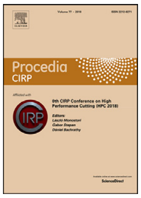
Procedia CIRP 90 (2020) 291–296

Contents lists available at ScienceDirect

Procedia CIRP

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



27th CIRP Life Cycle Engineering (LCE) Conference

Multidimensional assessment of passenger cars: Comparison of electric vehicles with internal combustion engine vehicles

Dennis Wilken[a,*], Matthias Oswald[a], Patrick Draheim[a], Christian Pade[a], Urte Brand[a], Thomas Vogt[a]

[a] *DLR-Institute of Networked Energy Systems e.V., Department Energy Systems Analysis, Carl-von-Ossietzky Str.15, 26129 Oldenburg, Germany*

ARTICLE INFO

Keywords:
Electromobility
Sustainable transport
Holistic assessment
Multi-criteria decision making (MCDM)
Battery-electric vehicle
Fuel cell electric vehicle
Life cycle assessment
Life cycle sustainability assessment
Total cost of ownership

ABSTRACT

In the pursuit of transforming the transportation sector towards sustainability, a technological shift in vehicle drive systems is being promoted worldwide. Conventional gasoline or diesel fueled cars powered by internal combustion engines (internal combustion engine vehicle, ICEV) are to be replaced with alternative cars that are electrically driven (electric vehicle, EV) and powered by a battery, which is either externally charged (battery-electric vehicle, BEV) or internally charged via a hydrogen fuel cell (fuel cell electric vehicle, FCEV). However, whether or not EVs are superior to ICEVs throughout their entire life cycle is still subject to debate. Though considerable numbers of environmental life cycle assessment (eLCA) studies and—to a much lesser extent—life cycle costing (LCC) and social life cycle assessment (sLCA) studies have already been conducted, their individual results alone do not allow decision-makers to draw conclusions concerning the overall sustainability performance of the various vehicle technologies. Therefore, we are presenting a novel approach to analyze ICEV-, BEV-, and FCEV-type passenger cars on a multidimensional basis. This approach is based upon and combines existing studies about eLCA, LCC, sLCA, and further assessments to carry out a comprehensive meta-analysis by using multi-criteria decision making (MCDM) methods. Through a transparent and differentiated presentation of the results, the adopted approach furthermore enables decision-makers to identify specific aspects influencing the overall performance of each vehicle technology and to take measures that allow for the implementation of sustainable vehicle concepts.

Peer-review under responsibility of the scientific committee of the 27th CIRP Life Cycle Engineering (LCE) Conference.

1. Introduction

With a 20% increase in greenhouse gas (GHG) emissions in Europe in 2016 (compared to 1990 levels) (Agency, 2019), the transport sector has not yet managed to initiate the necessary shift towards less climate-damaging transport technologies. Thus, climate-friendlier alternatives to conventional internal combustion engine vehicles (ICEVs) urgently needed. However, in order to prevent rebound effects and problem shifting, these alternatives need to be evaluated holistically, i.e., not only considering GHG emissions alone, but also other ecological, social, economic and technical aspects.

To date, environmental life cycle assessments (eLCA) make up the largest share of research on the sustainability impacts of vehicles. Among many others, the work by Bauer et al. (2015) constitutes a good example, since their study includes a rather broad set of environmental impacts. Faria et al. (2012) compared ICEV and electric vehicles (EVs) from an environemental and economic point of view and identified similar total costs of ownership (TCO) and lower GHG emissions for EVs. Wątróbski et al. (2017) looked at various electric freight vehicle models in urban areas in Poland, whereas Domingues et al. (2015) applied an multi-criteria deci-

---

[*] Corresponding author.

E-mail addresses: dennis.wilken@dlr.de (D. Wilken), matthias.oswald@dlr.de (M. Oswald).

https://doi.org/10.1016/j.procir.2020.01.101

Table 1
Assessment criteria and parameters as well as sustainability dimensions, stakeholders, areas of protection and issues affected.

