TÉCNICO LISBOA

Argument analysis of the debate on the energy transition of the German road transport sector

A visual analysis approach

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“The aim of argument, or of discussion, should not be victory, but progress.”

Joseph Joubert (1754-1824)

Resumo

De forma a fazer face à comummente necessidade de reduzir as emissões gasosas para a atmosfera como forma de limitar o aquecimento global do planeta Terra, a descarbonização do sector rodoviário Germânico prevê-se que seja conseguida através da redução do consumo global de energia e pela integração de tecnologias de baixo carbono para reduzir as emissões de gases de efeito de estufa.

O tema de investigação deste trabalho está diretamente relacionado com a análise destas tecnologias, incluindo veículos elétricos a baterias e veículos elétricos a pilhas de combustível, assim como a utilização de biocombustíveis e combustíveis sintéticos em veículos de combustão interna convencionais. Desta forma, os argumentes relevantes a favor ou contra a utilização de determinada tecnologia são identificados e mapeados de forma a identificar claramente as intercorrelações e as implicações resultantes de cada opção. Um mapeamento exaustivo de argumentos será o principal resultado deste processo permitindo visualizar como os diferentes argumentos identificados se relacionam entre si e em que medida as tecnologias possuem vantagens competitivas entre si.

Finalmente, uma análise de sensibilidade e incerteza é apresentada de forma a identificar as lacunas de conhecimento com impacto no futuro do setor de transporte rodoviário na Alemanha. Neste contexto, esta dissertação tem também como objetivo fornecer uma visão geral sobre os fatores que afetam a preferência por determinada tecnologia e descrever as características respetivas.

O trabalho realizado destina-se a servir de base para a discussão sobre como realizar uma transição energética no transporte rodoviário Germânico, proporcionando um estudo sólido e abrangente sobre as tecnologias disponíveis e mapeando os argumentos de apoio à decisão.

***Palavras-chave**:* transporte; energia; descarbonização; transição; argumentos

Abstract

In view of the commonly recognised need to reduce carbon emissions for limiting global warming, the decarbonization of the German road transport sector is aimed to be achieved through the reduction of its overall energy demand and the integration of low carbon technologies to reduce greenhouse gas emissions.

The object of investigation of this work is an argument analysis on these technologies which include battery electric vehicles, fuel cell electric vehicles as well as biofuels and synthetic fuels for the operation of conventional combustion engine vehicles. By this means, the relevant arguments counting in favour or against the application of a certain technology are identified and mapped to display their intercorrelations and the resulting implications. The argument map is considered the main outcome of this process aiming to visualise how the different identified arguments relate to each other and to which extent technologies hold competitive advantages to one another.

Finally, an uncertainty analysis is performed seeking to highlight knowledge gaps within the debate that impact the future of the German road transport sector. In this context, the goal is to provide an overview on the factors affecting the preference of a technology and to describe their respective characteriztics.

The performed work is intended to serve as a foundation for discussion on how to realise an energy transition of road transport in Germany by providing a sound and comprehensive study on the available technologies and mapping the respective supporting and objecting arguments.

***Keywords*:** transport; energy; decarbonization; transition; arguments

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BEV	Battery Electric Vehicle
CH_4	Methan
CO	Carbon monoxide
CO_2	Carbon dioxide
DLUC	Direct Land Use Change
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse gas emissions
H_2	Hydrogen
i.e.	Id est
ICEV	Internal Combustion Engine Vehicle
ILUC	Indirect Land Use Change
km	Kilometre
LUC	Land Use Change
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-Gas, -Liquid or -Heat
RE	Renewable Energies
TCO	Total Cost of Ownership
WLTP	World Light Vehicle Testing Procedure

1. Introduction

1.1. The German transport transition

With the Paris Agreement of 2015, all nations of the world have agreed on the common goal of limiting global warming to a maximum of 2°C in comparison to the pre-industrial era. Germany, which is among the largest emitters of greenhouse gas (GHG) emissions, has ratified the agreement in October 2016 and thus has, under international law, obligated itself to significantly reduce its GHG emissions (United Nations 2015).

Efforts to reduce Germany´s carbon footprint have already led to a decrease of GHG emissions in most sectors of its economy. Compared to 1990, the agriculture sector, the energy sector, the industry and private households have reduced their GHG emissions by 20%, 24%, 34% and 33%, respectively (2014 values). Only the transport sector has not achieved a reduction of its carbon footprint, but even shows a slight increase of GHG emissions from 163 Mt CO_2-eq. in 1990 to 164 Mt CO_2-eq. in 2014, which is due to higher volumes of traffic and the continuous use of fossil motor fuels for vehicle operation (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2015). Today, the transport sector accounts for around 18% of the total GHG emissions in Germany, with a growing share to be expected in view of decreasing emissions of other sectors (German Federal Environmental Agency (UBA) 2017).

In view of the current role of the German transport sector as a significant contributor to carbon emissions, the need for a sharp decarbonization unfolds. Considering increasing volumes of traffic and the high dependence on fossil fuels at present, both measures towards a reduction of overall energy demand of the sector as well as a decrease of transport-related GHG emissions need to be implemented. This two-fold approach is referred to as the German transport transition, which consists of two pillars, namely a mobility transition and an energy transition of transport, as described in the following.

The term mobility transition incorporates all efforts to reduce the final energy demand of transport without limiting mobility in general. This goal is strived for by means of applying a three-step strategy of consecutively avoiding, shifting and optimizing transport which includes a reduction of individual transport, a more collaborative use of means of transport and a general shift of the modal split. By this means, traffic volumes are intended to be reduced while assuring the fulfilment of all mobility requirements (Agora Verkehrswende 2017). The mobility transition is therefore characterized by a strong focus on changing mobility behaviour of users and consequently entails several political, societal and psychological questions that need to be addressed.

The energy transition of transport as the second pillar of the transport transition refers to a sector-wide decarbonization which entails the requirement of providing the demanded energy solely based on renewable energy sources. A large-scale direct and indirect electrification of transport is deemed to be the most effective approach to achieve such a decarbonization. The prerequisite is a decarbonized power system based on wind and solar as well as the integration of new energy carriers and drive technologies into the transport sector.

Analysing the different arguments that support or object the use of the technology options at disposal is the central aim of this work, which is further explained in chapter 1.3. Prior to that, the various available drive technologies and the respective energy carriers for realising the energy transition of transport are presented in the next chapter in order to provide the technical context for the subsequent argument analysis.

1.2. Decarbonizing the road transport sector

In the following, the different technologies considered for realising the energy transition of transport are briefly introduced with respect to their basic theory of operation and current relevance in the market. Only technologies are investigated that can be completely carbon neutral, which excludes alternatives such as hybrid electric vehicles and natural gas-powered cars, notwithstanding the fact that such technologies could potentially serve as a bridge to complete decarbonization.

Battery electric vehicles

Battery electric vehicles (BEVs) are vehicles that operate on electric energy provided by an on-board battery which feeds an electric motor. Due to the high efficiency of the electric motor of up to 95% and the possibility to recuperate a part of the mechanical energy during the breaking process, BEVs have the highest well-to-wheel-efficiency of all considered technologies (around 70%) (Hacker et al. 2014). *Figure 1* gives an overview of the system and the efficiency of the respective conversion steps.

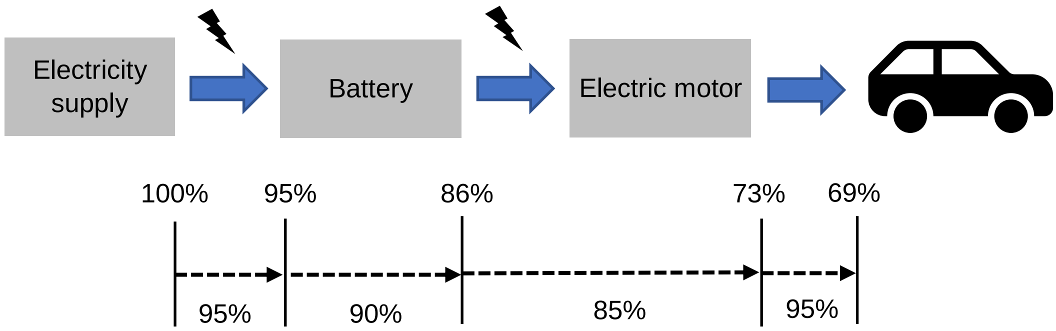


Figure 1: Overview on the components and efficiencies of a BEV system (own creation, data source: Agora Verkehrswende et al. (2018))

The concept of utilizing electric energy for transportation dates back to the 19th century when the first electric vehicles were tested in Berlin and London. It has not been until 1995, however, that the first electric vehicle for road traffic was produced in series (Hose et al. 2015). Yet, an uptake of the numbers of electric vehicles for road traffic has mainly occurred since the beginning of this decade. According to the Centre of Solar Energy and Hydrogen Research Baden Wurttemberg (ZSW), the global electric car stock surpassed 3 million vehicles in 2017 (ZSW 2018). In addition, more than 200 million electric two-wheelers are currently in operation (International Energy Agency (IEA) 2017). Germany has around 92,000 electric vehicles registered, out of which almost 54,000 are non-hybrid

BEVs (ZSW 2018). This translates to a fairly low current market share of only 0.2% (Federal Office of Motor Traffic 2018).

Fuel cell electric vehicles

Fuel cell electric vehicles (FCEVs) differ from BEVs in terms of the electricity supply. While BEVs carry batteries as a power storage facility to provide the motor with electric energy, an FCEV produces the demanded power on-board. Invented already in 1838, the fuel cell inverts the electrolysis and generates a current by transforming hydrogen and oxygen into water. This electricity is then used to operate an electric motor. Compared to BEVs, the system contains an additional step since electricity is utilized to first produce an energy carrier through electrolysis (hydrogen), which then allows the onboard reconversion into electricity (see *Figure 2*). The efficiency of the whole process is between 25-30%, considering losses related to the power transmission, the electrolysis efficiency, the hydrogen compression and transport as well as the efficiency of the electric motor (Agora Verkehrswende et al. 2018).

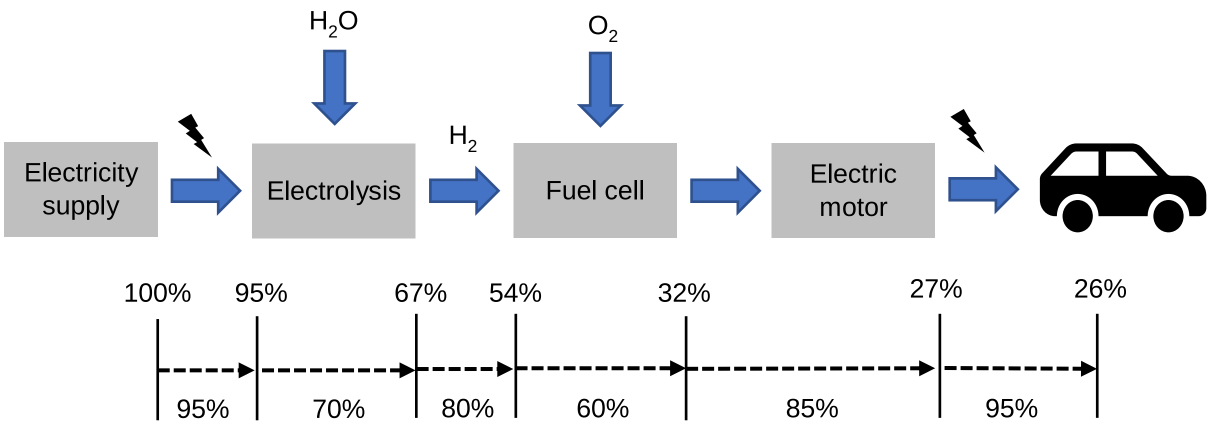


Figure 2: Overview on the process steps and the related efficiencies of a FCEV system (Own creation, data source: Agora Verkehrswende et al. (2018))

As of today, FCEVs remain a niche product with only very few vehicles being commercially available, which is mainly due to the underdeveloped refuelling infrastructure and the comparably high purchase costs. Apart from the use in FCEVs, hydrogen can also serve as the basis for the production of synthetic fuels, as described in the following.

Synthetic fuels

Synthetic fuels are an energy carrier and a potential substitute for the use of fossil motor fuels in road transport. They can occur in two different aggregate states: liquid or gaseous. Liquid synthetic fuels can be produced through methanol synthesis or Fischer-Tropsch-synthesis, which are summarized in the term *power-to-liquid* (PtL). Input elements are hydrogen and CO_2 or CO, which are transformed to synthetic fuels based on hydrocarbons (C_xH_yOH). This raw fuel is then refined and transformed into mechanical energy by the use of a combustion engine (Agora Verkehrswende et al. 2018). As shown in *Figure 3*, the overall efficiency of the process is considerably lower compared to the direct use of electricity in a BEV or the indirect use in an FCEV.

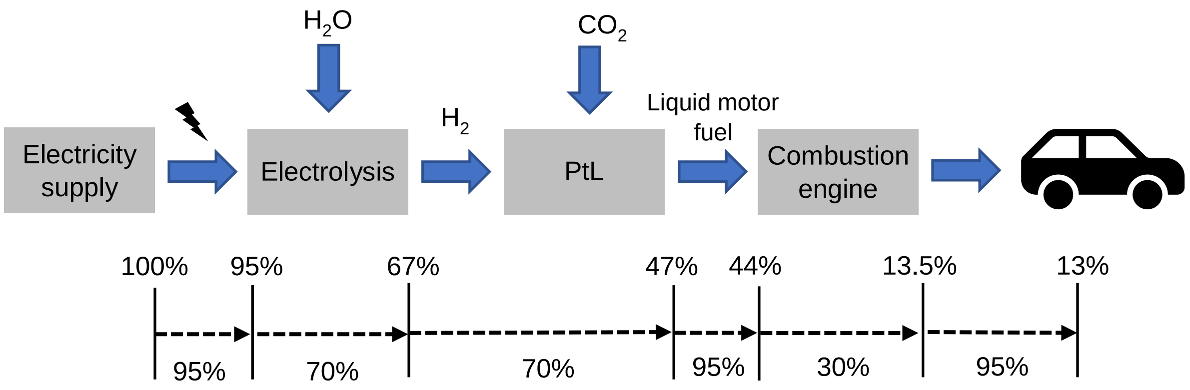


Figure 3: Overview on the process steps and the related efficiencies of a PtL system (own creation, data source: Agora Verkehrswende et al. 2018))

As compared to liquid synthetic fuels, gaseous synthetic fuels mainly refer to synthetic methane and, to a lesser extent, to hydrogen. The process steps of producing synthetic methane (also referred to as *power-to-gas* or *PtG*) are comparable to the PtL-process with regard to input elements. However, the overall efficiency of the PtG-process is marginally higher, as indicated in Figure 4. This is mainly due to the lower losses during the methanation step and the higher efficiency of the energy conversion in the combustion engine (Agora Verkehrswende et al. 2018).

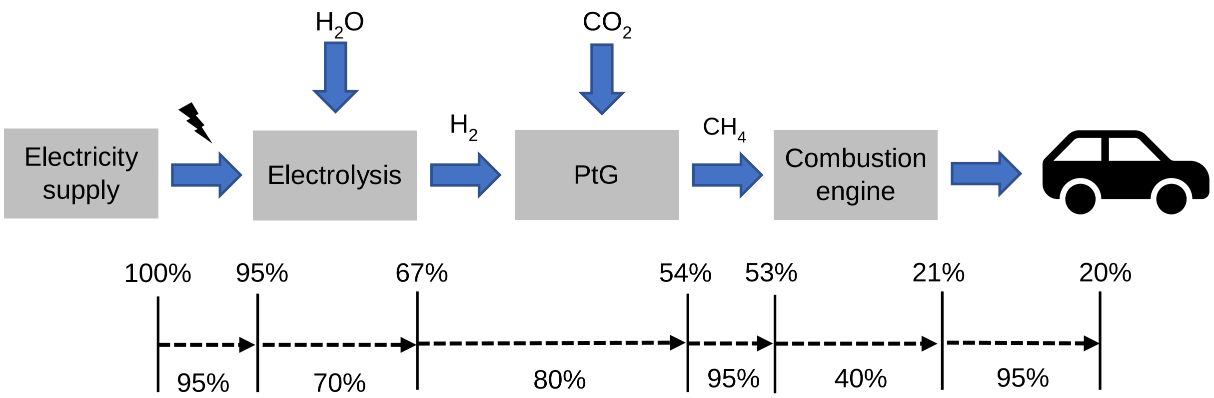


Figure 4: Overview on the process steps and the related efficiencies of a PtG-system (own creation, data source: Agora Verkehrswende et al. 2018))

In the following, the term *synthetic fuels* is used for both the liquid and gaseous form. Synthetic fuels are considered a potential alternative for fossil fuels allowing for a continued but less carbon-intensive operation of internal combustion engine vehicles (ICEVs). Another option for decreasing carbon intensity of ICEV operation are biofuels, as discussed in the following.

Biofuels

Like synthetic fuels, biofuels are an energy carrier that can be used to operate ICEVs. Biofuels are produced on the basis of organic matter and are considered theoretically carbon neutral since they only emit the amount of carbon that has previously been absorbed by the plant (neglecting the energy input needed for ploughing and conversion processes). Organic material for biofuel production can either be provided by cultivated biomass crops or by utilising non-edible organic waste products which are referred to as first and second generation biofuels, respectively (Malins 2017). In addition, the option of cultivating algae for biofuel production is investigated, which is referred to as the third generation of biofuels. In contrast to the other energy carriers presented, the main constraining factor for the use of biofuels is not necessarily the energy efficiency of its production (photosynthesis is energetically a very inefficient process), but rather the land needed for the cultivation of the energy crops (Helms et al. 2011). *Figure 5* displays the main process steps of an ICEV running on biofuels.

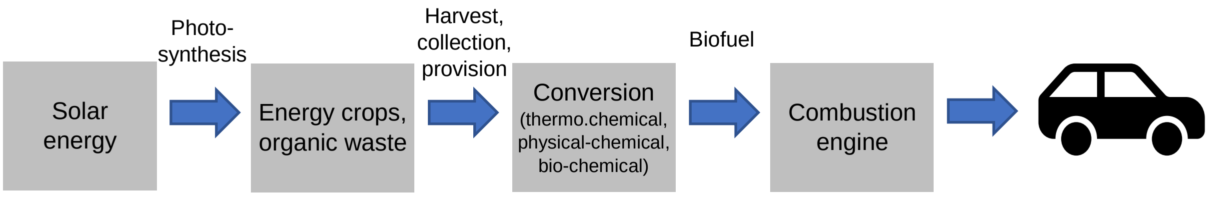


Figure 5: Overview on the process steps of using biofuels for transport from a well-to-wheel perspective (adapted from Thrän (2015))

The described technologies are the object of investigation in the framework of this thesis. In the following chapter, the research question is discussed in more detail, outlining the central goals of analysing the different options for decarbonizing the road transport sector introduced above.

1.3. Research question

As the title indicates, this thesis aims at conducting an argument analysis of the debate on the energy transition of the German road transport sector. In consideration of the different available drive technologies and their respective energy carriers presented in the previous chapter, the central guiding question for this thesis is the following:

Which technologies are necessary for a successful energy transition of road transport in Germany?

The main goal is to perform a detailed and comprehensive analysis of this question and the arguments that are brought forward in favour and against the application of the described technologies without raising the claim of identifying a single winner of the debate. Each considered technology is characterized by distinct benefits and restrictions regarding the technological, economic, ecological and societal feasibility of its integration into the German road transport sector. To identify these and to investigate the mutual implications and contradictions is the central goal of this work.

It is intended to illustrate the complexity of the debate on how to decarbonize road transport by applying a concept originating from the human science field called *argument map*. An argument map visualises and contextualises arguments that impact a given problem or object of interest (Rickels et al. 2011). By applying this tool, a visual approach is taken to address the research question and to display the multiple intercorrelations between the analysed arguments. The argument map is considered the main outcome of this thesis and is expected to:

- display which descriptive and analytical arguments exist for and against the application of the available drive technologies for realising the energy transition of transport,
- show how these arguments affect each other and which intercorrelations they entail and
- provide a neutral foundation for a fact-based discussion on the topic.

Upon completion of the argument analysis, the results are studied in search of inherent uncertainties that characterize the debate with the aim of indicating some answers to the following questions:

- Where do uncertainties occur within the debate?
- How can these uncertainties be categorised regarding their level and nature?
- Which conclusions can be drawn in terms of the future persistence of the identified uncertainties?

The energy transition of the German road transport sector is a highly complex project and represents a classical example for a post-normal science problem, which is characterized by a high uncertainty of facts, different values in dispute and a high urgency to act (Funtowicz, Ravetz 1993). Such a problem asks for a multi-dimensional analysis approach, which is aimed to be undertaken in the framework of this argument analysis.

This work is structured as follows: in chapter 2, the general methodology is outlined explaining the approach taken and introducing the argument analysis and uncertainty analysis tools. Chapter 3 presents the general structure of the argument map is presented considering its evolvement over time and the underlying concept of arrangement. The main part of this chapter consists of the presentation of the developed argument map. In accordance with the map´s structure, this part is organised in chapters reflecting the different argument clusters of the map. In chapter 4, the uncertainty analysis, which is performed to identify and characterize uncertainties within the debate, is described. Next, the results obtained from both the argument analysis and the uncertainty analysis are discussed in chapter 5 with the aim of highlighting the main findings from this work. Finally, the main conclusions are summarized and a future outlook is provided in chapter 6.

2. Methodology

2.1. General approach

As described above, the goal of this thesis is to conduct an argument analysis on the debate around different technologies for realising a decarbonization of the German road transport sector. The general methodology applied to perform this thesis consists of three main steps, namely the information acquisition, the development of the argument map and the analysis of uncertainties characterizing the debate. With respect to the time frame and the argument map development process, these milestones are addressed partly in a chronological order. However, they are also characterized by a high degree of interdependence. *Figure 6* depicts the outline of the methodology to be followed in the framework of this thesis with the three main work fields highlighted in green, blue and grey, respectively. An explanation of the three main work steps is given in the chapters below.

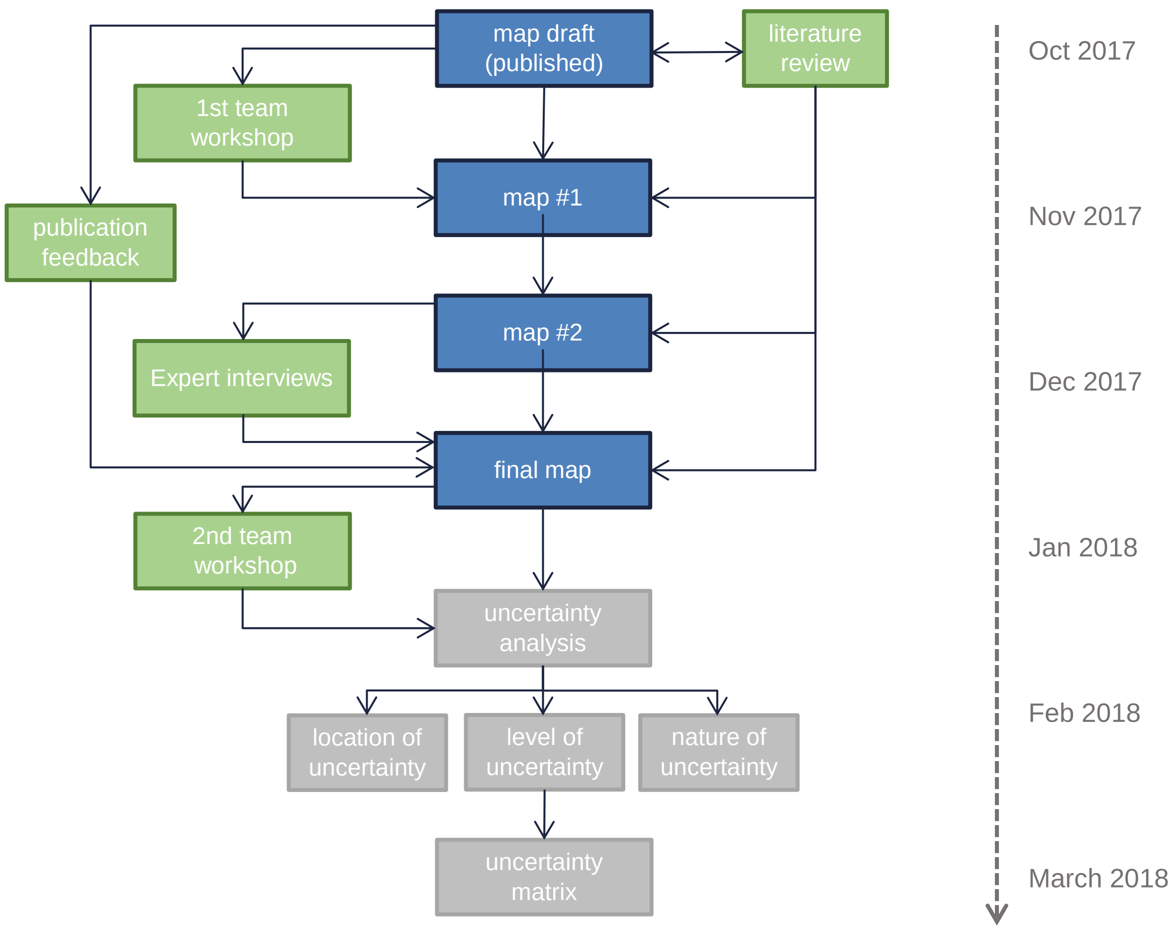
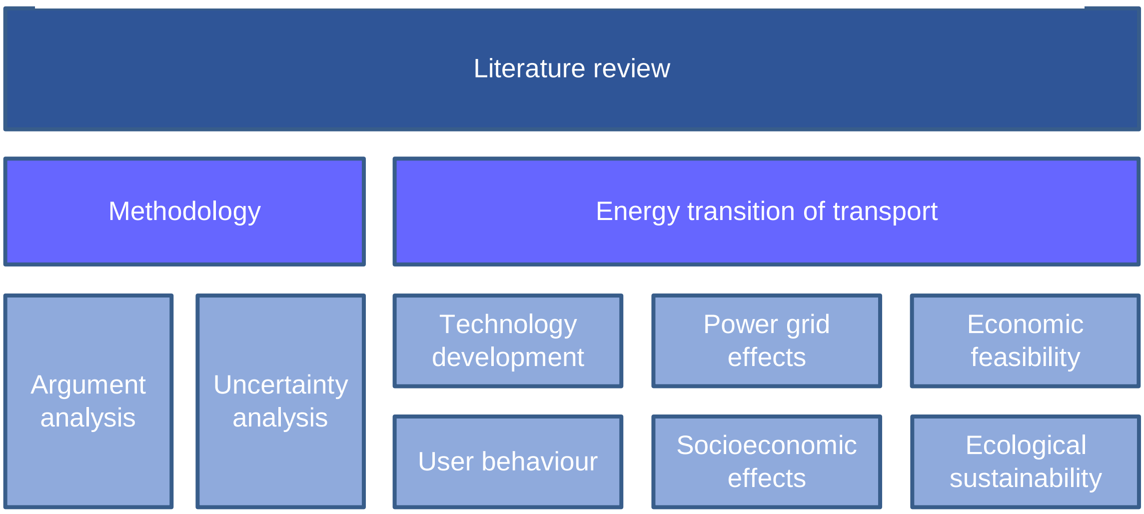


Figure 6: Overview on the general methodology displaying the three main steps information acquisition (green), argument map development (blue) and uncertainty analysis (grey) (own creation)

2.1.1. Acquisition of information (step 1)

This master thesis is grounded on a first draft of an argument map on the debate of battery electric vs. hydrogen powered vehicles, which was published by Reiner Lemoine Institut in October 2017 (Arnhold et al. 2017; Wantischke et al. 2018). Based on this work, the research question is modified and further arguments are analysed with the aim of developing a holistic and coherent representation of the debate on the energy transition of transport. The first step to pursue this goal is an extensive literature review of the scientific state of knowledge regarding the different dimensions that need to be considered. This process can be grouped into two main fields of interest: first, literature on the applied tools, namely the argument analysis and uncertainty analysis and, second, literature on the topic of decarbonizing the German road transport sector, considering all aspects relevant for a complete documentation of the arguments characterizing the debate. These aspects include research fields such as power grid effects, user behaviour, resource availability, technological development, economic feasibility, socioeconomic effects and ecological compatibility, which are extended with new fields of interests identified along the way. *Figure 7* visualises this approach.

Figure 7: Structure of literature review visualising the main research areas (own creation)



Regarding sources of information, a wide range of literature is consulted which includes scientific journals, library catalogues and subject specific websites as well as the study of topic-related and publicly available news feeds, newsletters and expert opinions. The latter is of relevance due to the high public and political interest in electric mobility and in the feasibility of the respective technologies. Thus, a strong focus is also set on the medial perception of the discussion. The process of reviewing relevant literature on the second literature field (see *Figure 7*) goes in hand with the second main work field, the development of the argument map. Therefore, both represent a continuous and conditional work process that is performed over the whole course of the thesis´ time frame instead of solely an initial familiarisation with the relevant background information.

As depicted in *Figure 6*, expert interviews as well as two internal RLI team workshops are conducted to obtain direct information of actors involved with the relevant fields of interest. In addition, external feedback on the published version of the argument map is collected in order to identify new, previously neglected dimensions of the debate. It is recognised that the direct acquisition of information may result in a certain degree of subjectivity of the obtained results. Therefore, the obtained information is subject to a thorough revision with the help of scientific resources. Interviews and workshops are thus intended to serve as a method for collecting indicators for further research rather than delivering arguments that are directly incorporated. A list of the institutions consulted in this context can be found in appendix C.1.

2.1.2. Argument map development (step 2)

Based on the literature review and the direct information acquisition through workshops, interviews and feedback on the published draft, the map is continuously modified and extended. Starting from the already existing draft of the map, different versions of the map are chronologically developed, each representing a specific stage in the overall process of the argument analysis. After completion of one version, it undergoes an analysis cycle concerning the integrity of the arguments considered: First, it is presented and discussed within the project team with the aim of identifying gaps, both regarding the contents as well as the logical structure of the map. The gaps identified are then the basis of further research, which consequently leads to the development of a new version of the map. This cycle is repeated various times until the final version of the argument map is considered to cover a sufficient amount of aspects of the debate.

As discussed in the previous chapter, the argument map development and the information acquisition are a combined and interlinked work process with continuous feedback loops. Therefore, the different map versions can be considered a documentation of the results obtained in the previous literature review and, in turn, the basis for detecting further research needs.

