comparison of only fuel consumption uncertainties. Ultimately all identified uncertainties are of practical value when they are combined into meaningful metrics of performance based on which the technology options can be usefully compared.

This was achieved in the robustness analysis in which the identified uncertainties were translated into uncertainties of the more meaningful performance metrics of total cost of ownership and lifecycle greenhouse gas emissions. Through this robustness analysis I was able to demonstrate that the seemingly indistinguishable uncertainty spaces of the different technology options transform into significant differences of robustness. In a Monte Carlo simulation of future states of the world BEV demonstrated the overall highest robustness regarding both TCO and LCE while FCEV seem particularly sensitive in their TCO evaluation and ICEV in their LCE evaluation. The observation that despite its uncertainties BEV seems overall a more robust option for the future of passenger vehicles is in congruence with recent market developments as well as political and industrial activity. For instance, while in the past having been outspokenly skeptic about BEV, the German Association of the Automotive Industry recently requested a major German charging infrastructure summit in order to more quickly advance the widespread adoption of BEV for passenger cars [258]. Moreover, a recent study by the German National Coordination Center for Charging Infrastructure revealed that in sum automakers with stakes in the German vehicle market expect there to be some ten million BEVs on German roads, corresponding to about a quarter of today's total passenger car fleet in Germany [259]. Similar specific fleet targets have not, in such seriousness, been made public for either FCEV or decarbonized ICEV.

5.2 Vulnerabilities and tipping points

Based on the Monte Carlo simulations within the robustness analysis vulnerabilities (i.e., uncertainties with high impact on the TCO and LCE valuation) could be identified for each of the three technology options, some of which are not necessarily obvious or congruent with the past and current public discourse on the technologies' vulnerabilities. Overall and independent of the vehicle technology, the vast majority of TCO-related vulnerabilities do not regard the details (and cost of) production of a vehicle but rather uncertainties regarding its operation.

For BEV, the future uncertainty of power price development for recharging seems a much more important impact on TCO robustness than for instance the battery price or capacity uncertainty or fuel use efficiency. This is particularly relevant as charging prices not only depend on the development of whole sale electricity prices but also on the evolution and scaling of charging technology. For instance if the cost of increasingly sought after fast charging services cannot be decreased significantly below current levels, the negative effect on BEV's TCO can be grave, even if at the same time battery cost is lowered. So, ironically while BEVs eventually might reach purchase price parity with combustion engine vehicles, their overall economic advantage is vulnerable to depreciate if average electric charging prices turn out to increase in the long term.

For FCEV, lifetime uncertainty is a more profound TCO-impacting vulnerability than it is for BEV and ICEV. This is due to the overall high purchase price of the vehicle. Even best case developments of fuel cell price development could not completely compensate this uncertainty. Only for high annual distances could a massive decrease in hydrogen fuel price compensate the vulnerability of an uncertain lifetime of the FCEV. However as a fuel cells lifetime is yet ultimately determined by its hours of operation, high annual distance would itself influence the overall lifetime of a FCEV negatively [260]. This constitutes, for instance, an inferiority to BEV technology whose limiting factor on lifetime is not the cyclic lifetime but almost entirely the calendric lifetime of the battery [156].

ICEV's TCO-related vulnerabilities lie clearly within the current state of conversion processes and their (d)efficiencies from well to wheel. Fuel price uncertainty is, except for very low annual distances, the dominating vulnerability regarding ICEV's TCO. Only minimization of fuel use (i.e., motor size and efficiency, driving behavior etc.) could directly and by design mitigate this vulnerability on the vehicle level. In the meantime further research and development and thus maturing of PtG and PtL-processes should bring clarity and ultimately reduce uncertainty about the price of alternative hydrocarbon fuels.

For PHEV the hybridization of the technology stack means that it aggregates all uncertainties of BEV and ICEV. However this diversifies PHEV's uncertainty portfolio and ultimately reduces their vulnerability to any single uncertainty. For instance the price uncertainties of both electric power and alternative hydrocarbon fuels are major vulnerabilities for TCO of PHEV, however when compared to their relative influence on BEV and ICEV, respectively, both uncertainties each have less impact on the overall TCO uncertainty of PHEV. Compared to these and other uncertainties, the uncertainty of battery capacity and battery price is negligible for PHEV. Such is the uncertainty about the operational split between electric and combustion motor (charge depleting mode vs. charge sustaining mode).

The single most important aspect which dominates the uncertainty of all vehicle technologies' LCE viability is the velocity and depth with which the primary energy supply of the electric power mix can be decarbonized. With a renewable share of 42.1 % in 2019 [261] German power mix has yet to achieve the majority of decarbonization. This matters especially for lower overall well-to-wheel-efficiency of a vehicle technology as it multiplies the root emissions. This is why both FCEV and ICEV are commonly supported with claims of leap-frogging the decarbonization of the electric power grid by scaling renewable energy generation directly and locally with hydogen and alternative hydrocarbon fuel production, both domestically and internationally [262, 263]. In fact, the results of the model show that at the current carbon intensity of the German power mix, both FCEV and ICEV would not provide a greenhouse gas advantage over current fossil fuel combustion engine vehicles. Moreover, in a worst case, ICEV's fuel cycle emissions can reach as high as 1 kg CO_2-eq./ km, exceeding current european fossil fuel ICEV regulatory emissions limits manifold. At the same time BEV's LCE can generally be considered on par or lower than those of today's fossil fuel based combustion engines vehicles [27].

Out of all three vehicle technologies, BEV is the only technology for which the production of the vehicle and its components can make a difference for overall LCE uncertainty. Especially for lower annual distances, the uncertainty with which battery lifecycle greenhouse gas emissions (esp. through energy intensity of production) are currently determined has a strong influence on the overall LCE valuation of the vehicle. Further improvement and standardization of battery production is therefor crucial to the climate viability of BEV technology for passenger transport. Positive signals in this regard have recently come from automakers. For instance at their battery day in September 2020 Tesla, Inc. announced their short-term goal of industrially scaling up a dry-electrode application within their new 4680 lithium-ion cells, which if successful would not only improve factory footprint and cost of production but it could also (and most importantly) drastically reduce the energy intensity of the cell production. This can be assumed because running dry room equipment and cathode drying are significantly large contributors to current battery cell production process energy use (43 % and 39 %, respectively [264]). In short, according to my robustness analysis if a dry electrode application can be successfully implemented by automakers and renewable energy penetration of the german power mix continues, BEV technology can robustly outperform the two other technology options with regards to lifecycle greenhouse gas emissions. Once this production process improvement is achieved, popular past studies questioning BEV's overall climate mitigation potential on the basis of their batteries' GHG footprint (such as a recent study by the Verein Deutscher Ingenieure (VDI) [265]) will be invalidated, as their assumptions will be based on outdated life cycle assessments of lithium ion battery cell production. Uncertainties regarding lifetime, battery capacity, geographic origin of battery production and vehicle fuel use (incl. HVAC of BEV) are, by comparison, not considerable vulnerabilities of BEV's climate viability.

