Technological Forecasting & Social Change 170 (2021) 120925

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

E-mobility from a multi-actor point of view: Uncertainties and their impacts

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ARTICLE INFO

Keywords:
E-mobility
Multi-criteria analysis
Sustainable transport
Technology diffusion

ABSTRACT

Germany has introduced measures favorable to the deployment of electric cars, but, so far, their diffusion has been slow. To assess the decarbonization of the transport sector, a wider range of factors and stakeholder priorities must be considered. A multi-criteria approach shows that car users and vehicle manufacturers are likely to resist e-mobility. However, a decision model based on the multi-criteria approach heavily depends on the characteristics of the car categories and on the weights determining stakeholders' motivations. In practice, neither the exact characteristics nor the exact weights are known exactly. By systematically varying the characteristics and weights, we take these uncertainties into account and test the robustness of the results. Moreover, we identify factors linked to policy measures promoting a particular car technology. Whilst we find that incentivizing the adoption of hybrids is possible, shifting the attitude of car users towards electric vehicles is difficult, since electric vehicles have disadvantages for this stakeholder. Electric utilities support electric vehicles, as they are consistent with their business model whilst government supports them only once ecological and economic concerns gain equal importance. This indicates that new approaches involving penalizing conventional cars may be necessary to the dissemination of electric cars.

1. Introduction

Transportation accounts for almost 25% of all emissions in the EU and road transport makes up three quarters of transport-related emissions (European Commission, 2017). Road transport is, therefore, a crucial focus of efforts to cut emissions; indeed, if this sector's carbon footprint is not substantially reduced, it threatens to become the largest source of European Union carbon emissions, dominating reductions in carbon intensity in other sectors (European Commission, 2017). Reducing CO_2 emissions represents the primary goal behind policies to support the diffusion of electric vehicles.

Germany, as an example of a prominent car market in Europe, introduced measures to penalize conventional vehicles whilst promoting battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). In order to decarbonize the road transport sector, the German government has set itself the target of there being nine million electric vehicles on the road by 2030, with this reliant on improvements in battery technology (Acatech, 2018). An annual circulation tax based on CO_2 tailpipe emissions has been in force since mid-2009, and is aimed at shifting consumers to lower emitting vehicles, with the emissions baseline, after which this tax is applied, having decreased each year to 2014 (Malina, 2016). However, there are indications that this measure has only had a modest impact, with Malina (2016) estimating that, even at its strictest, in 2014, the annual circulation tax only caused a 0.4% reduction in emissions in newly registered cars. To increase the adoption of BEVs, a purchase grant of at most 4.000€ for BEVs and 3.000€ for HEVs has been made available (until the end of 2021 at the time of writing) (Federal Government, 2019). In addition to these fiscal measures, BEVs are granted special privileges including exemptions from parking fees and the allocation of dedicated parking spaces (Deutsches Dialog Institut; Noerr LLP, 2018). However, these measures have hitherto not delivered a massive increase in electric vehicle adoption; of 3.6 million new passenger vehicle registrations in 2019 (Verband der Automobilindustrie, 2020), BEVs accounted for only around 63.000 (Kraftfahrt Bundesamt, 2019), or only 1.75%. Low acceptance, limited understanding of the benefits and costs associated with electric vehicles and the embedded position of conventional vehicles have been cited as reasons for the constrained diffusion (Biresselioglu et al., 2018). In addition, the high price for BEVs (Sierzchula et al., 2014), long payback, the limited availability of charging infrastructure (Hagman et al., 2016) and insufficient political actions in favor of BEVs are mentioned (Truffer et al., 2017).

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https://doi.org/10.1016/j.techfore.2021.120925
Received 1 November 2020; Received in revised form 23 May 2021; Accepted 25 May 2021

The diffusion of BEVs is determined by attitudes, support and resistance from a broad range of actors including cars-users, electric utilities, vehicle manufacturers and government as well as the socio-economic framework (see e.g., Truffer et al. (2017)). The factors that are relevant when deciding in favor of a specific car technology as well as their meaning differ between the stakeholders. Hence, for an appropriate assessment of decarbonization of the transport sector, we need to consider a wide range of aspects including the weighting of relevant factors by the stakeholders. In the literature, the list of factors as well as their weightings differ significantly: The RAC Foundation listed, for United Kingdom, price, running costs and reliability as the most important decision factors (RAC Foundation, 2017). In a consumer survey on purchases in the US, fuel efficiency and safety were highlighted as the key factors (Statista, 2020). According to Aral, price performance, safety and comfort were the major influences for consumers in Germany (Aral, 2019). Another German study lists reliability, purchase price and appearance as key factors (DAT Group, 2016). Ouyang et al. (2018) added the nature of after-sales services and reliability, especially with respect to batteries in electric cars, as factors. Lane and Potter (2007) pointed out that environmental aspects might be less relevant for car purchase decisions than stated in surveys. Surveys (e.g. (Chng et al., 2019)) showed that the weightings of factors were related to sociodemographic aspects like age and gender. Kohler et al. (2020) stressed that behavior patterns in combination with socio-technical frameworks have to be considered as a dynamic system. Therefore, it is very difficult to assess purchase decisions precisely. In addition, it has to be considered that, for governments, e-mobility is only one technology field among many others and that the governance of the e-mobility sector is embedded in the overall industrial and innovation policy (Tyfield and Zuev, 2018)

Aiming to support the understanding of stakeholders' decisions with respect to e-mobility and to support the design of more efficient policies, we analyze the meaning of factors relevant to car purchases, taking the perspective of different stakeholders into consideration. In particular, we investigate how uncertainties inherent in the weightings of the factors and the characteristics of cars influence the results. Simultaneously, we analyze how sensitive the attitudes towards a selected car technology are to changes in the assessment of factors. Based on the results, we draw conclusions for policy measures.

It is essential that policy makers set a clear vision for the expansion of electric cars, accompanied by targets in addition to standardized regulations and norms (Usmani et al., 2015). At the European level, policy makers could set stricter CO_2 targets and introduce directives in relation to alternative infrastructure which would aid the growth of electric cars (Usmani et al., 2015). Policies supportive of BEVs are motivated primarily by the drive to decarbonize the transport sector, but also have indirect benefits and costs (ancillary benefits and costs). It is important to understand how actors perceive these ancillary benefits and costs associated with BEVs, in order to gain a complete picture as to why stakeholders prefer one type of mobility option to others.

With more than 47 million passenger registered cars existing in 2019, Germany leads Europe (ACEA, 2019). As a country with a well-established car industry, a decarbonization of the German transport sector might be more challenging than for Denmark, Ireland or the Netherlands. Germany has ambitious GHG reduction targets. However, until now, the German government has not fixed a timeline for phasing out combustion engine cars and this leads to uncertainty regarding the future of the German transport sector. Due to the size of the German passenger car market, the existence of incumbent actors and the breadth of uncertainties associated with the future of the German transport sector, we selected Germany as an interesting context to which we could apply our novel approach.

The government, car users, vehicle manufacturers and electricity suppliers are the stakeholders which are important to the dissemination of e-mobility in Germany. The government's strategy is concerned with, on the one hand, making Germany an industrial leader in e-mobility through co-financing R&D and, on the other hand, promoting the ease of use of BEVs through the expansion of charging points (Nationale Plattform Elektromobilität, 2014). For vehicle manufacturers, BEVs represent a significant challenge in terms of overcoming technological lock-ins which may favor conventional vehicles (Barbieri et al., 2016). There is a danger that knowledge, networks and skills, built up over years, become obsolete (Steinhilber et al., 2013). It is considered vital that Germany expands the production of batteries domestically, even if this is unprofitable initially (Steinhilber et al., 2013). The current concentration of large-scale, low-cost battery production in Asia poses a risk for European manufacturers of BEVs (Steinhilber et al., 2013).

