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Citation for the original published paper (version of record):
Santos Andrade, T., Zhou, S., Yang, J. et al (2024). Energy efficiency of hydrogen for vehicle propulsion: On- or off-board H<inf>2</inf> to
electricity conversion?. International Journal of Hydrogen Energy, 92: 1493-1499.
http://dx.doi.org/10.1016/j.ijhydene.2024.10.349

International Journal of Hydrogen Energy 92 (2024) 1493–1499

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

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

Energy efficiency of hydrogen for vehicle propulsion: On- or off-board H_2 to electricity conversion?

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ARTICLE INFO

Keywords:
Fuel cells
Fuel cell vehicle
Batteries
Battery electric vehicle
Hydrogen economy
Combined heat and power plant

ABSTRACT

If hydrogen fuel is available to support the transportation sector decarbonization, its usage can be placed either directly onboard in a fuel cell vehicle, or indirectly, off-board, by using a fuel cell power station to produce electricity to charge a battery electric vehicle. Therefore, in this work, the direct and indirect conversion scenarios of hydrogen to vehicle propulsion were investigated regarding energy efficiency. Thus, in the first scenario, hydrogen is the fuel for the onboard electricity production to propel a fuel cell vehicle while in the second, hydrogen is the electricity source to charge the battery electric vehicle. When simulated for a drive cycle, results have shown that the scenario with the onboard fuel cell consumed about 20% less hydrogen, demonstrating higher energy efficiency in terms of driving range. However, energy efficiency depends on the outside temperature when heat loss utilization is considered. For outside temperatures of −5 °C or higher, the system composed of the battery electric vehicle fueled with electricity from the off-board fuel cell was shown to be more energy-efficient. For lower temperatures, the system composed of the onboard fuel cell again presented higher total (heat + electricity) efficiency. Therefore, the results provide valuable insights into how hydrogen fuel can be used for vehicle propulsion, supporting the hydrogen economy development.

Nomenclature

WLTP	Worldwide Harmonized Light Vehicles Test Procedure
FCV	Fuel cell vehicle
BEV	Battery electric vehicle
F_{wheels}	Wheel force
$F_{friction}$	Friction force
$F_{rolling}$	Rolling force
F_{acc}	Acceleration force
ρ_{α}	Air density
C_d	Aerodynamic drag coefficient
A_f	Cross-sectional area
v_{car}	Car speed
C_r	Rolling resistance coefficient
m	Car weight
g	Gravitational constant
r	Wheel radius
PMSM	Permanent magnet synchronous motor
IGBT	Insulated-gate bipolar transistor
SOC	State of charge
P_{req}	Power required to the wheels
CS	Number of cells in series
EC	Energy consumption
E_f	Energy efficiency
E_{drive}	Vehicle propulsion energy consumption
$E_{heat\ utilized}$	Vehicle heating energy consumption
$E_{total\ from\ H_2}$	Energy from hydrogen

1. Introduction

The hydrogen industry has been experiencing an investment boost due to the major role hydrogen fuel is speculated to play in the green energy transition [1–3]. Meanwhile, the energy scenario of decarbonization using hydrogen should be aligned with changes in the transportation sector responsible for large emissions [4–6]. However, to determine how hydrogen fuel can support the decarbonization of the transportation sector, it is crucial to understand the scenarios for converting hydrogen into vehicle propulsion [7,8]. Considering that there are two main options for zero-emission vehicles, battery or fuel cell, the

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https://doi.org/10.1016/j.ijhydene.2024.10.349
Received 13 August 2024; Received in revised form 23 September 2024; Accepted 24 October 2024
Available online 6 November 2024

two following approaches should be evaluated concerning the use of hydrogen aiming at vehicle propulsion. The first scenario is to have the fuel cell onboard using hydrogen as a fuel for the vehicle's propulsion while the second scenario is to have the fuel cell off-board using hydrogen as the electricity source to power a battery electric vehicle through a grid-connected electric power charging station, as illustrated in Fig. 1.