Sustainability dimensions or stakeholders and respective criteria	Parameter	Area of protection or issues affected (positively [+] or negatively [-])
Environment & human health		
Global warming potential (GWP)	g CO_2 eq/km	Global climate [-]
Terrestrial acidification potential (TAP)	g SO_2 eq/km	Natural/built environment [-]
Metal depletion potential (MDP)	g Fe eq/km	Natural resources [-]
Fossil resources depletion potential (FRDP)	g oil eq/km	Natural resources [-]
Photochemical oxidant formation potential (POFP)	g NMVOC/ km	Ozone layer/human health [-]
Particulate matter formation potential (PMFP)	g PM_{10} eq/km	Human health [-]
Human toxicity potential (HTP)	g 1,4-DB eq/km	Human health [-]
User (economic dimension)		
Capital expenditure (CAPEX)	€	Financial means of user [-]
Operational expenditure (OPEX)	€	Financial means of user [-]
Total costs of ownership (TCO)	€	Financial means of user [-]
User (technical dimension)		
Fueling/charging time (FT)	min	User comfort [-]
Fueling/charging points (FP)	#	User comfort [+]
Driving range (RNG)	km	User comfort [+]
Society		
Global warming potential (GWP)	g CO_2 eq/km	Intergenerational justice [-]
Metal depletion potential (MDP)	g Fe eq/km	Intergenerational justice [-]
Fossil resources depletion potential (FRDP)	g oil eq/km	Intergenerational justice [-]
Capital expenditure (CAPEX)	€	Intragenerational justice [-]
Operational expenditure (OPEX)	€	Intragenerational justice [-]
Total costs of ownership (TCO)	€	Intragenerational justice [-]

sion making (MCDM) method for an environmental impact assessment of six vehicles with different powertrains in Portugal. Onat et al. (2016) conducted an analysis of ICEVs, BEVs, plug-in hybrid vehicles (PHEVs) and hybrid electric vehicles (HEVs) in the US. They combined the MCDM method of TOPSIS with an intuitionistic fuzzy set and took macroeconomic, social, and environmental criteria into account.

In the study presented here, ICEVs, BEVs and, additionally to many other studies, also fuel cell electric vehicles (FCEVs) are compared by assessing various environmental, economic, technical, and social criteria as well as different fuel types and electricity sources. Furthermore, the MCDM method PROMETHEE is used to integrate and aggregate the assessment results across all criteria. In this context, special attention is paid to potential effects of criteria weights and preference thresholds on the final ranking of the alternatives.

2. Method

2.1. General approach

The first step comprised the development of a set of assessment criteria. Aiming at the realization of a comprehensive but practical assessment, a bottom-up approach was used to identify (only) those criteria that were relevant for and applicable to the comparative assessment of passenger cars. This resulted in the compilation of a number of criteria, which were grouped according to the stakeholders and sustainability dimension affected (see Table 1).

The second step consisted in the application of the compiled criteria. For reasons of practicability and simplicity, the principle method here was to use, as much as possible, scientific data and information that were already available. Consequently, one recent, extensive, and detailed high-quality dataset of an environmental life cycle assessement (eLCA) on passenger cars with various driving technologies and fuel alternatives (Bauer et al., 2015), has been selected as a starting point and base for a multidimensional assessment (step three). All other data that were needed to assess the non-environmental criteria have then, in step four, been generated based on the scope of the chosen eLCA. Through this approach the compatibility and comparability of data across all assessment criteria could be established.

2.2. Main assumptions

Aiming at the realization of an assessment that is, as much as possible, comprehensive, robust, and close to real-life use patterns of passenger vehicles, the following assumptions have been made while all assumptions already made by Bauer et al. (2015) have been adopted in order to keep the results comparable across all assessment criteria (as indicated below):

- The following vehicle/drive/fuel concepts were included in the assessment (Bauer et al., 2015): diesel-fueled ICEV (ICEV_diesel; as reference case); gas-fueled ICEV (ICEV_gas); BEV charged with electricity either from the European Union (EU) 2012 electricity mix (BEV_EU-mix), from wind power plants only (BEV_wind), or from photovoltaic power plants only (BEV_PV); FCEV fueled with hydrogen either produced from natural gas via steam methane reforming (FCEV_NG-SMR) or generated through electrolysis using electricity from the EU 2012 electricity mix (FCEV_EU-mix), wind power plants (FCEV_wind) or from photovoltaic power plants (FCEV_PV). As opposed to Bauer et al. (2015), HEV and PHEV have not been included as there are up to now no sufficiently robust data available on realistic or probable shares of distances driven electrically or fossil-fueled, so that assessment results based on these very uncertain data would be highly speculative.
- The evaluation is based on the consideration of the entire life cycle and includes the following phases: raw material supply, product manufacture, transport, use, end-of-life (Bauer et al., 2015).
- A lifetime driving distance for each alternative of 240,000 km is assumed for the evaluation within the use phase (Bauer et al., 2015), using the Worldwide harmonized Light vehicles Test Procedure (WLTP) to estimate the consumption rate.
- Since there is no vehicle model commercially available that can be purchased as either ICEV_diesel, ICEV_gas, BEV, or FCEV variant, data referring to vehicle characteristics could not be taken from one and the same model. Yet, all variants studied represent either “compact class” or “middle class” passenger cars. Since they are to a certain extent comparable and stand for the largest share of vehicle types currently on the roads in Ger-

