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Low demand solution for (sub)urban personal transport by a direct hybrid (fuel cell-supercapacitors) source

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Abstract

For urban or suburban transport, the power demand of a personal car does not exceed 30 kW/ton, far below the power offered by regular cars designed for any ride. Moreover, it was formerly shown that the above power could be attained by a 10 kW fuel cell directly hybridized to a supercapacitor string able to deliver a 20 kW power peak. This theoretical fact, corresponding to low resource demand in the car manufacturing, was validated up to ½ scale on the bench. Within a research project in University of Lorraine, the target is to validate the low-resource demanding concept in a real hydrogen electric vehicle (fuel cell range extender Renault Kangoo) and to examine related aspects by combining engineering sciences to social and human sciences and economics. After reminding the former validation on a bench, the paper describes current work on how the electrical power is managed in the Renault H₂ ZE Kangoo, by characterization of the fuel cell and thorough analysis of the transients of electrical and non-electrical variables available in the vehicle in various rides. Besides, risks and life cycle analysis of a one-ton hybrid vehicle have been evaluated in comparison with other 30 kW vehicles powered by either a fuel cell, or batteries or an internal combustion engine. Finally, social acceptability of the fuel cell cars by regular citizens is presented, revealing a positive opinion at fuel cells and hydrogen, however with a moderate readiness to its acquisition.

Keywords: Direct hybrid source; Fuel cell electric vehicle; Risk analysis; Social acceptability; Suburban transport.

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1- Introduction

Most electric (passenger) vehicles (EVs) are powered by large Li-ion batteries, with a power often in the range 60 - 120 kW. The high power range allows versatile rides on country roads or on motorways. The driving performances of such vehicles are however hindered by their restricted range, still under 300 miles for numerous models, and the time required in battery recharging: partial recharging of the battery in the high-power systems available on motorways can be achieved within half an hour, even though slower overnight recharging could be preferred for its higher durability. Alternative vehicles to EVs rely on the presence of a hydrogen fuel cell in the powertrain. For range extender vehicles, the modest fuel cell is set on to recharge the battery when its state of charge is estimated insufficient: the presence of the fuel cell and its hydrogen tank brings the vehicle an additional energy source to the Li-ion battery. On the contrary, in fuel cell - or hydrogen - electric vehicles (FCEVs), the powertrain results mainly from the presence of the powerful fuel cell (often over 120 kW) with a variable contribution of the battery; their significant hydrogen tank can allow them ranges over 500 miles. The fast refuelling makes the solution attractive, but most FCEVs are still at a cost in the order of 100 thousand Euros. Whatever the type of electric vehicle, they all exhibit too large power for urban and suburban rides, which represent for more than half of all journeys in Europe. Numerous vehicles, such as secondary personal vehicles, last-mile delivery vehicles, and even buses and trams, all being exclusively dedicated to urban and suburban rides, do not require such high range of power.

The power demand of a vehicle corresponds to its mechanical power P_{mech} at velocity v , considering the efficiency for conversion electrical power to mechanical power. Power P_{mech} is the sum of the variation of the mechanical kinetic and potential energies and the dissipation terms related to friction forces, as explained in former works [1, 2]. Because of the significance of (sub)urban rides in Europe, this calculation has been made for the case of the Renault Zoe with its characteristic parameters related to friction coefficient, drag coefficient and cross-sectional area, in the NEDC driving cycle profile emulating suburban transport in a flat area [3]¹. For the urban part of the cycle with velocity below 50 km/h, the power demand does not exceed 11 kW/ton vehicle, whereas for the final velocity peak at 120 km/h in the suburban section, the demand attains 30 kW/ton (Figure 1). Most EVs available on the market are presumably not suitable for low power-demanding driving in (sub)urban transport, while

¹ NEDC driving profile is more demanding than more recent WLTC1 and WLTC2 for mainly urban and suburban transport, but easier than higher velocity WLTC3 profile.

involving too much resources e.g. lithium in the batteries or platinum in the fuel cell: cheaper, less resource-demanding vehicles could be preferred for such transport mode.

Considering the potential market of non-stabilized speed vehicles, such as second family cars, busses, shared vehicles etc., it was planned to investigate the concept of a hydrogen electric vehicle with an undersized (30-40 kW) powertrain, with a lower amount of resources in its manufacturing and with an acceptable cost. Because of the frequent, sudden changes in the power demand in suburban transport, hybridization of the fuel cell by an energy storage system (ESS) - battery or supercapacitor – is known to allow a more efficient dynamics of the powertrain because of the slow response of fuel cells alone to power demand peaks. Besides, hybridization to an ESS would also permit partial recovery of the kinetic energy in deceleration or braking phases in the ride, as the fuel cell exhibits no power storage ability. In addition, the ESS is recharged by the fuel cell, and not by the grid.

The buffering action allowed by ESS is to avoid FC operation under idle conditions - at a voltage near the open circuit voltage, OCV - or on the contrary, at very high current density. In hybridized configurations, the middle-range power of the fuel cell with a more even profile, is to improve durability of the fuel cell. This has been often reported as for instance in [4 – 6]. Moreover, visible reduction in the hydrogen fed has been observed in most studies dealing with FC hybridization [1], [6, 7], regardless of the FC size and its hydrogen feeding system. This reduction although modest, is allowed by the fact that the presence of ESS can manage the transient changes in gas flow rates by the pneumatic control systems such as the compressor used for air supply, rendering unnecessary the usual excess in gases without hybridization. More importantly, it has been shown that the fuel cell could be undersized upon its hybridization to supercapacitors [5], [8, 9] or batteries [10 – 12]: appreciable reduction in the costs for the FC investment and maintenance as well as in the resources required in their manufacturing, can be expected for the same transport mission. Supercapacitors (SC) with their higher dynamics in the power storage and release, have appeared suitable for driving profiles with frequent changes in power demand as in urban or suburban transport, batteries being more appropriate for longer-distance or versatile rides. Besides, SCs do not contain Li and other critical metals massively present in batteries which represents an additional advantage.

Hybridization between the fuel cell and the ESS can be direct (or passive) or indirect (also active). In the first mode, the two components of the hybrid source (HS) are connected to each another without a current- or power-controlling system: therefore, their voltages have to match, taking into account the ohmic drop generated by the connection cable. In the second mode, the

voltage of one HS components is tuned to the level of the second component by use of a DC/DC converter. Thus, a converter can be inserted in the circuit downstream of the fuel cell, or after the battery. In other configurations, the two HS components are connected to their converter to form the hybrid source. Direct hybridization appears simpler since it does not involve the presence of converters between the HS components, thus avoiding the additional weights, volumes and costs induced by these converters. Related energy losses together with the often necessary temperature control of the converters, can also be avoided. However, for practical applications, in particular with batteries, most hybrid sources have still indirect configurations, for the sake of higher reliability and flexibility and safer operation [12, 13]. This important point is to be less significant by using supercapacitors (SCs), in particular because the linear relationship between their voltage and their SOC is to favor the power sharing with the fuel cell.

The paper reports on a research work conducted in view to operating an individual electric vehicle with a direct (FC-SC) hybrid source for urban/suburban driving (Hy2Car project, Nancy, France) on the basis of previous academic investigations [14]. In particular, it was there shown by simulation that for NEDC flat driving profile, a 10 kW fuel cell directly connected to 1 kWh SC strings allowing up to 20 kW would be a sufficient powertrain for a one-ton vehicle. Hy2Car project has aimed at proposing an alternative solution to personal transport with a modest energy, low local heat emissions by the undersized powertrain and at an expected reasonable cost. The overall project goes far beyond the development of a suitable powertrain, but to implement it in a real hydrogen vehicle and to examine related aspects of optimization and control of the powertrain, evaluation of hazards from and at the hybrid vehicle, its social acceptability (Are regular citizens ready to leapfrog to FCEVs when considering their next car acquisition?) and economic viability, and finally its life cycle analysis. Therefore, the Hy2Car consortium consists of 6 laboratories from University of Lorraine specialists of engineering, human or economic sciences (Figure 2).

