Fuel Cell Electric Scooter: Considerations toward an Optimized Architecture

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***Abstract*— This article presents the main aspects of the architecture of a fuel cell electric scooter. Based on a representative drive cycle the energy and power demand of such a vehicle are introduced and impacts of changes are discussed. Different possible energy and power sources like batteries, supercapacitors and fuel cell systems are introduced and characterized. Based on those system characteristics possibilities of a well adapted and available combination of energy sources is introduced. The power electronics needed for such a system are developed.**

I. INTRODUCTION

A change of our mode of energy consumption is imposed by the climate change and the shortage of crude oil. Two main axes are considered for the adaption of transportation applications due to those new constraints. Firstly the reduction of size; in Europe the mean driving distance per day is less than $40\,\mathrm{km}$ [1]. As those trips are mostly limited to one single user and a limited amount of charge, it would be possible to use smaller and lighter vehicles like scooters, which are more fuel efficient. Secondly, the use of renewable energies like electricity or hydrogen can answer to the challenges. A combination of both might lead to an electric driven scooter. There are some electric scooters available on the marked [2] but they suffer from limited range (around $60\,\mathrm{km}$) and long recharge time (around $5-8\,\mathrm{h}$) due to the use of batteries. The use of a hydrogen driven fuel cell system might answer to the two main constraints, as hydrogen has an higher energy density than batteries and can be recharged more rapidly. This article presents different energy and power sources and their combinations in order to find the most adapted combination.

II. SYSTEM DEMANDS

A. Specifications of the system

In order to evaluate correctly the energy and power demand of a fuel cell hybrid scooter it is important to define some key parameters. Those parameters are in agreement with existing electric scooter [2]–[5]:

- Mass (m): $200\,\mathrm{kg}$ (Scooter), $70\,\mathrm{kg}$ (Driver)
- Inertia or rotational mass (f): $5\,\%$
- Surface (S): $1\,\mathrm{m}^2$
- Drag coefficient: $\lambda = 0.9$
- Rolling resistance: $C_r = 0.01$

B. Energy and power demand

1) Calculation of energy and power demand: A speed profile and the system parameters are needed in order to determine the power needed by the vehicle as well as the energy consumed over the determined cycle.

$$P = \sum F \cdot v \quad (1)$$

$$E = \int P \mathrm{d}t \quad (2)$$

$$\sum F = F_{\mathrm{a+i}} + F_{\mathrm{roll}} + F_{\mathrm{aero}} \quad (3)$$

$$F_{\mathrm{a+i}} = m(1+f)\frac{\mathrm{d}v}{\mathrm{d}t} \quad (4)$$

$$F_{\mathrm{roll}} = m \cdot g \cdot C_r \quad (5)$$

$$F_{\mathrm{aero}} = 0.5 \cdot \rho \cdot \lambda \cdot S \cdot v^2 \quad (6)$$

The sum of forces contains the three different main kinds of forces. Firstly, the forces related to acceleration and inertia $F_{\mathrm{a+i}}$ in N (eq. 4). The rolling resistance F_{roll} in N (eq. 5) is calculated using the acceleration due to gravity $g = 9.81\,\mathrm{m\,s^{-2}}$. Thirdly, the aerodynamic drag force F_{aero} in N (eq. 6) is taken into account using the air density $\rho = 1.2\,\mathrm{kg\,m^{-2}}$. The hill climbing force is neglected in this case.

2) Drive cycle: The presented drive cycle is based on a representative drive in an european city. It is limited to a maximum speed of $50\,\mathrm{km\,h^{-1}}$ (Figure 1). This cycle takes around $37\,\mathrm{min}$ and covers a distance of $9.1\,\mathrm{km}$.
In order to be able to derive the system power and energy, the speed over time has to be known. Based on those data the acceleration and distance can be derived at each moment.