From the perspective of car users, electric cars imply a change in behavior (Jansson et al., 2011) and, therefore, car dealerships play an important role in overcoming resistance to adoption (Matthews et al., 2017). Consumers who have actively experienced charging technology and demonstration vehicles, as opposed to simply having seen written information about the performance of BEVs, are more likely to form a positive attitude towards BEVs (Gebauer et al., 2016). There is ongoing debate about business models for building and operating charging stations (Madina et al., 2016), however it is clear that distribution system operators (DSOs) will be responsible for making power available. It is also possible that DSOs might operate the charging infrastructure and integrate it into their assets. Alternatively, there could be a separate charging infrastructure operator or this infrastructure could be run by an independent e-mobility provider, with different implications for its financing (Theisen and Marques, 2010). It is essential that the deployment of this charging infrastructure is accompanied by effective information and communications technology (ICT) infrastructure, involving payment systems for electricity charging (Winning, 2015) and systems which further the establishment of "intelligent" e-mobility systems, based on local distribution of power for electric cars and car-sharing (BMWi, 2018). Regulators must determine which actor should ultimately bear responsibility for running the charging infrastructure and how a competitive market for recharging services can be created (Lo Schiavo et al., 2013).

For each of the actors discussed above, the policy intervention in favor of e-mobility causes direct and indirect effects. Measures related to climate change policy aim, primarily, to reduce emissions of greenhouse gases (GHG), however, at the same time, have impacts elsewhere on other kinds of emissions, the production of goods, energy prices and the labor market (see e.g., (Ekins, 1996; Groosman et al., 2011; Pittel and Rübbelke, 2008; van Vuuren et al., 2006)). Policies to promote the expansion of low-emission vehicles can also have considerable co-benefits for health outcomes thanks to lower pollution (Tseng et al., 2015). These side-effects derive from the initial goal of the policy and are considered as ancillary benefits and costs of a particular measure (Davis et al., 2000). These ancillary benefits and costs may change the decisions and preferences of actors and, therefore, mean that the policy measure does not have the desired effect, due to the impact of the ancillary effects (Vögele et al., 2020). We integrate these ancillary benefits and costs into a decision making model which predicts, for each stakeholder, which type of car they are likely to choose based on the criteria that are important to them.

We use a multi-criteria approach which is a common method for analyzing decisions (see, e.g. (Brans et al., 1986; Diakoulaki and Karangelis, 2007; Kumar et al., 2017; Pohekar and Ramachandran, 2004)). This approach is based on the assumption that decisions result from the evaluation of a set of criteria and the performance of decision

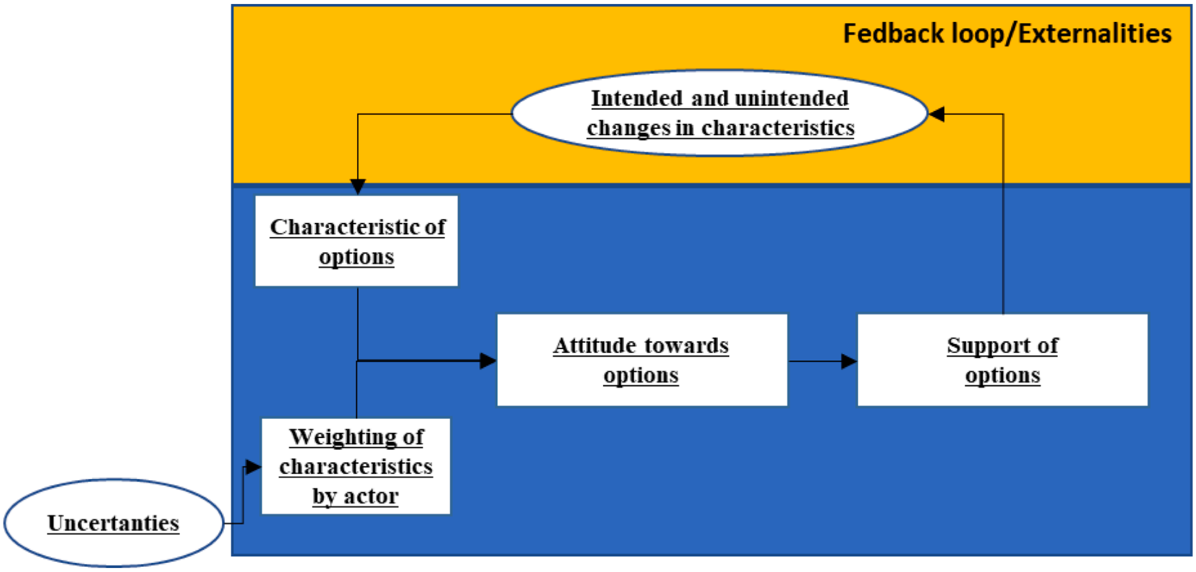


Fig. 1. Overview of primary and ancillary benefits

alternatives in relation to each of those criteria. A weighting is attached to each criterion, reflecting its importance to the decision maker. The overall performance of an alternative is calculated by summing up the alternative's performance indices on each criterion and multiplying those indices by the weightings attached to each criterion. This overall performance evaluation allows the decision maker to select the most beneficial alternative. Such approaches have been used, e.g. for energy planning problems (see Loken (2007)) and appraising transport projects (see e.g. Macharis and Bernardini (2015)). We extend this multi-criteria approach by including "externalities", interaction effects among the stakeholders. More precisely, this is the influence that a particular actor's position in relation to a mobility technology has on the decision of other actors.

We structure this paper as follows. After describing our method in detail in section 0, we present the outcomes of our MCDA-analysis for different scenarios in section 0. In sections 0, we discuss our results and compare our findings for Germany with the situation in Norway. Norway has experienced a rapid deployment of ZEVs ('zero emission vehicles'), with electric cars accounting for 40% of new car sales in 2018 (Bunsen et al., 2018). Norway is an outlier in the deployment of electric cars and could serve as an example for checking the results of our research and for drawing conclusions for other countries. We conclude in section 0.

2. Method

The primary benefit of policies to decarbonize transport by expanding the diffusion of electric cars is the reduction in resulting CO_2 emissions. This was the initial motivation for the government to introduce policies to support e-mobility, as decarbonizing transport is essential to meeting the goals for CO_2 reductions set out in the Paris Agreement (United Nations, 2015). However, the environmental benefits of BEVs or HEVs over vehicles with conventional internal combustion engines (ICE) will only form part of a stakeholder's decision and, for the non-governmental stakeholders, they may not be the overriding concern. The ancillary effects associated with a measure are arguably far more important in determining a stakeholder's decision to support a particular technology. These ancillary effects correspond to indirect effects from the policy to promote e-mobility, other than the environmental benefits. In Table 3, ancillary effects are categorized into the dimensions "economic", "social", "comfort" and "other"; side-effects from the ecological benefits motivating the policy towards e-mobility. For example, switching to e-mobility has economic implications for consumers, in terms of cost and for electric utilities, in terms of electricity sales.

In this study, we focus on the impacts of a policy in favor of the diffusion of electric cars on the preferences of stakeholders towards mobility options. We assume that:

- there are different groups of stakeholders, each with their specific set of preferences regarding mobility technologies, namely conventional ICE cars, HEVs and BEVs
- stakeholders must choose between these technologies.