For the “technical” completion of the project, it has been decided to validate the Hy2Car concept for this dedicated transport by thorough modelling of the powertrain and experiments in an electric vehicle, starting from the range extender electric H₂ ZE Renault Kangoo². The strategy adopted consists first in analyzing, measuring and modelling the existing Kangoo vehicle, then in achieving the necessary transformations in its powertrain and its energy

² This vehicle provided with a FC has no more been produced since early 2023.

management system. After the validation stage, a more suitable hybrid vehicle for suburban transport will have to be designed with a car manufacturing company.

The manuscript describes first the operation of the direct hybrid source in NEDC cycles at bench scale, with fuel cells varying from 50 W to 5.6 kW by model predictions and experimental data. Then, recent investigations in the various domains of the project and conducted on the basis of the Renault H₂ ZE Kangoo vehicle, are presented. After characterization of the FC-humidifier system of the H₂ ZE Kangoo vehicle and research on energy management in the vehicle, other investigations mentioned above have been undertaken in the project, namely, risk assessment of the Hy2Car concept, life cycle analysis of the vehicle and acceptability of FCEVs in France.

2 - Bench scale experiments with direct hybrid FC-SC sources

Numerous experiments have been carried out at bench scale to observe the potential of direct FC hybridization to SC strings in NEDC driving cycle protocol. The fuel cells used varied from single 100 cm² FC, short stacks of these cells, and larger stacks of different technologies with a power ranging from 1.2 to 5.6 kW. The size of SC strings was varied so that the maximum power drawn was equal or larger than that of the FC. The SC strings consisted of assembly of single Maxwell 3000 F 2.7 V elements.

First, a short stack of three 100 cm² FC cell (UBZM) was directly hybridized by 1 to 6 Maxwell SC elements to emulate the powertrain for a 6 kg vehicle in the NEDC driving cycle. Whereas simulations were conducted for various SC numbers, experiments were made with 1 and 3 SC only: in both cases, perfect agreement between model and experiments was observed [14] (data not shown).

The profile of the FC power was found to be nicely dampened by the assistance of a single SC element (Figure 3 left). In the first 13 minutes of the 20-minute cycle with low/moderate power demand, the fuel cell contributes actively to recharge the single SC as shown by the negative current peak of the SC peaks. In the second part of the cycle corresponding to suburban driving, the higher power demand is brought from the efficient power sharing between the FC stack and the SC, the SC contributing more than the FC in the three last power demand peaks of the NEDC cycle (Figure 3 left). For the 120 km/h peak with a 30 W/kg power demand, i.e. 180 W for the considered fictitious vehicle, the contribution of the FC was only at 69 W [14]. Hybridization of the short stack by a single 3000 F SC was shown effective but the state of

charge of the ESS varied by more than 30% over the cycle (data not shown). The 6 SC assembly directly connected to the 3-cell stack allowed the far more even contribution of the FC over the cycle: in the highest power peak, the FC stack contributed only to 32 W (Figure 3 right), the rest being supplied by the SC. In this strongly hybridized configuration, the transients of power demand are almost entirely covered by the SCs, while the FC contribution is even smoother which improves its durability. Besides, analysis of the SOC profile not shown revealed that the SOC of the capacitor strings varied by less than 5%.

Larger-scale tests were carried out with a 5.6 kW FC system consisting of 2 air-cooled Ballard FC stacks in series [3]. Each stack consisted of eighty 145 cm² cells. The SC string had a rated voltage at 145.8 V and an equivalent capacitance equal to 165 F. Considering partial recovery of the deceleration/braking power, the powertrain from the above direct hybrid source was shown by theory and practice, suitable to a fictitious 520 kg vehicle in the NEDC cycle in hour long tests. For the 120 km/h peak, the power peaking at 15.6 kW was covered by the FC (5.2 kW), the remaining part being supplied by the energy storage system (Figure 4). The ratio of the max. power demand over the max. power supplied by the FC was found at 3. This figure is very good agreement with previous experimental works with this driving cycle profile [5, 14] and models of direct FC-SC sources for one-ton passenger cars: completion of NEDC cycle should be possible with a 10 kW fuel cell hybridized by a SC string allowing a max. 20 kW power [14]. Besides, completion of the NEDC by the above FC alone is possible for a 183 kg vehicle only: hybridization of the FC allows a significant reduction in the fuel cell size for the same transport mission, as formerly reported. Here, because of the direct hybridization mode without converter in the hybrid source, the FC reduction factor could be also defined as the ratio of the vehicle weight with and without hybridization, i.e. 520 kg over 183 kg i.e. near 2.9.

The above ratio can be discussed in terms of hybridization degree (HD) proposed formerly for fuel cells hybridized with batteries or SCs [15] and defined as the ratio between the maximal power to be supplied by the ESS to the total power required for traction, here the power of the hybrid source:

$$HD = \frac{P_{ESS}}{P_{HS}} = \frac{P_{ESS}}{P_{FC} + P_{ESS}} \quad (1)$$

For the Hy2Car vehicle, HD would be near 70%. The powertrain in most hydrogen electrical passenger cars consists of a powerful fuel cell with a moderate size Ni-MH or Li-ion battery with a capacity in all cases (far) below 20 kWh [11, 15]. Altogether, HD criterion for passenger HEVs is usually below 20%. Similar comments can be made for hydrogen-fueled trucks driven

in long distance rides. On the contrary, for vehicles dedicated to shorter rides as in suburban areas, such as busses or utility vehicles for light transport or maintenance, the higher ESS contribution in the powertrain allows better management in the frequent changes in the power demand, also making it possible to recover the deceleration energy. In these vehicle categories, HD can thus vary from 20 to 70% [15]. In the present case, the HD is consistent with the high hybridization of the Hy2Car concept suitable for (sub)urban transport.

To conclude, the various experimental and theoretical work at different scales could validate the concept on a bench at ½ scale, all of this enabling the consortium to conduct further works more dedicated to the Hy2Car concept. Typical results of these works are presented below.

3- Current investigations related to the Renault H₂ ZE Kangoo

Five main investigations have been carried out in the area, as presented in this section.

3.1. Characterization of the fuel cell-air humidifier system

The fuel cell - humidifier system comparable to that in the Renault H₂-ZE Kangoo and shown in Figure 5a, was tested on a test bench for accurate characterization of its operation in the car: as for other components of the vehicle, the data obtained are to provide the values for the various parameters of this system. Because the fuel cell once installed on the bench could not benefit from the fluid cooling system of the Renault Kangoo vehicle, an in-house cooling system has been used to evacuate the heat produced. The fuel cell temperature in steady operations varied from 55°C at low current density (cd) to 65°C for the highest cd tested.