For the development of the argument map the software Argunet 2.0 is utilized. Argunet 2.0 is an editor that allows for the visualisation of complex debates by providing the user with a tool to reconstruct “a logically valid premise-conclusion structure” (Schneider et al. 2013). It enables the analyst to draw relations between arguments and to display their logical structure while at the same time maintaining a high degree of clarity. The final formatting of the argument map is conducted with the software yEd Graph Editor (yWorks GmbH 2018).

2.1.3. Evaluation and uncertainty analysis (step 3)

Once the final version of the argument map is completed, the obtained results are evaluated. In this step, the map is analysed with respect to uncertainties inherent to analysed arguments which represents an important step in the process, since it allows for an identification of knowledge gaps that need to be addressed in the future to provide the necessary information for a decision-making process. The uncertainty analysis attempts to answer questions such as where uncertainties become visible in the debate (location of uncertainty), what their degree of uncertainty is (level of uncertainty) and why they exist (nature of uncertainty) (Walker et al. 2003). The goal is to create an uncertainty matrix, in which these characteriztics are displayed for relevant arguments in the debate. A more detailed explanation of this matrix is given in chapter 2.3.

2.2. Argument analysis

The argument analysis method is a tool for structuring thoughts and supporting decision-making which is commonly used in the field of humanities, particularly in philosophical research (Hirsch Hadorn, Hansson 2016). According to Brun and Betz (2016), “argument analysis seeks to determine which claims are justified or criticized by a given argumentation, how strong an argument is, on which implicit assumptions it rests, how it relates to other arguments in a controversy, and which standpoints one can reasonably adopt in view of a given state of debate.” Argument analysis consists of two central steps; argument reconstruction and argument mapping, as will be described in more detail in the following chapters.

2.2.1. Motivation and goals

In light of the complexity that characterizes many controversial topics of interest and the related discussions, structuring of the arguments put forward is essential to allow for a better understanding of the different positions. This is particularly important when uncertainties are involved, various outcomes are to be considered and a variety of values are at stake (Brun, Betz 2016). Arguing for a specific course usually involves assumptions, premises and given parameters that certain conclusions are drawn from. The coherence of these thought structures, however, is not always intuitively understandable, be it due to the inherent complexity of the argument or the way it is communicated. A thorough and systematic analysis of an argument chain can help to assure the validity of the argument and detect potential inconsistencies (Bayer 1999).

An argument analysis aims for three central outcomes, namely (Brun, Betz 2016):

- a better reflection of the line of arguments within a debate through the consideration of the aforementioned goals of reconstructing arguments explicitly, precisely and transparently. Thereby, the general confirmability of arguments is improved.
- an identification of needs to revise a certain position, which is achieved by the addition or elimination of premises and (sub-)conclusions.
- a detection of tendencies within a debate regarding the overall conclusion that can be drawn from it, such as the lining or disarming of positions and the support of achieving a consensus.

Argument analysis therefore intends to structure complex, multi-layer debates by investigating the relevance of the inherent premises, identifying potential gaps in the argumentation and determining the contribution of the analysed arguments to the pursuit of solving a certain decision problem (such as the challenge of decarbonizing the German transport sector).

2.2.2. Argument reconstruction

Argument reconstruction represents the first step in any argument analysis. It refers to the practice of identifying arguments within a debate and describing their core statements in the clearest way possible. An argument per 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 (Skyrms 2000). Since this composition of statements is usually not clearly identifiable within a given text or debate, a reconstruction of the arguments is required. Based on this restructuring, an evaluation of the arguments can be performed with the use of certain evaluation criteria (see appendix B.2). Rather than representing a chronological order, the reconstruction and evaluation of arguments can be considered a process of “trial-and-error”. The foremost goal in this process is to achieve a high degree of explicitness, precision and transparency in the formulation of the arguments, reducing the risk of ambiguity in a statement. In the following, these three aspects are briefly introduced (Brun, Betz 2016):

- *Explicitness:* Premises and conclusions are extracted from written sentences and are respectively rephrased into statements that represent one (or more) comprehensible sentence(s).
- *Precision:* The goal of precision refers to the need of eliminating vagueness and ambiguity as far as possible by reformulating respective premises or conclusions. In this context, the principles of accuracy and charity are applied, with the latter referring to the practice of interpreting arguments consistently with what the author intended in case of potential inconsistencies within the line of argument.
- *Transparency:* Through abbreviation, simplicity and uniformity, arguments are intended to gain a high degree of clarity, which allows for a quick recognition of the meaning of each sentence.

These three dimensions of reconstructing an argument imply that this process entails a certain interpretative characteriztic due to the rephrasing of the original sentence(s). Therefore, not only one correct way to reconstruct an argument exists, but rather a variety of possible solutions. In order to ensure the results of an argument reconstruction to be as close to the objective of the author, the principle of charity is applied, which suggests to rephrase arguments “as strong and convincing as possible” (Rickels et al. 2011).

2.2.3. Argument mapping

Argument mapping provides a way to visualise a complex debate once the relevant arguments have been identified and their relations analysed. Apart from displaying the arguments themselves, an argument map also depicts how they correlate with each other by connecting arguments with arrows *supporting* (usually indicated by a green colour) or *attacking* (usually indicated by a red colour) another statement (Rickels et al. 2011). *Figure 8* provides a simple and abstract example of an argument map.

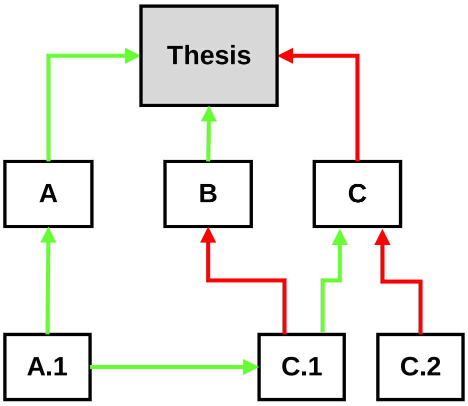


Figure 8: Example of a simple argument map (own creation)

As seen in *Figure 8*, arguments are displayed in a hierarchic order. Here, the thesis is supported by arguments A and B and attacked by argument C. In turn, A is supported by A.1 while C.1 attacks B and supports C. By means of such a map, relations between arguments can be displayed visually.

It is important to note that argument maps are not intended to provide a single decision recommendation or even solution for a certain problem or discussion. On the contrary, the neutrality of the whole argument analysis is of major importance in order to allow for different evaluations. Thus, an argument map mainly aims at visualising a debate as complete and dialectically coherent as possible without biasing the reader´s perception.

In the following, the main goals of mapping arguments are summarized, indicating how it can help to structure and facilitate complex debates (Brun, Betz 2016):

- Argument maps can enable proponents of a debate to arrive at well-considered and reflected positions after considering all relevant descriptive and normative premises of their respective arguments.
- In case of conflicting positions and interests, argument maps can provide a common foundation for a discussion by providing descriptive premises which are held true by all proponents. Based on this initial consensus, it can then help to identify the key (normative) premises or empirical assumptions that need to be agreed upon in order to come to a consensus.
- In the field of policy development, argument maps can be used to design policy measures that are aligned with many different, potentially colliding interests.

2.3. Uncertainty analysis

According to Walker et al. (2003), uncertainty refers to “any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system”. From this definition, it can be concluded that no system can ever be completely and universally understood. Hence, some aspects always remain uncertain, which entails the need to highlight them as such and to draw a clear line as possible between the known and the unknown.

In view of this realization, the future development of the road transport sector in Germany involves diverse uncertainties. Various challenges such as an increasing demand, the need to reduce emissions or the limited availability of resources ask for solutions which are often characterized by uncertainties, such as:

- Will behaviour change be possible on a large scale?
- What is the net greenhouse effect of autonomous driving technology?
- Can research on new materials for batteries solve potential shortages?

These are examples for uncertainties that accompany the discussion of potential solutions for transport-related challenges. It is necessary to identify and analyse such uncertainties in order to indicate where knowledge gaps exist and how further research could potentially close them. By performing an uncertainty analysis, the developed argument map is scanned for uncertainty indicators, such as contradicting research statements, inconsistent argument chains and uncertainties directly expressed within an argument. After identification, these uncertainties are then labelled with respect to three different dimensions: location, level and nature of uncertainties (Kwakkel et al. 2010).

The **location of uncertainty** describes where an uncertain aspect manifests itself in a model or analysis framework. It refers either to the framing, concept or parameters of the problem description of the model. *Table 1* displays the different possible locations of uncertainty based on Walker et al. (2003) and modified by Kwakkel et al. (2010):

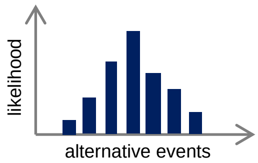
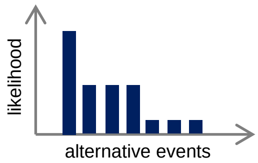
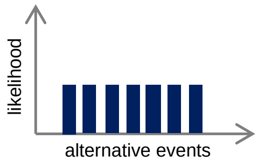
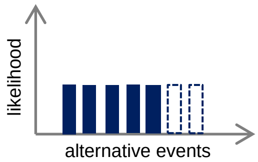
Table 1: Location of uncertainties (adapted from Kwakkel et al. (2010))

Location	Definition
System boundary	Uncertainties due to framing of the problem which lead to the inclusion of certain aspects of the real world and the exclusion of others. It refers to the economic, environmental, political, social and technological context of the analysed topic.
Conceptual model	Uncertainties referring to cause-effect-relations within the system
Computer model	Uncertainties referring to the structure of the computer implementation of the conceptual model. These can be subdivided into the model structure and model parameters (including parameters inside the model and input parameters to the model)
Input data	Uncertainties stemming from quality deficiency of the data considered, i.e. the definition of the parameter values inside the model
Model implementation	Uncertainties arising from the translation of the model into a computer code, e.g. bugs and errors
Processed output data	Accumulated uncertainties from previous stages

According to Kwakkel et al. (2010), four **levels of uncertainty** can be defined, namely shallow uncertainty (level 1), medium uncertainty (level 2), deep uncertainty (level 3) and recognised ignorance (level 4). This scale of uncertainty levels refers to differences in the likelihood assigned to things or events and relates to a scale of measurements.

In *Table 2*, the different levels of uncertainty and the respective measurement categories are listed and described.

Table 2: Levels of uncertainty and the related likelihood of things/events (adapted from Kwakkel et al. (2010) and Wanitschke (2018))

Level of uncertainty	Definition	Likelihood
Level 1: Shallow uncertainty	Multiple different scenarios can be enumerated and ranked according to their probability (with specified values)	
Level 2: Medium uncertainty	Multiple different scenarios can be enumerated and ranked according to their subjective or objective probability (only relational values)	
Level 3: Deep uncertainty	Multiple different scenarios can be enumerated but not ranked	
Level 4: Recognised ignorance	Certain scenarios can be identified without claiming completeness (alternative scenarios possible)	

The **nature of uncertainty** refers to the reason for an uncertainty and where it originates from. By defining the nature of an uncertainty, a better understanding of its inherent characteriztics is achieved that can help to develop possible strategies to handle uncertainties (Walker et al. 2003). Kwakkel et al. (2010) identify three different natures of uncertainties that are described in *Table 3*.

Table 3: Nature of uncertainty (adapted from Kwakkel et al. (2010))

Nature of uncertainty	Definition
Ambiguity	Uncertainty arising from the fact that the same data can be interpreted differently by different actors
Epistemology	Uncertainty due to gaps in knowledge, limited data availability that can potentially be reduced by more research and empirical data collection
Ontology	Uncertainty related to inherent randomness of nature, human behaviour as well as societal and technological variabilities

The three dimensions of uncertainty can be integrated into an uncertainty matrix that combines these uncertainty features and provides a graphical overview of their characteriztics. The matrix is utilized in this work to analyse the identified uncertainties.

The vertical axis of the matrix lists the different locations of uncertainty, while on the horizontal axis the levels and nature of uncertainty are located. Starting from identifying the location of an uncertainty, the levels and nature are typified. Since the allocation of uncertainties to one specific category can be difficult, the matrix allows for a multiple filling of boxes and therefore provides a tool to capture all relevant characteriztics of an uncertainty. *Table 4* depicts the concept of the uncertainty matrix.

Table 4: Concept of the uncertainty matrix (adapted from Kwakkel et al. (2010))

<table>
<tr><th colspan="2" rowspan="2">Location</th><th colspan="4">Level</th><th colspan="3">Nature</th></tr>
<tr><th>Level 1: Shallow uncertainty</th><th>Level 2: Medium uncertainty</th><th>Level 3: Deep uncertainty</th><th>Level 4: Recognised ignorance</th><th>Ambiguity</th><th>Epistemology</th><th>Ontology</th></tr>
<tr><td colspan="2">System boundary</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Conceptual model</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Computer Model</td><td>Model structure</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Parameters inside the model</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Input parameters to the model</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Input data</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Model implementation</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Processed output data</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

3. Argument map

3.1. General concept

3.1.1. Framework and premises

Referring to chapter 1.3, the goal of this thesis is to analyse the eligibility of different technologies to decarbonize the German road transport sector. In the following chapter, the general concept of this analysis is explained indicating the goals of this work, its general scope and underlying premises as well as its limitations. The aim is to define the intended outcome of the argument analysis and its role within the debate of the German mobility transition

As described in chapter 1.1, the German transport transition consists of two components: the mobility transition and the energy transition of transport. The energy transition of transport corresponds to a reduction of the carbon intensity of fuels as well as an increase of energy efficiency of transport (Agora Verkehrswende 2017; Bonghardt et al. 2013). The central focus of this work is set on analysing the eligibility of the different technologies to realise a decarbonization of the road transport sector in Germany. In order to achieve such a decarbonization, an electrification of the transport sector accompanied by an increased use of renewable energies is necessary (Hacker et al. 2014). In addition, synthetic fuels and biofuels as energy carriers replacing fossil fuels and allowing for a continuous operation of internal combustion engine vehicles are analysed.

The transport sector consists of different means of transportation, which all need to be considered when aiming at a complete decarbonization. However, within the framework of this thesis, only road bound traffic is analysed, without taking into account water, air and train traffic. This is the result of four central considerations:

1. *Final energy demand:* The road bound traffic accounts for 83% of the total final energy demand of the transport sector in Germany (data from 2016), whereas airplanes, trains and inland ships account for only 14%, 2% and below 1% of the total final energy demand, respectively (Radtke 2017).
2. *Carbon intensity:* Only 0.3% of the final energy demand of the road bound traffic is provided by renewable energy sources. The sector displays a very high degree of fossil fuel dependence with diesel and gasoline as the main motor fuels (Radtke 2017).
3. *Alternatives at disposal:* Due to the low energy density of batteries and hydrogen as compared to fossil motor fuels, the air and water transport sectors face a strong dependence on the latter. Alternatives are not expected to become a viable option in the short and medium term, hence these sectors are not considered (Agora Verkehrswende 2017). In comparison, various alternatives exist for fossil fuel powered combustion engines used on roads due to lower distances covered and a lesser importance of vehicle weight.
4. *Degree of carbonisation:* Assuming a degree of 80-95% of decarbonization of the German transport sector, the need for completely decarbonizing road bound traffic is obvious due to the aforementioned restricted potential of other sectors. While planes and ships might still rely on

fossil motor fuels to some extent in the long term due to technical and economic restrictions, road bound traffic can be decarbonized more realistically in light of the available and already implemented technologies (Agora Verkehrswende 2017).

5. *Electrified rail traffic:* The rate of electrification in the rail traffic sector is already at 60%, which indicates a high potential for decarbonization *without* the need of changing the technology currently utilized, but through integrating more renewable energies in the German electricity system (Allianz pro Schiene 2018).

In addition, several assumptions are made regarding the future of the German transport sector environment. These fundamental premises, on which the argument analysis is grounded, are listed and described in the following:

1. *Germany as the sole geographical context:* The motivation for choosing Germany as the focus area of this analysis is the consequence of various considerations. First, Germany is among the countries with the highest GHG emissions related to transportation which leads to a high urgency for action (International Council on Clean Transportation (ICCT) 2017a). Furthermore, Germany is characterized by a highly influential automobile industry. With more than 800,000 people employed in this sector and a contribution of around 13% to the German GDP, it has a high impact on political decision-making and thus also on the realisation of the German mobility transition (Deutscher Bundestag 2017; Federal Statistical Office 2017). In view of the different partly contradicting interests characterizing the debate around the decarbonization of the road transport sector in Germany, a fact-based analysis of the arguments is assumed to be more relevant than in other countries.
2. *2050 as a reference year:* 2050 is selected as a reference year for this work in accordance with most national and international climate protection programmes and initiatives. Among them, the Paris Agreement is the most relevant, setting the international framework for climate action in the upcoming years. Accordingly, the German Climate Protection Plan outlines its goals in light of the Paris Agreement and its taking effect in November 2016, aiming at "a vast carbon neutrality until 2050" (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety 2016). Therefore, the year 2050 represents the timely framework of this work without neglecting the required developments in the time span leading to the achievement of the set goals. In other words, the analysis is founded on present knowledge and considers possible future developments regarding the goal of decarbonizing the German road transport sector by 2050.
3. *Degree of total decarbonization:* According to the aforementioned Paris Agreement, the increase of the global average temperature is to be kept below 2°C in order to reduce risks and impacts of climate change (Conference of Parties 2015). To achieve this goal, efforts need to be made globally. For Germany as an industrial country, it translates to the target of decarbonizing its economy to 80 – 95%. This value span is the underlying assumption for the performed analysis.

4. *100% decarbonization of road bound traffic:* The analysis is performed on the premise that the road transport sector will become 100% carbon neutral. Therefore, only technologies are considered which can potentially be free of GHG emissions in the future. This consequently excludes any fossil fuel-based technologies from being considered as long-term alternatives, which also applies to fossil gas or hybrid solutions involving fossil fuel-based technologies. However, the possibility of using such technologies in the short and medium term as bridge technologies is accounted for. It is important to note though that the pathway to a complete decarbonization can only temporarily consider fossil fuel-based technology options, which is why only the four technology options introduced in chapter 1.2 are considered for the analysis.
5. *100% renewable energy:* Electrification is considered the most effective method to reduce GHG in the transport sector. However, this strategy only holds true when the electricity is produced on the basis of low-carbon and sustainable energy sources. Since the different technology pathways analysed in this work mostly rely on a renewable electricity supply to assure a low carbon footprint, a scenario of an electricity supply based on 100% renewable energies is considered.

3.1.2. Evolvement of the map structure

As described in the methodology chapter, the development of the argument map follows an iterative approach. Hence, the structure of the map changes during the course of the work varying the focus frequently on the basis of new insights gained through literature review and expert interviews. In the following, this process is briefly described to provide an understanding of how the final outline of the map has come about.

Initial structure

Initially, the research was focused on the question whether battery electric vehicles need to be complemented by fuel cell electric vehicles in the future. Assuming road transport in Germany will be mainly driven by BEVs, arguments for and against a consideration of FCEVs were collected and analysed. Consequently, other complementary technologies such as biofuels and synthetic fuels were neglected, limiting the analysis to electric vehicles only.

The map itself was accordingly structured following a pro-contra-approach with different arguments supporting and attacking the respective positions in favour of and against an integration of FCEVs into the transport system in addition to BEVs. *Figure 9* depicts the general structure of the first map.

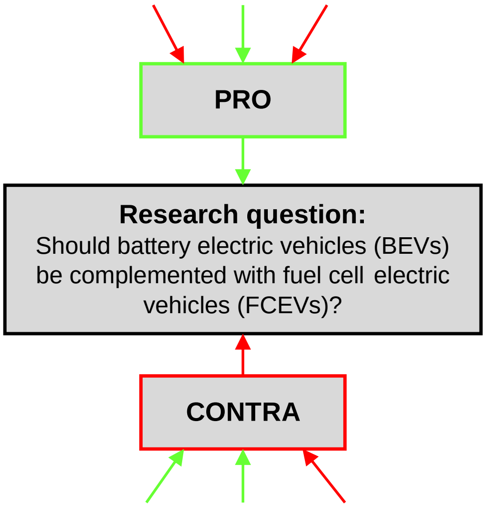


Figure 9: General structure of the initial map (own creation)

The limitations of this initial structure arise from the separation into contra- and pro-arguments and the restrictions such an outline entails:

- Arguments cannot be grouped into topic-specific clusters and are arranged solely based on their supporting or objecting character. Thus, the overall clarity of the map and its accessibility is affected.
- Restricting the analysis to the question whether BEVs should be complemented by FCEVs shortens the debate unjustifiably, since further technologies also have the theoretic potential to decarbonize the German road transport sector.
- Arranging the research question in the centre of the map and positioning the pro- and contra-arguments above and below, respectively, decreases the overall legibility of the map, since access to the map is less intuitive.

Final map structure

The limitations of the initial structure described above lead to the adaptation of the general outline of the map based on a slightly modified research question. During the course of research, it has become evident that the question if BEVs should be complemented with FCEVs restricts the debate and neglects the potential of other technologies. In addition, it has shown that BEVs most likely will not be able to cover all requirements of the road bound transport sector (Agora Verkehrswende 2017). Therefore, the research question has been adapted to:

Which technologies are necessary for a successful energy transition of road transport in Germany?

As explained in chapter 1, answering this question itself is not the central goal of this thesis, but rather the analysis of the different arguments for and against the available technology options, which include BEVs and FCEV as well as synthetic fuels and biofuels. Accordingly, the general map structure is changed from a centralized to a top-down approach, i.e. the central research question is placed at the top of the map. Underneath, the different considered technologies are listed, which are then linked to specific arguments supporting or contradicting the use of a technology. The arguments for and against the respective technologies are merged into thematic boxes that are subdivided into topic-related argument groups, providing a macrostructure that facilitates navigation through the map.

Downward, the level of detail increases when following a certain argument chain starting from a thesis (indicated by filled boxes) to the arguments supporting and attacking it (indicated by framed boxes). Theses are not necessarily referenced statements that represent conclusions from fact-based and referenced arguments. The separation into theses and arguments aims at increasing the legibility of the argument map on a micro-level. The green and red arrows indicate how the argument groups relate to each other and how they support or attack a certain technology.

Figure 10 depicts the concept of the argument map with the modified research question.

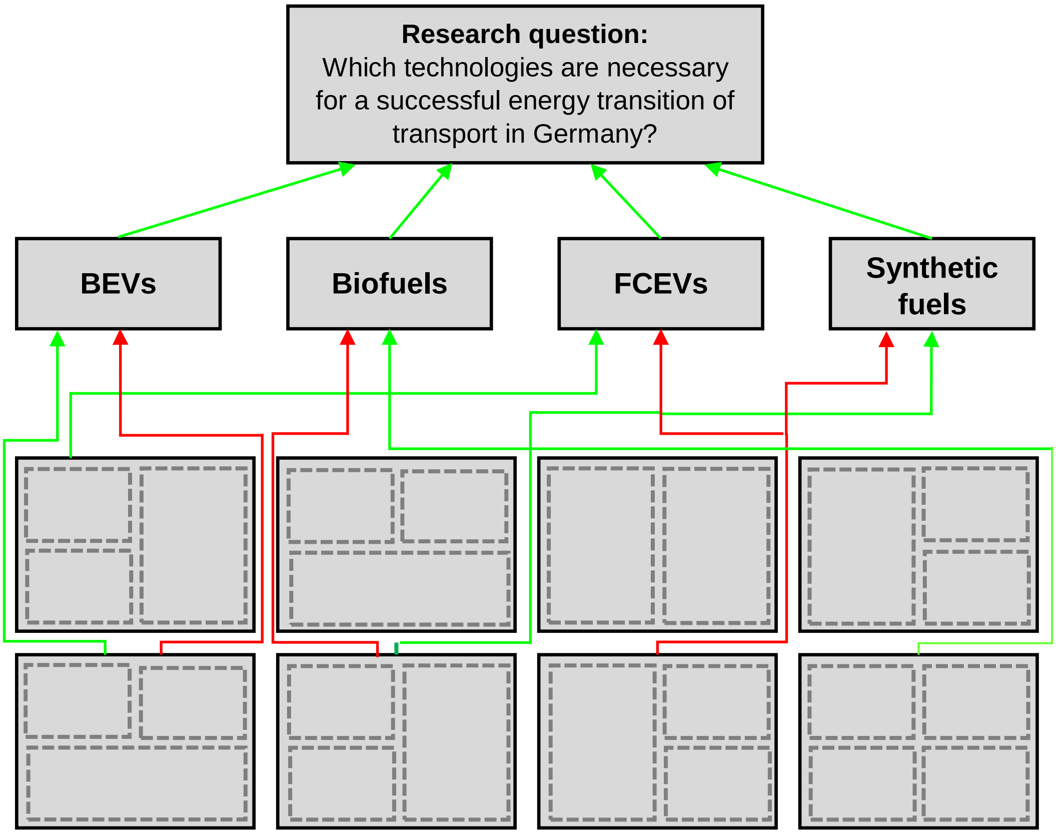


Figure 10: Conceptual display of the final map structure with argument clusters (black framed boxes), argument groups (dotted lines), arguments and theses (small framed and filled boxes) as well as their interlinkages (green and red arrows) (own creation)

3.1.3. Accessibility of the argument map

In view of the complexity of the map with over 400 different intercorrelating components, a high accessibility is required to avoid distraction. Access is therefore provided in two ways:

1. *Technology-oriented access:* Starting from a technology option, the different arguments for and against its consideration can be explored by following the arrows supporting and attacking this option. By this means, an overview on the characteriztics of a technology path is given without paying too much attention to the thematic context the different arguments are embedded in. The level of detail increases when advancing to the micro level of an argument chain.
2. *Topic-oriented access:* The second way to access the map is by selecting a specific topic of interest, analysing the argument chains it consists of in the required level of detail and then following the conclusions drawn from them regarding the different technology options. The focus is set to a lesser extent on comparing these technologies themselves, but rather on a certain relevant aspect of the debate and how this impacts the eligibility of the options at hand.

By enabling a twofold access to the map, the debate around the different aspects of the energy transition of transport is intended to be tracked on two levels by following a technology oriented as well as a more general approach.

For the ease of navigation in the map, each argument is numbered by means of a code indicating the cluster the argument belongs to (capital letter), the respective group (Arabic number) and the argument itself by following a chronological order of Arabic numbers. In case of a further division of an argument group into sub-groups, another Arabic number is added. This coding is explained by the following example: The argument "The costs for batteries are decreasing continuously" with the code "H.1.6.2" is located in cluster H ("Economic feasibility"), belongs to the first argument group within the cluster ("Comparison of TCO") and represents the second argument of the sixth sub-group ("Production costs"). The goal of this numbering system is to facilitate access to the map and to allow for a fast identification of the local position of a given argument. On the other hand, it helps to put a single argument in context with its thematic framework without actually studying the map. In terms of describing the work performed (which is the subject matter of the next chapter), it also helps" to build bridges" between the actual visual argument map and the textual explanation of its content.

In consideration of the high degree of interconnectivity and complexity, the accessibility of the map is aimed to be further increased by certain visual elements:

- *Different types of arrows:* By using different degrees of thickness, arrows directly supporting or objecting the use of a technology (thick arrows) are differentiated from arrows between arguments (thin arrows). Thus, the hierarchic level of an argument relation is indicated.
- *Numbering argument relations:* As explained above, thick arrows connect arguments or theses with one of the analysed technologies. The structure and volume of the map´s content implies that these arrows partly "cover long distances". In order to provide information which argument or thesis an arrow refers to, their respective numbers are located at the beginning and the end of a thick arrow.
- *Different colours for arguments and theses:* Boxes with a white background contain arguments, whereas boxes with a blue background indicate theses. In this context, theses represent assumptions or conclusions and are usually characterized by a high degree of controversy with different supporting and objecting arguments. By using a blue colour, their importance for understanding the debate around the energy transition of transport is highlighted.
- *Hierarchical arrangement of arguments:* Within an argument group or sub-group, all arguments are arranged in a vertical order of hierarchy. Thus, the level of detail increases when following an argument chain from top to bottom. This hierarchical arrangement allows for displaying the effect an argument has and which assumptions or conclusions it entails.

3.1.4. Argument map presentation

In the next chapters, the performed work is described following the structural order of the argument map as the outcome of the argument analysis. *Figure 11* below functions as a visual table of contents and serves as a guidance for the presentation of the map in the following chapters linking the different thematic fields with the respective chapters.

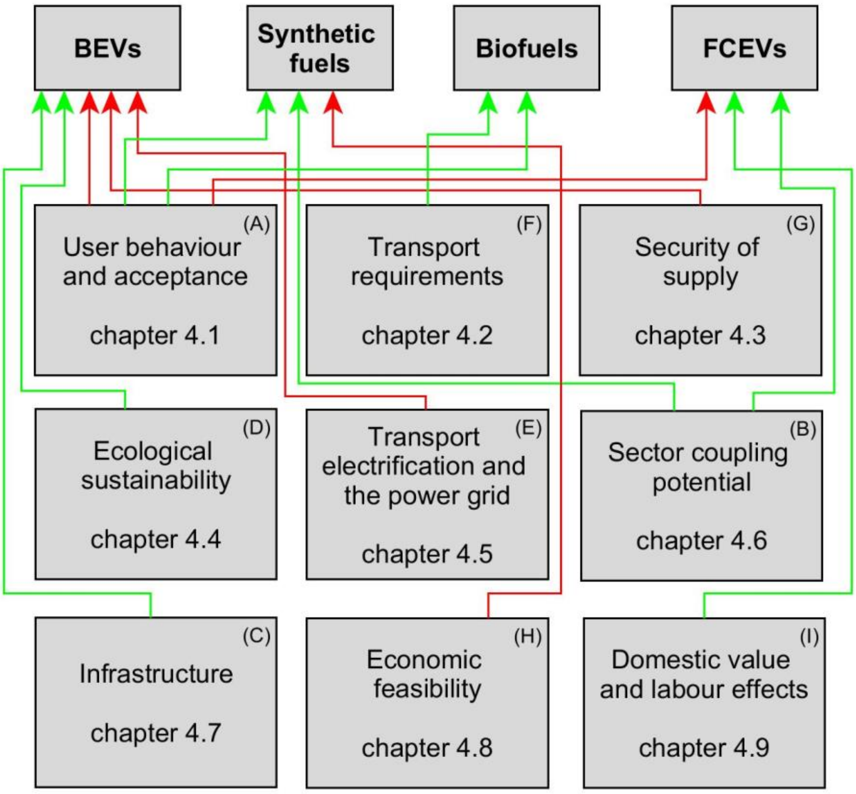


Figure 11: Visual table of map contents depicting the different argument clusters with reference to the respective chapters in the text (own creation)

Instead of analysing the specific technologies consecutively, the presentation of the performed argument analysis in the next chapters is separated into nine different thematic aspects in accordance with the nine argument clusters of the map (see *Figure 11*). These clusters and the group of arguments are presented in their relation to the technologies, that is, how they influence the eligibility of each technology option. The goal is not to list and explain each of the more than 400 processed arguments, but rather to present central argument chains and the inherent contradictions. The theses drawn from these different arguments are then related to a certain technology.

