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# Mobility from renewable electricity: infrastructure comparison for battery and hydrogen fuel cell vehicles

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## Summary

This work presents a detailed breakdown of the energy conversion chains from the electrical grid to the 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. A specific attention is given to an effective coupling with renewable electricity sources and associated storage needs.

Using actual market data, it is shown that, compared to FCEVs, BEVs and their infrastructure are twice more 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 vehicles (EVs) 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. Slow charging modes can achieve a charging infrastructure efficiency of 78% for residential energy storage systems coupled with AC chargers.

*Keywords: EV, charging, efficiency, energy consumption, infrastructure*

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## 1 Introduction

The transport sector contributes to two major environmental issues. First, urban areas are affected by high levels of local pollution (PM10, $NO_x$, $SO_x$, CO, noise…) and second, fossil fuel combustion in diesel and gasoline engines releases $CO_2$ into the atmosphere contributing to global warming. EVs address both issues; the first one as a direct consequence of electric drivetrains and the lack of fossil fuel combustion, the second one in parallel with the growing share of renewables in the electricity mix. Renewable electricity is an energy carrier of interest for many sectors, and its efficient use with regard to the service provided to the end user deserves to be closely examined.

This work compares the energy conversion chains and infrastructures required to deliver 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 barrier for the market development of EVs is the availability of these infrastructures, and simultaneously, without EVs on the road, the incentives to build a network are limited. But BEVs and FCEVs are not equally affected by this issue. Indeed, several options are available for BEVs: they could be recharged from an AC source overnight at home using standard domestic outlet or on public charging stations. It is estimated that 80% of the recharging events will occur at slow charging rates at home or at the office [1]. However, for the remaining 20%, the fast charging rates for BEVs still require significantly longer stops compared to other energy carriers (Table 1). In contrast, the only refilling option for FCEVs is to go to a hydrogen refilling station (HRS), allowing a full refill within 3 minutes [2] but currently with a very limited network. The autonomy flowrate, giving the range regained per minute of charge or refill, is a critical differentiating factor between charging modes for passenger vehicle and affects driver's behavior and consumer's choices. Table 1 gives an overview of the various options available.

Table 1 - Autonomy flowrates (adapted from Hõimoja *et al.* [3])

| **Vehicle type** | **BEV** | | **FCEV** | **ICEV** |
|---|---|---|---|---|
| **Charging mode** | Home outlet | Fast charger | HRS | Conventional refuelling station |
| **Energy carrier flow rate** | 2 to 6 kW | 50 kW<br>up to 150 kW | Up to 2 $\text{kg}\cdot\text{min}^{-1}$ | 35 $\text{L}\cdot\text{min}^{-1}$ |
| **Autonomy flow rate** | 0.2 – 0.6 $\text{km}\cdot\text{min}^{-1}$ | 3-5 $\text{km}\cdot\text{min}^{-1}$ (50 kW)<br>9-15 $\text{km}\cdot\text{min}^{-1}$(150 kW) | 160-220 $\text{km}\cdot\text{min}^{-1}$ | 370-430 $\text{km}\cdot\text{min}^{-1}$ (1) |

The autonomy flowrate represents also a significant constraint for infrastructure operators willing to serve a maximum number of customers per day. According to the Swiss oil industry [5], the average refuelling station in Switzerland delivers 2660 L of gasoline per day, which corresponds to approximately 33 000 km of autonomy for customers. 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 8 fast chargers at 50 kW must be operated simultaneously with no interruption and an HRS should be able to deliver 330 kg of hydrogen. The required infrastructure to deliver this mobility service and to ensure that renewable electricity sources are used is described in the following paragraphs.

### 2.1 Battery electric vehicles 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 to 6 kW (AC type 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 stations operators (DC chargers). The idea is to introduce a buffer battery to

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[1] For comparison purposes, the Hyundai ix35, available either with fuel cell or with internal combustion engine was taken as reference for the gasoline case (9.4 L/100km). The upper bound of the autonomy flowrate is based on a gasoline VW Golf consuming 8.0 L/100 km [4].

take into account the intermittency of the electricity production and to be able to fulfil charging demand at any time.

For individuals, several manufacturers offer small power packs or residential energy storage systems (ESS) in the range of 5 to 30 kWh. These systems can be used to store the energy produced with solar panels on the roof, or to ensure energy autonomy of the household during power cuts.

