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Original Research Paper

Power from above? Assessing actor-related barriers to the implementation of trolley truck technology in Germany

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ABSTRACT

In this paper, we present a new method to operationalize social barriers for innovative technologies. Technical feasibility and economic viability are no guarantee for the development and take-off of an innovation. We combine insights from multi-level perspective (MLP) and technological innovation systems (TIS) theory to develop a framework for the identification and evaluation of actor-centred barriers. We illustrate the method through an application to catenary hybrid truck (CHT) technology in Germany. Relevant stakeholders were identified via document research and subsequent network analysis, and then approached to fill out a survey. Additional data was gathered using semi-structured interviews with key actors, and content analysis. We show how the implementation of CHT may be hampered by resistance from the regime and by a lack of focused expectations and lobbying within the niche.

1. Introduction

The development of innovations is one of the key activities that humans undertake to tackle the world's challenges. In order to have the envisioned impact, technological innovations need to diffuse into the market and become a part of the dominant socio-technical system. While the diffusion itself is seen as a social process, the odds for such a successful diffusion are commonly assessed based on technological feasibility and economic viability (Al-Alawi and Bradley, 2013; Fleiter and Plötz, 2013; Gnann et al., 2018; Kluschke et al., 2019). More systemic analyses of the social dimension surrounding an innovation in the early stages of its development are not common practice. However, technological feasibility and economic viability are often not enough for an innovation to succeed, as examples such as wind power have shown, where development was slowed down because of social factors (Bell et al., 2013). Including the social dimension in an ex-ante assessment of what may keep an innovation in the development stage and prevent it from making it into the acceleration phase and further, can therefore provide valuable information for developers and policy-makers. The aim of this paper is to develop and illustrate the use of a new method to operationalize social barriers for innovative technologies.

A theoretical strand, which addresses the triangle of technology, economics and social aspects are sustainability transition studies. The frameworks and theories of this strand aim to explain the patterns of sustainability transitions, both on a macro and meso level. Two central frameworks of this research are the multi-level perspective (MLP) and technological innovation systems (TIS). The MLP aids in analysing large change processes, which originate in protected niches and can penetrate or replace a regime of status quo technologies, institutions and other sector- or practice-specific variables. TIS, on the other hand, form around individual innovations

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as they are developed and disseminate through society. Both research strands have more recently highlighted that actor choices and behaviour are central to innovation development and there have been calls for more detailed analyses of this particular aspect (Fischer and Newig, 2016; Geels, 2011; Markard et al., 2015). In both strands, researchers have therefore studied actors and agency in more detail over the last years, focusing on concepts such as legitimacy (Bergek, Jacobsson, & Sanden, 2008b; Markard et al., 2016), politics in transitions (Avelino et al., 2016; Kishna et al., 2017), and expectations or psychology more generally (Bakker, 2014; Budde et al., 2012; Upham et al., 2019). However, the authors did predominantly not connect this research back to the assessment-type analyses of barriers in TIS and of dynamics in MLP. Our analysis aims to contribute to this research gap with its operationalization of social barriers to enable a determination of their presence at certain points in time.

While analyses based on each of these two strands can provide valuable insights into the development of an innovation or sector, we argue that an assessment of actor-related barriers requires a combination of both. The TIS approach includes social aspects in its development functions of an innovation. However, in the sectors that face large challenges, such as energy, transport or healthcare, strong regimes often dominate and the dynamics between this regime and the innovation can have a strong impact on its development. We, therefore, think that for a full picture, these approaches should be studied together and base our assessment on a combination of MLP and TIS which Markard and Truffer (2008) have introduced.

The freight transport sector and the innovation of catenary hybrid trucks (CHT) in particular, will serve as the case to apply and test this method on. The transport sector is responsible for almost a quarter of worldwide CO_2 emissions (International Energy Agency, 2016) of which more than 20 % currently stem from truck transportation. In industrialized states, where passenger transport has levelled off, the growing heavy-duty transportation sector is of particular concern. Heavy-duty transport has not received as much attention in empirical research as passenger transport but, especially because of its continuous growth, improvements in this sector appear indispensable to achieve global sustainability goals. For the drastic changes envisioned to meet these goals, current efficiency measures do not seem to suffice and changes in the dominant technology of diesel-powered internal combustion engine (ICE) vehicles in road freight transport will be necessary (Moultak et al., 2017). The main alternative power trains to diesel run on CNG or LNG, biofuels, hydrogen or electricity (Den Boer et al., 2013). There is, however, currently no consensus as to which options are most likely to prevail (Moultak et al., 2017).

One group of alternatives, which has been coined by the term Electric Road Systems (ERS), includes inductive systems and systems with direct connections to the grid. These systems require infrastructure but retain the flexibility of current road systems. Catenary hybrid trucks, or trolley trucks, powered by renewable electricity, have been proposed as one type of ERS with the capability to reduce greenhouse gas (GHG) emissions in heavy road transport (International Energy Agency, 2017). Trolley trucks involve systems where heavy freight trucks on highly frequented highways are operated with electricity from overhead lines (Wietschel et al., 2017). The trucks combine a conventional engine with an electrical counterpart and additional small batteries to bridge distances without overhead lines as well as to allow overtaking of other vehicles on the highway. Similar concepts are already used for public transit buses in some cities (Wietschel et al., 2017). Especially for the complex system of freight transportation, with its many technological options and involved decision-makers and users, it remains unclear how successful the deployment of such a system will eventually be.

Currently, CHT are in an early phase of market development. Several trials of this technology have demonstrated the technical feasibility of CHT since 2016 on public roads in Sweden and Germany. In Sweden, it is a two kilometre stretch on the E16 motorway about 200 km north of Stockholm. The three test tracks on public roads in Germany have been equipped with 5, 6, and 12 km of overhead lines and are located on major roads (two highways and one main road) in northern, central and southern Germany, respectively. As CHT are not yet commercially available, existing diesel trucks have been retrofitted with an electric motor, a small battery and a pantograph to connect with the overhead lines. The pantograph is similar to one used in electric railway systems but two pantographs are required as the rubber tires isolate the truck electrically from the ground and two poles are needed for energy transfer. Two forms of CHT are currently under discussion: (1) Battery hybrid trucks that have a larger battery to store energy for propulsion that are able to drive noteworthy distances electrically off the overhead lines and (2) Diesel hybrid trucks that have an additional diesel engine and tank to drive on tracks without overhead lines. The latter are currently mainly used in field trials are current CHT are mainly retrofits to existing diesel trucks.

The aim of the present paper is to develop and test a method for investigating the potential for a widespread implementation of an innovation based on social factors. The currently uncertain future of CHT technology makes it an ideal case to explore and analyse barriers and the role of actors in the evolution to success or failure of a technological innovation, which could disrupt current practices, in real time.

The remainder of this paper is structured as follows. Section 2 gives a more detailed overview of the theoretical framework. Section 3 outlines the data and methods used for the assessment. Section 4 presents the results of the barrier assessment and Section 5 closes with a discussion of policy implications and the conclusion.

2. Theoretical framework

Over the last decade, empirical studies of transitions of large systems like the energy and transportation system and of the development and diffusion of sustainability innovations have become a central element of social science literature (Markard et al., 2012). As a traditional technology-oriented innovation approach, Roger's theory of the diffusion of innovation has commonly been used as a tool of empirical investigation. It focuses on characteristics of the innovation itself and accounts for social factors by way of the user perspective and the communication necessary for the diffusion of an innovation into society (Rogers, 2003). Authors from other strands of innovation and diffusion literature, however, have argued that for the study of sustainability transitions, a wider perspective is needed which looks at socio-technical systems as a whole. Geels et al. (2017) define socio-technical systems as "[t]he interlinked mix of technologies, infrastructures, organizations, markets, regulations, and user practices that together deliver societal function" (p. 1242). CHT technology fits this definition as it is part of a complex socio-technological system which delivers the societal function of goods transportation.