Stakeholders will prefer a particular mobility technology if they expect it to bring more benefits than the alternatives. Therefore, if the technology at the focus of the initial policy measure does not provide more benefits than an alternative, its diffusion will be limited.

Fig. 1 gives an overview of our approach. After specifying a policy intervention, we list both the primary effects and the associated ancillary effects. We classify all other effects resulting directly from the selection of a technology as "first order" effects. "Second order" effects, in the form of externalities, correspond to feedback effects from a stakeholder's decision to support a particular technology on the position of other stakeholders. For instance, governmental support of a technology option could lead to the introduction of incentives favorable to that option which would increase the confidence of vehicle manufacturers in a future market. Such feedback effects, in the form of externalities, add to the existing first order effects and alter the utility of a particular option from a stakeholder's point of view.

MCDA approaches have been widely used for the assessment of technologies and for scenario comparisons (see e.g. Parkinson et al. (2018), Baležentis and Streimikiene (2017), Wang and Poh (2014), Diakoulaki and Karangelis (2007) and Terrados et al. (2009)). For the assessment of the effects of an intervention on attitudes, we compare benefits of different technological options. Applying an outranking approach we assume that a decision maker will support the technology with the highest overall performance (see e.g. Behzadian et al. (2010)

Table 1
Factors relevant for decisions with respect to e-mobility.

Ecological Factors	Economic Factors	Social/ Political Factors	Comfort/ Performance	Other Factors
CO_2 emissions Local emissions	Cost of ownership Profit Employment Tax revenues	Impact on import dependency Impact on security of electricity grid	Charging time Range Others	Complementarity with existing structures Need for incentives

Source: (BMWi, 2019; Deloitte, 2020; Verband der Automobilindustrie, 2020)

Table 2
Overarching categories & actor-specific weightings.

Overarching Categories	Car Users*	Electric Utilities	Vehicle Manufacturers	Government
ecological aspects	0.1	0.05	0.02	0.13
economic aspects	0.37	0.44	0.73	0.67
social aspects	0	0.34	0	0.067
comfort/ performance aspects	0.42	0.02	0.08	0
other aspects	0.1	0.15	0.16	0.13

Remarks: Our analysis is based on existing studies on e-mobility. In these studies, the information on the assessment of the categories is not differentiated by the number of cars that car users own. Thus, we start our analysis by using published data on car users in general and do not distinguish between users purchasing their first or second car.
Source: Own compilation (data for car users based on Esch (2016) and Loken (2007)).

Regarding the factors which are relevant for the decision process, we employ a hierarchical approach by clustering all factors firstly into superordinate categories. In a second step, these categories are disaggregated into subcategories. The chosen assessment approach consists of four subsequent steps:

(i) Normalization of the assigned values with the aim of conducting a methodologically reliable comparison of factors with different units.
(ii) Weighting of benefit categories from the perspective of the actor in order to take the relative importance of categories into consideration.
(iii) Weighting of the different kinds of benefits within a category from the perspective of the actor.
(iv) Calculation and aggregation of the weighted values to a composite indicator reflecting the attitude of an actor towards a technology.

For the normalization, we employ a summation approach: the normalized indicators are calculated by dividing the score of a particular technology, in relation to a particular decision factor by the sum of the score values for all technologies on that particular decision factor.

Eq. 1 shows the normalization of the scored characteristic $x^k_{i,z}$.

$$u^k_{i,z} = \frac{x^k_{i,z}}{\sum_{k=1}^{n} x^k_{i,z}} \qquad (1)$$

with

$u^k_{i,z}$: normalized value of indicator i of the superordinate categories z assigned for technology k
n: number of technologies considered
$x^k_{i,z}$: value of indicator i of the superordinate category z assigned for technology k

In a next step, we introduce weighting factors for the superordinate categories which comprise indicators belonging to e.g. "economic aspects" or "ecological aspects". Within these aggregated categories, we use indicator-specific weighting factors.

Within the superordinate categories as well as in the subcategories, the weighting factors sum up to 1. Taking the weighting factors into consideration, the attitude of actor a can be assessed as follows:

$$P^a_k = \sum_{i=1}^{m} \sum_{z=1}^{o} w^a_i * v^a_{i,z} * u^k_{i,z} \qquad (2)$$

with

P^a_kperformance index
m: number of superordinate categories
o: number of subcategories
w^a_i: weighting factor of indicator category *cat,* with $\sum_{cat} w^a_i = 1;\ 0 \leq w^a_i \leq 1$
$v^a_{i,z}$:weighting factor of indicator z within indicator category i, with $\sum_{i} v^a_{i,z} = 1;\ 0 \leq v^a_{i,z} \leq 1$

Table 3
Subcategories & their actor-specific weightings.

Overarching Factor	Sub-Factors	Car Users	Electric Utilities	Vehicle Manufacturers	Government
Ecological	CO_2 Reduction	1/1	1/1	1/1	2/3
	Local Emissions	0/1	0/1	0/1	1/3
Economic	Cost	1/1	0/1	2/11	0/15
	Profit Car Production	0/1	0/1	8/11	7/15
	Profit Electricity Sales	0/1	1/1	0/11	1/15
	Employment	0/1	0/1	1/11	7/15
Social	Import Dependency	1/1	1/10	1/1	3/4
	Grid Security	0/1	9/10	0/1	1/4
Comfort	Charging	6/17	½	2/9	1/3
	Comfort	2/17	0/2	3/9	1/3
	Range	9/17	½	4/9	1/3
Other	Complementarity with existing structures	8/11	9/10	8/10	4/10
	Need for incentives	3/11	1/10	2/10	6/10

Remarks: Own compilation (data for car users based on Esch (2016)
The MCDA approach assumes that actors' preferences are based on the rational maximization of utility. Whilst this is a useful assumption for research purposes and policy interventions, it does not apply perfectly to the real world; it is limited by bounded rationality (Selten, 1990; Simon, 1990)

Table 4
Characteristics of different car categories.

Characteristics	unit	Electric Car	Car with internal combustion	Hybrid Car
A ECOLOGICAL FACTORS				
A-1 CO_2 emissions*	-	100**	25	74
A-2 Local emissions*	-	100	0	20
B ECONOMIC FACTORS				
B-1 Cost of ownership*	-	67	100	73
B-2a Profit Car production	-	50	100	90
B-2b Profit Electricity sales		100	0	25
B-3 Employment*	-	35	95	100
C SOCIAL/POLITICAL FACTORS				
C- 1 Impact on import dependency	-	5	1	2
C-2 Impact on the security of electricity supply	-	3	5	5
D COMFORT/ PERFORMANCE				
D-1 Charging time	-	1	5	5
D-2 Comfort		3	5	4
D-3 Range	km	2	5	5
E OTHER FACTORS				
E-1 Complementarity with existing structures		1	5	1
E-2 Need for incentives		1	5	3

Remarks: * Best performing technology = 100, ** Calculated based on data on average CO_2-emissions/kWh in Germany,
Sources: Own compilation based on Esch (2016) & Hyundai (2020)

The performance index P_k^a reflects the attitude of actor a to technology k.

If a stakeholder can choose between different technologies, they will prefer the one with the highest performance index (Nardo et al., 2005; OECD/EC/JRC, 2008). For more information on our methodology, the python code used to generate results (Grajewski et al., 2021) can be downloaded (https://github.com/mgrajewski/FastPyMCDA).

In the following section, we apply the "Ancillary Effects/MCDA" approach using the example of e-mobility. The introduction/extension of (an) environmentally friendly mobility system with a focus on cars used by private individuals is selected as the intervention that triggers the benefits. Hence, we classify reduction of CO_2 emissions as the primary target of the intervention.