For station operators, buffer batteries offer additional benefits such as lowering the power connection requirements, and relaxing the constraints on the grid. Tsirinomeny [6] 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.

Even if most of the energy losses will be associated to this intermediate storage, the vehicle side is often overlooked. Both charging modes are also 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. We can also 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 vehicles infrastructure

The infrastructure required to refill FCEVs comprises:

- a hydrogen production unit: a variety of techniques are used produce hydrogen, but the only one which can be directly related to renewable electricity is electrolysis, with currently two mature technologies at low temperatures: alkaline or proton exchange membranes (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 (bulk storage): usually gaseous hydrogen at 4 to 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, as the one developed by Linde ([7]).

- a hydrogen buffer or fueling storage (cascade refueling concept, with up to 90 MPa buffer tanks). Usually organized in a cascade system according to the National Renewable Energy Laboratory (NREL) recommendations [8].

- a dispenser with a fueling nozzle to connect to the car, including a cooling block to precool the hydrogen. Indeed, the hydrogen in the vehicle tank is subject to a rapid recompression throughout the fill, which generates heat, in addition to the Joule-Thomson effect at the fueling nozzle [9]. 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 [2], a precooling temperature of –40° C is recommended. Finally, in order to release the pressure in the filling 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

Very 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 is summarized in Figure 1 below.