Comparisons of the two scenarios have been scarcely reported. However, several works have investigated hydrogen fuel cell vehicles in comparison with battery electric vehicles, such as in terms of vehicle architecture [9], energy/cost efficiency [10–12], societal benefits [13], infrastructure requirements [14,15], environmental impact [16–18], and economic aspects [19,20]. Some general conclusions can be drawn from the comparison. In terms of energy efficiency, it is evident that the battery itself can deliver higher electrical efficiency than the fuel cell device. While the battery can reach efficiencies higher than 90%, the fuel cell can hardly reach 70% in the best case. This efficiency is usually translated into lower efficiencies for the fuel cell vehicle powertrain [10–12,15]. However, besides being more driver-friendly concerning refueling time [13,19], depending on the vehicle type [19], target range [13,14], driving pattern [12], and primary energy source [18,20], fuel cell vehicles can be more environment-friendly, i.e. provide lower carbon emissions, or be less energy consuming. For example, in Ref. [13], for vehicle ranges greater than 160 km, fuel cell vehicles outperformed batteries in terms of cost and efficiency depending on the primary source of energy. In Ref. [19], hydrogen fuel cells are shown to be suitable for long-range trips and high-utilization transport, being, for those cases, more cost-effective than battery-only vehicles providing lower storage cost and quicker fueling. Their work pointed out that a combination of batteries and fuel cells should improve the possibility of lower carbon emission transportation. In Ref. [20], the weel-to-wheel economic and environmental comparison indicated higher costs for fuel cell cars but lower total carbon emissions than battery-only vehicles.

Therefore, evaluating different case scenarios is crucial to understanding the limitations of the existing options. Furthermore, despite the relevant elucidations reported toward clean transportation, the vehicle system modeling comparison considering the usage of hydrogen, directly or indirectly, for vehicle propulsion, i.e. the "hydrogen to wheels" approach, is usually neglected. Recent studies suggest that the indirect usage of hydrogen, i.e. battery vehicle connected to a fuel cell power station, is related to lower carbon emissions [21], but lower energy efficiencies [22] than using the hydrogen directly onboard. Nevertheless, updated investigations are needed to understand each scenario's suitability for supporting the right allocation of hydrogen fuel. For instance, the energy efficiency comparison should also address the potential for heat usage. The heat produced in the onboard fuel cell can be useful for vehicle space heating, while the heat generated in the off-board fuel cell can be utilized in district heating. Thus, effective use of heat might play a significant role in the energy efficiency of each scenario.

Therefore, in this work, the design and modeling of the two systems, represented in Fig. 1, are investigated in terms of energy/thermal efficiency when simulated for a drive cycle. Thus, we aim to understand where the hydrogen fuel cell to electricity conversion is most efficient: onboard in a fuel cell vehicle or off-board powering a battery electric vehicle. Some specific contributions of this paper are.

- Modeling and simulation of the systems composed of the onboard and off-board fuel cell in terms of energy efficiency/hydrogen consumption for a drive cycle based on real vehicle driving data combined with reported values;
- Quantification of the energy consumption and efficiency for both proposed systems considering the use of the heat losses onboard or off-board for space heating or district heating distribution for ambient temperatures in the range of −15 °C–20 °C.

2. Methodology

2.1. System modeling

The proposed systems were designed and modeled using MATLAB, a widely adopted tool for system modeling, though alternative simulation platforms, such as Python, could also be utilized. The energy system diagram for both scenarios considered the following components: the wheels, the gear, the electric motor with inverter, the battery, and the fuel cell. Due to the faster dynamics of the battery compared to the fuel cell, fuel cell vehicles also have a battery to support the peak powers and to utilize the regenerative braking energy. For the system composed of the off-board fuel cell, the model also included an electric charger and off-board grid connecting components from the fuel cell to the vehicle. The onboard fuel cell system also comprises an onboard DC-DC converter between the fuel cell and the battery. The Worldwide Harmonized Light Vehicles Test Procedure (WLTP) Class 3 was used as the driving cycle reference [23]. The simulation was designed in a backward energy strategy and all the components were modeled in an electrical steady state. For a conservative approach between the two systems, the powertrain components of both systems were designed with similar parameters. Due to system simplification purposes and data availability, only passenger vehicles are considered in this model, but the analysis can be extended to heavy-duty vehicles in the future.

The wheel force (F_{wheels}) have been designed as the sum of friction, rolling resistance, and acceleration forces [24]

