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Mobility from Renewable Electricity: Infrastructure Comparison for Battery and Hydrogen Fuel Cell Vehicles

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Abstract: This work presents a detailed breakdown of the energy conversion chains from intermittent electricity to a vehicle, considering battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). The traditional well-to-wheel analysis is adapted to a grid to mobility approach by introducing the intermediate steps of useful electricity, energy carrier and on-board storage. Specific attention is given to an effective coupling with renewable electricity sources and associated storage needs. Actual market data show that, compared to FCEVs, BEVs and their infrastructure are twice as efficient in the conversion of renewable electricity to a mobility service. A much larger difference between BEVs and FCEVs is usually reported in the literature. Focusing on recharging events, this work additionally shows that the infrastructure efficiencies of both electric vehicle (EV) types are very close, with 57% from grid to on-board storage for hydrogen refilling stations and 66% for fast chargers coupled with battery storage. The transfer from the energy carrier at the station to on-board storage in the vehicle accounts for 9% and 12% of the total energy losses of these two modes, respectively. Slow charging modes can achieve a charging infrastructure efficiency of 78% with residential energy storage systems coupled with AC chargers.

Keywords: electric vehicle; hydrogen; fuel cell vehicle; charging efficiency; energy consumption; charging infrastructure

1. Introduction

The transport sector contributes to two major environmental issues on both the local and global scale. First, urban areas are affected by high levels of noise and air pollution (PM10, NO_x, SO_x, CO, etc.), and second, fossil fuel combustion in diesel and gasoline engines releases CO₂ into the atmosphere, contributing to global warming. Electric vehicles (EVs) address both issues: the first one as a direct consequence of electric drivetrains and the lack of fossil fuel combustion and the second one in parallel with the growing share of renewables in the electricity mix. The principle of sector coupling (SC) was introduced in order to take the full benefits of the stochastic nature of wind and solar energy for industrial, mobility and residential applications [1]. In this work, passenger transportation with battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCEVs) is investigated. In the spirit of SC, electrolytic hydrogen production was considered rather than coal gasification, natural gas, biomass or direct solar pathways. This work compares the energy conversion chains and infrastructures required to deliver an effective driving range for EVs. Taking into account the whole energy chain, from renewable electricity to useful energy in the vehicle and eventually the distance covered with one electric charge or a hydrogen refill, it presents an updated and realistic comparison of practical ranges achievable with a given amount of renewable electricity.

2. Infrastructure Specifications to Couple EV Charging with Renewables

EVs require a specific charging infrastructure to either recharge batteries or refill hydrogen tanks, similarly as conventional refueling stations are needed for internal combustion engines vehicles (ICEVs). One of the major barriers to the commercialization success of EVs is the availability of these infrastructures, and simultaneously, without EVs on the road, the incentives to build a network are limited. However, BEVs and FCEVs are not equally impacted by this issue. Indeed, several options are available for BEVs: they could be recharged at home from an AC source using a standard domestic outlet or at public charging stations. It is estimated that 80% of the recharging events will occur at slow charging rates at home or at the office [2]. However, for the remaining 20%, the fast charging options for BEVs still require significantly longer stops compared to other energy carriers (Table 1). In contrast, the only refilling option for FCEVs is the hydrogen refilling station (HRS), allowing a full refill within 3 min [3], but currently, it is limited to a few sites. The autonomy flow rate, giving the range regained per minute of charge or refill, is a critical differentiating factor between charging modes for passenger vehicles and affects driver's behavior and consumer's choices. Table 1 gives an overview of the various options available.

Table 1. Autonomy flow rates (adapted from [4]).