3) Energy and power demand: The power demand of the scooter based on data introduced above can be seen in Figure 2. It shows positive powers during acceleration and

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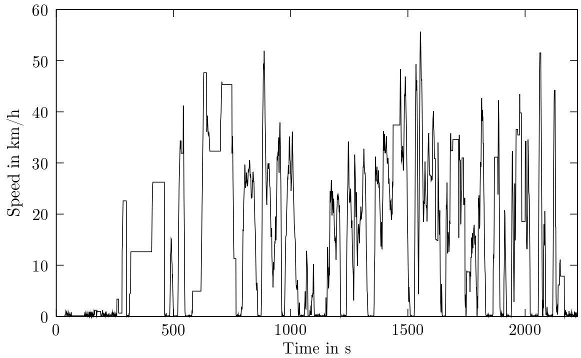

Fig. 1. Representative drive cycle

negative powers during breaking, the average power is 271 W, the power at top speed without acceleration is 1.8 kW and different power peaks between $5 - 10$ kW can be observed. The energy demand over a total distance of 80 km[1] is 2.64 kWh without energy recovery and 1.47 kWh with total energy recovery.

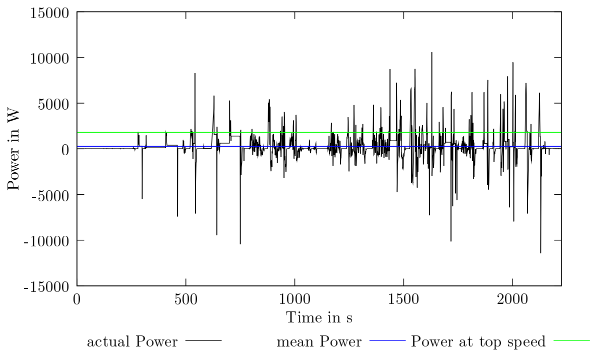

Fig. 2. Power demand during drive cycle

4) Influence of power demand: The power demanded by the scooter is governed by the acceleration. Figure 3 shows the time needed to accelerate up to 50 km h^{-1} for different system powers (assuming a constant maximum torque). It can be seen, that 35 s are needed to accelerate up to maximum speed with a system power of 2 kW. Using 3 kW reduces the acceleration time down to 19 s; 4 kW $\equiv$ 13 s; 5 kW $\equiv$ 10 s. Due to the fact that a system size and weight of every power supply raises proportionally, the conclusion is made that a power of 3 kW provides a reasonable acceleration. Moreover, most of the energy sources introduced below as well as electric motors are able to provide peak powers well above nominal powers for short time intervals.

III. Energy sources

Different sources can supply the power and energy needed, some of the most popular are introduced hereafter.

[1]mean weekly drive distance

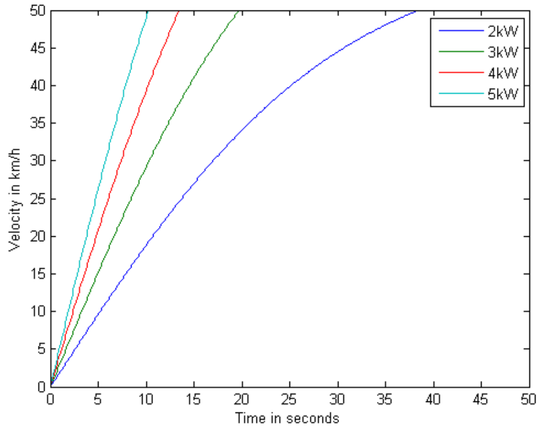

Fig. 3. Time to accelerate up to 50 km h^{-1}

A. Fuel Cell System

1) Fuel Cell: A fuel cell is an electrochemical device able to transform chemical energy (mostly from hydrogen) directly into electrical energy, thus providing system efficiencies up to 50 %. Different types of fuel cell systems are existing, but for mobile applications mostly PEMFC are used [6]. Those fuel cells are working at temperatures below 80 °C providing the advantage of rapid start-up and easy handeling. At the same time the low operating temperatures impose difficulties of water handling, leading to the fact that rapid load changes shall be avoided [7].

A single fuel cell is able to provide a voltage of $0.6 - 1$ V depending on the current demanded from the system, therefore several fuel cells are connected to form a fuel cell stack. The amount of current that can be demanded from the fuel cell is proportional the cell area (and the hydrogen supplied). An extensive fuel cell model was introduced by Gao et al. [7], [8].