Table 2
Cost factors and assumptions made for economic assessment.

	VW Golf 1.5 TSI ACT (gas)	VW Golf 2.0 TDI SCR (diesel)	VW e-Golf (BEV)	Hyundai Nexo (FCEV)
Investment costs (Volkswagen et al., 2019), (Volkswagen and e-Golf, 2019), (Hyundai Motor Deutschland GmbH 2018)	26,270 €	28,925 €	35,900 €	69,000 €
State/vendor subsidy(BMWi, 2019)	–	–	4000 €	4000 €
Fuel costs (ADAC 2019)	1.46 €/l	1.30 €/l	0.3 €/kWh	9.5 €/kg
Consumption rate (WLTP) (Volkswagen, 2019)	0.065 l/km	0.054 l/km	0.169 kWh/km	0.0095 kg/km
Maintenance costs (Propfe et al., 2012)	0.072 €/km	0.072 €/km	0.059 €/km	0.07 €/km
Vehicle tax (BMF 2019)	136 €/a	284 €/a	62 €/a	68 €/a

many. Note that the environmental and human health assessment is based on a fictitious "middle class" car model that has been modelled by Bauer et al. (2015), whereas the economic assessment is based on real car "compact class" models.

2.3. Environmental and human health assessment

As already explained in Section 2.1, environmental and human health (E&HH) assessment criteria as well as the assessment results were directly taken from Bauer et al. (2015). These criteria cover, on the one hand, those E&HH issues that are at the foreground of political and public debate with respect to the environmental sustainability of cars (i.e., global warming potential and particulate matter formation). On the other hand, criteria were included that are much less publicly discussed, although they represent issues significantly affected by the life cycle of passenger vehicles, too (see all other E&HH criteria listed in Table 1).

2.4. Economic and technical assessment

The economic and technical assessment is done from the perspective of the car owner/user as one of the most strongly involved stakeholders in the context of the economic/ technological sustainability/feasibility of passenger cars (cf (Lieven et al., 2011)). The economic assessment is based on the TCO calculation approach. In doing so, all financial liabilities that have to be borne by the owner of the vehicle during the utilization phase are summed up to a total cost figure (Bubeck et al., 2016). However, due to the very different character of capital investment expenditure (CAPEX) and operational expenditure (OPEX) that may very likely be viewed differently by the car buyer/owner, both TCO as well as CAPEX and OPEX figures are displayed throughout the whole assessment.

Pursuant to the net present value approach, the cash outflows are discounted—assuming a rate of 3.1% (Bubeck et al., 2016)—with respect to the year they incur. All relevant costs taken into account as well as specific assumptions made for TCO calculations are presented in Table 2.

Insurance costs were neglected as there is no evidence for cost differences resulting from the type of drive/fuel system specific to each of the assessed alternatives. Furthermore, no resale was considered since the vehicles were assumed to have reached the end of their lifetime by the end of the considered utilization period. The considered lifetime in this study amounts to 17 years and was calculated from the average annual distance travelled by passenger cars in Germany in 2018 (KBA 2019) and the total lifetime distance set in this study according to Bauer et al. (2015) (see Section 2.2). The technical assessment evaluates the time needed to fuel/charge the vehicle (Michaelis et al., 2013), the number of fueling/charging points publicly available (MWV 2019; Bundesnetzagentur 2019; H2Mobility 2019), and the maximum driving range possible within one fueling/charging cycle (Volkswagen and e-Golf, 2019; Hyundai Motor Deutschland GmbH 2018; Volkswagen, 2019).

2.5. Social assessment

Since each of the identified assessment criteria that refer to social/societal issues is identical to a criterion already used within the environmental/human health or economic assessment (see Table 1), the social assessment was realized through the application of specific weighting scenarios as part of the MCDM process (see Section 2.6) instead of a double-evaluation of E&HH or economic criteria.