Changes in such systems have been studied with a variety of frameworks such as strategic niche management (SNM), transition management (TM), the multi-level perspective (MLP), and technological innovation systems (TIS). SNM focuses on the circumstances under which niche emergence is possible and concentrates on the internal processes within a niche (Schot and Geels, 2008). TM is a governance approach with a participatory focus aiming at facilitating transitions. MLP and TIS are overarching frameworks which allow for the assessment of transitions as processes and for interactions between different levels and development phases. Questions of larger sector developments have commonly been studied with the use of MLP, while many technology-centred studies have employed the TIS framework. Application examples include sectors such as energy, transportation (Geels, 2012), or food (Markard et al., 2012), and innovations such as wind power (Wieczorek et al., 2015) and fuel cells (Musiolik and Markard, 2011; Suurs et al., 2009). Due to this encompassing view, we choose these two frameworks as the theoretical basis for the barrier assessment. Since SNM has been contextualized with the MLP (Schot and Geels, 2008) and TIS intend to inform policy-making as a central aim (Markard et al., 2012), parts of the processes central to SNM and TM are nevertheless indirectly included.

In the MLP, conceptualization of socio-technical systems is made up of three related levels: the *niche* level, the *regime* level, and the *landscape* level (Geels, 2002). Interactions of these analytical levels drive transitions. The *regime* stands for the dominant sociotechnical system which changes incrementally but is subject to lock-in mechanisms. For CHT, this stable configuration is represented, amongst other elements, by the combination of trucks powered by combustion engines, asphalted highways, and gas stations providing the diesel fuel for trucks – both in a physical sense as well as in the related "user practices, […], symbolic meaning [s], […], policy issues and particular stocks of knowledge" (Markard and Truffer, 2008, p. 607). In contrast to the dominant regime, *niches* represent spaces where innovations develop which have the potential to disrupt the regime from which they differ. *Niches* in the case of CHT technology are, for example, applications of the technology in field trials. The *landscape* level includes exogenous factors which influence the regime and niche developments such as demographic trends, elections, or economic crises (Geels et al., 2017). For TIS, "the focus is on the prospects and dynamics of a particular innovation […] that has the potential to contribute to far reaching changes" (Markard and Truffer, 2008, p. 596). A TIS is defined as "a set of elements, including technologies, actors, networks and institutions, which actively contribute to the development of a particular technology field" (Bergek et al., 2015, p. 52). The performance of a TIS is assessed based on eight functions which are influence by these structural elements and are considered necessary for the innovation's success. For CHT, a TIS can hence be conceptualized as all the actors, actor networks, and institutions who contribute to its functional development.

Markard and Truffer (2008) have argued for the merits of combining the two approaches of MLP and TIS in order to create synergies between the meso and macro processes under study. TIS can add more detailed analyses of niche developments to an MLP perspective, while the MLP can add to the TIS by further outlining the relation between niche and regime (Markard and Truffer, 2008). In TIS terms, the technology of CHT can currently be argued to be at the development stage (Hekkert et al., 2011). The question is then, whether the conditions at this stage are given for it to manage developing into the take-off stage. In MLP terms, there is already a niche which has brought about the technology of CHT, and the question is whether it is strong enough to have the potential to change or replace the regime. We argue that this current stage of the technology of CHT allows for an application of the joint frameworks of MLP and TIS and use this experimental approach for our analysis.

Barriers to CHT innovation development can be identified in both MLP and TIS transport-related literature. However, as Markard and Truffer (2008) point out, a general performance assessment framework has so far not been developed by either MLP or TIS scholars. Nevertheless, each research strand formulates a conducive or close-to-ideal situation where barriers are presumably absent. In TIS this can be seen in the step where policy recommendations are based on the removal of barriers. In MLP, this can be seen in the marked endpoint of transitions which takes place when the barriers posed by the current regime are successfully dealt with or removed, and the niche becomes or replaces the regime. It is, hence, possible to list barriers based on both the TIS and MLP approach, against which the situation around CHT can then be compared.

In order to generate a general list of barriers with the application case in mind, we conducted a keyword search and a bibliography check for literature applying the frameworks of MLP and TIS in transport studies. This literature yielded a list of 12 barriers (Bergek et al., 2008a; Figenbaum, 2017; Geels, 2011; Geels et al., 2014; Nykvist and Nilsson, 2015; Markard and Truffer, 2008; Suurs and Hekkert, 2009).[1] We then restricted this list of barriers to social or actor-centred barriers. Since both research strands have highlighted the need for more detailed analyses of actor choices and behaviour in recent years (Fischer and Newig, 2016; Geels, 2011; Markard et al., 2015), we looked into this direction for a first indication. While the authors in this area have predominantly not connected their research back to the assessment-type analyses of barriers in TIS and of dynamics in MLP and did hence not provide further social barriers directly, a number of central concepts in the studies of actors and agency could be made out in this literature. Legitimacy (Bergek et al., 2008b; Markard et al., 2016), politics and actor coalitions (Avelino et al., 2016; Kishna et al., 2017), as well as expectations or psychology more generally (Bakker, 2014; Budde et al., 2012; Upham et al., 2019) were found to be central points of study.

Based on these considerations, the list was restricted to six social or actor-centred barriers that are claimed to stand in the way of innovation development (see Fig. 1). Amongst the process functions of a TIS, legitimation and advocacy coalitions were chosen since

[1] The full list of barriers based on this literature can be found in Supplementary file 1.

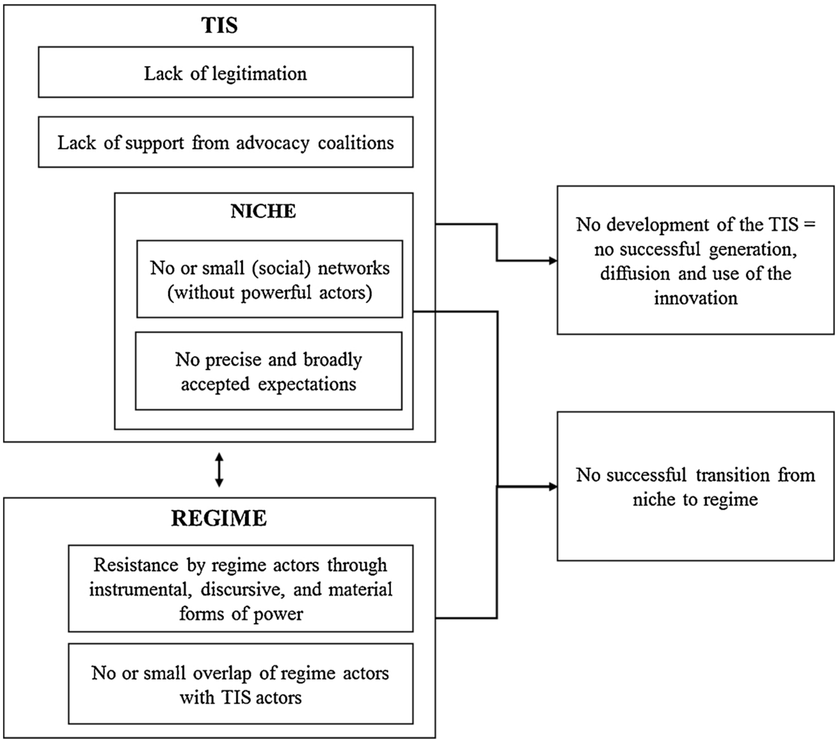

Fig. 1. Actor-related barriers to the transition.

these are central in the more detailed studies of agency and actors. Additionally, while all TIS functions are in some way connected to actors as a structural element, these two functions in particular are a direct reflection of actors' opinions and activities (Markard et al., 2015). The importance of these two functions in the development stage of a TIS between development and take-off phase also matches the current stage of the application case of CHT (Hekkert et al., 2011). In the niche, the development of social networks and of precise and broadly accepted expectations are considered to be key. In a new technology niche, networks between actors allow for visibility, learning effects and power that goes beyond the individual actor (Budde et al., 2012). Precise and broadly accepted expectations enable the niche actors to avoid misunderstandings and work towards a common vision. The focus on expectations and networks aligns with the literature on strategic niche management, which identifies these factors as key elements of niches (Smith and Raven, 2012). In the MLP literature, the regime is mainly characterized as an obstructing force to alternative developments. The central barrier in the regime is therefore resistance by regime actors. The barrier is split into the three forms of power which Geels et al. (2014) distinguish with respect to regime resistance: instrumental, discursive, and material power. Regime actors can also take part in alternative developments and thereby strengthen them. The last barrier assesses the extent to which this overlap is present as an antidote to regime resistance.