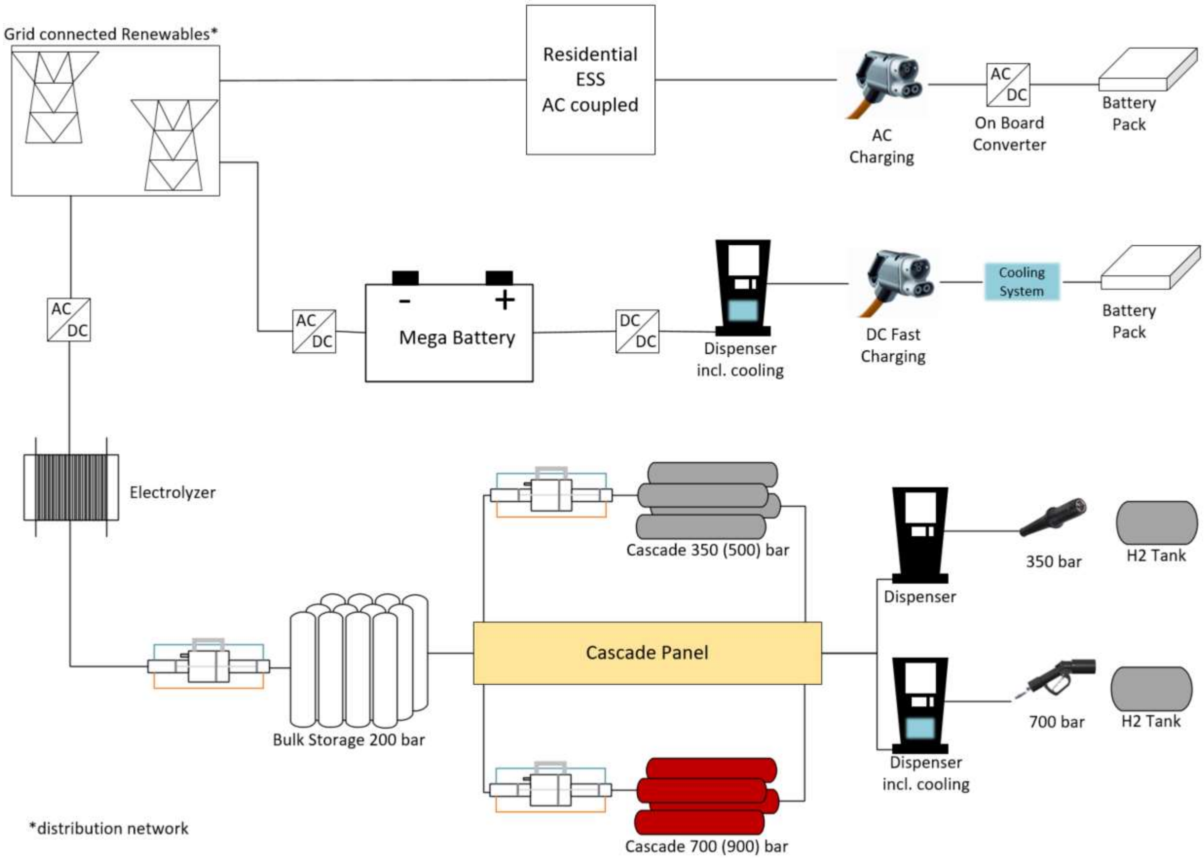

Figure 1 - Layout for EVs refilling modes

## 3 Novel method for grid to mobility assessments

Life cycle assessment (LCA) applied to the transport sector is usually broken down in the Well-to-Wheel (WtW) analysis approach, as the one conducted by the European Union [10]. Conceived originally for ICEVs as the reference case, refilling events are not explicitly highlighted, and the methodology doesn't fit to the specificities of EVs.

### 3.1 Literature review

An extensive literature is available on BEVs and FCEVs, with several efficiency comparisons. However, the results are very diverse, ranging from BEVs being 1.25 to 3.9 times more energy efficient than FCEVs ([11]–[14]). 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 is often overlooked and the coupling with renewable is not technically addressed.

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 [15]) and the definition of a standardized hydrogen refilling protocol (the first version of the SAE J2601 was published in 2010 [16]). 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. 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 installations defined in Figure 1, we can identify a pattern in the conversion of grid electricity to a mobility service for EV drivers.

### 3.2.1 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 AC/DC conversion is usually required, except in the case when a direct DC coupling with solar panels is feasible.

### 3.2.2 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 for grid independent refuelling at any point of time. It covers the use of megabatteries (MW/MWh), electrolyzers and first compression steps for the bulk storage.

### 3.2.3 Energy carrier to on-board storage

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

### 3.2.4 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 kWh stored on-board are converted into km driven, which are assessed on standardized driving cycles such as those conducted by the US 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 expected for BEVs and FCEVs. The corresponding equipment and processes investigated are summarized in Table *2*. Efficiency estimates are based on literature and published data for commercially available products.

Table 2 - Grid to mobility segmentation

| Step | BEVs Slow | BEVs Fast | FCEVs 35MPa and 70MPa |
|---|---|---|---|
| **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<br>DC coupled | Variable load electrolysis<br>Purification<br>20 MPa compression |
| **Energy carrier to on-board storage** | On-board AC/DC conversion | Dispenser DC/DC conversion<br>Battery Thermal Management | 50 MPa cascade compression<br>90 MPa cascade compression<br>–40°C precooling<br>Dispenser Vent |
| **On-board storage to mobility** | EPA combined cycle | EPA combined cycle | EPA combined cycle |

The discharge efficiency of the storage on-board the BEV itself is not explicitly mentioned but is accounted in the conversion to a mobility service.

## 4.1 BEV

We consider AC and DC charging modes, in order to evaluate the conversion of kWh of grid 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. Roundtrip AC efficiencies reported by various manufacturers of lithium-ion systems are comprised between 89% and 92 % ([17],[18]).

For commercial installations, batteries in the megawatt 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 levelling and buffering as well as relaxing the constraints for grid connection ([3], [6], [19]). A real implementation of a DC fast charging station coupled with a battery storage system was performed by Sbordone *et al.* [20] with a peak shaving strategy. The system efficiency is highly depending on the technology with reported efficiencies ranging from 65 to 90%.

### 4.1.2 Dispenser and charging events

Losses are also reported during charging events due to power electronics and heat management. AC charging mode involve 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 an various BEVs and report efficiencies in the range of 85 to 92% [21].

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 to 5% (and up to 10% in hot weather conditions) of the total energy transferred to the battery [21]. These energy expenses are expected to increase with fast charging capabilities, especially above 150 kW, when a cooling of the charging cord will be also required.

Finally, efficiencies reported by fast charger manufacturers are usually accounting 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, consumptions of BEVs varies in the range of 15 to 24 kWh/100km (Hyundai Ioniq to Tesla Model X) [22].

## 4.2 FCEV

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

### 4.2.1 Electrolysis

Commercially available PEM or alkaline electrolyzers can achieve a system consumption in the range of 4.0 - 5.0 kWh/Nm$^3$ ([10],[23]). Slightly higher values are reported by NOW [24]: in the range of 4.5 - 7.0 kWh/Nm$^3$ expected to go down to 4.3 - 5.7 kWh/Nm$^3$ or 4.1 - 4.8 kWh/Nm$^3$ within 10-20 years for respectively alkaline and PEM electrolyzers. If electrolysis cannot be performed on site, an additional penalty for transportation in tube trailer would be around 0.6 kWh/kg $H_2$ transported [25].