Vehicle Type	BEV	BEV	FCEV	ICEV
Charging mode	Home charging	Fast charging	HRS	Conventional refilling station
Energy carrier flow rate	2–6 kW	50 kW up to 150 kW	up to 2 kg · min ⁻¹	35 L · min ⁻¹
Autonomy flow rate	0.2–0.6 km · min ⁻¹	3–5 km · min ⁻¹ (50 kW) 9–15 km · min ⁻¹ (150 kW)	160–220 km · min ⁻¹	370–430 km · min ⁻¹

For comparison purposes, the Hyundai ix35, available either with a fuel cell or with an internal combustion engine, was taken as a reference for the gasoline case (9.4 L/100 km). The upper bound of the autonomy flow rate is based on a gasoline VW Golf consuming 8.0 L/100 km. For BEVs, the upper bound is based on the Hyundai Ioniq electric (15.5 kWh/100 km), and the lower bound is based on the BYD e6 (29 kWh/100 km). All vehicle consumptions are based on [5].

Additionally, the autonomy flow rate represents a significant constraint for infrastructure operators willing to serve a maximum number of customers per day. According to the Swiss oil industry [6] and the Swiss Federal Office for roads [7], the average refueling station in Switzerland delivers around 46,000 km of autonomy to its customers every day. This autonomy delivered to a set of vehicles is defined as a mobility service. To deliver the same mobility service within the opening hours, at least 11 chargers at 50 kW must be operated simultaneously with no interruption, and an HRS should deliver 460 kg of hydrogen. The required infrastructure to deliver this mobility service using intermittent renewable electricity sources is described in the following paragraphs.

2.1. Battery Electric Vehicle Infrastructure

BEV can be either recharged with AC sources, using the converter placed on-board the vehicle, or with DC chargers. AC mode is typically limited to 3–6 kW (AC Types 1 and 2) and is usually associated with domestic chargers and overnight charging. DC sources, or fast chargers, can deliver up to 150 kW using actual connectors (CCS, CHAdeMo, Tesla).

For the coupling with renewable electricity, two similar strategies (but at different scales) can be adopted for individuals (AC chargers) and fast charging stations operators (DC chargers). The idea is to introduce a buffer energy storage system (ESS) to take into account the intermittency of the renewable electricity production and to be able to fulfill charging demand at any time.

For individuals, several manufacturers offer small power packs or residential ESS in the range of 5–30 kWh. These systems can be used to store the energy produced with solar panels on the roof, to ensure energy autonomy of the household during power cuts or to accommodate time-of-use or demand charge rate schemes.

For station operators, buffer batteries offer additional benefits such as lowering the power connection requirements and relaxing the constraints on the grid. Tsirinomeny [8] estimated a typical battery for a station serving 200 BEVs/day to have a capacity of 2.2 MWh and a maximum power output of 1.6 MW (32 chargers at 50 kW with a peak grid demand of 400 kW).

Even if most of the energy losses will be associated with this intermediate storage, the vehicle side is often overlooked. Both charging modes are significantly affected by vehicle side components, such as the on-board converter for AC charging and the cooling via the battery management system (BMS) during fast charge. Additionally, we can mention some losses occurring within the charger to cool down the cord, which is expected to be required above 150 kW.

2.2. Hydrogen Fuel Cell Electric Vehicle Infrastructure

The infrastructure required to refill FCEVs comprises:

- A hydrogen production unit: A variety of techniques is used to produce hydrogen, but the only one currently available and directly related to renewable electricity at a large scale is water electrolysis, with two mature technologies at low temperatures: alkaline or proton exchange membrane (PEM) electrolyzers. Additionally, if the hydrogen is not produced on-site, it has to be transported in gaseous form, typically in tube trailers at 20 MPa.
- A hydrogen storage system (supply storage): usually gaseous hydrogen at 4–20 MPa in steel cylinders.
- A hydrogen compression system: Several compressor technologies are available such as diaphragm or reciprocating compressors, comprising, for example, gas booster or ionic compressors, similar to the one developed by Linde [9].
- A hydrogen buffer or fueling storage: usually organized in a cascade system up to 90 MPa according to the National Renewable Energy Laboratory (NREL) recommendations [10].
- A dispenser: includes a fueling nozzle to connect to the car and a cooling block to precool the hydrogen. Indeed, the hydrogen in the vehicle tank is subjected to a rapid recompression throughout the fill, which generates heat, in addition to the Joule–Thomson effect at the fueling nozzle [11]. High temperatures can lead to an under filling of the tank, but also can damage the composite layer of the hydrogen tank. According to the fueling protocol SAE J2601 [3], a precooling temperature of $-40\text{ }^{\circ}\text{C}$ is recommended. Finally, in order to release the pressure in the fueling nozzle at the end of the refilling, the hydrogen contained in the hose between the last valve of the HRS and the entry point of the vehicle is vented into the air.