The fuel cell stack used for bench tests consisted of 70 cells approx. 200 cm² in area with metal bipolar plates, derived from the Genepac technology formerly developed by CEA in France. Whereas the fuel cell is operated in the vehicle at pressure level in the range 1.5-2 abs. bars, in dead-end mode at the anode, the valves at the fuel cell inlet and outlets were disconnected here to allow operation at pressure close to the ambient level and in continuous flow of hydrogen and air. Hydrogen was fed dry with a stoichiometric factor at 1.2. Dry air from the compressor ($\lambda_{O_2} = 2.5$), was humidified by capturing the humidity contained in the oxygen-depleted air leaving the fuel cell by pervaporation through the humidifier membrane separating the two gaseous streams. The humidifier formerly on the market, consisted of two chambers, approx. 35 mm high, 250 mm long and 258 mm broad, separated by the membrane: gases were circulated through the 113 channels 250 mm long and 1.14 mm wide.

The pressure drop in the FC cathodic chamber was found reasonable, attaining 170 mPa at 240 STP L/min (Figure 5 b), a flow rate value suitable for operation at 84 A. The voltage at individual cells was shown to be even within 10 mV in the stack, except for the 6 cells placed farthest from the gas inlets (Figure 5c). The stack voltage was measured at various current levels in 5 min. long chronopotentiometry tests, with replicate series of measurements. Corresponding power attained nearly 3.5 kW at 84 A (0.42 A/cm²) (Figure 5d); larger currents could allow power from the stack up to 4 kW. For the conditions considered, the individual cell voltage was in the order at 0.7 for current density from 0.1 to 0.25 A/cm², and was below 0.6 V for cd larger than 0.4 A/cm². From the profile of the variation, mass transfer control is already visible at this moderate cd value. The data obtained at ambient pressure and reported in Fig. 5d, were fitted to the usual law for the single cell voltage:

$$V = V_0 - r \cdot i - \frac{RT}{2F} \sinh^{-1} \left(\frac{i}{2i_{0a}} \right) - \frac{RT}{\alpha_c F} \sinh^{-1} \left(\frac{i}{2i_{0c}} \right) + \frac{RT}{F} \ln \left(1 - \frac{i}{i_L} \right) \quad (2)$$

where V_0 is the equilibrium voltage at T, r the specific ohmic resistance of the cell (0.05 Ohm cm²), i_{0a} and i_{0c} , the charge transfer exchange current density at the anode (0.5 A cm⁻²) and at the cathode (4.2 10⁻⁵ A cm⁻²) respectively, α_c , the charge transfer coefficient for O₂ reduction (0.5) and i_L is the limiting current density at the cathode (0.6 A cm⁻²).

Besides, cooling of various gas streams in the system, collection of the water recovered and mass balances indicated that the air injected to the fuel cell has a relative humidity near 60%, whereas the gases leaving the cathode chamber were nearly saturated. More accurate results should be allowed after implementation of dual temperature-humidity probes in the system shown in Figure 5a.

Although stable and reproducible, the performances of the fuel cell on the bench were only moderate. This is certainly caused by the ambient pressure level in the FC: operation in higher pressure as in the Renault H₂ ZE Kangoo vehicle should significantly improve the power from the stack. Such conditions, also with dead end mode for the anode, will soon be investigated, yielding the various electrochemical and physical parameters of the (FC-humidifier) system present in the existing vehicle.

3.2. Energy management of the direct hybrid source in the vehicle in suburban transport

Contrary to the ideal situation of standard driving profile e.g. NEDC where FC and SCs perfectly share the power demand of the vehicle, in a real vehicle the driver may decide on the

ride and how fast to drive, taking into account the power of the car engine, the speed limits and the traffic conditions. Because of the modest size of the fuel cell, and to a larger extent – the restricted energy content of the SCs, in the order of 1 kWh - Hy2Car vehicle cannot be driven blind. As a matter of fact, Hy2Car driving will have to be partly guided online by an energy management system (EMS) of the two HS components for the sake of a safe ride, i.e. with a balanced power sharing. The role of this system to be developed, is thus to anticipate the energy demand over the ride and to manage the state of charge of the SC's: online connection to global positioning system (GPS) is thus necessary. The ride would thus have to be pre-defined by the driver and the EMS could decide or suggest recommendations on the optimal driving of the vehicle. Through optimization of the EMS, and upon possible slight changes in the FC or SC dimensioning, more flexibility in the ride – in case of unexpected changes in the ride – would also be possible.

Aside work on the elaboration of computational tools - hard and soft – for energy management of the powertrain, “serious” games being real-time adaptative on board computers or networks, are currently under development. The games with online indication of velocity, location and elevation, distance and levels of SOC and H₂ amount in the car, are periodically shown in dedicated communication events to present the Hy2Car concept to the public, making them aware of driving with this sober vehicle with its restricted energy. These games benefit from the ongoing progress of the model for the embarked powertrain. Up to now, models are constructed on the basis of electrochemical and electrical data gained in previous bench-scale operation of 5 kW fuel cells, with or without supercapacitors strings. Such tools once fully developed, could be implemented for driver recommendation or for sizing of the Hy2car vehicle according to the most frequent kind of journey.

For completion of the dual-tool task, it is first required to characterize accurately the powertrain of the original Renault H₂ ZE Kangoo by numerous tests, to record the time variations of the available - electrical or not - variables in a given ride and to interpret these data using previously developed models for the fuel cell, battery and traction of the vehicle. These parameters are to be injected in the models both in the office computer or in the game.

Acquisition and treatment of data in the H₂ ZE Kangoo under operation

The existing E-car is provided with an OBD-II multichannel plug in the car cabin allowing monitoring of numerous variables in the vehicle and to establish online diagnosis of the car main components. Using the dedicated software with a Klavlar© device connected to the OBD-II plugs, data can be recorded at a frequency near 20 Hz. Various types of data can be recorded:

the data are related to (i) the vehicle performance e.g. velocity or engine torque, or (ii) the braking system, (iii) the battery operational conditions namely current and voltage, state of charge and state of health, (iv) heating and air conditioning, (v) monitoring of the engine operation. All the collected data are indexed by the time and the vehicle position (including elevation). The recorded data in the form of text files could easily be used in usual programming languages.

Rides of various types, lengths and slopes have been tested up to now without the contribution of the fuel cell: the vehicle was then a regular battery vehicle. Variations of the current and the battery voltage could be followed as exemplified in Figures 6 and 7, here for urban driving. In the ride section shown in Figure 6, the battery current rapidly increases in acceleration phases - such as times 104 and 116 s - with accordingly faster decrease in SOC. In some parts of the section, battery recharging can be observed in braking phases together with downward slopes as for instance between 80 and 100s. The complete ride around the test platform considered in Figure 7 was completed with measurement of elevation profile. In the steep upward slope in the ride as between 250 and 275s, the high power demand is shown by the sharp current peaks, with the steeper decrease in the battery SOC. Recharging of the battery in downward slopes could not be observed in Figure 7 because of the lower slope value in the ride: the battery current then very small, kept nevertheless its polarity and the state of charge remained nearly constant. Besides, the negative voltage peaks are related to the positive peaks of the battery current I_b , as can be expected from its decreasing relationship with I_b . Because battery voltage V_b can be expressed as a function a function of SOC and I_b owing to (modest) ohmic drop and electrode overpotentials, the various data with moderate or significant change in current and SOC will be treated for estimation of the electrochemical parameters involved in the V_b vs. I_b relationship. The model for the battery, although irrelevant for the Hy2Car vehicle, is required for accurate modelling of the original Renault H₂ ZE Kangoo.

The main steps currently covered in this project part are: (i) implementation of a packaged data acquisition system to be disconnected after acquisition for remote data transfer, (ii) calibration of the physical models for the genuine Renault H₂ E-Kangoo, and for the planned hybrid (FC-SC) vehicle, (iii) Use of 3D data from “Grand Nancy” community for simulation of the rides in the area.