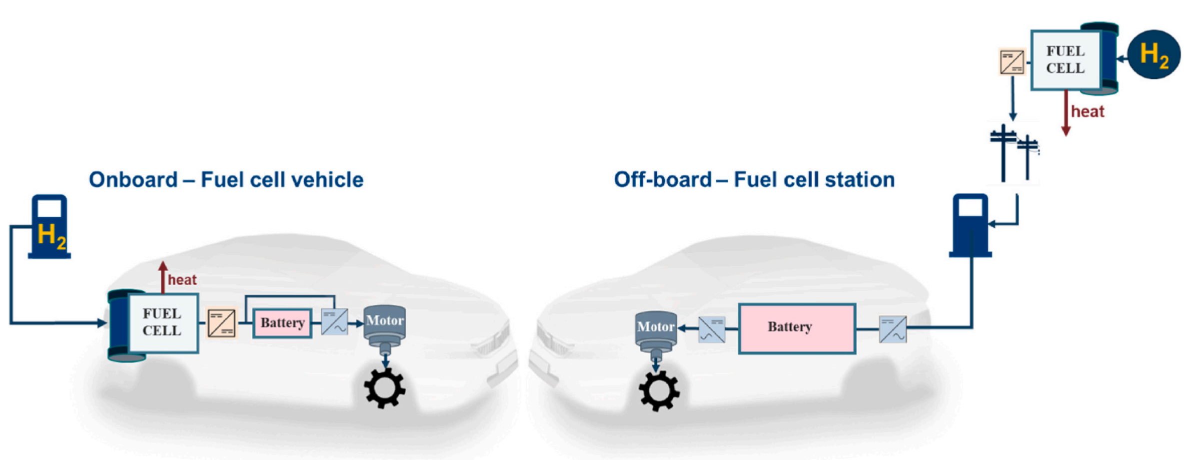

Fig. 1. Schematic illustration of the two possible scenarios for fuel cells aiming at vehicle propulsion: onboard and off-board fuel cells.

$$F_{wheels} = F_{friction} + F_{rolling} + F_{acc} \tag{1}$$

where

$$F_{friction} = \frac{1}{2}\,\rho_\alpha\, C_d\, A_f\, {v_{car}}^2 \tag{2}$$

$$F_{rolling} = C_r\, m\, g \tag{3}$$

$$F_{acc} = m\, a \tag{4}$$

in which ρ_α refers to the air density in kg/m^3, C_d to the aerodynamic drag coefficient, A_f to the vehicle's cross-sectional area in m^2, v_{car} to the vehicle speed in m/s, C_r to the rolling resistance coefficient, m to the vehicle's mass in kg, g to the gravity constant in m/s^2, and a to the acceleration in m/s^2. The weight difference between the vehicles was based on the fuel cell system and battery weight of high-performance fuel cells and battery electric vehicles [25,26]. Considering the total useful specific energy for the fuel cell system and the battery as proposed in Ref. [13], a 300 kg higher weight is assumed for the battery car. The gear was a single step with a gear ratio of 10 and 97% efficiency based on experimental published data [27]. Table 1 summarizes the vehicle specifications described. Further, the electric motor and the inverter presented in both vehicles were an eight-pole permanent magnet synchronous motor (PMSM) and DC-AC IGBT converter with the same parameters as previously described in Refs. [28–30]. The other converters presented in both systems were assumed to have 95% efficiency based on typical values [31–34].

To model the battery of both the vehicles illustrated in Fig. 1, reported data of voltage and state of charge (SOC) of a pouch-cell Li-ion battery was used [35–37]. When used as the energy source of an electric vehicle, a voltage range of 3.2–3.9 V for a SOC range of 20–90% SOC was demonstrated for the battery cell. Thus, in our model, a relation of voltage and SOC (%) could be designed per cell of the Li-ion battery presented in both powertrains, i.e. battery and fuel cell vehicle, as shown in Fig. 1, as

$$V_{battery} = SOC\,(\%) + 3\,CS \tag{5}$$

where the CS refers to the number of cells in series, i.e. 100. In the modeling, the battery capacity of the battery electric vehicle and the fuel cell vehicle was assumed to be 105.0 kWh and 1.6 kWh, consistent with high-performing electrified cars. Regarding the battery resistance, based on the values of the hybrid vehicle, i.e. 3 mΩ for a 30Ah battery cell, the same ratio of resistance and capacity was kept for the batteries in our model accounting for the resistance loss increase while reducing surface area.

Regarding the fuel cell model for both onboard and off-board systems, current and voltage data collected on the fuel cell stack of a commercial fuel cell vehicle, i.e. Toyota Mirai, in both city driving and motorways were used to construct a power-efficiency curve, as shown in Fig. 2. Due to the ohmic and mass transport losses increase at higher power outputs, the higher the power, the lower the fuel cell efficiency of

Table 1
Vehicle specifications in which BEV refers to the battery electric vehicle and FCV to the fuel cell vehicle.

Parameter (initials)	Value (unit)
Mass (m) - BEV	2300 (kg)
Mass (m) - FCV	2000 (kg)
Air density (ρ_α)	1.225 (kg/m^3)
Aerodynamic drag coefficient (C_d)	0.3 (−)
Cross-sectional area (A_f)	2.5 (m^2)
Rolling resistance coefficient (C_r)	0.009 (−)
Gravitational constant (g)	9.82 (m/s^2)
Wheel radius (r)	1.3 (m)
Gear ratio	10 (−)
Gear efficiency	97%