2.1. Actors and their weightings

Following Figenbaum and Kolbenstvedt (2016) and Assum et al. (2014), we distinguish between:

- Car users: "Car user" represents a private person who is interested in using a car for personal transportation
- "Car Users_1st car": Car users looking for a new car, who do not already own a car. This covers the purchase of a car user's first car, the replacement of their existing car or the purchase of a car after a period of no vehicle ownership.
- "Car Users_2nd car": Owners of ICE or PHEV looking for a second car
- Vehicle manufacturers: "Vehicle manufacturer" corresponds to a company that produces cars.
- Electric utilities: "electric utility" stands for a company which sells electricity.
- Authorities at national, regional and local level: "Government" is used as a proxy for decision makers who focus on objectives on a national (or at least regional) political level.

Whilst the distinction between car users looking for a first or second car is relevant to the discussion, in our analysis, we firstly focus on users seeking to purchase their first car (Car Users_1st car). Aspects related to the buyers of a second car will be stressed in the discussion section. As mentioned, we assume that each of the group of actors has their own set of interests. Accordingly, they assess means of transport (and respectively cars) differently. Car users are strongly interested in cost and comfort aspects (see e.g. Junquera et al. (2016)), vehicle manufacturers and electric utilities are more focused on profits and, for the government, reduction in emissions and employment are key issues. Factors in which each actor is interested are listed in Table 1.

In Table 2, the overarching categories and their actor-specific weightings are given. More specific sub-criteria are regrouped under each of these broad categories. Each stakeholder attaches different importance to each category. For instance, it is assumed that the German national government is driven largely by ecological aspects, with its new *Climate Protection Law* indicating the strength of this commitment. However, the government must also be attentive to social and economic aspects which also feature highly in the decision structure. Vehicle manufacturers are largely motivated by economic aspects whereas electric utilities are focused on both economic and social aspects relating to import dependency and grid security. The decision of car users is dominated by economic and comfort aspects with other categories being very much secondary.

In Table 3, the subcategories and their actor-specific weightings are reproduced. The total weighting the actor attaches to the overarching factor is distributed among the sub-categories according to their specific interests.

2.2. Alternatives and their characteristics

Regarding the alternatives available to the stakeholders, we consider the possibility of buying and using:

- a battery electric vehicle (BEV),
- a car with internal combustion engine (ICE) and
- a (plug-in) hybrid electric vehicle (HEV)

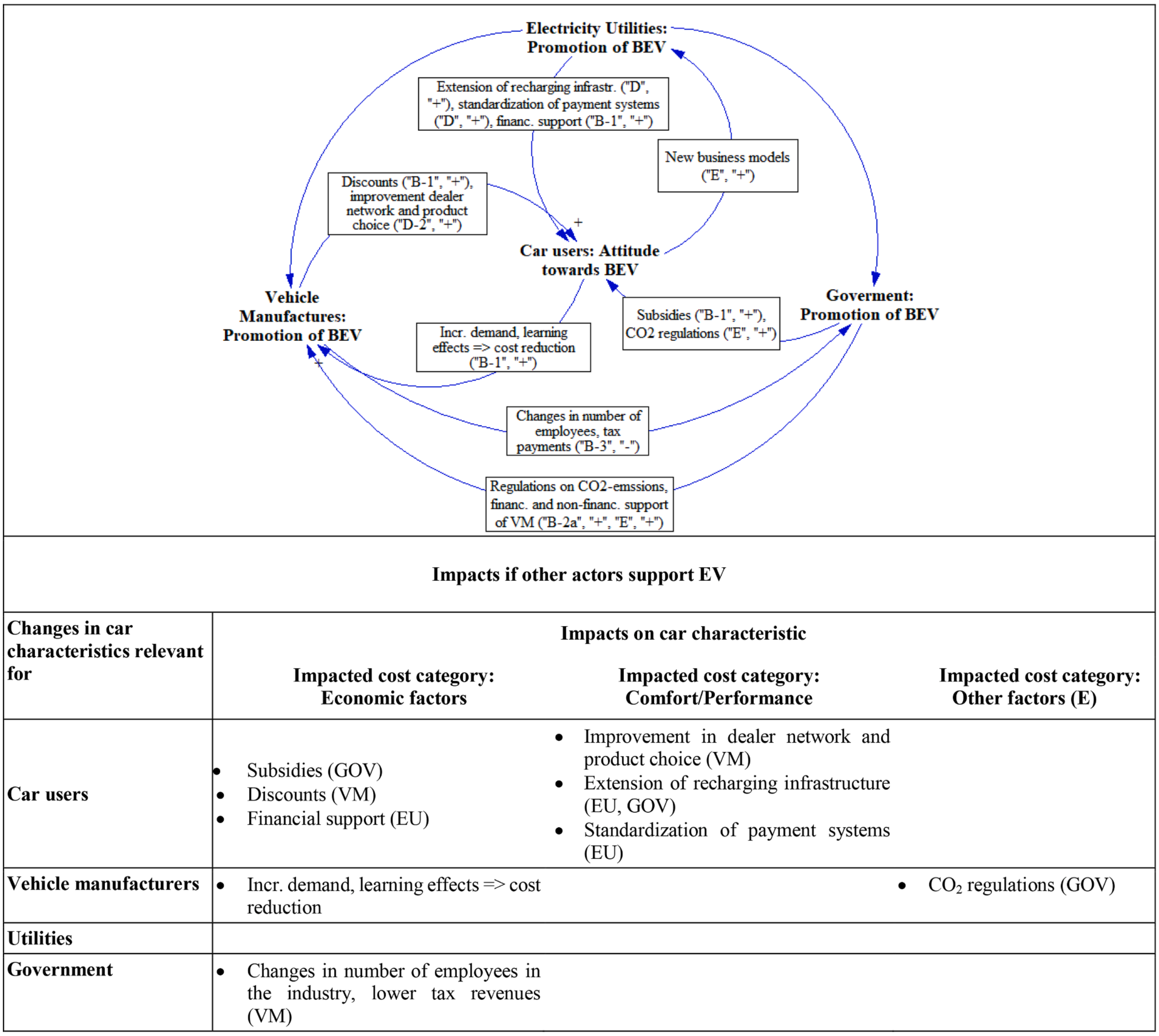
For a representative and fair comparison, we assume that the selected cars are compact/ medium cars. The specification assigned to the three car categories is based on the latest data for selected cars of this category. To increase comparability, we limit the choice to cars of one car manufacturer. As a representative example for a BEV, we select the Hyundai IONIQ Electric and the Hyundai i30 Fastback as a prototypical ICE. The Hyundai IONIQ Plug-In Hybrid represents HEVs in our study.

Based on the list of characteristics in which the actors are interested, we specify the values for the indicators for each car category (Table 2). For indicators which were difficult to quantify, we use a scale ranging from 1 ("very low"/"very bad") to 5 ("very high"/"very good").

3. Externalities

There are different interactions, in several directions, among the stakeholders identified in section 0. To foster the diffusion of EVs and HEVs, the German government introduced specific incentives directed at car users, as BEVs and HEVs were disadvantaged compared to well-established ICE technology. Currently, the purchase of a BEV has a 6.000€ subsidy (with an additional 3.000€ if the car is purchased between July 2020 and December 2021). Half of the bonus is paid by the government and the rest is paid by the car industry. For plug-in hybrid cars, the bonus amounts to 4.500€ (with an additional 1.250€ if the car is purchased in the period between July 2020 and December 2021). Again, the government and the industry bear the costs of the bonus evenly.

