

Energy management of multi-storage systems in electric vehicles

Moure¹, Artal²

¹*Christophe Moure, Applus IDIADA group, christophe.moure@idiada.com*

²*Natalia Artal Paracuellos, Applus IDIADA group, natalia.artal@idiada.com*

Short Abstract Summary

Over the last years, electric vehicles have gradually been introduced to roads around the world. However, the initial feedback of end-consumers shows that the range of the traction battery (on average between 120 and 180 km) is a serious handicap, and limited use and lack of flexibility seem to be the main obstacle to the widespread market introduction of electric vehicles.

For the above reason, new green energy sources have been rolled out in the automotive sector to cover drivers' expectations, and new technologies such as fuel cell systems, supercaps and other clean power sources are being used as range extender kits in electric vehicles and/or lifecycle traction battery extenders.

But what happens if an electric vehicle combines more than one energy storage technology? This paper is aimed at enhancing the understanding of new technologies related to sustainable mobility in only one platform.

1 Introduction

In 2009, Applus IDIADA had the opportunity of electrifying a Nissan Cabstar light-duty truck as shown in Figure 1. The goal was to convert it to electric drive without sacrificing any of the key specifications, especially speed, hill-climbing and general comfort.



Figure 1: Light truck electrified by Applus IDIADA

A few years later, the high cost of batteries and the limited vehicle range led to the consideration of the integration of a new updated configuration of the vehicle to satisfy market demands. The available space over the chassis enables this vehicle to be a laboratory platform for new power and energy traction sources.

The objective of this work is to develop a new control systems algorithm of an electric vehicle platform by integrating two additional energy storage systems within an electric vehicle, which will be a case study of the wide range of possibilities of multi-energy storage systems configuration. The fuel cell system provides capacity of storage, i.e. energy; and the supercaps sustain high power demands and prevent current peaks of battery.

The outcome of this work is an increment of the total range of the vehicle as well as an extension of the battery lifecycle.

2 Energy Management

An electric vehicle with three energy storage systems shows the complexity of commanding different control systems in only one vehicle. Both new systems can supply the required energy to propel the electric motor and the fuel cell system can also recharge the high-voltage battery.

The fuel cell system provides an additional range in proportion to the capacity of hydrogen storage tanks, the tanks that supply energy to the fuel cell power module (FCM). This system converts the initial electric vehicle into a fuel cell range extender vehicle.

A dynamic DC/DC converter adapts FCM voltage to the high-voltage battery voltage in order to act at the same voltage rate. A second DC/DC converter, in this case bi-directional, does the same with the supercap system, which provides instantaneous high power to satisfy high demands. Consequently, this is not only a fuel cell range extender vehicle, but a multi-energy storage electric vehicle combining high power and high energy as illustrated in Figure 2.

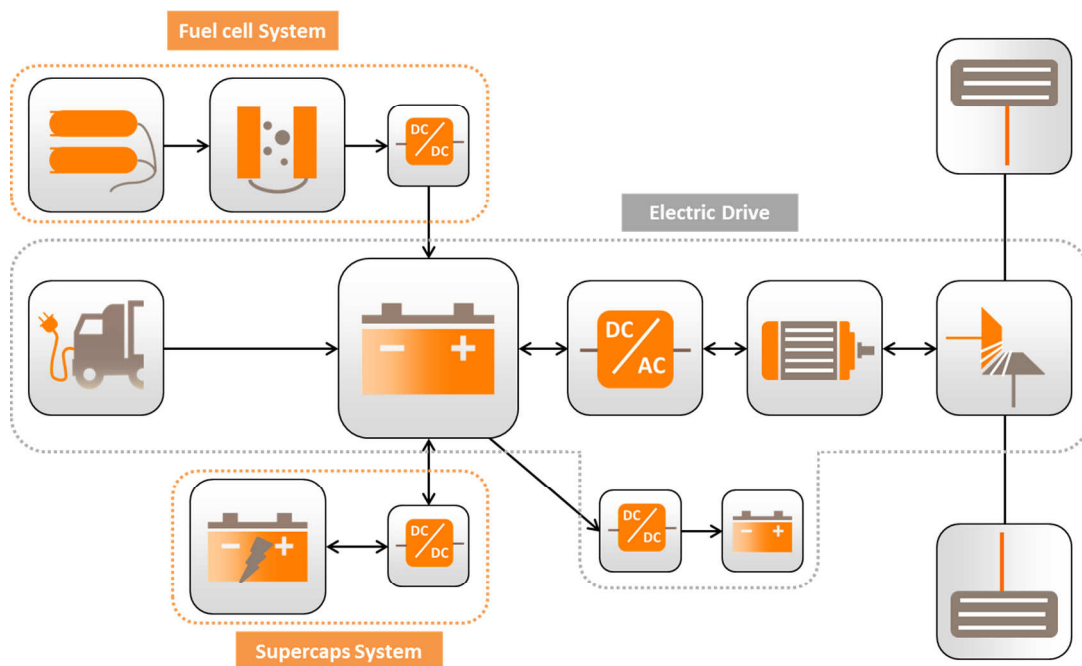


Figure 2: Architecture of the multi-energy storage electric vehicle

Based on this vehicle topology, the challenge of the energy management algorithm is to make the most of each energy source, i.e. high-voltage battery, fuel cell and supercaps. Nowadays, freedom and constraints related lithium batteries are well-known and extensively described in literature. Therefore, the final purpose is to take advantage of the strengths of one energy source to cover the limitations of the others, which will lead to obtaining a multi-energy storage system with an extended capacity and an increased lifecycle.