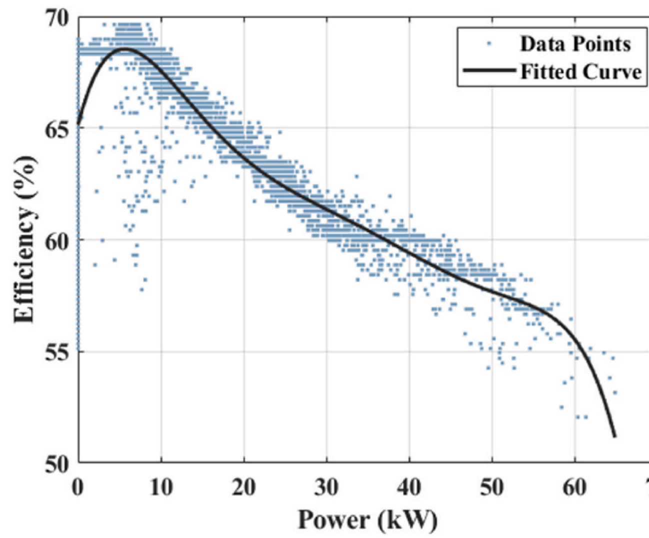

Fig. 2. Fuel cell efficiency-power profile obtained from collected data of a commercial fuel cell vehicle.

the fuel cell as shown in Fig. 2. Thus, the fuel cell model has a peak efficiency of about 67% at around 6 kW, which is consistent with the vehicle manufacturer's information [25]. For the onboard fuel cell operation, its delivered power should follow the vehicle's required power, while for the off-board fuel cell, its operation was assumed to be at its peak efficiency since constant power could be managed off-board. In the fuel cell vehicle, a control strategy is implemented to split the required power between the small battery and the fuel cell.

To implement a control strategy for the fuel cell vehicle, voltage and current data collected in the commercial fuel cell vehicle from both the fuel cell and the battery as well as acceleration values, were used as a reference. The total power required from the energy source was assumed to be the sum of the power of the battery and the fuel cell power. When the battery power data was negative, the power coming into the battery was modeled as coming from the vehicle braking energy if the acceleration was negative, or from the fuel cell if the acceleration was positive or zero. The following control strategy was designed to represent the collected data. The fuel cell provides most/total of the power required if the power required is lower than 10 kW or if the acceleration is zero, as exemplified in area A of Fig. 3. Further, the operation of the fuel cell is avoided if the power required is lower than 5 kW, where instead the

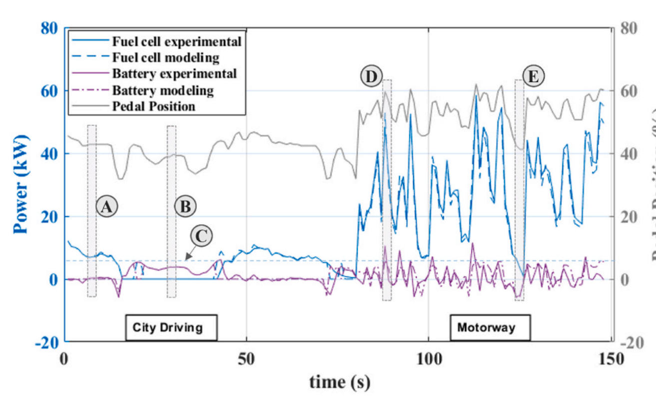

Fig. 3. Data collected on the battery and the fuel cell power from the commercial fuel cell vehicle, along with the data modeling fit using the control strategy implemented. The rectangular areas (A, B, D, and E) and the line (C) refer to: fuel cell mode (A), battery mode (B) when power is lower than 5 kW (C), peak power mode in which the fuel cell provides 90% of the power (D), and battery charging mode (E).

battery mode is preferably used, as shown by areas B and line C in Fig. 3. The total peak powers required to the wheels from the energy source, i.e. fuel cell and battery, is about 90% provided by the fuel cell and 10% by the battery, as shown by area D. When the acceleration is negative (pedal positive slope decrescent), the battery charges (negative power), as shown by area E. The obtained profile, summarized in Table 2, was assumed to be representative of a commercial fuel cell vehicle, i.e. Toyota Mirai. Apart from all the electric efficiency for the components specified, heat loss usage was also considered to evaluate the system efficiency, as described in the next subsection.

