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

A visual analysis approach

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Abstract— **The object of investigation of this work is the performance of an argument analysis on technologies for decarbonizing the German road transport sector which include battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs) as well as biofuels and synthetic fuels for the operation of conventional internal combustion engine vehicles (ICEVs). The relevant arguments are brought forth 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 at visualising 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. The results of this work are intended to serve as a foundation for discussion on how to realize 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—energy; transport; transition; decarbonisation

I. INTRODUCTION

In view of the current role of the German transport sector as a significant contributor to greenhouse gas (GHG) 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 in transport. The former refers to all efforts to reduce the final energy demand of transport without limiting mobility in general, while the latter means a sector-wide decarbonization of energy supply [1]. For realizing such a decarbonization, different technologies are considered which are briefly introduced in the following with respect to their basic theory of operation.

A. *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%) [2]. As of today, BEVs represent the most advanced alternative drive technology with more than 3 million vehicles in operation worldwide and an additional 200 million electric two wheelers registered [3].

B. *Fuel cell electric vehicles*

Fuel cell electric vehicles (FCEVs) differ from battery electric vehicles in terms of 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 (hydrogen) through electrolysis, which then allows the on-board reconversion into electricity. The well-to-wheel 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 [4]. 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.

C. *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 are produced through methanol synthesis or Fischer-Tropsch-synthesis, which are summarized in the term *power-to-liquid* (*PtL*) while gaseous synthetic fuels (*power-to-gas* or *PtG)* mainly refer to synthetic methane and, to a lesser extent, to hydrogen [4]. The main input substances for the production of synthetic fuels are hydrogen and carbon dioxide. Provided that the electricity required for the different process steps originates from renewable energy (RE) sources, the use of synthetic fuels allows for a carbon neutral operation of conventional internal combustion engines vehicles (ICEVs). However, well-to-wheel efficiency is comparably low level of between 13-20% [4].

D. *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 utilizing non-edible organic waste products, which are referred to as first and second generation biofuels, respectively. In addition, the option of cultivating algae for biofuel production as the third generation of biofuels is investigated [5].

The described technologies are the object of investigation in the framework of this thesis. Its central aim is to perform a detailed and comprehensive analysis of these technologies with respect to their eligibility for a successful energy transition of road transport. By identifying relevant arguments in favour and against the application of the described technologies, an argument map is developed that intends to visualise the debate without raising the claim of identifying a single winner of the debate.

II. METHODOLOGY

The methodology followed in this work is displayed in *Fig. 1*. It consists of three main steps, as explained below.

A. *Information of acquisition*

The first step represents 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 characterising the debate. The literature review is accompanied by direct information acquisition through expert interviews and internal team workshops.

B. *Argument map development*

Argument mapping provides a way to visualise a complex debate once the relevant arguments have been identified and their relations analysed [6]. Based on the literature review and 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. For the development and formatting of the argument map the softwares *Argunet 2.0* and *yEd Graph Editor* are utilized [7, 8].

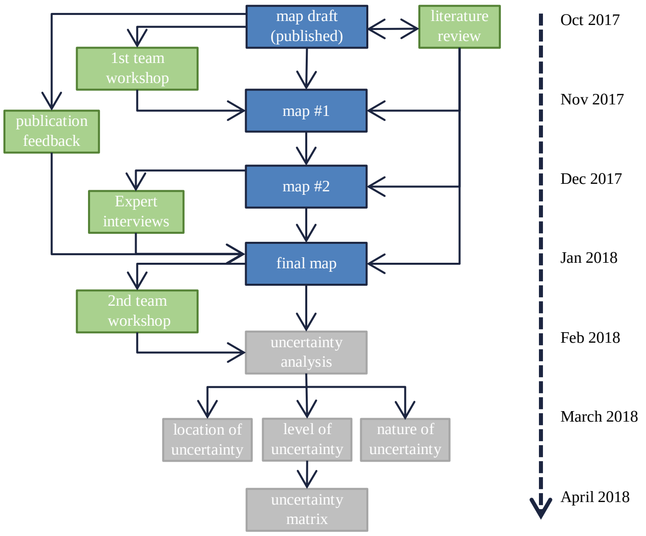

Fig. 1: Applied methodology (own creation).

C. *Uncertainty analysis map development*

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 in the identified 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.

III. ARGUMENT MAP

In this chapter, the performed work is described following the structural order of the argument map as the outcome of the argument analysis. The map is organized in nine argument clusters that are related to specific topics of the debate on energy transition in transport. These are subdivided into topic-related argument groups, providing a macrostructure that facilitates navigation through the map. The green and red arrows indicate how the argument groups relate to each other and how they support or attack a certain technology.

