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Plug-in Fuel Cell Electric Vehicle Concept in Relation to Driving Practices in the Czech Republic

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ABSTRACT: The transition to fossil-free transport is an unavoidable challenge that is ahead of us in the Czech transport sector in the not-too-distant future. The most promising alternatives to fossil fuels, currently under serial production, are battery electric vehicles and fuel cell electric vehicles. This article introduces a concept of plug-in fuel cell electric vehicle which combines the advantages of the two, optimized for use in the Czech Republic. The assessment is driven by the criteria of powertrain component dimensioning, non-exhaust emissions and operational economy. The total weight of the powertrain and the derived emission footprint of the concept vehicle is calculated based on state-of-the-art battery, fuel cell and hydrogen storage technologies. The concept is then compared to other alternative powertrains in terms of the operational economy, based on energy and fuel costs in the Czech Republic in May 2023. We demonstrate that the plug-in fuel cell electric vehicle can cover the overwhelming majority of driving routes of Czech drivers using the highly efficient battery electric propulsion, while the rest can be serviced using the fast-refuelling fuel cell electric powertrain. In addition, the concept vehicle can be significantly lighter than an equivalent battery electric vehicle, which leads to a considerable reduction of non-exhaust emissions. As far as the operational economy is concerned, we determine that the operating costs of the concept vehicle are equal to those of the battery electric vehicle for shorter routes and lower than those of the fuel cell vehicle for longer routes. We therefore conclude that the plug-in fuel cell electric vehicle can be a viable alternative to the current clean transport technologies as it combines the benefits of the two most popular fossil-free alternative transport powertrains in the Czech Republic while striking a good balance between energy efficiency, non-exhaust emission reduction, driver convenience and operating costs.

KEYWORDS: Hydrogen mobility; alternative powertrain; vehicle weight; non-exhaust emissions; operational economy

1. INTRODUCTION

One of the greatest challenges that humanity is facing in the 21st century is the climate change caused by greenhouse gases emitted by human civilization (United Nations, n.d.). The transport industry is one of the biggest polluters and transport emissions are rising year by year (IEA, 2022). Consequently, the current powertrains using fossil fuels are being replaced by new emission-free technologies. Table 1 shows the comparison of powertrain components of vehicle types relevant for this article.

As of 30th June 2023, there are 28 721 BEV and 24 FCEV in the Czech Republic and the number of registrations rises every year as evidenced by Figure 1 (Centrum dopravního výzkumu v. v. i., 2023b).

The most promising technologies seem to be battery electric vehicles and fuel cell electric vehicles (FCEV). However, at the moment, none of these technologies achieves the drivers' expectations, as for the internal combustion engine vehicles parameters. Today, the batteries have lower energy storage density (energy accumulated per unit volume or mass) than a typical gasoline tank (gasoline 12.8 kWh/kg, battery 0.240 kWh/kg) (Energy Education, n.d.), which leads either to a lowered driving range or a significantly increased vehicle weight (Tian et al., 2021). Hydrogen fuel can facilitate driving ranges comparable to ICEV, but it has to be compressed to high pressures and the energy efficiency (the ratio between the useful output and input of an energy conversion process) of the driving cycle is much lower than that of BEV (Burkhardt, Patyk, Tanguy, & Retzke, 2016). This article proposes a concept plug-in fuel cell electric vehicle that combines the benefits and minimizes the drawbacks of both most popular alternative powertrains (Das, Tan, & Yatim, 2017; de Almeida & Kruczan, 2021; Napoli et al., 2017; Sulaiman et al., 2018).

Vehicle type	Abbreviation	Traction battery + electromotor	Internal combustion engine	Fuel cell + hydrogen storage	Charging port
Battery electric vehicle	BEV	•	-	-	•
Fuel cell electric vehicle	FCEV	•	-	•	-
Internal combustion engine vehicle	ICEV	-	•	-	-
Plug-in fuel cell electric vehicle	PFCEV	•	-	•	•
Plug-in hybrid electric vehicle	PHEV	•	•	-	•

Table 1. Comparison of powertrain components of relevant vehicle types. Dots indicate components that are part of the powertrain, dashes indicate that the component is absent.