Unlike for BEV, vehicle-cycle-related uncertainties of FCEV and ICEV do not considerably impact the bottom line of their overall LCE. This is because the carbon intensity of the electric power for the production of hydrogen and subsequent alternative hydrocarbon fuels is so impactful. This is also why fuel use of FCEV and especially ICEV matters in determining in overall LCE valuation. This will however lose its meaning once (or if) electric power for the production of both hydrogen as well as alternative hydrocarbon fuels can reach significant levels of decarbonization.

Closely associated with the concept of vulnerabilities is that of tipping points. My analysis showed that in theory a dichotomy of future states of the world can be identified in which BEV technology is either robustly superior or robustly inferior (with regards to TCO and LCE) to both FCEV and ICEV technology. However as this tipping point regards multiple parameters of the model simultaneously, deriving a simple narrative is not as trivial as the term "tipping point" would suggest. The only tangible argument I make here is that the (multivariate) tipping point can be argued to be further away from today's realities of FCEV and ICEV than it is for BEV. More specifically, in order for FCEV or ICEV to be robustly superior to BEV, prices of both hydrogen as well as alternative hydrocarbon fuels would have to be reduced by multiple factors from current price levels (from 10 to 3 EUR/kg for hydrogen [14, 168] and from around 3 to 1 EUR/L for alternative hydrocarbon fuels [46, 172]) while at the same time being produced almost solely with decarbonized energy sources, an objective I argue to be overall harder and more long-term than the pending sort-term efficiency improvements of battery production, one of the core tipping point parameters for BEV. In other words, if fuel use efficiency and fuel price, as well as carbon intensity of power for fuel cycle don't considerably improve by multiple factors from the today's state for both ICEV and FCEV, according to my analysis neither technology will show a clear TCO or LCE advantage even over unsubsidized long-range BEV.

The nature of uncertainty matters in determining the best strategy for handling knowledge-deficit. If the nature of uncertainty is irreducible, more research will not necessarily yield better knowledge. Resources should be allocated to research aimed at reducible uncertainties of the decision problem and on joint sense-making and integrating frames of reference. Based on the robustness analysis some pivotal uncertainties are reducible as they regard technological developments such as dry electrode implementation for BEV as well as mature renewable hydrogen and alternative hydrocarbon fuel production for FCEV and ICEV, respectively. In this regard my analysis overall suggests that BEV technology is very likely to be a robust option for decarbonizing passenger transport in the short term. At the same time both FCEV and ICEV technology still bear a credible potential for emerging as robust technology choices in the long term.

The results of my analysis overall support the notion that it seems strategically useful to keep all technological options open to stay adaptive to unforeseeable developments and hedge against the identified vulnerabilities of each technology. Accordingly, based on my findings I propose to maintain the paradigm of technology openness, however with a narrower and more specific meaning than before: The fact that not none of the technology options is free of uncertainties or vulnerabilities must not translate into a wait-and-see-strategy (commonly used as an argument against short-term BEV adoption) but rather a strategy of parallel advancement of all options. While this comes at a higher upfront cost, it can increase the transport transition's long-term resilience and helps avoid momentous lock-in decisions. In the end the macro-economic expense for maturing both new BEV and FCEV infrastructures is relatively small compared to other German infrastructure budgets [170]. Ultimately, with diesel and gasoline technology Germany is already affording parallel and fully incompatible fuel infrastructures.

5.3 Limitations and future research

I have reason to believe I have outlined most of the pivotal uncertainties affecting Germany's energy transition of passenger vehicle road transport as the amount of new arguments added to the map decreased noticeably from one expert interview to the next. However I do not claim my results to be exhaustive as only 13 experts have been consulted for producing the argument map. Moreover the knowledge space on the problem will extend with time and detail. The argument mapping process as well as the consequent uncertainty analysis can and will be continued as knowledge evolves. The map is publicly available and open for contributions at kialo.com [20].

It is important to note here that while rich in results my robustness analysis is based on a static model with uncertainties included as parameters. In that it represents the technical more than the behavioral aspects of the problem components. It evaluates the vehicle technologies' economic and climate feasibility without feedback loops between model entities under the assumption of unbounded supply of resources and instant availability of the vehicle technology products at any given time. This limits my model's viability and generalizability for the vehicle technology question as a global, socio-technical problem. For instance, while security of supply was identified as an uncertainty it was included in the robustness analysis only implicitly through price uncertainties. Temporal aspects such as scaling and ramping-up of production for battery and fuel cell technology were also not included in the model. For instance, while BEV seems the overall most robust choice for road-bound passenger vehicles, in the end all three vehicle technologies can become necessary simply if supply of core components such as battery cells cannot follow an exponentially increasing demand for BEV technology. This is not a negligible challenge. For instance, on their battery day in September 2020 the car maker Tesla, Inc. confirmed they will have to purchase battery cells from current suppliers such as Panasonic, LG and CATL long into the future even though Tesla, Inc. is ramping up their own cell production. Furthermore, in my model cost improvements of BEV and FCEV were mainly driven by cost improvements of their core components such as battery and fuel cell. Other non-linear cost decreases such as economies of scale are likely. For ICEV on the other hand, further price depreciation might be triggered by events such as regulatory bans and a decreasing popularity of the technology itself due to other climate-unrelated adverse effects of the combustion engine (e.g., local air and noise pollution). A growing number of international government targets for phasing out sales of new ICEVs put increasing pressure on the entire technology as a future option for Germany [56, 57].

Another limitation of my robustness analysis is its focus on the vehicle level. This matters as a vehicle itself is only an artefact interdependent on other socio-technical regimes of transport, especially culture and symbolic meaning, markets and user practices, as well as (fuel) distribution networks [15]. Especially in the case of BEV and FCEV, for both of which a new fuel (or charging) infrastructure must be developed as part of the technology uptake, including interdependencies between vehicle artefact and fuel infrastructure into a robustness analysis model would yield more fine-grained results for different possible futures. For instance, while BEV technology began as a range limited technology confined to urban contexts, it is become more popular with rural than with urban consumers [266], presumably for reasons "outside" the vehicle such as superior charging opportunities in rural homes [140]. Whether an improved charging infrastructure in cities will alleviate this or whether urban centers will ultimately become the consumer base for options other than BEV is out of my analyses' scope. Likewise, my analysis does not allow for conclusions about whether or not a quick and large-scale decarbonized production of hydrogen and alternative hydrocarbon fuels is itself viable or not. My analysis only showed that compared to other uncertainties it is crucial to produce fuel with as low a carbon footprint as possible. A similar limitation lies with my model's exclusion of user behavior. For instance, if rebound-effects in passenger transport are as grave as some literature implies, then compensation of climate mitigation effects would have to be accounted for. More specifically, if the improving economy of battery electric vehicles leads to ever more cars, more performant engines and more annual driven distance, climate gains can be be overproportionally lower than expected when , especially when compared to ICEV which might not trigger such strong rebound-effects. Further research on the robustness of vehicle technology options should employ a more wholesome Monte Carlo simulation, in which a dynamic model (e.g., agent-based) would also include aspects of the mobility transition and most (or all) of its socio-technical regimes and actors (see also Fig. 2.1 in Chap. 2).