The full argument map is displayed in the appendix of this document. Due to the high image depth, a digital viewing is recommended to allow for zooming in and out at will.

Fig. 2 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.

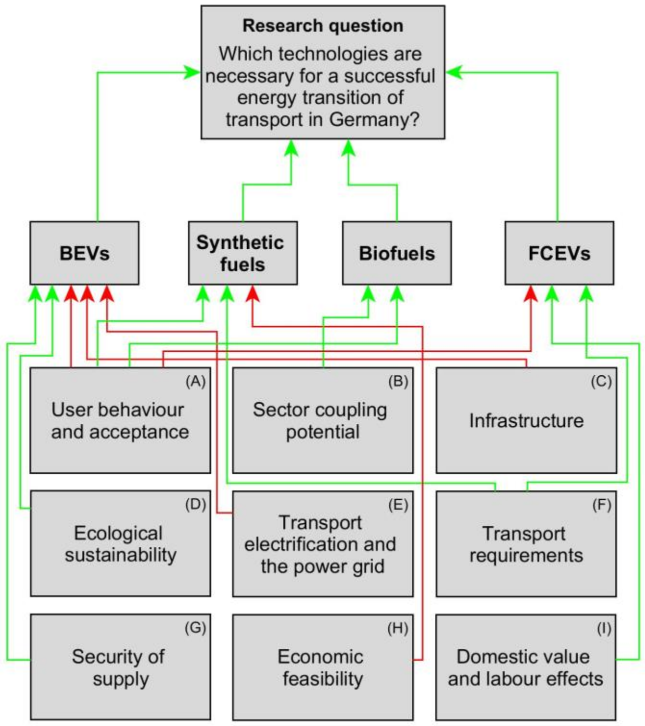

Fig. 2 Visual table of map contents depicting the different argument clusters with reference to the respective chapters in the text (own creation).

A. *User acceptance and behaviour*

This argument cluster analyses the available technologies from a user perspective, focusing on the shortcomings of BEVs and FCEVs compared to ICEVs.

The user acceptance of BEVs is affected by two central inherent limitations, which are both related to the lower range compared to conventional ICEVs. First, the comfort of usage is decreased by the need to recharge more frequently compared to the refuelling patterns of fossil fuel powered vehicles. Second, the predictability of travel is affected due to the limited range of current BEVs and the insufficient charging infrastructure [9]. Estimating travel is further impeded by ambient temperature effects on the storage capacity of batteries and by misleading range indications of battery manufacturers [10]. These arguments 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 therefore might not affect user friendliness in the long term. Hence, lower user acceptance of BEVs can be considered a preliminary argument against their integration in the German road transport sector, particularly in view of inherent advantages of electric drive technologies such as higher acceleration and lower noise emissions [11].

Regarding FCEVs, disadvantages with respect to the user´s acceptance lie in the currently limited availability and in persisting security concerns. The former is mainly related to the very low market penetration resulting in a limited disposability of models and high purchase costs, which makes the technology not competitive at present [12]. In addition, the refuelling infrastructure is still underdeveloped, which affects the ease of operation. However, in terms of refuelling, FCEVs have a competitive advantage to BEVs in view of the low refuelling time of around 3 minutes [13]. In consideration of the aforementioned security concerns, the use of hydrogen is still perceived as risky by the general public, a phenomena commonly referred to as the Hindenburg-Syndrome [14]. In view of 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.

Using biofuels and synthetic fuels would allow 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. Regarding user friendliness, the on-going operation of ICEVs has the advantage that no change of user behaviour is necessary, which represents a central argument against the use of BEVs. 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.

B. *Sector coupling potential*

The potential of utilising hydrogen and synthetic fuels in other industry sectors is frequently discussed as an argument for its utilisation for FCEVs and ICEVs, respectively. The energy sector is expected to rely on hydrogen and synthetic fuels in the future as a way 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. However, suggesting the integration of hydrogen and synthetic fuels in road transport based on their use for energy storage purposes is controversially discussed.

First, it is argued that other options are available for accommodating an increased share of RE in the power system, such as the installation of small-scale RE power plants (e.g. solar PV on private homes), which could help to stabilise the grid. Besides, stationary and mobile batteries are another option for providing flexibility in the power system. Considering a high expected number of BEVs, large battery capacities would become available for balancing the power grid [15].

Second, the potential of hydrogen and synthetic fuels for utilising excess electricity, as frequently advocated, is restricted, since the sole operation of production plants in times when excess electricity is available is not economic [4]. Therefore, additional power generation capacities are needed to assure sufficiently high operation hours of these plants, which 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.