2.6. Integration and aggregation of assessment results

To be able to achieve an overall result (i.e., ranking) with respect to the comparison of the sustainability performances of all of the studied vehicle types, the individual assessment results were integrated and aggregated throughout all assessment dimensions and criteria. This was done by applying the PROMETHEE MCDM method (Brans and Vincke, 1985). PROMETHEE establishes a ranking of alternatives based on criteria values, preference functions, and criteria weights. In order to exclude bias and keep the assessment feasible, neither stakeholder representatives nor "experts" were involved in this study. Instead, six *weighting scenarios* (S1–S6) with varying weight distributions as well as nine *preference scenarios* with varying preference and indifference thresholds for the performance values of each criterion were defined in order to demonstrate the impact the chosen criteria and their respective phenotypes (i.e., values) may have on the overall performance of each alternative. For the baseline scenario (S1) equal weights were used for each and every criterion. All other weighting scenarios were either based on different sustainability goals (e.g., intergenerational and intragenerational justice) or on the degree of economic and technical performance of the alternatives from a car buyer's or car user's perspective. Criteria particularly relevant to the scenario's main focus were weighted twice as heavy (i.e., twice as important) as all regular criteria; criteria which were rated as not relevant at all to the respective scenario focus received a weighting factor of zero (i.e., these criteria could not contribute to the overall performance evaluation).

The preference scenarios, on the other hand, used linear preference functions with varying (combinations of) thresholds for the transitions from indifference to weak preference (either 0, 1, 10, 25, or 30 percent or the value of standard deviation) as well as from weak to strong preference (either 0, 10, 20, 30, 50, 80, or 100 percent or the value of distance between minimum and maximum value) to account for the impacts that these thresholds might have on the overall performance evaluations. During the integration and aggregation process, each weighting scenario has been applied to each preference scenario for a total of 54 scenarios.

3. Results and discussion

Fig. 1 shows how each vehicle type assessed performs with respect to each E&HH, economic, and technical criterion. Since all but two criteria (i.e., RNG and FP) have to be minimized ("[-]") for a