3.3. Process safety methods applied to risk assessment of the Hy2Car concept car

Basically, the Hy2Car concept is a hybrid electrical vehicle to be equipped with a moderate fuel cell and supercapacitor strings. Two main sources of hazards can be identified, namely (i) the fuel cell together with the hydrogen tank, and (ii) the supercapacitor strings with its electrolytic solvent. In the current version of the project on the basis of a one-ton vehicle, the fuel cell had a 10 kW (2x5 kW) rated power and the hydrogen storage was twice that of the H₂ ZE Kangoo i.e., with two 74 L cylinders at max. 350 bars. Maxwell supercapacitors (3000 F, rated voltage at 2.7 V) were used for energy storage in the car. The electrolytic medium impregnating the separator was an acetonitrile solution of tetraethylammonium tetrafluoroborate, and the electrodes consisted of activated carbon supported by an aluminium sheet acting as the collector. As in most other comparable investigations, the case of interest was compared to two reference vehicles with the same weight (1 ton) and overall power (30 kW): one was a conventional diesel ICE vehicle, the second one a 30 kW FCE vehicle.

For this preliminary investigation, two methods were successively employed. First, Preliminary Hazard Analysis (PHA), including feedback analysis of recent dramatic events, has been conducted. Secondly, Fire and Explosion Index (F&EI) method was used to quantify the potential fire and explosion risk of a process and its content, as described in [16, 17] for hydrogen-based processes.

PHA leads to identification of several failure modes during the life phases of the various systems. PHA could notably reveal that FC vehicles are presumably not of a more dangerous driving than regular vehicles [18, 19]. Indeed, failures related to the on-board fuel cell and hydrogen storage have relatively low probability of occurrence as explained below. For hydrogen storage, leak rate from the tank is near $3 \cdot 10^{-6} \text{ h}^{-1}$ whereas rupture of piping or valves are a thousand times lower [18]. The most likely event resulting from a crash (likelihood over 98%) is material damage to the car without additional hazard related to hydrogen [19]. Besides, the estimated frequency of jet fire of hydrogen issuing from the safety valve upon leak or ignition, is around $5.5 \cdot 10^{-5}$ per car per year, with consequences comparable to those encountered in approx. 2% of accidents with ICE vehicles [18].

The risk level related to maintenance activities does not seem to be increased by the presence of hydrogen, which may seem counter-intuitive [20]. As a matter of fact, high-risk activities encountered when repairing FCEVs are, for instance, occurrence of an electric shock, the generation of electrostatic discharges when grounding the hydrogen circuit, hydrogen tank leak and generation of explosive atmospheres. However, high-risk activities associated with conventional vehicle repairs, such as exposure to harmful substances (e.g., asbestos,

combustion gases), oxyacetylene welding or resistance welding, have a risk score (combination of frequency and severity) which is generally higher than those determined for fuel cell vehicle maintenance [20].

PHA as well as the feedback analysis, has stressed the importance of considering the refuelling phase in the risk assessment. Indeed, several accidents already occurred during such phase, as for instance in 2008 and 2010 in the USA, upon equipment failure leading to explosion [21]. A comprehensive study of incidents/accidents occurring in refuelling stations carried out by [22], demonstrated that such events were mainly the fact of failures caused by design error with insufficient planned fatigue of screw joints and flanges. A complementary risk analysis based on Dynamic Bayesian Network including technical failures and human error in the design, demonstrated that the probability of a hydrogen leak followed by an explosion in refuelling stations is approximately 1.10^{-4} year⁻¹ (Wang and Gao 2023 [23]), which is only ten times larger than the frequency of tank truck rupture according to the National Institute for Public Health and the Environment of Netherlands). More recent feedback in 2019 (Gangneung, South Korea and Sandvika, Norway) confirmed the above causes of tragedy. Another situation is the case of H₂-based prototypes whose technology is not fully mature, thus more prone to failure and sometimes to explosion as in June 2023 in Naples at a solar-aided prototype car.

PHA has also been performed on SCs, taking into account the risks related to both chemicals and operating conditions. The main hazardous substance is volatile acetonitrile, whose vapours may be ignited or decompose into hydrogen cyanide and other toxic gases when exposed to an intense heat source. Therefore, specific precaution should be taken to avoid leaks. More generally, SCs are designed to work under temperature conditions ranging from -25 to 70°C. Extreme weather or operating conditions, can lead to the supercapacitor overheating [24], which may even lead either to the capacitor deformation or to the rupture of the safety vent with leakage of toxic/flammable gases. Such risks are largely reduced by using solid-state electrolytes. Although some car models rely on SCs e.g. Lamborghini Sian or Extrem Hybrid, no experience feedback on accidents involving such equipment has been reported up to now.

Based on the PHA conclusions, Fire and Explosion Index method was then used to highlight the risks associated to such phenomena. In this method, risk factor F₃ includes all the factors contributing to the occurrence of fires and explosions. F₃ is therefore calculated as the product of two hazard factors F₁ and F₂, F₁ representing the general process hazards with a series of penalties for each item, and F₂ being related to the specific risks in the processes, namely the physical and chemical conditions in the process under operation. The fire and explosion index

(FEI) was calculated by multiplication of risk factor F_3 by material factor MF related to the species or material considered, here hydrogen, acetonitrile or diesel fuel. Refuelling and driving situations were considered in the analysis. It should be stressed that this risk assessment tool was designed for large facilities, thus perfectly suited to industrial equipment handling or storing more than 1,000 lb (i.e., 454 kg) of flammable materials, which is the case for refuelling facilities but obviously not for the vehicles. In the latter case, the use of FEI is relevant for comparison, but will overestimate the risk.

As shown in Figure 8, the diesel ICE vehicle exhibits the lowest hazards factors and indexes in both modes (refuelling or driving), except for F_1 factor, which is due to a higher risk of spillage [17]. As already shown by PHA, the refuelling phase exhibits a higher risk than the driving phase for Hy2Car hybrid car and the FC vehicle. For both vehicles, FEI reaches 130 whereas that of the diesel ICE vehicle attains only 35. The difference in risk levels between the three vehicles during the driving phase is much smaller. It should also be kept in mind that only fire and explosion risks are studied by this method, and that FEIs tend to be overestimated for small quantities of fuel. The high hazard factors and indexes for hydrogen-based vehicles are the fact of the high MF value for hydrogen ($MF = 21$). Hy2Car vehicle contains less hydrogen than the considered FC vehicle but the additional presence of acetonitrile ($MF = 16$ owing to its low boiling point, high flammability and toxicity – Table 1) represents an appreciable secondary hazard source, in particular in driving.

FEI method allows a couple of immediate recommendations to be made. In addition to recommendations related to hydrogen presence, it is strongly recommended to define the SC location in parts of the vehicle with the lowest risk of mechanical shocks, and to monitor the temperature in the vicinity of the SC strings as well as the acetonitrile leaks and the solvent evaporation rate. It might be also envisaged to use others SCs with more viscous solvents such often-used propylene carbonate [25] or even ionic liquids. An additional analysis was performed by considering alternative solvents (Table 1) and material factors based on mass percentages [26], instead of using a conservative approach by choosing the maximum MF i.e., 21. By using propylene carbonate instead of acetonitrile, MF can be reduced by 10% and even by 60% by using γ -butyrolactone (G.B.L) [27, 28] with higher flashpoint and reduced health hazard (Table 1). Moreover, acetonitrile substitution by γ -butyrolactone decreases F_2 factor by diminishing both toxic materials and storage criteria (Table 2) which lowers the global risk to an acceptable level.