In light of the call in the innovation literature for more detailed analyses of actors and their relationship to innovation development, these six barriers related to the conceptual levels of TIS, niche, and regime constitute the focus of our analysis (Geels, 2011; Markard et al., 2015). The absence of these barriers does not automatically guarantee a successful diffusion or transition of the studied innovation. However, a situation in which these barriers are absent has the potential to contribute to the development and take-off of an innovation. Discovering the presence of one or more barriers can point actions towards specific system aspects whose change might have a positive impact on the development and take-off of the innovation if that outcome is deemed desirable. This study presents a test of this approach.

3. Data and methods

The data requirements for the project are set by the operationalization of the six identified actor-centred barriers shown in Fig. 1 and Table 1. Where possible, the operationalization was based on literature of TIS and MLP and case studies dealing with innovations in the mobility and transportation sector.

The operationalization shows the necessity for three types of information: actors' connections, actors' characteristics, and actors' opinions. To cover this variety of data needed for the barrier assessment, a combination of methods was chosen. This differs from other studies in the transition research area which have commonly used event history analyses or expert accounts to assess a number of indicators. The choice for the combination of different methods was made here, since some barriers required data on opinions and activities from individual actors which were expected not to be fully publicly available in documents and not to be known by other

Table 1
Operationalization of barriers.

Level	Barrier	Operationalizing question
TIS	*Barrier 1:* Lack of legitimation	Is the depiction of CHT more positive or negative 1) by relevant actors 2) by the media?*
	Barrier 2: Lack of support from advocacy coalitions	Do actors 1) improve and 2) lobby for the improvement of technical, institutional and financial conditions for CHT?**
Niche	*Barrier 3:* No or small (social) networks (without powerful actors)	1) What is the size of the networks? 2) Are powerful actors present?
	Barrier 4: No precise and broadly accepted expectations	In how far do the descriptions of expectations and visions for CHT overlap between the actors?
Regime	*Barrier 5:* Resistance by regime actors through 1) instrumental, 2) discursive, 3) and material forms of power	1) Does the regime mobilize more resources than the niche? 2) Do regime actors dominate the discourse? 3) Do regime actors improve the technical dimension of the current regime to avoid regulation?***
	Barrier 6: No or small overlap between regime actors and TIS actors	How large is the overlap between regime actors and TIS actors?

* Operationalization based on van Alphen et al. (2010).
** Operationalization based on Negro and Hekkert (2008) and Suurs and Hekkert (2009).
*** Operationalization based on Geels et al. (2014).

actors who could be interviewed as experts. This makes the methods used here more diverse than in other studies but adds richness to the individual accounts. When combining methods, Hermans and Thissen (2009) recommend “to identify methods that differ in focus but that are similar in terms of information needs and sources of information” (p.814). This recommendation was followed so that multiple barriers could be assessed based on the same data sources and analytical method. Information on actors’ connections was gathered through a social network analysis (SNA) based on documents and a survey. Information on actors’ characteristics and opinions were then gathered from the same data sources and supplemented with interviews. Fig. 2 depicts these combinations.

3.1. Actors’ relations

The relevant actors around CHT were determined and put in relation to one another through an SNA. To identify the actors, keyword searches were performed in Google and LexisNexis, yielding actor websites, publications, and newspaper articles in which all actors which had been involved in CHT projects or had talked about the technology could be identified. The search was performed for the years 2013–2018 with German and English keywords with the aim to all actors around CHT on a global scale. This list was supplemented by an expert account with central actors of the socio-technical system of road freight transportation. This way, 95 key actors, predominantly in the form of organisations, were identified.

Table 2 provides an overview of the identified actors based on an institutional categorization. The categorization shows that the highest number of actors was found in Germany and that most actors were found in industry and government, closely followed by actors involved in research and development around CHT. Furthermore, most identified actors were directly involved in field trials in one of the identified countries and few outside actors had joined the conversation around the technology. For analytical purposes, we perceived all organizations as single, homogenous actors. While micro-level processes within organizations can offer additional insights, this system boundary in the analysis matches the more meso-level characteristic of the combined TIS and MLP approach.

The same documents were used to determine the connections between actors. Official communication and project collaboration were counted as indicators of a mutual connection. Official communication refers to exchanges between actors about CHT in publicly available documents such as press releases, referring, for example, to each other’s work or opinions. Project collaboration refers to

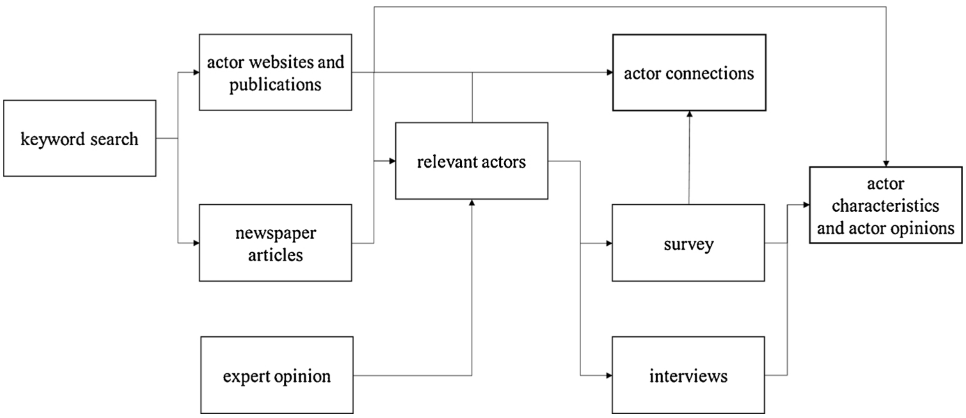

Fig. 2. Data sources and usage pathways.

Table 2
Institutional and governance level typology of relevant actors around CHT.