Based on energy storage systems and vehicle characteristics after electrification as illustrated in Figure 3, simulations were performed to evaluate the overall benefits for the energy consumption, on the battery lifecycle, etc.

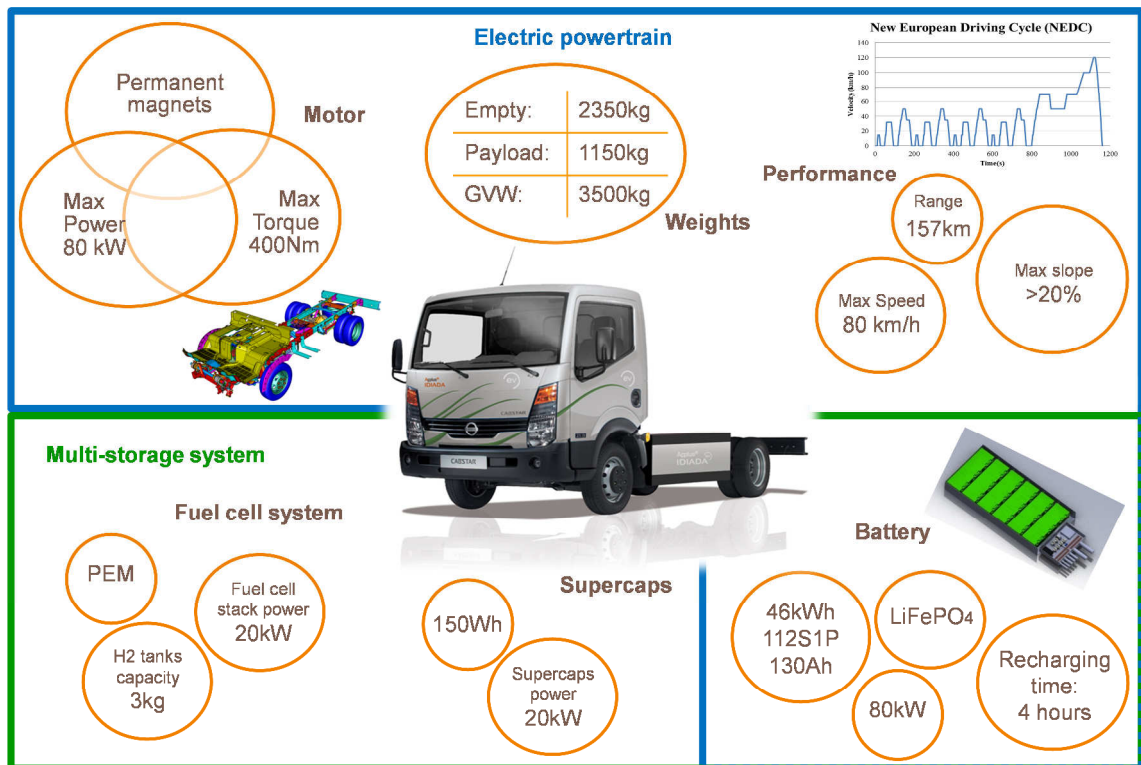


Figure 3: Vehicle characteristics

2.1 Baseline vehicle

The Nissan Cabstar was originally fitted with a 2.5l 130HP/270Nm diesel engine and the goal was to convert it to electric drive without sacrificing any of the key specifications, specifically speed, hill-climbing, comfort and acceptable range for a standard fleet with minimal changes to the frame. As this vehicle category is focused on urban and interurban driving, the main targets were reviewed in order to be more appropriate to the final use, as shown in Figure 4 below.



Figure 4: Vehicle main targets considered in the electrification process

The goal was to have a range close to 157 km using the NEDC as driving cycle. Therefore it was critical to know the energy needed for this target to determine the battery size. For this reason, a vehicle simulation was run with all the known parameters on the NEDC.

The battery pack was chosen through a benchmark of different suppliers with emphasis on energy density, power density, safety and cost. The final choice was a pack supplied by an external pack manufacturer specialized in large packs for use in public transportation vehicles. The pack is composed of 112 130 Ah Lithium Iron Phosphate cells with a nominal voltage of 3.2 V each. The cells are all connected in series and split in two enclosures, two packs, with four slave control modules in each and a master in one of the enclosures. The nominal voltage of the pack is 358.4 V and the energy content is 46.6 kWh. The total battery weighs approximatively 550 kg. Cells with better energy density were available in 2009 on the market, but they were not as safe and proven as LiFePO₄ – Lithium Iron Phosphate cells.

The motor technology was a state-of-the-art brushless DC with permanent magnets powered by a three-phase inverter. The motor weight is 50 kg and the peak power is 145 kW, which gives a power density of 2,90 kW/kg adapted and relevant for the current application. The motor can produce the peak power during 30-90 s, sufficient if the driving environment is an urban area. The motor and inverter package was purchased before the battery pack and extensively benchmarked on a motor dynamometer. It allowed plotting of the efficiency map for different power and velocity levels, which was the basis for the further energy consumption simulation.