Besides, the preliminary work presented here has to be followed by HAZOP (HAZard and OPerability) studies to better understand the failure modes and complemented by the application of inherent safety principles to avoid hazards and to reduce risks at source.

3.4. Life cycle analysis of the Hy2Car vehicle

An initial assessment of the potential environmental impact of the fuel cell/supercapacitor/hydrogen tank system was carried out by comparison with a Li-ion battery, both fitted to a vehicle with the same specifications. The hybrid vehicle considered was equivalent to that investigated in section 3.3. The life cycle assessment was carried out in accordance with ISO 14040 standard, using SIMAPRO 9.1 software and the Ecoinvent 3 database. CML procedure was used to estimate the various environmental impacts caused by the chemicals involved in the object or the process. The Li-ion battery inventory was adapted from [29]: as the battery is assumed to be manufactured in China from Chilean lithium, the geographical origin of the data corresponds in descending order of preference to China, RoW (world excluding Europe), GLO (world) and RER (Europe excluding Switzerland). The supercapacitor inventory is the result of a compromise between data from the manufacturer (Maxwell) and ref. [30]. Due to lack of data, the energy requirement for the supercapacitor production has not been accounted for. As no quaternary ammonium salts could be found in the Ecoinvent database, it has been replaced by a generic tertiary amino compound. The inventory for the two hydrogen tanks (2x30 kg) was taken from [31].

The CML impacts of the hybrid FC-SC vehicle were calculated with reference with those of a Li-ion vehicle, normalized to unity when the hybrid vehicle had a lower impact than the BEV. Else, the impact of the hybrid vehicle was set to 1, and that of the Li-ion vehicle was normalized accordingly. From the manufacturing point of view (Figure 9), the Li-ion battery presents higher impacts than the equivalent system composed of two 5 kW fuel cells, a 1-kWh supercapacitor (allowing a max. power at 20 kW) and two 74 L hydrogen tanks weighing 30 kg each. The copper-based collector is the most impacting element of the Li-ion battery from the point of view of the global warming potential (39%) and of the abiotic resource depletion (42%). CML impacts related to toxicity in the HyCar vehicle are significantly lower than that of the battery vehicle, presumably because of the absence of lithium and without side formation of toxic, hazardous chemicals during its production. The platinum-based catalyst is the most impacting element for the fuel cell / supercapacitor system, as it contributes by 75% to the abiotic resources depletion indicator and by 44% to the global warming potential. Although

visible, the Pt impact in the Hy2Car vehicle is far lower than that estimated for a regular HFCV, because of the far lower fuel cell power and amounts of platinum involved in our vehicle.

3.5. Acceptability of fuel cell electric vehicles: social representation of FC and FCEVs

The Hy2Car project is no ordinary "development" of fuel cell cars, as it aims to provide a specific transport solution for cities and suburbs. Although fuel cell cars make a modest contribution to personal transport, they are a means of transport in the making, are part of the energy transition and can provide a partial solution. With this in mind, it seems essential to investigate the way in which citizens, potential users of FCEV perceive this means of transport. Better knowledge of people's representations of the fuel cell and its use in a means of transport are to enable to identify their point of view and also to understand the determinants of this perception.

Social representations are common sense knowledge [33]. They are socially developed, shared and they orient human behaviors. A three-component model [34] emphasizes the role of knowledge, experience and involvement in their development. Because the impact of each of these dimensions on social representations has been shown in numerous studies as in [35], this theoretical framework has been used as the background for the study. However, social representations can be studied through research related to attitudes and behaviors [36, 37]. In addition, since the Hy2Car project aims to offer a specific transport solution for cities and suburbs, we felt it necessary to take into account research on attitude and behavior related to environment [38]. Finally, as this project is linked to the energy transition involving a variety of stakeholders, it was appropriate to pay attention on research on confidence in researchers, industrials and politicians [39, 40]. These theoretical backgrounds helped to draw up a questionnaire. It began with a short introduction on FC and its functioning, then present the study purpose, namely to collect people's opinion on fuel cells.

3.5.1. Methodology

Variables

Various socio-demographic variables were considered as independent variables, such as gender, age, car ownership (no vs. yes), number of kilometers travelled per month, and area of residence (rural vs. urban). Two other variables i.e. knowledge about the FC and pro environmental involvement, were added. We distinguished between so-called 'objective'

knowledge acquired through learning (reading, teaching) measured for instance with a score-based quiz, and estimated knowledge, i.e. the subjective (individual/personal) estimation of the level of knowledge.

Participants

311 students and non-students (158 women, 152 men, 1 unknown), with an average age of 25.7 years ($SD = 7.73$) completed the survey. 187 of them owned a car and travelled on average 905 km per month.

Measures

Osgood scale from 1 to 7 was used in the various questionnaire items.

Participants' level of knowledge about fuel cells was first measured in the questionnaire with a quiz containing 9 statements: each statement had to be judged true or false, scoring one point for each question they answered correctly.

Nine items assessed afterward their involvement in environmental issues with scores from 1 for "it's essential" to 7 "it's unimportant". Thirteen items were then proposed to measure the possible actions that participants would be ready to promote the FC, from 1 "I would certainly not do it" to 7 "I would certainly do it". Three items were after proposed to estimate their level of knowledge on scales ranging from 1 - no knowledge - to 7 for significant knowledge on fuel cell, electric and conventional cars. Five sentences were afterward aiming at measuring the level of confidence in researchers, the government, oil companies, the car industry and local councilors, from 1 (not at all) to 7 (entirely). Participants were also asked to evaluate on the same scale, if these different targets were competent to make objective judgements on risks and benefits of fuel cells and finally to express whether they thought they would take their personal interests into account. Participants were then asked to give their opinion about using a car with a fuel cell with three 7-point Osgood scales (e.g. "good-bad", "interesting-without interest", "negative-positive"). Finally, five items related to the perception of the risks related to the use of fuel cells and fuel cell vehicles, were to be assessed with score from 1, "not at all" to 7 "entirely".

3.5.2. Results.

Descriptive, inferential and correlational statistics and structural equation modelling were performed using SPSS 26 software. A principal component analysis was carried out on the responses enabling the related items to be classified according to 8 dimensions.

Representations of the fuel cell car

Overall, the 311 participants have a fairly positive opinion of the fuel cell car (88%) and 12% a fairly negative opinion. However, it appears that men ($M = 5.61$, $SD = 1.15$) have tendentially a better opinion than women ($M = 5.15$, $SD = 1.47$; $t(308) = 1.870$, $p = .062$, where M is the arithmetic mean, SD the standard deviation, t , the Student parameter at 95% and p the complement to unity of the probability). The assessment of the risks associated with the fuel cell car is more shared between the two genders. In fact, its use was estimated rather risky (41% vs. 31% who thought it was not so, while 28% did not express). Moreover, accidents with a FCEV are viewed as more dangerous than with an ICE vehicle (52% vs. 38% respectively) while 10% of participants have no real opinion. For this last item, gender was found to have an impact on risk perception since compared to men, women ($M = 3.21$, $SD = 1.44$) felt that an accident with a FCEV was less risky than with an ICE vehicle ($M = 2.77$, $SD = 1.725$; $t(305) = -2.403$, $p = .017$). Finally, are French citizens ready to FC cars? The answers are fairly well balanced with 30.5% surveyed people considering to buy a FC car, 33.2% not intending to buy a hydrogen vehicle (Figure 10), the others (36.3%) having no definitive point of view about their next car acquisition.