2.3. Summary of Required Layouts

Extremely diverse layouts can be proposed for EV refilling infrastructure coupled with renewables. For illustrative purposes, the minimal layout is represented in the graph below, assuming an HRS with on-site electrolysis. The scope and boundaries of the study are summarized in Figure 1 below.

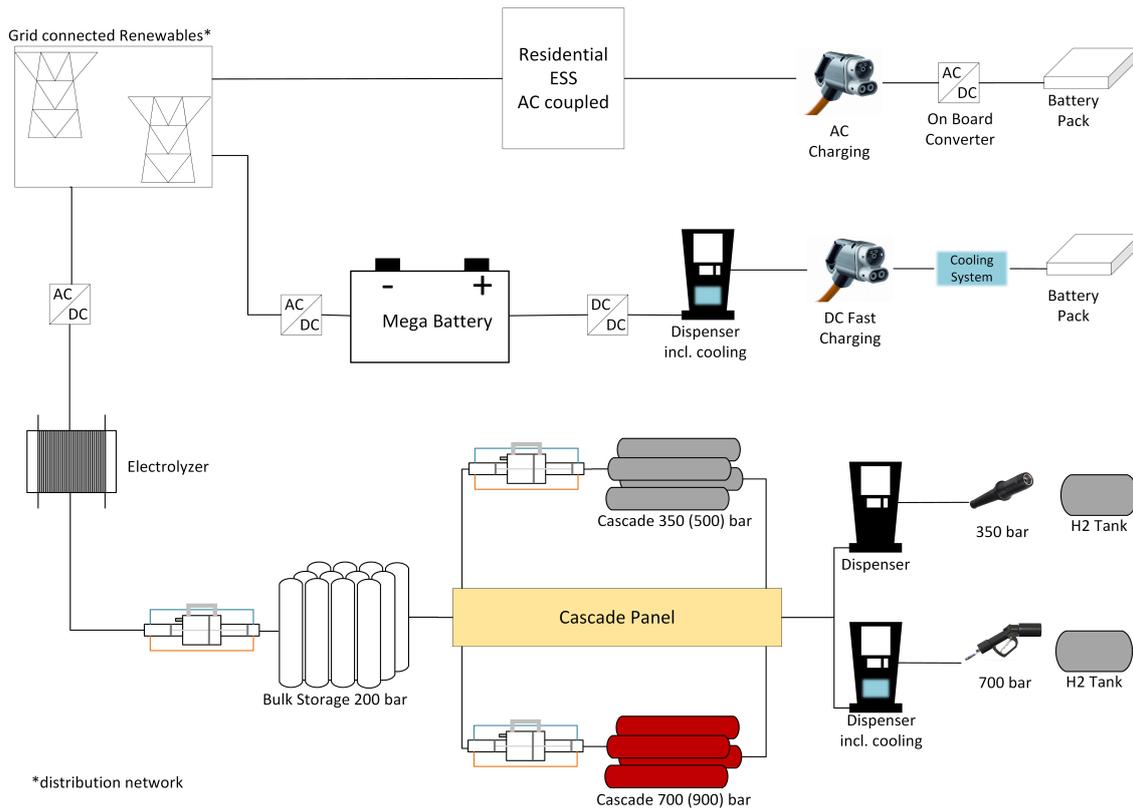


Figure 1. EVs' refilling pathways.

3. Novel Method for Grid to Mobility Assessments

Life cycle assessment (LCA) applied to the transport sector is usually broken down into the well-to-wheel (WtW) analysis approach for the usage phase [12]. Conceived originally for ICEVs as the reference case, refilling events are not explicitly highlighted, and the methodology does not fit the specificities of EVs. Indeed, well-to-tank (WtT) usually covers the energy carrier production and transport, and tank-to-wheel (TtW) covers the energy consumption of the vehicle, but the distribution of the energy carrier to the vehicle is hidden in the WtT part and is therefore often neglected.