2.2 Fuel cell system

2.2.1 Impact on the vehicle range

The objective is to improve the capabilities and performance of the electrified vehicle. The fuel cell system can be considered as a hybrid system; or in other words a range extender. It gives flexibility in controlling the energy balances and therefore in energy saving.

One of the key points is to increase total range with such technology. As mentioned previously the electrified vehicle range target was 157 km using the NEDC as driving cycle (and around 130 km in real cycle, urban cycle). With this new system fitted on the vehicle, the first step was to identify what would be the most adapted range increase.

As a consequence user expectations and needs were classified according to the power requirements of the vehicle in full EV mode and the proximity to a hydrogen refueling station as illustrated in Figure 5.

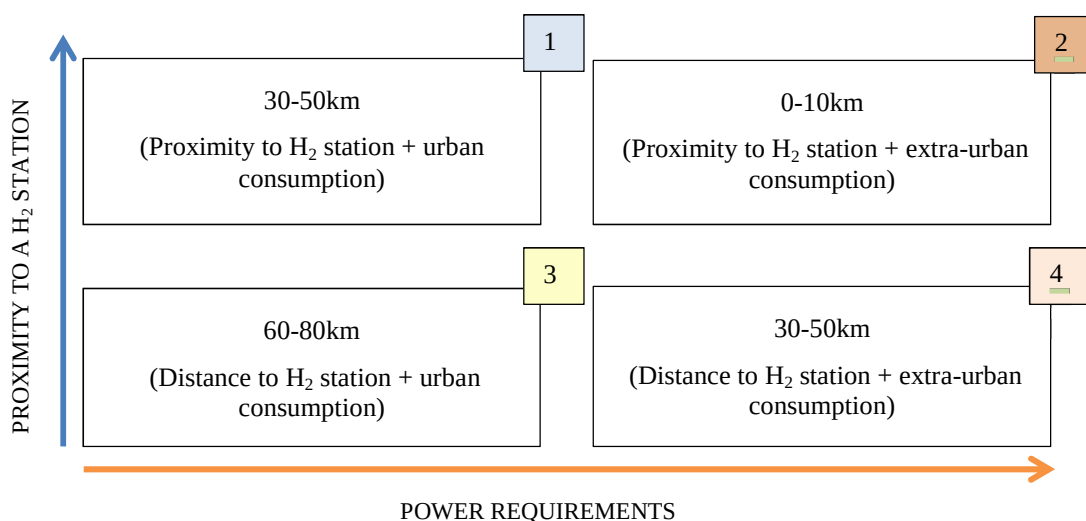


Figure 5: Vehicle range in electric drive according to user expectations

Based on this study, it was decided to double the vehicle range to cope with all the possible configurations and user needs. The gross vehicle weight is a constant that cannot be modified without structural modifications of the chassis and should remain the same, i.e. 3500 kg. In that case the payload was reduced to install fuel cell, tanks and piping. This allows the energy capacity stored in the vehicle to be doubled without considering any additional loss:

- Original capacity from the traction battery: 46 kWh
- Capacity stored in the hydrogen tanks: 46 kWh
- Final capacity to double the range: 92 kWh

2.2.2 System characteristics

One kilogram of hydrogen is equivalent to 15–18 kWh of energy capacity and represents 35,38 l considering the fuel cell efficiency of 60 %. Therefore, 3 kg would be necessary to obtain the 46 kWh and double the vehicle range. According to these results the hydrogen tanks with a total capacity to store around 110 l will be required in this vehicle as shown in Figure 6.

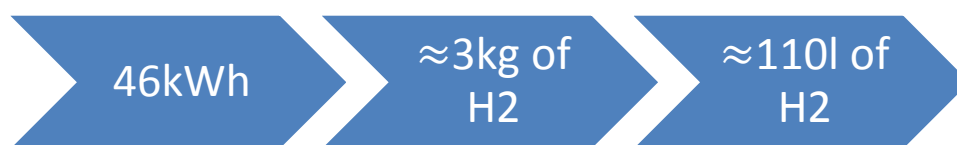


Figure 6: Characteristics of hydrogen tanks for fuel cell system

With respect to the rest of the performances regarding power, speed and slope, the targets were maintained in order to reach values as the original electrified vehicle: 80 kW as maximum power and 80 km/h as maximum speed. Therefore, the fuel cell stack was designed to have a maximum power of 20 kW.

Further to the modifications in the vehicle, the payload was affected by the fuel cell. This system consists not only of the fuel cell stack and the hydrogen storage element (H₂ tanks), but also of auxiliary components to complete the whole system such as DC-DC converter, piping, valves, compressor, etc. As a consequence the new payload was calculated according to the weight of each element as presented in Table 1.