Knowledge about fuel cell cars

Using comparative analysis, knowledge emerged as the most important factor in favor of the fuel cell. The higher the level of objective knowledge, the more positive the opinion of the fuel cell ($\beta = .211$, $t = 3,800$, $p < .001$) where β is the value of the probability distribution. Similarly, the greater the level of estimated knowledge, the more positive the opinion of the FC car ($\beta = .254$, $t = 4,602$, $p < .001$). It moreover appears that the greater the objective knowledge, the greater the behavioral intention to become informed ($\beta = .131$, $t = 2.325$, $p = .021$), the greater the behavioral intention to promote the FC ($\beta = .140$, $t = 2.484$, $p = .014$), the greater the perception of the risk of using a fuel cell vehicle ($\beta = .153$, $t = 2.666$, $p = .008$).

Environmental involvement

Participants' environmental involvement and pro-environmental behavior had little effect on their representation of the fuel cell car. They only had an effect on the intention to buy via the intention to promote.

Factors facilitating or moderating purchase intention

In order to identify the factors that influence the decision to buy (or not) a fuel cell vehicle, a general model has been built up with the following dimensions: confidence in oil and car

companies, in politicians, in researchers, behavioral intention to promote the fuel cell vehicle, intention to obtain information about it, general opinion about the fuel cell vehicle, pro-environmental behavior and environmental involvement. Only the dimensions with a significant effect are shown (Figure 10). It appears that trust and environmental involvement initiate other dimensions, while attitudes (opinions and behavioral intentions) have direct effects on the decision to buy or not to buy a FCE vehicle.

To refine this result, this model was split according to the valence of the purchase intention: yes vs. no. However, the number of participants with a strong purchase intention was too low ($N < 100$), so the modelling could not be carried out. Modelling on participants who had no intention of buying a FCEV (Figure 11), on the other hand, highlights the absence of the opinion factor in the model. This result tends to confirm the discrepancy with our descriptive results. In other words, people are favorable to the FCEV, but this favorability depends on factors other than a priori opinion and does not systematically lead to an intention to buy one.

4- Conclusion

Technically speaking, vehicles dedicated to (sub)urban transport could be designed with an approx. 30 kW/ton powertrain consisting of a 10 kW fuel cell directly hybridized to 1 kWh SC string allowing a maximal 20 kW power. Validation of the concept in a real electric car is in progress, with the electrochemical investigation of the car fuel cell and the energy management of the pristine range extender vehicle. After gaining better knowledge on the vehicle bus CAN and the ECUs added in the implementation of the fuel cell, the energy management of the existing range will be understood and modelled using the parameters estimated in characterization steps of the fuel cell, the battery and the SC string. The battery will later be disconnected from the powertrain and operated only as the vehicle auxiliary power unit (APU), while the hybrid source dimensioned for a 1.5 tons vehicle will be connected to the engine inverter.

Analysis of the risk from the vehicle indicates the dual hazard in refuelling and driving from the presence of both hydrogen and acetonitrile, a very volatile solvent. However, leak and evaporation risks of the solvent could be largely reduced by using heavier solvent-containing SCs. More accurate risk assessment will be obtained by combining the presented data to the results of HAZOP investigations. Life cycle analysis of the (FC-SC) hybrid vehicle is in overall more positive than that of Li-ion battery EV, also because of the 5 to 10 times lower Pt amount in the powertrain, in comparison to that in regular FCEVs. Analysis of the social representation

of hydrogen and fuel cells for transport, indicated a very positive opinion of both of them from citizens, however with a much more balanced willingness to buy a FCEV as the next vehicle. Further investigations in this social aspect will focus on the hybrid nature of Hy2Car, its far lower resource amount involved, together with its dedicated use in (sub)urban rides and its performance limits.

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Table 1: Properties of various solvents used in supercapacitors. n.i.a: no information available

Material	Properties	Boiling Point (°C)	Flash. Point (°C)	Auto Ign. T (°C)	LEL (%v.)	UEL (%v.)	NFPA rating and MF			
							NR	NF	MF	NH
Acetonitrile		82	2	524	4.4	16	0	3	16	3
Ethylene Carbonate		243	143	435	3.6	16.1	1	1	14	2
Propylene Carbonate		240	116	430	1.8	14.3	1	1	14	2
Butylene Carbonate		240	121	421	n.i.a.	n.i.a.	1	1	14	2
γ -Butyrolactone		204	98	435	1.4	16.1	0	1	4	1

Table 2: Fire and Explosion Index classification for Fuel-Cell/Supercapacitor vehicles

Substance/Process Unit		FC-SC Acetonitr.	FC-SC Propyl. C.	FC-SC G.B.L.
Material Factor MF (based on mass percentage)		16.63	14.88	6.14
State of Operation		Driving		
1. General Process Hazards	Penalty Factor Range	Penalty Used	Penalty Used	Penalty Used
Base factor	1.00	1.00	1.00	1.00
A. Exothermic factor	0.30 to 1.25	0.5	0.5	0.5
B. Endothermic factor	0.20 to 0.40			
C. Material Handling and Transfer	0.25 to 1.05			
D. Closed Processing Unit	0.25 to 0.90			
E. Access	0.20 to 0.35	0.35	0.35	0.35
F. Drainage and Spillage Control	0.25 to 0.50			
General Proc. Hazards Factor (F1)		1.85	1.85	1.85
2. Special Process Hazards				
Base Factor	1.00	1.00	1.00	1.00
A. Toxic Materials	0.20 to 0.80	0.6	0.4	0.2
B. Sub-Atmo. Pressure	0.50			
C. Operation in or near Flammable Range				
C1. Tank Farms Storage Flammable Liquids	0.50	0.5	0.3	0.3
C2. Process upset/purge fail.	0.30			
C3. Always in Flam. Range	0.80			
D. Dust Explosion	0.25 to 2.00			
E. Pressure	0.16 to 1.95	1.2	1.2	1.2
F. Low Temperature	0.20 to 0.30			
G. Quantity of Flam. Material				
G1. Liquids/Gases: Process				
G2. Liquids/Gases: Storage		0.15		
H. Corrosion and Erosion	0.10 to 0.75			
I. Leakage – Joints & Packing	0.10 to 1.50	0.1	0.1	0.1
J. Use of Fired Equipment				
K. Hot Oil Heat Exchange Sys.	0.15 to 1.15			
L. Rotating Equipment	0.50			
Special Proc. Hazards Factor (F2)		3.55	3.00	2.80
Process Unit Hazards Factor (F1x F2) = F3		6.57	5.55	5.18
Fire and Explosion Index = F3xMF		109.26	82.58	31.81

Table 3: Inventory for the supercapacitor strings

Name	Provider	Quantity
Acetonitrile	Acetonitrile, market for (GLO)	23.5 kg
Carbon	Activated carbon, granular, market for (GLO)	17.6 kg
Quaternary salt	Chemical, organic, market for (GLO)	11.8 kg
Aluminium	Aluminium, wrought alloy, market for (GLO)	49.5 kg
Paper-joint	Graphite paper, 100% recycled, market for (RoW)	15.3 kg
1-kWh supercapacitor		108 kg

Table 4: Inventory for the fuel-cell

Name	Provider	Quantity
Nafion membrane	Inventory from [32]	0.08 kg
Carbon for electrode	Inventory from [32]	0.55 kg
Platinum	Platinum, market for (GLO)	0.006 kg
Silicone gaskets	Silicone product, market for (RER)	0.31 kg
Bipolar plates	Titanium, primary, market for (GLO) + metal working, average for metal working manufacturing (GLO)	1.39 kg
Terminal plates	Aluminium, wrought alloy, market for (GLO) + metal working for aluminium product manufacturing	1.40 kg
Various steel pieces	Steel, chromium steel 18/8, hot rolled, market for (GLO) + metal working, chromium steel product manufacturing (GLO)	1.70 kg
5-kWh fuel-cells		2x5 kg

Figure captions

Figure 1: Variation of the car velocity and power demand for a vehicle with Renault Zoe specifications for the NEDC driving profile.