Third, the usage of hydrogen and synthetic fuels for other applications than road transport deems more appropriate due to a lack of alternatives in non-road transport sectors. Air and water traffic, for instance, require high energy densities due to weight and volume restrictions and will therefore rely on synthetic fuels in the future [16]. Hydrogen, in turn, could be more efficiently used in road transport due to lesser conversion losses. However, hydrogen production is expected to be limited in the future, which may result in conflicts of interests with other sectors such as the chemistry industry [4]. Furthermore, a reconversion of hydrogen into electricity is more efficient than its use in FCEVs, let alone a further transformation into synthetic fuels.

C. *Infrastructure*

A suitable infrastructure is an essential requirement for assuring a smooth implementation of a new technology into the road transport sector. BEVs require a comprehensive charging infrastructure, while the integration of FCEVs into the market entails the need for establishing an infrastructure for hydrogen distribution. For the distribution and refuelling of biofuels and synthetic fuels, in turn, the existing infrastructure could be partly used, which represents one central argument for their implementation [17].

The installation of parallel infrastructures for BEVs and FCEVs is discussed controversially with respect to its financial implications. Yet, studies indicate a continuously decreasing cost for the implementation of both charging stations and hydrogen refuelling infrastructure. In fact, the installation of parallel infrastructures for BEVs and FCEVs would result in relatively low costs compared to other road infrastructure projects. This, however, is only valid if economies of scale effects occur, which require a large-scale integration of both technologies into the market [18].

The currently low extension of installed infrastructure for BEVs and FCEVs represents a main hindering factor for their market integration. Apart from financial efforts, technological as well as legal restrictions exist that need to be addressed to provide wide access to charging and hydrogen refuelling. In turn, justifying the use of biofuels and particularly synthetic fuels with the argument of taking advantage of existing distribution networks is only partially valid, since their production would require new infrastructures for generating and transporting H_2 and CO_2 as the main input substances for synthetic fuels [19].

D. *Ecological sustainability*

Various factors need to be considered when assessing the ecological sustainability of drive technologies, which include life cycle energy consumption, emissions during production and operation as well as effects on the natural environment.

BEVs are often declared to be a clean alternative to conventional ICEVs, based on the fact that their operation is comparably energy efficient and does not lead to local emissions of GHGs or other harmful substances [20]. However, this neglects the impact of the electricity mix on the carbon footprint of BEVs. Unless the required power is exclusively produced on the basis of RE sources, indirect carbon emissions result from the operation of BEVs which in turn reduces their ecological sustainability [21]. Furthermore, the production of BEVs entails negative environmental effects of two dimensions: first, providing the required resources for battery production often takes place under poor ecological conditions [1]. Second, the high energy intensity of battery production leads to high GHG emissions which again depend on the respective country´s mix of power generation [22].

Like BEVs, FCEVs are characterised 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 as compared to BEVs. Apart from electricity supply, hydrogen production entails further negative effects on the environment, particularly due to the water demand for electrolysis [4].

In contrast to BEVs, conventional ICEVs are characterised by lower emissions during the production phase [22]. While using biofuels and synthetic fuels for operation could potentially reduce the net carbon footprint of current fossil motor fuels, negative environmental effects during operation persist in the form of GHG and particle emissions, leading to a continuation of existing environmental stress and health damage [23]. In addition, impacts on the environment occur in consequence of land use for cultivating energy crops for biofuels and due to the very high energy demand for producing synthetic fuels [4, 5].

As a conclusion, all analysed drive technologies are characterised by certain negative impacts on the natural environment and contradict the illusion of an ecological road transport. In terms of GHG emissions, the direct electrification is expected to hold the largest reduction potential due to the efficiency of energy use [20].

E. *Transport electrification and the power grid*

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 and could lead to grid overloads [24]. These are suspected to occur due to a high simultaneity of charging processes at night in consequence of a homogeneous driving and charging routine, which is particularly relevant in view of limited capacities of the electricity distribution network [25]. In addition, an increased share of fluctuating RE will lead to a lower predictability of power generation and an increase of power peaks. Various measures are discussed to address the risk of increased power peaks and potential grid overloads.

First, bidirectional charging could provide mobile storage capacities and balance differences in power supply and demand, a concept which is commonly referred to as *vehicle-to-grid* [1]. However, critics argue that both the legal framework and the economic feasibility hinders the implementation of such a system.

Second, a central management of BEV charging processes can assure an optimal utilization of existing grid capacities and allows for a higher number of BEVs to be integrated. In this context, the main goal is to reduce simultaneity of charging, for which various tools are at hand such as the concept of random charging or flexible electricity prices to provide incentives for shifting charging processes to times of lower general electricity demand [26]. However, a central management system requires a significant financial investment. Furthermore, introducing flexible electricity prices could lead to rebound effects eventually causing new power peaks.