A central aim of the argument map is to display correlations between specific thematic fields and to show how an argument can be either in favour or against the usage of a technology, depending from which perspective it is analysed. Therefore, the presentation of the map is particularly focused on arguments that simultaneously have a supporting and an attacking character.

Each of the following chapters is structured as indicated below:

1. *Presentation of the thematic context of the argument cluster:* This first part of each chapter contextualises the topic on hand. It provides an explanation of the aspects this cluster includes and the central conclusions regarding the different technology options. To achieve this, the macro-structure of the respective cluster is displayed at the beginning of each chapter providing a visual table of contents.
2. *Presentation of the argument groups within the cluster and the respective theses:* Secondly, argument groups are discussed that combine arguments of a certain topic. By introducing

each chapter with a thesis statement, the main conclusion of this group is presented in the beginning and then discussed by means of considering the supporting and objecting arguments.

3. *Explanation of central arguments supporting and attacking the thesis:* The most relevant arguments within an argument group are then presented providing additional information that puts its role in context with the thesis concluding from this argument group.

This structure recurs in each of the following chapters and aims at ensuring a consistent and comprehensive presentation of the performed argument analysis on the energy transition of the German road transport sector. Each chapter is referenced to the location in the map by using the coding system introduced in chapter 3.1.3. By this means, it is intended to relate the written content with its visual display.

The map itself as well as a comprehensive list of all arguments considered can be found in appendix A and D.

3.2. User behaviour and user acceptance (cluster A)

This argument cluster analyses the available technologies from a user perspective, focusing on the shortcomings of BEVs and FCEVs compared to ICEVs. In the following, the arguments supporting and attacking the thesis above are presented and their intercorrelations analysed. This chapter is structured in accordance with the argument map (see appendix A), as depicted in *Figure 12.*

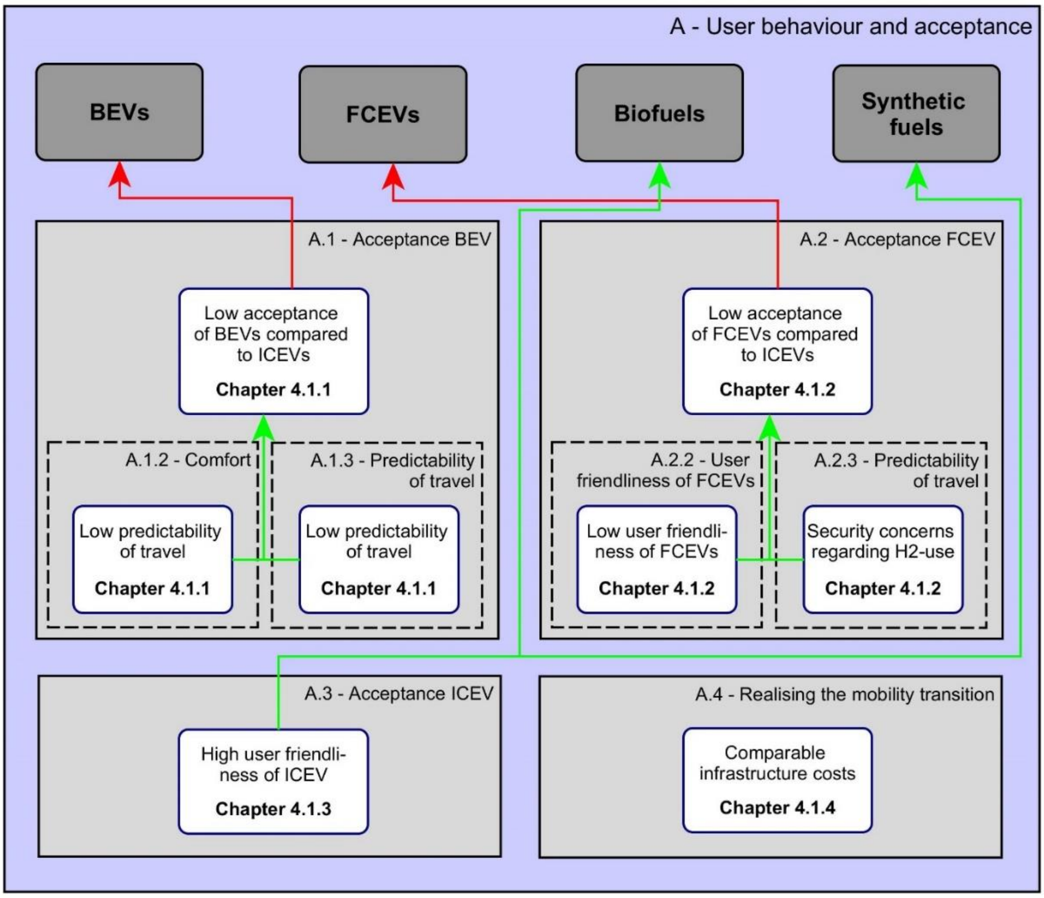


Figure 12: Structure of cluster A displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.2.1. Acceptance of battery electric vehicles (A.1)

Thesis: "BEVs are characterized by a lower user acceptance compared to ICEVs."

The arguments influencing the acceptance of BEVs can be grouped into two sub-argument groups; *comfort of usage* and *predictability of performance*, as described below.

Comfort of usage

The comfort of using BEVs is restricted by the relatively low range of models currently available on the market and the resulting need to recharge in a higher frequency compared to the refuelling frequency of conventional ICEVs. This argument is supported by findings of socioeconomic research considering mobility behaviour as routine behaviour and pointing out that an intended change of behaviour needs to result in the establishment of a new routine to be permanent (Canzler 2018). With regard to adaptation of BEVs, the user´s routine (refuelling his or her car every 600-800 km at a gas station) needs to be changed into a potentially less predictable new charging routine (due to lack of infrastructure or predictability, as discussed below). Objecting this argument, the possibility of charging at home is brought forward with the potential to increase the comfort of supplying the vehicle with energy.

Certain operation characteriztics of a BEV also affect the comfort of use, namely the relatively high acceleration and the low noise emissions of electric motors (European Alternative Fuels Observatory

2017). While a higher acceleration is generally perceived as a factor increasing the pleasure of driving, low noise emissions can have a positive as well as a negative effect: on the one hand, a low noise level has benefits regarding health and comfort of driving. However, it is also related to a certain security risk leading to a higher probability of accidents, in particular at lower velocities when noise from roll friction is lower than the electric motor sound (Duddenhöffer 2013).

Predictability of performance

Restrictions in the predictability of performance also affect the acceptance of BEVs and support the thesis introduced in the beginning of this chapter. These restrictions are mainly related to three characteriztics of current BEVs.

First, the performance of batteries and thus the range of a BEV fluctuates and depends on various user related factors such as driving behaviour and the use of on-board devices (such as air conditioning) (Öko-Insitut 2017). In addition, the storage capacity of battery cells is strongly affected by the ambient temperature resulting in considerably lower ranges in winter (DEKRA 2018). Second, range declarations of manufacturers usually do not represent realistic values and significantly deviate from ranges achieved in praxis. However, this is expected to change with the worldwide harmonized light vehicle testing procedure (WLTP) introduced in September 2017, aiming at reducing deviations by 50% (International Council on Clean Transportation (ICCT) 2017a). Finally and most importantly, the current charging infrastructure is not sufficient and impedes the planning of longer trips with BEVs (Öko-Institut 2017a). This argument in turn is objected by pointing at the temporal component of this statement: an improvement of the present infrastructure limitations can enable a universal access to charging stations and potentially lead to the redundancy of the argument. Insufficient knowledge is identified as another reason for a low acceptance of BEVs. Through targeted information and education programmes, however, these knowledge gaps can be closed and a higher acceptance of BEVs can be achieved (Götz et al. 2012).

The arguments discussed above mainly support the thesis of a currently lower acceptance of BEVs. Nevertheless, they are mostly related to restrictions that can be overcome in the future and lead to higher user friendliness. Therefore, lower user acceptance of BEVs can be considered a preliminary argument against their integration in the German road transport sector.

3.2.2. Acceptance of fuel cell electric vehicles (A.2)

Thesis: "FCEVs are characterized by a lower user acceptance compared to ICEVs."

Since both FCEVs and BEVs rely on an electric motor for driving, their respective acceptance is partly affected by similar arguments. Whereas the predictability of performance is not a superordinate issue for FCEVs, certain user-related arguments such as the impact of a low noise level and high acceleration are relevant for both technologies. Therefore, the thesis above assumes a lower acceptance of both BEVs and FCEVs. Below, the arguments that support and object this thesis are presented.

User friendliness

Compared to ICEVs and even BEVs, FCEVs are less integrated in the automotive market. Due to low production rates, the costs of manufacturing are considerably higher than for other vehicles (Wolfram, Lutsey 2016). The very low number of vehicles commercially available and the high costs lead to a low attractiveness to the user. However, this conclusion only represents the current picture and with recently announced efforts by various OEMs to intensify the development of FCEVs, an improvement of both model availability and vehicle costs can be expected (Toyota, Hyundai 2017).

In terms of the ease of refuelling, FCEVs have a competitive advantage to BEVs regarding the needed time. While even current fast charging stations require a minimum of 15 to 20 min for charging, the refuelling of hydrogen only needs around 3 min, comparable to the consumed time for refuelling an ICEV with petrol (Deutsches Zentrum für Luft und Raumfahrt 2014). This argument contradicts the thesis of a low acceptance of FCEVs. In contrast to BEVs, however, a refuelling at home is not possible, which in turn reduces the comfort of usage.

Security concerns

The use of hydrogen is generally seen with a certain degree of scepticism, which has been described as the so-called Hindenburg-Syndrom. The term originates from an accident involving a German zeppelin with the name of Hindenburg in 1937 that was caused by an inflammation of the carried hydrogen (Roche et al. 2009). This general scepticism towards the use of hydrogen affects the acceptance of FCEVs negatively.

Considering these arguments, the thesis of lower acceptance of FCEVs is widely supported. In accordance with the acceptance of BEVs, however, several arguments might become obsolete in the future if FCEVs are widely integrated in the market.

3.2.3. Continued operation of internal combustion vehicles (A.3)

Thesis: "ICEVs are characterized by the highest user acceptance."

The use of biofuels and synthetic fuels allows for a continued operation of ICEVs due to their theoretical potential to be carbon neutral. Considering the high energy density of both fuel types, ranges of conventional ICEVs powered with fossil fuels can be reached. With respect to user friendliness, the ongoing operation of ICEVs has the advantage that no change of user behaviour is necessary, which represents a central argument against the use of BEVs (see chapter 3.2.1). However, the continuous operation of ICEVs entails certain competitive disadvantages regarding the user friendliness such as noise emissions or lower average acceleration. Consequently, the potential benefits of BEVs and FCEVs are in turn contra-arguments against the continued operation of ICEVs.

3.2.4. Realising the mobility transition (A.4)

Thesis: "The mobility transition has the potential to fundamentally change user behaviour and will lead to a significant reduction of kilometres travelled."

As stated in chapter 1.1, the mobility transition is not the main subject of this argument analysis. Nevertheless, the transformation of mobility and the inherent change of user behaviour will have significant impact on the choice of the drive technology. The energy transition of transport and the mobility transition are interlinked and need to be considered together for a successful transport transition of Germany. Therefore, the central arguments for and against the thesis stated above and how they impact the use of different drive technologies are discussed in the following.

The main goal of the mobility transition is an overall reduction of kilometres travelled by means of a more efficient use of the vehicle fleet and a shift of the modal split (see chapter 1.1). Its main pillars are the reduction of individual travel, an increased share of public and muscle driven transport and a more effective transport system. Consequently, the total number of vehicles is expected to decrease (Agora Verkehrswende 2017). However, several obstructions hinder a realisation of the mobility transition. In Germany, cars have the role of a cultural good that guarantees flexibility of mobility and functions as a symbol for social status while providing a comfortable and subjectively secure means of transport. In addition, the legislative framework is not in favour of a shift of the modal split, for which the so-called *Stellplatzverordnung* that dictates the of car parking lots in new houses provides a good example (Canzler 2017). Furthermore, the mobility transition is hindered by high prices for public transport, subsidies on diesel and no financial costs for the use of road infrastructure.

Megatrends such as autonomous driving could also have a negative impact on the reduction of kilometres travelled and rather lead to an increase of transport volumes due to the possibility of a more effective usage of travel time, which in turn might result in larger commuting distances and the circulation of empty autonomously driving vehicles "on-demand" (Agora Verkehrswende 2017).

In summary, the mobility transition is expected to lead to a reduction of demand for individual transportation through a change of travel behaviour and a more efficient use of means of transport.

3.3. Transport requirements (cluster F)

Currently, most of the road transport sector relies almost exclusively on fossil fuels. A transition towards a decarbonization needs to assure that all mobility services are provided. In the following chapter, the eligibility of different technologies, particularly BEVs, to meet the requirements of the road bound passenger and freight transport is analysed. This chapter is structured in accordance with the argument map (see appendix A) as depicted in *Figure 13*.

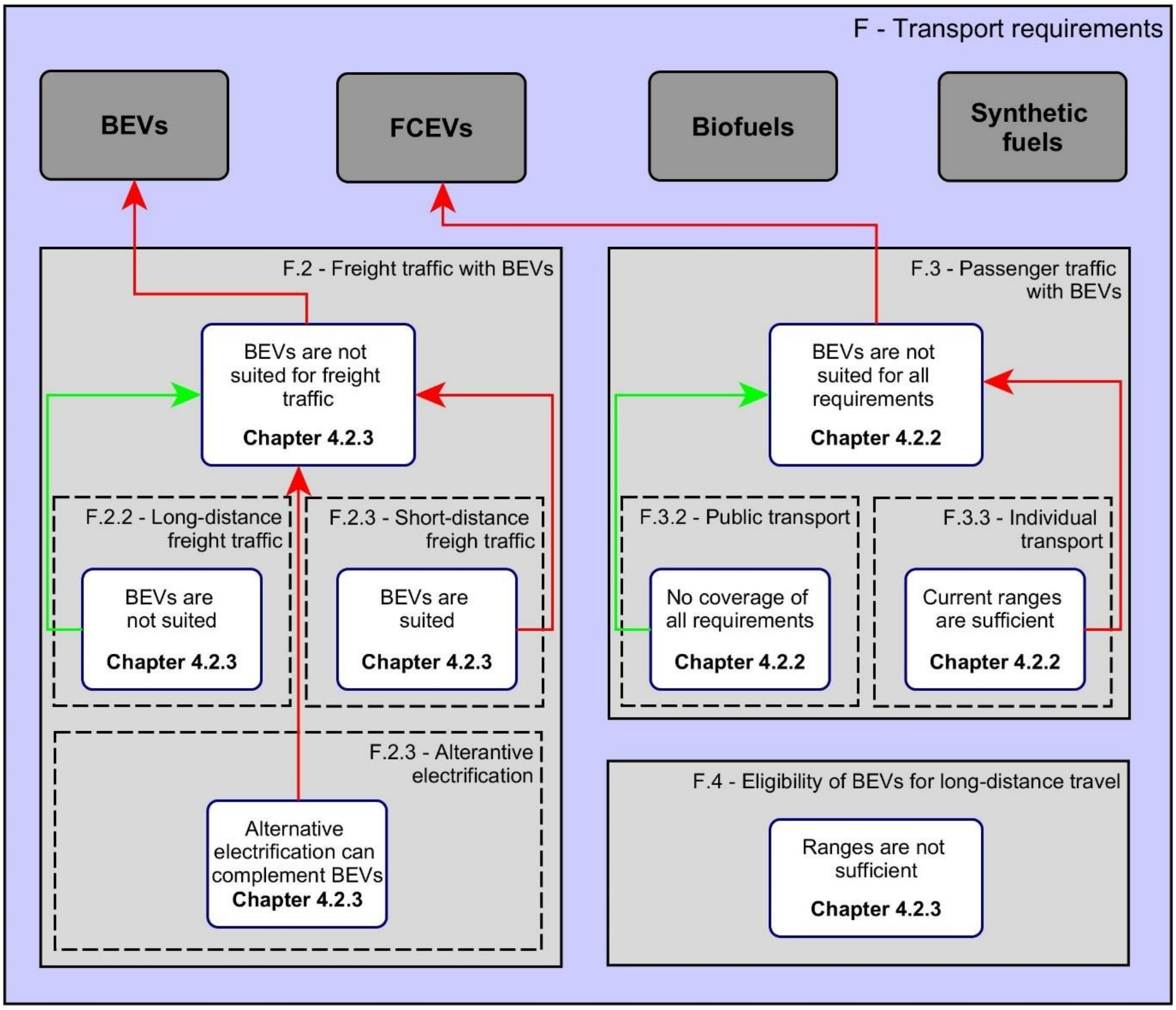


Figure 13: Structure of cluster F displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.3.1. Eligibility of BEVs for long-distance travel (F.4)

Thesis: "BEVs are not suited for long-distance travel."

The main restriction of current BEVs in terms of meeting all road transport requirements is the comparably low range that makes them seem less suitable for long-distance travel. This is particularly relevant for freight transport, as will be discussed in chapter 3.3.3. The thesis that current ranges of BEVs are insufficient is objected by a number of arguments. First, various options for extending the range of BEVs are at hand such as battery swapping, fast charging stations or inductive charging.

Battery swapping allows for a fast exchange of empty batteries. However, a battery swapping system would require a significant amount of exchange batteries for assuring the efficiency of the system and would moreover become obsolete if a fast charging infrastructure is implemented (den Boer et al. 2013). Inductive charging, on the other hand, would be related to significant costs, since it requires a large-scale modification of road infrastructure (International Council on Clean Transportation (ICCT) 2017b).

Theoretically, current batteries can already serve for long distances, but the limited energy density entails a significant increase in weight to ensure the required ranges. However, with regard to technological development of batteries, a further increase of storage density at relatively lower costs is expected to allow for sufficient ranges in the future (Kreyenberg et al. 2015). The Fraunhofer Battery Alliance (2017) estimates that new battery cells can enable a significantly higher storage density in the future, potentially shifting the limits of current lithium ion battery development.

In the following chapters, the limitations of BEVs for passenger and freight road transport and the resulting competitive advantages of available alternatives are analysed in more detail.

3.3.2. Passenger road transport (F.3)

Thesis: "BEVs cannot meet all requirements of passenger road transport which implies the need of alternative drive technologies."

This chapter is sub-divided into public and individual passenger transport due to their respective individual characteriztics regarding the possibility to integrate BEVs.

Public road transport

In light of the limited range of BEVs, the eligibility of BEVs for public transport depends on the covered distance. The local public transport sector is characterized by comparably short distances with frequent stops (particularly in urban areas) and therefore offers considerable potential for the use of BEVs. In fact, the trend of electrifying urban public transport is already taking place. In China, for instance, more than 300,000 electric buses are already in operation (Öko-Institut 2017a). In rural areas, however, electrification of road transport is a more complex undertaking because of longer distances to be covered and a generally higher dependence on a private car (Agora Verkehrswende 2017).

While BEVs are increasingly integrated in the local public transport sector, their potential for long-distance travel is limited in consequence of the restrictions described in chapter 3.3.1. By shifting passenger transport to the railway, these limitations could be partially compensated (Agora Verkehrswende 2017). Nevertheless, it is expected that alternative technologies need to be considered for meeting all requirements of long-distance public road transport.

Individual road transport

In 2016, the average distance covered by a passenger per drive was only 14 km (Federal Office of Motor Traffic 2017). Therefore, most individual transport requirements can already be met by BEVs today. Two factors can be identified that will further increase the potential of electrifying individual road transport: first, battery capacities are expected to increase, allowing for longer distances to be covered in the future (see chapter 3.3.1). Second, electrifying other modes of transport such as bikes or motor scooters can help to further decrease carbon emissions and complement BEVs in individual road transport. In this context, the mobility transition discussed in chapter 3.2.4 has a great influence on how individual travel behaviour will change and to which extent BEVs can cover the mobility services for individual road transport. This, in turn, affects the need of considering alternative drive technologies.

3.3.3. Freight road transport (F.2)

Thesis: "BEVs cannot meet all requirements of freight traffic and therefore need to be complemented by alternative drive technologies."

The eligibility of BEVs for freight road transport is analysed in this chapter considering short- and long-distance transport as well as potential alternatives for electrifying the freight road transport sector.

Short-distance freight traffic

Current ranges of BEVs already allow for the operation of freight vehicles on short distances which is also reflected by a growing market for commercial, short-distance BEVs (Fraunhofer ISI 2013). The potential of using BEVs for freight transport is supported by the fact that, similar to passenger transport, average distances are in a range that can easily be served by BEVs; in Germany, more than 80% of freight traffic is below 150 km (Arlt 2017). Therefore, in terms of short-distance travel, BEVs are considered a feasible alternative to conventional ICEVs. Regarding longer distances, however, their use is limited, as discussed below.

Long-distance freight traffic

Long-distance freight traffic is characterized by transport distances that BEVs will most likely not be able to cover (Agora Verkehrswende 2017). Theoretically, batteries could be scaled up to provide the necessary storage capacity, but due to the currently limited energy density of around 150 Wh/kg, the battery weight would increase significantly, which would in turn reduce the allowed payload of the vehicles (e-mobil BW GmbH 2017). Despite this limitation, several OEMs have announced electric trucks for long distance travel, which indicates a potential enlargement of the sphere of action of BEVs.

Increasing transport volumes and distances, however, counteract the integration of BEVs in the long-distance freight transport sector. In contrast, as Fischedick and Grunwald (2017) point out, innovations such as 3D printing could have a significant impact on transport volumes and might reduce overall demand for long-distance freight transport.

In consideration of the limitations of BEVs, the use of synthetic fuels and biofuels for a continuous operation of ICEVs could complement a direct electrification of road transport. Another factor that might fundamentally change the scope of long-distance transport are alternative electrification concepts, as discussed in the following.

Alternative electrification of freight road transport

Various options are discussed for the alternative electrification of freight road transport. First, the “rail before road”-principle is frequently advocated to reduce freight transported via roads. However, the capacities of the railroad system in Germany are limited and clearly below current freight transport volumes (Agora Verkehrswende 2017). Second, more disruptive innovations could replace freight transport on roads in the long term. Two examples for such innovations are the “Hyperloop” and “Cargo Sous Terrain” concepts that both envision a complete shift of freight transport from the road to underground transport systems (MIT Hyperloop Team 2017; Cargo Sous Terrain 2016). A less disruptive but more advanced approach is the implementation of an electric catenary system on highways to allow for BEV usage. On two German highways such systems are currently being installed and tested. However, barriers in the existing infrastructure such as tunnels or bridges need to be addressed (Federal Ministry of Transport and Digital Infrastructure 2016). Hybrid trucks could solve this challenge with alternative energy providers such as batteries or fuel cells ensuring the energy supply outside the catenary system (Öko-Insitut e.V. et al. 2016). This would in turn require the replacement of the entire vehicle fleet, which would only be alleviated by the short life cycle of trucks potentially allowing for a fast technology shift (Arlt 2017). An electrification of highways by means of a catenary system would also make a transboundary implementation necessary due to the high share of international freight traffic and require the installation of an extensive network of high voltage power lines, which would demand for the national and international approval of significant financial investments.

In consideration of the arguments presented above, the need of complementary technologies for covering all requirements of long-distance transport is widely supported.

3.4. Security of supply (cluster G)

Thesis: “A mix of different technologies is needed to assure security of supply and to reduce geographical dependences.”

Security of supply is an important aspect to consider when transforming the road transport sector. Currently, the supply of energy for road transport mainly relies on the import of fossil motor fuels with a share of over 90% of the final energy demand (Federal Statistical Office 2018). The implementation of low carbon drive technologies will significantly change import relations and geopolitical dependences, which could affect a secure supply of relevant materials. In the following chapters, the different argument clusters regarding the security of supply of the analysed technologies are presented.

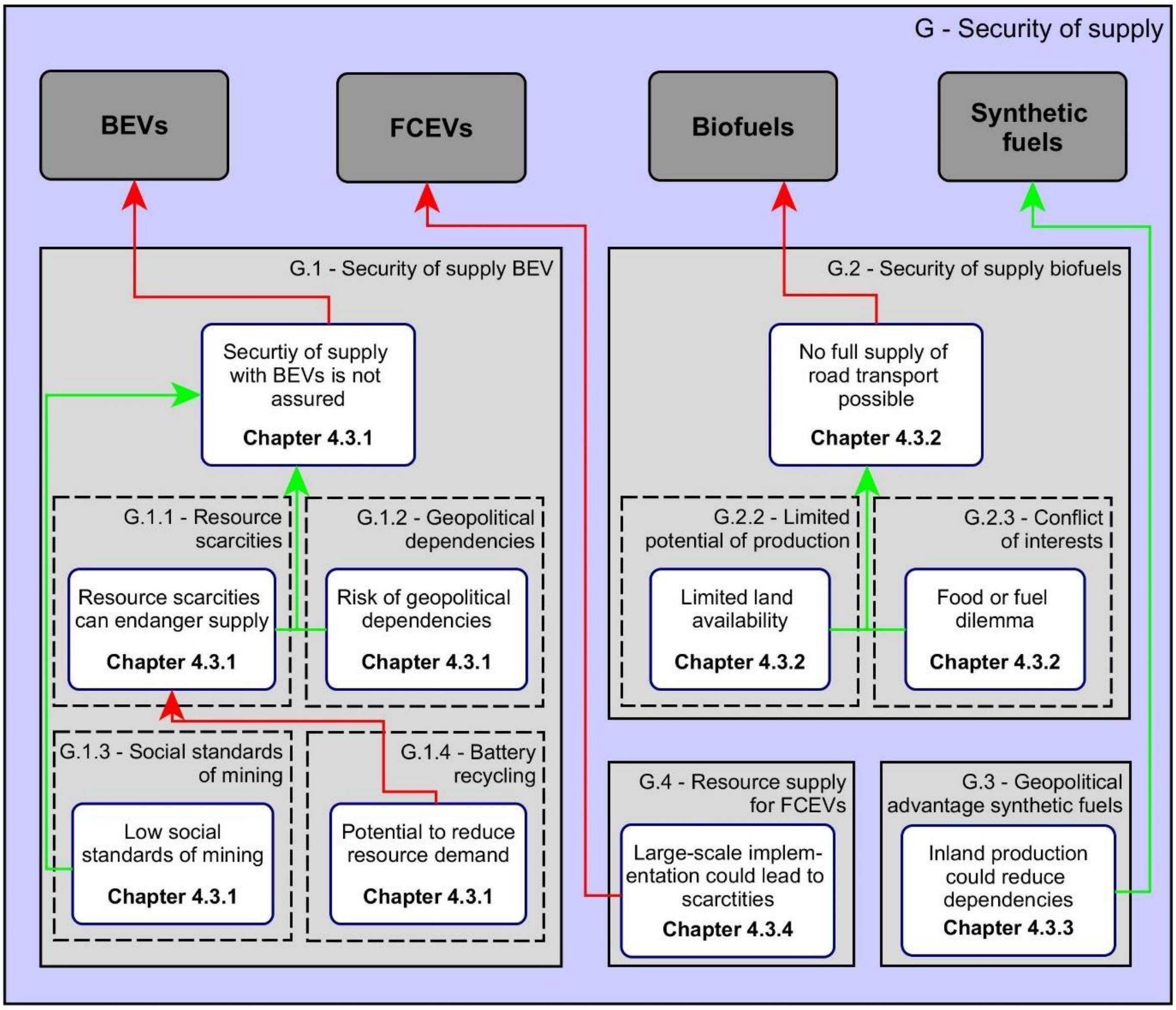


Figure 14: Structure of cluster G displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.4.1. Security of supply for BEVs (G.1)

Thesis: "BEVs cannot securely supply the road transport due to resource scarcities and geopolitical dependences."

Resource scarcities and geopolitical dependences

The international trend towards electrifying road transport is expected to lead to a demand growth of resources needed for the production of batteries (Agora Verkehrswende et al. 2018). This might result in potential scarcities in the supply of these relevant resources, as different studies imply, and could eventually lead to the risk of an insecure supply of BEVs (DLR, Wuppertal Institut 2014). The argument of potential resource scarcities is intensified by the fact that most battery relevant raw materials, such as lithium and cobalt, are only available in a few countries. In contrast, the German Institute of Applied Ecology (2017b) has come to a distinct conclusion, stating that the reserves of all raw materials relevant for BEVs exceed the predicted demand. However, it is stated that political procurement risks could lead to short-term scarcities that could affect the supply of these raw materials (Agora Verkehrswende 2017). Such short-term shortages of supply could also result from a quickly growing demand that does not allow for a timely development of sufficient mining capacities (Öko-Institut 2017b). A sharp increase of demand for BEVs in the market might lead to scarcities from the perspective of battery production as well if capacities cannot be extended at the same pace.

The argument of resource scarcities affecting the availability of BEVs is objected by the thesis that the risk of scarcities will lead to intensified research efforts that will eventually result in the occurrence of alternatives for currently indispensable resources. This phenomena has been observed in 2010 when an abrupt price increase of noble earths needed for the construction of electric motors led to its substitution by other materials (Pavel et al. 2016). Another argument for intensified research in potential alternatives are the increasing resource prices resulting from a higher demand (Öko-Institut 2017b).

As discussed above, the risk of resource scarcities for battery production due to the monopolistic structure of this sector might impact their availability for a sufficient production of BEVs. This translates to a potential geopolitical dependence of Germany, which is supported by the argument that a higher electricity demand in consequence of more BEVs might also require an import of electricity. These geopolitical dependences, however, could be reduced in the long term with the exploration of new mining sites. This can lower the monopoly status of certain countries and lead to a more competitive market for raw materials that are relevant for battery production. Sweden, for instance, is among the countries investigating the exploration of cobalt and lithium in consideration of an expected increase of resource demand (Nordström 2018).