Furthermore, electric utilities support the purchase of BEVs. Many of them sponsor the installation of home charging stations with 5.00€ to 1.000€. Non-financial support includes promoting the deployment of charging infrastructure. Other examples for the interaction between stakeholders include expanding the portfolio of BEV and HEV cars as well as their promotion by the vehicle manufacturers.



Impacts if other actors support EV

Changes in car characteristics relevant for	**Impacts on car characteristic**		
	Impacted cost category: Economic factors	**Impacted cost category: Comfort/Performance**	**Impacted cost category: Other factors (E)**
Car users	• Subsidies (GOV) • Discounts (VM) • Financial support (EU)	• Improvement in dealer network and product choice (VM) • Extension of recharging infrastructure (EU, GOV) • Standardization of payment systems (EU)	
Vehicle manufacturers	• Incr. demand, learning effects => cost reduction		• CO_2 regulations (GOV)
Utilities			
Government	• Changes in number of employees in the industry, lower tax revenues (VM)		

Remarks: "+": positive impact, "-" : negative impact

Impacts if other actors support EV

Changes in car characteristics relevant for	**Impacts on car characteristic** **Impacted cost category: Economic factors**	**Impacted cost category: Comfort/Performance**	**Impacted cost category: Other factors (E)**
Car users	Subsidies (GOV) Discounts (VM) Financial support (EU)	Improvement in dealer network and product choice (VM) Extension of recharging infrastructure (EU, GOV) Standardization of payment systems (EU)	
Vehicle manufacturers	Incr. demand, learning effects => cost reduction		CO_2 regulations (GOV)
Utilities			
Government	Changes in number of employees in the industry, lower tax revenues (VM)		

Remarks: "+": positive impact, "-" : negative impact

We model these interactions and externalities by changing selected car characteristics accordingly. Hence, in addition to the default calculations, we analyze changes in car characteristics to assess the strength and outcome of such interactions.

4. Results

4.1. *Prioritization of car technologies whilst externalities are excluded*

In this section, we present our results from the modelling of stakeholders' preferences towards the three types of cars considered. After a short overview of the default scenario, which represents the current

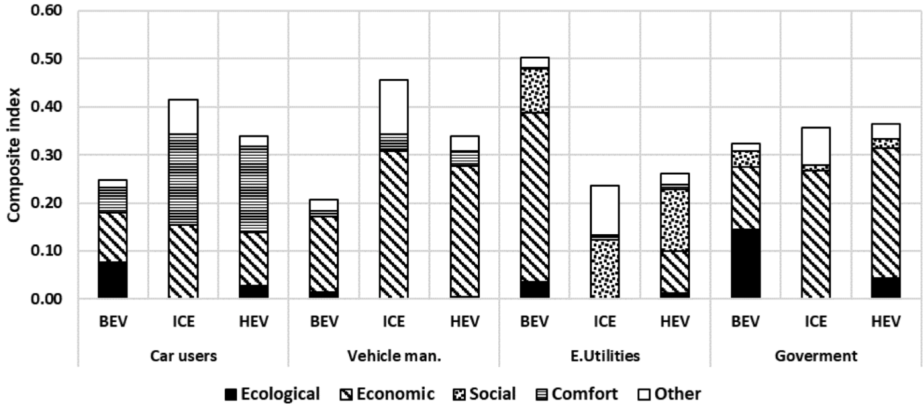


Fig. 2. Initial preferences for all actors under default conditions (excluding externalities).

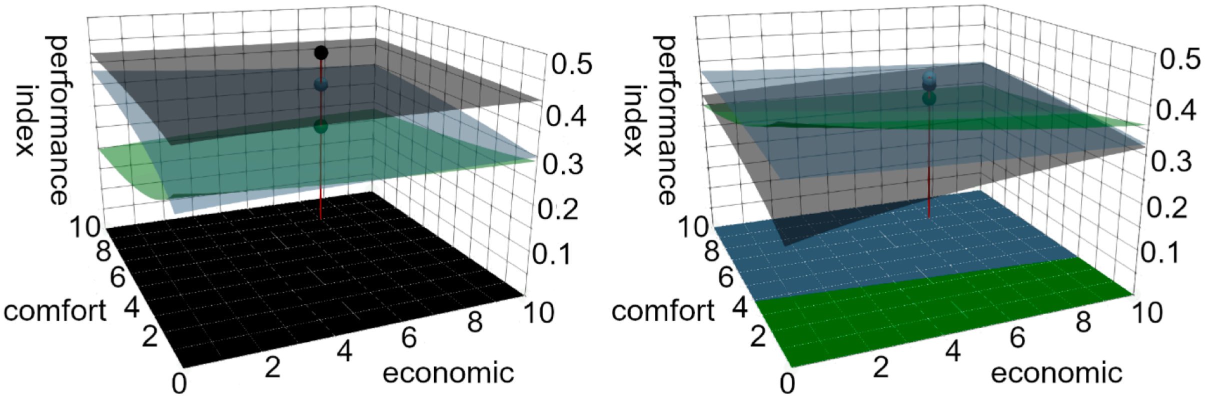


Fig. 3. Car users' attitudes under default conditions (left) and raised ecological awareness (ecological = 9, right). The red line indicates the car users' default weighting of comfort and economic aspects.

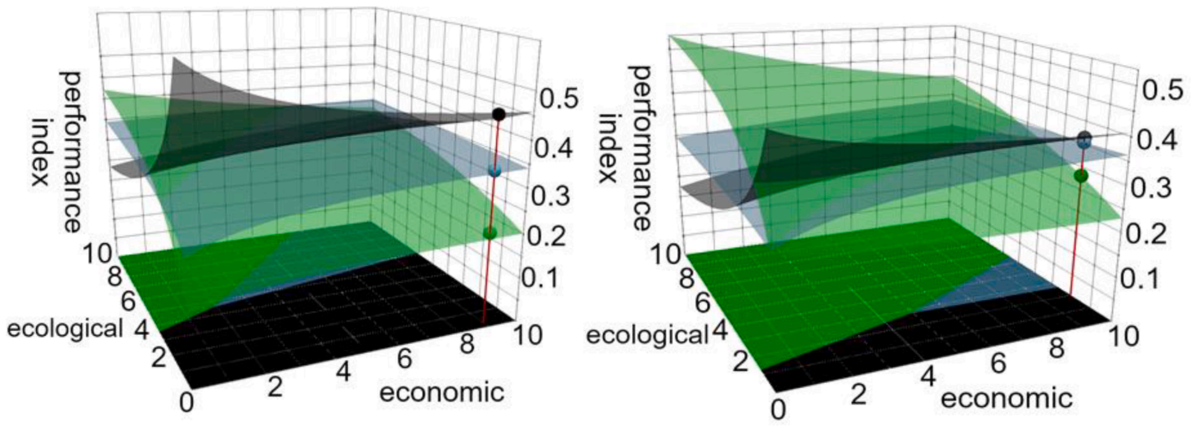


Fig. 4. Preferences of the VMs (left) and the Government (right) under default conditions. The red line indicates the stakeholder's default weighting of economic and ecological aspects.

state in Germany, we investigate the preferences of the stakeholders in more detail. We perform a sensitivity analysis by systematically varying the most relevant weights and visualizing the corresponding performance indices. This allows us to identify tipping points. In a second step, we investigate the influence of externalities like subsidies on preferences of car users.

Error! Reference source not found.Error! Reference source not found. shows the initial stakeholder preferences under default conditions in Germany. The performance index for each type of car (on the z axis) is determined by the weightings for the main factors ecological, economic, comfort, social and other, multiplied by the values in Table 4. The results do not show a complete picture of preferences, as they omit externalities, namely how stakeholders influence each other.