Figure 2: Research investigations in the whole Hy2Car project to be conducted in addition to the development and control of the direct hybrid (FC-SC) powertrain.

Figure 3: Simulated power demand and its distribution in a fictitious 6 kg vehicle in the NEDC driving profile with a direct (FC-SC) hybrid source: left, three 100 cm² FC and one 3000 F SC; right, three 100 cm² FC and six 3000 F SC. Experiments conducted with the left hybrid source validated the simulation.

Figure 4: Simulated and experimental power demand and its distribution in a fictitious 520 kg vehicle in the NEDC driving profile with a direct (FC-SC) hybrid source (5.6 kW FC, 10 max. kW SC)

Figure 5: a) Fuel cell-air humidifier system used on the test bench; b) Pressure drop in the cathode chamber versus the air flow rate; c) distribution of single cell voltage in the stack from the back side of the cell, i.e. farthest from the gas inlets; d) experimental variations of the stack voltage and power with the current density. All measurements made at pressure close to ambient, $\lambda_{O_2} = 2.5$, $\lambda_{H_2} = 1.2$.

Figure 6: Section of a ride in urban area with profiles of car velocity, battery current and state of charge. Negative current corresponds to the battery recharging, and positive current is for its discharging.

Figure 7: Ride around the test platform with profiles of car velocity, battery current and state of charge, voltage and elevation. Figure du haut: revoir titres aux axes des ordonnées (enlever right, dans la légende, à côté de SOC %). En fait, la figure avait été revue, no worry

Figure 8: Hazard factors F_1 and F_2 with Fire and Explosion Index (FEI) for the three vehicles compared in refuelling or in driving mode.

Figure 9: Normalized CML impacts for the manufacturing of the Li-ion battery and the fuel-cell and supercapacitor system

Figure 10: Structural equation-based model for intention to buy an FCEV or not. Possible covariances: confidence in scientists, companies and politicians. The values are weighing parameters for the significance of the effect

Figure 11: Structural equation-based model of factors leading in not to buy an FCEV. Possible covariances: confidence in scientists, companies and politicians. The values are weighing parameters for the significance of the effect

Figure 1

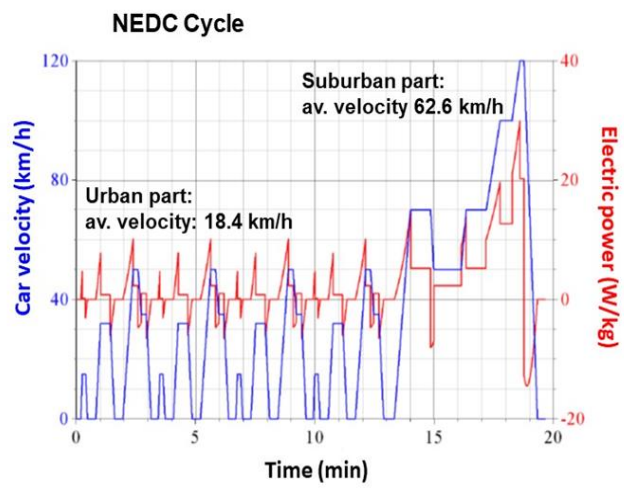


Figure 2

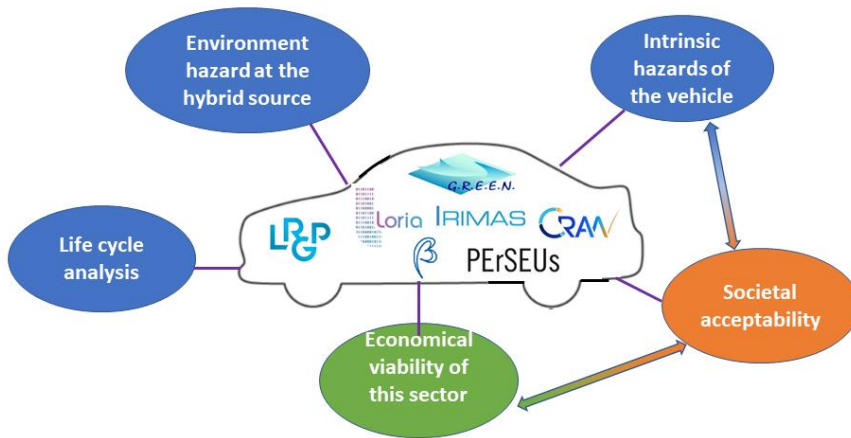


Figure 3

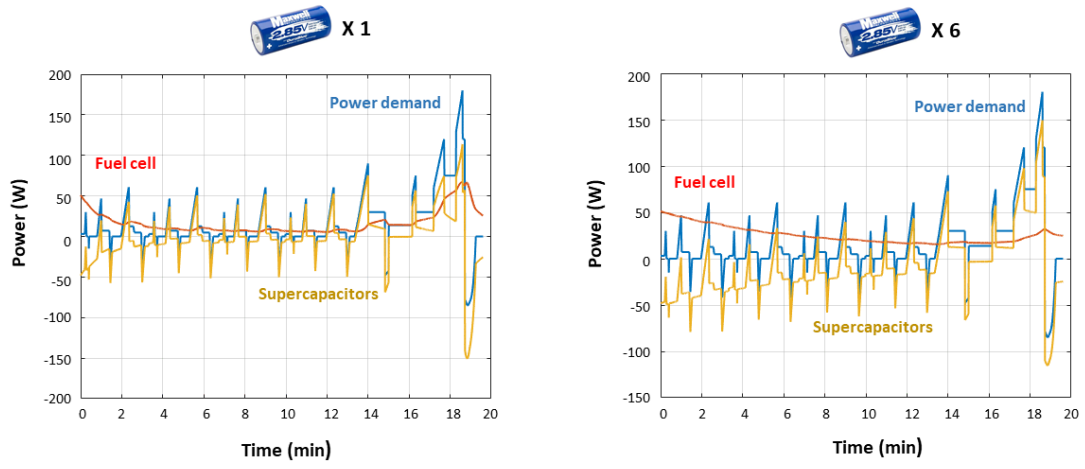
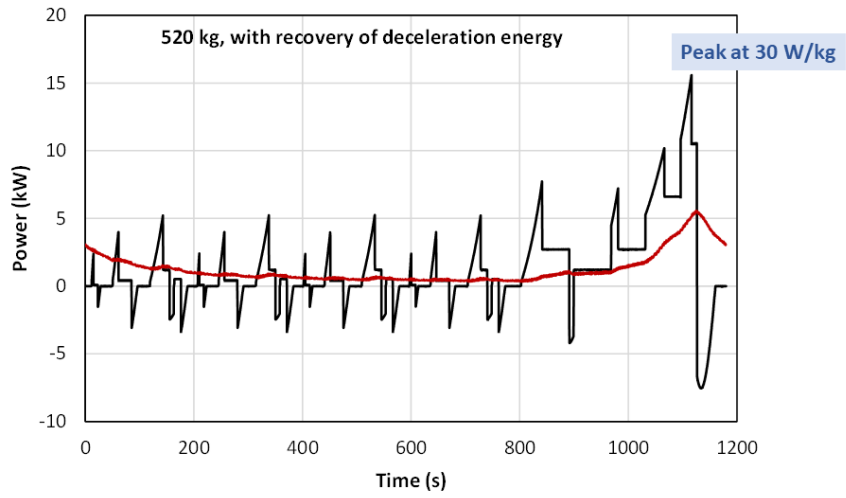