One aspect of my model which I technically do not consider a limitation but which I want to address here is the definition of well-to-wheel efficiency and its being based on the secondary energy form of electricity. There are arguments which claim the primary-energy-based well-of-wheel efficiency of BEV to be as low as 15 % due to inefficient yield of photovoltaics in Germany when compared to solar power plants in regions with high solar irradiation such as North Africa or Patagonia [267]. Based on this observation one could argue my analysis to be biased towards BEV. I find this is a flawed argument. The debate around renewable energy being a primary vs. secondary energy source ultimately regards the global allocation of renewable power generation. However today's realities are far passed this point, as every major economy around the global has been ramping up domestic generation of renewable power. So under the premise of renewable power being generated not only in the most suitable region of the world, but also in Germany itself, defining well-to-wheel efficiency on a secondary energy basis is the most reasonable approach for the vehicle technology question. After all, a hypothetical German passenger vehicle fleet made up entirely of BEVs would likely not consume more than only double of what electric power Germany is currently exporting [181, 259].

Differences in taxes and subsidies have not been included in my model as to keep the analysis clear of regulatory mechanisms. Ultimately my analysis is not aimed at comparing vehicle technology alternatives to the fossil fuel combustion engine vehicle but to give guidance on which of the technological alternatives might be best suited to substitute Germany's current fossil fuel-passenger vehicle nexus. In any case vehicle-based subsidies become too expensive beyond the first 1-2 % of takeup, after which point broader policy mechanisms are needed, such as mandates and quotas, as well as fuel economy regulations or binding CO_2 targets [268].

Ultimately the research object of this work covers only about two thirds of all German road-transport-related greenhouse gas emissions. The remainder is mostly associated with heavy duty vehicles such as trucks or busses, which make up 35 % of all transport-related greenhouse gas emissions [4, 134]. Since their use cases and cost parameters differs strongly from those of passenger vehicles it is unjustified to assume the results in this work to also apply to heavy-duty traffic. However with some effort the uncertainties and models of this work can be adjusted and applied to this other great road-bound GHG emitter.

As part of my approach for the robustness analysis I have broadly brushed over varieties within the different vehicle technology options, including different cell chemistry of lithium-ion batteries for BEV, differences in hydrogen production (electric versus thermal), as well as differences among the various options of alternative hydrocarbon fuels for ICEV. While this could have potentially rendered my analysis useless it was my exactly my intention to determine whether these details mattered in the broad range of current and future uncertainties. I argue that my results show with sufficient precision that overall BEV is the most robust choice regarding both its economic and climate mitigation feasibility, independent of technological distinctions within each technological branch. Further analysis of cross-sections within the results of my Monte Carlo simulation may find some more details regarding these technology-specific differences and may complement my tipping point analysis with one or another detail.

Furthermore, the exploratory nature of my robustness analysis and its results could, in theory, be further developed to allow for the integration of a robust optimization method, which could aim at optimizing each technologies option's vehicle parameters while acknowledging and integration the presence of uncertainty about the world or about the conceptualization of the problem itself. Ultimately robustness could be treated as its own objective in an optimization model [269–271] in order to proactively optimize a vehicle *for* any given uncertainty, instead of just evaluating it on the basis of uncertainty.

Finally, I would like to remark on the application of uncertainty theory. Applying uncertainty concepts has not been as straight forward in the end as I had hoped in the beginning. At times there was much ambiguity which left room for (unconscious) subjective interpretation and alteration. Searching for uncertainty can be both exciting and discouraging at the same time. It is exciting for the curious theorist and discouraging for the diligent practitioner. On the one hand there is much to find and learn while searching for uncertainty - and in this sense it is very rewarding even in practice - but on the other hand there never seems to be an end to where uncertainty can lead the researcher. Similarly, the term "recognized ignorance" seems like a comforting mitigation of the negative notion of ignorance, but at the end of the day it is hard if (not almost impossible) to know what is and what is not recognizable about one's absence of knowledge.

Chapter 6

Conclusions and outlook

> *"The illusion that we understand the past fosters overconfidence in our ability to predict the future."*
> — Daniel Kahnemann

6.1 Research summary

The passenger vehicle sector in Germany is under increasing pressure to reduce its GHG emissions. Dominated by internal combustion engine vehicles running on fossil fuels passenger vehicles account for a large portion of all German GHG emissions and have not been able to significantly reduce their GHG emissions since 1990. As a scalable remedy there are generally three distinct technology options for decarbonizing passenger vehicles in Germany:

A internal combustion engine vehicles (ICEV) supplied with alternative hydrocarbon fuels,

B fuel cell electric vehicles (FCEV) supplied with hydrogen, or

C battery electric vehicles (BEV) supplied with electric energy.

Even though the ambition to decarbonize German passenger vehicles is unambiguous, public disagreement about the "best" option(s) persist to this day. While uncertainty arguably plays a major role in this disagreement, past research has touched only superficially on the difference between what we do and *do not* know in order to assess how robust the feasibility of any of the technology options is with regards to possible future states of the world.

In order to operationalize the general technology question I spanned my research along two core research questions:

Q1 How do the alternative vehicle technology options compare with regard to their underlying uncertainties?

Q2 Which of the three alternative vehicle technologies can be considered the most robust solution for decarbonizing passenger cars in Germany?

I approached the two research questions each with a different methodology:

M1 - Uncertainty analysis: By dialectically mapping the arguments within the debate on the problem I identified and classified uncertainties for each vehicle technology option and conducted an uncertainty comparison of all three technology options.

M2 - Robustness analysis: I employed the results of the uncertainty analysis to inform and conduct a Monte Carlo experiment assessing both total cost of ownership and life cycle emissions of each of the technology options for a wide range of conceivable future states of the world.

The results of my analysis can be condensed into six main conclusions:

C1 My uncertainty analysis showed that all three drive technology options are affected by a similar number and quality of uncertainties as part of five uncertainty clusters: security of supply, economic developments, technological developments, GHG balancing and socio-technical interdependence with the mobility transition. There is not one single vehicle technology which does not face irreducible, conceptual and surprise-laden uncertainties.

C2 Seemingly equal uncertainty assessments of the different technology options translate into significant differences of robustness regarding total cost of ownership (TCO) and life cycle GHG emissions (LCE) of each vehicle technology.