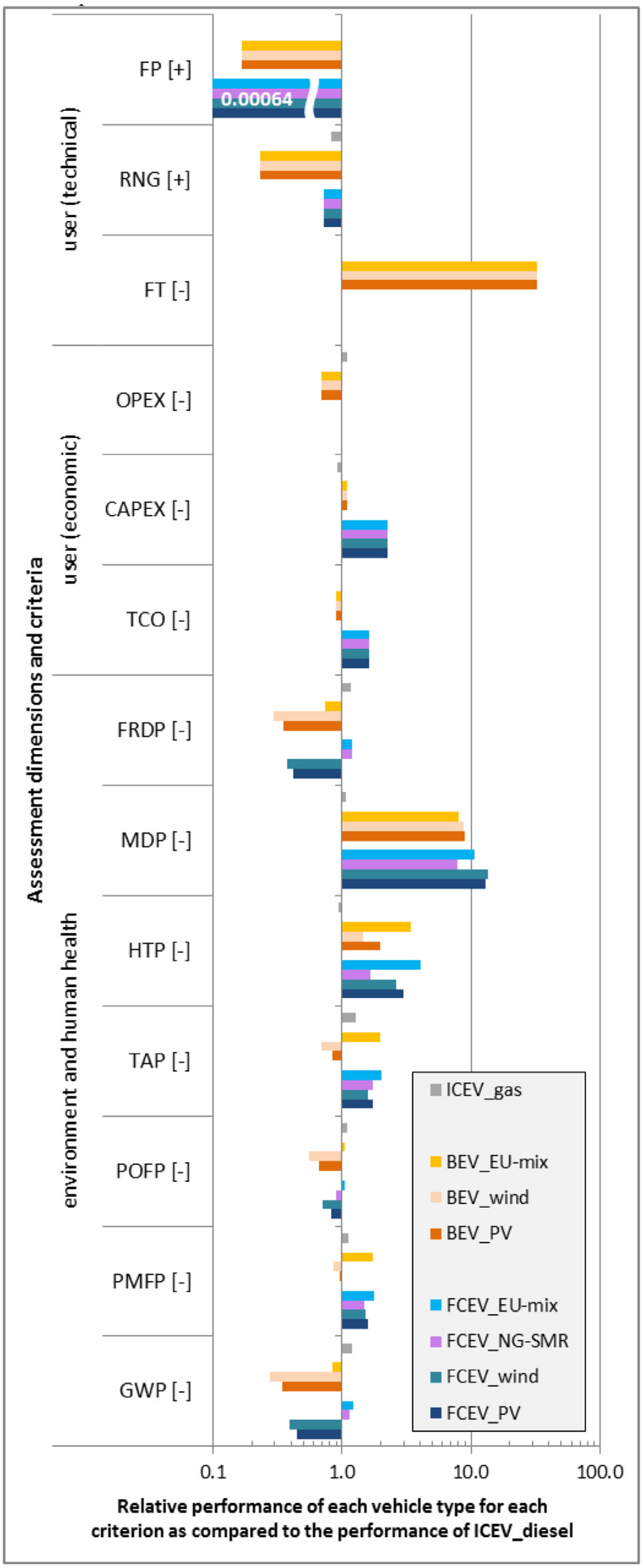


Fig. 1. Relative performance of each vehicle type for each criterion as compared to the performance of ICEV_diesel (data for environment and human health data adopted from (Bauer et al., 2015)).

maximum sustainability performance, the smaller the performance values are for a specific vehicle type, the more sustainable does the respective vehicle type appear (except for RNG and FP, where the sustainability is higher for larger performance values; "[+]"). All values are plotted as *relative* performances of each alternative as compared to the reference type ICEV_diesel. Thus, the resulting values are dimensionless. Furthermore, only unweighted values with no preference thresholds applied are depicted. Please note that, for reasons of better readability, a logarithmic scale is used and values below 0.10 were cut off. Generally, it becomes apparent that ICEV_gas performs same as, or very similar to, ICEV_diesel in every criterion assessed. For all other alternatives, the picture is quite heterogeneous and thus calls for a differentiated examination:

For most of the EV-type alternatives, the sustainability performance is worse for the majority of *E&HH criteria* as compared to the ICEV types. This is especially true for the criterion metal depletion potential (MDP), for which all EV alternatives show performance values that are roughly eight to fourteen times worse than the ICEV alternatives.

Similar but less severe results can also be seen for the criteria human toxicity potential (HTP), terrestrial acidification potential (TAP), and particulate matter formation potential (PMFP), although the _wind and _PV alternatives generally perform less worse than their _EU-mix counterparts, or even a little better than the ICEV alternatives.

(BEV_wind/PV for TAP and PMPF). Considerable improvements in most of the EV-type alternatives can be seen for the criteria global warming potential (GWP) and fossil resources depletion potential (FRDP), where values are 15% to 71% lower as compared to the ICEV alternatives. However, this does not hold true for the FCEV_EU-mix and FCEV_NG-SMR alternatives, where values are 15% to 23% higher. BEV/FCEV_wind/PV and FCEV_NG-SMR show also a more sustainable performance than the ICEV types with respect to photochemical oxidant formation potential (POFP), whereas the BEV/FCEV_EU-mix alternatives perform slightly worse.

Since all economic and technical data differentiate *between* but not *within* the group of BEV-type and FCEV-type alternatives, the resulting values are identical for all BEV_ and for all FCEV_ alternatives, respectively. When comparing both groups, differences in the *economic and technical performance* appear to be quite large, which can be seen most drastically with all three technical criteria: the BEV group performs much worse with regard to driving range (RNG) and fueling/charging time (FT), whereas the FCEV group performs worst for the number of fueling/charging points publicly available (FP).

Compared to both ICEV alternatives, the performance values are considerably worse for BEV for all three technical criteria (FP, RNG, FT). FT is same and RNG only slightly worse for FCEV as compared to ICEV, whereas FP is much worse. Economically, FCEV show significantly worse performance compared to ICEV regarding total costs of ownership (TCO), which is mainly due to much higher capital expenditures (CAPEX) at same operational expenditures (OPEX). BEV, on the other hand, perform slightly better then ICEV with respect to TCO, because OPEX of BEV are significantly lower at only slightly increased CAPEX.