	International	Sweden	USA	Germany (federal level)	Baden-Württemberg	Hessen	Schleswig-Holstein
Government		Energimyndigheten; Näringsdepartementet; Region of Gävleborg; Trafikverket; Vinnova	California Energy Commission; EPA; City of Los Angeles; SCAQMD	BaSt; BMU; BMVI; BMWI; UBA; SRU	E-mobil BW; City of Kuppenheim; Regierungspräsidium Karlsruhe; City of Rastatt; VM BW	Hessen mobil; VM Hessen	MELUND SH; County of Stormarn; City of Lübeck; LBV SH; VM SH
R&D	INFRAS	Chalmers; KTH; RISE Viktoria		DLR; DVGW-Forschungsstelle KIT; Fraunhofer IAO; Fraunhofer ICT; Fraunhofer IML; Fraunhofer ISI; Fraunhofer IWES; FZI; ifeu; Intraplan Consult; M-Five; Öko-Institut; PTV Transport Consult	HS Heilbronn;	TU Darmstadt	FH Kiel; TU Dresden; TU Hamburg - Harburg
Industry	CLECAT; DAF; Daimler; Ford; IVECO; Mack Trucks; MAN Truck & Bus; Renault; Scania; Siemens; Volvo		LA Metro; Port of Long Beach; TransPower	BGL; Deutsche Bahn; DSLV; VDI/VDE; VDV	Casimir Kast; Huetteman Holding; Mayr-Melnhof; Netze BW; Smurfit Kappa; Spedition Fahrner; SWEG; VSL BW	Contargo; DAW; ENTEGA; HEAG mobilo; Hegro Eichler; Meyer Logistik; RWZ; Spedition Schanz	Hans Lehmann KG; LHG; Schleswig-Holstein Netz AG; Spedition Bode; Unternehmerverband Logistik SH
Society	ICCT			ADAC; Agora Verkehrswende; Allianz pro Schiene; Greenpeace; NABU			

signed and publicly stated agreements about project collaboration around CHT, for example in terms of technology development or research. In addition, the 95 key actors were approached with an online survey to verify and supplement the connections. The survey was in the field from March to April 2018 and reached a return rate of 47 %. A closed-ended roster was used on which actors could indicate multiple actors with which they had communicated or had been in close contact about CHT during the last five years. This approach verified most pre-identified connections and added further connections which fits the expectation that actors would have had more communication about the technology than public records show.

Since the barrier operationalization requires the assessment of actor connections based on the conceptual levels of niche, TIS, and regime, each actor was categorized accordingly. We based this classification on information derived from the documents and survey. The classification of regime actors was assigned if the actors provided a statement about the technology but their actions predominantly draw on the intangible rules of the fossil-fuel based road freight transport regime.[2] Original equipment manufacturers (OEMs), which were not directly involved in field trials are one example of this category.[3] Actors which were predominantly involved in related regimes such as rail freight transport were classified as parallel regime actors. At the TIS level, two main categories of actors were identified. The first are organizations which focus on alternative transport and have assessed the technology without being a part of the niches. The second are environmental NGOs which are not involved in the niches but engage with the technology, for example in reports or by hosting events. Only few actors were identified as pure niche actors. The group which fit this level are local energy providers which had no role in the transportation regime prior to joining niche trials for CHT.

It is important to note that actors could be classified as belonging to more than one level. The possibility for such a classification has been illustrated in MLP literature before with, for example, incumbents (representing the regime) as niche innovators of battery-electric vehicles (Späth et al., 2016). The two possible combinations are regime - TIS and regime - niche. TIS - niche is not a possible combination since a niche actor is automatically a part of the TIS but not the other way around. A majority of actors was found to belong to more than one level, as many established industry actors, commonly operating within the regime, also experiment with the technology of CHT in niches (see also Fig. 3). The work of regime - TIS actors predominantly takes place in the old regime but they now contribute to the CHT TIS development. Technical universities fit this category. Regime - niche is the dominant actor category. The niches were initiated in a top-down manner and actors already involved in regime activities provide funding and project coordination. Additionally, the main participants of the niche trials stem from the regular logistics sector as part of the regime and an established truck company providing the trial vehicles.

The list of actors and their connections resulted in a data matrix supplemented with an attribute dataset containing the assigned levels. For further analysis, these matrices were imported into the SNA software UCINET. Fig. 3 shows the final network of actors according to conceptual level based on UCINET's optimization algorithm (Borgatti et al., 2013).

3.2. Actors' characteristics and opinions

Actors' characteristics and opinions were collected for the 95 actors identified in the first research step. Characteristics were found in descriptive information from websites, documents and the survey and included semi-quantitative assessments based on the included five-point Likert items. Opinions were gathered from documents, the survey, and interviews and consequently analysed with content analysis. The additional interviews were held with the six actors with the highest centrality index, who are arguably the most connected and influential actors. The semi-structured interviews followed a topic list of questions and were executed and recorded via telephone (except for one interview that was held in person).[4] For the assessment of dominant sentiments in the public, needed for the assessment of the first barrier, 74 newspaper articles in the five-year time frame between 2013 and 2018 were analysed.

Content analysis techniques were used for a systematic analysis of documents and texts according to predetermined as well as iteratively developed categories. We used quantitative content analysis for the analysis of overall sentiment scores towards CHT in newspaper articles.[5] A more qualitative approach to content analysis was used for the assessment of barriers where the operationalization did not suggest fixed codes for assessing the data. Here, themes were developed while assessing the raw data and were then reported with the aid of illustrative quotes. Some actor statements were used as data for more than one barrier. A niche actor statement conveying a negative sentiment could, for example, also contain expectations and was then additionally coded under barrier 4.

While TIS do not, by definition, end at national borders and the initial actor overview had a global focus, the barrier assessment narrowed down the analysis to Germany. Table 3 provides an overview of the used methods sorted by the individual barriers. Based on the data analysis, each barrier was then scored on a five-point scale, i.e. *no barrier*, *no to moderate barrier*, *moderate barrier*, *moderate*

[2] Further information about the classification scheme can be found in Supplementary file 2.

[3] Based on Table 2, the following examples can be provided for the categories: a regime actor of the category OEM was the Daimler AG; the Allianz pro Schiene is an example for a parallel regime actor in the rail transport regime. At the TIS level, Agora Verkehrswende and the ICCT represent organizations with a focus on alternative transport who have assessed the technology without being a part of the niches and Greenpeace and NABU are examples of engaged environmental NGOs. Entega and Netze BW as local energy providers represent examples of niche actors. Examples for the dual category of regime - TIS are technical universities like the TU Dresden or TU Darmstadt. The combination of regime - niche is assigned to funding organizations such as the Federal Environmental Ministry of Germany (BMU) and logistics companies such as Bode, Fahrner, Schanz and Meyer as well as the truck producer Scania.

[4] A copy of the interview topic list will be provided upon request. All identified interviewees were German which matches the mother tongue of the interviewer.

[5] The logic for the sentiment scoring of the individual articles is illustrated in Supplementary file 3.

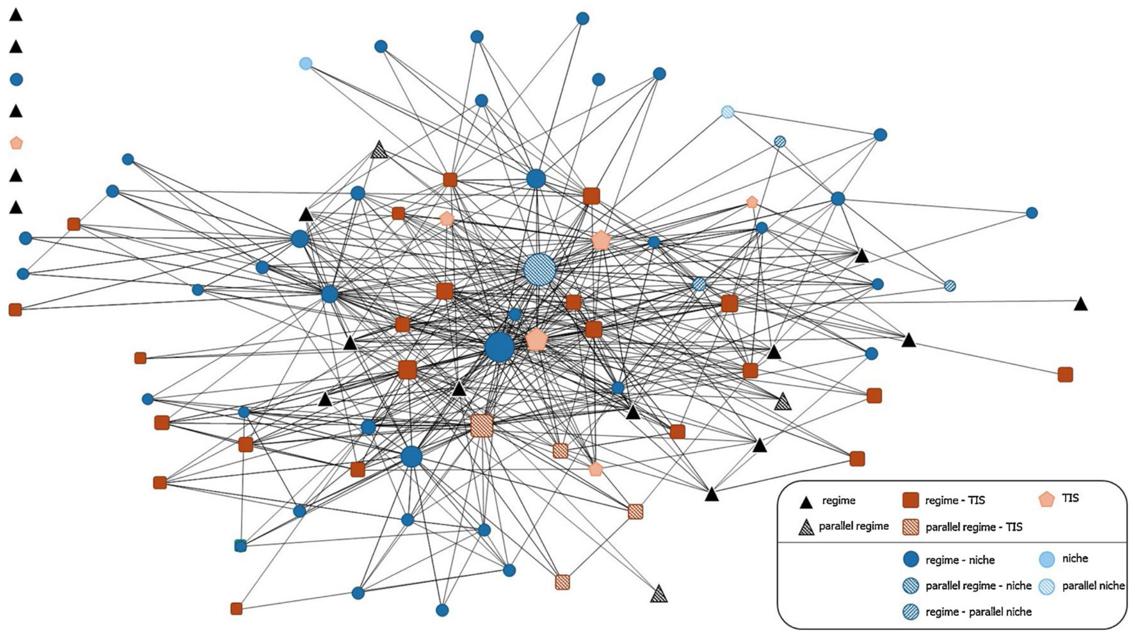

Fig. 3. Network depiction of joint network based on content analysis and survey. Node size illustrates centrality scores. Isolates listed in the top left corner were identified as relevant for CHT by experts and in the literature but had no direct communication or collaboration around CHT with other actors.