Obviously, two extremes form, with the government and electricity utilities strongly in favor of BEVs, at one end, and vehicle manufacturers and car users preferring conventional ICE vehicles, at the other end. Although, in Figure 2, the government's preferences are towards HEVs, based on the mobility technologies' performance across the different

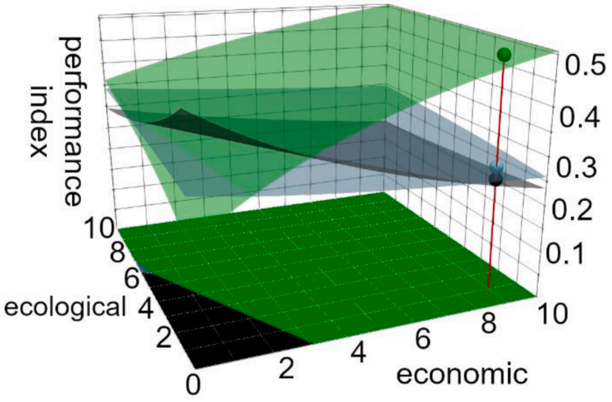


Fig. 5. Preferences of E.Utilities under Default Conditions

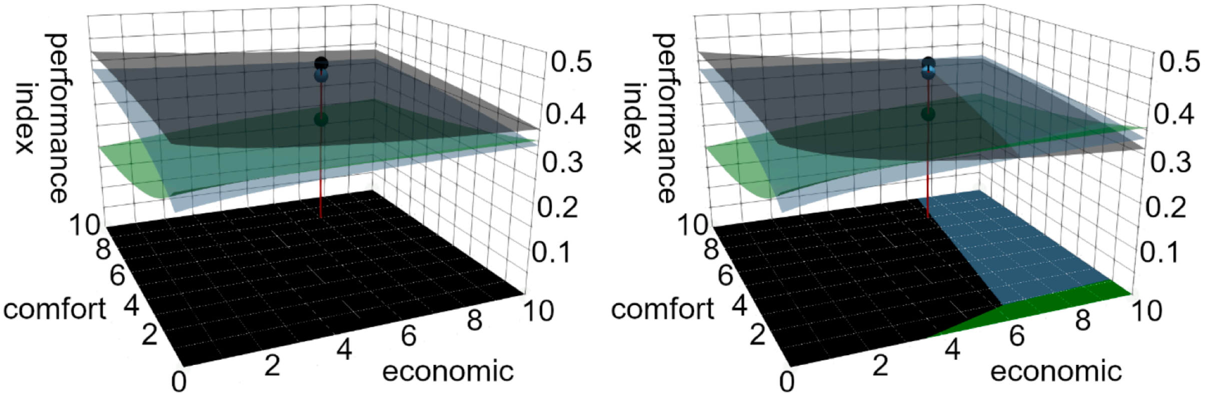


Fig. 6. Preferences of car users for cost parity (left) and cost advantages due to subsidies (right), both for low ecological weighting (ecological = 2).

categories and the weightings attached to these categories, legal obligations force the government to favor BEVs over HEVs. HEVs enjoy a stronger position than BEVs among vehicle manufacturers and car users. For car users, HEVs are more economically attractive and perform better in the comfort dimension. Vehicle manufacturers face less disruption to their business model from HEVs (they are more compatible with their existing competencies) and this feeds through to better profitability from HEVs compared to BEVs. Therefore, our model provides a realistic description of the current state and, thus, passes an essential plausibility check.

5. Car users

In the default scenario (*ecological* = 2, *economic* = 7, *comfort* = 8), reflecting car users' current preferences in Germany, BEVs struggle to diffuse at all. We illustrate our results in Fig. 3 (left). Here, we systematically vary *economic* and *comfort* to conduct a sensitivity analysis; the red line indicates the assumed default values of *economic* and *comfort*.

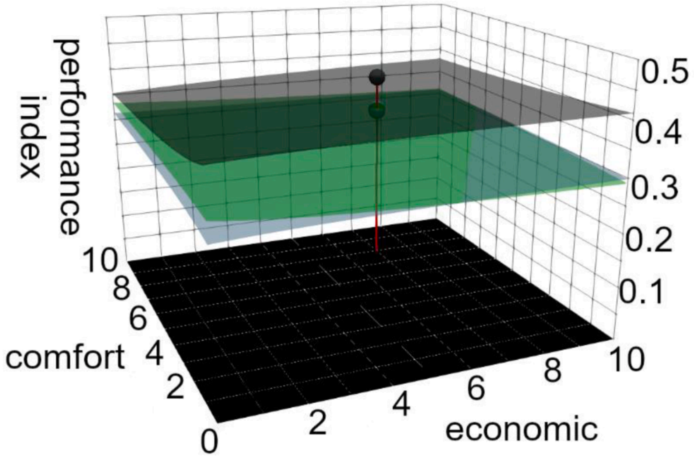


Fig. 7. Car users' attitudes if recharging a BEV is as easy as refueling an ICE.

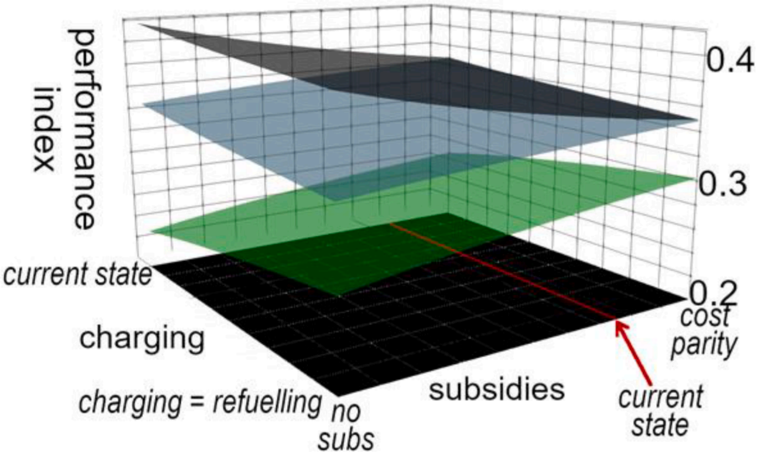


Fig. 8. Combined effects of subsidies and improved charging possibilities on car users' preferences under otherwise default conditions.

The bottom in this figure and many of the subsequent figures is colored according to the outcome of the decision (green: BEV, blue: HEV, black: ICE)[1]. In order to assess the stability of a decision for a given set of weights, we present the performance indices depending on *economic* and *comfort* as translucent surfaces. According to our model, car users favor ICEs over HEVs regardless of the values of *economic* and *comfort* when the default ecological weighting is assumed (ecological = 2). BEVs are, by a wide margin, less attractive than ICEs even if economic and comfort aspects play a minor role. Under current conditions, BEVs simply face too great a disadvantage in comfort and economic aspects compared to the other two options. Even for *ecological* = 9, greater than the weightings for both *economic* and *comfort*, the break-through of BEVs against HEVs is constrained (Fig. 3, right), although BEVs now appear to gain greater ground against ICE vehicles, as shown by the performance indices. These indices are extremely close for the three types of cars such that, given the uncertainties related to modeling, a certain dissemination of BEVs may be expected according to our model in this case. Still, BEVs do not prevail under otherwise default conditions. High ecological awareness among car users alone is insufficient for BEVs to become the dominant choice of car, unless comfort aspects are secondary. However, if ecological aspects are at least as important as the comfort and economic aspects, ICEs will no longer be considered.