Since the overall performance of each vehicle type assessed does not become apparent (neither absolute nor relative to each of the other alternatives) from the parallel depiction of the performances for each criterion, individual results have been integrated and aggregated with PROMETHEE (see Section 2.6). Fig. 2 shows the ranking of all studied alternatives that results from equally weighting all criteria combined with an indifference threshold of 10% and a strong preference threshold of 20%. In Fig. 2, each alternative is represented by a colored column (on the x-axis), where each color block represents one criterion that contributes positively

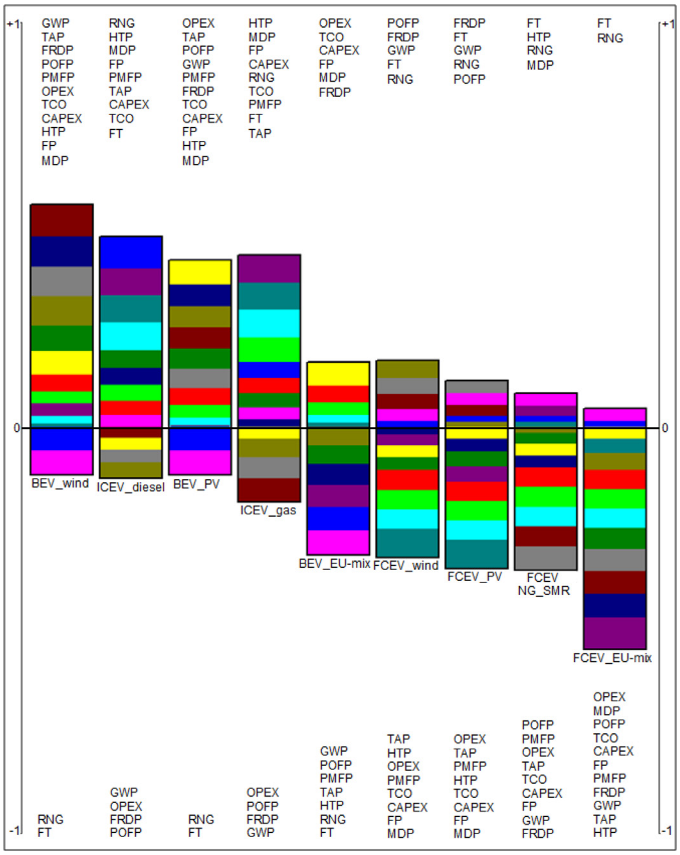


Fig. 2. Overall ranking of all alternatives as a sum of the individual criteria impacts. Alternatives are ranked according to their relative sustainability performance, starting with the best on the left to the worst on the right.

(i.e., blocks above 0 on the y-axis) or negatively (i.e., blocks below 0 on the y-axis) to the overall performance; the height of each color block and thus the total height of the whole staple above or below 0 represents the degree to which the respective criterion contributes (either positively or negatively) to the overall performance of the alternative in question. In this specific combination of weighting and preference scenarios, BEV_wind performs best, followed by ICEV_diesel and BEV_PV. Both BEV_wind/PV rank best at all criteria, except for RNG and FT, resulting in ranks one and three, respectively. ICEV-gas reaches rank four, although the sum of all positively contributing criteria is larger than for third ranked BEV_PV. This is because the sum of all four criteria contributing negatively is relatively larger and thus leads to a lower rank for ICEV_gas as compared to BEV_PV. All FCEV alternatives are ranked low, with FCEV_EU-mix being lowest. Right in the middle, in between the higher and lower ranks, is BEV_EU-mix.

In order to test the ranking method and explore the impact of weighting and preference thresholds, combinations of all six weighting and all nine preference scenarios (see Section 2.6) were implemented. Fig. 3 shows, in how many cases of all 54 weighting/preference-scenario combinations each of the vehicle alternatives assessed (columns) reaches a certain ranking (lines; from rank 1 through rank 8). It can be seen that the weights and preference thresholds only marginally affect the rankings: The BEV alternatives based on renewable electricity (i.e., BEV_wind/PV) share the upper ranks with the conventional vehicles (i.e., ICEV_diesel/gas) in the majority of scenario combinations, whereas BEV_EU-mix and all of the FCEV alternatives are mostly ranked lower.