Third, extending the existing power grid is another possibility to address potential grid overloads. 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 provides 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 [27]. 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 an even higher number of vehicles to be integrated. However, the financial implications of such an extension are not predictable yet.

F. Transport requirements

A transition towards a decarbonisation needs to assure that all current mobility services are provided. In this chapter, the eligibility of different technologies, particularly of BEVs, to meet the requirements of the road bound passenger and freight transport is analysed.

The main restriction of present BEVs in terms of meeting all road transport requirements is the comparably low range that makes them seem less suitable for long-distance travel. Yet, several arguments contradict this statement pointing at the various existing options for extending the range of BEVs such as battery swapping, fast charging stations or inductive charging. However, they are partly bound to significant technological and financial efforts [28]. Higher energy storage capacities as a result of new battery technologies could also relativize the problem of limited ranges in the future [29]. Nevertheless, the current state of the art of BEVs does not allow for all transport requirements to be met.

Regarding freight transport, distances of travel are particularly high, which restricts the use of BEVs further and most likely requires the use of alternative drive technologies [1]. While BEVs could in fact play a significant role in short-distance freight traffic, various options are discussed for decarbonising long-distance transport of goods. 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 bound freight transport. Another factor that might fundamentally change the scope of long-distance transport of goods are alternative electrification concepts. 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 well below current freight transport volumes [1]. 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. However, such a system would require a cross-boundary implementation as well as a substitution of the entire vehicle fleet [17].

While the requirements of freight transport will probably entail the need for alternatives to BEVs, the passenger transport sector provides more possibilities for the use of electric vehicles. The average distance covered by a passenger per drive in Germany is only 14 km [32]. Therefore, most individual transport mobility demands can already be met by BEVs today. In addition, electrifying other modes of transport such as public buses, bikes or motor scooters can help to further decrease carbon emissions and complement BEVs in individual and public road transport. In the framework of the mobility transition as part of the transport transition in Germany, the usage of these means of transport is expected to increase in context of the aspired shift of the modal split (see also chapter I) [1].

G. Security of supply

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 [33]. The implementation of low carbon drive technologies will significantly change import relations and geopolitical dependences which could affect a secure supply of relevant materials.

The international trend towards electrifying road transport is expected to lead to a demand growth of resources needed for the production of batteries for BEVs [4]. While the physical availability of resources is generally assessed to be sufficient, their local concentration in very few, partly instable countries entails political procurement risks [1, 34]. In addition, the social standards of mining in these countries are often below international standards, which leads to a moral controversy that could be addressed by the implementation of resource partnerships and certificates that assure the fulfilment of certain social and ecological standards of mining [23].

Regarding biofuels, the security of supply is mainly related to the limited availability of agricultural land for cultivating energy crops and the restricted potential of using organic waste for biofuel production. 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 transport sector [35]. In addition, the cultivation of plants for powering vehicles is highly disputable from an ethical perspective, which is referred to as the food or fuel debate. Third generation biofuels based on non-edible organic matter could only partly devitalize this controversy [5].

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: electricity in the required amounts 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 [4]. This would counteract the argument of a higher geopolitical independence of energy supply for the road transport sector.

FCEVs, in contrast to BEVs, require less scarce resources and are therefore considered to provide a more secure supply from this perspective. However, shortages of supply affecting BEVs might impact FCEVs as well due to the fact that they also require a small battery for operation [36].

H. *Economic feasibility*

The concept of total costs of ownership (TCO) is utilised for comparing the economic feasibility of BEVs and FCEVs in comparison with ICEVs. It refers to all costs related to the vehicle purchase, the necessary charging or fuelling infrastructure as well as the operation such as service and repair costs [37].

Regarding BEVs, it is expected that TCO will fall below the level of other drive technologies in the medium term. One reason for this prediction can be found in the lower operation costs due to lower energy costs and less sensitivity to failure. In terms of production costs, the reduction potential for BEVs is evaluated to be higher compared to FCEVs and ICEVs, since batteries as the main cost factor are characterised by continuously falling prices [38]. Improvements in battery design and economies of scale effects in consequence of mass production of battery units are expected to lead to lower costs per battery produced [20].

The TCO of ICEVs depend largely on the cost of decarbonising the fuels used. Both biofuels as well as synthetic fuels are characterised 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 [1]. This is partly related to conversion losses that imply a comparatively high electricity demand, as well as to the costly supply of CO_2 needed for synthetic fuel production [4]. In contrast, sector coupling of hydrogen and synthetic fuels can help to reduce overall system costs.