Table 1: Weight study

Element	Weight (kg)
Total weight before fuel cell integration	2350
Payload before fuel cell integration	1150
Max weight	3500
DC/DC weight	25
FC box	50
H ₂ tanks	103
Additional weight (piping, valves and boundaries)	25
Total payload after fuel cell integration	947

2.2.3 Control strategy

When hybridizing a vehicle it is possible to control in charge-depleting or charge-sustaining mode. The decision depends on many factors, such as battery capacity, electric motor power, ambient temperature, etc. As the original traction battery was maintained, the energy capacity was significant and therefore it was decided to use a charge-depleting strategy.

The control of the fuel cell was designed using a state machine as a basis to set the fuel cell command at any moment. Four states have been considered as shown in Figure 7:

- Vehicle OFF: the traction system is shut down
- Vehicle checks: the vehicle is switched on, basic checks are in progress and it is impossible to drive.
- Electric vehicle: the vehicle can be driven and the energy comes only from the traction battery.
- Hybrid vehicle: the vehicle can be driven and the energy comes from the traction battery or the fuel cell system.

The *hybrid vehicle* state is divided into several sub-states to define the most adequate power needed from the fuel cell. This depends mainly on the battery state of charge, the battery temperature, the hydrogen level and the fuel cell temperature.

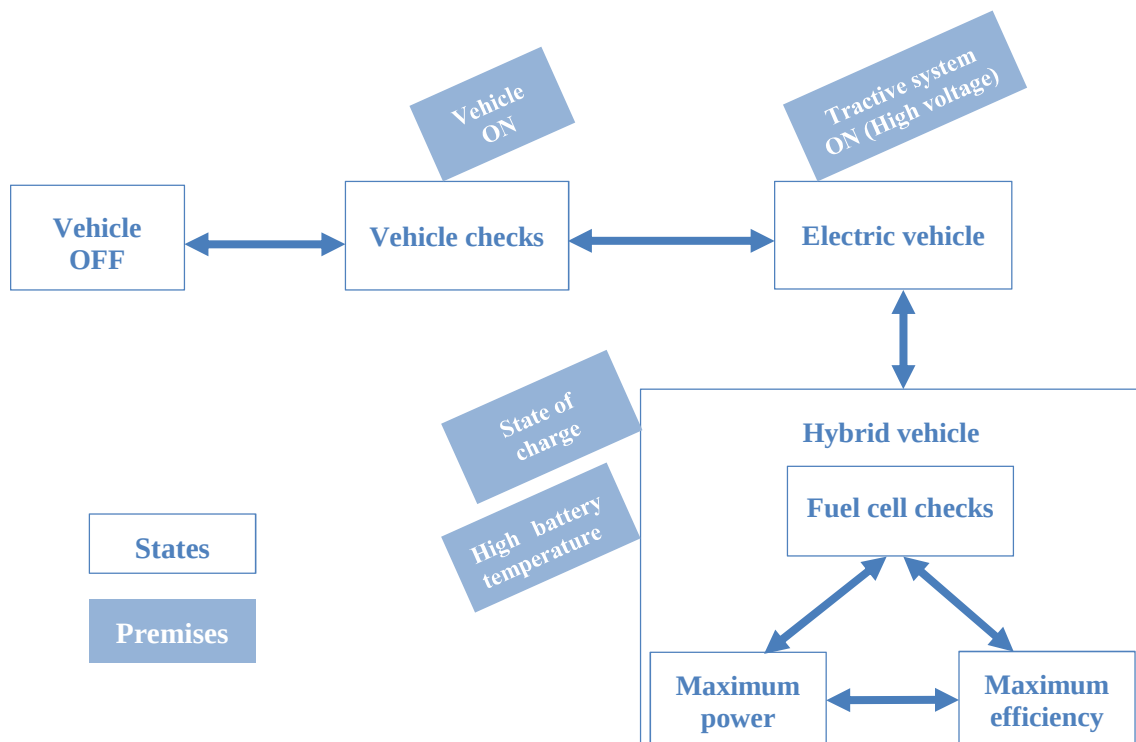


Figure 7: Fuel cell control

2.3 Supercap system

2.3.1 Impact on the battery lifecycle

The supercap technology allows the battery lifecycle to be improved. Their energy capacity is small, but they can recover/provide high power. Therefore they will reduce the power during regenerative braking and accelerations, which will avoid high discharge/charge current flowing through the battery.

The goal with respect to the vehicle lifetime is 400000 km, which implies driving 2931 NEDC cycles. As a consequence, the purpose is to reduce the energy needed from the battery to reduce the energy throughput of the traction battery and to limit the current peaks.

2.3.2 System characteristics

The supercap system is defined by several parameters, such as capacitance (F), voltage (V), power (W), etc. The most important ones within the framework of this study were the energy capacity and the maximum power, which are the key factors to evaluate the benefits for the battery.

Based on the vehicle characteristics, the energy capacity was calculated by evaluating the kinetic energy available while braking from 80 km/h to 0 km/h. The vehicle weight is 3500 kg and the initial speed is 80 km/h, therefore the kinetic energy is 864197.5 J by applying the equation (1),

$$E_c = \frac{1}{2} \cdot m \cdot v^2 \quad (1)$$

As 1 Wh is equivalent to 3600 J, the kinetic energy for a braking from 80 km/h to 0 km/h would be 240 Wh. However, the complete energy cannot be recovered while braking. As a consequence it was considered that more than half of the kinetic energy can be recovered with an efficient regenerative system, which implies a supercap capacity of 150 Wh.