5.1. Vehicle manufacturers (VMs) and government

As comfort aspects are not likely to play a significant role from a VM's perspective, we now systematically vary *economic* and *ecological*. Unless ecological aspects far outweigh economic aspects, VMs have no reason to produce BEVs in our model (Fig. 4, left). We consider this scenario unlikely. For *ecological* below approx. 4 (still significantly more than today), vehicle manufacturers will only choose ICEs in our model, even if economic aspects play a minor role. Under current conditions (*economic* = 9, *comfort* = 1), it takes an ecological weighting of at least 6 to cause a shift towards HEVs. VMs do not prefer BEVs regardless of the value of *economic*. However, under high ecological awareness (*ecological* = 9), the performance indices are very close together, meaning that the decision in favor of one vehicle type is less firm than suggested by the model. Under reasonable assumptions about the weightings, VMs will not produce BEVs according to our model unless forced to by externalities which we do not consider here. However, there may be a broad shift towards HEVs if there is a substantial rise in ecological awareness.

If economic considerations substantially outweigh ecological ones, there is no reason for the government to support BEVs (Fig. 4 right), as ICEs yield a significantly higher performance index. The difference between the performance indices is substantial, leading to a firm decision in favor of ICEs. Under increasing ecological awareness and unchanged economic priorities, the government opts to support HEVs. Only if economic and ecological priorities are more or less balanced, will BEVs appear preferable from the government's point of view. On the other hand, the German administration does currently support HEVs and BEVs with considerable subsidies. We assume that this discrepancy to our model is due to externalities (e.g. commitment to international GHG reduction targets) which are not modeled here.

5.2. Electric utilities

Massive deployment of electric vehicles implies substantial changes to the power system. However, according to our analysis, electric utilities strongly support BEVs for economic reasons. This indicates the fact that the higher the weighting for *economic,* the greater the advantage of BEVs over the other types of cars, from the perspective of the electric utilities (Figure 5). Due to the large difference in performance indices, this decision is firm and robust against uncertainties in weights or values. Electric utilities will only prefer ICEs if neither economic nor ecological factors play a significant role. This would only apply if concerns about grid security were dominant.

5.3. Impact of externalities: influence of subsidies and charging infrastructure on car users

In 2020, BEVs are heavily subsidized by the German government and to lesser extent by the vehicle manufacturers (see 0). We investigate the effect of subsidies by assuming cost parity among all vehicle types, i.e. the price differential affecting BEVs and HEVs compared to ICEs, is eliminated by subsidies. In this scenario, the subsidies are slightly higher than in 2020. With the corresponding modification of values in our model, we repeat the investigations of section 0. The results (Fig. 6) can be directly compared with the ones displayed in Fig. 3. The subsidies make the performance indices of the three types of cars converge compared to the default scenario, but car users still opt for ICEs in all cases if the value of *ecological* = 2. In fact, at the time of writing this article, sales of BEVs in Germany are increasing rapidly. This is not in contradiction to our model, as the fraction of BEVs sold is still low despite this increase. Car users are, in reality, far less homogenous than

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[1] The diagrams can be 'read' by looking at the 'floor' of the figure, which is a projection of the best performing technology against the two criteria that constitute the grid of the horizontal plane. Hence, in Fig 3, for instance, the left hand figure shows ICE cars (black) predominate for all weightings of comfort and economic criteria, while the right hand figure shows HEVs (blue) dominate where comfort is highly weighted and BEVs (green) dominate where comfort is weighted low

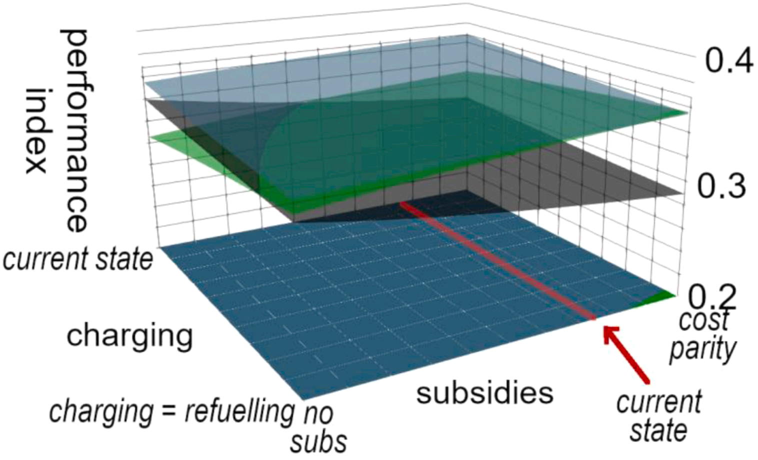

Fig. 9. Combined effects of improved charging and subsidies under high ecological weighting.

assumed in our model, and decisions may heavily depend on externalities. Both effects are not modeled here. Our model indicates that ICEs by far dominate sales, and that is what we experience in the German market.

Due to the ineffectiveness of the subsidies in our model, we examined the effect of even higher subsidies. In our model, we raised the level of subsidies, such that the initial cost disadvantage of BEVs and HEVs relative to ICEs transforms into a cost advantage of the same size. This corresponds to subsidies of approx. 24.000€ for BEVs and 18.000€ for HEVs in total. Even with these enhanced subsidies, we do not expect a widespread dissemination of BEVs as comfort aspects prevent this (Fig. 6, right). Despite their low purchase cost, car users will only consider BEVs if comfort aspects like range play a minor role. However, HEVs appear to be a better choice for car users. Nonetheless, a broad shift to BEVs cannot be induced by subsidies alone, no matter how high these subsidies are.

In addition to price, aspects related to charging time and range (subsumed in the category *comfort*) form an obstacle to the widespread adoption of electric mobility. As shown in Fig. 6, the performance index of BEVs significantly decreases as the weighting attached to comfort rises whereas, the performance index of ICEs rises substantially with increasing importance of comfort. In our model, range and charging time for BEVs do not fully meet the average car user's demand. Besides granting subsidies, the government can improve charging infrastructure by regulatory measures.

The quality and availability of charging infrastructure together with charging time is coded in the values of D-1 (comfort| charging; Table 4). In order to investigate the effect of such governmental measures on the car users' preferences, we consider the default scenario (see section 0), but modify the values associated with D-1 for BEVs from 1 to 5. We thereby assume that recharging the battery is as convenient, in terms of ease, speed of charging and availability of charging stations, as refueling an ICE vehicle. This setup is very optimistic and beyond the scope of governmental action which cannot shorten charging times through legislation alone. In Fig. 7, it can be seen that the improved charging is insufficient for BEVs to breakthrough, under default ecological awareness. This is due to the fact that the range of BEVs is inferior in addition to the remaining disadvantages in cost (in the default scenario, there are no subsidies). If we go further and consider the combined effect both of subsidies and improvements in charging, Error! Reference source not found. indicates that the boost to the performance index from better charging is limited and that the effect of the subsidies is greater. However, although the performance indexes converge slightly, the combined effect of cost parity and easy charging is insufficient for BEVs to break through. It is only when ecological = 9, as in Fig. 9, that we see that, under the combined effect of subsidies and improved charging, that HEVs become dominant. This, however, is not the desired result of the policy which is to, ultimately, promote BEVs.

6. Discussion

The results show that vehicle manufacturers are one of the stakeholders which shows resistance to the transition to BEVs. Such a change involves the acquisition of new competencies in manufacturing, especially of batteries, and new abilities in maintenance and servicing (Deloitte, 2019), whilst destroying the value of existing competencies around engine design (Teece, 2018). This is, clearly, disruptive for manufacturers and entails difficult investment and restructuring. Externally, path dependencies have hindered the transition to BEVs in Germany. Modest R&D support for e-mobility coupled with the late deployment of incentives, partly as a result of waiting for German models to become available delayed change (Meckling and Nahm, 2018). These findings are in line with our model which assumes the reluctance of VMs to switch to producing BEVs, even for increased ecological awareness, at which point the VMs transition to producing HEVs.