3.1. Literature Review

An extensive literature is available on BEVs' and FCEVs' energy intensity, with several efficiency comparisons. However, the results are extremely diverse, ranging from BEVs being 1.25–3.9-times more energy efficient than FCEVs [13–18]. The main difference originates from the system definition, especially regarding the site of hydrogen production (transport required or not), the primary energy source and the useful unit considered (energy out of the motor or converted into effective distance driven). In addition, a detailed description of recharging events and the coupling with renewables are rarely addressed. Too often, BEVs' losses are solely based on charging and discharging of the on-board battery, while FCEVs' losses include electrolyzer, compressor and fuel cell operation. The influence of charging events is mostly considered via the charging time or the electricity mix used, and the mode of charging (fast or slow) was anticipated to have an impact on the aging of batteries, but not explicitly on the efficiency [19].

Most of these studies were published prior to 2010, before the momentum towards fast DC charging (the SAE J1772 incorporated DC charging only in its 2012 revision [20]) and the definition of a standardized hydrogen refilling protocol (the first version of the SAE J2601 was published in 2010 [3]). As a consequence, BEV charging efficiencies are quite accurate when referring to slow charging modes, but inadequate for assessments with fast charging modes. Concerning FCEVs, only a

limited energy system analysis of the refilling process has been provided yet with primary data coming from demonstrators [21,22]. In order to address these gaps, we introduced a new segmentation and adapted the WtW approach to EV specificities.

3.2. Grid to Mobility Approach

Based on the pathways defined in Figure 1, we can identify a pattern in the conversion of intermittent grid electricity to a mobility service for EV drivers.

i Grid to useful electricity:

Useful electricity is considered as electricity compatible with the main equipment of the refilling infrastructure. Electrochemical devices, either batteries or electrolyzers, operate on DC currents; therefore, preliminary AC/DC conversion is usually required, except in the case when a direct DC coupling with solar panels is feasible or if the ESS includes the converter.

ii Useful electricity to energy carrier:

Two different energy carriers are commercially investigated for EVs: electricity stored in batteries or hydrogen. We define the energy carrier as the energy stored in large quantities at the station for grid independent refueling at any point in time. It covers the use of megabatteries (MW/MWh), and the operation of electrolyzers and first compression steps for the bulk storage of hydrogen.

iii Energy carrier to on-board storage:

Refilling and recharging events were often neglected for ICEVs due to the very simple equipment required and the insignificant energy consumption in that case. However, for EVs, this step can be particularly challenging. For example, both BEVs and FCEVs require thermal management systems.

iv On-board storage to mobility:

After all the conversions occurring prior to and during charging events, the energy transferred is ultimately converted into a mobility service for the driver. The energy stored on-board is converted into km driven, which is assessed on standardized driving cycles such as those conducted by the U.S. Environmental Protection Agency (EPA).

4. Case Study and Data Collection

The subdivisions presented in Section 3.2 are applied to the typical set of refilling modes for BEVs and FCEVs. The corresponding equipment and processes investigated are summarized in Table 2. Efficiency estimates are based on the literature and published data for commercially available products.

Table 2. Grid to mobility segmentation.

Step	BEV Slow	BEV Fast	FCEV 35 MPa and 70 MPa
Grid to useful electricity	No conversion required	AC/DC conversion	AC/DC conversion
Useful electricity to energy carrier	Storage in stationary battery AC coupled	Storage in stationary battery DC coupled	Variable load electrolysis Purification 20 MPa compression
Energy carrier to on-board storage	On-board AC/DC conversion	DC/DC conversion Battery thermal management	50-MPa cascade compression 90-MPa cascade compression −40 °C precooling Dispenser vent
On-board storage to mobility	EPA combined cycle	EPA combined cycle	EPA combined cycle

4.1. BEV

We consider AC and DC charging modes, in order to evaluate the conversion of kWh of intermittent electricity to km driven with a BEV. Without constraints and incentives to adapt charging schedules, production and consumption cannot match and require therefore the introduction of storage systems.