The supercaps are not connected directly to the traction battery. A bi-directional DC/DC converter is located between both to control and monitor this storage system. As a consequence, the supercap power is limited by the DC/DC converter and the related power electronics. The required power from the supercap system was calculated from the regenerative braking system installed in the vehicle. As shown in Figure 8, the maximum electrical power while braking is 27 kW within a NEDC drive cycle, therefore the DC/DC converter was selected to have a maximum power of 20 kW.

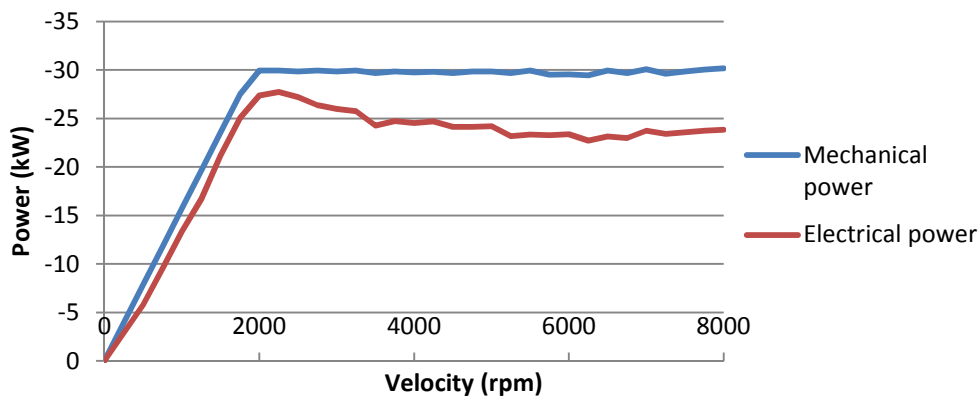


Figure 8: Power during regenerative braking

2.3.3 Control strategy

The basis of the supercap system control is a power command sent to the DC/DC converter, which implies calculating the most appropriate one at any moment.

Whereas the fuel cell system can be considered as a range extender of the traction battery, the supercaps are used dynamically to support the traction battery. As they can deliver/recover up to 20 kW while accelerating/braking, the control algorithm has been defined in the following way as illustrated in Figure 9:

- The required vehicle power P_V is calculated according to the driver demand
- The needed fuel cell power P_{FC} is calculated
- The power needed from the battery and supercaps P_{BS} is P_V minus P_{FC}
- The supercap power P_S is calculated according to a set of conditions, such as P_{BS} , acceleration during the last milliseconds, etc.

The purpose is to use the supercaps only during a significant acceleration and when the power needed from the traction battery is relevant. Therefore, they are used only when P_{BS} is higher than 26 kW and the acceleration is bigger than 1 m/s^2 during 0.5 s for instance.