A fuel cell generates electric energy, reaction by-products and heat from entropy variation. This heat has to be evacuated by a cooling system. In some conditions, the inlet gas has to be heated and/or humidified before entering the stack, which requires the recovery of water and heat from the outlet of the fuel cell stack. Furthermore, a fuel cell has to be supplied with the reactants. All this auxiliaries belong to the fuel cell system. For a first approach it can be said, that the fuel cell systems doubles the size and the volume of the fuel cell stack.

An overview of existing fuel cell stacks for transportation applications provided the following datas on fuel cell stacks: the specific power is 1.0 kW kg^{-1} and the energy density is 0.9 kW L^{-1}.

More information about fuel cell systems are given by Blunier and Miraoui [6], [9].

2) Hydrogen storage: In most cases fuel cells have to be supplied with hydrogen [4]. In order to be able to supply the scooter with hydrogen an adapted infrastructure has to be available. For the moment some remote hydrogen fueling stations are available all over the world.

Hydrogen can be stored by different means. The most considered are listed hereafter.

- **Liquid hydrogen storage** in order to liquefy hydrogen, it has to be cooled down to temperatures of around $20\,\mathrm{K}$ and pressures around $8-10\,\mathrm{bar}$. The cooling and pressurization requires an energy that can rate up to $30\,\%$ of the energy stored inside the hydrogen, furthermore outgassing effects occure, thus limiting the storage time.
- **Compressed hydrogen storage** in pressurized gas tanks. Those gas tanks avoid gas leakage the hydrogen is stored at pressures between $350\,\mathrm{bar}$ and $700\,\mathrm{bar}$. Nowadays, compressed hydrogen tanks are made of reinforced carbon fibers.
- **Metal hydride storage** are solid state materials that store, depending on the material used, around $5\,\mathrm{wt}\,\%$ of hydrogen. In order to release hydrogen heat has to be supplied to the storage material. Waste heat from the fuel cell can be used.

All technologies have proved their viability, current challenges are the reduction of weight and volume, cost, leakage and recharge times. Our study is based on the results of demonstration cars with hydrogen storages of with a capacity of around $1.2\,\mathrm{kWh\,kg^{-1}}$ and $0.6\,\mathrm{kWh\,L^{-1}}$.
A introduction on hydrogen storage is given in [9] and [10].

B. Batteries

Since their invention around the year 1800 by Alessandro Volta batteries are widely used for the most different applications. That is why only the four main battery types used in small transportation application are introduced here, [3]. An overview of the most important battery characteristics; namely the specific energy in $\mathrm{Whkg^{-1}}$, the energy density in $\mathrm{WhL^{-1}}$, the specific power in $\mathrm{Wkg^{-1}}$, the electromotive force in V, the costs in EUR $\mathrm{kWh^{-1}}$and the system cycles with a decharge of $80\,\%$; are given in Figure 4.

1) Lead acid battery: The lead acid (Pb) battery is the most widely used battery, it is present in nearly every vehicle and has also been used for different electric vehicle applications. The Lead acid battery is a fairly robust system which already has been commercialized largely leading to a reasonable price. All other characteristics have been outperformed by more recent battery technologies.

2) Nickel metal hydride battery: The nickel metal hydride (NiMH) battery has been introduced commercially about 20 years ago. The NiMH battery outrages the Pb battery in every characteristic but the EMF which can be balanced by a higher number of elementary cells. Unfortunately, the NiHM battery suffers from a higher self discharge of up to $5\,\%$ per day.

3) Sodium metal chloride battery: The sodium metal chloride battery also Zebra battery shows good characteristics for a reasonable price. The highly reactive reactants (sodium and molten sodium metal) are separated safely by both solid and liquid electrolyte. The main disadvantage is that the zebra battery is operating at temperatures of around $300-350\,°\mathrm{C}$. In order to keep the battery at working temperature it cannot be stored in operation mode for a long time. Due to those isolations issues zebra batteries are considered mainly for larger scale applications.

4) Lithium ion battery: The lithium ion (Li Ion) battery offers high specific energy and specific power. Due to the use of the rare metal lithium, the cost of such a battery is high. The main application for the moment is portable like in laptop computers or mobile phones. The wast use of lithium ion batteries for transportation application will lead to a shortage in lithium and a further rise in price. However, initial worries on the explosion safety of those battery have been solved.