4.1.1. Stationary Storage

For domestic installations, renewable electricity can be locally produced with solar panels. Even if the current produced is already in a DC form, residential ESS are usually AC coupled, requiring the use of inverters. Round trip AC efficiencies reported by various manufacturers of lithium-ion residential ESS are between 89% and 92% [23,24]. For commercial installations, batteries in the MWh range are required. Several technologies are available, and we can mention, for example, flow batteries (e.g., all vanadium or zinc bromine), lithium-ion, lithium polymer and lithium titanate. Introducing mega batteries in stations with multiple fast chargers has several benefits such as peak shaving, load leveling and buffering, as well as relaxing the constraints for grid connection [4,8,25]. A real implementation of a DC fast charging station coupled with a battery storage system was performed by Sbordone et al. [26] with a peak shaving strategy. The system efficiency is highly dependent on the chemistry of the battery with reported efficiencies ranging from 65–90%.

4.1.2. Dispenser and Charging Events

Losses are also reported during charging events due to power electronics and thermal management. AC charging mode involves the use of the charger on-board the vehicle, which is basically an AC/DC converter. The Idaho National Laboratory (INL) performed test bench measurements with various BEVs and reported charging efficiencies in the range of 85–92% [27]. The INL also investigated fast DC charges and especially the consumption of the battery management system. The energy used during fast charge events for the cooling was found to be in the range of 3–5% (and up to 10% in hot weather conditions) of the total energy transferred to the battery [27]. These energy expenses are expected to increase with fast charging capabilities, especially above 150 kW, when cooling of the charging cord will also be required. Finally, the efficiencies reported by fast charger manufacturers usually account for the AC/DC conversion, so a typical value of 98% for a DC/DC is used.

4.1.3. Vehicle Efficiency

According to EPA measurements, consumption of BEVs varies in the range of 15–29 kWh/100 km (Hyundai Ioniq to BYD e6 [5]).

4.2. FCEV

Unlike BEV infrastructures, FCEV infrastructures integrate by definition storage capacity and some flexibility in the energy carrier production. No simultaneity is required between hydrogen production and hydrogen delivery.

4.2.1. Electrolysis

Commercially available proton exchange membrane (PEM) or alkaline electrolyzers can achieve a system consumption in the range of 4.0–5.0 kWh/Nm³ [12,28]. Slightly higher values are reported by NOW [29]: in the range of 4.5–7.0 kWh/Nm³, expected to go down to 4.3–5.7 kWh/Nm³ or 4.1–4.8 kWh/Nm³ within 10–20 years for alkaline and PEM electrolyzers, respectively. If electrolysis cannot be performed on site, an additional penalty for transportation in the tube trailer would be around 0.6 kWh/kg H₂ transported [30].

4.2.2. Compression

Practical measured compression energy varies from 2.7–4.2 kWh/kg H₂ [31] for 90 MPa. At the station at the University of California-Irvine (UCI) [22], a consumption of 2.68 kWh/kg H₂ was achieved, and 70-MPa refills exhibited only 11% more compression energy consumption than the 35-MPa refills. In order to make the distinction between the compression required for the supply storage (energy carrier stage) and the one required for the refilling (energy carrier to on-board storage), the following conversion efficiency values were adopted:

- 95% for 20 MPa (nominal pressure of supply storage systems) starting from the outlet pressure of the electrolyzer, corresponding to 1.8 kWh/kg H₂.
- 98% and 97% for respectively 35-MPa and 70-MPa refills, corresponding in total to 2.5 kWh/kg H₂ (93%) and 2.8 kWh/kg H₂ (92%), in line with the 11% difference reported by UCI [22] and with the numbers published by Stolten [30].

Efficiency improvements for the compression work are limited by the cascade design and thermodynamics: a perfect isothermal compression at 70 MPa would require 2.1 kWh/kg H₂.