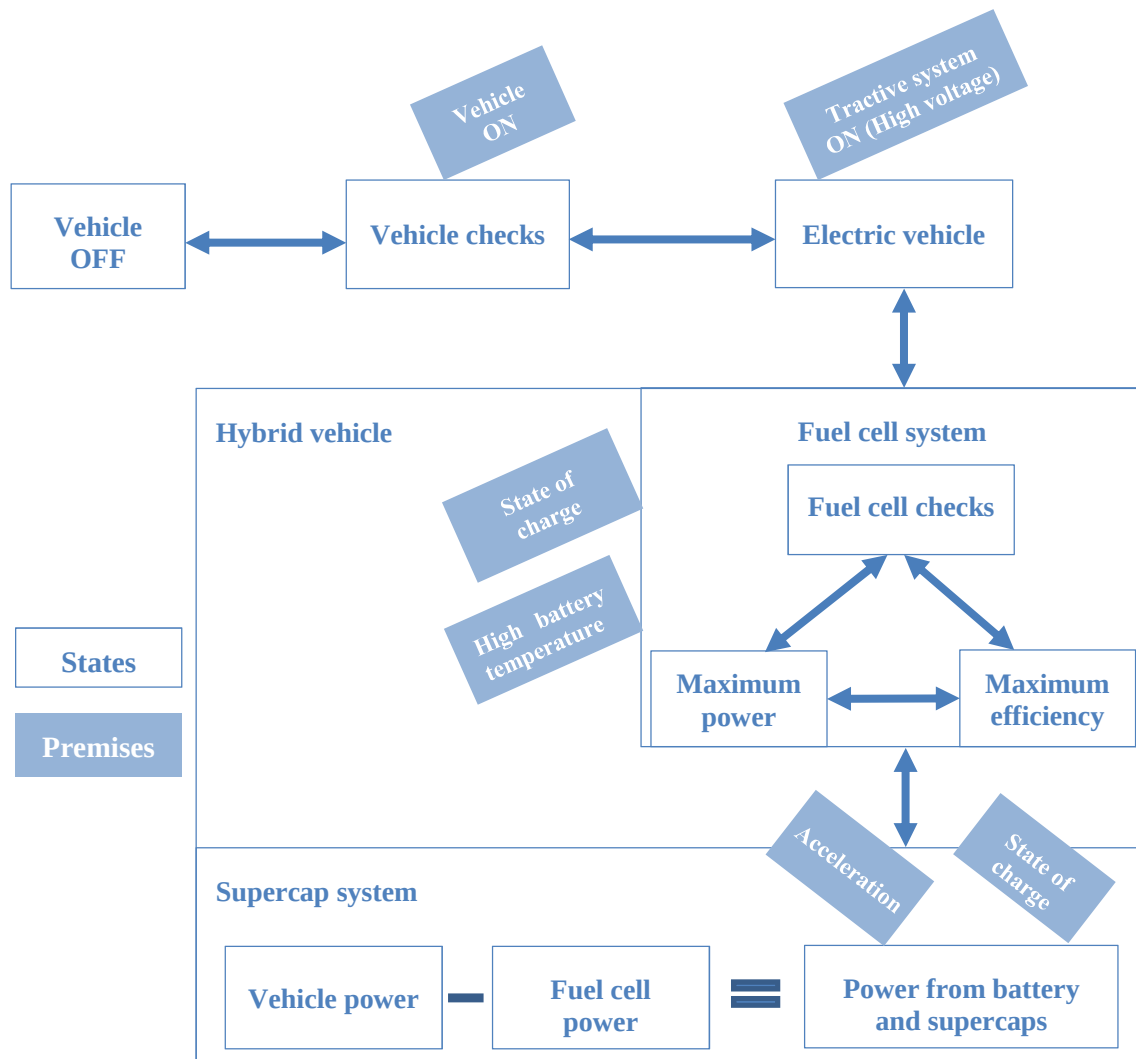


Figure 9: Fuel cell + Supercaps control

2.4 Energy consumption simulation

The energy consumption simulation is the result of the control strategies of different multi-storage systems, taking into account initial and final conditions and specific and /or restrictive premises of each storage system. While new energy storage systems are integrated on the baseline vehicle, the main outcome is to evaluate the impact on the vehicle range, the battery energy throughput and the battery cycles required to fulfill the vehicle lifetime targets.

The addition of the fuel cell system to the baseline electric vehicle (EV) converts the platform into a hybrid vehicle (HEV) or in other words, an EV with range extender system based on fuel cell technology. From the HEV (fuel cell system), the integration of supercaps renames the platform as HEV (fuel cell system + supercaps).

All these configurations, EV, HEV (fuel cell system) and HEV (fuel cell system + supercaps) are evaluated during NEDC taking the baseline EV as point of reference in terms of autonomy, energy consumption and high-voltage battery power profile.

2.4.1 Baseline vehicle (EV)

For the baseline EV, the starting point of the simulation is based on the premise of full capacity of high-voltage battery, 100% of state of charge.

Figure 10 describes the power profile of the baseline vehicle according to the speed profile for only one NEDC. This power profile is repeated as many times as allowed by the high-voltage battery capacity.

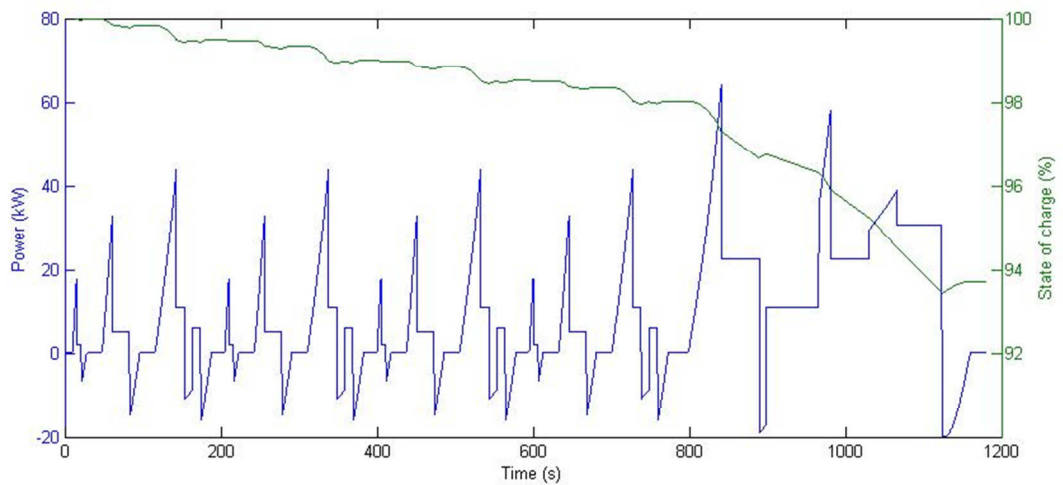


Figure 10: Power demand vs State of charge during the first cycle of NEDC

The right axis shows the evolution of state of charge of the high-voltage battery during this first cycle. The energy consumption every NEDC run represents 6.3% of the state of charge as illustrated.

The evolution of driven kilometers up to discharging the high-voltage battery is another parameter to be compared between the three different types of vehicles. In this case, the average of consumption per kilometer is 296.5 Wh/km and the total number of kilometers is 157.1 km. These data are the set values to compare the enhancement of the new energy systems integration.