Social standards of mining

The social standards of mining in countries that provide the main share of materials relevant for BEV-production are often below international standards. Child labour and poor general working conditions have been documented in various mines, particularly in the Democratic Republic of Congo where weak governmental structures and an informal character of the mining sector can be observed (Öko-Institut 2017b). The social standards of mining do not directly affect the security of supply but lead to the question which ethical standards should be applied. This moral controversy, as argued by the German Expert Council on the Environment, could be solved by the implementation of resource partnerships and certificates that assure the fulfilment of certain social and ecological standards of mining (2017).

Battery recycling

Another factor influencing the supply of BEVs is the degree to which batteries are recycled, since it holds great potential to reduce the demand of natural resources. As of today, however, battery recycling is not efficiently practised (Swedish Environmental Research Institute (IVL) 2017). It is argued that a battery recycling system could be established based on the implementation of resource inventories and circulation passes for relevant materials (Expert Council on the Environment 2017). Economic incentives and the currently untapped technological recycling potential are also brought forward as ways to increase the degree of recycling. These supportive arguments are objected by the reference to limitations set by the financial and energetic effort of recovering a high percentage of the materials a battery consists of (Swedish Environmental Research Institute (IVL) 2017).

3.4.2. Biofuels potential (G.2)

Thesis: "Biofuels cannot provide sufficient energy supply for the road transport."

The role of biofuels in the future road transport sector depends, among other factors, on their ability to provide a secure supply. Two central factors restricting this ability have been identified in the performed analysis: first, the limited availability of agricultural land for producing biofuels and, second, the conflict of interests which arise from their use.

Restricted potential

Several studies argue that the potential for producing biofuels in Germany is limited and can cover at most 19% of the future energy demand of the whole transport sector (Kreyenberg et al. 2015). This includes transport sectors other than road transport as well, which are characterized by less potential alternatives (such as air and water traffic) and further restrict the availability of biofuels for road transport. The main limiting factors for biofuel production are the land availability for cultivating biomass crops and the energy use that is up to 9 times higher per MJ of fuel produced compared to conventional fuels (Edwards et al. 2011). In addition, biomass waste which could reduce the space requirements and improve the carbon footprint of biofuel production is not available at the required scale (Malins 2017). However, considering the potential of third generation biofuels produced on the basis of algae, energy efficiency of production could be improved.

Conflict of interests

The most consistent argument against the use of biofuels is the conflicting interests it entails. Should crops that could serve human or livestock as food be instead utilised for powering automobiles in view of increasing global demand for food products? This is the central question in the debate of the moral controversy around biofuels. The main supporting and objecting arguments are discussed in the following.

The central argument against the cultivation of biomass crops is the generally limited availability of agricultural land, which needs to be used exclusively for food production purposes. This statement is supported by the reference to intensified conflicts of land use in consequence of growing food prices which are considered to be the result of a growing world population that is expected to amount to 9 billion people by 2050 (United Nations 2017). This argument, however, is objected by Malins (2017) who states that the cultivation of biomass crops in Germany only has a limited impact on the food security in other world regions. Another factor affecting the availability of agricultural land is seen in the effects of climate change on the production of food. With rising temperatures and increasing risks of natural disasters, limitations in the productivity of agricultural lands are expected to occur in many parts of the world (Expert Council on the Environment 2017).

In view of a potential attenuation of the described conflict of interests, the possibility of using biofuels that do not directly compete against food production capacities is discussed. In particular, non-edible second and third generation biofuels (mainly algae, cellulosic and waste biomass) could help to reduce conflicts of interests (Malins 2017). Yet, the question of competing land use forms remains and represents an unchallengeable argument against the use of biofuels.

3.4.3. Geopolitical advantage of synthetic fuels (G.3)

Thesis: “The integration of synthetic fuels into the German road transport sector reduces import dependences.”

In comparison with BEVs, the use of synthetic fuels could lead to a lower geopolitical dependence due to the possibility of producing synthetic fuels inland. In addition, the need for potentially scarce resources for the production of batteries would be reduced. However, the potential of a domestic production of synthetic fuels is restricted considering the limited renewable electricity generation potential. Hence, new import dependences might arise if the required amounts of electricity could be generated more economically in other parts of the world. The direct local usage of this electricity for the production of synthetic fuels could eventually lead to a scenario in which a great share of the synthetic fuels would be imported (Agora Verkehrswende et al. 2018). This would counteract the argument of a higher geopolitical independence of energy supply for the road transport sector.

3.4.4. Resource supply of FCEVs (G.4)

Similar to BEVs, FCEVs are characterized by a dependence on potentially scarce resources that could endanger their large-scale production. One of these resources is platinum that is required for the construction of fuel cells. However, in accordance with the evaluation of the scarcity of resources relevant for BEVs, the increasing demand for platinum is not expected to exceed its supply (Agora Verkehrswende et al. 2018). The presumption of a secure supply of platinum is backed by the fact that platinum is a relevant raw material for the manufacturing of current vehicles. With an expected decrease of this type of vehicles, the availability of platinum in the market should be assured.

Potential resource scarcities might occur in a different form: since FCEVs also require a battery for its operation, shortages of supply affecting BEVs might also affect FCEVs (Randelhoff 2014). Since batteries of FCEVs are smaller compared to BEVs, the argument of growing dependences regarding the production of batteries can be considered less relevant.

3.5. Ecological sustainability (cluster D)

Various factors need to be considered when assessing the ecological sustainability of drive technologies such as life cycle energy consumption, energy efficiency of operation and effects on the natural environment. In this chapter, the ecological sustainability of the analysed drive technologies is addressed, following the structure presented in *Figure 15* below.

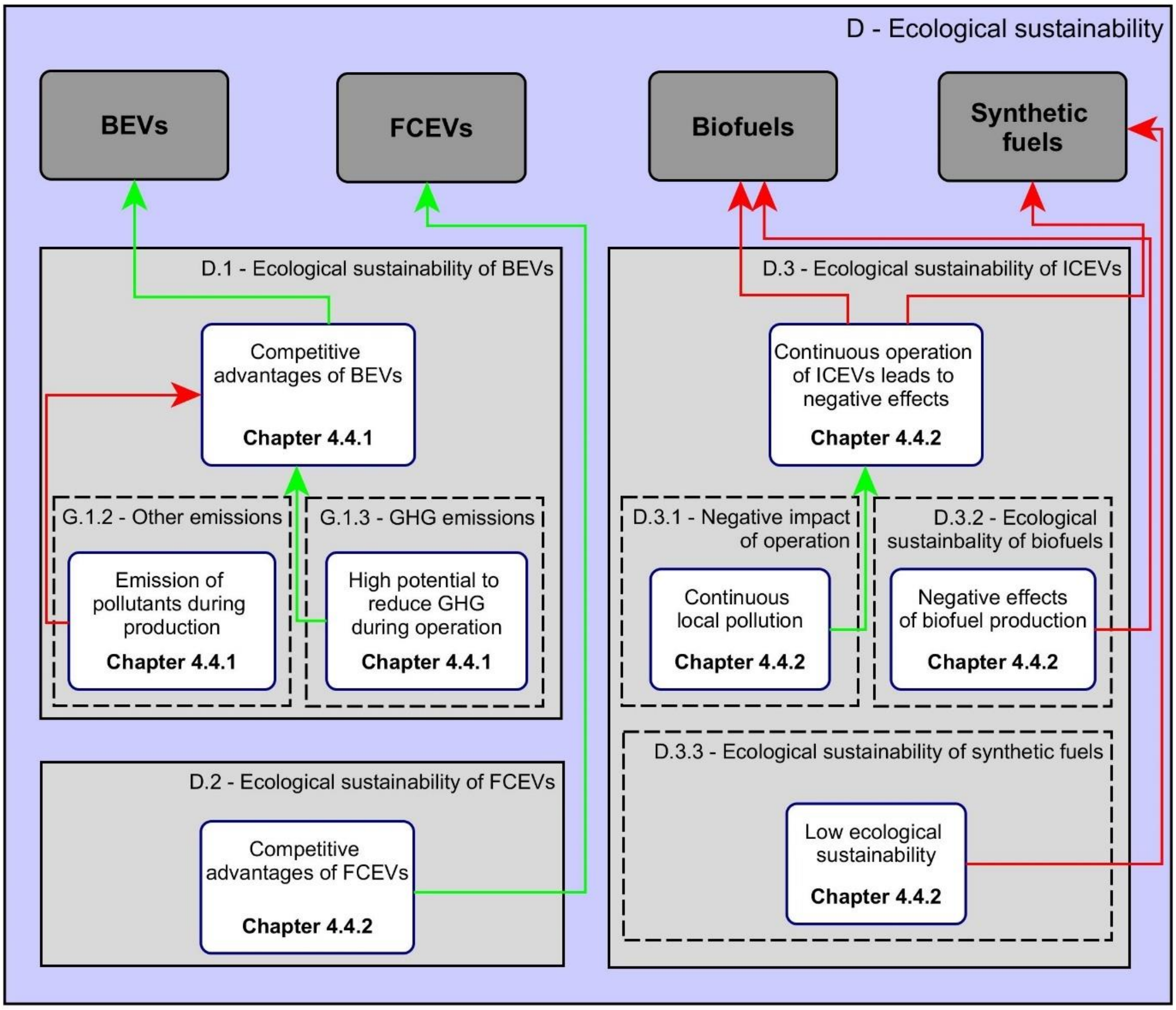


Figure 15: Structure of cluster D displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.5.1. Ecological sustainability of BEVs (D.1)

Thesis: "BEVs have significant competitive advantages regarding their ecological sustainability."

BEVs are often declared to be a clean alternative to conventional ICEVs without consideration of the negative ecological impact they entail. In the following, different aspects influencing the ecological sustainability of BEVs are discussed.

Greenhouse gas emissions

The thesis of a higher ecological sustainability of BEVs is grounded on the fact that their operation is more energy efficient than any other drive technology (see chapter 1.2) (International Council on Clean Transportation (ICCT) 2016). It is argued that the lower energy consumption will automatically lead to less GHG emissions during operation. However, this neglects the impact of the electricity mix in the respective country of operation on the carbon footprint of BEVs. Unless the required power is exclusively produced on the basis of renewable energy sources, indirect carbon emissions result from the operation of BEVs, which in turn reduces their ecological sustainability (IVL Swedish Environmental Research Institute 2017). Two central arguments contradicting this objection are brought forward: first, even with the existing electricity mix in Germany, the operation of a BEV is characterized by lower GHG emissions compared to conventional ICEVs (International Council on Clean Transportation (ICCT) 2018). Second, the power sector in Germany, as in most other countries, is characterized by a trend of decarbonization that will eventually lower the carbon footprint of BEV operation (International Energy Agency (IEA) 2016). However, even in case of a 100% RE power generation, emissions cannot be avoided entirely due to the energy input required for installation, operation and demolition of RE power plants.

Apart from emissions related to the operation of BEVs, the production phase is a relevant contributor to the carbon footprint of a BEV over its whole life cycle. Due to the energy intensive production of batteries, the construction of BEVs entails higher GHG emissions than the construction of conventional vehicles, which affects the overall environmental performance (Notter et al. 2010). Currently, 1 kWh of battery capacity is related to an energy input of roughly 1,000 MJ (IVL Swedish Environmental Research Institute 2017). In literature, this is referred to as the “ecological backpack” a BEV carries during operation. The observed trend to larger and therefore heavier batteries can lead to an increase of GHG emissions in the production of batteries and further increase carbon emissions of BEV production. In contrast, production related carbon emissions can potentially be reduced as a result of improvements in battery development (International Council on Clean Transportation (ICCT) 2018). Furthermore, the expected increase of battery production can lead to economies of scale that can allow for a relative reduction of GHG emissions (IVL Swedish Environmental Research Institute 2017). In addition, battery recycling has the potential to reduce carbon emissions of battery production by up to 10% per km driven (International Council on Clean Transportation (ICCT) 2018). These trends, combined with the expected decarbonization of power sectors worldwide, tend to result in a lower carbon footprint of the production phase of BEVs in the future.

As a conclusion, both production and operation of BEVs entail the emission of GHGs. However, consensus exists among the consulted literature regarding the lower levels of carbon emissions per km travelled of a BEV compared to the other analysed drive technologies.

Other emissions

Apart from GHG emissions, the environmental sustainability of BEVs depends on other factors as well which mainly relate to the ecological effects of battery production. First, the mining of resources needed for battery production leads to negative impacts on the environment, such as pollution of air and water resources. The latter is referred to as acid mine drainage, which is a particular problem of informally organised mining sectors such as the cobalt mining industry in the Democratic Republic of Congo (Agora Verkehrswende 2017). Second, during the actual BEV production phase, pollutants are emitted at higher levels compared to conventional vehicles due to the higher energy and resource demand of production (Notter et al. 2010). However, these emissions are concentrated locally and do not occur during the operation phase, whereas ICEVs are characterized by a pollutive operation that leads to a decentralised and country-wide emission of harmful pollutants.

In summary, the assumption that BEVs are per se more ecologically sustainable neglects the different factors that impact the carbon footprint of both production and operation of BEVs. In terms of GHG emissions during operation, however, BEVs already represent the least carbon intensive alternative drive technology.

3.5.2. Ecological sustainability of FCEVs (D.2)

Thesis: "FCEVs have competitive advantages regarding their ecological sustainability."

Like BEVs, FCEVs are characterized by an emission-free operation and, in addition, require less scarce resources for production. However, the higher energy input per km travelled also multiplies the environmental impacts related to the supply of electricity and consequentially leads to more emissions per km. Apart from electricity supply, hydrogen production entails further negative effects on the environment, particularly due to the water demand for electrolysis. This can lead to a high pressure on water resources and to conflicts of interests, especially in arid regions where water is a scarce resource (Agora Verkehrswende et al. 2018). Therefore, the ecological sustainability of FCEVs is affected by various factors that can jeopardise their competitive advantages and thus relativize the thesis stated above.

3.5.3. Negative effects of ICEVs (D.3)

Thesis: "The continuous operation of ICEVs leads to a prosecution of negative environmental effects."

The central argument for a continuous operation of ICEVs is the possibility to significantly lower the related carbon emissions by shifting from fossil fuel powered operation to carbon neutral alternatives, namely biofuels and synthetic fuels. Both unite the fact that their use for operating ICEVs could significantly reduce net carbon emissions while avoiding negative environmental effects of BEVs or FCEVs. However, ICEVs emit pollutants and particles during operation and therefore lead to a continuation of existing environmental stress and health damage (Expert Council on the Environment 2017). In the following, the characteriztics of biofuels and synthetic fuels regarding their environmental performance are described.

Ecological sustainability of biofuels

Thesis: "The production of biofuels has worse impacts on the environment than available alternatives."

The environmental impact of biofuels is characterized by different dimensions. First, GHG emissions can result from land use changes. These changes occur due to the need of large areas for cultivating biomass crops in combination with the limited availability of suitable lands (Malins 2017). In this context, it is differentiated between direct land use change (DLUC) and indirect land use change (ILUC): DLUC means the transformation of natural ecosystem into agricultural land, while ILUC refers to the shift of use of agricultural lands to biomass crops cultivation (Helms et al. 2011). DLUC is particularly held responsible for increasing the carbon footprint of biofuels, since the carbon storage capacity of cultivated land is considerably lower compared to the previous natural ecosystem (Ahlgren, Di Lucia 2014). Furthermore, the energy input for processing the harvested crops and their transformation into biofuels for ICEVs leads to GHG emissions. Eventually, these factors add up to a higher carbon footprint compared to a BEV (assuming a 100% RE power supply). Advocates of biofuels argue that this is only a valid statement for first and second generation biofuels and disregards the fact that biofuels produced on the basis of biomass waste have a considerably lower carbon footprint than conventional biofuels (Helms et al. 2011). However, as discussed in chapter 3.4.2, the potential of biofuels produced from organic waste is limited. Besides, other negative environmental effects are caused by biofuel production such as eutrophication, erosion and overstraining of water resources (HWWI Insights 2011)

Ecological sustainability of synthetic fuels

Thesis: "Synthetic fuels have a lower ecological sustainability compared to other technologies."

The thesis is mainly grounded on the fact that the production of synthetic fuels is significantly more energy-intensive compared to all other options available due to the additional conversion step of transforming hydrogen to synthetic fuels (see chapter 1.2). This automatically results in a higher carbon footprint in consequence of the increased demand for electricity generation. The negative environmental impact of hydrogen and carbon dioxide supply needs to be accounted for as well, since they represent the input substances for producing synthetic fuels such as synthetic methane or diesel (Agora Verkehrswende et al. 2018). Regarding the supply of hydrogen, the related effects on the environment have been discussed in chapter 3.5.2. Providing carbon dioxide is the second crucial step in the process of synthetic fuel production. To guarantee a low emission of GHG, it needs to be either extracted from biomass waste or directly absorbed from the air. The former is characterized by a limited potential (see chapter 3.4.2), while for the latter the technology is not developed yet. In addition, large areas of land would be required for a sufficient supply of carbon dioxide (Agora Verkehrswende et al. 2018).

3.6. Transport electrification and the power grid (cluster E)

The electrification of transport has multiple effects on the power grid. Shifting from fossil fuels to direct or indirect use of electricity in road transport implies an increase of the German power demand in the future. In addition, a large-scale implementation of BEVs will have an impact on the shape of the demand curve. That is, recharging patterns will highly influence the amount of electricity that needs to be provided at a given time. Therefore, it is argued that an increased share of BEVs could lead to grid overloads (Schill, Gerbaulet 2015). This prediction and the effects an electrified road transport might have on the power grid are discussed in this chapter, which is organised in line with the structure of the respective cluster in the argument map, as depicted in *Figure 16.*

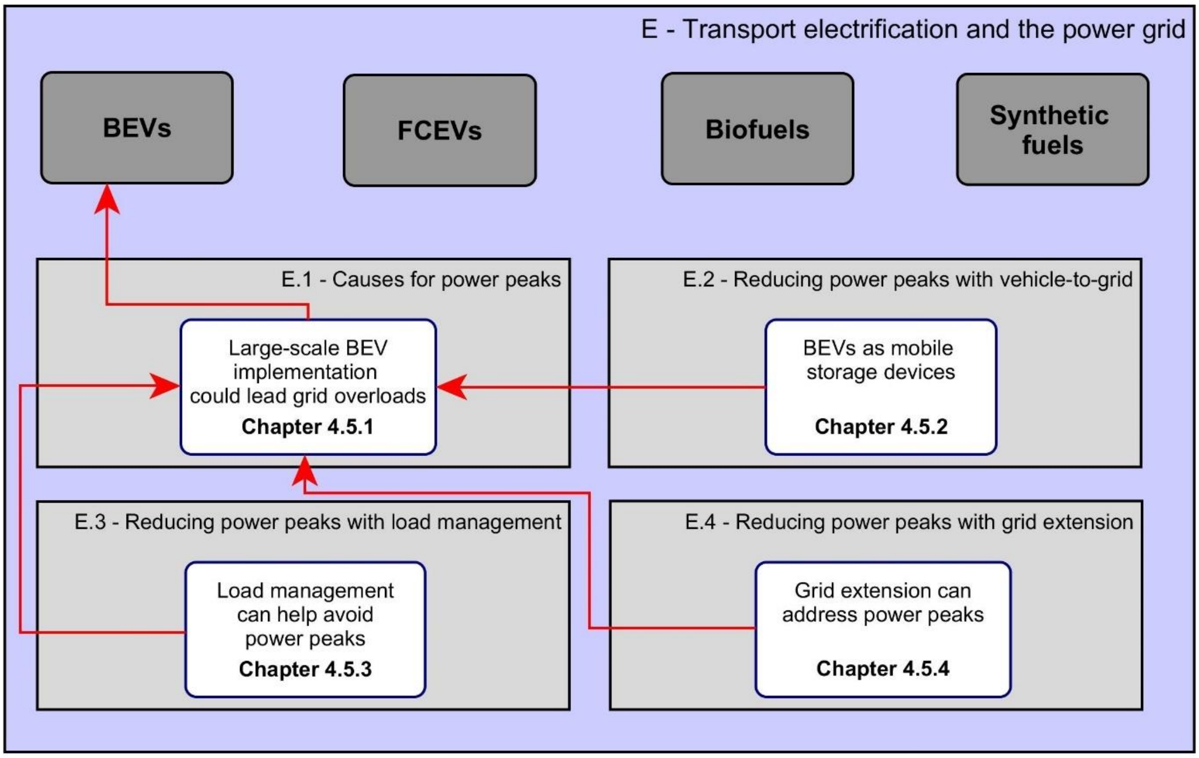


Figure 16: Structure of cluster E displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.6.1. Causes for potential grid overloads (E.1)

Thesis: "As a result of large-scale electrification of road transport, the likelihood of power grid overloads will increase in the future."

The power demand of the German transport sector is expected to increase as a result of a wide electrification of road transport (Öko-Institut 2017a). Therefore, the existing power grid will be strained by the need of accommodating higher power volumes, even though the increase of electricity demand might be partly lessened by a more efficient use of energy in transport in general, as discussed in chapter 1.1.

In addition to a higher overall power demand, the characteriztics of BEV usage impose further pressure on the power grid, which entails the risk of grid overloads. These are suspected to occur due to a high simultaneity of charging processes at night in consequence of a homogeneous driving and charging routine. This is particularly relevant in view of limited capacities of the electricity distribution network that only enables a low number of simultaneous charging processes (Götz 2016). In addition, an increased share of fluctuating renewable energies will lead to a lower predictability of power generation and an increase of power peaks (Agora Verkehrswende 2017).

The risk of grid overloads is relativized by the fact that Germany currently generates more electricity than needed and has an export surplus which could theoretically be used to charge 20 million BEVs (Fraunhofer IWES 2017). However, the temporal availability of excess electricity does not necessarily correlate with the demand for charging, especially when considering the shift towards a more fluctuating and less predictable power generation based on renewable energies.

The fear of grid overloads is also contradicted by a reference to other countries that already have a high share of BEVs without a significant increase of power peaks or even blackouts. In Norway, for instance, almost 40% of all newly registered cars in 2017 were either BEVs or PHEVs which did not result in a considerably higher pressure on the electricity grid (European Alternative Fuels Observatory (EAFO) 2018).

As seen, a large-scale integration of BEVs in the road transport sector will inevitably have an impact on the power grid, yet the extent of which is not fully predictable. In the following, several strategies to address such grid overloads are presented.

3.6.2. Reducing power peaks with vehicle-to-grid (E.2)

Thesis: "The vehicle-to-grid concept can provide mobile storage capacities that help to reduce power peaks and avoid grid overloads."

Vehicle-to-grid refers to the concept of using BEVs not only for transport but also as mobile storage devices and active participants of the power system (Agora Verkehrswende 2017). Bidirectional charging of BEVs is the underlying technology that allows for both the charging of the battery and the feeding of electricity into the grid. Thereby, a mobile storage capacity of around 120 GW to 130 GW would be theoretically available in case of a complete substitution of the current vehicle fleet (Agora Energiewende 2014). Regarding potential grid overloads, such a capacity could significantly contribute to balancing the power demand. Critics argue that both the legal framework and the economic feasibility hinders the implementation of a vehicle-to-grid system (Agora Verkehrswende 2017). In light of the required financial and technological efforts to realise such a system, valid business models are needed for an economic application which do not exist yet. This is crucial in view of the impact bidirectional charging can have on the technical performance and lifetime of the battery (Schill, Gerbaulet 2015). Against this background, as the German thinktank Agora Verkehrswende (2017) indicates, bidirectional charging can particularly generate income for fleet managers in the future and can be a viable business model due to the flexible operation of the vehicles.

3.6.3. Reducing power peaks with load management (E.3)

Thesis: "Load management can avoid power grid overloads and allows for high BEV integration rates without the need for grid extension."

A central management of BEV charging processes can assure an optimal utilization of existing grid capacities and a maximisation of the number of BEVs that can be integrated (Götz 2016). The main strategy for assuring that a high number of BEVs does not lead to grid overloads lies in the reduction of simultaneous charging processes. To avoid simultaneity various methods are discussed. The principle of random charging can locally counteract the occurrence of charging overlaps and assure an optimal utilisation of power grid capacity (Götz 2014). Through such a central management of charging, power peaks could be addressed and overloads avoided. Another option is the implementation of a flexible electricity price system to manage charging of BEVs (Geske 2016). Such financial incentives could help to shift charging to times when electricity supply exceeds demand, again leading to a levelling of the power demand curves. However, it is argued that a wider application of a cost-efficient charging strategy to shift demand to times of lower electricity prices can have an impact on the price dynamics and lead to rebound effects that eventually cause new power peaks. In turn, these dynamics might result in the increase of electricity prices if no central management entity controls the charging processes (Veldman, Verzijlbergh 2015). The implementation of such a central load management system would require significant financial efforts for installing the needed information and communication infrastructure (around 10,000 € per charging station) (Götz 2016). In summary, load management offers relevant potential to reduce negative impacts on the power grid caused by a high number of BEVs, but possible financial and technical rebound effects need to be addressed.

3.6.4. Reducing power peaks with grid extension (E.4)

Thesis: "Potential negative impacts on the power grid as a result of a large-scale implementation of BEVs can be met by an extension of the grid infrastructure."

A third strategy to avoid grid overloads is an extension of the existing power distribution infrastructure in the course of integrating more BEVs into the road transport sector (Geske 2016). In this context, the time frame of a large-scale implementation of BEVs is expected to allow for a successive and realistic extension of the power grid and provide a sufficient room of manoeuvre. In fact, up to 6 million BEVs could be integrated in the existing power grid without the need of extension, but with an accompanying charging profile optimisation and a limit for the extension of fast charging infrastructure (Götz 2014). In other words, it is argued that there is enough capacity available for the uptake of BEVs, which can be increased over time to allow for the integration of an even higher number of vehicles. However, this position is contradicted by the reference to the costs of a large-scale extension of the power grid infrastructure.

3.7. Sector coupling potential of hydrogen and synthetic fuels (cluster B)

The potential of utilising hydrogen and synthetic fuels in other industry sectors is frequently discussed as an argument for its utilisation in road transport. The energy sector is expected to rely on hydrogen and synthetic fuels in the future as a mean to store excess energy in consequence of an increased share of fluctuating renewable energies in the power system. Therefore, it is argued that the energy stored in hydrogen and synthetic fuels could be used for the operation of ICEVs, establishing a system that couples different sectors, namely the energy and road transport sector. Such a sector coupling is expected to potentially reduce total system costs. In the following chapters, the different arguments supporting and objecting the use of hydrogen and synthetic fuels in road transport are presented.

Figure 17 provides an overview of the macrostructure of this cluster including references to the chapters describing the respective argument groups.

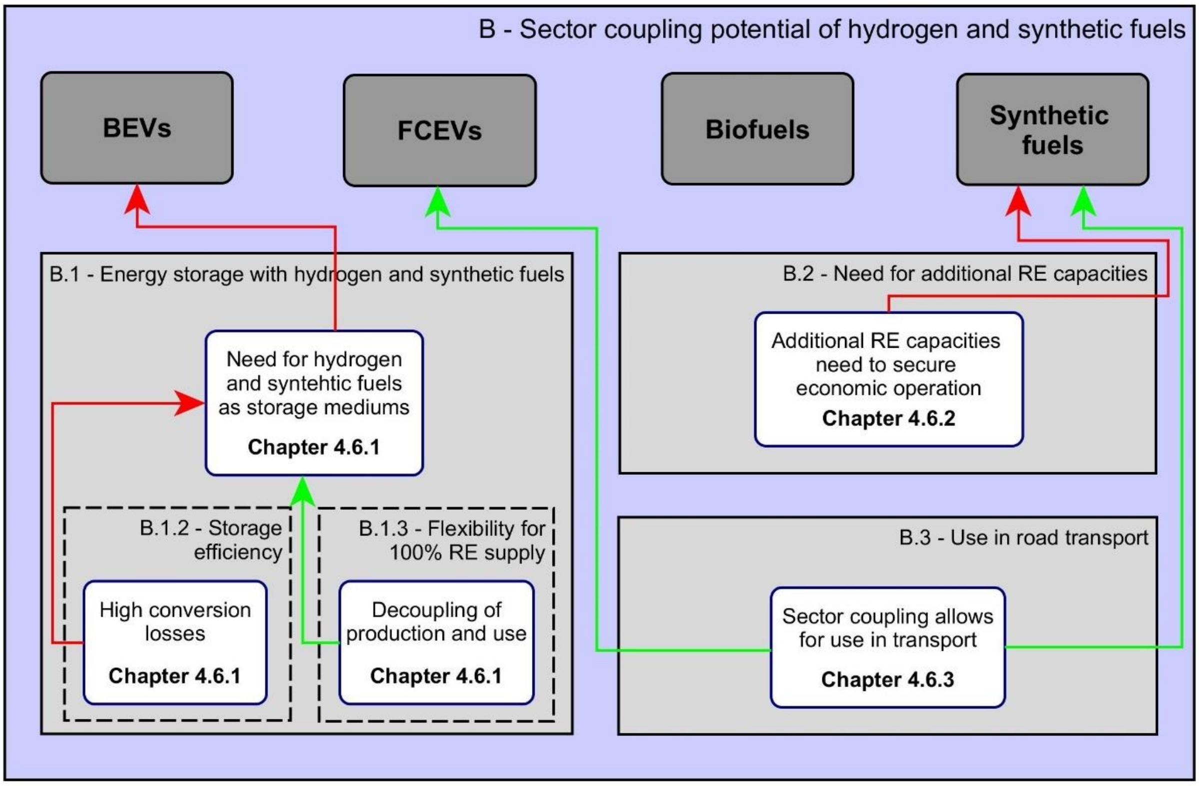


Figure 17: Structure of cluster B displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.7.1. Energy storage with hydrogen and synthetic fuels (cluster B.1)

Thesis: "Synthetic fuels and hydrogen can be used for energy storage to compensate for overproduction of electricity in consequence of an increased implementation of fluctuating renewable energy plants."

The decarbonization of the German power sector with a high share of power plants utilising renewable energy sources will lead to the need of storing unused electricity. The utilisation of this excess electricity to produce hydrogen and potentially further transform it to synthetic fuels is seen as a possibility to balance uneven supply and demand of electricity with multiple benefits (Fraunhofer IWES 2017): On the one hand, this would hold the potential to provide the flexibility needed for a power system entirely based on renewable energies and, on the other hand, it would allow for a compensation of geographical heterogeneities in power generation, as described in the following.