2.2. Heat loss usage

The heat losses from both systems could be useful for space heating inside the vehicle or delivered in district heating, especially in low-temperature seasons or areas. Analyzing how much of this heat could be used is key to understanding the efficiency that both systems might achieve. When heat usage is considered, it refers mainly to the heat generated inside the vehicle (due to onboard component losses) and to the heat from the off-board fuel cell operation that can be delivered to a district heating system. Therefore, the heat not used for the vehicle space heating and the heat from other off-board components is wasted. To address the heat loss usage, we have considered that 75% of the total heat generated inside the car due to losses in various components could be used for direct space heating [38–40]. Further, based on [41], we have considered that the vehicle would need up to 40 Wh/min of space heating energy for the case where the difference in the temperature inside and outside the vehicle is 25 °C. Assuming that the temperature inside the vehicle should be kept at 20 °C, this data was extrapolated for outside temperatures of −15 °C, −5 °C, 5 °C, 15 °C, and equal or higher 20 °C. Thus, the relation of the outside and inside temperature difference (ΔT) and the energy consumption inside the vehicle in Wh/min (EC) was determined according to

$$EC = 1.6\Delta T \tag{6}$$

Considering the WLTP driving cycle, this corresponds to a consumption of up to 0.072 kWh/km in the case of −15 °C outside temperature. For the off-board fuel cell, it was assumed that 90% could be utilized in the heat distribution through the district heating [42,43]. Note that the efficiency when the heat loss usage is considered, i.e. useful usage of the hydrogen energy, is calculated as a function of the total energy consumption of the vehicle (propulsion + heating), the total heat utilized heat, and the total energy coming from the hydrogen as

$$E_f = \frac{E_{drive} + E_{heat\ utilized}}{E_{total\ from\ H_2}} \tag{7}$$

3. Results and discussion

3.1. Component loss and energy consumption

To evaluate the overall energy/hydrogen consumption of the onboard and off-board systems, first, the loss contribution to propel the vehicle of each system component was determined for a base case where no losses are used for heating. As shown in Fig. 4, overall, the hydrogen consumption in the off-board system was about 20% higher, 8.0 g/km,

Table 2
Control strategy implemented based on the vehicle driving data collected. P_{ref} refers to the power required from the wheels, and F_{acc} refers to the acceleration force.

Mode	Condition
Fuel cell mode	5 kW < P_{req} < 10 kW and $F_{acc} = 0$
Battery mode	P_{req} < 5 kW or $F_{acc} < 0$
Hybrid mode	P_{req} > 10 kW and F_{acc}>=0

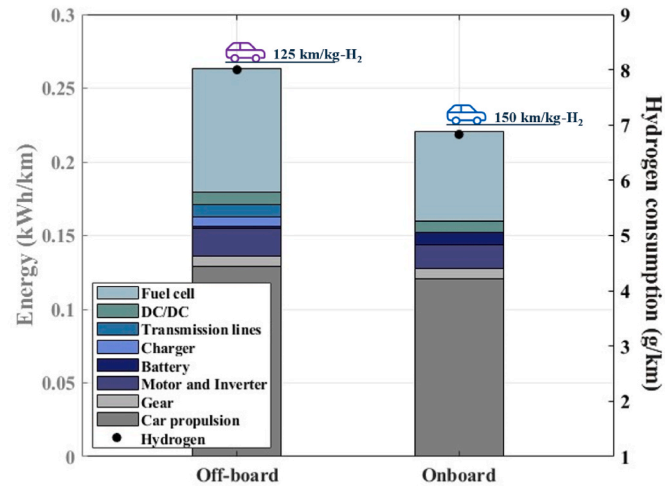

Fig. 4. Energy usage (car propulsion; road load) and losses per component (kWh/km) for the off-board and onboard system along with the total hydrogen consumption (g/km) and the indication of the driving range of each vehicle in the system (km/kg-H_2).

while for the onboard system, 6.7 g/km. In other words, by using 1 kg of hydrogen, the off-board system could propel the vehicle for about 125 km while the onboard system could propel the vehicle for about 150 km. Thus, the onboard system was shown to be about 20% more energy-efficient than the off-board system in terms of driving range, assuming that all the heat losses are not utilized.

The energy consumption difference between the systems can be first associated with the vehicles' weight difference, which demanded a high energy requirement per km for car propulsion (related to the rolling and acceleration forces: Eqs. (3) and (4)) in the off-board system, as shown in Fig. 4. This energy demand difference automatically affected the transmission, motor, and inverter losses which are also slightly higher for the battery vehicle (off-board system). Thus, even though the battery electric vehicle is highly efficient, the battery weight increases the total energy consumption of the system. Regarding the battery loss itself, the loss in the battery present in the fuel cell vehicle was higher due to the higher resistance/smaller active surface area of smaller batteries, thus adding more battery losses in the onboard system compared to the off-board system. Besides having different sizes, the batteries present in the fuel cell vehicle and the battery electric vehicle also have different profiles during their operation due to their different roles in each vehicle. Thus, in the battery vehicle, the battery is the only energy source, and it reduces its SOC until its minimum. In the case of the WLTP driving cycle, the battery electric vehicle has shown a range autonomy of about 470 km until the battery reaches its minimum SOC. Meanwhile, in the fuel cell vehicle, the battery acts as a secondary energy source, supporting the peak powers and avoiding critical operation [44], and due to its smaller size, the SOC varies in cycles. Fig. 5A and B shows the SOC variation for the batteries in the battery electric vehicle and the fuel cell vehicle, respectively.