The biggest “winners” from the diffusion of e-mobility are the electric utilities. There will be a substantial growth in power demand which leads to opportunities for these companies to offset losses in revenues attributed to the growth of decentralized production of electricity by private households (prosumers) and energy efficiency measures (Salisbury and Toor, 2016). Electric utilities are considered key partners in the transition to e-mobility. They are members of the German National Electric Mobility Platform (Wentland, 2016) and are often considered the natural actors to build and operate chargers, as they are capable of making long-term investments in infrastructure and have a good knowledge of demand management (Karali, 2017; Salisbury and Toor, 2016).

Norway, which has been comparatively successful in the dissemination of e-mobility (IEA, 2018), offers insights as to how to shift car users' preferences towards BEVs. Norway's approach towards promoting BEVs is based largely on making conventional cars economically less attractive (Fridstrøm, 2019; Norwegian Ministry of Transport and Communications, 2016). BEVs are exempted from VAT and a substantial registration tax levied on other vehicle types. Furthermore, BEVs are allowed to use bus lanes and they have free access to road ferries. Beside special regulations on parking slots, in some cities, the parking fees are reduced for BEVs (IEA, 2018). The principle behind Norwegian electric mobility policy is that it should be cheaper to purchase zero emissions vehicles than conventional cars and this is reinforced by legislation mandating that all passenger cars and light vans sold in 2025 in Norway will be zero emissions (Norwegian Ministry of Transport and

Communications, 2016). This is reinforced by stricter vehicle emissions targets, exceeding those of the EU, imposed by the Norwegian Government (Figenbaum, 2017).

In Norway, there is a need to persuade car users that BEVs can be used on long as well as short journeys (Assum et al., 2014). “Range anxiety” hinders the confidence of car users in adopting BEVs and a weak relationship exists between the expansion of public charging infrastructure and adoption (Illmann and Kluge, 2019). In Norway, the majority of BEV users have private chargers (Illmann and Kluge, 2019) and the diffusion of BEVs has been successful despite the fact that there are relatively few chargers per electric vehicle (Gnann et al., 2018). This leads to a debate about whether it is worth building up charging infrastructure which may have to be funded by public investment (Gnann et al., 2018). If ‘range anxiety’ has more to do with perceptions than reality, unnecessary chargers may be built which are then hard to operate profitably (Assum et al., 2014). In fact, the positive effect that public chargers have on adoption is outweighed by ‘peer effects’, namely that the increase of BEVs in a particular geographical area spurs on other users to also adopt BEVs (Illmann and Kluge, 2019). This could be a factor behind the wider diffusion of BEVs in Norway, namely that other car users followed the lead set by early adopters. Interestingly, in a German study, increasing the number of chargers was found to have a stronger effect on the adoption of Plug-in hybrids than BEVs (Illmann and Kluge, 2019). Since HEV users have a conventional engine as backup and, therefore, are not completely reliant on a battery being charged, they can be more risk-taking regarding the availability of charging infrastructure, whereas potential BEV adopters remain reluctant to shift (Illmann and Kluge, 2019). This is a possible reason why HEVs largely retain preference over BEVs even when the disadvantages between BEVs and ICEs are removed, as shown in section 0.

A dynamic to do with multiple car ownership is also present in Norway and has implications for the adoption of BEVs. Just under 80% of Norwegian BEV users have access to a second vehicle compared to just under half of ICE users (Figenbaum and Kolbenstvedt, 2016). Using German and Swedish data, Jakobsson et al. (2016) find that BEVs are most suited to replacing second cars – cars which do shorter, everyday journeys involving carrying fewer passengers. If BEVs mainly replace second cars, it could be that increasing their diffusion simply increases vehicle ownership (Figenbaum, 2017) which has implications for sustainability and BEVs must have success among single vehicle households and replace cars on long journeys (Figenbaum, 2018).

Our results for Germany are in line with that the experiences gained in Norway that a use of BEVs as second cars combined with subsidies and a widespread charging network foster the development of e-mobility. However, our results show that deployment is strongly influenced by additional factors specific to the German context. In contrast to Norway, in Germany, there is a powerful car industry with a strong interest in selling conventional, well-established and technologically mature cars. Hence, the German government is more reticent about ambitious measures with respect to e-mobility than the Norwegian government. The specific CO_2 emissions of generating electrical power may be another reason for differences between policies regarding e-mobility in Norway and Germany. In Norway, electricity is mainly generated by hydroelectric power plants and nearly CO_2-free, whereas, in Germany, coal-fired power plants still cover a substantial part of the electricity production. Therefore, a switch to BEVs in Germany will result in a proportionally lower reduction of CO_2 emissions than in Norway and this further challenges the calculation for the government, in terms of support for BEVs.

7. Conclusions

The decarbonization of the mobility sector is one key challenge for reaching the goals specified in the Paris Agreement. Despite implementing different supportive measures, the diffusion of BEVs in Germany has been slow so far. By employing a multi-criteria approach and using the example of Germany, we examine the influence of different criteria on the purchases of cars by private households. Furthermore, we explore why other stakeholders, important to the dissemination of BEVs, support particular types of vehicles. In our approach, we distinguish between changes in the characteristics of cars (e.g. cost, comfort) and the weightings attached to the characteristics by selected groups of stakeholders. The results show that, under default conditions, high ecological awareness among car users alone is insufficient for battery electric vehicles to prevail over other options, unless comfort aspects become secondary which, of course, is very unlikely. We conclude that a broad shift to BEVs cannot be bought by subsidies alone, regardless of the amount. According to our calculations, even if charging infrastructure is improved, the dominance of ICEs will persist. If both subsidies and the improvement of charging possibilities are combined with changes in the car users’ ecological awareness, our results indicate that HEVs will become the most attractive option, outperforming BEVs.

This indicates that this current policy mix of pushing BEVs by providing subsidies and improving the charging infrastructure will not be sufficient for BEVs to become the dominant vehicle choice of car users. The results suggest that a more effective policy would be to penalize conventional cars more strongly, as in Norway. It also appears necessary, that, if the government is serious about BEVs being the preferred vehicle choice in Germany, then it will have to discourage HEVs too. This would help to shift car users definitively towards BEVs from ICEs and HEVs. Since BEVs present challenges for vehicle manufacturers in the economic dimension, policy will have to support their adaptation efforts if resistance is to be overcome. This could be through, for example, promoting the domestic manufacturing of batteries (e.g. Steinhilber et al. (2013)) and supporting the development of new skills relevant to e-mobility as opposed to conventional mobility. Countries without an influential car industry like Norway might face less resistance against the transformation to electric mobility. In Germany, however, this is a point that will require significant attention. Electric utilities have a lot to gain from e-mobility, as they will be able to sell more electricity. However, they will have to design business models for running the charging infrastructure effectively.

A more advanced study than ours needs to consider the heterogeneity of the actors, in particular the car users. This and a more refined analysis of uncertainties in both weightings and characteristics appear as natural starting points for further research on attitudes of actors towards different mobility options as well as the decarbonization of the transport sector in general. Crucially, this must be accompanied by research with consumers to identify practical approaches to remedy the difficult adoption of electric cars, especially in view of the accelerated decarbonization targets contained within the Climate Protection Law.

Declarations of Competing Interest

None.

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