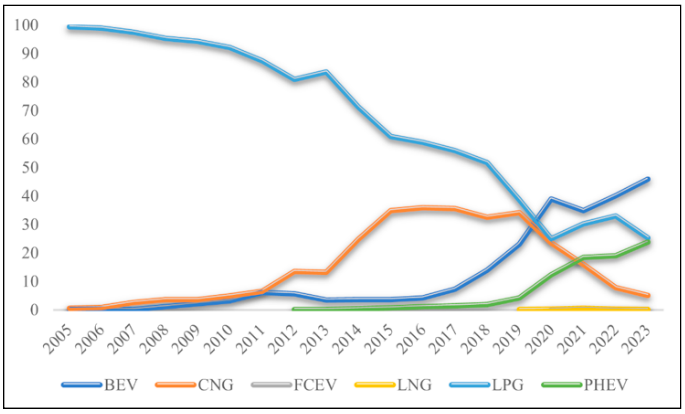

Figure 1. Evolution of vehicle registration rates by alternative fuel type and year of last registration.

2. PFCEV CONCEPT PHILOSOPHY

The PFCEV is analogous to a plug-in hybrid electric vehicle with a combustion engine. In both cases the propulsion of the vehicle is provided by an electromotor powered by the energy from a traction battery designed to satisfy the energy requirements of shorter everyday commuting. If the state of charge (SoC) of the battery drops below a certain level, the range extender is activated – in the case of the PFCEV a fuel cell. The fuel cell power output is designed to cover the average energy consumption in order to continuously fulfill the powertrain energy demand. The battery of the vehicle can be charged from the electricity network, just like BEV. The PFCEV therefore draws on the main BEV benefits – high powertrain efficiency, rechargeability outside public infrastructure and braking energy recuperation; and those of the FCEV – higher driving range, faster refuelling and lower vehicle weight.

Between 2017 and 2019, a traffic survey named "Česko v pohybu"("Czechia in motion"), which monitored societal driving habits, was carried out in the Czech Republic. The results of the survey are presented in Table 2. According to the data collected, 93.59% of all journeys performed by personal vehicles are shorter than 40 km, with 98.50% being shorter than 100 km (Centrum dopravního výzkumu v. v. i., 2020). Therefore, traction battery capable of 100 km driving range should satisfy the overwhelming majority of everyday commuters. Nevertheless, one of the often-cited reasons why customers prefer ICEV to BEV is the latter's insufficient driving range (Vinš & Kosova, 2020). Drivers rightfully expect their personal vehicle to be able to cover 100% of their driving needs, such as holidays abroad or business trips, without the necessity of extended recharging stops. For this reason, it is appropriate to design the hydrogen-based part of the PFCEV powertrain to provide total driving range of 400 km. In this way, the concept vehicle would be able to serve 99.96% of all personal vehicle routes in the Czech Republic without refuelling (Centrum dopravního výzkumu v. v. i., 2020) and the rest with a short refuelling stop.

Journey length	0-100 km	100-400 km	>400 km	Total
Amount of journeys	11 193	166	5	11 364
Amount of journeys (%)	98.50	1.46	0.04	100.00

Table 2. An overview of personal vehicle routes in the Czech Republic, 2017-2019.

2. CONCEPT PARAMETERS

The vehicle selected to serve as the basis of the concept was Škoda Enyaq iV 80 – a battery electric vehicle with an estimated real-world driving range of 420 km and an electric motor with 150 kW power (Škoda Auto, n.d.). It was chosen due to its driving range similar to that of the proposed concept and because it is the most popular BEV in the Czech Republic (Centrum dopravního výzkumu v. v. i., 2023).

2.1. Traction Battery

The average consumption of Škoda Enyaq iV 80 is 17.7 kWh/100 km (EV Database, n.d.). This would mean that a battery with enough stored energy for 100 km driving range should have a capacity of 17.7 kWh. However, the real-world experience of driving electric vehicles shows that it is better to keep some reserve capacity, especially in winter conditions. The battery should therefore be designed for the worst-case scenario, which is travelling on a highway in winter (speed 110 km/h, temperature -10 °C). This corresponds to the energy consumption of 24.8 kWh/100 km (EV Database, n.d.). The useable battery capacity should then be 25 kWh (27 kWh total capacity). Since the battery used in PFCEV is lighter than in the original BEV, it will have slightly lower energy consumption – this effect is neglected for simplicity.

A typical battery used in personal BEV today has the energy storage density of 0.24 kWh/kg (Wen, Zhao, & Zhang, 2020). For the battery considered in the PFCEV concept, that would mean the weight of 113 kg. In comparison, the Enyaq iV 80 has a traction battery with 77 kWh of useable capacity (total capacity 82 kWh), which is 229 kg heavier (the battery weight is calculated using the parameters above, the actual weight difference might be somewhat higher). The smaller battery size provides PFCEV many benefits, such as easier thermal management (Singh et al., 2021) and lower vehicle dead weight (Shiau, Samaras, Hauffe, & Michalek, 2009). In contrast, the PFCEV battery is larger than a typical FCEV battery – Hyundai Nexo 1.56 kWh (Hyundai, n.d.). This results in a bigger available capacity for energy regeneration during braking, which can be useful as is shown by FCEV with small traction batteries especially during long downhill road sections (Konradt & Rottengruber, 2021).