Despite the lower battery losses, the off-board system had more components related to carrying the electricity from the fuel cell to the vehicle that involved losses, e.g. off-board board converters, thus more energy was required from the fuel cell, which also resulted in less useful energy from the hydrogen. Therefore, even though the off-board fuel cell could operate with delivering power at the peak efficiency while the onboard fuel cell operated at lower efficiency following the driving cycle power requirement, the total energy required was higher from the off-board fuel cell. Fig. 6 shows the onboard fuel cell power variation along with the related heat generated during 5 driving cycles (~9000 s). Even though the onboard system demonstrated higher energy efficiency in terms of driving range, both systems have a significant amount of heat

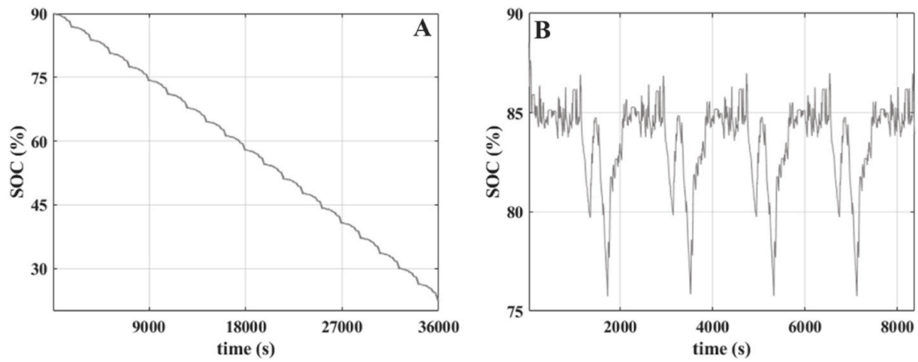

Fig. 5. Battery SOC profile obtained from our system modeling during the drive cycle for the battery electric vehicle (A) and the fuel cell vehicle (B).

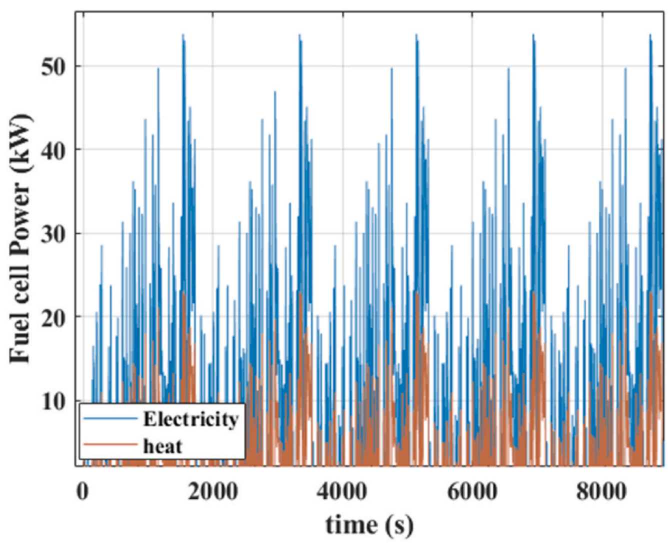

Fig. 6. Fuel cell power profile obtained for the onboard fuel cell model.

losses in their components that could be used for space heating, both inside the vehicle as well as delivered in the district heating in case of the off-board fuel cell. Heat usage can play a relevant role in the system's energy efficiency as further discussed.

3.2. Heat usage and system efficiency

The heat usage inside the car is related to the outside temperature since lower temperatures require higher heating energy, as previously described in Eq. (6). In the case of the onboard system, all the losses are generated inside the vehicle, and no extra heating energy is needed since the heat generated from the components ("losses") can already cover all the heating energy demand even for an outside temperature as low as −15 °C. In the case of the off-board system, since the vehicle onboard losses cannot cover all the heating needed to heat the vehicle for temperatures of 5 °C or lower, it requires extra energy for heating from the vehicle (i.e., the battery), increasing the average consumption. Therefore, lower temperatures are related to higher energy consumption for the off-board scenario, while for the onboard scenario, the energy consumption is virtually the same regardless of ambient temperature. Thus, the off-board system has shown higher energy consumption for all the temperatures as a consequence of not only its heavier vehicle weight and off-board component requirement, as discussed in the previous subsection but also the extra heating energy needed. Since the total energy consumption is proportional to the amount of hydrogen consumed and to the vehicle driving range per mass of hydrogen, the onboard system was more energy efficient in terms of driving range per kg-H_2. Thus, while the onboard system presented a driving range of 150 km/kg-H_2, the off-board system presented a driving range of 94–125 km/kg-H_2 for temperatures ranging from −15 to 20 °C. Fig. 7 presents the energy consumption per km at different temperatures for off-board and onboard divided into the drive energy (car propulsion, car extra heating), useful energy losses (losses used for heat onboard, and losses used off-board, i.e. in the district heating), and heat losses wasted (in the onboard, and off-board components). Meanwhile, Table 3 presents the total driving range per kg of H_2 for both scenarios at different temperatures. Despite the high driving range of the onboard system, as also shown in Table 3, the lower the vehicle driving range, the higher the total energy available to be used in the district heating. Thus, due to the different energy utilization for both scenarios, as shown in Fig. 7, the total losses and the system combined electricity and heat efficiency per km of H_2 are dependent on the outside temperature, as further discussed.