Balancing geographical heterogeneity in power generation

The geographic differences of potentials for power generation from renewable energies can lead to power grid overloads, particularly when considering an expected increase of RE power generation (Association of German Chambers of Commerce and Industry (DIHK) 2015). The production of hydrogen and synthetic fuels can help to reduce this disequilibrium since it allows for a decoupling of production and use of the electricity generated (Fraunhofer ISE 2013). The use of hydrogen and synthetic fuels, however, is not the sole option for balancing geographical differences in power production and reducing grid overloads. A more decentralised power system with a growing share of small-scale RE power plants such as solar PV on private homes can also help to stabilise the grid.

Providing flexibility for 100% renewable energies

The timely adjustable production of synthetic fuels can balance power demand and thus provide flexibility for a high percentage of RE in the electricity mix (Fraunhofer ISE 2013). This argument is objected by the reference to the availability of other means to provide flexibility in the power system such as batteries. Considering a high expected number of BEVs, large battery capacities would become available for balancing the power grid. As stated before, between 120 GW and 130 GW of storage capacity would be theoretically available in case of a complete substitution of the existing vehicle fleet (Agora Energiewende 2014). However, batteries are rather viewed as an option for short-term storage than for balancing long-term gaps between power supply and demand. Due to this limited potential of batteries for storage, a general consensus exists regarding the need for synthetic carriers for energy storage (Fraunhofer IWES 2010). Yet, objection against their use for energy storage purposes persists in view of conversion losses, which are particularly high for synthetic fuels that require an additional conversion step (see chapter 1.2) (Agora Verkehrswende 2017).

3.7.2. Need of additional RE-capacities (B.2)

Thesis: "The production and use of hydrogen and synthetic fuels will require additional power generation capacities."

In the previous chapter, the role of hydrogen and synthetic fuels as means to reduce power losses by using excess electricity was discussed. In contrast, various studies indicate that a sole operation of plants for producing hydrogen and synthetic fuels in times when excess electricity is available is not economic (Agora Verkehrswende et al. 2018). Therefore, additional power generation capacities are needed to assure sufficiently high operation hours. This, in turn, leads to the need for more RE generation to assure a clean electricity supply and to minimize the carbon footprint of hydrogen and synthetic fuels. Several arguments indicate that this additional need for RE capacities goes in hand with negative effects. First, the geographical heterogeneities in the power generation potential could be reinforced. Second, RE plants, particularly on-shore wind parks, face growing public resistance which is expected to increase with an additional need for RE capacities. However, acceptance could be improved by focusing instead on the installation of off-shore wind parks and small-scale PV solar power plants that are characterized by a lower degree of objection (Kress, Landwehr 2012). Notwithstanding, public resistance of tapping more renewable energy sources remains a relevant argument due to the limited potential of off-shore wind power and the resulting need to install higher capacities of wind turbines inland (Fraunhofer ISE 2013).

3.7.3. Use in road transport (B.3)

Thesis: "The need of hydrogen and synthetic fuels as an electricity storage option enables their use in the road transport sector."

In the following, this thesis is analysed separately for synthetic fuels and hydrogen.

Synthetic fuels for road transport

The approval of utilising synthetic fuels for road transport based on the fact that such energy carriers might be needed for storage purposes in the future is discussed controversially. The most prominent argument against such a conclusion is the need for fossil fuel alternatives in other sectors that are characterized by a lower availability of potential alternatives than the road transport sector. This mainly refers to air and water traffic. In addition, these sectors will face an increasing energy demand that will further increase competition on synthetic fuels (International Civil Aviation Association (ICAO) 2016). In view of the low energy efficiency of the production process and the generally limited potential of synthetic fuels, a use in road transport is not reasonable, as argued by opponents of synthetic fuels for ICEVs.

Hydrogen for road transport

One central argument for using hydrogen for road transport in an FCEV is the higher energetic efficiency in comparison to transforming hydrogen into synthetic fuels for ICEVs (see chapter 1.2). In addition, hydrogen is a more efficient medium for energy storage than synthetic fuels, since less conversion steps are needed. However, hydrogen production is expected to be limited in the future which in turn may result in conflicts of interests with other sectors such as the chemistry industry (Agora Verkehrswende et al. 2018). Furthermore, a reconversion of hydrogen into electricity is more efficient than its use in FCEVs, let alone a further transformation into synthetic fuels. These arguments militate against the use of hydrogen in road transport.

In terms of the economic feasibility of utilising hydrogen and synthetic fuels as energy carriers for the road transport sector, significantly higher costs are predicted compared to the direct electrification by use of BEVs. According to a study of the Federal Ministry of Transport and Digital Infrastructure (2014), however, using hydrogen and synthetic fuels in different sectors can reduce the overall system costs due to a collaborative utilisation of production and distribution infrastructure.

In view of the restrictions described above, sector coupling of energy and transport in terms of using hydrogen and synthetic fuels is potentially feasible but more attractive for sectors with less alternatives for fossil energy carriers at disposal.

3.8. Infrastructure (cluster C)

A suitable infrastructure is an essential requirement for assuring a smooth implementation of a new technology in the road transport sector. According to the German Petroleum Industry Association, there are currently more than 14,000 gas station operating in Germany that ensure a secure supply with gasoline and diesel for ICEVs. In comparison, only around 4,000 publicly accessible charging stations and less than 50 hydrogen refuelling stations were installed by the end of 2017

(Bundesnetzagentur 2018). Thus, it is evident that the current infrastructure does not yet allow for a large-scale implementation of neither BEVs nor FCEVs. The following chapter discusses the role of infrastructure in the debate around the energy transition of road transport and covers advantages and disadvantages of implementing parallel infrastructures for FCEVs and BEVs, the respective costs as well as the potential of using existing petroleum and gas infrastructure.

*Figure 18*Figure 17 depicts the general structure of this cluster and indicates which of the argument groups the following chapters refer to.

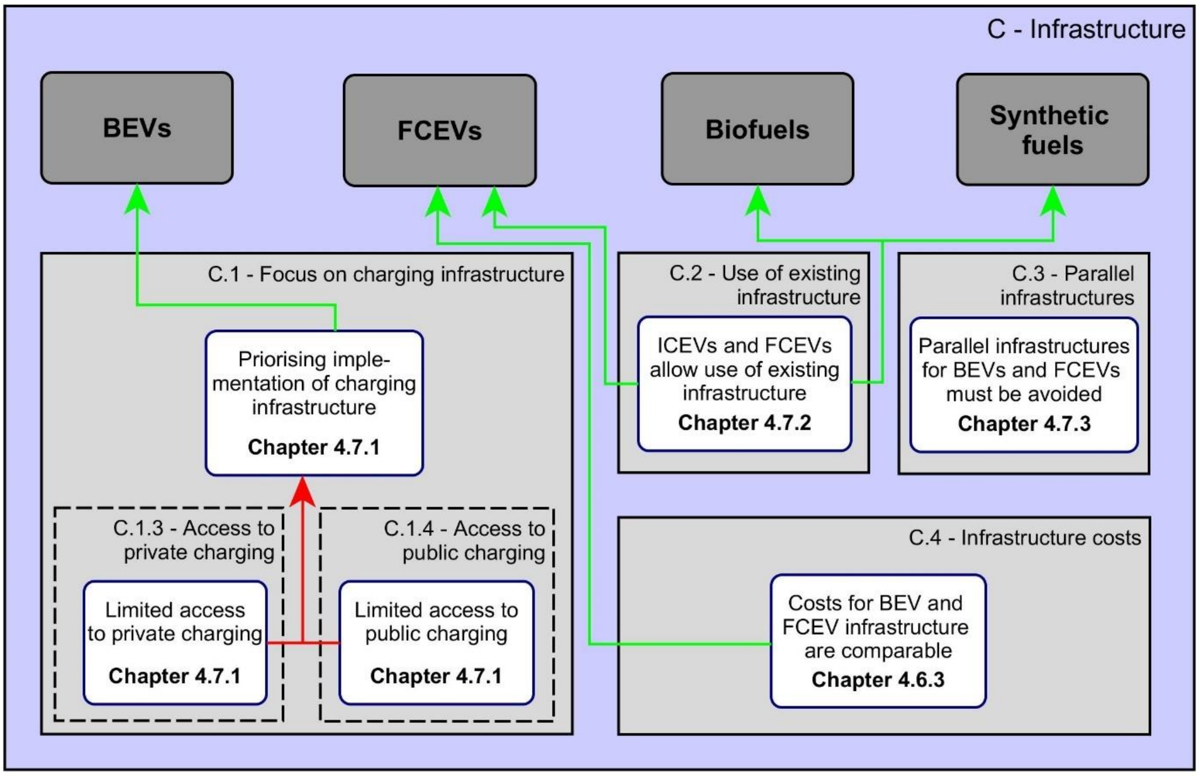


Figure 18: Structure of cluster C displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.8.1. Focus on charging infrastructure (C.1)

Thesis: "The extension of charging infrastructure for BEVs is to be prioritised due to the already progressed implementation."

This thesis represents a pro-argument for focusing on BEVs rather than on FCEVs. The higher number of charging stations is brought forward as the central argument supporting it. However, the insufficient total number of charging stations and the resulting lack of universal access contradicts this thesis. In the following, this argument is looked at from two different perspectives; access to private and access to public charging infrastructure.

Access to private charging infrastructure

Three central arguments hinder access to private charging. First, in areas or buildings characterized by a high population density such as apartment blocks in cities, the available space for the implementation of charging stations is limited. Second, the current legal framework in Germany represents a hindering factor (Expert Council on the Environment 2017). The main restriction identified in this context is the need of approval of the house owner for the installation of a charging station (Schaufenster Mobilität 2015). However, notarial clauses can be applied as rules of exception. In addition, these legal restrictions can be removed in the long term by the enacting of respective laws. Therefore, a contradictory legal framework is only seen as a factor preliminary hindering access to private charging infrastructure.

Access to public charging infrastructure

Limitations in the access to public infrastructure arise mainly from a slow rate of installation which is partly due to difficulties in the approval of fast charging stations. These difficulties refer to land development plans and other local restrictions hindering the installation of such stations (Schaufenster Mobilität 2015). At the same time, various options are discussed for integrating public charge points in already existing infrastructure and hereby increasing the accessibility to public charging infrastructure. Examples include the installation of street lamps providing both light as well as electricity for BEV charging and the modification of already existing distribution boxes into charging stations (RheinEnergie AG 2018).

Referring to the thesis stated above, it can be concluded that charging stations are already being implemented on a large scale as compared to the installation of a hydrogen refuelling infrastructure. A preference of one technology over the other, however, cannot be derived from this current head start, as will be further discussed in the following chapters.

3.8.2. Use of existing infrastructure (C.2)

Thesis: "Synthetic fuels and biofuels allow for a continuous use of the existing petroleum and gas infrastructure for distribution."

The possibility of using existing infrastructure is one central argument for considering synthetic fuels and biofuels in the energy transition of transport (Arlt 2017). In addition to using existing gas stations, the distribution system of the natural gas infrastructure could be utilised for the transport of PtG-products such as hydrogen or synthetic methane (e-mobil BW GmbH 2017). However, hydrogen could only be integrated to a limited extent with a share of 5% to 15% of the total gas volume (Fischedick, Grunwald 2017). Thus, the usage of synthetic fuels implies the need of extending existing infrastructure which relativizes the thesis stated above.

3.8.3. Parallel infrastructures for BEVs and FCEVs (C.3)

Thesis: "The installation and operation of parallel infrastructures for BEVs and FCEVs must be avoided."

This normative statement is based on the premise that the construction of parallel infrastructures will automatically result in higher costs. However, the installation of parallel infrastructures would actually be relatively cost-efficient compared to other infrastructure projects, as Robinius et al. (2018) pointed out. Moreover, economies of scale are expected to have a reducing impact on the costs of infrastructures. Hence, if the number of FCEVs increases to more than 15 million vehicles, the costs for an FCEV infrastructure would in fact lie below the costs for a corresponding charging infrastructure for a BEV fleet of a comparable size.

Another argument against the avoidance of parallel infrastructures is the dogma of technology openness, as argued by the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (2016): Technology openness is needed “in order to leave open a room of manoeuvre for new disruptive innovations”. Regarding the construction of parallel infrastructures, such a room of manoeuvre would be represented by the provision of a suitable infrastructure for a large-scale implementation of both BEVs and FCEVs. In the debate around the energy transition of transport, the relation between insufficient infrastructure and low technology uptake is often referred to as a chicken-and-egg problem. In accordance with the technology openness concept it is argued that providing a suitable infrastructure is needed first to trigger technology adaptation.

Regarding hydrogen refuelling infrastructure, this solving strategy of the chicken-and-egg problem is already applied with the *National Innovation Programme Hydrogen and Fuel Cell (NIP)* that currently installs a nationwide network of hydrogen stations in order to activate the market of FCEVs (NOW GmbH 2016). Thus, an installation of parallel infrastructures is already taking place, which represents an argument against the normative dogma of avoiding such a coexistence of networks of energy supply for road transport.

3.8.4. Infrastructure costs (C.4)

Thesis: “The costs for the required infrastructures for BEVs and FCEVs are comparable, which leads to no competitive advantage of either technology in this regard.”

As the thesis above indicates, this chapter focuses on the infrastructure costs related to BEVs and FCEVs. The argument that infrastructure related costs are of the same magnitude for both technologies is supported by a reference to the high costs of fast charging stations that amount to around 40,000€ per station, significantly higher than the costs for conventional charging stations (Öko-Insitut 2017). This is critical since mainly fast charging stations are required for a future charging infrastructure able to provide electricity for all transport services, particularly for long-distance travel. However, as mentioned above, infrastructure costs for FCEVs are only competitive if a high number of such vehicles is in operation. Given the various limitations of hydrogen production (as discussed in the previous chapters), FCEVs are expected to cover only a small fraction of road transport. In view of this outlook, positive effects of economies of scale are less likely to have a significant impact. Besides, a high workload is required to assure an economic operation of a hydrogen refuelling station, which is again bound to a large vehicle fleet (Robinius et al. 2018). Independently from vehicle numbers, however, the costs of installing a hydrogen refuelling station have been reduced by half between 2008 and 2014 and amount to around one million euros per station (NOW GmbH 2017).

3.9. Economic feasibility (cluster H)

This argument cluster deals with the economic feasibility of the analysed technology options for realising the energy transition of transport. In this framework, the concept of *Total Cost of Ownership (TCO)* is introduced which refers to all costs related to the vehicle purchase, the necessary charging or fuelling infrastructure as well as the vehicle operation such as service and repair costs (Öko-Insitut e.V. et al. 2016). TCO is used to compare new to existing drive technologies (BEVs and FCEVs vs. ICEVs) with a focus on the user perspective. This chapter looks at different factors influencing TCO dynamics with the aim of describing how they affect the respective technologies. It is structured in accordance with the composition of the argument map, as visualised in *Figure 19*.

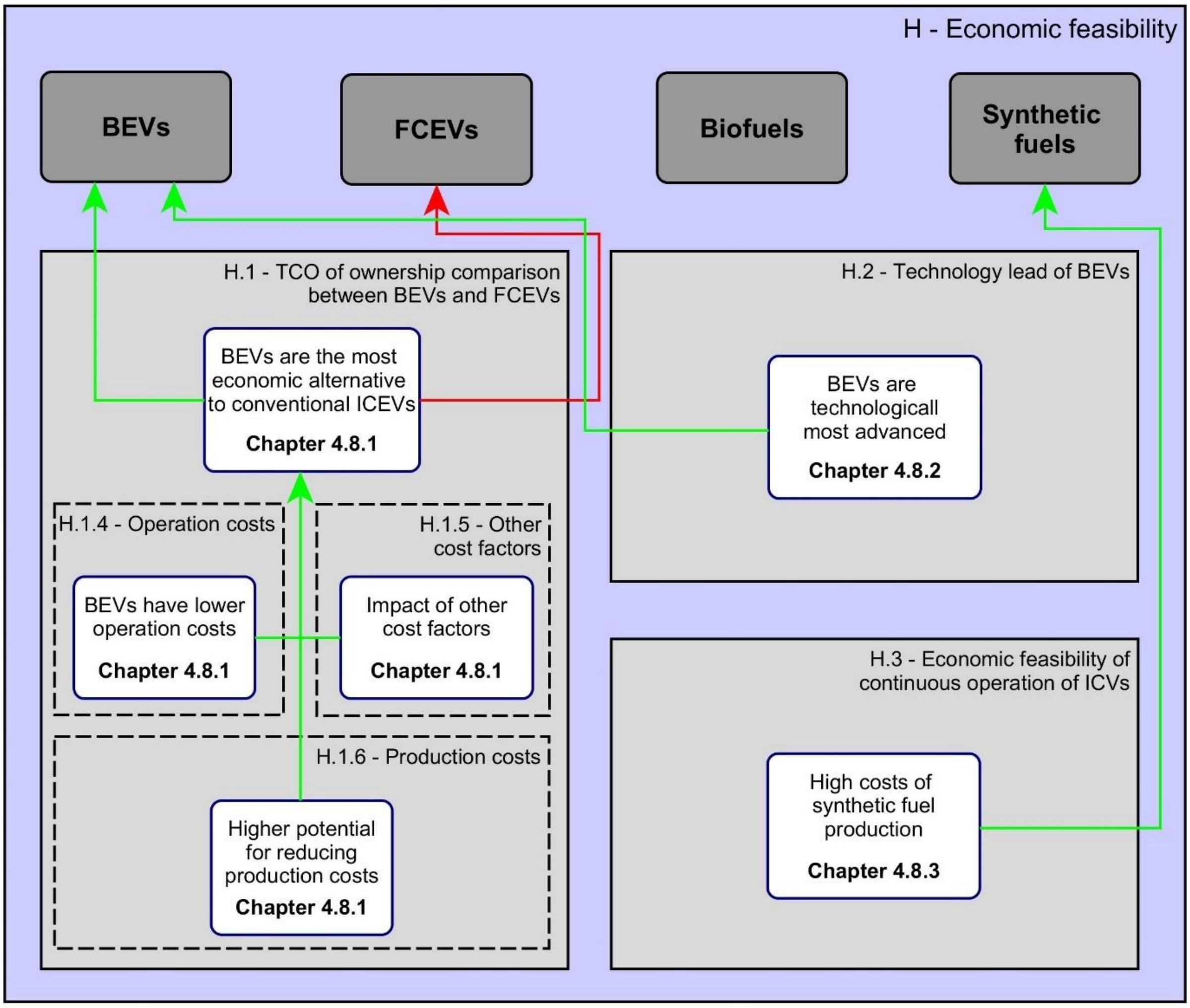


Figure 19: Structure of cluster H displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.9.1. Comparison of Total Cost of Ownership (H.1)

Thesis: "The TCO of BEVs are lower in comparison to other technologies."

Various arguments are brought forward, both supporting and objecting this thesis. In the following, these arguments and their implications are described, integrating them into sub-groups which refer to operation costs, production costs and other factors influencing the TCO.

Operation costs

In the medium term, it is expected that operation costs of BEVs will fall below the level of other drive technologies. This prospect is grounded on the argument that lower energy costs will allow for a more economic operation of the vehicle. In this context, the coupling of BEVs with the power grid through bidirectional charging, which is discussed in chapter 3.6.2, plays a crucial role, since it enables the participation of BEVs in the control market and therefore offers an option to generate income. However, bidirectional charging can reduce the lifetime of the battery and in turn counteracts the reduction of operation costs. In addition, with flexible electricity prices, the timing of charging of BEVs would allow for a relocation of charging processes to times of lower prices and therefore further reduce costs of operation (Geske 2016).

Furthermore, it is argued that BEVs would be less affected by potentially higher energy taxes due to the more efficient operation (see chapter 1.2). Such an increase of taxes might result from a reduced income of fossil fuel taxes in conjunction with a decarbonization of the road transport sector and lower demand for carbon-intensive motor fuels (Fischedick, Grunwald 2017). Objecting this logic of argumentation, other means of compensating for lower fossil fuel taxes exist such as a sector independent carbon tax or a poll system that puts a tax on the use of road infrastructure instead of a specific energy carrier (Agora Verkehrswende 2017). In this case, no drive technology would have a competitive tax advantage in terms of its operation costs.

Production costs

In the future, the potential of reducing TCO for BEVs is evaluated to be higher compared to FCEVs and ICEVs. The main cost factor of a BEV is the battery production, which is characterized by continuously falling prices (Nykvist, Nilsson 2015). Improvements in battery design and economies of scale effects in consequence of a mass production of battery units are expected to lead to lower costs per battery produced (International Council on Clean Transportation (ICCT) 2016).

This large-scale production of batteries also entails an increase in demand of scarce materials which might result in higher prices of these materials (see also chapter 3.4.1). However, the costs for material supply only represent a marginal fraction of the overall battery costs and therefore are not expected to significantly influence production costs in the future (Bloomberg 2017).

Other cost factors

Two other important factors impact the TCO of BEVs: an unpredictable second-hand market and battery usage at the end of its lifetime. Regarding the value of used BEVs, no reliable data exists yet due to a low number of BEVs in the second-hand market. Therefore, a coherent comparison of TCO is not feasible (Öko-Institut 2017a). Usage after lifetime is another factor that needs to be taken into account when analysing TCO. For instance, batteries can be used as stationary storage devices at the end of their lifetime, which increases the overall economic competitiveness of BEVs (Agora Verkehrswende 2017).

As shown, the prospect of lower TCO of BEVs compared to FCEVs and ICEVs depends on partly unpredictable market dynamics which are subject to technological, political as well as social framework conditions.

3.9.2. Technology development (H.2)

Thesis: "In comparison to other technologies, BEVs are characterized by the most advanced technological development."

The level of technological development of the analysed energy carriers and the respective drive technologies differs greatly and has significant impact on the overall cost of their application. While ICEVs have been integrated into the whole transport sector, the technological development of carbon neutral fuels for the operation of ICEVs is still at an early stage and characterized by comparatively high costs (see also chapter 3.9.3). Likewise, FCEVs have not yet been integrated into the automotive market to a relevant extent. In addition, hydrogen production is currently a relevant cost factor hindering a large-scale uptake of this technology (NOW GmbH 2017).

In contrast, BEVs are characterized by the most advanced technological development and are already established in the German automobile market and represent a continuously growing share of the vehicle fleet (Federal Office of Motor Traffic 2018). In view of voluminous direct electrification programmes of German OEMs, the trend of increasing numbers of BEVs in the road transport sector is expected to continue resulting in economies of scale that can lead to a further reduction of costs.

3.9.3. Economic feasibility of continuous operation of ICEVs (H.3)

Thesis: "The high costs of producing synthetic fuels are brought forward against the continuous operation of ICEVs in the road transport sector."

The TCO of ICEVs depend largely on the cost of decarbonizing the fuels used. Both biofuels as well as synthetic fuels are characterized by higher costs of production compared to conventional motor fuels. In particular, the economic feasibility of power-to-gas and power-to-liquid production facilities is not proven (Agora Verkehrswende 2017). This is partly related to conversion losses that imply a comparatively high electricity demand and therefore a strong dependence on price developments (Federal Ministry of Transport and Digital Infrastructure 2014). In fact, the production and use of synthetic fuels in combustion engines is characterized by an 80% lower efficiency than the direct use of electricity in a BEV. Another significant cost factor for the production of synthetic fuels is the supply of carbon dioxide, especially when captured from air (Agora Verkehrswende et al. 2018). In contrast, the costs of hydrogen as the second important input substance are estimated to lie in an economically viable range between 8,9 ct/kWh and 19,1 ct/kWh in the future (Robinius 2016). However, it is argued that directly using hydrogen in an FCEV instead of a further transformation into synthetic fuels is more reasonable from an economic perspective.

In terms of factors positively affecting the economic feasibility of synthetic fuel production, sector coupling can help to reduce overall system costs, as discussed in more detail in chapter 3.7. Thus, both gas and power industry could benefit from the creation of a new market for synthetic fuels and exploit new business segments while utilising existing gas and electricity infrastructure (Federal Ministry of Transport and Digital Infrastructure 2014).

3.10. Domestic value and labour effects (cluster I)

The automotive industry in Germany has a crucial role regarding the number of jobs related to the production, distribution, sale and operation of vehicles. In 2016, almost 800,000 people were directly or indirectly employed in this sector which provides an indication of its importance for the German economy (Deutscher Bundestag 2017). Thus, a central concern communicated in the debate of the energy transition of transport is the possible loss of jobs in vehicle manufacture as a result of a shift of drive technologies. In this chapter, this concern is analysed from different angles focusing on the effects on the domestic value and labour market.

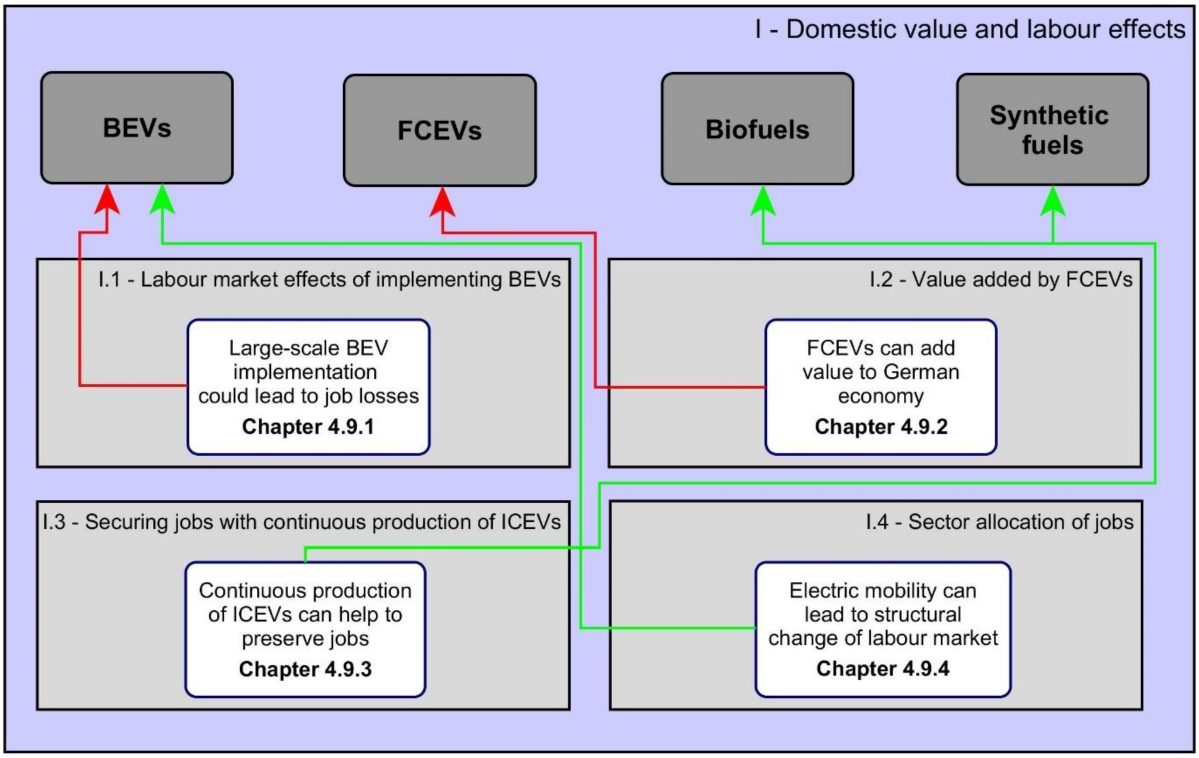


Figure 20: Structure of cluster I displaying its argument groups and argument sub-groups with the main theses and references to the respective chapters in the text (own creation)

3.10.1. Labour market effects of implementing BEVs (I.1)

Thesis: "Focusing only on BEVs entails the risk of negative socioeconomic effects and job losses."

The impact of shifting from conventional vehicles to BEVs in terms of labour market effects is discussed controversially. Two arguments supporting the thesis above are frequently brought forward: first, the general complexity of manufacture decreases when substituting combustion engines with electric motors since less components are required (Peters et al. 2012). Hence, it is argued that considerably less workforce is required to build a BEV compared to an ICEV, which would consequently lead to a reduction of jobs in the automotive industry.

The second argument refers to the production of the battery which represents the most work-intensive step of manufacturing a BEV. The production of batteries is geographically concentrated in few countries, mainly Japan, South Korea and China, with the latter holding a share of around 43% of the global battery production capacity (McKinsey 2017). Therefore, the domestic labour market is expected to be negatively affected by an increased share of BEVs in the vehicle fleet. An objection of this argument is the possibility of establishing a domestic battery industry to secure jobs related to the automotive industry in a BEV-based future of the road transport sector (Fraunhofer ISI 2017). The prospect of a national or European battery production is supported by the fact that considerable BEV research and development is already taking place: after Japan, Germany has the highest number of patents in the field of BEVs (Fraunhofer ISI 2017). Contradicting this argument, the head start of other countries is to be considered as well as their competitive economic advantage in terms of production costs. In addition, battery production is generally characterized by a high degree of automatization that is expected to increase in the future and counteract the intention of securing jobs in the automotive industry (Deloitte 2017).

3.10.2. Value added by FCEVs (I.2)

Thesis: "The production of FCEVs could help to add value to the German economy and create jobs."

In contrast to BEVs, the implementation of FCEVs is viewed as a chance to add value to the German economy and create new jobs in the automotive industry (Schade et al. 2014). In the field of fuel cell development, Germany is already among the global market leaders. Focusing on this technology can thus reinforce this position and lead to positive effects on the labour market, especially when considering the less developed market of FCEVs. Therefore, a promptly establishment of a FCEV production infrastructure has the potential for shifting from fossil to electric mobility without the negative socioeconomic effects of BEV implementation. However, it has to be considered that, similar to BEVs, the complexity of FCEVs is lower compared to ICEVs with several workforce-intensive vehicle components becoming obsolete (such as the exhaust system) (Peters et al. 2012).

3.10.3. Securing jobs with ICEVs (I.3)

Thesis: "The continuous operation of ICEVs can lead to a preservation of jobs in the automotive industry."

A central argument for a continuous operation of ICEVs is the possibility to secure jobs that are related to the manufacturing of the more complex drive technology. Thus, the consideration of ICEVs in the energy transition of transport is viewed as a strategy to maintain Germany´s status as a global player in the automotive industry. This position is contradicted by the reference to the dependence on international market developments. Currently, around 60% of all vehicles produced in Germany are exported, indicating the impact a shift of demand in other markets can have on the domestic automotive industry sector (Fraunhofer ISI 2017). In key markets such as India and China, a trend to electrify road transport can be observed, which eventually is expected to result in a decrease of ICEV demand that could in turn lead to lower production levels in Germany (International Energy Agency (IEA) 2017).