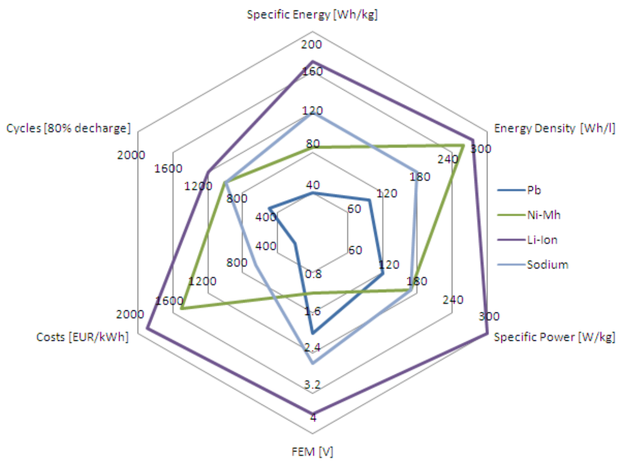

Fig. 4. Overview of different battery characteristics

The different battery technologies offer different characteristics; the costs vary with the characteristics. In any case the time of recharge reaches from $20\,\mathrm{min}$ for a rapid $60\,\%$ recharge of a NiMH battery up to $8\,\mathrm{h}$ for a full recharge of a lithium ion or lead acid battery.
An alternative to the recharge of a battery installed inside the vehicle would be a battery swap. Therefore, the battery type, dimension and size has to be normalized in order to facilitate the creation of a swap station infrastructure. At the same time the ownership of the battery has to be reconsidered. That is why a vehicle installed battery is considered in this case.

C. Supercapacitors

Capacitors are separated condensor plates able to rapidly provide a considerable power. Due to recent developments the power and energy that can be supplied by a supercapacitor has risen so that a power application became reasonable. A supercapacitor can hold a voltage of $1-2.7\,\mathrm{V}$. In order to protect the supercapacitor a voltage balance system has to be foreseen. Even though supercapasitors have very high power densities of $15\,\mathrm{kW\,kg^{-1}}$ the energy densities are limited to $5\,\mathrm{Wh\,kg^{-1}}$. This is why supercapacitors are mainly used to supply power peaks.

IV. System Architecture

A. Main assumptions

Until now the power and energy demand of the scooter has been introduced as well as the energy densities of different

energy and power sources. In order to study aspects of the system architecture, the energy supply will be directly connected to the energy demand, considering an unity drive train.
The system weight is evaluated for a system that is able to provide a maximum power of 3 kW and an energy stored of 2 kWh. Three aspects are considered:

- the fuel cell stack weight, which is linked to the *power* supplied by the fuel cell system
- the hydrogen storage weight, which is linked to the *energy* supplied by the fuel cell system
- the battery weight. The battery weight is calculated to meet the energy and power demands.

The size of the fuel cell system increases from 0 % of the total system (power or energy are provided entirely by the battery system) up to 100 % (power or energy are provided entirely by the fuel cell) with regard to the power demand and with regard to the energy demand. The completement is done using the battery. Based on the two battery sizes, to meet the energy demand and to meet the power demand, the larger is considered. This leads to a three dimensional surface of system weights. For each combination the minimum system weigth and its repartition on fuel cell system, hydrogen storage and batteries is given. The fuel cell system takes into consideration system auxiliaries, that lead to a fuel cell system weight of $0.498\,\mathrm{kg\,k^{-1}W}$. The weight evaluation does not take the further system aspects like the minimum battery voltage into consideration.

B. Combination of energy sources

1) Fuel cell / Lead acid battery: Figure 5 shows that for a combination of a fuel cell system and a lead acid battery, the fuel cell system provides weight advantages both with regard to energy and power. The minimum system weight is 11.59 kg and is entirerly provided by the fuel cell system. A fuel cell system weight of 6.03 kg is taken into account as well as a hydrogen storage weight of 5.56 kg. As the power and energy are completely provided by the fuel cell system, there is no battery system foreseen. Even thought this solution seams interesting due to the fact that the use of only one energy source simplifies the system and its control, this solution is not likely to be feasible. This article is focussed on energetic aspects and leaves aside dynamic aspects, that might also impose the use of a secondary power source next to the fuel cell system in order to meet dynamic demands.