4.2.3. Precooling and Refilling Event

Precooling is one of the critical processes to allow a fast refilling of FCEVs at 70 MPa. High pressure hydrogen needs to go through a heat exchanger before being transferred to the car via the filling nozzle. The cooling block is usually maintained at −40 °C in order to keep the station ready at any point of time. As a consequence, the energy requirement for cooling reported per kilogram of hydrogen delivered ranges from above 20 kWh/kg H₂ (HRS with low frequentation in Germany [32]) to only 1.4 kWh/kg H₂ (HRS with attached fleet [22]). Elgowainy and Reddi [33] estimated that, for high HRS capacity utilization, the electricity consumption for H₂ precooling can be even lower than 1 kWh/kg H₂. Additionally, another process causes losses during the refilling: the remaining hydrogen in the hose has to be vented in order to release the coupling. Considering a hose of six meters under 70 MPa [34], approximately 7 g of hydrogen is vented after each refill. This quantity is negligible.

4.2.4. Vehicle Efficiency

Similarly, as for BEV, the U.S. EPA also measured efficiencies of the conversion from on-board storage to mobility for FCEVs. The measured figures vary from 0.92–1.26 kg H₂/100 km [5]; however, the set of commercially available vehicles is still limited.

4.3. Results and Discussion

The mobility service achievable with 100 kWh of intermittent electricity and the corresponding losses along the grid to mobility pathway are presented in Figure 2. In order to observe the final conversion into mobility service at the same scale, an arbitrary scaling factor is fixed in order to highlight a typical 46% efficiency of the fuel cell drive train [17].

4.3.1. Discussion

For all modes, most of the infrastructure losses occur during the conversion from useful electricity to energy carrier. Refilling events (energy carrier to on-board storage) have a limited contribution in the overall efficiency except for home charging. Finally, considering the grid to on-board storage conversion, the fast charging infrastructure for BEVs is only 15% more effective than HRS, and only two thirds of the initial energy effectively reach the vehicle. The vehicle side conversion is the discriminating criterion. That is why hybrid FCEV concepts with optimized battery size and fuel cell power can offer significant advantages [35].