Table 3
Data source and data analysis per barrier.

Operationalizing question	Data source	Data analysis
TIS, Barrier 1: Is the depiction of CHT more positive or negative 1) by relevant actors 2) by the media?	1) Newspaper articles; survey; interviews 2) Newspaper articles	1) Content analysis of direct quotes and semi-quantitative analysis of Likert-scales 2) Content analysis for sentiment assessment (negative, neutral, positive) of full articles
TIS, Barrier 2: Do actors improve and lobby for the improvement of technical, institutional and financial conditions for CHT?	Actor websites; actor publications; survey; interviews	Activity overview from descriptive information
Niche, Barrier 3: 1) What is the size of the networks? 2) Are powerful actors present?	1) Sources for SNA (actor websites; actor publications; newspaper articles; survey) 2) Sources for SNA (see above); survey	1) Division of network via conceptual level attribute in UCINET 2) Calculation of centrality scores of niche actors vs. other actors in UCINET; semi-quantitative analysis of Likert-scales
Niche, Barrier 4: What is the level of overlap between actors' descriptions of expectations and visions for CHT?	Newspaper articles; survey; interviews	Content analysis of direct quotes and overlap assessment through frequency counts
Regime, Barrier 5: 1) Does the regime mobilize more resources than the niche? 2) Do regime actors dominate the discourse? 3) Do regime actors improve the technical dimension of the current regime to avoid regulation?	1) Survey 2) Newspaper articles 3) Actor websites; actor publications	1) Semi-quantitative analysis of Likert-scales 2) Quantitative content analysis and frequency counts 3) Activity overview from descriptive information
Regime, Barrier 6: What is the overlap between regime actors and TIS actors?	Sources for SNA (see above)	Numerical comparison of mixed-level with single-level actors

to full barrier, and *full barrier*. A moderate barrier was assigned if the assessment yielded a balanced picture while the categories between the extremes were assigned to situation with a tendency in either direction but no clear result. For the barriers with sub-questions, an average was created out of the individual sub-scores. Each of the sub-question received the same weighing.

4. Results

The results for the actor-related barriers are summarized in Table 4. The following subsection will analyse the individual barriers in more detail.

Table 4
Overview of barrier assessment results.

Level	Barrier	Barrier assessment results
TIS	*Barrier 1:* Lack of legitimation	no barrier
	Barrier 2: Lack of support from advocacy coalitions	no to moderate barrier
Niche	*Barrier 3:* No or small (social) networks (without powerful actors)	no barrier
	Barrier 4: No precise and broadly accepted expectations	moderate barrier
Regime	*Barrier 5:* Resistance by regime actors through instrumental, discursive, and material forms of power	moderate barrier
	Barrier 6: No or small overlap between regime actors and TIS actors	no barrier

4.1. Barrier 1: lack of legitimation

The assessment of legitimation is based on data retrieved from relevant actors and from the media. The presence of processes of legitimation is assessed based on visible legitimation activities by actors in the TIS, operationalized as positive depictions and framing of CHT in contrast to neutral or negative depictions.

4.1.1. Actors

Six of the identified relevant actors, all of them classified as regime actors, put forward clearly negative accounts of the technology. Negative depictions revolve around the perceived erroneous application context of the technology, its competition for funds with rail-based solutions, the perceived lacking feasibility of implementing this technology internationally, and the high costs exemplified by one of the actors asking:

> "Will it really be possible to build such a massive and new infrastructure like electric lines next to highways across borders in a conceivable time frame?"

However, 48 actors depict CHT positively, with the majority of them classified as regime-niche and regime-TIS actors. Positive depictions revolve around impacts on the environment, climate, and other external elements, advantages over alternative technologies, and CHT as a business case as exemplified in one article which states:

> "According to calculations of the environmental ministry, e-mobility with overhead lines is more energy-efficient than purely battery-electric transport. And the efficiency of current transport with combustion engines as well as the utilization of synthetic fuels, which are produced with the aid of eco-energy, are beat by the CHT by miles."

4.1.2. Media

Overall, 10 newspaper articles were categorized as negative, 38 as having a neutral tone, and 26 as being positive towards the technology. Negative articles were generally more upfront about criticizing the technology, for example including statements such as "spanning highways with overhead lines, that initially sounds like the next large-scale project doomed to failure - a combination of truck toll and Elbphilharmonie". Positive accounts, on the other hand, were subtler by using positive language and less counter-arguments rather than openly voicing their support for the technology. Overall, the positive depictions of the technology by actors directly and in the media dominated, so no barrier was identified.

4.2. Barrier 2: Lack of support from advocacy coalitions

The results on the extent to which actors improve and lobby for the improvement of technical, institutional, and financial conditions for CHT provide a mixed picture.

4.2.1. Technical conditions

Extraction of information on technology development from actor websites and actor publications provides a list of project and research activities which have allowed the technology of CHT to reach the technological readiness to be applied in field trials. The development of the necessary pantograph technology and infrastructure has been so far mainly covered by R&D activities of the Siemens Company. Partners to this development were research institutes of technical universities, both in Sweden and in Germany. In addition, the technology requires adjusted hybrid propulsion vehicles. In Sweden, Siemens cooperated directly with the truck manufacturer Scania to add the pantograph technology to trucks and integrate the external power supply into the propulsion of the vehicles. In addition, network operators are part of the actor landscape to adjust the grid requirements. Improvements of technical conditions have therefore happened continuously and are ongoing. Regarding specific lobbying activities to enable further improvements, the lobbying of actors for field trials is central. The planned field trials are seen, by many actors, as a way to further develop and improve the technology:

> "[In the trial], important traffic- and energy-technical aspects are investigated to enable a later comprehensive extension of the system."

Single lobbying efforts are detectable in public documents, both specific to field trials as well as for the more general development of the technology. As an industry actor, Dieter Fahrner, director of Spedition Fahrner recounts:

> "I heard about the planned catenary tests in Schleswig-Holstein and Hessen through the press. So I asked our representative in the state parliament why the state of the auto-mobile is actually not involved in such tests. I made a route suggestion and everything finally really got rolling when the Transportation Ministry stepped in."

Another industry actor stresses that the technology can only reach its full potential if it becomes the only one supported by government:

> "And what has to happen. Well, at some point the Federal Government or the ministries have to let go of being completely open in terms of propulsion options and of continuing to research in a results-open way about the different propulsion technologies. At some point they have to decide for one technology and pursue that one."

Nevertheless, most actors currently still favour "technology-openness", that is researching and developing many alternatives, instead of focusing all efforts on only one technology like CHT. Overall, the actions so far show that actors improve technical conditions and that individual lobbying efforts aim at furthering this improvement.