The prospect of securing jobs by limiting a shift towards electrified drive technologies and maintaining ICEV production in Germany is supported by the possibility of focusing on hybrid technologies. By combining different electric and conventional drive technologies, a successive electrification is strived for that secures the ongoing operation of ICEVs in the short term and can have a positive impact on the labour market due to the increased complexity of vehicle manufacture (Fraunhofer ISI 2017). It is argued, however, that a delayed transition from ICEVs to BEVs by promoting hybrid technologies entails the risk of additional job losses in the long term (International Energy Agency (IEA) 2016).

3.10.4. Sector relocation of jobs (I.4)

Thesis: "The energy transition of transport requires a structural change which can lead to the creation of new jobs in other sectors."

The large-scale implementation of BEVs will most likely result in job losses in the automotive industry, as discussed in chapter 3.10.1. Yet, looking at the general labour market, most studies analysing the socioeconomic effects of a transition from ICEVs to BEVs indicate positive net effects (Fraunhofer ISI 2017). It is assumed that the electrification of road transport by means of integrating BEVs in combination with realising the mobility transition creates new business models and increases demand for labour in sectors not directly linked to the automotive industry. An example for such inter-sectoral "spill-over-effects" is the use of vehicle batteries for storage of excess solar power, which adds value to the solar PV industry and can trigger socioeconomic benefits (International Energy Agency (IEA) 2016).

Hence, it can be concluded that job losses in the automotive industry are likely to occur, but the demand of labour in other sectors in consequence of new applications and business models may offset these losses.

4. Uncertainty analysis

4.1. Motivation and goals

In the framework of this analysis, arguments for and against different drive technologies are researched and contextualised. This process is characterized by uncertainties arising from various origins: first, the analysis is based on assumptions and premises (see chapter 3.1.1) that are subject to a certain degree of uncertainty, either because they refer to future developments that are not yet predictable or because they represent simplifications of reality. Second, arguments itself might be uncertain if the analysed literature reveals contradictory research results or if the conclusions drawn from them are ambiguous. Third, uncertainties arise from dynamics outside the framework of the argument analysis, which directly or indirectly impact the future viability of certain arguments and their implications.

As seen, uncertainties are inherent to the analysed system on different levels. The motivation for performing an uncertainty analysis is therefore primarily to identify where these uncertainties are located in the system and which specific characteriztics they are distinguished by. In the following, the main goals of this process are listed:

- *Identifying knowledge gaps:* Uncertainties can give a hint on potential knowledge gaps and indicate where further research could help to close such gaps. In this context, the uncertainty analysis aims at disclosing aspects of the debate that are unknown.
- *Characterizing uncertainties:* By classifying uncertainties in terms of their location in the system, i.e. in the argument map, their uncertainty level and their nature, a better characterization is strived for that allows for a deeper understanding of their context.
- *Defining decision framework:* The identification and characterization of uncertainties is intended to help setting a decision framework by being able to better assess what is known, what can potentially be known in the future and what will most likely remain unknown.

In the following chapter, the applied process of identifying uncertainties is described.

4.2. Identification of uncertainties

The process of identifying uncertainties consists of three different steps, as explained below:

1. *Scanning map:* First, the map itself is the main object of investigation in the framework of the uncertainty analysis. All arguments are screened regarding their probability with the aim of identifying those that are characterized by controversial input data, i.e. contradictory research results, and conclusions based on uncertain premises which are not necessarily located within the scope of the map.
2. *Expert opinions:* As a second step, internal and external experts are consulted and requested to list relevant uncertainties in the discussion of the German transport transition, particularly regarding the energy transition of transport. Frequently expressed or similar uncertainties are

summarised and generalised. A complete list of all institutions interviewed in this context can be found in appendix C.1.

3. *Underlying uncertainties:* Finally, the scope is broadened further by focusing on factors that are not directly influencing the debate but could potentially be of major importance for the development of the road transport sector.

The result of these three steps is a list with identified uncertainties that are then characterized in more detail with respect to their location, level and nature, as discussed in the following chapter.

4.3. Characterization of uncertainties

In total, 18 uncertainties have been identified in consequence of the process described in the previous chapter. Each of these represents a premise, argument or conclusion that entails a certain level of uncertainty which affects the energy transition of the German road transport sector. In the following, three examples of these uncertainties and their relevance for the debate are presented. A list of all identified uncertainties including their respective characteriztics can be found in appendix C.2. With respect to the time frame of this thesis, it is noted that the list represents a preliminary overview without claim of completeness.

4.3.1. Example: Political decision-making

The unpredictability of political decision-making represents a main uncertainty that affects the debate around the energy transition of transport in multiple ways. Political answers are required for certain questions, such as:

- How will potential driving bans, as discussed currently, affect user behaviour?
- Which financial incentives will support or penalise certain drive technologies (such as carbon tax, subsidies, etc.)?
- Which influence will the automotive industry have on political decision-making in the future?

These questions indicate that political decisions can have a wide range of possible effects which not necessarily reflect the most economic, technologically reasonable or socially just solution at disposal. Various reasons for this political uncertainty can be identified. One is seen in the discrepancy of time frames: the energy transition of transport is a long-term process which by far exceeds the horizon of legislative periods. Furthermore, conflicting interests characterize the political debate which lead to disagreement among the stakeholders as to which technology path to follow.

This is reflected in the evaluation of the uncertainty of political decisions for which the uncertainty matrix introduced in chapter 2.3 is used:

Table 5: Uncertainty matrix depicting characteriztics of the uncertainty of political decision-making (own creation)

Location	Level				Nature		
	Level 1: Shallow uncertainty	Level 2: Medium uncertainty	Level 3: Deep uncertainty	Level 4: Recognised ignorance	Ambiguity	Epistemology	Ontology
System boundary			x		x		x
Conceptual model							

Computer Model	Model structure							
	Parameters inside the model							
	Input parameters to the model							
Input data								
Model implementation								
Processed output data								

As seen in *Table 5*, the location of the uncertainty of political decisions is identified to be beyond the system boundary, since the political dimension itself is considered only to a limited extent but rather represents a framework condition for the evolvement of the argument map. Due to the generally high degree of unpredictability of political developments as well as their impact on multiple aspects of the debate, the level of uncertainty is set at level 3 (deep uncertainty). Regarding the nature of uncertainty, political decisions both contain elements of ambiguity and ontology. Ambiguity, in this context, refers to the arbitrariness of interpreting certain information which form the basis of a political decision. On the other hand, political decisions have also an ontological dimension since certain future developments are simply unknown. Examples for such ontological aspects are the change of majorities in parliament or the occurrence of tipping points that will fundamentally change the foundation of political decision-making.

4.3.2. Example: Range of BEVs

As discussed in chapter 3.3, BEVs are currently not able to provide sufficient ranges for all transport requirements but, as a result of technological improvements, ranges have been increasing continuously over the last years, trend that is expected to continue in the future. These improvements were mainly the consequence of better storage capacities of batteries. However, the potential of further increasing storage capacity of batteries is characterized by a certain degree of uncertainty and entails questions, such as:

- Which upper limit exists for the improvement of battery storage capacities?
- What is the potential of innovative battery solutions such as solid-state batteries?
- Which economic effects will a higher range imply?

These questions are subject to uncertainties that result from the unpredictability of technological developments. Consequently, the potential of increasing BEV ranges is an uncertainty of the system´s input data, as depicted in *Table 6*.

Table 6: Uncertainty matrix depicting characteriztics of the uncertainty of BEV range developments (own creation)

Location	**Level**				**Nature**		
	Level 1: Shallow uncertainty	Level 2: Medium uncertainty	Level 3: Deep uncertainty	Level 4: Recognised ignorance	Ambiguity	Epistemology	Ontology
System boundary							

Conceptual model								
Computer Model	Model structure							
	Parameters inside the model							
	Input parameters to the model							
Input data			x				x	x
Model implementation								
Processed output data								

Regarding the level of uncertainty, the range potential of BEVs is assessed as “medium uncertain” (level 2) since historical developments as well as physical limitations allow for a rather clear prediction of the future potential of BEV ranges. However, disruptive and innovative battery technologies could evolve and fundamentally shift technological boundaries. This possibility refers to the ontological nature of battery development, which also has an epistemological dimension, since further research could help to close the existing knowledge gaps (regarding the development of batteries).

4.3.3. Example: Decarbonization of power sector

A decarbonized power sector is an underlying premise for the comparison of different drive technologies in this work (see chapter 3.1.1). BEVs, hydrogen and particularly synthetic fuels are only feasible options for decarbonizing the German road transport sector if the required electricity is produced with a low carbon footprint (Agora Verkehrswende et al. 2018). However, the current share of renewable electricity generation in Germany amounts to only 33% (Federal Statistical Office 2018). Even though an uptake of renewable energies in the electricity mix is expected, uncertainty remains as to which extent a clean electricity supply will be realised in the considered time-period. This uncertainty entails questions such as:

- How quickly will renewable energies be integrated into the power sector?
- What is the future share of renewable energies in the power mix?
- Will a large-scale integration of renewable energies lead to grid overloads or insecurities of supply?

These questions display both an epistemological as well as an ontological nature of uncertainty: new technologies for power generation are not sufficiently investigated yet (epistemology) and, at the same time, are bound to social and technological variabilities beyond influence (ontology). Potentially increasing public resistance against the installation of wind parks is an example for such a social variability that cannot be fully predicted and therefore remains uncertain. In addition, this uncertainty has a global dimension since the carbon footprint of using the analysed drive technologies is affected by the power mix of both the country of production and operation (see chapter 3.5).

The supply of electricity represents an input to the system since the analysed drive technologies rely on electrical power at different stages of use. Therefore, the decarbonization of the power sector is an uncertainty located in the input data of the system. The level of uncertainty is evaluated as medium uncertain (level 2). *Table 7* below visualises the uncertainty matrix of decarbonizing the power sector.

Table 7: Uncertainty matrix depicting characteriztics of uncertainty of decarbonizing the power sector (own creation)

Location		**Level**				**Nature**		
		Level 1: Shallow uncertainty	Level 2: Medium uncertainty	Level 3: Deep uncertainty	Level 4: Recognised ignorance	Ambiguity	Epistemology	Ontology
System boundary								
Conceptual model								
Computer Model	Model structure							
	Parameters inside the model							
	Input parameters to the model							
Input data			x				x	x
Model implementation								
Processed output data								

5. Discussion of results

More than 400 arguments and theses for and against the use of the analysed technologies were identified and mapped according to their logical relevance for decarbonizing road transport in Germany. The main findings of this analysis are described in the following with the aim of indicating the central benefits and limitations of each investigated technology. By presenting the external impact factors influencing the energy transition of transport, the work is put in context with the framework conditions that impact the superiority or inferiority of a certain technology. Furthermore, inherent characteriztics of the analysed arguments are explained in order to provide a better understanding of the differences in their quality. Finally, the limitations of this work are discussed highlighting gaps of knowledge and indicating potential for further research.

5.1. Technology-related findings

Three drive technologies (BEVs, FCEVs and ICEVs) and four respective energy carriers (electricity, hydrogen, biofuels and synthetic fuels) are the object of investigation. For each, relevant supporting as well as objecting arguments can be identified, of which the most predominant ones are briefly summarized and discussed in the following.

BEVs are the most advanced of the analysed technologies in terms of technological development and current market penetration. The concept of directly using electricity for powering a vehicle is characterized by a high well-to-wheel efficiency and the potential to significantly reduce carbon emissions of road transport. For most applications BEVs already provide sufficient ranges and the progressing installation of charging infrastructure is expected to close existing gaps to a wide extent. A central argument for the use of BEVs is the potential for low TCO in consequence of the comparably low energy demand for operation and expected economies of scale. Limitations have been identified regarding their use in freight road transport where long distances and the limitations of payloads imply restrictions that current BEVs are not able to address entirely. The effect of a large-scale implementation of BEVs is also discussed controversially from a socioeconomic perspective, with concerns being raised over its impact on the labour market in Germany. Additionally, challenges are expected to occur regarding the integration of large numbers of BEVs into the German electricity grid. High simultaneity of charging could potentially lead to power peaks and grid overloads, while the planned increase of RE power generation additionally reduces predictability of supply. Various strategies to address these developments are discussed, which include grid extensions, bidirectional charging and load management as well as the increase of storage capacities (which represents a central argument for the use of hydrogen and synthetic fuels in road transport). Concerns also exist over the acceptance of BEVs by the user in view of current range limitations and high purchase costs. While these restrictions will probably be overcome in consequence of technological development and higher production rates, challenges persist regarding the production of batteries due to an increasing demand for scarce resources and an energy-intensive manufacturing. Overall, the use of BEVs implies various competitive benefits over other drive technologies. Yet, certain limitations are entailed that mainly reflect current restrictions with the potential of being solved in the long term.

FCEVs are the second drive technology based on the use of electricity which is generated on-board by means of a fuel cell. This indirect use of electricity entails a central advantage: The high energy density of hydrogen as an energy carrier allows for the coverage of longer distances compared to BEVs and in this sense serves as an ideal complementation for BEVs to meet all requirements of road transport. Another benefit is the high disposability of the required resources since both electricity and water as inputs for hydrogen production are theoretically available without physical limitations (although the impacts of the required electricity generation capacities need to be considered). Provided that electricity is generated from RE sources, the carbon footprint of FCEVs can be reduced significantly, particularly since vehicle production is less resource- and energy-intensive as compared to BEVs. Another frequently communicated argument for the use of hydrogen in FCEVs is the potential of coupling the energy and road transport sector. Hydrogen is expected to be needed for energy storage in a future power system mainly based on renewable energies and therefore could also be used as an energy supplier for road transport as well. The high energy demand for production, however, poses a relevant limitation and makes the use of hydrogen in FCEVs highly disputable. Power generation, hydrogen production and the reconversion into electricity to power the vehicle entail significant losses that result in high energetic and financial costs. In view of the high energy intensity of using hydrogen for FCEVs, other applications appear more attractive such as a direct return as reconverted electricity into the power grid. Thus, the use of FCEVs in the road transport sector can most likely only complement BEVs in cases where the latter´s ability to meet transport requirements is limited.

The third drive technology considered in this work are ICEVs operated on alternative fuels, namely biofuels and synthetic fuels. Several arguments support the continuous use of this technology: existing distribution infrastructure could be used, high energy density of fuels would allow for ranges commonly demanded in road transport and the automotive industry in Germany could possibly be strengthened as a global leader in the market of ICEVs. However, ICEVs are characterized by inherent disadvantages that make a long-term use highly problematic. First, the global automotive sector displays a trend towards electrification which will most likely lead to a decreasing demand for ICEVs that would jeopardize positive labour market effects in any case. Second, several objections are stated which refer more specifically to the feasibility of biofuels and synthetic fuels as means to decarbonize ICEV operation.

While biofuels do have certain advantages such as a (theoretically) carbon neutral operation and the possibility to be produced domestically, their potential is limited due to the restricted availability of land for cultivating biomass crops. The very concept of using biomass for powering vehicles is highly controversial and leads to conflicting interests with food supply. Besides, the carbon footprint of biofuel production is in fact comparably high due to a significant energy input and the resulting carbon emissions. Only biofuels produced from organic waste products offer the potential to address both the problems of conflicting land use and a high carbon footprint, but considering the relatively low amounts of organic waste at disposal, they could only cover demand to a very limited extent.

Synthetic fuels as the second option for a decarbonized operation of ICEVs face similar challenges which are foremost related to the high energy input. The process chain of producing hydrogen by means of renewable electricity, transforming it into synthetic fuels which are then combusted in a relatively inefficient combustion engine requires energy input four to five times higher compared to the operation of a BEV (Agora Verkehrswende et al. 2018). This in turn results in very high production costs that could only partially be reduced by coupling different sectors of application and thereby reducing relative costs for production and distribution infrastructures. Consequently, both biofuels and synthetic fuels for the operation of ICEVs could potentially fill certain market niches of the transport sector (particularly of the non-road transport sector) but are very unlikely to supply the sector on a large scale.

The goal of this thesis is not to indicate which of the analysed technologies should be integrated into the German road transport sector and which should not. Instead, the main arguments for and against their respective use that currently or in the long term affect the feasibility of integration are discussed with the aim of indicating which mutual benefits and limitations exist. In this respect, it has become obvious that BEVs show relevant advantages compared to FCEVs and particularly ICEVs operated on alternative fuels. However, this does not imply that the latter should not find application. It rather provides a hint for ranking the scale of potential for application.

5.2. Findings from argument analysis

Applying argument analysis on the question of how to decarbonize German road transport lead to certain findings related to the methodology itself. In the following, these are discussed briefly.

- *Arbitrariness of argumentation:* Arbitrariness of argumentation refers to the phenomena that the hierarchic organisation of arguments is partly variable at will. That is, if an argument A objects argument B and is in turn attacked by argument C, argument C could possibly (but not necessarily) be in favour of argument A. The following practical example clarifies this: In the map (see appendix A), argument D.1.3.1 states that “BEVs have a higher potential to reduce GHG emissions of the road transport sector”. This thesis is objected by the reference to the dependence of a BEV´s carbon footprint on the electricity mix in the country of production and operation (D.1.3.3), which is in turn attacked by the fact that “even today, the operation of a BEV in Germany is characterized by lower GHG emissions compared to conventional ICEVs” (D.1.3.7). Thus, argument D.1.3.7 could also be considered as a direct support of argument D.1.3.1. The consequence of such arbitrariness of argumentation is that, when studying the map, visual indicators such as red or green arrows can influence the reader´s perception of the general degree of support or objection for a certain technology.
- *Arguments with multiple implications:* Several arguments in the debate around the energy transition of transport have multiple implications, meaning that one argument can support or object various others. For instance, the lower service expenditures for BEVs (A.1.4.9) on the one hand contradicts the thesis of a restricted user acceptance of BEVs (A.1.1) and on the other hand supports the thesis that focusing on BEVs entails the risk of negative socioeconomic effects and job losses (I.1.1). Such arguments play a crucial role since they connect different clusters of the map and display the high degree of interconnectivity of the

various aspects of the debate. They underline the need for a holistic approach and for a consideration of how interlinkages between argument can affect their respective validity.

- *Normative vs. descriptive arguments:* As stated in chapter 1.3, the goal of this analysis was to avoid normative arguments and instead follow a factual approach. In view of the consulted scientific literature that most arguments have been drawn from and are referenced to, this goal has been met to a large extent. However, a certain degree of subjectivity persists in two ways. First, the thesis that summarizes each cluster and argument group of the map (marked in blue) represents a conclusion from the previous arguments. Each thesis represents commonly communicated statements that reflect prominent, partly subjective opinions in the debate which are then fed with descriptive arguments in favour or against the considered thesis. The thesis that BEVs are not eligible for long-distance travel due to insufficient ranges provides an example (F.4.1): Being frequently communicated as a main restriction for the use of batteries, more arguments are actually contradicting than supporting this thesis (see chapter 3.3.1). A second dimension of subjectivity arises from underlying normative assumptions. That is, certain developments are preferred over others without a factual justification. For instance, it is frequently argued that the construction of parallel infrastructures for BEV charging and FCEV refuelling is to be avoided (C.3.1). However, as the argument analysis has shown, no factual argument can support this thesis. On the contrary, from an economic and technological perspective, the installation of parallel infrastructures is feasible (see chapter 3.8.3).

5.3. Limitations of the analysis

In the previous chapter, general conclusions from the performed argument analysis of the German energy transition of road transport were presented. The subject matter of this chapter are the limitations arising from its application which partly result from inherent restrictions of the methodology and partly from the characteriztics of the analysed topic. In the following, these limitations are discussed and put in context aiming at an explanation of the inherent causes and the strategies applied to address them.

- *Time frame:* As stated in the introduction to the argument map, 2050 was chosen as a reference year for the analysis in accordance with various national and international environmental programmes (see chapter 3.1.1). Yet, in consideration of the temporal reference, certain arguments are rather reflecting a status quo while others consider developments over time. Hence, the comparability of such arguments is not always assured. The following argument relation provides an example: Regarding the installation of charging stations, it is argued that the legal framework currently hinders the implementation of charging infrastructure in a private context (C.1.3.4). This argument is objected by the reference to the possibility of overcoming such present legal barriers by changing the respective laws in the future (C.1.3.7). Such temporal discrepancy in argumentation affects the quality of the respective arguments. In other words, argument C.1.3.4 refers to a verifiable status quo but neglects the possibility of change, while argument C1.3.7 implies a potential future development that is not predictable. The reason for considering both types of argument lies in the fact that the energy transition of transport, as the phrasing implies, represents a process of change rather than a direct shift from status quo to a desired scenario x. Therefore, both current limitations as well as predictions of their relevance in the future are necessary to be contemplated, even if this automatically provokes uncertainty (as discussed in chapter 4).

- *Visual limitations:* The argument map entails certain limitations in consequence of the visual structuring of arguments. The map consists of nine clusters, 34 argument groups, over 400 arguments and as many mutual connections. This leads to a relatively complex map structure, even though measures have been taken to increase its accessibility (see chapter 3.1.3). Yet, to maintain a high degree of legibility and to avoid overloading of the map, not every single possible interlinkage between arguments has been displayed, which in some respects limits the integrity of the analysis. By focusing on the most relevant interrelations, however, a clearer arrangement of arguments is achieved.
- *No consideration of political dimension:* Even though political decision-making can have an impact on almost all aspects of the debate, it was not the main object of investigation. The choice not to consider political decisions in the analysis is grounded on the approach to provide a foundation for political discussion rather than to analyse how current or future policies support or hinder certain developments. Thus, the analysed arguments are predominantly based on technological, economic, social and ecological research results. Political decisions are subject to change and are therefore not a central element of the analysis. However, they do play a role within the argument analysis for putting other arguments into context. The reference to the Federal Transport Infrastructure Plan and the financial means it provides, for example, supports the argument of an economic implementation of parallel infrastructures (C.3.6). Nonetheless, the main goal is not to reflect on current political conditions, but instead to set the framework for political decision-making.
- *Influence of (uncertain) external factors:* The analysis is influenced by multiple factors which are located outside the system boundary. That is, they are not directly a subject of the performed work but have a significant impact on the results. Above, the political dimension of the debate has already been discussed, which represents such an external factor. Furthermore, the energy transition of road transport is to be seen in an international context since markets are interconnected and thus developments in one country inevitably have an impact on another country. The automotive industry represents an ideal example: An increasing demand for electric cars in India, the exploration of new lithium mining sites in Chile, a decarbonization of the power sector in China - they would all directly impact the future of the German road transport sector: a higher international demand for electric vehicles might lead to a decrease of sales of ICEVs and weaken the German car industry, new mining sites could reduce the geopolitical dependence on scarce resources and less GHG emissions related to power generation may result in a higher ecological sustainability of battery production. Such developments are very difficult to predict and characterized by a high degree of uncertainty (see chapter 4). They are located outside the scope of analysis and therefore limit its informative value. Nevertheless, by identifying external factors and characterize the

related uncertainties, their role within the debate is acknowledged and the need for future consideration emphasized.

6. Conclusions and outlook

Which drive technologies are necessary for a successful energy transition of road transport in Germany? The goal of this thesis was not to provide a definite answer to this question, but rather to identify and contextualise the main arguments by applying the argument analysis methodology. Object of investigation was to analyse the eligibility of three central technologies: Battery electric vehicles, fuel cell electric vehicles and internal combustion engine vehicles powered by biofuels and synthetic fuels. Mapping the different arguments for and against the respective technologies as well as their interrelations was intended to provide a visual access to the topic and by categorising arguments into topic-related clusters and groups, the complexity of the debate was aimed to be illustrated. The creation of the map followed a trial and error approach: literature research led to the creation of a first map, which was then modified based on input obtained from expert interviews and internal team workshops at Reiner Lemoine Institut (a documentation of which can be found in the appendix B.4) which in turn led to a wider range of literature review. This process was repeated various times and led to the final version of the map presented in this work.

Following the argument analysis, uncertainties identified within the debate were investigated with the purpose of obtaining a better understanding of existing knowledge gaps. These uncertainties were derived from the argument map itself, but their identification was also based on surveying internal and external experts as well as studying underlying aspects that impact the debate. The characterization of the identified uncertainties regarding their location, level and nature helped to indicate which uncertainties are expected to persist and which could potentially be reduced by means of further scientific research.

Regarding the outcomes of this thesis, three central conclusions can be derived from the performed work:

1. *Ranking of technologies:* As mentioned above, analysing and displaying the main arguments characterizing the debate was aimed for instead of concluding which drive technology should be pursued for decarbonizing the German road transport sector. Notwithstanding, in view of the different arguments analysed, a ranking of technologies is deemed possible. BEVs are characterized by a multitude of advantages over the other investigated technologies and are expected to play a major role in the future road transport sector in Germany. On the other hand, FCEVs and ICEVs powered by biofuels and synthetic fuels both have valid arguments in favour of their use and thus could potentially provide a reasonable complementation of BEVs. To which extent each technology will be implemented, however, is not possible to predict and currently remains uncertain.
2. *Persistence of uncertainties:* A central finding of the argument analysis is the fact that arguments are often characterized by uncertainty which occurs on different levels within the debate around the decarbonization of road transport. These uncertainties refer to a wide range of potential developments such as technological progress, economic feasibility or user behaviour. Although they may partly be dissolved through further research, uncertainty will

continue to form a central part of the debate around the energy transition of road transport in Germany.

3. *Work in progress:* The performed analysis represents a work in progress which means that no claim is made on the completeness of the considered arguments. The depth of detail can be increased, both horizontally (in terms of exploring further topics) as well as vertically (referring to the level of detail of an argument chain). In addition, some identified uncertainties might be addressed by means of further research, while others will only dissolve over time. Therefore, a continuous adaptation of the work is required. Given the available time and the current state of research, the work on hand represents an overview of the many relevant aspects of the debate without calling for complete integrity or neglecting the space for improvement.

In view of these central conclusions, the potential for future work is deviated, which can be grouped into three areas of interest.

1. *Extension of the argument map:* The argument map is considered a preliminary visualisation of the debate. Over time, additional arguments might become relevant, existing uncertainties might be solved and even new technologies could be under consideration in the long term. Regarding the identified uncertainties, a more detailed investigation of their respective characteristics could possibly close existing knowledge gaps. In this case, the eligibility of the analysed technologies will need to be re-evaluated in the future. Thus, diverse potential exists for a future extension of the argument map.
2. *Simulation of the future German road transport:* Based on the performed analysis, scenarios can be developed to simulate the range of possibilities in terms of how the German road transport sector will evolve. The identified uncertainties can serve as indicators for defining the margins of the input values for developing such scenarios.
3. *Political analysis:* As stated before, the argument map is intended to serve as a foundation for a political discourse. In this context, an analysis of the conclusions drawn from the map could provide further insight on the topic from a political science perspective.

Realising a transition of the German road transport sector towards an ecologically, economically and socially sustainable future represents a complex undertaking, as this work has shown. The question of how a decarbonization can be achieved and which arguments are involved regarding the use of different drive technologies has been the subject matter of this analysis. The results show a tendency towards favouring direct electrification of road transport but also highlights the fact that uncertainties considerably impede the validity of certain arguments and affect the predictability of their future impact. This entails the need for further investigation of how these uncertainties can be dealt with and which scenarios could be developed that cover the widest range of future developments possible.

As seen, predictions on the future of road transport are difficult. However, in light of increasing negative effects of global warming, the general need for decarbonization remains certain which is particularly valid for the carbon-intensive transport sector. To put it in the words of the Australian environmentalist and politician Bob Brown, “the future will either be green or not at all.”

Appendix

A Argument analysis

A.1 Argument map instructions

Due to the high image depth, a digital viewing is recommended to allow for zooming in and out at will. The following guidelines are intended to support navigation through the map:

1. The map follows a top-down approach. That is, the research question and the investigated technologies are located on the top, while the arguments are organised below in clusters highlighted in different colours.
2. The argument code indicates the cluster the argument belongs to (capital letter), the respective group (Arabic number) and the argument itself by following a chronological order of Arabic numbers. In case of a further division of an argument group into sub-groups, another Arabic number is added. To provide information which argument or thesis an arrow refers to, their respective numbers are located at the beginning and the end of a thick arrow. (for further explanation see chapter 3.1.3).
3. Blue boxes represent theses and white boxes arguments in support or objection of these.
4. Red arrows indicate objecting argument relations, while green arrows refer to arguments supporting another argument or thesis. By using different degrees of thickness, arrows directly supporting or objecting the use of a technology (thick arrows) are differentiated from arrows between arguments (thin arrows).

B Methodology

In the following, further information on the argument analysis methodology is provided that is not directly relevant for the performed word. Instead, it is aimed to extend the general understanding of this methodology by specifying different argument types, explaining strategies for evaluation and providing an example of application.

B.1 Further information on the argument analysis methodology

Depending on the nature of the statements forming an argument, different types of arguments can be identified, such as convergent arguments or chain arguments. Their characteriztics are related to the logical structure of their premises and conclusions and how they relate to each other. *Table 8* gives an overview of the various types of arguments and provides an explanation of their characteriztics as well as the respective indicators (K. Covey 1985).

Table 8: Overview on different argument types (adapted from Brun, Betz (2016))

Argument type	Definition	Indicator words	Logical structure
Linked argument	At least two premises must be combined to support conclusion	And, as well as, thus, since	Premise 1: If A, then B. Premise 2: A Conclusion: B
Convergent argument	Two or more premises independently support the conclusion	Besides, as well as, also, furthermore, moreover	Premise 1: A Premise 2: B Conclusion: C
Sub argument	The argument´s conclusion is the premise of another argument	-	Premise: A Sub-conclusion: B Conclusion: C
Chain argument	Argument that contains more than one sub-argument	-	Premise: A Sub-conclusion 1: B Sub-conclusion 2: C Conclusion: D

B.2 Evaluation of arguments

One of the central goals of an argument analysis is the evaluation of the quality of the arguments put forward. The foremost goals of evaluating arguments are to first investigate whether the premises are true and, in case they are, analyse how these support the conclusion of the considered argument (Skyrms 2000). The truthfulness of an argument is frequently analysed with the help of so-called truth tables.

Truth tables provide a way to symbolize the truth or falsity of complex arguments by analysing for each argument the truthfulness of its constituent statements/premises. It therefore helps to structure the interdependences of statements that form an argument and how their respective truth or falsity affects the truth or falsity of the complex argument. A truth table of a complex argument entails a case for each combination of truth or falsity of its constituent arguments and for which of these the argument itself is true or false (Skyrms 2000). *Table 9* below depicts an example for such a truth table.