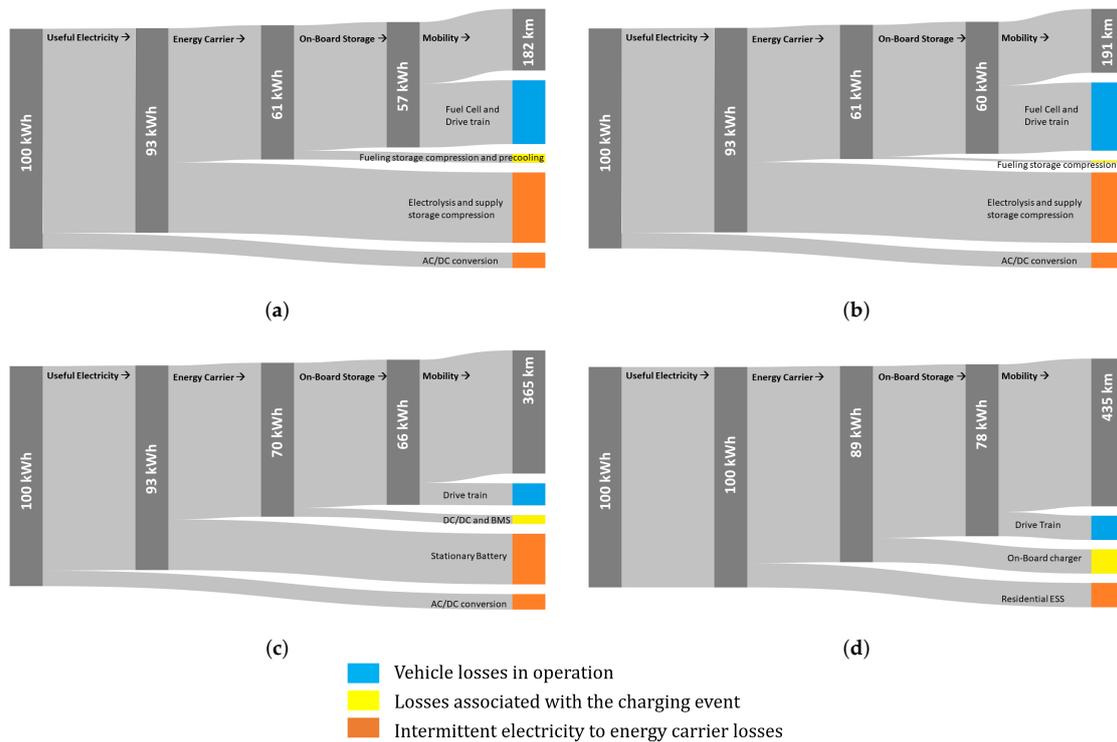


Figure 2. Sankey diagram of the grid to mobility conversion efficiencies for (a) 70 MPa H₂, (b) 35 MPa H₂, (c) 50-kW fast charger coupled to a stationary battery and (d) a home charger coupled with a residential ESS. (a) 70 MPa; (b) 35 MPa; (c) fast charging; (d) home charging.

Interestingly, increasing the delivery pressure from 35 MPa to 70 MPa only costs 5% more energy. The large difference observed between the two BEV modes is mainly due to the fact that a less efficient technology was selected for the megabattery (75%) compared to the residential ESS (89%), to depict the likely investment decision of station operators and the numbers reported in Section 4.1.1. The impact of these values is investigated in the sensitivity analysis.

For comparison, we can note that introducing 57 kWh of energy (the FCEV 70-MPa case) in the form of gasoline in an ICEV will offer only 100 km of driving range (not to mention that all upstream conversions are also energy intensive).

4.3.2. Sensitivity Analysis

As highlighted in Sections 4.1 and 4.2, some of the major components of EV charging infrastructures exhibit very diverse efficiencies. To illustrate how some single components of the grid to mobility conversion chain affect the final results, a sensitivity analysis was performed. The results are presented in Figure 3. Lab- and pilot-scale installations may report numbers outside of the mentioned ranges, but the general trend is shown in this tornado chart.

The graph presented in Figure 3 is also a way to estimate how future technologies' developments will affect the BEV versus FCEV competition. Indeed, the FCEV market and technology are in an earlier stage of development than BEV, and larger efficiency gains, especially on the vehicle side, are expected. On the other hand, the BEV market is going toward longer range and larger vehicles. Thus, we can expect some increase in their energy consumption per kilometer. With BEVs and FCEVs covering more segments of the passenger vehicle market in the future, a more specific comparison could be made. Regarding infrastructure, the efficiency of the electrochemical device used to produce or store the energy carrier is clearly the discriminating parameter. In a SC perspective, the flexibility of this device should also be considered. Finally, limited gains can be made on hydrogen compression,

as optimized pressure cascades have a greater impact on economics than on energy efficiency [36]. The energy consumption associated with hydrogen precooling is mostly related to the utilization ratio of the station and not related to technological developments [37]. The expected development of 350-kW ultra-fast DC chargers after 2020 will be accompanied with larger losses from the BMS, and the cooling of the charging cord should be added in the overall DC/DC efficiency. Even if the performance specifications of ultra-fast chargers are not yet publicly available, the overall picture will remain similar, according to the relative importance of BMS and DC/DC.