C3 BEV technology demonstrates overall the highest robustness regarding both TCO and LCE compared to that of FCEV and ICEV. However, BEV's economic feasibility showed to be vulnerable particularly to the price of charging (and the underlying price of electric power). At the same time battery production still constitutes a vulnerability for BEV's overall climate feasibility. The realization of large energy savings potentials through process improvements such as dry electrode application could ultimately mitigate this risk for good.

C4 ICEV technology based on alternative hydrocarbon fuels would in theory allow for a total decarbonization of Germany's current fleet. However, this concept has serious vulnerabilities regarding both its economic and climate feasibility most of which are rooted in the concept's overall (d)efficiencies from energy well to vehicle wheel. A designated supply with renewable energy as well as serious efforts to minimize ICEVs' fuel use (e.g., motor size and efficiency, driving behavior) could directly and by design mitigate this vulnerability.

C5 FCEVs offer better robustness than ICEVs regarding overall LCE valuation (largely due to superior well-to-wheel-efficiency) and are not as vulnerable to battery-production-related uncertainties as BEV. However, FCEV show serious vulnerability in their economic feasibility as long as both vehicle and hydrogen prices can not be drastically reduced in the near future.

C6 According to a tipping point analysis none of the three technologies can be demonstrated to reliably outperform their competitors in all future states of the world. Each of the three technologies still has distinct vulnerabilities and associated risks. However, it can be argued that today's reality is closer to the point of clear superiority for BEV than for FCEV or ICEV.

Broadly speaking my research contributes further arguments of why BEVs should be considered the most reliable option for decarbonizing passenger vehicles in Germany.

6.2 Practical implications

Based on my research results and conclusions I argue for some practical implications regarding the future of vehicle technologies in Germany.

Battery electrification of vehicles

When I started my research in 2016 the question about passenger vehicles in Germany seemed equitable and equally open to all technological options. Since then, German registrations of battery electric passenger vehicles have grown exponentially and the number of BEVs on German streets has increased twenty-fold [272].

Now, at the end of 2020 my analysis has fittingly (not to say luckily) narrowed in on battery electrification as the most reliable option to decarbonize Germany's car sector, potentially at economic benefits. My research thus agrees with and supports current vehicle market developments as well as German policy mechanisms such as purchase incentives and regulatory fleet targets which aim at accelerating the substitution of legacy vehicle technology with its electrified counterpart. According to my research there is little to no reason to believe that this short-term electrification effort is mislead. On the contrary I argue that, technologically, there are only few aspects which stand in the way of a clear consensus in science and public about battery electrification being the undisputed passenger vehicle of the future in terms of economic and climate feasibility.

If the cost of charging can be kept at reasonably low levels and if the looming efficiency gains for battery production can be achieved as envisaged, BEV should be able to lift today's remaining doubts and concerns regarding the electrification of passenger vehicles.

Mobility transition

Transport transition is the product of mobility transition and energy transition of transport. It is the overarching policy framework, in which the quest for the "best" passenger vehicle technology is embedded.

While my research focused on vehicle technologies and their economic and climate feasibility, it uncovered that there are strong inter-dependencies between the technological aspects (i.e., energy transition of transport) and the social, behavioral aspects (i.e., mobility transition). I argue that, while I was able to show that all vehicle technology options are affected by the uncertainty levels of the mobility transition (niche innovations, regime trajectories, landscape developments), a potential future shift in societal and behavioral patterns might benefit the electric power train more than it would benefit a legacy powertrain. Past requirements for a vehicle (fast refueling, high driving ranges above 500 km) might not translate straight into the future as mobility consumption patterns are increasingly influenced by sharing and automation concepts, both made possible through advancing digitization of vehicles and their infrastructure. A resulting shift away from purchasing long-term car ownership to purchasing temporary mobility services can distribute vehicle availability requirements over entire fleets and thus devalue the (past) importance of any individual vehicle's performance. I characterized this and other possibilities as a conceptual uncertainty, meaning it has the potential to redefine the vehicle decision problem on a fundamental level.

While I do not believe this to put my conclusions at risk I argue that the vehicle problem stands is less and less a silo problem but should be increasingly analyzed within the dynamics of the mobility transition. Arguing against battery electric vehicle technology purely based on its current driving ranges, for instance, is short-sighted in that regard and compares apples with pears from the larger perspective of transport transition as a whole.

Technology openness

While my research suggest battery electrification as a clear and reliable contender for future passenger vehicles, I argue on the same results that the technology openness paradigm in Germany should be maintained to avoid the trap of overconfidence and to stay adaptive to unforeseeable developments "outside of the vehicle".

Yet I stress that in practice this *must not* translate into a wait-and-see-strategy, which is how both proponents and opponents of technology openness readily misconstrue the term for their own side of the argument. Instead, technology openness must stand for a strategy of deliberate and parallel advancement of all technology options. While this comes at a higher upfront cost, it increases the long-term resilience of transport's sustainable transition and helps avoid any momentous short-sighted lock-in decisions. For instance, my robustness analysis showed that while hybridization incorporates all vulnerabilities associated with both the electric and combustion engine powertrain, it helps to hedge against any one of the individual risks.

Ultimately even though BEVs are on the rise, all options might still be needed in the short- and mid-term, simply if supply of a single technology, however superior, does not upscale quickly enough to meet what climate mitigation targets demand.

6.3 Outlook

At the end of the day alternative vehicle technologies are a means to the end of leveraging renewable energy technologies' potential to decarbonize the entire energy-mobility nexus - no more, no less. In this regard, battery electrification but also renewable hydrogen and alternative hydrocarbon fuels can be a self-fulfilling prophecy as scaling up means improving economic and climate feasibility.

However, according to Warren Buffet successful investment strategies are "simple but not easy" [273]. If this has any implication for the sustainable transition of transport, BEVs are a considerable option for a sustainable transition of transport, based on the comparative technological simplicity of their drive train and their need for additional infrastructure development. I believe my research, along with recent market developments, confirm this for passenger vehicles. Today other major vehicle segments such as heavy duty trucks and buses find themselves at the same technological crossroads passenger cars were at only a few years ago. Whether battery electrification will begin to similarly penetrate those more demanding vehicle sectors will be seen in the coming years.

My research has contributed a comprehensive analysis and discussion of major uncertainties und vulnerabilities regarding the decarbonization of passenger vehicles in Germany. This is of paramount importance in the current times of disagreement and uncertainty as it allows to focus on robust aspects and separate the relevant arguments of the debate on vehicle technology from the negligible ones. Better background knowledge of what is uncertain improves plausibility of future analysis and empowers thorough sensitivity analysis. My work provides future transport analysts with a foundation for their models and assumptions. Thus, my work can serve as a reference for better understanding, framing and modeling the road transport problem and its uncertainties.