Table 9: Truth table of logical value combinations of constituent statements (adapted from Skyrms (2000))

Case	Premises/constituent statements				Conclusion statements			
	p	**q**	**~p**	**~q**	**p&q**	**~p&~q**	**pvq**	**~pv~q**
Case 1	T	T	F	F	T	F	T	F
Case 2	T	F	F	T	F	F	T	T
Case 3	F	T	T	F	F	F	T	T
Case 4	F	F	T	T	F	T	F	T

Referring to *Table 8*, the premises or constituent statements *p* and *q* can either be true (T) or false (F) (the denial of the statement, depicted by the symbol ~, is false and true accordingly). The different combinations of the premises´ logic values represent four cases that are characterized by conclusion statements with different logic values (true or false). The conclusion statements are statements that are connected by *logical connectives*, namely the words *and* (indicated by the symbol *&*) and *but* (indicated by the symbol *v*) (Skyrms 2000).

It is important to note that the fact that a conclusion is considered true does not necessarily imply that the premises for this conclusion are also characterized by an empiric truth. In the first instance, it only states that *if* the premises of an argument are considered true, then the conclusion is true as well. An evidential link between the two of them m

In a second step, different **evaluation criteria** are applied such as validity, soundness, strength and cogency of each argument is performed. The following table depicts these four evaluation criteria and their respective definition:

Table 10. Evaluation criteria for the assessment of arguments (adapted from Brun, Betz (2016))

Evaluation criteria	Definition
Validity	A valid argument cannot be false if all of its premises are true
Soundness	A sound argument is a valid argument with a high probability are
Strength	A strength argument is an invalid argument with a high probability that its premises are true
Cogency	A cogent argument is a strong argument with all true premises

The truth tables introduced above can also be used to analyse the validity of an argument. As stated, an argument is valid if the conclusion is true in every case the premises are all true. Various conclusion statements represent valid arguments depending on the logic values of the respective premises. The conclusion statement *~p&~q*, for instance, is valid only in case 4 when both premises *p* and *q* are false and, accordingly, *~p* as well as *~q* are true. Thus, truth tables are a useful tool for the evaluation of complex arguments that allows for a structured and complete representation of all possible combinations of logic values of the premises and conclusions a complex argument consists of.

B.3 Application example: Analysing the climate engineering debate

The concept of mapping arguments that form the discussion of a certain topic originates from the field of human science. It has been applied in various ways such as for analysing the logical arguing structure of the philosopher Descartes, the life-coverage of political debates of the Green Party in Germany or to an in-depth analysis of the aspects involved with the debate on climate engineering (Rickels et al. 2011). In the latter, the authors tried to display the arguments for and against the application of large-scale interventions into the climate system to countermand or at least reduce global warming. This is aimed to be achieved through two conceptually different methods: the removal of causes for climate change (CDR) and solar radiation management (SRM). CDR attempts to reduce the amount of greenhouse gases in the atmosphere and includes methods such as CO_2-capture from the air and underground storage or increasing ocean alkalinity through iron fertilization to stimulate algae growth. SRM, on the other side, refers to measures treating the symptoms rather than the causes of climate change. This includes interventions such as the injection of reflective aerosols into the atmosphere to reduce the short-wavelength rays reaching Earth in order to allow for a cooling effect in the lower atmosphere (Ginzky et al. 2011).

In their work, Rickels et al. (2011) have analysed the discussion around this highly controversial topic from a technical, economic, ecological as well as from an ethical perspective, considering social and (geo-)political effects, religious objections, material and non-material costs, environmental impacts and fundamental inherent risks. They collected and reconstructed the respective arguments for and against a deployment of CDR and SRM and pulled these together by creating an argument map on the moral controversy of the deployment of climate engineering (Betz, Cacean 2012). The map is constructed by grouping the arguments into topic-related boxes, which are then concentrated in clusters that capture the superordinate thematic field the respective boxes refer to. This concept of structuring the argument map is adapted for this work as well.

B.4 Organisational structure of team workshop

The following image visualises the approach taken for organising and conducting the internal RLI team workshop.

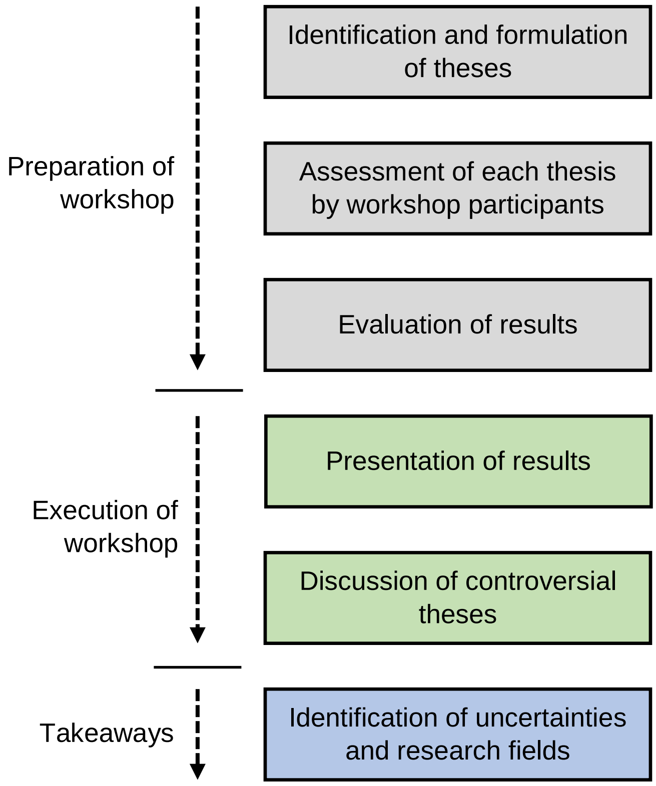


Figure 21: Concept of internal RLI team workshop (own creation)

C Uncertainty analysis

C.1 Interviewed institutions

In the framework of this work, experts from various institutions have been interviewed to identify hitherto unconsidered arguments and to obtain an understanding of the main uncertainties involved in the debate from the perspective of the different stakeholders. Out of the 11 experts interviewed, 7 hold a doctor´s degree and 3 habilitated. The following table depicts the name of the institution as well as the interview date.

Table 11: List of interviewed institutions (own creation)

Insitution name	Interview date
Agora Verkehrswende	January 26, 2018
Insitut für Betriebliche Bildungsforschung (IBBF)	January 16, 2018
International Council on Clean Transportation (ICCT)	January 10, 2018
Mercator Research Institute on Global Commons and Climate Change	February 21, 2018
M-Five	January 11, 2018
Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie	January 19, 2018
Öko-Institut e.V Insitute of Applied Ecology	February 15, 2018
Swiss Federal Laboratories for Material Science and Technology	January 25, 2018
Technische Universität Berlin	April 5, 2018
Technische Universität Trier	January 15, 2018
Wissenschaftszentrum Berlin für Sozialforschung	January 5, 2018

C.2 Uncertainty matrix

Table 12: Uncertainty matrix displaying the respective location, level and nature of uncertainty as well as the applied instrument for identification (own creation)

Uncertainty	Description	Location	Level	Nature
Origin: map				
Changing freight volumes	How will transport volumes change in light of megatrends such as digitalisation and automatization?	Input data	2	Ontology
Disruptive freight transport systems	What potential have innovative transport system and can they lead to a shift from road to other modes of transport?	System boundary	4	Epistemology, ontology
Range potential of BEVs	Will BEV be able to cover distances of conventional ICEVs?	Input data	2	Epistemology, ontology
Realisation of mobility transition	Will the mobility transition be realised and how will it affect user behaviour in the future?	System boundary, input data	3	Ontology
Development of infrastructures	How will costs affect the construction of parallel infrastructures?	Conceptual model	2	Ontology
Decarbonization of power sector	Which degree of power sector decarbonization will be achieved nationally and internationally?	System boundary	2	Epistemology, ontology
Alternative materials for batteries	Can new battery technologies solve current challenges (costs, ranges, scarcity of resources, etc.)?	System boundary	2	Epistemology
Security of resource supply	How will the market for battery relevant materials develop in the future (prices, demand, new mining)?	System boundary, input data	2	Ontology
Change of German automotive industry	Which parts of the value chain of future automotive technologies will remain in Germany?	System boundary	3	Epistemology
Potential of new biofuels (3rd generation)	What potential do new biofuels have to solve current constraints (space requirements, conflicting interests)?	System boundary, conceptual model	3	Epistemology
Reduction potential of TCO	How will input factors develop in the future (energy prices, taxes, second-hand market, etc.)?	Input data	1	Epistemology, ontology
Disruptive power generation technologies	Can disruptive power generation technologies enable a large-scale availability of clean and cheap power?	System boundary	4	Epistemology
Domestic production capacities	How realistic is the development of domestic production capacities for new drive technologies?	Conceptual model	3	Epistemology, Ontology
Origin: expert interviews				
Political decisions	Which political decisions will support or hinder the implementation of the respective drive technologies?	System boundary	3	Ambiguity, ontology
User acceptance	Will the user be willing to change and adapt his or her user behaviour?	System boundary	2	Epistemology, ontology
Tipping points	Which impact could tipping points have?	Conceptual model	4	Ontology
Origin: underlying uncertainties				
International development	How will the international landscape develop regarding demand, production locations, market player, etc.?	Input data, conceptual model	2	Epistemology, ontology
Climate change dynamics	Which impact would quickly increasing negative effects have on the German transport transition?	System boundary	2	Ontology

D List of arguments

In the following table, all arguments displayed in the argument map are listed with their respective code, title, description and reference. It is intended to serve as a comprehensive list of reference.

Table 13: List of arguments with respective code, title, description and reference (own creation)

Argument code	Argument title	Argument description	Reference
Cluster A: User acceptance and behaviour			
A.1.1.	Acceptance of BEVs	BEVs are characterized by a lower user acceptance as compared to alternative drive technologies.	Thesis
A.1.2.1	Comfort of charging	The restricted range of driving entails a frequent charging of a BEV and reduces the comfort of usage.	Thesis
A.1.2.2	Home charging	The possibility of charging in a private context increases the comfort of usage.	Fraunhofer ISE 2011
A.1.2.3	Behaviour change	Assuring the availability for usage (by charging the battery) requires a behaviour change in comparison with the use of conventional vehicles.	Conclusion
A.1.2.4	Quiet electric motor as security risk	The low levels of noise emissions of an electric vehicle at low speeds are preceived as a potential security risk factor.	Duddenhöffer 2013
A.1.2.5	Increased comfort of driving	Electric vehicles are characterized by a higher comfort of driving due to the characteriztics of an electric motor as compared to ICVs.	Conclusion
A.1.2.6	Routine character of travel behaviour	The requirement for a change of bevaviour is that it allows for the establishment of a a new routine, since the will of changing user bevahiour is otherwise fairly low.	Canzler 2018
A.1.2.7	BEVs aggravate routine establishment	The restricted range of BEVs and a still limited charging infrastructure aggravates the establishment of a routine behaviour.	Canzler 2018
A.1.2.8	Low noise operation	The noise emissions of an electric vehicle are lower than of an ICV.	EAFO 2017
A.1.2.9	Acceleration	An electric motor allows for a higher accelaratiion compared to a combustion engine.	Grunditz 2016
A.1.3.1	Ignorance of the user	Low acceptance of BEV-use is partly due to gaps of knowledge.	Götz et al. 2012
A.1.3.2	Providing information	User acceptance is dependent on the level of knowledge, which can be increased through information and education campaigns.	Götz et al. 2012
A.1.5	Market lead BEVs	In contrast to FCEVs, BEVs have a significantly higher avialability in the market.	Destatis 2017
A.1.4.1	Predictability	The use of BEVs impedes the preditability of individual mobility.	Thesis
A.1.4.2	Misleading range indications	The range indications of manufacturers are well below ranges covered in practise.	ICCT 2017
A.1.4.3	Insufficient charging infrastructure	The present charging infrastructure is insufficient and reduces the flexibility of using BEVs.	Öko-Institut 2017
A.1.4.4	Fluctuating battery capactities	The driving range of BEVs is not constant and depends on various factors.	Thesis
A.1.4.5	WLTP	The "worldwide harmonized light vehicle testing procedure" (WLTP) tightens the lab requirements for calculating the power demand of BEVs (expected reduction of deviation:50%)	ICCT 2017
A.1.4.6	Future extension	In the future, a restricted charging infrastructure will not be a relevant argument against the use of BEVs.	Own argument
A.1.4.7	Power demand of on-board devices	The operation of devices such as air conditioning or radio depends on the user and has a significant impact on the driving range of a BEV.	Öko-Institut 2017
A.1.4.8	Impact of temperature	At low temperatures, storage capacity of current battery cells is reduced which leads to a lower driving range.	DEKRA 2018

Argument code	Argument title	Argument description	Reference
A.1.4.9	Low service expenditures	As a result of the low complexity of an electric motor in comparison with a combustion engine, less service and repair work is required.	Öko-Institut 2017
A.2.1	Acceptance of FCEVs	FCEVs have critical disadvantages that lead to a lower acceptance compared to other technology options.	Thesis
A.2.2.1	User friendliness of FCEVs	FCEVs have a low user friendliness.	Thesis
A.2.2.2	Model availability	The currrent market availability of FCEVs is restricted, which leads to a lower acceptance.	Öko-Institut 2017
A.2.2.3	Lower flexibility of refuelling	Compared to BEVs, FCEVs cannot be refuelled at home.	Own argument
A.2.2.4	Short refuelling time	Compared to BEVs, the time consumed for refuelling is lower.	DLR 2014
A.2.2.5	Costs of FCEV	The currently lower production rate of FCEVs compared to BEVs results in higher production costs and thus higher purchase prices.	ICCT 2016
A.2.2.6	Increasing volume of FCEV production	Various car manufacturers have announced an increase of production rates of FCEVs.	Toyota 2015; Hyundai 2015
A.2.3.1	Security concerns hydrogen	Security concerns exist regarding the use of hydrogen.	Thesis
A.2.3.2	Low actual security risk	The risks of using hydrogen are limited.	IEA 2015
A.2.3.2	Hindenbrug-Syndrome	Historical accidents caused by inflamed hydrogen have led to scepticism towards the use of hydrogen.	Roche 2010
A.3.1	User friendliness of ICEVs	The use of biofuels and suitable synthetic fuels in ICEVs is characterized by a high user friendliness.	Thesis
A.3.2	Competitive advantages	Combustion engines have competitive disadvantages.	Thesis
A.3.3	No need for behaviour change	The use of synthetic fuels and biofuels in combustion engines enables the retention of current user behaviour.	No reference
A.3.4	Driving range	The high energy density of biofuels and synthetic fuels allows for driving ranges comparable conventional fossil fuels.	Agora Verkehrswende 2018
A.4.1	Reduction of kilometres travelled	A reduction of kilometres travelled will have positive effects on the energy demand of the transport sector	Thesis
A.4.2	Road charge	A distance-dependent road charge system can lead to a reduction of kilometres travelled.	SRU 2017
A.4.3	Autonomous driving	Autonomous driving could lead to an increase of kilometres travelled.	Agora Verkehrswende 2017
A.4.4	Lower number of vehicles	The number of vehicles on German roads is expected to decrease in the future.	Agora Verkehrswende 2017
A.4.5	Car dependence in rural areas	Rural areas are characterized by a strong dependence on privately owned cars.	Agora Verkehrswende 2017
A.4.6	Mobility transition	The mobility transition aims at a more efficient use of means of transport and a change of the modal split.	Agora Verkehrswende 2017
A.4.7	Foot and bike traffic	Foot and bike traffic will increase in Germany.	Agora Verkehrswende 2017
A.4.8	Electrification of two-wheel vehicles	The electrification of two-wheel traffic is advancing and will lead to a decrease of the use of cars.	Canzler, Wittowsky 2016
A.4.9	Obstruction of the mobility transition	Realising the mobility transition is aggravated by various obstacles.	Conclusion
A.4.10	Car as a cultural good	The role of cars as a cultural good makes a realisation of the mobility transition in Germany difficult.	Canzler, Wittowsky 2016
A.4.11	Car parking regulations	The mandatory construction of car parking lots in new houses supports the continuous preference of cars and counteracts efforts to transform the modal split.	Canzler 2017
Cluster B: Sector coupling potential of hydrogen and synthetic fuels			
B.1.1	Use as energy storage	Hydrogen and synthetic fuels can be used for energy storage purposes in a RE based power system.	Fraunhofer IWES 2017
B.1.2.1	Conversion losses	The production of hydrogen and synthetic fuels is characterized by high conversion losses.	SRU 2017
Argument	**Argument title**	**Argument description**	**Reference**

Argument code	Argument title	Argument description	Reference
B.1.2.2	Additional conversion step	High conversion losses result from the conversion of hydrogen to synthetic fuels.	Agora Verkehrswende 2017
B.1.2.3	Efficiency of hydrogen storage	The storage of power with hydrogen is characterized by significant losses (60-70%).	Agora Verkehrswende 2014
B.1.3.1	Flexibility for 100% RE	The timely adjustable production of hydrogen and synthetic fuels can balance power demand and enable a high percentage of RE in the electricity mix.	Fraunhofer ISE 2013
B.1.3.2	Balancing geographical differences	The geographical differences of potentials for power generation from renewable energies can be balanced by hydrogen storage.	DIHK 2015
B.1.3.3	Flexibility through other storage options	Other storage options such as batteries can provide the required flexibility for 100% RE.	Agora Verkehrswende 2014
B.1.3.4	Use of excess energy	Excess electricity can be used to produce hydrogen and synthetic fuels for future use.	NOW 2017
B.1.3.5	Chronological decoupling	Production and use of hydrogen are decoupled.	Fraunhofer ISE 2013
B.1.3.6	Mobile storage capacity	With a complete substitution of the existing vehicle fleet, between 120 GW and 130 GW storage capacity would be theoretically available which could be used for bidirectional charging.	Agora Verkehrswende 2014
B.1.3.7	Battery as short-term storage	Batteries are not ideally suited for long-term storage and are only an option for a short-term storage of electricity.	Agora Verkehrswende 2014
B.1.3.8	No alternatives	The use of hydrogen and synthetic fuels for energy storage purposes is necessary, since other storage technologies only have a limited potential.	Fraunhofer IWES 2010
B.1.3.9	Securing sufficient operating hours	The production of hydrogen and synthetic fuels relies on sufficiently high operation hours to assure its economic feasibility.	Agora Verkehrswende, Agora Energiewende 2018
B.2.1	Need for additional RE	Securing sufficient operation hours for PtL/PtG-plants entails the need of additional renewable energy power plants.	Thesis
B.2.2	Securing low carbon footprint	A power generation based on renewable energies is necessary to assure a low carbon footprint of alternative fuels such as synthetic fuels.	BMVI 2014
B.2.3	Acceptance of additional RE	An increased installation of RE plants faces growing public resistance.	IÖW 2012
B.2.4	Alternative power generating technologies	Disruptive technologies such as fusion could allow for a cheap and clean power generation.	IPP 2011
B.2.5	Advantage PV	Decoupling production and use of power allows for an increased share of solar PV generation that is characterized by a high public acceptance.	IÖW 2012
B.2.6	Increased offshore wind	An increased share of offshore wind power plants would be characterized by a higher acceptance.	UBA 2014
B.2.7	Limited potential	The potential of offshore power generation in Germany is limited and amounts to a maximum of 300 TWh per year.	Fraunhofer 2013
B.3.1	Use of hydrogen in transport	The need of hydrogen as an electricity storage option allows for its use in the transport sector.	Thesis
B.3.2	Use of synthetic fuels in road transport	The need of hydrogen for electricity storage enables the use of synthetic fuels in the road transport sector.	Thesis
B.3.3	Reduction of system costs	The inter-sectoral use of a hydrogen infrastructure can lead to a reduction of system costs.	BMVI 2014
B.3.4	Efficiency of fuel cell	The direct use of hydrogen in a fuel cell is more effective than the conversion into synthetic fuels.	Agora Verkehrswende, Agora Energiewende 2018
B.3.5	Restricted potential of hydrogen production	The potential for hydrogen and synthetic fuel production will be limited even with a significant increase of RE capacities which can lead to conflicts of interest between different sectors.	Agora Verkehrswende, Agora Energiewende 2018
B.3.6	No use in road transport	The use of synthetic fuels in other sectors is more reasonable.	Thesis
B.3.7	Reconversion	A reconversion of hydrogen into electricity is more efficient than its use in an FCEV.	Agora Verkehrswende, Agora Energiewende 2018)

code			
B.3.8	No alternatives in other sectors	As opposed to the road transport sector, other sectors (air, rail and water) will rely on the use of hydrogen and synthetic fuels.	Agora Verkehrswende, Agora Energiewende 2018
B.3.9	Application in other transport segments	The use of synthetic fuels in air, rail and water transport is to be preferred.	Agora Verkehrswende 2017
B.3.10	High specific energy	Synthetic fuels are characterized by a high specific energy.	Hydrogen Council 2017
B.3.11	Increasing fuel demand of other segments	Other transport sectors will also face an increasing energy demand.	ICAO 2016
		C - Infrastructure	
C.1.1	Focus on charging infrastructure	The extension of the charging infrastructure is to be prioritised due to the already progressed implementation.	Thesis
C.1.2	Access to charging infrastructure	Access to charging infrastructure is limited.	Öko-Institut 2017
C.1.3.1	Access to private charging infrastructure	The access to private charging stations is particularly restricted.	Thesis
C.1.3.2	Problem of space	The available area for the installation of charging stations is limited, particularly in areas of high population density such as appartment buildings.	No reference
C.1.3.3	Relevance of private charging	85% of all charging takes place in private charging stations.	SRU 2017
C.1.3.4	Legal framework	The current legal framework aggravates the implementation of charging infrastructure in a private context.	SRU 2017
C.1.3.5	No “obligation to tolerate”	Currently, the installation of a charging station requires the agreement of the house owner. So far, no "obligation to tolerate" exists.	Schaufenster Elektromonilität 2015
C.1.3.6	Rules of exception	Notarial clauses can help to remove existing legal barriers.	Schaufenster Elektromobilität 2015
C.1.3.7	Change of laws	Current legal barries can be solved by changing the respective laws.	No reference
C.1.4.1	Public charging stations	The access to public charging stations is still limited.	Thesis
C.1.4.2	Existing charging stations	In January 2018, more than 4,000 public charging stations were already in operation in Germany.	Bundesnetzagentur 2018
C.1.4.3	Approval of fast charging stations	Land development plans and local restrictions can prevent fast charging stations from being approved.	Schaufenster Elektromobilität 2015
C.1.4.4	Integration of charging infrastructure	Charging stations can be integrated in existing road infrastructure.	No reference
C.1.4.5	Integration in street lamps	Charging stations can be integrated in street lamps.	RheinEnergie 2018
C.1.4.6	Modification of distribution boxes	The main telecommunication company of Germany (Deutsche Telekom) plans to transform more than 12,000 distribution boxes to charging stations.	Electrive 2018
C.2.1	Use of existing infrastructure	The continuous operation of ICVs and the integration of FCEVs would allow for a usage of existing infrastructure.	Thesis
C.2.2	Use of existing gasoline infrastructure	The use of biofuels and liquid synthetic fuels allows for an integration in the existing gasoline infrastructure and does not require a significant extension.	Arlt 2017
C.2.3	Use of existing gas infrastructure	For the transport of PtG-products (especially hydrogen), existing natural gas pipelines could be used.	e-mobil BW 2017
C.2.4	Potential synthetic methane	Synthetic methane could entirely replace natural gas while using the same infrastructure.	BMVI 2014
C.2.5	Limited potential of hydrogen integration	Hydrogen can be integrated to the natural gas infrastructure to a limited extent (5-15%).	Fischedick et al. 2017
C.3.1	Parallel infrastructures	The installation and operation of parallel infrastructures for BEVs and FCEVs must be avoided.	Thesis
C.3.2	Progressing extension of hydrogen infrastructure	Until 2027, the number of hydrogen refuelling stations in Germany (currently 43) is expected to increase by the factor of 9 to 20.	LBST 2017
Argument	**Argument title**	**Argument description**	**Reference**

Argument code	Argument title	Argument description	Reference
C.3.3	Technology openness	Only technology openness can assure that the most suitable technology asserts itself in the long term.	BMUB 2016
C.3.4	Economic infrastructure installation	The installation of parallel infrastructures would be relatively economic compared to other infrastructure projects.	Robinius et al. 2018
C.3.5	Economies of scale infrastructure	The installation of a hydrogen infrastructure for 15 million FCEVs would be cheaper than for a comparable charging infrastructure.	Robinius et al. 2018
C.3.6	Available financial means	The Federal Transport Infrastructure Plan 2030 holds a sum of 265 billion euros for transport infrastructure and therefore sufficient financial means exist for the installation of parallel infrastructures for BEVs and FCEVs.	BVWP 2016
C.4.1	Infrastructure costs	The costs for the required infrastructure of BEVs and FCEVs are comparable.	McKinsey 2010
C.4.2	Costs of fast charging infrastructure	The costs for the installation of a fast charging station are around 42,000 € and significantly higher than for conventional charging stations.	Öko-Insitut et al. 2017
C.4.3	Costly low.scale hydrogen production	The investment costs of a hydrogen infrastructure are only competitive at a market penetration of more than 10 million FCEVs.	H2Mobility 2017
C.4.4	Need of a high workload	A high workload is required to assure an economic operation of a hydrogen fueling station.	Robinius 2018
C.4.5	Cost reduction of hydrogen fueling stations	The costs of installing a hydrogen fueling stations have been reduced by half between 2008 and 2014 (currently around one million euros).	NOW 2017
D – Ecological sustainability			
D.1.3.1	GHG reduction	BEVs have a higher potential to reduce GHG emissions of the road transport sector.	Thesis
D.1.3.2	Primary energy efficiency	BEVs have the highest primary energy efficiency from well to wheel of all alternative technologies and require less additional RE power plants compared to hydrogen or synthetic fuel scenarios.	ICCT 2016
D.1.3.3	Dependence on electricity mix	GHG emission levels of the production and operation of BEV slightly depends on the electricity mix of the respective country which will not necessarily be based on RE.	IVL 2017
D.1.3.4	Lower carbon footprint because of second life	The use as a stationary storage device after the end of its life cycle allows for a relative reduction of GHG emissions per km of around 42%.	ICCT 2018
D.1.3.5	GHG emissions in battery production	Due to the energy-intensive production of batteries, the construction of BEVs leads to higher GHG emissions than the construction of conventional vehicles.	Notter et al. 2010
D.1.3.6	Decarbonization of electricity sector	A decrease of GHG emissions from power generation is expected to take place in most energy markets (on average ca. 30% until 2030).	IEA 2016
D.1.3.7	Current advantage of BEVs	Even today, the operation of a BEV in Germany is characterized by lower GHG emissions compared to conventional ICEVs.	ICCT 2018
D.1.3.8	GHG emission reduction with economies of scale	The expected increase of battery production can lead to a relative reduction of GHG emissions.	IVL 2017
D.1.3.9	Energy-intensive battery production	The production of batteries for BEVs requires a significant input of energy of around 1000 MJ per kWh of battery capacity.	IVL 2017
D.1.3.10	Role of battery recycling	A higher degree of recycling can reduce GHG emissions of battery production relatively by 10% per km driven.	ICCT 2018
D.1.3.11	Battery as weight factor	The observed trend to larger and therefore heavier batteries can lead to an increase of GHG emissions in the production of batteries.	ICCT 2018
D.1.3.12	Saving potential through technological advances	Advances in battery development such as a higher energy density, new materials, longer battery lives, etc. can lead to a reducion of GHG emissions over a battery´s life cycle.	ICCT 2018

code			
D.2.1	Ecological sustainability of FCEVs	FCEVs have competitive advantages with regard to ecological sustainability.	Thesis
D.2.2	Ecological effects of additional power demand	The higher power demand compared to BEVs increases negative impacts related to power generation based on RE.	Conclusion
D.2.3	Smaller battery	FCEVs need a considerably smaller battery which lowers the relative share of GHG and pollutant emissions of the battery production.	No reference
D.2.4	Negative environmental impacts	The production of hydrogen is related to negative environmental impacts.	Thesis
D.2.5	Resource demand of power generation	The additional installation of RE power plants due to a higher power demand leads to a higher use of natural resources.	UBA 2014)
D.2.6	Water demand for electrolysis	The water demand for producing hydrogen leads to potential conflict of interests, particularly in arid regions.	Agora Verkehrswende, Agora Energiewende 2018
D.3.1	Environmental impact during operation	The continuous operation of internal combustion engines leads to a prosecution of negative environmental effects.	Thesis
D.3.2	Continuous operation ICEVs	Synthetic fuels and biofuels allow for the continuous operation of ICEVs with lower emissions.	Conclusion
D.3.3	Noise emissions	The operation of ICEVs implies continuous noise emissions.	EAFO 2016
D.3.4	Pollutants during operation	In contrast to BEVs, the use of synthetic fuels and biofuels leads to more negative environmental effects during operation.	Conclusion
D.3.5	Carbon footprint of synthetic fuels	Synthetic fuels can be produced with a low carbon footprint.	Agora Verkehrswende 2017
D.3.6	Emission of nitrogen oxides	In contrast to ICVs, BEVs emit no nitrogen oxides.	EAFO 2017
D.3.7	Emission of small particles	Biofuels and synthetic fuels can lead to the continued emission of small particles.	EAFO 2017
D.3.2.1	Negative environmental performance	The production of biofuels has worse impacts on the environment than available alternatives.	Thesis
D.3.2.2	GHG emissions caused by LUC	The transformation of natural areas into agricultural land for biofuels can lead to the emission of GHG and affect the carbon storage capacitiy of these lands.	Ahlgren, Di Lucia 2014
D.3.2.3	Carbon footprint of biofuels	Considering a power generation based completely on RE, an ICEV powered with biofuels has a lower environmental performance than a BEV (CO2-eq., eutrophication, etc.).	Helms 2011
D.3.2.4	Other negative environmental effects	Apart from GHG, the production of biofuels on the basis of cultivated plants is related to further negative environmental effects such as eutrophication, erosion and overstraining of water resources.	HWWI Insights 2011
D.3.2.5	Indirect land use change	The shift of agricultural lands as a result of an increased cultivation of biomass crops leads to indirect land use changes (ILUC).	Malins 2017
D.3.2.6	Direct land use change	Production of biofuels can lead to direct land use changes (LUC) by transforming natural ecosystems into agricultural land.	Helms, 2011
D.3.2.7	Emissions caused by ICEVs	The continuous operation of ICEVs with alternative fuels can lead to a further emission of GHG, small particles and other substances.	No reference
D.3.2.8	Need for land use change	The need of large areas for biomass crops as well as the limited availability of suitable lands require LUC.	Malins 2017
D.3.2.9	Carbon footprint of organic waste biofuels	Biofuels based on organic waste have a significantly lower carbon footprint than conventional biofuels.	Helms 2011
D.3.2.10	Space requirements	The production of biofuels is characterized by high space requirements for the cultivation of biomass crops.	Agora Verkehrswende 2017
D.3.2.11	Biofuels based on organic waste	Organic waste can be used for the production of biofuels.	Malins 2017
D.3.3.1	Ecological sustainability of synthetic fuels	Synthetic fuels have a lower ecological sustainability compared to other technologies.	Thesis
Argument	**Argument title**	**Argument description**	**Reference**