2.2. Hydrogen storage tank

The declared energy consumptions of FCEV currently available on the Czech market are 0.79-0.89 kg H_2/100 km for Toyota Mirai II (Toyota, 2021) and 0.95 kg H_2/100 km for Hyundai Nexo (Hyundai, n.d.). For the PFCEV concept, the consumption of Hyundai Nexo is used, because it is an SUV with comparable weight to the Enyaq. Similarly to the traction battery, it is most appropriate to consider real consumption in winter. For Nexo, that amounts to 1.18 kg H_2/100 km (Poul & Špička, 2022). In the case of a purely hydrogen-powered distance of 300 km, approx. 3.5 kg of hydrogen is needed. Hydrogen storage pressure vessels are presently subject to a rapid technological advancement focused primarily on lowering the storage vessels' weight and volume. The currently available pressure vessels require 13.5 – 17.3 kg of vessel per kg of stored H_2 (Faurecia, 2019; Hua, Roh, & Ahluwalia, 2017; HyJack, n.d.; Toyota, 2014). Using the state-of-the-art vessels, that would imply the hydrogen storage weight of 47.8 kg. An equivalent FCEV with 400 km driving range would need 4.7 kg H_2, which would result in a 16 kg heavier hydrogen storage.

2.3. Fuel cell stack

Power output of the fuel cell stack needs to be capable of sustaining battery SoC at a preset minimal level under common operation. Since shorter routes should mostly be covered by energy stored in the traction battery, it can be presumed that the fuel cell will operate during long distance routes. Therefore, the fuel cell needs to be able to handle extended driving at highway speed. It is also necessary to take into account that fuel cells operate most efficiently at around 50% power load (Sahu, Krishna, Biswas, & Das, 2014; Sharer & Rousseau, 2013). For energy consumption of 24.8 kWh/100 km the fuel cell power output must then be around 55 kW. The power density (power output per unit of mass) of the best available fuel cell stack on the market (Ballard) is 2.4 kW/kg (ExtremeTech, 2019; Ballard Power Systems, 2020; Toyota, 2014). The weight of the fuel cell stack would be consequently 22.9 kg.

Figure 2 shows the schematic representation of PFCEV concept components. The arrows show directions of energy flows. Blue color represents hydrogen, yellow represents electricity and grey represents kinetic energy.

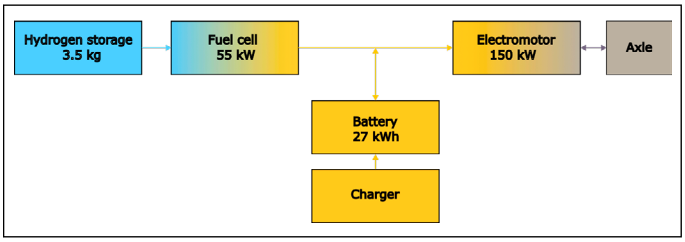

Figure 2. PFCEV powertrain.

2.4. Concept weight

Table 3 presents a comparison of PFCEV powertrain weight with equivalent alternative fuel vehicles of the identical driving range. The FCEV parameters were adapted from Hyundai Nexo whose hydrogen tank size was recalculated to reach 400 km driving range.

Powertrain type	BEV	PFCEV	FCEV
Battery weight	342	113	44.6
Fuel cell stack weight	0	22.9	50
Hydrogen storage + fuel weight	0	47.8 + 3.5	63.7 + 4.7
Total weight	342	187.2	163

Table 3. Powertrain weight (kg) comparison for vehicles with 400 km driving range.

The above-mentioned data (Table 3) show clearly that the PFCEV powertrain is 155 kg lighter than that of Škoda Enyaq iV 80 and only 24 kg heavier than that of the equivalent FCEV. It should be noted that there is a slight difference in driving range between BEV and the Enyaq, 400 km to 435 km respectively.

Another factor that influences the weight of the entire vehicle is the fact that the larger battery weight increases the weight of other vehicle components. Changing a vehicle component weight, a battery in this case, by 1 kg changes the weight of the whole vehicle by 1.41-1.50 kg (Malen, 2007; Nicoletti et al., 2021). Since SUV class usually reaches higher weight, it is appropriate to take the lower value of 1.41 kg. An estimation, reflecting the above-mentioned information, gives the following total weights of 400 km driving range vehicles: BEV 2094 kg, PFCEV 1899 kg and FCEV 1865 kg (the original Škoda Enyaq iV 80 weight being 2117 kg).