4.2.2. Institutional conditions

Improving institutional conditions is understood as seeking to change regulations, norms, and routines in favour of the development and implementation of CHT technology. In Germany, the analysed publications show that government programmes have been introduced which supported research on CHT technology. For example, The Action Programme Climate Protection 2020, passed by the federal cabinet in December 2014, included the decision to organize CHT field trials. Full planning approval procedures for highway infrastructure in Germany can currently take years, but exemptions were made for the trials in order to speed up their implementation, as stated by one of the administrative actors:

> "[…] we have discussed now that we do not need to conduct a formal approval procedure. (…) And there [in the planning approval procedure], there are exceptional facts of the case, if those are fulfilled you can abstain from a planning approval procedure. (…) […] and we see there actually, that all these points are fulfilled and will, therefore, not conduct a formal procedure."
>
> "We were faced with the challenge to get through the entire procedure within three quarters of a year to even be allowed to build. And that went in a way that is actually unparalleled in a new… so if one would now for example build something like that on another highway […], you would not be able to do it in this way. That, we are talking about pilot projects here [… t]hat means one can simplify certain steps in the procedure."

A second example of support for the improvement of institutional conditions regards the case of Hessen, where industry and government have worked together to allow an additional amount of 1000 kg of actual load for trucks in order to circumvent the problem raised by the fact that CHTs are heavier than current regulations allow.

These two examples can be seen as a first step to questioning routine behaviour and conventional regulations. Especially in the case of approval procedures, industry and administrative actors in two states openly lobbied for the exemptions and continue to argue for the necessity of similarly accelerated procedures for a more permanent catenary infrastructure after the trials:

> "One has to actually rather think big and say: no, we need a clear decision on the direction. And then it has to be clear that the technology must come nation-wide as soon as possible. And I could also imagine, and this direction is thought about currently, if future projects should not be secured more strongly through appropriate laws. So, I could for example imagine that one simply enacts a project law where the German Bundestag says, we as the Federal Republic of Germany now go with the catenary technology."

Improvements and first lobbying efforts, but so far no greater changes in the institutional landscape of laws and regulations could hence be found.

4.2.3. Financial conditions

The improvement of financial conditions is understood as directly supporting the development of CHT by financial means, including both funding research and technology development as well as financing field trials and comparable activities. So far, publications show that the financial support for CHT has mainly come from actors categorized as both regime and niche. On the one side, industry actors have developed the prototypes of the technology for Sweden, USA, and Germany. On the other side, government actors provided and are going to provide the main share of the funding for the trial projects. Overall, the project budgets show that there has been considerable financial support for the development of CHT technology. However, besides public suggestions of the German environmental ministry for future financing possibilities such as an integration into the toll system, government-directed lobbying of private actors for future market viability of the technology remains largely absent from publications as well as from the direct answers provided by the surveyed and interviewed actors. Only one actor from the R&D side openly called for financial support and incentives which the government could and should provide to make the technology a success:

> "Well and then, with this system, one has to of course not only invest money for the infrastructure and create all prerequisites for it, but also make sure that there are sufficient incentives for the vehicle owners to use the system. That means that lastly, we would have to see with regards to price politics, energy prices, that that becomes respectively attractive for companies and that one

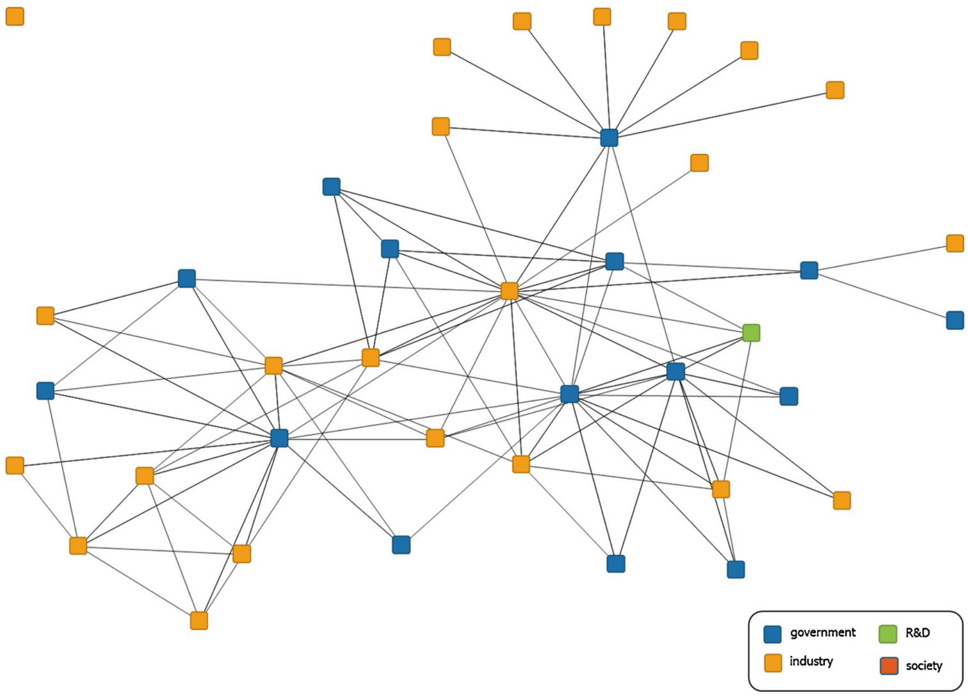

Fig. 4. Visualization of the niche actor network.

doesn't get the idea to immediately fetch what is lost in petroleum tax on the electricity side. That would not be incentive-politics that one could do in the end."

While favourable financial conditions were reached for the trial phase, lobbying activity with regard to improved financial conditions thus appears very low. Overall, we observe an advocacy coalition supporting the maturation of CHT technology through improving technical, institutional, and financial conditions but a lack in lobbying for further improvements.

4.3. Barrier 3: no social networks or small social networks without powerful actors

After assigning all actors to the three conceptual levels, the network of niche actors could be separated from the total network of all actors. For this barrier, the size of the sub-network of niche actors as well as the power of these niche actors in comparison to actors of the other conceptual levels was assessed.

4.3.1. Niche network size

38 out of a total of 95 identified relevant actors form the niche around field trials in Germany. At 40 %, this presents a large share of the actors found to be involved in the topic of CHT up to this point in time.

Except for one actor who is not connected to any of the others, all of these niche actors form a network based on communication and close exchange about CHT (see Fig. 4).

4.3.2. Niche actor power

Additionally, based on two network analysis metrics, we found powerful actors to be a part of the niche. First, a statistical test shows that the mean of the centrality values found for niche actors in the total network of all actors was considerably higher than for actors who were not a part of the niche (niche: mean = 157,368, n = 40, std. dev. = 376,014; non-niche: mean = 65,187, n = 55, std.dev. = 156,796). Central actors can be considered powerful because they connect other actors and can serve as brokers of ideas and opinions in the network. Secondly, some actors in the niche network have considerable instrumental power. The survey gathered data on the number of employees and the annual revenue or budget of the actor organisations, expressed on five-point Likert items. Five niche actors were part of the two highest employee number ranges and 10 actors in the niche occupied our highest revenue/budget category of above €200 million per year. Overall, the niche network is highly connected and contains powerful actors.

4.4. Barrier 4: No precise and broadly accepted expectations

We measured broad acceptance of expectations based on the extent to which actors agreed within certain themes of expectations towards CHT. In the survey, three closed-ended questions were designed to capture expectations regarding (1) the potential for sustainability improvements through the technology, (2) expectations regarding the chances for the establishment of the technology, and (3) expectations about the financial profitability of the technology on the market. For each of these questions, around half of the niche actors chose one particular answer, indicating a medium overlap in expectations for this part of the assessment. Specifically, 11 out of 17 (65 %) agreed that the technology of CHT has the potential to improve the sustainability of freight transport, seven out of 17 (41 %) agreed that there is a high chance for the technology to establish itself, and seven out of 17 (41 %) agreed that the technology will be profitable on the free market in the future.

Additionally, expectations found in the open actor statements were coded according to dominant topics which resulted in 11 main themes. Leading expectation themes, as those who were referenced by the highest number of actors, are *contribution to climate protection or reaching climate goals*, *application context*, *field trials*, *costs and financing*, and *modal shifts*.