code			
D.3.3.2	Air capture	In order to assure a low carbon footprint of synthetic fuels, the required CO2 needs to be obtained directly from the air.	Agora Verkehrswende, Agora Energiewende 2018
D.3.3.3	Space requirements of CO2 absorption	The removal of CO2 from the atmosphere requires significant land areas.	Agora Verkehrswende, Agora Energiewende 2018).
		E – Transport electrification and the power grid	
E.1.1	Overload of power grid	A high number of BEVs could lead to an overload of the power grid.	Schill et al. 2015
E.1.2	Increase of power peaks	A high simultaneity of charging processes as well as the large-scale implementation of fast charging infrastructure will lead to power peaks that can result in a grid overload.	Conclusion
E.1.3	Capacity of distribution grid	Only a limited amount of BEVs can be integrated in the low voltage power grid.	Götz 2016
E.1.4	Increase of power demand	The expected shift of energy carriers in transport will lead to an increase of power demand	Öko-Institut 2017
E.1.5	Success models	The transport sector of other countries such as Norway already has a high share of BEVs that are operated without negative effects on the power grid.	The Norwegian Smartgrid Centre 2015
E.1.6	Export surplus	Currently, Germany generates more electricity than needed and has an export surplus which could theoretically be used to charge 20 million BEVs.	Fraunhofer IWES 2018
E.1.7	Power grid effects	A higher shareof BEVs requires a powerful fast charging system which could negatively affect the power grid.	Passier, 2016; BDEW 2017
E.1.8	Fluctuation of power generation	A higher share of RE will lead to a lower predictability of power generation and an increase of power peaks.	Agora Verkehrswende 2017
E.1.9	Temporal availability	The temporal availability of excess electricity does not necessarily correlate with the demand for BEV-charging.	No reference
E.2.1	Vehicle-to-grid	BEVs can be used as mobile storage devices (Vehicle-to-grid concept) to avoid power peaks.	Agora Verkehrswende 2017
E.2.2	Legal framework	The current legal framework hinders the realisation of the vehicle-to-grid concept.	Agora Verkehrswende 2017
E.2.3	Insufficient business models	Current framework conditions do not allow for the implementation of an economically viable business model, since the costs are higher than potential revenues.	Volkswagen AG et al. 2016
E.2.4	Potential for fleet managers	Bidirectional charging can generate income for fleet managers in the future and can be a viable business model.	Agora Verkehrswende 2017
E.3.1	Load management	Load management can avoid power grid overloads and allows for a BEV integration rate of up to 80% without the need for grid extension.	DeHoog et al. 2015
E.3.2	Central load management	A central management of charging processes can assure an optimal utilization of existing grid capactities.	Götz 2016
E.3.3	Flexible electricity prices	Flexible electricity prices can be used in the future to manage charging of BEVs.	Geske 2016
E.3.4	Reduction of simultaneity	Potential grid overloads can be addressed by reducing the number of simultaneous charging processes.	Geske 2016
E.3.5	Implementation of ICT infrastructure	The realisation of a central load management requires the implementation of an expensive information and communication infrastructure (around 10.000€ per charging station).	Götz 2016
E.3.6	Electricity price rebound effect	A higher market penetration and a wider application of a cost-efficient charging strategy can lead to rebound effects which might result in the increase of electricity prices.	Geske 2016
E.4.1	Adaptation of power grid	Potential burdens on the power grid can be met by an extension of the grid infrastructure.	Geske 2016
Argument	**Argument title**	**Argument description**	**Reference**

code			
E.4.2	Costs grid extension	The costs for extending the grid are a barrier	Thesis
E.4.3	Sufficient room for manoeuvre	The timeframe of a large-scale implementation of BEVs allows for a successive extension of the power grid.	NPE 2015
E.4.4	Energy storage with PtX	Energy storage with PtX can help to reduce the need for a grid extension.	DVGW 2015
E.4.5	Integration in existing grid	Up to 6 million BEVs could be integrated in the existing power grid without the need of extending the grid.	Götz 2014; Geske 2016
F – Transport requirements			
F.1.1	Necessary complementation of BEVs	Alternative fuels need to be considered to compensate the inadequacies of BEVs.	Thesis
F.1.2	Coverage of all transport requirements	BEVs are not suitable for all transport requirements.	Thesis
F.2.1	Freight traffic	BEVs are not suited for freight traffic.	Thesis
F.2.2.1	Long-distance freight traffic	BEVs can currently not cover all requirements of long distance freight traffic.	Thesis
F.2.2.2	Increasing transport volume	The past increase in freight transport volumes will continue in the future.	Hütter 2016
F.2.2.3	Long distance	Long-distance freight traffic is characterized by long transport distances that BEVs will most likely not be able to cover.	Agora Verkehrswende 2017
F.2.2.4	Innovations in freight transport	Innovations such as 3D printing or flexible supply chains can change production and transport of goods and reduce transport volumes in the long term.	Fischedick, Grunwald 2017
F.2.2.5	Product announcements	Several OEMs have already announced electric trucks (e.g. Tesla, Mercedes)	Electrive 2017
F.2.2.6	Payload reduction	Achieving longer drive ranges is related to a higher battery weight that reduces the payload of the vehicles.	e-mobil BW 2017
F.2.2.7	Insufficient energy density	The energy density of current batteries is only between 100 and 150 Wh/kg.	e-mobil BW 2017
F.2.3.1	Short-distance freight traffic	BEVs are already suitable for short-distance freight traffic.	Thesis
F.2.3.2	Low average transport distances	More than 80% of freight transport distances are below 150km.	Arlt 2017
F.2.3.3	Models	The market of BEVs for commercial use and for short distances is growing.	Fraunhofer ISI 2013, Electrive 2018
F.2.4.1	Alternative electrification of freight traffic	Alternative electrification concepts can also lead to a decarbonization of long-distance freight traffic.	Thesis
F.2.4.2	Disruptive transport systems	Innovative transport systems like "Hyperloop" or "Cargo Sous Terrain" could potentially replace road bound freight traffic in the long term.	MIT Hyperloop 2017, Cargo Sous Terrain 2016
F.2.4.3	“Rail before road”	A shift from road to rail can support the decarbonization of freight transport.	Agora Verkehrswende 2017
F.2.4.4	Electric catenary system	An electric catenary system could enable frieght transport with BEVs.	Öko-Institut 2017
F.2.4.5	Restricted potential of railroad freight traffic	The capacities of the railroad system in Germany are restricted and are below current freight transport volumes.	Agora Verkehrswende 2017
F.2.4.6	Need for high voltage power lines	An electric catenary system requires the installation of accompanying high voltage power lines to assure a sufficient power supply.	Arlt 2017
F.2.4.7	Replacement of vehicle fleet	Using an electric catenary system requires the replacement of all currently operating trucks.	No reference
F.2.4.8	Barriers of existing infrastructure	Barriers in the existing infrastructure such as tunnels or bridges aggravate the implementation of an electric catenary system.	BMVI 2016
F.2.4.9	Cross-border freight transport	The use of an electric catenary system is not reasonable without a cross-national concept.	INFRAS 2015
F.2.4.10	Short life cycles of trucks	The short life cycles of freight vehicles allow for a fast technology shift.	Arlt 2017
Argument	**Argument title**	**Argument description**	**Reference**

code			
F.2.4.11	Hybrid trucks	Outside the electric catenary system, other energy carriers such as batteries or hydrogen could take over.	Öko-Institut, KIT, INFRAS 2016
F.3.1	Passenger traffic	BEVs cannot meet all requirements of passenger traffic.	Thesis
F.3.2.1	Public transport	BEVs are suited for public transport to a limited extent.	Thesis
F.3.2.2	Alternative electrification	Through a shift to other means of transport, the electrification of public transport can be supported.	Agora Verkehrswende 2017
F.3.2.3	Short-distance road bound traffic	For short distance traffic, technologies for a direct electrification are already in use.	Slavik 2014
F.3.2.4	Shift to railway	By shifting passenger transport to the railway, the road transport sector can be unburdened.	Agora Verkehrswende 2017
F.3.2.5	Rural public transport	BEVs are not eligible for public transport in rural areas due to limited drive ranges.	Agora Verkehrswende 2017
F.3.2.6	Electric buses	Battery electric buses for urban public transport are already available.	Electrive 2018
F.3.2.7	China	In China, there are more than 300,000 electric buses in operation.	Öko-Institut 2017
F.3.3.1	Everyday practicality	Current ranges of BEVs are sufficient for most applications in passenger transport.	BMVI 2016
F.3.3.2	Low average distance	The average distance covered per drive in the motorized individual road transport sector is less than 17 km.	Destatis 2013
F.3.3.3	Electrification of other modes of transport	By electrifying other modes of transport such as bikes or motor scooters, the decarbonization of the road bound passenenger transport can be achieved.	IEA 2017
F.3.3.4	Less importance of long-distance travel	In respect of the mobility transition, the importance of cars for long-distance travel is expected to further decrease.	BMZ 2018
F.4.1	Long-distance travel	The ranges of current BEVs are not sufficient for long-distance travel.	Thesis
F.4.2	Inductive charging	Wireless inductive charging could allow for a dynamic energy feed during operation and the coverage of long distances.	EAM 2017
F.4.3	Fast charging	Fast charging stations enable a fast charging of empty batteries and allow for a usage of BEVs for long distances.	Schill 2015
F.4.4	Battery swapping	Battery swapping can allow for a fast and efficient replacement of empty batteries with charged batteries.	ICCT 2013
F.4.5	Range	The range of BEVs increases contrinuously.	Thesis
F.4.6	Oversizing	For long distances, BEVs require very large batteries that negatively affect their carbon footprint and their economic operation.	Thesis
F.4.7	Costly inductive charging infrastructure	Dynamic inductive charging systems require high investments in road infrastructure, even if only parts of the road system need to be equipped with the necessary technology.	ICCT 2017
F.4.8	Number of swapping batteries	For a functioning and effective battery swapping system, a high number of exchange batteries would be required.	ICCT 2013
F.4.9	Obsolence	An effective fast charging infrastructure would make a battery swapping system obsolete.	ICCT 2013
F.4.10	Decarbonizing battery costs	Battery costs decrease and allow for an increase of range without significantly higher costs.	Kreyenberg 2015; Schühle 2014
F.4.11	Storage density	The increasing storage density leads to a lower battery volume at the same performance.	No reference
F.4.12	New battery cells	New battery cells can allow for a significantly higher storage density in the future.	Fraunhofer 2017
F.4.13	Limited potential	The potential of increasing storage density of current lithium batteries is limited (ca. 900 Wh/l).	Fraunhofer 2017

Argument code	Argument title	Argument description	Reference
G – Security of supply			
G.1.1.1	Scarcity of battery relevant resources	BEVs cannot securely supply the road transport due to resource scarcities and limited production capacities.	Thesis
G.1.1.2	Low production capacities	The low capacity of battery production will be a bottleneck even with sufficient resource availability.	Rasilier 2010, Öko-Insitut 2017
G.1.1.3	Insecure resource supply for battery production	The supply of resources for the battery production is not secured in the long term.	DLR 2015, Fraunhofer ISI 2009
G.1.1.4	No physical scarcities	The worldwide availability of resources relevant for battery production does not exceed the predicted demand, even when applications apart from BEVs are considered.	Agora Verkehrswende 2017
G.1.1.5	Political procurement risks	Unpredictable political reasons can lead to a (short-term) scarcity of resources.	Agora Verkehrswende 2018
G.1.1.6	Resource alternatives	Alternative resources could solve the problem of potential scarcities.	Thesis
G.1.1.7	Short-term increase of demand	In the short term, a sharp increase of BEVs can lead to a shortage of supply if new mining sites cannot be tapped in time.	Agora Verkehrswende 2017
G.1.1.8	Higher research efforts	The risk of potential resource scarcities can lead to a more dedicated reserach on alternatives.	Conclusion
G.1.1.9	Noble earths example	A price increase of noble earths needed for the production of electric motors in 2010 led to the research and development of alternatives.	Pavel et al. 2016
G.1.1.10	Increase of resource prices	A continuous demand increase of relevant resources will lead to higher prices in the long term.	Agora Verkehrswende 2017
G.1.1.11	Increasing resource demand	A higher demand of BEVs will result in an increase of resource demand for batteries.	Agora Verkehrswende 2017
G.1.1.12	Cobalt royalties	The Democratic Republic of Congo plans to increase the royalties on cobalt.	Electrive 2018
G.1.1.13	Resource efficient battery production	Technical innovations can enable a more resource efficient battery production in the future.	Agora Verkehrswende 2017
G.1.2.1	Geopolitical dependences	The focus on BEVs leads to geopolitical dependences.	Thesis
G.1.2.2.	Power import for BEVs	A purely battery electric vehicle fleet would also require the import of electricity.	DLR et al. 2015
G.1.2.3	Resource monopolies	The resources needed for battery production (such as lithium) are available only in few countries.	Bloomberg 2017
G.1.2.4	Higher geopolitical stability	International trade has the potential to enhance geopolitical stability.	Agora Verkehrswende, Agora Energiewende 2018
G.1.2.5	Reduction of dependences	Geopolitical dependences as a result of focusing solely on BEVs can be reduced in the long term.	Thesis
G.1.2.6	Monopoly of cobalt mining	The Democratic Republic of Congo holds a share of more than 50% of the global cobalt production and the available resources.	USGS 2017
G.1.2.7	New mining sites	In the long term, the exploration of new mining sites can help to decrease the monopolistic character of battery relevant resources.	The Local 2018
G.1.2.8	Sweden	Countries like Sweden are exploring possibilities to start mining relevant raw materials.	The Local 2018
G.1.3.1	Low social standards	The mining of resources for the production of batteries takes placeunder poor social conditions.	Thesis
G.1.3.2	Poor working conditions	The mining of resources for the production of batteries is often characterized by poor working conditions.	Agora Verkehrswende 2017
G.1.3.3	Cobalt mining in Congo	The mining of cobalt in Congo is part of the informal sector with weak governmental structures.	Agora Verkehrswende 2017
G.1.3.4	Resource scarcities	The observance of social and ecological standards can be assured by resource partnerships and certificates.	SRU 2017
G.1.4.1	Higher rate of recycling leads to lower demand	Recycling of batteries will lead to a reduction of resource demand.	Thesis
Argument	**Argument title**	**Argument description**	**Reference**

code			
G.1.4.2	Insufficient battery recycling	An efficient recycling system for used batteries does not exist.	IVL 2017
G.1.4.3	Implementation of recycling infrastructure	Various measurements such as a resource inventory or circulation passes can support the establishment of recycling structures.	SRU 2017
G.1.4.4	Legal promotion	Legal measurements can create economic incentives and lead to an increase of the degree of recycling.	IVL 2017
G.1.4.5	Current potential	Already today the technology exists for recovering a higher share of raw materials used in batteries.	IVL 2017
G.1.4.6	Higher degree of recycling	Technological development can increase the degree of recycling in the future.	IVL 2017
G.1.4.7	Limited recycling potential	The potential of recycling is limited and mainly restricted to cobalt, nickel and copper.	IVL 2017
G.1.4.8	Costs	An economic recovery of materials from batteries is only possible to a limited extent.	IVL 2017
G.1.4.9	Energy input	A higher degree of recycling requires a higher energy input for raw materials recovery.	IVL 2017
G.2.1	Supply with biofuels	Biofuels cannot provide sufficient energy supply for the road transport.	Thesis
G.2.2.1	Limited potential	The theoretic potential of producing biofuels in Germany is limited to max. 19% of the future energy demand of the whole transport sector.	DLR. Ifeu, LBST, DFZ 2015
G.2.2.2	Land availability	In Germany the availability of land for the cultivation of biomass crops is limited.	Destatis 2016
G.2.2.3	Waste material availability	The limited availability of organic waste limits the their largescale use for the production of biofuels.	Malins 2017
G.2.2.4	Well-to-wheel efficiency of biofuels	The production of biofuels is related to an energy consumption up to 9 times higher than for supplying conventional fuels and electricity for BEVs.	JRC European Commission 2011
G.2.2.5	Potential of 3rd generation biofuels	Biofuels produced from algae (3rd generation) could allow for a more efficient production of biofuels in the future.	Malins 2017
G.2.3.1	Conflict of interest	The cultivation of energy plants to produce biofuels leads to conflicts of interest with the cultivation of food for humans and livestock.	Malins 2017
G.2.3.2	Attenuation of conflict of interest	The production of biofuels does not necessarily lead to a restriction of food production.	Thesis
G.2.3.3	Usable areas for food production	The production of food requires all available agricultural areas.	Thesis
G.2.3.4	Food and fuel	Byproducts of the production of biofuels can be used as feed for livestock.	Malins 2017
G.2.3.5	2nd and 3rd generation biofuels	Biofuels of the 2nd and 3rd generation do not lead to conflicts of interest.	Malins 2017
G.2.3.6	Growing food prices	The expected increase of food prices intensifies potential conflicts around agricultural land.	Labsorde 2011
G.2.3.7	Climate change	Climate change will lead to failure of crops that will additionally put a sufficient food availability at risk.	SRU 2017
G.2.3.8	Population growth	The predicted population growth limits the availability of agricultural land for the production of biofuels.	UN 2017
G.2.3.9	Low global impact	The cultivation of plants for biofuels in Germany as a low impact on food security in countries with food shortages.	Malins 2017
G.3.1	Geopolitical advantage of synthetic fuels	The integration of synthetic fuels in the German road transport sector reduces import dependences.	Thesis
G.3.2	Fuel import	The restricted potential of power generation based on RE in Germany could require the import of synthetic fuels.	DLR, Ifeu, LBST, DFZ 2015
G.3.3	Reduction of resource dependences	The use of synthetic fuels decreases the dependence on scarce resources.	Thesis
G.3.4	Electricity import	The restricted potential of power generation based on RE could require the import of electricity in the future.	DLR et al. 2015

Argument code	Argument title	Argument description	Reference
G.3.5	Eligibility of other regions	Other countries have a greater potential of producing synthetic fuels economically.	Agora Verkehrswende, Agora Energiewende 2018
G.3.6	Current energy import	Currently, the major share of fuels used in road transport is also imported.	Agora Verkehrswende, Agora Energiewende 2018
G.3.7	Cost reduction through imports	The import of synthetic fuels allows for a reduction of the total costs of providing synthetic fuels.	Agora Verkehrswende, Agora Energiewende 2018
G.3.8	Land use	The generation of a sufficient amount of electricity for synthetic fuels require large areas of land.	Fraunhofer IWES 2017
G.3.9	Avoidance of electricity import	Germany has a current export surplus of electricity of over 50 TWh which could be used for the production of hydrogen and synthetic fuels.	Statista 2016
G.4.1	Resource supply of FCEVs	The large-scale production of fuel cells is endangered by potential resource scarcities.	Thesis
G.4.2	Platinum availability	The production of fuel cells requires platinum for which only limited reserves exist.	Agora Verkehrswende, Agora Energiewende 2018
G.4.3	Low resource intensity	The production of fuel cells requires less critical resources than the production of BEVs.	Agora Verkehrswende, Agora Energiewende 2018
G.4.4.	Sufficient reserves	The predicted demand of all relevant resources for the production of fuel cells will not exceed its supply.	Agora Verkehrswende, Agora Energiewende 2018
G.4.5	BEV analogy	FCEVs are dependent on the same resources as BEVs.	Conclusion
G.4.6	Batteries in FCEVs	FCEVs also need a (comparably smaller) battery for operation.	Randelhoff 2014
		Cluster H: Economic feasibility	
H.1.1	Economic feasibility of BEVs	BEVs are the most economic alternative to ICVs.	Thesis
H.1.2	Economic feasibity of FCEVs	The economic feasibility of FCEVs is not guaranteed.	Thesis
H.1.3	TCO comparison	The TCO of BEVs are lower in comparison to other technologies.	Öko-Institut, KIT, INFRAS 2016
H.1.4.1	Operation costs	The operation costs of BEVs are lower compared to other technology options.	Thesis
H.1.4.2	Lower charging costs	The costs for battery charging can be reduced by shifting the charging process to times of lower electricity prices.	Geske 2016
H.1.4.3	Participation in control market	Bidirectional charging enables the participation of BEVs in the control market and therefore offers an option to generate income.	Geske 2016
H.1.4.4	Operation costs no purchase argument	Lower long-term operation costs only represent a purchase argument to a limited extent as long as the purchase price is not competitive in light of other technology options.	Conclusion
H.1.4.5	Higher energy taxes	BEVs would be less affected by potentially higher energy taxes due to the more efficient use of energy.	Conclusion
H.1.4.6	Reduction of life cycle	Bidirectional charging leads to a reduction of a battery´s life cycle.	Schill 2015
H.1.4.7	Relation between purchase and operation costs	Users only offset costs with purchase costs for the first five years of operation.	Hidrue et al. 2011
H.1.4.8	Fossil fuel tax compensation	The decarbonization of the transport sector will lead to a reduced income of fossil fuel taxes which entails the need for a higher taxation of other energy carriers.	Fischedick, Grunwald 2017
H.1.4.9	Compensation through toll system	Income decline of fuel taxes can be compensated by the implementation of a fuel independent tax system that puts a tax on the use of road infrastructure instead of a specific energy carrier.	Agora Verkehrswende 2017
H.1.4.10	Compensation through carbon tax	A sector independent carbon tax could compensate lower fuel tax income.	Fischedick, Grunwald 2017
H.1.5.1	Parity of costs	BEVs will achieve robust TCO-parity with ICVs in the early 20ies.	IEA 2017
Argument	**Argument title**	**Argument description**	**Reference**

code			
H.1.5.2	Unpredictable second hand market	The value loss of a BEV during its life cycle is difficult to predict and does not allow for an assessment of its economic feasibility.	Öko-Institut 2017
H.1.5.3	Second life of batteries	Batteries of EVs can be used as stationary storage devices at the end of its lifetime which increases the economic competitiveness of BEVs.	Agora Verkehrswende 2017
H.1.6.1	Reduction potential	The potential for reducing production costs s higher for BEVs than for alternative technologies.	Thesis
H.1.6.2	Reduction of battery prices	The costs for batteries decrease continuously.	Nykvisst, Nilson 2015
H.1.6.3	Increasing raw material prices	The growing demand will result in an increase of prices for resources relevant for the production of batteries such as cobalt.	Agora Verkehrswende 2017
H.1.6.4	Battery design	Improvements in battery cell design can lead to lower production costs in the future.	ICCT 2016
H.1.6.5	Economies of scale	The expected mass production of battery units will lead to lower costs per battery produced.	ICCT 2016
H.1.6.6	New materials	Expensive materials can potentially be replaced by more economic options.	ICCT 2016
H.1.6.7	Marginal share of total costs	The costs for resources are marginal in relation to the total costs of a battery.	Bloomberg 2017
H.2.1	Technology lead of BEVs	In comparison to other technologies, BEVs are characterized by the most advanced technological development.	IEA 2017, Bloomberg NEF 2017
H.2.2	Establishment of BEVs	In contrast to FCEVs, BEVs are already established in the German automobile Market.	Kraftfahrt-Bundesamt 2017
H.2.3	Plans to invest	OEMs focus increasingly on direct electrification of vehicles and set a focus on the development of BEVs.	Elective 2017
H.2.4	Economies of scale BEV	Economies of scale can lead to a further reduction of costs for BEVs.	Fraunhofer ISI 2014
H.3.1	Costs of synthetic fuels	The high costs of producing synthetic fuels count against their use in the transport sector.	Thesis
H.3.2	Lower costs of electricity generation	Until 2050, a decrease of electricity generation costs is expected (3 to 3.5 ct/kWh).	Agora Verkehrswende, Agora Energiewende 2018
H.3.3	Economic feasibility of synthetic fuels	Currently, the economic feasibility of PtG and PtL plants is not Proven.	Agora Verkehrswende 2017
H.3.4	Costs of hydrogen generation	The production of hydrogen for the use in transport is not yet economically feasible.	NOW 2017
H.3.5	Lower costs of hydrogen production	The development of a hydrogen supportive electricity and gas market is economically viable. The expected costs of hydrogen production in the future amount to 8,9 bis 19,1 ct/kWh.	Robinius 2016
H.3.6	Creation of new markets	Production, distribution and use of synthetic fuels opens up new business segments.	BMVI 2014
H.3.7	Dependence on electricity prices	The economic feasibility of PtX-plants depends directly on the dynamics of the electricity price which cannot be predicted.	BMVI 2014
H.3.8	Costs of CO2 supply	The supply of CO2 from air capture represents a significant cost factor for the production of synthetic fuels.	Agora Verkehrswende, Agora Energiewende 2018
H.3.9	Efficiency of indirect electrification	The indirect electrification of transport by the use of hydrogen in a fuel cell or for the production of synthetic fuels for internal combustion engines is energetically not efficient.	Conclusion
H.3.10	Beneficiary gas industry	The production of synthetic fuels and hydrogen based on the PtX-principle allows for the continuous use of existing gas infrastructure and creates new markets for the operators.	BMVI 2014
H.3.11	Beneficiary power industry	The production of hydrogen and synthetic fuels is a new enery storage option and allows for the exploitation of new business segments for the power industry.	BMVI 2014
Argument code	**Argument title**	**Argument description**	**Reference**

H.3.12	Energy demand of synthetic fuels	The production and use of synthetic fuels in combustion engines is characterized by an efficiency around 80% lower than a direct use of electricity in a BEV (Assumption: 100% RE-power, 70% electrolysis efficiency, 30% combustion engine efficiency).	acatech et al. 2017
I - Domestic value and labour effects			
I.1.1	Job losses	Focusing only on BEVs entails the risk of negative socioeconomic effects and job losses.	Thesis
I.1.2	Foreign production	Battery production is concentrated in other countries.	NPE 2016
I.1.3	Potential of new battery technologies	New battery technologies can lead to a geographical shift of battery expertise.	No reference
I.1.4	Market leader China	Today, around 43% of the global BEV production takes place in China.	McKinsey 2017
I.1.5	National battery production	The development of a battery industry in Germany can contribute to secure jobs in the automotive industry.	Fraunhofer ISI 2017
I.1.6	High degree of automatization	The battery production is characterized by a high degree of automatisation and has little potential for securing jobs in the automobile industry.	Deloitte 2017
I.1.7	Innovative Germany	After Japan, Germany has the highest number of patent applications in the field of BEVs.	Fraunhofer ISI 2017
I.1.8	Head start of other countries	The market structures in other countries allow for a cheaper battery production than in Germany.	No reference
I.1.9	Market monopoly	96% of the global battery cell production falls upon China, Japan and South Korea.	Fraunhofer ISI 2017)
I.2.1	Value added by FCEVs	The production of FCEVs could help to add value to the German economy and create jobs.	Schade 2014, Peters 2012
I.2.2	Fuel cell development	Germany is one of the market leaders in fuel cell development. Focusing on this technology can reinforce this position and lead to the creation of more jobs in this sector.	No reference
I.2.3	Complexity of electric motor	Producing electric motors is less complex than combustion engines, which leads to less workforce required and consequently to a loss of jobs.	FAZ 2016
I.3.1	Securing jobs with ICEVs	The continuous operation of ICEVs can lead to a preservation of jobs in the automotive industry	Thesis
I.3.2	Workforce for ICEV manufacturing	Manufacturing ICEVs is more work-intensive than other drive technologies.	Fraunhofer ISI 2017
I.3.3	Role of PHEVs	Hybrid technologies such as PHEVs can support a structural change of the automotive industry while securing jobs related to the production of ICEVs.	Thesis
I.3.4	Irrelevance of the German pathways	Sector relocations will occur independently from decisions made in Germany.	Thesis
I.3.5	Market share of PHEVs	German OEMs hold a share of 30% in the market for PHEVs.	Fraunhofer ISI 2017
I.3.6	Complexity of PHEVs	The complexity of PHEVs requires expertise in electric motors as well as combustion engines.	Fraunhofer ISI 2017
I.3.7	Risk of retardation	A delayed transition from ICEVs to BEVs by promoting bridge technologies such as PHEVs entails the risk of additional job losses in the long term.	IEA 2016
I.3.8	Megatrends	Megatrends such as digitalisation, automatisation and sharing economy will inevitably lead to a loss of jobs in the automobile industry.	Kelkar et al. 2017
I.3.9	Dependence on international development	Jobs in the automotive industry in Germany depend to a large extent on the dynamics in foreign markets.	Conclusion
I.3.10	Export of vehicles	Currently, around 60% of all vehicles produced in Germany are exported.	Fraunhofer ISI 2017
I.3.11	Importance of the German market	Around 60% of the vehicles annually registered in Germany are produced by German OEMs.	Fraunhofer ISI 2017
I.3.12	International trend of electrification	The key markets such as India and China are characterized by a trend to electrify road transport.	IEA 2017

Argument code	Argument title	Argument description	Reference
I.3.13	International market	The trend towards electric vehicles in the international	Fraunhofer ISI 2017

	development	vehicle market can lead to job losses in Germany.	
I.4.1	Sector allocation of jobs	The energy transition of transport requires a structural change which can lead to the creation of new jobs in other sectors.	Thesis
I.4.2	Spill-over effect	A wider use of batteries in the transport sector can lead to spill-over effects which other sectors (such as the solar PV-sector) can benefit from	IEA 2016
I.4.3	Value added by BEVs	Studies analysing the socioeconomic effects of a transition from ICEVs to BEVs generally indicate positive net effects on the labour market.	Fraunhofer ISI 2017
I.4.4	Market player Germany	With a growth of the market share of Germany in the electric vehicle market, positive socioeconomic effects can be generated.	Fraunhofer ISI 2017
I.4.5	Market share BEVs	The current market share of German OEMs in the electric vehicle market is around 20% (comparable with the conventional automotive market).	Fraunhofer ISI 2017

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