And yet, as my research is a contemporary piece of evidence in a fast-paced and complex transition of Germany's transport sector, the methods I proposed should be reapplied in the future and the uncertainty list updated and consolidated so that the robust parts of our knowledge on decarbonizing passenger vehicles in Germany may keep on growing.

Appendix A

Argument mapping

Table A.1: *Argument mapping scope of expertise*

Institution	
	Agora Verkehrswende
	Berliner Verkehrsgesellschaft (BVG)
	EMPA - Material Science and Technology
	International Council on Clean Transportation (ICCT)
	Mercator Research Institute on Global Commons and Climate Change (MCC)
	M-Five
	National Organisation Hydrogen and Fuel Cell Technology (NOW)
	Öko-Institut
	Research Institute for Topics of Continuing Vocational Education and Training in Companies (IBBF)

Continued on next page

Table A.1 – *Continued from previous page*

	Technische Universität Berlin (TUB)
	University Trier
	Wissenschaftszentrum Berlin (WZB)
Position	
	Deputy head of division
	Director and project manager
	Head of department
	Head of department
	Head of working group
	Managing director
	Professor emeritus
	Program manager
	Project manager
	Research fellow
	Scientific consultant
	Senior associate
	Sustainability delegate

Continued on next page

Table A.1 – *Continued from previous page*

Expertise	
	Applied geography, spatial development and regional planning
	Electric mobility and autonomous driving
	Freight transport
	Infrastructure, mobility system monitoring
	Land use, infrastructure and transport
	Mobility transition educational programs
	Mobility, futures, innovation, economics
	Power engines (formerly: internal combustion engine technology)
	Product development and mechatronics
	Resources and transport
	Road, marine, and air transportation
	Science policy studies
	Technology and society

Appendix B

Model and Monte Carlo simulation parameters

Table B.1: *Reference values for passenger cars [21]*

technology	model	curb weight (kg)	price (EUR)	other
BEV	Ford Focus Electric (2018)	1,630	34,900	23 kWh (C_{batt})
	Hyundai IONIQ Elektro Trend (2016)	1,495	33,300	28 kWh (C_{batt})
	VW e-Golf 7 (2017)	1,615	31,900	35.8 kWh (C_{batt})
	Hyundai Kona	1,760	34,400	64 kWh (C_{batt})
	Renault Z.E. 50 (2019)	1,577	32,990	52 kWh (C_{batt})
	average	**1,615**	**33,498**	40.6 kWh (C_{batt})
FCEV	Toyota Mirai (2015)	1,860	78,540	1.6 kWh (C_{batt}), 114 kW (P_{fc})
	Hyundai Nexo (2018)	1,889	69,000	1.6 kWh (C_{batt}), 120 kW (P_{fc})
	average	**1,875**	**73,770**	**1.6 kWh (C_{batt}), 117 kW (P_{fc})**
PHEV	Audi A3 Sportback e-tron (2016)	1,615	39,400	11.4 kWh (C_{batt})
	Hyundai IONIQ PlugIn-Hybrid (2019)	1,570	32,900	8.9 kWh (C_{batt})
	Ford Kuga 3 PHEV (2019)	1773	39,300	14.4 kWh (C_{batt})
	average	**1,653**	**37,200**	**11,6 kWh (C_{batt})**
ICEV	Ford Focus (2018)	1,386	18,700	
	VW Golf 7 (2017)	1,206	18,075	
	Kuga 3 (2019)	1,493	31,900	
	Hyundai 30 1.4 T-GDI DCT (2018)	1315	24,550	
	Renault Clio 5 (2019)	1,137	12,990	
	Audi A3 Sportback (2017)	1,315	31,200	
	average	**1309**	**22,888**	

Table B.2: *Vehicle model parameters, based on [26, 27] and average vehicle values of table B.1*

	BEV	FCEV	PHEV	ICEV
curb weight (kg)	1615.00	1875.00	1653.00	1309.00
vehicle price (EUR)	33498.00	73770.00	37200.00	22888.00
battery capacity (kWh)	40.60	1.60	11.60	
fuel_cell_power (kW)		117.00		
battery price (EUR/kWh)	175.00	175.00	175.00	
fuel cell price (EUR/kW)		250.00		
higher heating value hyrdogen (kWh/kg)		33.30		
higher heating value synfuel (kWh/L)			11.60	11.60
mass of vehicle's fixed parts X_1 (kg)	35.25	35.25	42.39	58.76
LCE of vehicle's fixed parts X_2 (g CO_2-eq.)	1140.00	1124.00	1656.00	1716.00
electric energy for producing fixed parts X_3 (kWh)	1141.00	1074.00	1174.00	1120.00
LCE for vehicle's scaling parts X_4 (g CO_2-eq./kg)	2.40	2.41	2.41	2.40
el. energy of vehicle's scaling parts production X_5 (kWh/kg)	2.41	2.43	2.38	2.25
weight to LIB capacity ratio X_9 (kg/kWh)	7.52		7.52	
fixed carbon intensity of LIB production X_{10} (g CO_2-eq./kWh)	24.50		24.50	
weight to fuel cell power ratio X_{12} (kg/kW)		5.00		
fixed carbon intensity of fuel cell productionX_{13} (g CO_2-eq./kW)		56.48		
el. energy of fuel cell production X_{14} (kWh/kW)		40.89		

Table B.3: *Range of possible states of the world for Monte Carlo simulation*

	min	max
wtt_efficiency BEV (%)	65.00	90.00
wtt_efficiency FCEV (%)	35.00	60.00
wtt_efficiency ICEV (%)	50.00	80.00
carbon_intensity_FCE (g CO2-eq./kWh)	0.00	500.00
carbon_intensity_VCE (g CO2-eq./kWh)	0.00	500.00
charge_depeting_mode (%)	30.00	90.00
carbon_intensity_BCE (g CO2-eq./kWh)	0.00	1000.00
lifetime (a)	8.00	15.00
annual_distance (km/a)	40000.00	40000.00
hydrogen_fuel_price (EUR/kg)	2.00	10.00
electric_power_fuel_price (EUR/kWh)	0.05	0.50
synthetic_fuel_price (EUR/L)	0.50	3.00
discount_rate (%/a)	1.50	3.00
battery_price (EUR/kWh)	65.00	175.00
fuel_cell_price (EUR/kW)	25.00	250.00
fuel_economy BEV (kWh/100 km)	12.00	25.00
fuel_economy FCEV (kg/100 km)	0.75	1.20
fuel_economy ICEV (L/100 km)	3.00	10.00
battery_cap FCEV (kWh)	1.00	3.00
battery_cap BEV (kWh)	10.00	100.00
battery_cap PHEV (kWh)	10.00	30.00
fuel_cell_power (kW)	80.00	130.00
maintenance_cost BEV (EUR/km)	0.02	0.10
maintenance_cost FCEV (EUR/km)	0.02	0.10
maintenance_cost PHEV (EUR/km)	0.03	0.07
maintenance_cost ICEV (EUR/km)	0.03	0.08
energy_intensity_BCE (kWh/kWh)	10.00	500.00

Appendix C

Uncertainty quantifications

Table C.1: *Quantification of parameter uncertainties, BEV*

Well-to-tank-efficiency

transmission: 95% , charging: 90% [46, 274]

Total one-way losses in a grid-integrated vehicle system (incl. building circuits, power feed components and electric vehicle) can range up to 36% [195].

power generation and storage: 95%, transmission charging: 89% [252]

Current charging losses average at around 15% [275].