Within each individual theme or topic, the overlap and precision of expectations was assessed and subsequently aggregated over all themes. Within the themes *costs and financing*, *alternative technologies*, and *citizen acceptance*, actors provided diverse and often contradicting expectation statements resulting in a low overlap. One government and one industry actor, for example, expects costs for logistics companies to go down using CHT, due to aspects like fuel savings, while two industry actors expect financial challenges because of the high infrastructure costs. One government actor does not see alternative technologies as competition due to different application contexts and one industry actors sees advantages due to the comparative immaturity of other technologies such as hydrogen fuel cell trucks, while another expects the possibility that developments in battery technology might make such “in between charging solutions” obsolete in a few years. Citizen acceptance is deemed critical by one industry actor while a government actor stresses the opportunities in including citizens early-on. Strong overlap could be found in the themes of *climate protection*, *modal shifts*, *local emissions*, *business opportunities*, *transport volumes*, and *regulations*. Here, government and industry actors expect lowered CO_2 emissions, no competition with rail haulage due to growing demand for both modes, lowered local emissions resulting in a better environmental and living quality, new business opportunities, continuously growing transport volumes, and the necessity for nation-wide regulations for a successful diffusion of the technology. Finally, a medium overlap was found for the themes of *application context* and *field trials*. The aggregated medium to high overlap in the open-ended statements and the medium overlap in the closed-ended statements overall indicated a moderate barrier.

4.5. Barrier 5: Resistance by regime actors through instrumental, discursive, and material forms of power

4.5.1. Instrumental power

To get a sense of the (relative) instrumental power of regime actors, that is their ability for resource mobilization, we gathered data on the resources of both regime and niche actors through the survey. 45 % of all identified niche actors and 46 % of all identified regime actors provided answers regarding their resources in terms of employees and annual revenue or budget in the survey. This data was not sufficient to compare the resources of niche and regime in absolute terms. Furthermore, most niche actors are also regime actors. While overall the regime appears to mobilize more resources, the niche actors around CHT also mobilize a considerable amount of resources. Therefore, this barrier was scored between a full and a moderate barrier.

4.5.2. Discursive power

The public discourse in German newspapers is clearly dominated by the German Federal Ministry for the Environment (BMU) with a total of 17 quotes. Further actors with a certain dominance in the discourse were Siemens (nine quotes), the transportation Ministry of Hessen (six quotes), and the research institute Öko-Institut (four quotes). The four most dominant actors were categorized as either belonging to regime-niche, regime-TIS, or TIS. Hence, the discourse is not dominated by actors who exclusively classify as regime actors. Nevertheless, the fact that three discourse-dominating actors have a dual classification bears the risk that these actors will change their support for the niche or TIS in the future and return to being regime actors entirely. Due to this risk, we score this barrier somewhere in between moderate barrier and no barrier.

4.5.3. Material power

Avoiding regulations is the activity of warding off “possible regulation by promising that solutions are ‘just around the corner’” (Geels et al., 2014, p. 33) and pursuing innovation efforts within the boundaries of the regime. For the regime at hand, this would mean that actors continue to work or support work on the efficiency of fossil-fuel powered trucks in order to avoid future regulations which completely rule out such trucks as a transport choice. Through continuous technical improvements, regime actors can be argued to work on keeping the focus on regulatory instruments which can be fulfilled through efficiency measures. This way, they ward of other, potentially stricter, regulations which would force them to exclusively produce hybrid or entirely alternatively powered trucks. Improving regime technology is, therefore, a counter-force to the development of CHT because it lessens the pressure for the production of hybrid or alternatively powered trucks needed for the CHT system.

All seven truck producers with the highest market share in Germany[6] structure their online presence on trucks and sustainability around two topics: fuel efficiency and alternative driving technologies. In all cases, the reduction of emissions of conventional trucks takes up most space in the companies’ strategies for a more sustainable future. Governmental regime actors also put forward a mix of supporting alternative propulsion technologies, especially on the side of environmental ministries, and supporting efficiency programs, especially on the side of transportation ministries. This indicates that regime actors expect to be able to meet the demands of the future with a mix of efficiency improvements in old technology and some additional developments of alternative technologies.

[6] DAF, Iveco, MAN, Mercedes-Benz, Renault, Scania, Volvo.

This way a full shift to alternative technologies is not presented as necessary. The sub-barrier could therefore be scored somewhere in between a moderate and a full barrier. However, this bears some speculation, and the direct connection between improving efficiency and avoiding stricter future regulations is not voiced by any of the actors. Therefore, this sub-assessment was not counted towards the final score of barrier 5 which aggregates to a moderate barrier.

4.6. Barrier 6: No or small overlap of regime actors with TIS actors

The scoring of this barrier identifies whether the actors surrounding the innovation of CHT have developed or gathered for this technology specifically, or whether they have already had a place in the fossil-fuel based road freight transport regime before the development of this TIS. In the analysis, 28 out of all 95 identified relevant actors were classified as actors enacting the conceptual level of TIS. An additional 43 actors were identified as enacting the niche. As outlined in section 3, the niche actors automatically form a part of the TIS since all actors supporting the technology directly were assigned to this level, fitting the indirect or direct support necessary to count as a TIS actor. Of these 71 actors, 62 actors were also identified as regime actors. 37 of these actors were both found to be a part of the German trial niches and the regime of fossil-fuel based road freight transport, three as a part of a parallel niche and the regime, and 22 as part of the TIS and the regime. Actors which were part of the relevant niche or TIS but were identified as actors of a parallel regime, such as the regime of rail freight transport, were not counted towards this score. The fact that many actors can be assigned to two levels, can be attributed to the types of actors which have been and are active in the early stages of CHT development. Besides the initiating industry actor Siemens, actors from the government and research sector became involved and local field trials include logistics companies with prior experience in haulage. So far, besides Siemens, the parallel regime of rail transportation has not been involved. Specialized companies from other fields outside the fossil-fuel based transport regime are also not largely involved, since infrastructure has so far been provided by a single actor and the required diesel or hybrid trucks originate from established truck manufacturers, with retrofitting that is also provided by actors out of the regime. At this point of CHT development, the actor landscape, therefore, is quite homogenous in this respect. Overall, the large majority of niche and TIS actors found in this research were also identified as regime actors. Therefore, this barrier was scored as absent.

5. Discussion and conclusions

The potential for a widespread uptake and roll-out of a technological innovation that has proven to be technically feasible and economically viable often remains highly uncertain. In this paper, we proposed an *ex-ante* assessment tool to identify social barriers to the implementation of innovations. We combined insights and ideas derived from MLP and TIS. We illustrated the use of this method through an application to catenary hybrid truck technology in Germany. Our method is actor-oriented and is based on a comparison between the current, actual actor situation around an emerging technology (with proven technical feasibility and economic viability) and the (hypothesized) ideal situation (as posited by MLP and TIS theory).

With specific regard to CHT technology in Germany, we find a fairly tight overlap between the actual and the ideal situation in terms of barriers to implementation, with the exception of the following: The support from advocacy coalitions had slight shortcomings, and in the niche we found that expectations were neither very precise nor broadly accepted. Furthermore, we found that regime actors resist niche developments to some extent.

Following the case-specific recommendations based on our assessment, we address the methodological and theoretical contributions of our work and discuss avenues for further research.

5.1. Recommendations for stimulating CHT

Our analysis shows that if the goal is a widespread implementation of catenary hybrid trucks, there is arguably a need for measures to remove the three identified actor-related barriers.

5.1.1. Achieving more support from advocacy coalitions

With regard to advocacy coalitions, we find that actors in the niche have offered and are offering technical, institutional, and financial support for CHT but that there is little lobbying by these actors to further improve the situation in each of these dimensions. Very few of the participating actors actively push for the technology beyond what is necessary for the establishment of the trials.