3. WEIGHT DEPENDENT EMISSIONS

Lowering the total vehicle weight has a positive impact on several operational elements. This section concerns the benefits of the lower weight during road contact. Even though most road wear and tear in everyday operation is caused by heavy duty and bus transport, it is important to find out how the incoming transition to emission-free mobility and the accompanying vehicle weight increases impact on road wear. Special attention is placed on particulate matter smaller than 2.5 μm ($PM_{2.5}$) and 10 μm (PM_{10}) respectively. Timmers and Achten claim that every kilogram of vehicle weight is responsible for 0.00490 mg/vkm of PM_{10}, 0.00264 mg/vkm of $PM_{2.5}$ and the total road wear of 0.00979 mg/vkm (Simons, 2013; Timmers & Achten, 2016).

Another phenomenon tied to the vehicle weight is the tyre wear. The heavier the vehicle is, the more pressure tyres endure, which manifests as a higher concentration of particulate matter released from the tyre surface. Similarly, to road wear, the tyre wear can be quantified per kg of vehicle weight. PM_{10} emissions are 0.00408 mg/vkm, $PM_{2.5}$ emissions are 0.00286 mg/vkm and total tyre wear emissions are 0.0573 mg/vkm (Simons, 2013; Timmers & Achten, 2016).

Resuspension, or the stirring of particulate matter as a result of vehicle passing, is significantly impacted by vehicle weight as well. Experimental measurements of resuspension dependence suggest that the number of stirred particulates rises linearly with vehicle weight (Gillies, Etyemezian, Kuhns, Nikolic, & Gillette, 2005). Timmers and Achten claim that PM_{10} and $PM_{2.5}$ emissions caused by resuspension are 40 mg/vkm and 12 mg/vkm respectively for a typical ICEV. Presuming that a typical BEV is around 24% heavier, it is simple to determine its emissions and analogously the emissions for PFCEV and FCEV. Table 4 present the non-exhaust emissions of the three examined powertrains as determined by their weight.

Powertrain type	BEV	PFCEV	FCEV
PM_{10} emissions – road wear	10.26	9.31	9.14
$PM_{2.5}$ emissions – road wear	5.53	5.01	4.92
Total road wear	20.50	18.59	18.26
PM_{10} emissions – tyre wear	8.54	7.75	7.61
$PM_{2.5}$ emissions – tyre wear	5.99	5.43	5.33
Total tyre wear	119.99	108.81	106.86
PM_{10} emissions – resuspension	49.60	44.98	44.18
$PM_{2.5}$ emissions – resuspension	14.88	13.49	13.25
Total PM_{10} emissions	68.40	62.04	60.93
Total $PM_{2.5}$ emissions	26.40	23.93	23.50

Table 4. Non-exhaust emissions for alternate powertrain vehicles (mg/vkm)

The Table 4 shows clearly that the PFCEV causes less particulate matter emissions from road and tyre wear than the equivalent BEV, by approximately 9%. On the other hand, FCEV emissions are 2% lower than those of PFCEV. The Table 4 also shows that PFCEV emissions caused by resuspension are around 11% higher than those of ICEV, which is a significantly better result than for the BEV.

4. OPERATING ECONOMY

The price per kilometre driven for the alternative powertrains considered in this article depends on the energy price evolution and the ratio between electric energy and hydrogen prices. While the prices of hydrogen at public refuelling stations should be more or less the same, electric energy prices depend on the recharging mode - recharging privately from the alternating current (AC) network or public direct current (DC) and ultra-fast charging (UFC) stations. The prices also differ depending on the charging station provider and the services offered. PFCEV operating economy is also significantly affected by the profile of routes the vehicle will take due to its ability to combine both energy sources.

The price per kilometre driven is calculated based on the energy prices available in May 2023. The price of electricity can differ by up to 400 % depending on the recharging mode. The price of AC charging is 4.59-10 CZK/kWh. Public DC charging under 150 kW costs 11-13 CZK/kWh and UFC above 150 kW costs 13-18 CZK/kWh (ČEZ, 2023b; E.ON, 2023b; PRE Mobilita, 2023). The price of hydrogen at the only full-sized public refuelling station in the Czech Republic (ORLEN Benzina, 2023) is 278 CZK/kg.

A comparison of the cost per kilometre travelled for all three powertrain types is based on the data in Table 5 which shows the average electricity and hydrogen consumption of the alternative powertrain vehicles.

Average consumption	BEV	PFCEV	FCEV
kWh/100 km	24.8	24.8	-
kg H_2/100 km	-	1.18	1.18

Table 5. Average consumption.