Charging losses expected to decrease dramatically down to 10% in the future [49].

Fuel consumption (midsize car)

11.7 ... 20.6 kWh/100 km [55]

18 ... 26 kWh/100 km [252]

0.64 MJ/km (in 2050) [253]

12.8 ... 22.7 kWh/100 km (urban ... highway) [49]

Continued on next page

Table C.1 – *Continued from previous page*

14 ... 23 kWh/ 10 km [35]

Survey over 1074 electric vehicle drivers on their average electricity demand: 16,6 kWh/ 100 km [254]

Vehicle lifetime

Cyclic battery lifetime is not a limiting factor: Latest Tesla capacity and driving distance data shows that on average Model S battery degradation would allow for more than 500,000 km driven before the state of charge reaches 80 % (first-life threshold) [156].

Most BEV manufacturers provide battery warranties for less than ten years which leaves uncertainty as to how much the practical lifetime of the vehicle is determined by the calendric lifetime of the battery [157].

It can not be assumed that traction batteries will definitely outlast vehicle life. A universally valid assumptions about battery lifetime do not exist as battery ageing over all BEV models stronly depends on user behavior, battery temperature during operation, number and character of charging cycles, charging behavior and technology. [35]

Annual distance driven

maximum frequency at around 10,000 km (gasoline) and 20,000 (diesel) for both cars and light duty vehicles [253]

Technology specific parameters

Battery capacities of electric vehicle currently on the market range from 10 to 100 kWh [49, 50].

Battery pack price

Tesla aims to be at $100 per kWh by the end of last year [276]. Tesla has produced some 500,000 model 3 by the end of 2019. [277].

Audi says it is buying batteries at $114 per kWh for its upcoming e-tron quattro. [276]

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Table C.1 – *Continued from previous page*

The average battery pack fell 85% from 2010 to 2018, averaging at $176/kWh (cell price 127 $/kWh) [278].

Learning rate for battery pack price is at 18% [24, 278] .

Price expectations of an average battery pack are around $94/kWh by 2024 and $62/kWh by 2030 [278].

Battery pack prices are expected to fall well below 100 €/kWh between 2020 and 2030 [22, 24].

At 10 million German BEV in 2030 2018's average battery pack price of some 180 €/kWh could be further reduced to 75 €/kWh in 2030 and 65 €/kWh long term [279].

The sensitivity of battery pack prices to commodity prices seems largely overrated. According to Bloomberg NEF doubling price of lithium, cobalt or nickel would increase overall battery pack price of a nickel-manganese-cobalt (NMC) 811 battery less than 6%, 3% and 5% respectively [278].

Hyundai Motor Co. estimates electric vehicle battery prices will level off by 2020 due to supply constraints of key ingredients [280].

Tesla expects global shortages of nickel, copper and other electric-vehicle battery minerals in the near future due to underinvestment in the mining sector [281].

currently 130 bis 170 Euro/kWh, after 2025 (depending on R&D success of cell chemistry) under 100 ... 150 Euro/kWh [35]

Scaling up production lets Volkswagen reduce cost of its LIB cells for its VW ID.3 to under 100 USD [282].

Fuel price

Expert expectations about wholesale electricity price development in Germany are largely pessimistic: over 70% expect strong price increases, less than 10% expect the opposite [153].

Long term average electricity price projections range from 100 €/MWh (industry) to 180 €/MWh (services in 2035) [283].

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Table C.1 – *Continued from previous page*

	EPEX spot market projection: 40 €/MWh in 2020, 60 €/MWh in 2030 [284]
	Long-term retail electricity price could stay at around 5 €-Ct/kWh for energy intensive industry [285].
	Wholesale market price projections: 30 €/MWh (2020), 70 to 80 €/MWh (2030), 90 to 100 €/MWh (2040 to 2050) [154]
	Fast charging and other additional utility services might increase charging prices far above standard utility prices [248, 249].
	According to a 2019 price review of all German charging tariffs average charging prices range between 23 and 32 €-Ct/kWh but can be as high as 0.60 or even 1.60 €/kWh [286].
	More than half of analysed charging services cost significantly more than normal household utility price, with prices of up to 55 €-Ct/kWh [287].
Maintenance cost	
	2.3 ... 6.2 €-Ct/km [253]
	3.3 ... 4.9 €-Ct/km (VW e-Golf @30,000 ... @10,000 km/a [21]
	8.8 ... 10.4 €-Ct/km (Tesla Model 3 @30,000 ... @10,000 km/a [21]
	4.6 ... 5.9 €-Ct/km (Nissan Leaf @30,000 ... @10,000 km/a [21]
	Cost for maintenance and repair of an electric vehicle are some 30% lower those of an equivalent ICEV [288]. Long term this number is expected to increase to 60% [289]
Carbon intensity of power	
	Vehicle, fuel cell and fuel production in Germany: 474 g CO_2-eq./kWh [290]
	Battery production globally: 1106 g CO_2-eq./kWh (China, 26% market share), 745 g CO_2-eq./kWh (China, 24% market share), 663 g CO_2-eq./kWh (USA, 33% market share), 634 g CO_2-eq./kWh (Korea, 12% market share) [291]

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Table C.1 – *Continued from previous page*

Energy consumption of LIB pack production

Top-down-allocation using (mostly secondary) industry data, including the energy use of the entire factory. This leads to comparatively high energy uses 91 – 294 kWh/kWh. [49]

Bottom-up-allocation with detailed energy accounting for every single process step, generally leading to an overall underestimation of the total productions energy use as low as 0.28 kWh/kWh [49]

Newer life cycle assessments based on study-oriented primary data indicate comparatively high energy uses in the range of 147 to 464 kWh/kWh [49]

Past and newer studies about greenhouse gas emissions of cell production and packing show a large discrepancy of numbers. Newer and more detailed studies which take into account high-volume manufacturing differ by a factor of up to 50, indicating large production efficiency potential. [292]

In 2019 the Swedish environmental research institute IVL updated their original 2017 study on lithium-ion vehicle battery production an found significantly lower greenhouse gas emissions of lithium-ion batteries (from 150 - 200 down to 61 - 106 g CO_2-eq./kWh) “mainly due to improved efficiency in cell production” (from 650 MJ/kWh in 2017 down to 216.2 MJ/kWh in 2019) [220, 264]