Despite the higher consumption for the system composed of the off-board fuel cell previously shown in Fig. 7, the temperatures and heat utilization affect the overall system efficiency differently. Since the heat losses onboard are higher for the fuel cell vehicle, the heat utilized onboard follows the heating energy required inside the vehicle. In the case that the temperature is −15 °C, the total energy needed to heat the vehicle is about the same as the maximum energy that can be utilized from the fuel cell vehicle component losses. Therefore, in this case, the fuel cell vehicle component losses can be used at their maximum for space heating, and the highest efficiency is reached at this point: about 90% for the onboard fuel cell system minimizing the heat waste as shown in Fig. 8. Despite its high efficiency at −15 °C, for all the other temperatures, the higher the temperature, the more onboard losses are wasted. Thus, the system composed by the onboard fuel cell has its efficiency reduced to 55% for the case where all the heat is wasted (>20 °C). On the other hand, the losses from the off-board fuel cell can still be utilized in the district heating for all temperatures. As follows, for the off-board fuel cell scenario, the system also reaches higher efficiencies at lower temperatures due to the possibility of using both the onboard and off-board losses. Nevertheless, the higher the outside temperature, the higher the efficiency of the system composed by the off-board fuel cell compared to the system composed by the onboard fuel cell due to the possibility of still utilizing the off-board fuel cell losses in the district heating. Thus, while at 20 °C the onboard fuel cell system reaches 55% efficiency, for the off-board fuel cell system, the efficiency is 78%. Therefore, if both driving and heating energy are considered, having an off-board fuel cell is more energy-efficient and provides less energy waste per km at ambient temperatures higher than −5 °C, while for lower temperatures, the system composed of an onboard fuel cell is more energy-efficient. Thus, when the energy values are considered per kg of H_2, as shown in Fig. 8, instead of per km, as shown in Fig. 7, the scenario is more favorable to the off-board system. In any case, due to the high losses added to the systems, especially from the fuel cells, the utilization of the heat loss generated can significantly increase the systems' efficiency. To sum up, heat usage is crucial in a "hydrogen to

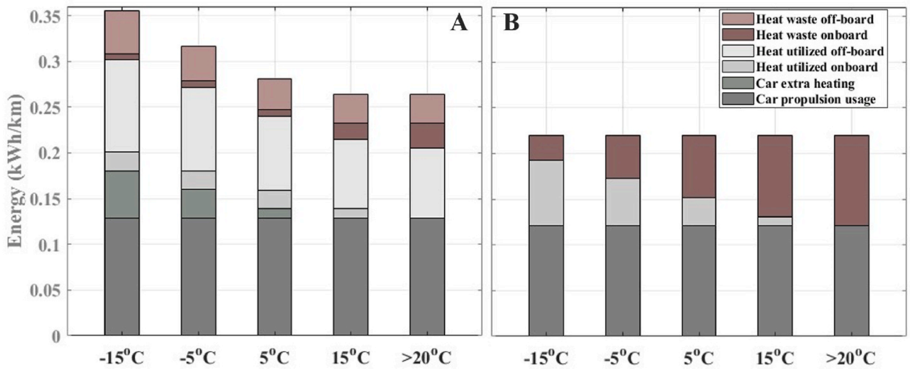

Fig. 7. Energy consumption (kWh/km) at different outside temperatures for the off-board (A) and onboard (B) scenarios.

Table 3
Driving range (km/kg-H2) and useful off-board energy (kWh/km) for the off-board and onboard systems in the temperature of −15°C–20°C.

System	Off-board	Onboard	Off-board	Onboard
Temperature (°C)	Driving range		Useful off-board energy	
	(km/kg-H_2)		(kWh/km)	
−15	94.3	151.5	0.1008	0.0
−5	104.2	151.5	0.0910	0.0
5	117.6	151.5	0.8080	0.0
15	125.0	151.5	0.0759	0.0
>20	125.0	151.5	0.0759	0.0

wheels" analysis.