2) Fuel cell / Nickel Metal Hydride battery: Figure 6 shows that for a combination of a fuel cell system and a nickel metal hybride battery, the fuel cell system still shows advantages with regard to the system weight. This leads to a minimum system weight of 11.59 kg devided into a fuel cell system weight of 6.03 kg and a hydrogen storage weight of 5.56 kg. In this case, as well as in the case of a fuel cell system combined with a lead acid battery, no battery is added to the system, leading to a more simple system architechture and system command, but at the same time imposing constraints on the system dynamics.

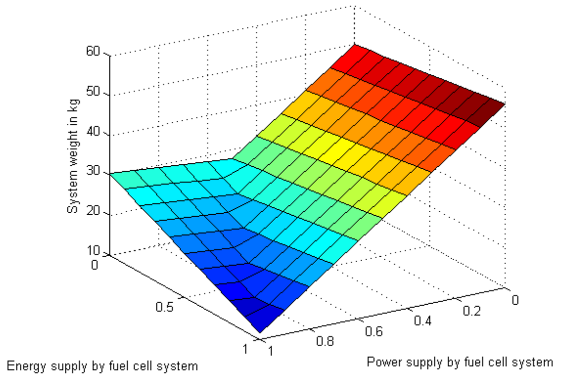

Fig. 5. Fuel cell system with hydrogen storage and lead acid battery

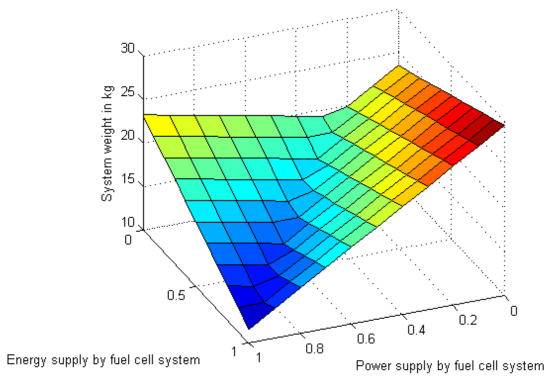

Fig. 6. Fuel cell system with hydrogen storage and nickel metal hydride battery

3) Fuel cell / Lithium Ion battery: Figure 7 still shows that the minimum total system weight is obtained by a combination of fuel cell system, hydrogen storage and battery system. Using those three means the total system weight can be reduced to 11.09 kg divided into 1.81 kg for a fuel cell stack providing a maximum power of 0.9 kW, a hydrogen storage of 2.22 kg, which is equivalent to a pure hydrogen weight of 20 g able to provide an energy of 0.8 kWh. The complement with a power of 2.1 kW and 1.2 kWh is provided by a lithium ion battery of 7.06 kg.
With regard to systems introduced above the system architecture of a combined fuel cell system with battery is more complex and the system commande has to be desiged properly, still the gain in overall system weight is 0.5 kg or 4.5 % of the overall system weight. Even though this the validity of this gain has to be considered carefully, such a gain in the system weight might be a step forward in order to optimize the overall system. Furthermore, the combination of a fuel cell system with a battery system will lead to better dynamic response than a pure fuel cell system, thus improving system performance.

4) Fuel cell / Supercapacitor: Figure 8 shows the combination of a fuel cell system with hydrogen storage with a