From a transitions research perspective, the establishment of formal networks has been one way to create legitimacy and support the overall creation of the TIS (Musiolik and Markard, 2011). In the case of stationary fuel cells in Germany, this establishment was "driven by the goal of establishing the technological field and not primarily of serving particular firm interests" (Musiolik and Markard, 2011, p. 1919). The establishment of a formal network along the lines of what we have established as actor connections in this paper is therefore one recommendation to achieve more support from advocacy coalitions. Such a formal network can be created top-down by the German government which is currently funding the trial projects, for example through requirements for cooperation between the individual projects in follow-up grants. However, the authors add that other researchers such as Garud and Karnøe (2003) or van de Ven (2005) have found comparable achievements in situations of less formal actor collaboration. Since our barrier assessment has shown a connected actor network in the niche, such more informal collaborations, for example led by industry, might suffice to create a functioning system during and after the field trials.

5.1.2. Achieving more precise and broadly accepted expectations

Our assessment hints at a need to have stakeholders thinking of their respective expectations about CHT technology in a more precise and mutually agreed upon manner. The presence of expectations, often caused by varying interests, is a common challenge in the scientific and practical work towards sustainable development.

A certain amount of consensus is needed not only for envisioning what the future could look like given prevailing uncertainties but also for immediate decision-making and the success of an innovation (Alkemade and Suurs, 2012). Two approaches which allow for the discussion and possible convergence of (more precise) expectations are foresighting and joint model building.

Foresighting approaches for sustainable development can take many forms such as “adaptive foresight, the German Future process, Visions assessment, Leitbild assessment, several sorts of participatory and constructive technology assessment or strategic conversations” (Truffer et al., 2008, p. 1364). Truffer et al.'s (2008) own approach of Sustainability Foresight was originally developed for the German utility sector to develop multiple possible development paths and strategies based on the found scenarios. The authors found that the Sustainability Foresight method reduced potential conflict and misunderstanding. This approach can, therefore, be recommended as one possible option to achieve a greater overlap of more precise expectations about CHT technology.

In recent literature on sustainable transport planning and on decision-making in complex ecological and economic systems, the benefits of participatory and joint modelling for consensus-building and strategy-making have been pointed out (Costanza and Ruth, 1998; Macmillan et al., 2014; te Brömmelstroet and Bertolini, 2011). Modelling “can help to build mutual understanding, solicit input from a broad range of stakeholder groups, and maintain a substantive dialog between members of these groups” (Costanza and Ruth, 1998, p. 185). Joint modelling is more resource-intensive than foresighting approaches. However, it specifically tackles the issue of precision of expectations because assumptions have to be discussed in detail before putting them in any given model.

In the research efforts around CHT, modelling and different pathway approaches have already been taken or planned, especially with regard to technology development and market introduction scenarios (Öko-Institut, 2016; Wietschel et al., 2017). These efforts point to the importance of the inclusion of and discussion with a wide variety of stakeholders. For one study, scientific workshops were held, specifically on the technical dimensions of CHT (Bundesministerium für Verkehr und digitale Infrastruktur, 2016). For the other project, expert participation and a project advisory council were meant to ensure that project results would be available to actors in politics and industry for discussion early on (Öko-Institut, 2016). Results were also meant to inform other political decision-making processes and be presented to the interested public (Öko-Institut, 2016). While the willingness for cooperation and scenario-building can, therefore, be attested in parts, there is room for the introduction of foresighting approaches and joint model building. The efforts that are currently made give no explicit space to the discussion of scenarios for the technology within the entire freight transportation sector. The recommended joint approaches would require additional resources and organization, but based on the barrier assessment analysis, the potential benefits for the implementation of the technology could outweigh these efforts in the future.

5.1.3. Reducing the resistance of regime actors

We identify possible sources of resistance by actors of the fossil-fuel based road freight transport regime, particularly with regard to instrumental and material power. This means that regime actors use their resources, regular activities and processes to withstand changes which would be brought about by the implementation of CHT technology. While the analysis at this point in time only shows a moderate barrier when summing up the current resistance of the regime, this can be the case because of the early development stage of the technology. At the time of the empirical analysis, the trial projects were in the planning phase. The data shows that the involved actors present their expectations as very contingent on context factors. Non-involved regime actors have not actively mobilized against the technology but remain in a waiting position. Therefore, the current moderate resistance has to be viewed in context, and resistance may increase with the possible direct involvement of powerful regime actors in the future. Overall, regime resistance in the ICE-dominated transport sector would have to be reduced if the goal is to ensure an implementation of the technology.

In recent innovation literature, such destabilizing efforts have attracted more attention (Kivimaa and Kern, 2016; Wesseling and van der Vooren, 2017) and suggestions have been made to counter the resistance of regime actors. Kivimaa and Kern (2016) suggest an innovation policy mix which also includes destructive policies aiming at the destabilization of regimes. More specifically, Kivimaa and Kern (2016) put forward four ways in which destructive policy instruments can influence the innovation system: (1) control policies, (2) significant changes in regime rules, (3) reduced support for dominant regime technologies, and (4) changes in social networks through the replacement of key actors. In the case of CHT technology, this could translate to quotas for zero emission vehicles for manufacturers, reduction of diesel tax benefits and strong carbon taxation in freight, or the installation of environmental friendly actors in key ministries.

5.2. Contributions and further research

This paper is meant as a first step in the development of an *ex ante* assessment method for implementation of innovations that takes actors into account.

Methodologically, we add value in two particular ways. First, we use network analysis, which has been a suggested method with possible added value for the study of innovations and transitions by Geels (2011). It allows us to depict and analyse the ties between stakeholders. This not only helps to identify ‘the movers and the shakers’ involved with a certain technological innovation, but also serves as the basis for the assessment of barriers to innovation implementation. Further research on technological innovation including the use of network analysis could map the dynamics of possible network changes over time.

Second, our tool is also based on the gathering of primary data from actors through a survey and interviews, yielding information on their personal expectations. This adds a more nuanced view of actors' positions and expectations than what is possible with secondary data such as documents and expert accounts alone. Further research remains necessary on how to account for (1) multiple and changing level affiliations of actors, (2) the connection between actors' interests and their actions, and (3) the connections of actor-related barriers with other barriers.

In terms of theory, we have followed Markard and Truffer (2008), who see value in the combination of both the *transition perspective* represented by MLP and the *emerging technology perspective* represented by TIS. When applying MLP and TIS to other cases in the future, we suggest that more complex actor configurations which occur in practice should be taken into account for theory development. Further research could analyse how differences in framing relate to the development of an innovation in different political contexts.

Also in terms of theory development, we suggest research to focus on dynamics over time – as we picked up signals regarding the altering expectations and preferences of individual stakeholders depending on changes in the environment in which they operate. For example, in voicing their expectations, stakeholders gave clear qualifiers of aspects or developments that their support is contingent upon. Their support would no longer hold if the government withdrew their support for CHT, if it would prove to not be profitable, if international agreements to reduce CO_2 would cease to exist or if the problem would be solved by means of other technologies. This shows the fragility of actors' support for a new alternative in the ICE-dominated transport sector. Furthermore, the visibility of the technology and thereby its local impact will grow along further development stages. As with other large infrastructure projects, this can lead to the involvement and possible opposition of further actors. To provide room for such considerations, the framework would currently have to be applied and tested at multiple points in time. Further research could identify specific points in time which appear crucial for a re-assessment.

All in all, we think that ex ante assessments of innovations are not well-covered in MLP and TIS frameworks – particularly in a fashion that is clearly operationalised and measured. While such assessments are not meant to predict the future, they can indicate barriers for a transition before it takes place and when adjustments can still be made. Future research can profit from going beyond historic cases to show ways to impact the challenging transitions ahead of us.

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Appendix A. Supplementary data

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