### 4.2.2 Compression

Practical compression energy measured varies from 2.7 kWh/kg $H_2$ to 4.2 kWh/kg $H_2$ [26] for 90 MPa. At the station from UCI [27], a consumption of 2.68 kWh/kg $H_2$ 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 bulk storage (energy carrier stage) and that required for the refilling (energy carrier to on-board storage stage) the following conversion efficiencies values were adopted:

- 95% for 20 MPa (nominal pressure of bulk storage systems) starting from the outlet pressure of the electrolyzer, corresponding to 1.8 kWh/kg $H_2$.
- 98% and 97% for respectively 35 MPa and 70 MPa refills, corresponding in total to 2.5 kWh/kg $H_2$ (93%) and 2.8 kWh/kg $H_2$ (92%) in line with the 11% difference reported by UCI [27] and with the numbers published by Stolten [25].

Efficiency improvements for the compression work are limited by cascade design and thermodynamics: a perfect isothermal compression at 70 MPa will require 2.1 kWh/kg $H_2$.

### 4.2.3 Precooling

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 permanently 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 $H_2$ (HRS with low frequentation in Germany [28]) to only 1.4 kWh/kg $H_2$ ([27] HRS with attached fleet). Elgowainy and Reddi [29] estimated that, at high HRS capacity utilization, the electricity consumption for $H_2$ precooling can be even lower than 1 kWh/kg $H_2$.

### 4.2.4 Vehicle efficiency and others

Similarly, as for BEV, the U.S. EPA also measured efficiencies of the conversion from energy carrier to mobility for FCEVs. The measured figures vary from 0.92 to 1.26 kg $H_2$/100 km [22], however the set of commercially available vehicles is still limited.

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 6 meters under 70 MPa [30], approximately 7g of hydrogen are vented after each refill. This quantity is negligible.

## 4.3 Results and discussion

The results are presented with respect to 100 kWh of grid electricity. In order to observe the final conversion into mobility service on the same scale, an arbitrary scaling factor is fixed in order to highlight the typical 50% efficiency of the fuel cell. Results are presented in Figure 2.