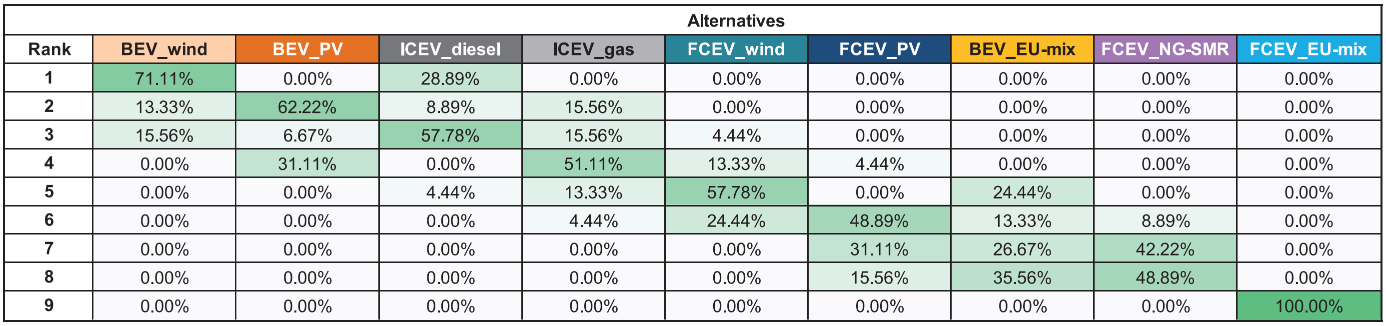
4. Summary and conclusion

A novel approach was presented that assesses various types of EVs against ICEVs over a number of criteria from different sustainability dimensions. In order to support decision-making that simultaneously accounts for various possible stakeholder perspectives, results were integrated and aggregated across a wide range of weighting and preference-threshold scenarios. Moreover, data referring to the developmental status quo of the technologies have been used instead of rather speculative anticipitations of possible future improvements especially of EVs. The assessments showed that BEVs charged with renewable electricity appear generally more sustainable than their ICEV counterparts and BEVs charged with electricity from mixed sources. FCEVs do in general perform worse as compared to all other alternatives.

The applied approach proved to be practical as it is straightforward and incorporates assessment results that had already been generated by others elsewhere. Yet, there is prospect for further improvement since, for example, further assessement criteria, especially from within the social sustainability dimension (such as job creation potential), more elaborated weighting factors or detailed use case parameters would enhance the overall validity and comprehensiveness of the sustainability assessment approach presented.

Credit Author Statement

Dennis Wilken: Conceptualization, Investigation, Writing- Original draft, Writing - Review & Editing. **Matthias Oswald**: Methodology, Formal analysis, Investigation, Writing- Original draft, Writing - Review & Editing, Visualization. **Patrick Draheim**: Investigation, Writing- Original draft, Writing - Review & Editing, Visualization. **Christian Pade:** Investigation, Writing- Original draft, Writing



	Alternatives								
Rank	BEV_wind	BEV_PV	ICEV_diesel	ICEV_gas	FCEV_wind	FCEV_PV	BEV_EU-mix	FCEV_NG-SMR	FCEV_EU-mix
1	71.11%	0.00%	28.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
2	13.33%	62.22%	8.89%	15.56%	0.00%	0.00%	0.00%	0.00%	0.00%
3	15.56%	6.67%	57.78%	15.56%	4.44%	0.00%	0.00%	0.00%	0.00%
4	0.00%	31.11%	0.00%	51.11%	13.33%	4.44%	0.00%	0.00%	0.00%
5	0.00%	0.00%	4.44%	13.33%	57.78%	0.00%	24.44%	0.00%	0.00%
6	0.00%	0.00%	0.00%	4.44%	24.44%	48.89%	13.33%	8.89%	0.00%
7	0.00%	0.00%	0.00%	0.00%	0.00%	31.11%	26.67%	42.22%	0.00%
8	0.00%	0.00%	0.00%	0.00%	0.00%	15.56%	35.56%	48.89%	0.00%
9	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%

Fig. 3. Rank distribution of all alternatives based on the combination of all six weighting scenarios and all nine preference scenarios.

- Review & Editing, Visualization. **Urte Brand**: Investigation, Writing - Review & Editing, Supervision. **Thomas Vogt:** Writing- Reviewing and Editing, Supervision.

References

ADAC, ADAC Autokosten Frühjahr/sommer 2019, https://www.adac.de/_mmm/pdf/autokostenuebersicht_47085.pdf. [Accessed: 19.08.2019].

E.E. Agency, Greenhouse gas emissions from transport in Europe, https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11. [Accessed: 06.09.2019].