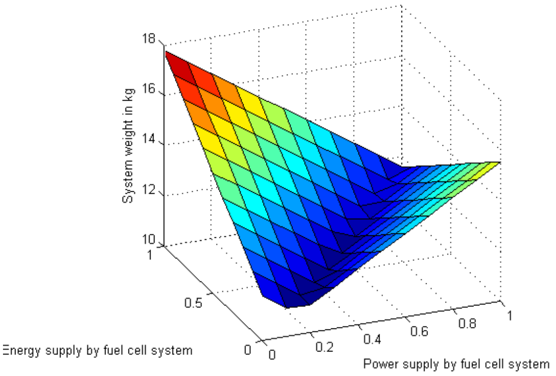

Fig. 7. Fuel cell system with hydrogen storage and lithium battery

supercapacitor pack. It can be seen that the minimum system weight is obtained if the energy is provided by the fuel cell system and the power is provided by the super capacitors. This leads to a total system weight of $5.76\,\mathrm{kg}$ devided to $5.56\,\mathrm{kg}$ for the hydrogen storage and $0.20\,\mathrm{kg}$ for the super capacitors. It can easily be seen that this solution is not feasible, as it does not consider a fuel cell system to transform the hydrogen in electrical energy. However, in such a configuration using a fuel cell system that supplies the mean power, will meet the system demands. A fuel cell system providing the mean power of around $200\,\mathrm{W}$ has a weight of $0.15\,\mathrm{kg}$, leading to an overall system weight including fuel cell system of $5.91\,\mathrm{kg}$. This means less than halve of the weight of a pure fuel cell system. Still, the system considerations presented here are based on energetic aspects. Further considerations with regard to dynamic and electric aspects, like the energy storage capabilities of the super condensators and their voltage development, have to be made in order to verify the feasability of the approach, as has been also done by [5].

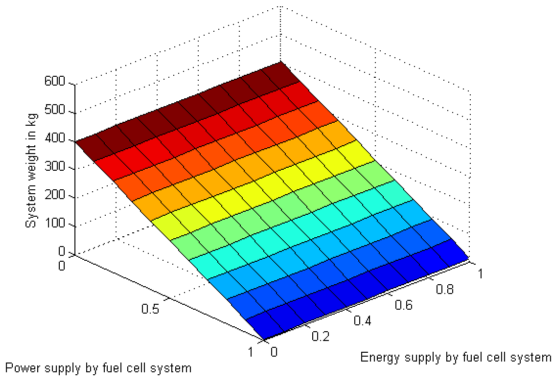

Fig. 8. Fuel cell system with hydrogen storage and supercapacitor

C. Power Electronics

Nearly every system using electric energy needs power electronic devices in order to distribute the electric energy according to its needs. The power electronic devices are closely linked to the control system. A well adapted control system is important not only to make the system work, but also to optimize system efficiency. A well adapted system architecture including power electronics devices is thus essential to design a well working, efficient system.

Depending on the type of bus and electric machine used to provide the cinetic energy needed, a power electronics device, often in form of a DC/AC converter, will be used.

All energy sinks and sources will be connected to a bus. According to the characteristics of the bus (AC or DC voltage at different voltage levels) an adapted power conversion system has to be chosen in order to connect the different energy sources with the bus. If a DC bus is used (which is the case in most transportation application [11]) and the energy sources are DC sources (which is the case for fuel cell systems, battery systems and supercapacitors) DC/DC converters are used.

A fuel cell system, providing energy, will be connected to a unidirectional DC/DC converter with, most of the time, high conversion ratio as fuel cells are current intensive sources (low voltage, high current) [12]. The reversible energy source will be connected to a bidirectional DC/DC converter. Depending on the DC-link voltage and the source voltage and its nature (bidirectional, reversible or not), the power electronics of a fuel cell hybrid electric scooter has thus to be considered carefully regarding compactness, cost and efficiencies.

V. Conclusions and Perspectives

This article introduces the main aspects of system architecture in order to design a fuel cell hybrid electric scooter. A small personal transportation system with limited range might be an interesting alternative for the future. Based on a representative drive cycle it is shown that a maximum power of $3\,\mathrm{kW}$ and a stored energy of $2\,\mathrm{kWh}$ might be sufficient for daily needs. Different energy sources are introduced and evaluated regarding specific power and specific energy. The introduced energy sources/storages contain PEMFC systems including system aspects and hydrogen storage, batteries and supercapacitors. The results show that the association of a fuel cell system with a Li Ion battery or a super capacitor show potential. Especially the association of a fuel cell system with super capacitors might lead to a gain of $50\,\%$ in system weight (down to $6\,\mathrm{kg}$). Therefore, further work will be done on the dynamical and electrical dimensioning of such a system. Finally, the importance of power electronic devices and control system for a well balanced system is introduced.

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