BEV consumption, Traction battery, FCEV consumption and Hydrogen storage tank are described in paragraphs 2.1, 2.2 and 2.3 respectively.

Table 6 shows the prices at public charging stations as offered by ČEZ, E.ON and PRE (the three major public charging providers in the Czech Republic). The prices reflect the situation as of May 2023.

Type of recharging/Provider	ČEZ	PRE	E.ON	Avg. price
Public AC	8	8	10	8.7
Public DC	13	11	12.5	12.2
Public UFC	18	13	17	16.0
Non-public	5.43	5.49[1]	4.591	5.17

Table 6. Electricity recharging prices (CZK/kWh).

As the frequency and type of recharging have a major impact on the total cost per km, we used the Euroenergy's estimate for the year 2025 as shown in table 7. The Euroenergy's estimate takes into account all journeys regardless of their length, however the percentage distribution of charging is also influenced by the planned travel distance. Based on the numbers of trips from Table 2 and Euroenergy's estimate the frequencies of each type of recharging were estimated for intervals of journey lengths 0-100 km, 100-400 km and >400 km. Out of journeys between 0-100 km, we assume almost 82% use non-public recharging, which includes both residential and recharging at work. As the travel distance increases, the assumption of higher use of non-public, DC and UFC charging increases as well. This is presented in the third and fourth column of Table 7. The estimates are made in order to keep the total number of recharging in all travel intervals in line with EuroEnergy's estimates.

Type of recharging	0-100 km	100-400 km	>400 km	EuroEnergy
Public AC	14.10	10	0	14
Public DC	2.40	45	50	3
Public UFC	2.40	45	50	3
Non-public	81.20	0	0	80
Amount of journeys (%)	98.50	1.46	0.04	100

Table 7. Frequency of use for each type of charging (%).

1 Average of high and low tariffs of D27d (BEV charging special tariff) (ČEZ, 2023a; E.ON, 2023a; PREdistribuce, 2023)

The average recharging electricity price for a given distance interval was calculated by multiplying the percentages presented in Table 7 by the average price of their respective types of recharging as presented in Table 6. The results of this calculation are shown in Table 8.

Route length	0-100 km	100-400 km	>400 km
Price (CZK/kWh)	6.08	13.54	14.08

Table 8. Average recharging cost in each distance interval.

A BEV with a calculated range of 400 km charges at the lowest average price, i.e. 6.08 CZK/kWh. For distances above 400 km, we assume the user's willingness to charge faster and at a higher price, i.e. 14.08 CZK/kWh. In contrast, for a PFCEV the price calculation is more complex and includes the user's choice whether to switch on the fuel cell to supply electricity while driving. We assume that the planned journey of up to 100 km is driven on traction battery power only, i.e. at a price of 6.08 CZK/kWh. For journeys over 100 km, we assume the fuel cell is triggered at a battery SoC of 50%, i.e. at a distance of 50 km. Furthermore, the vehicle continues to run on energy extracted from hydrogen. The FCEV cannot be recharged, so the price per km is the same for all distance intervals and corresponds to the price of H_2 per kg. The cost of operation of alternative powertrain vehicles reflecting the above mentioned is presented in Table 9.

Vehicle type	0-100 km	100-400 km	>400 km
BEV	1.51	1.51	2.17
PFCEV	1.51	3.06	3.13
FCEV	3.28	3.28	3.28

Table 9. Cost of operation per 1 km of vehicles in each distance range (CZK).

The average yearly mileage of a personal vehicle in the Czech Republic is 14 569 km (Centrum dopravního výzkumu v. v. i., 2023a). Based on the distribution of journey lengths (Table 2) and the costs presented in Table 9 it is possible to estimate yearly costs of operation for the examined vehicles. The resulting costs are BEV 21 987 CZK, PFCEV 22 323 CZK and FCEV 47 792 CZK. The data presented here show that at current energy prices the BEV is the cheapest to operate as far as fuel costs are concerned. However, the PFCEV is significantly cheaper to operate than the FCEV regardless of route length while benefiting from fast refuelling during long driving distances. Whether this liberty is worth the increased operating costs compared to the BEV is impossible to say, as this option remains at each user's choice. Interestingly, the vehicle that is the cheapest to operate has the highest emissions and vice-versa (as shown in Table 4). This further shows the potential of PFCEV as a compromise between BEV and FCEV.

This article does not examine the associated costs connected to the examined powertrains such as the cost of infrastructure, vehicle servicing, repairs and taxes. These extra costs require separate study and are out of the scope of this article. However, they are still an important component of the transition to clean mobility and should be kept in mind.