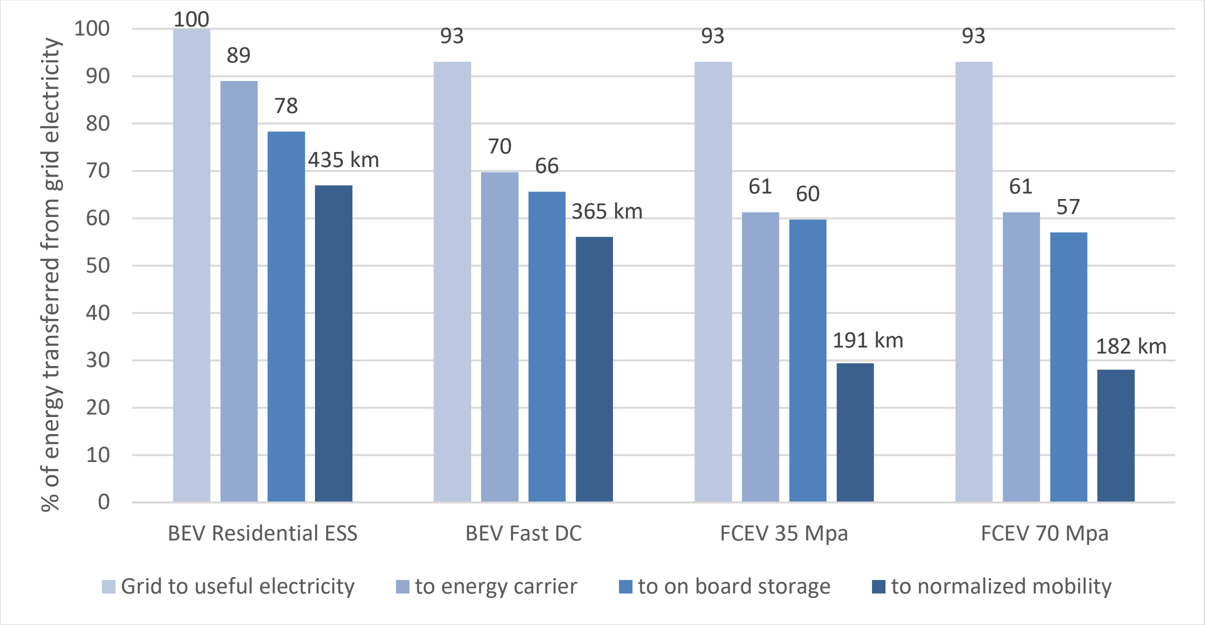

Figure 2 - Grid to mobility conversion efficiencies

### 4.3.1 Discussion

For all modes, most of the infrastructure losses occurs during the conversion from useful electricity to energy carrier. Refilling events (energy carrier to on-board storage) have a minor contribution in the overall efficiency. And finally, considering the on-board storage stage, the fast charging infrastructure for BEVs is only 15% more effective than HRS.

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, to depict likely investment decision of station operators.

Most of the difference observed in the final mobility service is due to the conversion occurring on-board the vehicle. For comparison, we can note that introducing 57 kWh of energy (FCEV 70 MPa case) in the form of gasoline in an ICEV will offer only 100 km of driving range (not mentioning that all upstream conversions are also energy intensive).

### 4.3.2 Sensitivity analysis

As highlighted in § 4.1 and 4.2, some of the major components of EV recharging 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 with this tornado chart.

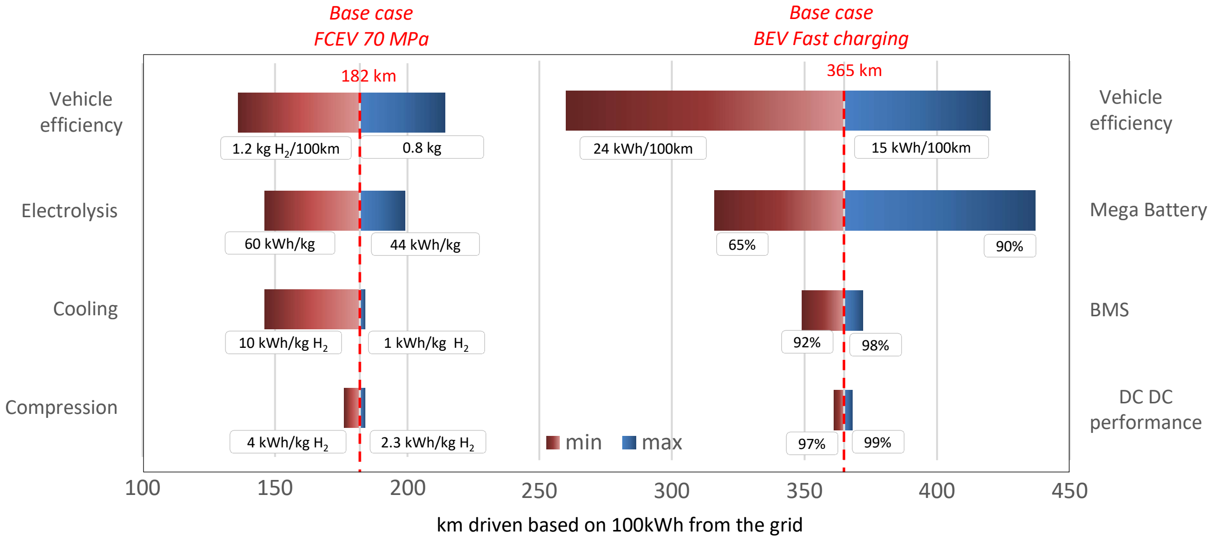

Figure 3 - Sensitivity analysis

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 is in an earlier stage of development than BEV and larger efficiency gains, especially on the vehicle side are expected. On the other hand, BEV market is going towards more range and larger vehicles, thus we can expect some increase in the energy consumption per kilometre. Additional phenomenon such as waste heat utilization and winter effect can heavily affect the energy consumption of BEVs [31] and cannot be observed with traditional tank to wheel approaches. Simulation results performed by Li *et al.* [32] show that with the heating system activated, the on-board storage to mobility efficiency of BEVs goes down from 73% to 45%, to compare with 46% down to 39% for FCEVs.