Bauer, C., Hofer, J., Althaus, H.-J., Del Duce, A., Simons, A., 2015. The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. Appl. Energy 157, 871–883.

BMF, Kfz-Steuer-Rechner, https://www.bundesfinanzministerium.de/Web/DE/Service/Apps_Rechner/KfzRechner/KfzRechner.html. [Accessed: 2.9.2019].

Bubeck, S., Tomaschek, J., Fahl, U., 2016. Perspectives of electric mobility: total cost of ownership of electric vehicles in Germany. Transp Policy (Oxf) 50, 63–77.

Brans, J.P., Vincke, P., 1985. A preference ranking organisation method. Manage Sci. 31 (6), 647–656.

BMWi, 2019, Richtlinie zur Förderung des Absatzes von elektrisch betriebenen Fahrzeugen (Umweltbonus).

Bundesnetzagentur, Liste der gemeldeten Ladeeinrichtungen, https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/HandelundVertrieb/Ladesaeulenkarte/Ladesaeulenkarte_node.html. [Accessed: 30.08.2019].

Domingues, A.R., Marques, P., Garcia, R., Freire, F., Dias, L.C., 2015. Applying multi--criteria decision analysis to the life-cycle assessment of vehicles. J. Clean. Prod. 107, 749–759.

Faria, R., Moura, P., Delgado, J., de Almeida, A.T., 2012. A sustainability assessment of electric vehicles as a personal mobility system. Energy Conversion Manag. 61, 19–30.

H2Mobility, Netzausbau live - der aktuelle stand für Deutschland, https://h2.live/. [Accessed: 5.9.2019].

Hyundai Motor Deutschland GmbH, Der neue Hyundai NEXO (2018), https://www.hyundai.news/fileadmin/de/Pressemappen/Nexo/hyundai-nexo-sep2018-technische-daten.pdf. [Accessed: 23.08.2019].

KBA, Verkehr in Kilometern der deutschen Kraftfahrzeuge im Jahr 2017, https://www.kba.de/DE/Statistik/Kraftverkehr/VerkehrKilometer/verkehr_in_kilometern_node.html. [Accessed: 27.8.2019].

Lieven, T., Mühlmeier, S., Henkel, S., Waller, J.F., 2011. Who will buy electric cars? An empirical study in Germany. Transp. Res. Part D 16 (Nr. 3), 236–243.

J. Michaelis, P. Plötz, T. Gnann and M. Wietschel, Vergleich alternativer antriebstechnologien batterie-, plug-in hybrid- und brennstoffzellenfahrzeug, *Alternative Antriebskonzepte bei sich wandelnden Mobilitätsstilen: tagungsbandbeiträge vom 08. und 09. März 2012 am KIT, Karlsruhe*, 2013.

MWV, Tankstellenbestand, https://www.mwv.de/statistiken/tankstellenbestand/. [Accessed: 16.7.2019].

Onat, N.C., Gumus, S., Kucukvar, M., Tatari, O., 2016. Application of the TOPSIS and intuitionistic fuzzy set approaches for ranking the life cycle sustainability performance of alternative vehicle technologies. Sustain. Prod. Consumption 6, 12–25.

Propfe, B., Redelbach, D, Santini, Friedrich, H., 2012. Cost analysis of plug-in hybrid electric vehicles including maintenance & repair costs and resale values. World Electric Vehicle J. Nr. 26.

Volkswagen A.G., Emissionswerte und emissionsnormen , https://www.volkswagen.de/de/technologie/wltp/emissionswerte-und-emissionsnormen.html. [Accessed: 16.7.2019].

Volkswagen A.G., Der e-Golf. Technik und Preise (2019), https://www.volkswagen.de/de/dialog-center/downloadcenter.html. [Accessed: 19.08.2019].

Volkswagen A.G., Der Golf, Golf Variant & Golf Alltrack. Technik und Preise (2019), https://www.volkswagen.de/content/dam/vw-ngw/vw_pkw/importers/de/dialogcenter/brochures/golf-bq/golf_preisliste.pdf/_jcr_content/renditions/original.media_file.download_attachment.file/golf_preisliste.pdf. [Accessed: 19.08.2019].

Wątróbski, J., Małecki, K., Kijewska, K., Iwan, S., Karczmarczyk, A., Thompson, R., 2017. Multi-Criteria analysis of electric vans for city logistics. Sustainability 9 (Nr. 8), 1453.