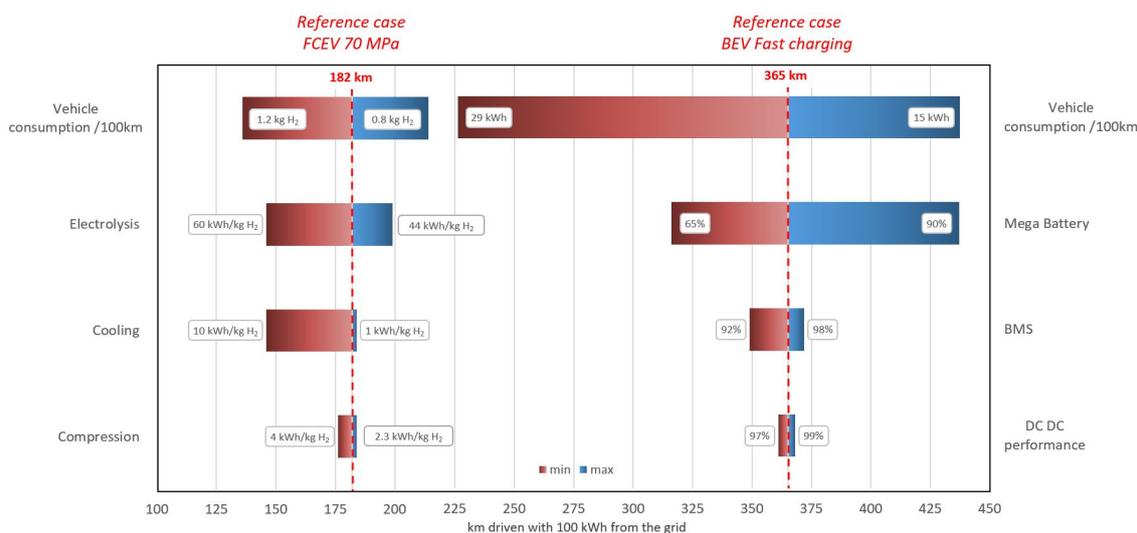


Figure 3. Sensitivity analysis.

Additional considerations such as waste heat utilization and winter effects can heavily affect the energy consumption of BEVs [38] and cannot be observed with traditional TtW approaches. Simulation results performed by Li et al. [17] show that with the heating system activated, the on-board storage to mobility efficiency of BEVs goes down from 73% to 45%, as compared with the 46% down to 39% for FCEVs.

5. Conclusions

The development of electric mobility is often understood as the development of green mobility. However, the link between renewable electricity and mobility, although well defined in theory, is not always converted into effective measures to guarantee this connection. Based on this situation, the scaling of renewable electricity production needs is underestimated, and the benefits of hydrogen mobility are blurred. In order to benchmark and compare EV infrastructures coupled with renewables, a grid to mobility approach was introduced. A comprehensive data collection for all components and processes occurring prior and during charging events was performed to ascertain as realistic efficiencies as possible. First of all, it should be noted that the charging infrastructure is a major contributor to the overall energy efficiency of electric mobility. The exemplary cases presented in this study show that only 57–78% of the energy from the grid is effectively transferred to the vehicle. Additionally, under the assumptions used in this work, it could be shown that up to 15% less energy is transferred to BEVs using fast DC chargers compared to domestic AC chargers. For FCEVs, the penalty linked to the production of the energy carrier is partially compensated by the fact that no stationary battery storage system is required. However, the final conversion occurs on-board the vehicle, within the fuel cell, which caps the overall efficiency of FCEV mobility to about half of the BEV one. Further studies should incorporate cost considerations regarding the infrastructure for electric mobility [39] and appropriate scaling needs [40]. A realistic business case and pricing strategies including the benefits of SC should be developed [18]. Grid-scale equipment such as megabatteries can

heavily impact the costs of recharging stations and electricity network operators. Upscaling electric mobility needs to be accompanied with effective coupling with intermittent renewable electricity sources. Efficiency considerations might then be balanced with cost and flexibility constraints for grid integration. Furthermore, the scope of the vehicles can be extended to small lorries and buses, which are more and more available with electrified drivetrains in combination with batteries and hydrogen fuel cell range extenders.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating current
BEV	Battery electric vehicle
BMS	Battery management system
DC	Direct current
EPA	Environmental Protection Agency
ESS	Energy storage system
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
HRS	Hydrogen refilling station
ICEV	Internal combustion engine vehicle
LCA	Life cycle assessment
PEM	Proton exchange membrane
PM	Particulate matter
SAE	Society of Automotive Engineers
SC	Sector coupling
TtW	Tank-to-wheel
WtT	Well-to-tank
WtW	Well-to-wheel

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