2.4.2 Baseline vehicle with fuel cell system (HEV, fuel cell system)

The starting point of this second part of the simulation is based on the premise of full capacity of battery (100% of state of charge) and 100% of hydrogen tank capacity.

The evaluation of driven kilometers during the total run of the HEV (fuel cell system) presents an average of consumption per kilometer of 150.8 Wh/km and the total number of driven kilometers is 308.9 km.

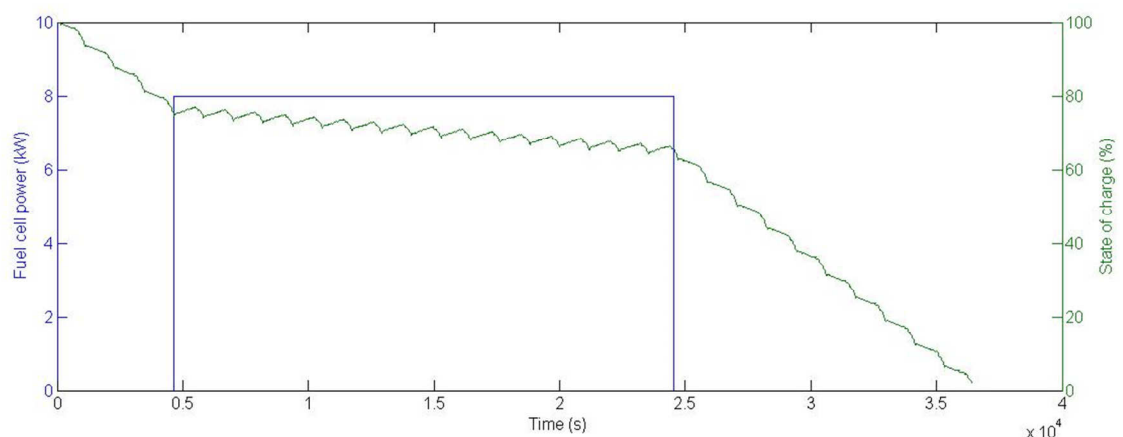


Figure 11: State of charge of battery vs Power profile of fuel cell stack up to the end of range

Figure 11 describes the discharge curve of the battery state of charge and the power profile of the fuel cell stack. The fuel cell is activated when the state of charge reaches a given threshold and runs until having the hydrogen tanks empty. When the battery reaches 1% of its total capacity, it disconnects itself by opening the high-voltage relays as a protection measure to avoid over-discharges and thus, permanent damage.

The range was nearly doubled, with a 98.3 % increase compared to the baseline vehicle. This is due to the fact that 5% of the hydrogen must always remain in the tank, which implies not using 100 % of hydrogen tank capacity.

On the other hand, the fuel cell stack only works at maximum efficiency point during NEDC. Therefore, considering the control strategy previously mentioned, it is not necessary to use the fuel cell system at maximum power. This operating point is more inefficient, and consequently, it consumes much more instantaneous quantity of hydrogen.

2.4.3 Baseline vehicle with fuel cell and supercap system (HEV, fuel cell system + supercaps)

The starting point of the simulation is based on the premise of full capacity of battery, 100% of hydrogen tank capacity and full capacity of supercaps (100% of state of charge).

The consumption is slightly reduced to 150.7 Wh/km compared to the vehicle equipped with fuel cell and the driven kilometers covered are 309.2 km.

Figure 12 below defines explicitly what the real impact of supercap integration is. This figure depicts the battery power behavior along the first NEDC.

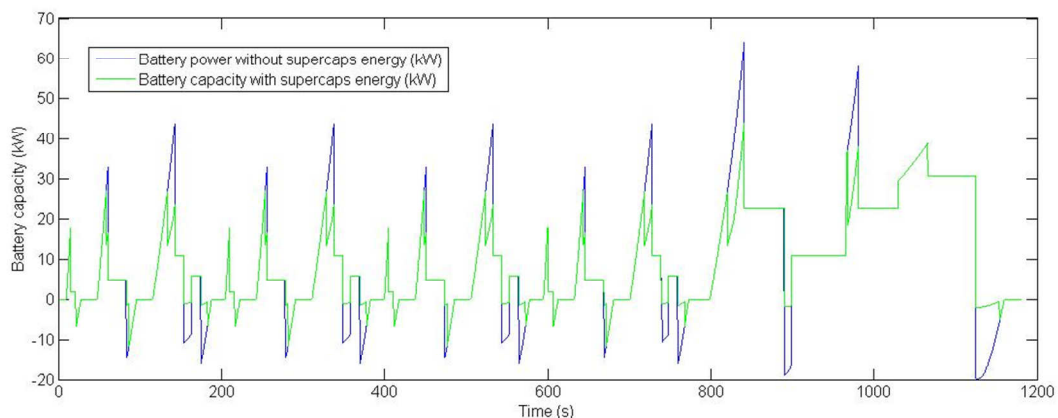


Figure 12: Battery power without supercap energy vs battery power with supercap energy

The blue line shows the battery power required during the first NEDC cycle without the contribution of supercaps. The green line shows the battery power with the help of supercaps. These help to reduce the high-voltage battery peaks while accelerating and braking, and consequently, prolong the lifecycle of the main energy storage.