I. *Domestic value and labour effects*

The automotive industry in Germany has a crucial role regarding the number of jobs related to the production, distribution, sale and operation of vehicles. Thus, a central concern communicated in the debate around the energy transition of transport is the possible loss of jobs in vehicle manufacture resulting from a shift of drive technologies.

Particularly, a large-scale introduction of BEVs into the German road transport sector is discussed controversially with respect to potential job losses in consequence of, first, a lower complexity of manufacture and, second, the geographical concentration of expertise. The latter refers to the fact that battery production, which represents the most work-intensive step of manufacturing, mainly takes place in Asia [39]. Therefore, the domestic labour market is expected to be negatively affected by an increased share of BEVs in the vehicle fleet, even though a domestic battery production could potentially counteract negative impacts of BEVs on the labour market. Considering the general labour market, most studies analysing the socioeconomic effects of a transition from ICEVs to BEVs indicate positive net effects [40]. It is assumed that the electrification of road transport by means of integrating BEVs, in combination with a realisation of the mobility transition, will create new business models and increase demand for labour in sectors not directly linked to the automotive industry.

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 [41]. 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 to realise a shift 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) [42].

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. However, the global dependence of the German automotive industry needs to be considered. In key markets such as India and China, a trend towards road transport electrification can be observed, which is expected to eventually result in a decrease of ICEV demand that could in turn lead to lower production levels in Germany [3].

IV. UNCERTAINTY ANALYSIS

In the framework of this analysis, arguments for and against different drive technologies are researched and contextualised. This process is characterised by uncertainties arising from various origins: first, the analysis is based on assumptions and premises 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 that 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 characteristics 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.
- *Characterising uncertainties:* By classifying uncertainties, a better characterisation is strived for that allows for a deeper understanding of their context.
- *Defining decision framework:* The identification and characterisation of uncertainties is intended to help setting a decision framework by allowing for a better assessment of what is known, what can potentially be known in the future and what will most likely remain unknown.

In total, 18 uncertainties have been identified based on the developed argument map. Each of these represents a premise, argument or conclusion that entails a certain level of uncertainty which affects the energy transition in the German road transport sector. All uncertainties have been characterised according to their location, level and nature of uncertainty, as explained in the following [43]:

- *Location of uncertainty:* The location of uncertainty refers to its specific point in an analysis framework. It is either related to the framing, concept or parameters of the problem description of the model.
- *Level of uncertainty:* Four levels of uncertainty can be defined: 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.
- *Nature of uncertainty:* Nature of uncertainty refers to the reason for an uncertainty and where it originates from. It can be due to the ambiguity, epistemology or ontology of a statement. By defining the nature of an uncertainty, a better understanding of its inherent characteristics is achieved that can help to develop possible strategies to handle uncertainties.

The three dimensions of uncertainty can be integrated into an *uncertainty matrix* that combines these uncertainty features and provides a graphical overview of their characteristics. *Tab. 1* depicts the concept of the uncertainty matrix.

Tab. 1. Uncertainty matrix

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								
Model implementation								
Processed output data								

A list of all identified uncertainties including their respective characteristics can be found in the appendix of the main thesis document.

V. DISCUSSION OF RESULTS

More than 400 arguments and theses for and against the use of the three different technologies were identified and mapped according to their logical relevance for decarbonising road transport in Germany. The goal of this thesis was 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 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 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.

Applying argument analysis on the question of how to decarbonise German road transport leads to certain findings related to the methodology itself, as discussed below:

- *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. 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.
- *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. Yet, with respect to 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.

- *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. 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. Besides, links between arguments that have not been visualised in the map are nonetheless considered within the textual description of the clusters in chapter 4 of the thesis document.

- *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. 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. Another significant external factor is the international context of the energy transition of road transport. Markets are interconnected and thus developments in one country inevitably have an impact on another country. Such developments are very difficult to predict and characterised by a high degree of uncertainty. They are located outside the scope of analysis and therefore limit its informative value. Nevertheless, by identifying external factors and characterise the related uncertainties, their role within the debate is acknowledged and the need for future consideration emphasized.

VI. CONCLUSIONS

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 characterising the debate was aimed for instead of concluding which drive technology should be pursued for decarbonising the German road transport sector. Notwithstanding, in view of the different arguments analysed, a ranking of technologies is deemed possible. BEVs are characterised 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 do 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 characterised by uncertainty, which occurs on different levels within the debate around the decarbonisation 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 (increasing 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 decarbonisation 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 view of increasing negative effects of global warming, the general need for decarbonisation 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.”

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