Table C.2: *Quantification of parameter uncertainties, FCEV*

Well-to-tank-efficiency
transmission: 95% , electrolysis: 70% , compression and distribution: 80% [46, 274]
production and storage: 69%, distribution and supply: 95% [252]
Thyssenkrupp's *Zero-Gap*-electrolyzer demonstrated an efficiency of 82% [293].
Fuel consumption (midsize car)
Toyota rates Mirai's fuel economy at 0.76 kg/100km but real-world tests have shown a considerably higher use of around 1 kg/100km [255]
"A moderate increase in energy efficiency from 53% to 55% (midrange), or 57% (which is optimistic), is expected at the stack level between 2010 and 2030. However, manufacturers are expected to prioritize cost improvements over efficiency in their future development of fuel cell technology." [45]
0.8 ... 1.2 kg/100 km [252]
0.84 kg/ 100 km in 2050 [253]
0.75 kg/100 km [256]
0.75 ... 1 kg /100 km [35]
Vehicle lifetime
U.S. Department of Energy lifetime targets for stationary and transportation fuel cells are 40,000 hours and 5,000 hours, respectively, under realistic operating conditions. A lifetime of some 10 years seems plausibly achievable. [260]
20.000 h were demonstrated in 2018 [35]
Annual distance driven

Continued on next page

Table C.2 – *Continued from previous page*

maximum frequency at around 10,000 km (gasoline) and 20,000 (diesel) for both cars and light duty vehicles [253]

Battery pack price

Tesla aims to be at $100 per kWh by the end of last year [276]. Tesla has produced some 500,000 model 3 by the end of 2019. [277].

Audi says it is buying batteries at $114 per kWh for its upcoming e-tron quattro. [276]

The average battery pack fell 85% from 2010 to 2018, averaging at $176/kWh (cell price 127 $/kWh) [278].

Learning rate for battery pack price is at 18% [24, 278] .

Price expectations of an average battery pack are around $94/kWh by 2024 and $62/kWh by 2030 [278].

Battery pack prices are expected to fall well below 100 €/kWh between 2020 and 2030 [22, 24].

At 10 million German BEV in 2030 2018's average battery pack price of some 180 €/kWh could be further reduced to 75 €/kWh in 2030 and 65 €/kWh long term [279].

The sensitivity of battery pack prices to commodity prices seems largely overrated. According to Bloomberg NEF doubling price of lithium, cobalt or nickel would increase overall battery pack price of a nickel-manganese-cobalt (NMC) 811 battery less than 6%, 3% and 5% respectively [278].

Hyundai Motor Co. estimates electric vehicle battery prices will level off by 2020 due to supply constraints of key ingredients [280].

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currently 130 bis 170 Euro/kWh, after 2025 (depending on R&D success of cell chemistry) under 100 ... 150 Euro/kWh [35]

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Table C.2 – *Continued from previous page*

Scaling up production lets Volkswagen reduce cost of its LIB cells for its VW ID.3 to under 100 USD [282].

Fuel cell price

”The costs of fuel cell systems are also expected to decrease considerably, but cost estimates are highly uncertain.” [45]

225 €/kW for recent fuel cell system at production scale of 1,000 units per year, estimating large price decreases for higher production volumes: 83 and 53 €/kW for production volumes of 10,000 and 100,00 units per year respectively. Official price target is 40 €/kW [294].

At a production volume of 300,000 costs of some 30 €/kW (optimistic) could be achieved [295].

Lowest estimate at 21 €/kW [296].

230 $ /kW at ”low” and 53 $/kW at ”high” production numbers (some 100,000 units) [297]

1034, 1838 and 1700 Toyota Mirai have been sold in the US in 2016, 2017 and 2018 respectively, a tenth of that in Europe [298].

At 3,000 vehicles per year manufacturing cost is estimated to be some $183/kW for the 114 kW Toyota Mirai fuel cell system [299].

Fuel cell system cost estimated to be 200 and 50 $183/kW for 1000 and 100,000 units produced per year, respectively [299].

Fuel price

Experience rates of electrolyzer technology is comparable to that of LIB technology [24], indicating the downward price developments could show the same trajectory if production uptake took place. Accordingly price uncertainty is directly coupled to the uncertainty of the speed of cumulated production of that electrolyzer technology [165].

Including cost of pipeline infrastructure with a probability of 90% hydrogen production costs could lie anywhere between 2.7 and 8.7 €/kg [168]

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Table C.2 – *Continued from previous page*

Hydrogen production cost in 2050 lies between 1.5 and 6.1 €/kg [300].

Maintenance cost

2.7 ... 7.3 €-Ct/km [253]

1.6 (Hyundai Nexo) €-Ct/km @60,000 km/a [21]

Carbon intensity of power

Vehicle, fuel cell and fuel production in Germany: 474 g CO_2-eq./kWh [290]

Battery production globally: 1106 g CO_2-eq./kWh (China, 26% market share), 745 g CO_2-eq./kWh (China, 24% market share), 663 g CO_2-eq./kWh (USA, 33% market share), 634 g CO_2-eq./kWh (Korea, 12% market share) [291]

Energy consumption of LIB pack production

Top-down-allocation using (mostly secondary) industry data, including the energy use of the entire factory. This leads to comparatively high energy uses 91 – 294 kWh/kWh. [49]

Bottom-up-allocation with detailed energy accounting for every single process step, generally leading to an overall underestimation of the total productions energy use as low as 0.28 kWh/kWh [49]

Newer life cycle assessments based on study-oriented primary data indicate comparatively high energy uses in the range of 147 to 464 kWh/kWh [49]

Past and newer studies about greenhouse gas emissions of cell production and packing show a large discrepancy of numbers. Newer and more detailed studies which take into account high-volume manufacturing differ by a factor of up to 50, indicating large production efficiency potential. [292]

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Table C.2 – *Continued from previous page*

	In 2019 the Swedish environmental research institute IVL updated their original 2017 study on lithium-ion vehicle battery production an found significantly lower greenhouse gas emissions of lithium-ion batteries (from 150 - 200 down to 61 - 106 g CO_2-eq./kWh) “mainly due to improved efficiency in cell production” (from 650 MJ/kWh in 2017 down to 216.2 MJ/kWh in 2019) [220, 264]