## 5 Conclusion

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 of the overall energy efficiency of electric mobility. The exemplary cases presented in this study show that only 57% to 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 production of the energy carrier is partially compensated by the fact that no stationary battery storage system is required, however, the final conversion occurring on-board the vehicle, within the fuel cell, cap 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, and develop realistic business case and pricing strategies for the various charging modes available. Grid scale equipments 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 renewable electricity sources and to go beyond the current green certificate approach. 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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## References

[1] “Battery Electric Vehicle Driving and Charging Behavior Observed Early in The EV Project.” [Online]. Available: http://papers.sae.org/2012-01-0199/. [Accessed: 02-Feb-2017].

[2] “SAE J2601. Fueling protocols for light duty gaseous hydrogen surface vehicles.” SAE International, Jul-2014.

[3] H. Hõimoja, A. Rufer, G. Dziechciaruk, and A. Vezzini, “An ultrafast EV charging station demonstrator,” in *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012 International Symposium on*, 2012, pp. 1390–1395.

[4] U.S. Environmental Protection Agency, “Find and Compare Cars.” [Online]. Available: http://www.fueleconomy.gov/feg/findacar.shtml. [Accessed: 03-Feb-2017].

[5] Union Pétrolière Suisse, “Rapport annuel 2015.” [Online]. Available: https://www.erdoel.ch/images/com_evdocs/ev_jb_2015_fr.pdf. [Accessed: 01-Feb-2017].

[6] M. Tsirinomeny, H. Hõimoja, A. Rufer, G. Dziechciaruk, and A. Vezzini, “Optimizing EV driving-recharge time ratio a under limited grid connection,” in *Power Electronics, Machines and Drives (PEMD 2014), 7th IET International Conference on*, 2014, pp. 1–6.

[7] M. Mayer, “From prototype to serial production - Manufacturing hydrogen fuelling stations,” presented at the A3PS Conference 2014, 2014.

[8] G. Parks, R. Boyd, J. Cornish, and R. Remick, “Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs : Systems Integration.” May-2014.

[9] C. J. B. Dicken and W. Mérida, “Measured effects of filling time and initial mass on the temperature distribution within a hydrogen cylinder during refuelling,” *J. Power Sources*, vol. 165, no. 1, pp. 324–336, Feb. 2007.

[10] R. Edwards, J.-F. Larive’, D. Rickeard, and W. Weindorf, “WELL-TO-TANK Report version 4.a: JEC WELL-TO-WHEELS ANALYSIS,” Publications Office of the European Union, EUR - Scientific and Technical Research Reports, 2014.

[11] U. Bossel, “Does a Hydrogen Economy Make Sense?,” *Proc. IEEE*, vol. 94, no. 10, pp. 1826–1837, Oct. 2006.

[12] J. Van Mierlo, G. Maggetto, and P. Lataire, “Which energy source for road transport in the future? A comparison of battery, hybrid and fuel cell vehicles,” *Energy Convers. Manag.*, vol. 47, no. 17, pp. 2748–2760, Oct. 2006.

[13] S. Campanari, G. Manzolini, and F. Garcia de la Iglesia, “Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations,” *J. Power Sources*, vol. 186, no. 2, pp. 464–477, Jan. 2009.

[14] C. E. Thomas, “Fuel cell and battery electric vehicles compared,” *Int. J. Hydrog. Energy*, vol. 34, no. 15, pp. 6005–6020, Aug. 2009.

[15] SAE International, “J1772: SAE Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler.” Feb-2016.

[16] “J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles - SAE International.” [Online]. Available: http://standards.sae.org/j2601_201003/. [Accessed: 14-Feb-2017].

[17] “Tesla Powerwall.” [Online]. Available: https://www.tesla.com/powerwall. [Accessed: 16-Jun-2017].

[18] LG Chem, “LG Chem ESS Products.” [Online]. Available: http://www.lgchem.com/upload/file/product/ESS_LGChem_ENG[0].pdf. [Accessed: 16-Jun-2017].

[19] H. Höimoja, M. Vasiladiotis, and A. Rufer, “Power interfaces and storage selection for an ultrafast EV charging station,” in *Power Electronics, Machines and Drives (PEMD 2012), 6th IET International Conference on*, 2012, pp. 1–6.

[20] D. Sbordone, I. Bertini, B. Di Pietra, M. C. Falvo, A. Genovese, and L. Martirano, “EV fast charging stations and energy storage technologies: A real implementation in the smart micro grid paradigm,” *Electr. Power Syst. Res.*, vol. 120, pp. 96–108, Mar. 2015.