5. CONCLUSION

The article presents a concept of a plug-in fuel cell electric vehicle (PFCEV) which combines the advantages of battery electric and fuel cell powered vehicles. The vehicle selected for these purposes was Škoda Enyaq iV 80 which is the most popular BEV in the Czech Republic with around 400 km driving range. The concept contains a battery designed for purely battery powered driving range of 100 km which is enough to serve 98.50% of all journeys driven in the Czech Republic. Therefore, a very high percentage of journeys would be covered by a highly energy efficient battery powered powertrain. Another 1.46% of journeys would be covered by a hydrogen fuel cell-based range extender which extends the range by 300 km. In the remaining journeys, the fast refuelling, typical for hydrogen vehicles, would be used. It is important to note that the survey this distribution is based on focuses on current driving behaviours in the Czech Republic, therefore only a minority or respondents drive a BEV of FCEV. This article presumes that the driving patterns of Czech drivers will be the same after transitioning to electric mobility but the shift from refuelling at petrol stations to recharging could somewhat change the distribution of journey lengths.

Further, the article examines the parameters of the PFCEV powertrain and their influence on the total vehicle weight. The ideal parameters selected for the PFCEV concept vehicle are as follows: usable battery capacity of 25 kWh, fuel storage capacity of 3.5 kg H_2, fuel cell stack power of 55 kW, and total vehicle weight of 1899 kg. The PFCEV concept is 195 kg lighter than an equivalent BEV and 34 kg heavier than an equivalent FCEV. Note that these parameters are derived from combining elements of separate powertrains which currently do not coexist in a production vehicle and so the real-life parameters of the vehicle could differ.

The next part of the article analyses the effects of vehicle weight on road wear, tyre wear and particulate matter resuspension. It was found that PFCEV emits significantly fewer emissions than an equivalent BEV, but slightly more than an equivalent FCEV thus showing itself to be a promising compromise between the two alternative powertrains.

The final part of the article concerns operational economy of PFCEV. It was determined that the yearly cost of operation for the concept vehicle is comparable to an equivalent BEV and less than half compared to an equivalent FCEV. The cost calculations are based on the prices available at the time this article was written, therefore the numbers are certain to change in the future. Despite that, the conclusions derived from the data should still apply in the future especially since the majority of hydrogen is set to be produced using electricity.

Relying on the data presented in this article, the authors conclude that the hybridization of a plug-in battery and hydrogen fuel cell electromobility is a promising approach for personal transportation. The use of PFCEV creates a new possibility to decarbonize transport and offers a potentially fossil emission-free mobility that is not hampered by a limited driving range or a low energy efficiency. Another asset of the hybridization is a lower total vehicle weight compared to BEV, which leads to lower non-exhaust emission impact than in the case of the purely battery-based mobility. At the same time the concept vehicle also costs less to operate than FCEV which could mean lower overall costs for the transition to alternative mobility.

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REFERENCES

Ballard Power Systems (2020). High Performance Fuel Cell Stack Innovations in Proton Exchange Membrane Fuel Cell Stack Design. Retrieved 11 August 2022 from https://www.ballard.com/docs/default-source/default-document-library/high-performance-fuel-cell-stack-white-paper-14-september-2020.pdf

Burkhardt, J., Patyk, A., Tanguy, P., & Retzke, C. (2016). Hydrogen mobility from wind energy – A life cycle assessment focusing on the fuel supply. *Applied Energy*, *181*, 54–64. Retrieved from https://doi.org/10.1016/j.apenergy.2016.07.104

Centrum dopravního výzkumu v. v. i. (2020). Česko v pohybu. Retrieved 11 August 2022, from https://www.ceskovpohybu.cz/

Centrum dopravního výzkumu v. v. i. (2023a). Řidiči s elektromobily ujedou v Česku za rok přes 12 tisíc kilometrů – více než řidiči aut benzínových. Retrieved 11 October 2023, from https://www.cistadoprava.cz/tiskove-zpravy/ridici-s-elektromobily-ujedou-v-cesku-za-rok-pres-12-tisic-kilometru-%E2%80%93-vice-nez-ridici-aut-benzinovych/

Centrum dopravního výzkumu v. v. i. (2023b). Registrace všech čistých vozidel v ČR dle NAP ČM. Retrieved 25 September 2023, from https://www.cistadoprava.cz/registrace-vsech-cistych-vozidel-v-cr-dle-nap-cm/

Centrum dopravního výzkumu, v. v. i. (2023). Registrace nových osobních vozidel v ČR | Centrum dopravního výzkumu, v. v. i. Retrieved 12 May 2023, from https://www.cistadoprava.cz/registrace-novych-osobnich-vozidel-v-cr/