Figure 4



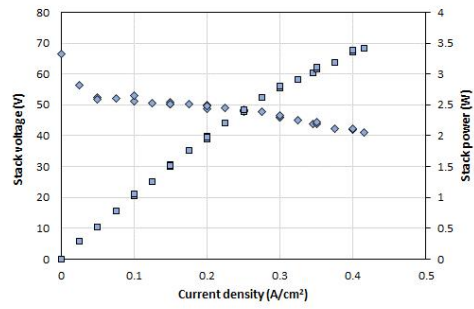
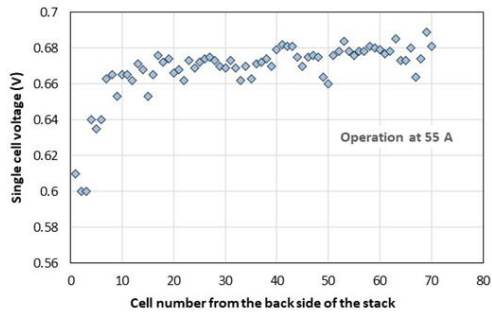
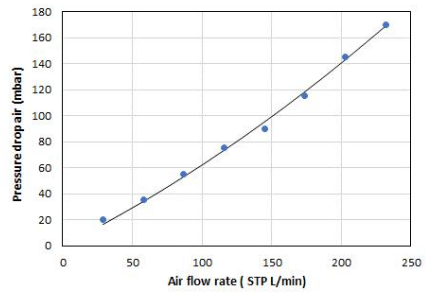
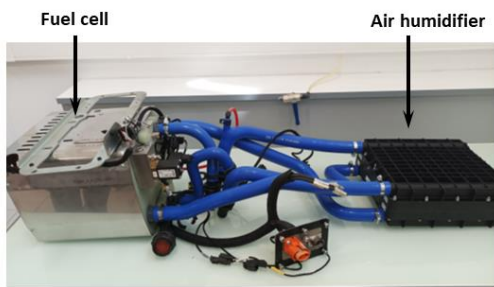


Figure 5

Figure 6

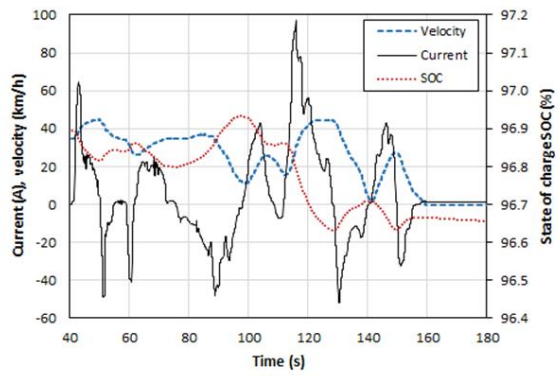


Figure 7

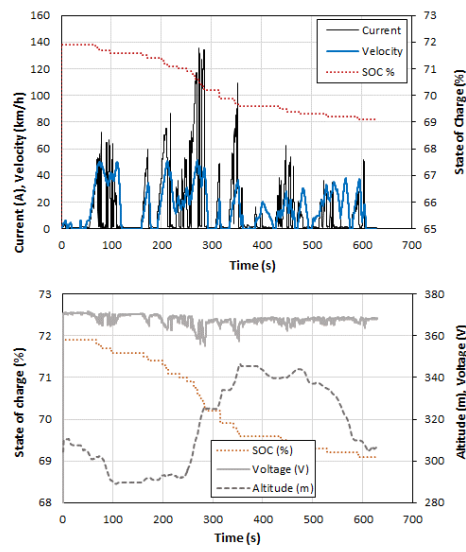


Figure 8

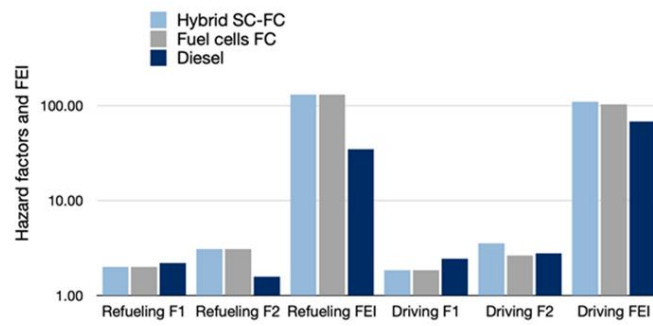


Figure 9

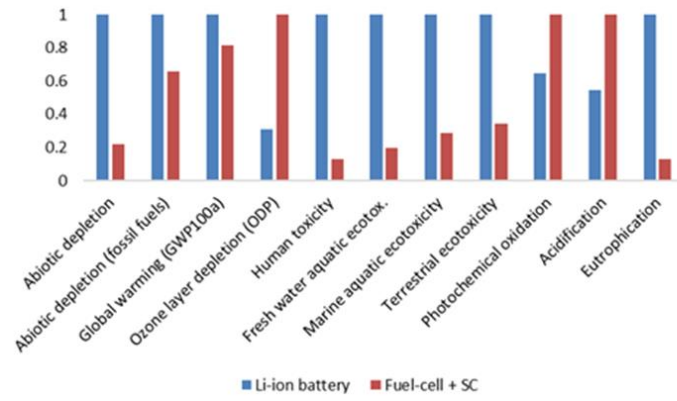


Figure 10

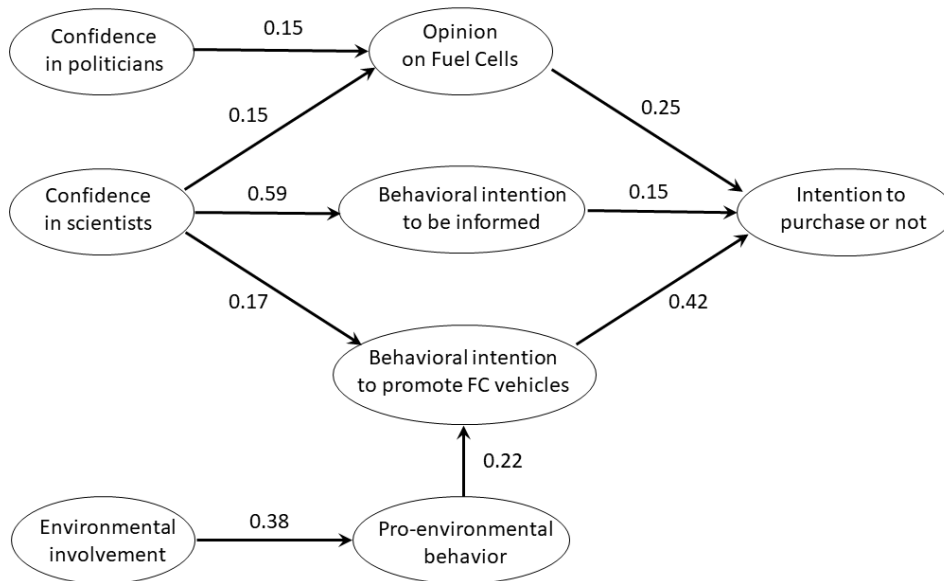


Figure 11