2.4.4 Simulation comparison

Table 2 below presents the scenario of the baseline vehicle considering different energy storage systems. The following values show how the fuel cell system has a remarkable impact on the vehicle range and how the supercap system softens the battery power peaks.

Table 2: Simulation comparison

	EV	HEV (fuel cell system)	HEV (fuel cell system + supercaps)
Total range	157.1 km	308.9 km	309.2 km
Battery energy consumption	296.5 Wh/km	150.8 Wh/km	150.7 Wh/km
Maximum battery power	64 kW	64 kW	44 kW
Minimum battery power	-19.8 kW	-19.8 kW	-11.5 kW
Energy throughput until battery empty	53.7 kWh	82.7 kWh	73.3 kWh
Battery cycles required for the vehicle lifetime	2931	2296	2035

As mentioned previously, the expected vehicle lifetime is 400000 km. Therefore, the last point of this study was to analyze the impacts of each technology on the energy throughput and the battery cycles required to fulfill the vehicle lifetime target. The first step was to calculate the number of discharge/charge cycles necessary until having the high-voltage battery empty. Indeed, even if the battery capacity is 46 kWh, more than this quantity can be consumed as the regenerative braking strategy allows energy to be recovered while driving.

As shown in Table 2, the energy throughput with the fuel cell vehicle is higher than the baseline vehicle. This phenomenon is explained by the fact that more energy is recovered while braking, which recharges the high-voltage battery more. The energy throughput for the vehicle equipped with fuel cell and supercap systems is lower, as part of the energy comes from the supercaps, which allows the required battery cycles to be reduced to 2035.

Reducing the required battery cycles allows the costs to be decreased, which is beneficial for the final customer and the manufacturer. The vehicle lifetime can exceed more than 400000 km with the same high-voltage battery. In addition, other chemistries and battery solutions with less demanding top requirements are possible during the development with less battery cycles needed.

3 Conclusions

The reduced range, or rather, the lack of energy capacity of electric vehicles together with limited lifecycle of lithium ion batteries were the key targets of this study.

One of the premises for the integration of the fuel cell system was to double the initial range of the baseline vehicle, 157.1 km. This target was fulfilled as the vehicle range of the HEV (fuel cell system) was satisfactorily increased up to 308.9 km.

The impact expected for the supercap system was a prolongation of battery lifecycle by reducing the battery energy throughput and absorbing the peaks of power and thus, avoiding battery over-heating. The task of the supercap system was to supply energy during peaks of power demand and reduce the power provided by the battery. This target was also fulfilled as the maximum and minimum battery powers required during a driving cycle were reduced to 44 kW and -11.5 kW. In addition, the energy throughput required to reach the vehicle lifetime was significantly reduced from 2931 for the baseline vehicle to 2035 cycles for the HEV (fuel cell + supercaps).

This study has successfully demonstrated the feasibility of different energy sources combined with a full electric traction platform. The integration of fuel cell technology based on fuel cell stacks and hydrogen tanks has led to an increment of total vehicle range. The implementation of supercap technology has

presented the prolongation of the lifespan of high-voltage battery by reducing the needed battery power and the total number of cycles required for the same number of kilometers driven.

Within the framework of this study, the baseline vehicle was an existing electric vehicle. Therefore, another scenario would be an approach of investigation starting from scratch. A virtual vehicle would be developed from the beginning and the study would be focused on selection and definition of three energy sources, high-voltage battery, fuel cell system and supercap system, in terms of capacity and power.

Acknowledgments

This study was developed within the framework of a project in Applus IDIADA. The authors would like to express their gratitude to the Powertrain team for their contributions and valuable discussions about the concepts described.

References

- [1] Haiming Xie, Hongxu Chen, Guangyu Tian, Jing Wang, State Key Laboratory of Automotive Safety and Energy, Tsinghua University, China, *A Stochastic Model Predictive Control Strategy for Energy Management of Series PHEV*, EVS 28
- [2] Feroli, Diego, *Control and Design of PEM Fuel Cell-Based Systems*, Phd thesis in Universitat Politècnica de Catalunya, 2009.
- [3] Roche, M., Artal, N., *Evaluation of Fuel Cell Vehicle regarding Hybridization Degree and its Impact on Range, Weight and Energy Consumption*, EEVC 2014

Authors

Mr. Christophe Moure holds an Information Systems Engineering degree from the National Institute of Applied Sciences of Rouen in France. He joined Applus IDIADA group five years ago as project engineer for developing powertrains of hybrid and electric vehicles. Prior to that he worked for five years for Delphi Diesel Systems in France coordinating the design and development of functional safety aspects within a diesel vehicle and customized strategies regarding engine control (vehicle driveability, start/stop systems or full hybrid, etc.).

Ms. Natalia Artal graduated in Mechanical Engineering from the University of Zaragoza (Spain). She holds a Master's degree in Eco-efficiency and Energy Markets and is a post-graduate in Renewable Energies. She participated in a HEV project at TATA Motors LTD, Spain. She joined IDIADA in 2012 and has worked as EV implementation supporter in Japan. Currently, she is involved in electrification and new technologies integration projects: fuel cell, supercaps, etc.