[21] Idaho National Laboratory, “Vehicle Testing - Light Duty - Electric | Advanced Vehicle Testing Activity.” [Online]. Available: https://avt.inl.gov/fuel-type/electric. [Accessed: 02-Feb-2017].

[22] U.S. Environmental Protection Agency, “Fuel Economy of Vehicles.” [Online]. Available: http://www.fueleconomy.gov/feg/. [Accessed: 02-Feb-2017].

[23] D. Stolten and World Hydrogen Energy Conference, Eds., *Hydrogen and fuel cells: [fundamentals, technologies and applications ; contributions to the 18th World Hydrogen Energy Conference 2010, Essen]*, 2. Reprint. Weinheim: Wiley-VCH, 2011.

[24] T. Smolinka, M. Günther, and J. Garche, “NOW-Studie: Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien,” Fraunhofer ISE, 2011.

[25] D. Stolten, R. C. Samsun, and N. Garland, Eds., *Fuel cells: data, facts and figures*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA, 2016.

[26] S. Sprik, J. Kurtz, C. Ainscough, M. Jeffers, G. Saur, and M. Peters, “Hydrogen Station Data Collection and Analysis,” 2016. [Online]. Available: https://www.hydrogen.energy.gov/pdfs/review16/tv017_sprik_2016_o.pdf. [Accessed: 03-Feb-2017].

[27] T. Brown, S. Stephens-Romero, and G. Scott Samuelsen, “Quantitative analysis of a successful public hydrogen station,” *Int. J. Hydrog. Energy*, vol. 37, no. 17, pp. 12731–12740, Sep. 2012.

[28] Clean Energy Partnership, “Veröffentlichung der Projektergebnisse - Stand 01/2015.” [Online]. Available: https://cleanenergypartnership.de/fileadmin/Assets/user_upload/Veroeffentlichung_Projektergebnisse-11_4_NKBF98.pdf. [Accessed: 15-Feb-2017].

[29] A. Elgowainy and K. Reddi, “Hydrogen Fueling Station Pre-cooling Analysis,” presented at the 2015 DOE Hydrogen and Fuel Cells Program Annual Merit Review, 2015.

[30] WEH GmbH Gas Technology, “TK17 H2 70 MPa Datasheet.” [Online]. Available: http://www.weh.com/attachments/file/download/id/1490/. [Accessed: 02-Feb-2017].

[31] S. Karlsson, “The variation of BEV energy use and range depending on climate and driving conditions in Sweden,” presented at the European battery, Hybrid & Fuel Cell Eletric Vehicle Congress, EEVC 2017, Geneva, Switzerland, 2017.

[32] M. Li, X. Zhang, and G. Li, “A comparative assessment of battery and fuel cell electric vehicles using a well-to-wheel analysis,” *Energy*, vol. 94, pp. 693–704, Jan. 2016.

# Authors

Yorick Ligen holds an engineering degree from Ecole Centrale Paris and a MSc in Energy and Economics from ETH Zürich. After one year managing projects related to the commissioning and the installation of hydrogen refilling stations in Germany, he joined the doctoral program in energy at EPFL. In the group of Prof. Hubert Girault, he is currently developing a demonstrator for electric mobility infrastructure, including a redox flow battery, a fast DC charger, alkaline and PEM electrolyzers, compressors and dispensers for battery electric vehicles and hydrogen fuel cell vehicles.

Dr. Heron Vrubel received his PhD from EPFL in 2013 working in the field of electrocatalysts for the Hydrogen Evolution Reaction. He later joined the group of Prof. Hubert Girault as a post-doctoral research fellow. In 2014 he became responsible for the installation of a Demonstration site dedicated to new technologies for renewable energy production and energy storage. He is currently managing the Grid2Mobility project in the city of Martigny.

Prof. Hubert Girault studied in France and obtained his PhD in England. After 6 years as a lecturer at Edinburgh University, he was appointed in 1992 as Professor at the Ecole Polytechnique Fédérale de Lausanne. His research activities span from nano electrochemistry to megawatt electrochemical energy storage and he has supervised more than 60 theses. In 2015, his laboratory moved to the new EPFL campus in Valais. Overall, his group has published more than 500 articles and 25 patents. He is the author of 2 textbooks and currently Associate Editor for Chemical Science.

Dr. Veronique Amstutz graduated and obtained her PhD in EPFL, in chemistry and electrochemistry respectively. Her work focused on redox flow battery and water electrolysis research.