Table C.3: *Quantification of parameter uncertainties, ICEV*

Well-to-tank-efficiency
transmission: 95%, electrolysis: 70% , PtL: 70%, distribution: 95% [46, 274]
42% and 51% for methane with atmospheric and biogenic carbon, respectively [55]
maximum process chain efficiencies: 57% for methane, 48% for diesel, 35% for gasoline [8, 301]
fuel production and storage: 44%, distribution and supply: 96% [252]
Fuel consumption (midsize car)
0.82 ... 2.84 MJ/km, with fuel demand dropping by up to 60% by 2050 [55]
Research has shown that actual on-road fuel consumption was 24% and 40% higher than official type-approval levels in 2015 and in 2017, respectively [250,251].
5.5 ... 8 L/100 km [252]
4 L/100km in 2050 [253]
survey: diesel and gasoline fuel use at 6.36 and 7.88 L/ 100 km [302]
Vehicle lifetime
In January 2019 some 40% vehicles in Germany had been used for ten years or more, with an average lifetime of 9.5 years [303]
Around 25% of German vehicle kilometers are driven in cars older than ten years [158].
Annual distance driven
maximum frequency at around 10,000 km (gasoline) and 20,000 (diesel) for both cars and light duty vehicles [253]
Fuel price

Continued on next page

Table C.3 – *Continued from previous page*

Production costs via FTS lie between 0.49 (in 2050) and 1.75 €/L (2030). [172]

Production costs range from 1.5, 1.1 and 0.7 to 3.1, 2.6 and 1.8 €/L in 2022, 2030 and 2050 respectively. In 2022 lowest production cost of 1.1 €/L can be achieved in Iceland but only at a limited capacity of 50 TWh [46].

2.8 €/L [252]

Minimum fuel prices at filling stations in 2050, produced with 5 MW and 500 MW at 3 €-Ct/kWh and atmospheric carbon are 2.3 and 1.4 €/kg for methane, 2.1 and 1.1 €/L for diesel as well as 2.7 and 1.4 €/L for gasoline. Those prices can be decreased by using biogenic carbon: 1.5 and 1 €/kg for methane, 1.4 and 0.8 €/L for diesel as well as 1.8 and 0.9 €/L for gasoline [8, 301].

Based on price projections of both electrolyzer and synthezizer as well as renewable power generation a nominal price increase of fuel is to be expected compared to fossil sources. [35])

Maintenance cost

2.8 ... 7.5 €-Ct/km [253]

4.2 ... 5.8 €-Ct/km (VW Golf @30,000 ... @10,000 km/a [21]

5 ... 6.5 €-Ct/km (VW Passat @30,000 ... @10,000 km/a [21]

PHEV: 2.4 ... 6.8 €-Ct/km [253]

Carbon intensity of power

Vehicle, fuel cell and fuel production in Germany: 474 g CO_2-eq./kWh [290]

Battery production globally: 1106 g CO_2-eq./kWh (China, 26% market share), 745 g CO_2-eq./kWh (China, 24% market share), 663 g CO_2-eq./kWh (USA, 33% market share), 634 g CO_2-eq./kWh (Korea, 12% market share) [291]

Appendix D

Correlation coefficients

Table D.1: *Correlation coefficients for BEV,* $\alpha = 0.05$

	TCO	LCE	CAPEX	FCE	OPEX	VCE
CAPEX	0.13	0.13	1.00			0.19
FCE	0.02	0.63		1.00	0.08	
OPEX	0.32	0.05		0.08	1.00	
VCE	0.02	0.57	0.19			1.00
lifetime	-0.19	-0.07				
annual_distance	-0.90	-0.33				
battery_cap_BEV	0.11	0.15	0.88			0.21
battery_price	0.06		0.44			
X11		0.48				0.81
carbon_intensity_VCE		0.08				0.30
carbon_intensity_BCE		0.21		-0.01		0.31
fuel_price	0.21				0.67	
fuel_use	0.09	0.19		0.29	0.27	
OM_price	0.21				0.64	
discount_rate	-0.06				-0.18	
carbon_intensity_FCE		0.59	-0.01	0.93		
wtt_efficiency		-0.09		-0.12		

Table D.2: *Correlation coefficients for FCEV,* $\alpha = 0.05$

	TCO	LCE	CAPEX	FCE	OPEX	VCE
CAPEX	0.15		1.00			0.03
FCE	0.01	0.98		1.00	0.05	
OPEX	0.19	0.04		0.05	1.00	
VCE	0.01	0.10	0.03			1.00
lifetime	-0.20	-0.03				
annual_distance	-0.94	-0.12				
battery_cap_FCEV	0.01		0.01	-0.01		0.04
fuel_cell_power	0.04	0.01	0.25			0.11
battery_price			0.01			
fuel_cell_price	0.14		0.96			
X11		0.01				0.15
carbon_intensity_VCE		0.09				0.97
carbon_intensity_BCE				-0.01		0.09
fuel_price	0.12				0.65	
fuel_use	0.05	0.19		0.19	0.22	
OM_price	0.13				0.67	
discount_rate	-0.04		-0.01		-0.20	
carbon_intensity_FCE		0.93		0.94		
wtt_efficiency		-0.21		-0.21		

Table D.3: *Correlation coefficients for ICEV,* $\alpha = 0.05$

	TCO	LCE	CAPEX	FCE	OPEX	VCE
CAPEX			1.00			
FCE	0.13	1.00		1.00	0.22	
OPEX	0.54	0.22		0.22	1.00	
VCE		0.03				1.00
lifetime	-0.17					
annual_distance	-0.78	-0.03				
carbon_intensity_VCE		0.03				1.00
fuel_price	0.41				0.76	
fuel_use	0.31	0.41		0.41	0.54	
OM_price	0.13			-0.01	0.23	0.01
discount_rate	-0.09				-0.15	
carbon_intensity_FCE		0.87		0.87		
wtt_efficiency		-0.16		-0.16		

Table D.4: *Correlation coefficients for PHEV,* $\alpha = 0.05$

	TCO	LCE	CAPEX	FCE	OPEX	VCE
CAPEX	0.03	0.03	1.00		-0.01	0.09
FCE	0.07	0.95		1.00	0.21	
OPEX	0.31	0.21	-0.01	0.21	1.00	
VCE		0.19	0.09			1.00
lifetime	-0.20	-0.04				
annual_distance	-0.91	-0.16				
battery_cap_PHEV	0.02	0.04	0.73			0.12
battery_price	0.02		0.66			
X11		0.14			-0.01	0.76
carbon_intensity_VCE		0.05			0.01	0.41
carbon_intensity_BCE		0.08			0.01	0.31
fuel_price_phev_el	0.13				0.44	
fuel_price_phev_chem	0.17		-0.01		0.52	
fuel_use	0.02	-0.05		-0.05	0.07	
fuel_use_phev_el	0.06	0.07		0.07	0.18	
fuel_use_phev_chem	0.12	0.27		0.28	0.38	
OM_price	0.09				0.30	
discount_rate	-0.07				-0.21	
carbon_intensity_FCE		0.82		0.87		
wtt_efficiency	-0.03	-0.18		-0.19	-0.09	
charge_depleting_mode	-0.10	-0.29		-0.29	-0.28	

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