ČEZ. (2023a). Ceník elektřiny pro domácnosti. Retrieved 24 May 2023 from www.cez.cz/kontakty

ČEZ. (2023b). Smlouvy, ceník a OPD. | Futurego.cz. Retrieved 15 May 2023, from https://www.futurego.cz/cs/smlouvy-cenik-a-opd

Das, H. S., Tan, C. W., & Yatim, A. H. M. (2017). Fuel cell hybrid electric vehicles: A review on power conditioning units and topologies. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. Retrieved from https://doi.org/10.1016/j.rser.2017.03.056

de Almeida, S. C. A., & Kruczan, R. (2021). Effects of drivetrain hybridization on fuel economy, performance and costs of a fuel cell hybrid electric vehicle. *International Journal of Hydrogen Energy*, *46*(79), 39404–39414. Retrieved from https://doi.org/10.1016/j.ijhydene.2021.09.144

E.ON. (2023a). Ceník Komplet elektřina za věrnost na 2 roky 4/23. Retrieved 24 May 2023 from https://www.eon.cz/

E.ON. (2023b). Pro řidiče - E.ON Drive. Retrieved 15 May 2023, from https://www.eon-drive.cz/pro-ridice/

Energy Education. (n.d.). Energy density. Retrieved 30 August 2022, from https://energyeducation.ca/encyclopedia/Energy_density

EV Database. (n.d.). Energy consumption of full electric vehicles cheatsheet - EV Database. Retrieved 26 May 2023, from https://ev-database.org/cheatsheet/energy-consumption-electric-car

ExtremeTech. (2019). 2019 Hyundai Nexo Review: 380 Miles (on Hydrogen). Can Your EV Go That Far? - ExtremeTech. Retrieved 19 August 2022, from https://www.extremetech.com/extreme/280219-2019-hyundai-nexo-review-380-miles-on-hydrogen-can-your-ev-go-that-far

Faurecia. (2019). *H2 Mobility Faurecia Hydrogen Strategy*. Retrieved 24 May 2023 from https://www.faurecia.com

Gillies, J. A., Etyemezian, V., Kuhns, H., Nikolic, D., & Gillette, D. A. (2005). Effect of vehicle characteristics on unpaved road dust emissions. In *Atmospheric Environment, 39,* (Vol. 39, pp. 2341–2347). Elsevier Ltd. Retrieved from https://doi.org/10.1016/j.atmosenv.2004.05.064

Hua, T. Q., Roh, H. S., & Ahluwalia, R. K. (2017). Performance assessment of 700-bar compressed hydrogen storage for light duty fuel cell vehicles. *International Journal of Hydrogen Energy*, *42*(40), 25121–25129. Retrieved from https://doi.org/10.1016/j.ijhydene.2017.08.123

HyJack. (n.d.). Cylinder G - Type 4, Hyjack : Hydrogen Online. Retrieved 11 August 2022, from https://hyjack.tech/ecosystem/product/32

Hyundai. (n.d.). Hyundai NEXO - Technické údaje. Retrieved 29 August 2022 from www.hyundai.cz

IEA. (2022). Transport – Analysis - IEA. Retrieved 12 May 2023, from https://www.iea.org/reports/transport

Konradt, S. C., & Rottengruber, H. (2021). Determination of the optimal battery capacity of a PEM fuel cell vehicle taking into account recuperation and supercapacitors. *Automotive and Engine Technology 2021, 6:3*, *6*(3), 181–189. Retrieved 25 May 2023 from https://doi.org/10.1007/S41104-021-00086-1

Malen, D. E. (2007). Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients. Retrieved 2 September 2022 from www.a-sp.org

Napoli, G., Micari, S., Dispenza, G., Di Novo, S., Antonucci, V., & Andaloro, L. (2017). Development of a fuel cell hybrid electric powertrain: A real case study on a Minibus application. *International Journal of Hydrogen Energy*, *42*(46), 28034–28047. Retrieved from https://doi.org/10.1016/j.ijhydene.2017.07.239

Nicoletti, L., Romano, A., König, A., Köhler, P., Heinrich, M., & Lienkamp, M. (2021). An Estimation of the Lightweight Potential of Battery Electric Vehicles. *Energies*. Retrieved from https://doi.org/10.3390/en14154655

ORLEN Benzina. (2023). ORLEN Benzina - Tiskové centrum, všechny informace pro médiamedia | Benzina. Retrieved 11 May 2023, from https://www.orlenbenzina.cz/pro-media/orlen-unipetrol-otevrel-verejnou-vodikovou-stanici-v-praze-na-barrandove