4. Future work

This work brought forward the energy conversion analysis from hydrogen fuel to wheels; however, further investigations could support a deeper understanding of the advantages of the onboard versus off-board systems, such as economic and environmental evaluation. Thus, considering the component costs, the heat and electricity price in different seasons, as well as the life cycle assessment could bring more clarifications regarding in which scenario hydrogen fuel might be better utilized. For instance, although the system composed of the off-board fuel cell presented higher efficiency for most of the temperature range analyzed, the value of the heat in the district heating is significantly lower in the summer than in the winter which should be accounted for in a deeper comparison. Furthermore, this analysis could also be valuable to evaluate different types of vehicles such as heavy road vehicles, e.g. buses and trucks, and this is a future investigation topic. Additionally, the different power dynamics for the off-board and onboard fuel cells, i.e. constant power output versus fluctuating power to meet the vehicle requirements, should result in a different degradation mode between the systems. To address lifetime degradation due to usage, the system's durability under these varying conditions is a worthy topic to be investigated in future work as well. Further, although all the components of the energy systems are currently available commercially, the applicability of the hydrogen at a commercial scale either onboard or off-board depends on other factors such as the hydrogen infrastructure and economic aspects. Concerning this work, relevant insights were addressed for scenarios where a hydrogen fuel cell is utilized aiming at car propulsion: using it directly onboard in a fuel cell vehicle or using it off-board to power a battery electric vehicle.

5. Conclusion

This work conducted an energy analysis comparison for the propelling of electric vehicles, from hydrogen fuel to wheels. In such a way, we have considered that hydrogen would be an available fuel to either provide electricity to power a battery electric vehicle, i.e.off-board scenario, or to fuel a fuel cell vehicle, i.e. onboard scenario. The following conclusions were found in this work.

- When the heat loss utilization is neglected, the onboard scenario was more energy efficient in terms of driving range (km driven per kg of H_2) than the off-board scenario. The onboard system could drive about 20% more km per mass of hydrogen than the off-board scenario. This was mainly attributed to the heavier battery and the off-board components needed to transport electricity from the off-board fuel cell to the vehicle.
- When heat utilization is considered, the onboard system still consumes less energy than the off-board fuel cell system, being a better option in terms of driving range per kg of H_2. However, the heat utilization and the system efficiency depend on the ambient temperature. For temperatures higher than −5 °C, the system composed

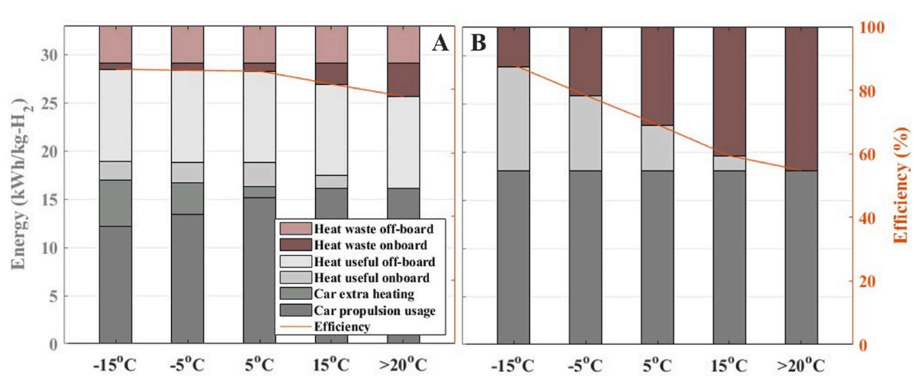

Fig. 8. Energy usage and losses (kWh/kg-H_2) and efficiency (%) for the off-board (A) or the onboard (B) scenarios at different outside temperatures.

of the off-board fuel cell reached higher energy efficiencies (heat + electricity) per mass of hydrogen compared to the onboard system. This was mainly attributed to the off-board fuel cell heat utilization by the district heating regardless of the ambient temperature.

CRediT authorship contribution statement

Tatiana Santos Andrade: Writing – original draft, Methodology, Investigation. **Shangwei Zhou:** Writing – review & editing, Investigation. **Jia Di Yang:** Writing – review & editing, Investigation. **Nimananda Sharma:** Writing – review & editing, Investigation. **Rhodri Jervis:** Writing – review & editing. **Torbjörn Thiringer:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors acknowledge the financial support from Chalmers' Area of Advance Transport and Adlerbertska Forskningsstiftelsen. The authors also thank DAAD for connecting researchers in the hydrogen area.

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