Poul, A., & Špička, L. (2022). Spotřeba paliva u automobilů s vodíkovým článkem. *Energie*, *21*(1), 28–30. Retrieved 24 May 2023 from https://www.cistadoprava.cz/odborne-clanky-konference-rozhovory/spotreba-paliva-u-automobilu-s-vodikovym-clankem/

PRE Mobilita . (2023). Chci dobíjet pravidelně. | PREmobilita. Retrieved 15 May 2023, from https://www.premobilita.cz/cs/dobijeni-elektromobilu/dobijeni-na-prepoint/chci-dobijet-na-prepoint/chci-dobijet-pravidelne/

PREdistribuce. (2023). PRE PROUD FIX 02/2023. Retrieved 24 May 2023 from www.premereni.cz

Sahu, I. P., Krishna, G., Biswas, M., & Das, M. K. (2014). Performance Sstudy of PEM Ffuel Ccell under Ddifferent lLoading Cconditions. In *Energy Procedia*, *54*, (Vol. 54, pp. 468–478). Elsevier Ltd. Retrieved from https://doi.org/10.1016/j.egypro.2014.07.289

Sharer, P., & Rousseau, A. (2013). Benefits of Fuel Cell Range Extender for Medium-Duty Vehicle Applications.*World Electr. Veh. J*. Retrieved from https://doi.org/10.3390/wevj602045210.3390/wevj6020452

Shiau, C. S. N., Samaras, C., Hauffe, R., & Michalek, J. J. (2009). Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. *Energy Policy*, *37*(7), 2653–2663. Retrieved from https://doi.org/10.1016/j.enpol.2009.02.040

Simons, A. (2013). Road transport: new life cycle inventories for fossil-fuelled passenger cars and non-exhaust emissions in ecoinvent v3. *International Journal of Life Cycle Assessment*, 1–15. Retrieved from https://doi.org/10.1007/s11367-013-0642-9

Singh, R., Lapp, G., Velardo, J., Long, P. T., Mochizuki, M., Akbarzadeh, A., ... Busse, K. (2021). Battery cooling options in electric vehicles with heat pipes. *Frontiers in Heat and Mass Transfer*, *16.* Retrieved from https://doi.org/10.5098/hmt.16.2

Škoda Auto. (n.d.). ENYAQ iV. Retrieved 12 August 2022, from https://www.skoda-auto.cz/modely/enyaq/enyaq-iv

Sulaiman, N., Hannan, M. A., Mohamed, A., Ker, P. J., Majlan, E. H., & Wan Daud, W. R. (2018, October 15). Optimization of energy management system for fuel-cell hybrid electric vehicles: Issues and recommendations. *Applied Energy*, *228*, 2061-2079. . Elsevier Ltd. Retrieved from https://doi.org/10.1016/j.apenergy.2018.07.087

Tian, Y., Zeng, G., Rutt, A., Shi, T., Kim, H., Wang, J., ... Ceder, G. (2021, February 10). Promises and Challenges of Next-Generation 'beyond Li-ion' Batteries for Electric Vehicles and Grid Decarbonization. *Chemical Reviews, 121*(3), 1623-1669. American Chemical Society. Retrieved from https://doi.org/10.1021/acs.chemrev.0c00767

Timmers, V. R. J. H., & Achten, P. A. J. (2016, June 1). Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment*, *134,* 10-17. . Elsevier Ltd. Retrieved from https://doi.org/10.1016/j.atmosenv.2016.03.017

Toyota. (2014). *Outline of the Mirai Key Specifications*. Retrieved 12 August 2022 from www.toyota-europe.com

Toyota. (2021). ZCELA NOVÁ TOYOTA MIRAI, 7. Retrieved 29 August 2022 from https://pdf.sites.toyota.cz/cenik_mirai.pdf

United Nations. (n.d.). Causes and Effects of Climate Change. | Climate Action. United Nations. Retrieved 11 August 2022, from https://www.un.org/en/climatechange/science/causes-effects-climate-change

Vinš, M., & Kosova, S. (2020). Here Comes the Electric Car: Delving into Young Czech Consumers' Motivation in Buying an Electric CarHERE COMES THE ELECTRIC CAR: DELVING INTO YOUNG CZECH CONSUMERS' MOTIVATIONS IN BUYING AN ELECTRIC CAR. *Perner's Contacts*, *15*(2). Retrieved from https://doi.org/10.46585/pc.2020.2.1643

Wen, J., Zhao, D., & Zhang, C. (2020). An overview of electricity powered vehicles: Lithium-ion battery energy storage density and energy conversion efficiency. *Renewable Energy*, *162,* 1629–1648. Retrieved from https://doi.org/10.1016/j.renene.2020.09.055