POLITECNICO DI TORINO

Master degree in Automotive Engineering
Propulsion System Development

Master Degree Thesis

Analysis of Fuel Cell System for Automotive and Modelling of a Range Extender FCV based on PEMFC

Supervisors

Prof. Federico Millo

Prof. Vittorio Ravello

Company tutor

Eng. Massimo Milizia

Eng. Alberto Bertone

Eng. Patrizio Turco

Candidate

Michele Settembrino

S264907

Academic Year 2020/2021

Firstly, I would like to thank my University Supervisors, Prof. Federico Millo and, in particular, Prof. Vittorio Ravello, for their fundamental support during each phase of this thesis, to numerous advices given to me during these months and for what I have learn from their courses.
I would like to thank my Company Supervisor, Eng. Alberto Bertone and, in particular, Eng. Massimo Milizia, for their support and patience during my thesis activity along these months. For me, it was a pleasure work with them.
I would like to thank Teoresi Group to have accepted my application for this project.
Then, I would like to thank my university colleagues for these unique years that I've spent with them: it was pleasure work with them and share my passion for Automotive Field. A special thank to NO-Manager group and to two fantastic Manager Danilo and Pierpio for the time spent with me not only at Politecnico.
I would like to thank all my friends with which I've shared fantastic moments during these years.
I would like to, thank in particular, Samuele, Nicolò, Luca and Ciccio for what they have done for me and for how they have believed in me.
I would like to thank my roommates, Nando, Andrea and, with particular regard, Pippo (and Francesca), Alberto, Alessandro and Gianni: during these years they have been as a second family for me.
I would like to thank my relatives.
Last but not least, I would like to give the greatest thanks my fantastic family, my Mom and Dad which have supported me during these years regardless all difficulties, and Alessio from which, despite it is the little brother, I have learned and continue to learn a lot.

CONTENTS

GLOSSARY

AFC – Alkaline Fuel Cell

DMFC – Direct Methanol Fuel Cell

FC – Fuel Cell

FCs – Fuel Cell System

GHG – Greenhouse Gas

HU – Hybridization Unit

ICE – Internal Combustion Engine

MCFC – Molten Carbonate Fuel Cells

MEA – Membrane Electrode Assembly

MEGA – Membrane Electrode and Gas Diffusion Layer Assembly

PAFC – Phosphoric Acid Fuel Cell

PEM – Proton Exchange Membrane

REX – Range Extender

RH – Hybridization Ratio

SOC – State of Charge

SOFC – Solid Oxide Fuel Cell

TTW – Tank to Wheel

WLTP – Worldwide Harmonised Light Vehicle Test Procedure

WTT – Well to Tank

WTW – Well to Wheel

ABSTRACT

One of the biggest challenges for the Automotive Industry during next decade will be to develop low environmental impact and possible cost-effective solutions for the powertrain architecture and, thus, limit their dependency on fossil fuel. Already in the early 2000s, OEMs have invested huge amount of funds to research different ways to lower noxious emissions in order to comply the more and more stringent regulation by central governments. Moreover, local authorities, as the European Commission and EPA (*Environmental Protection Agency*, in USA,) have imposed CO_2 limitations and, therefore, the car makers are trying to optimize the conventional ICE-based vehicles and launch alternative type of powertrains, including pure battery electric vehicle (*BEV*) and hybrid vehicle (*HEV*), which combine, generally, at least on electric motor and a common engine. In addition to the abovementioned layouts, an attractive way to reduce both greenhouse gas effect and pollution can be the deployment of the *Fuel Cell System* (*FCs*) for vehicles to produce electric energy from the reaction of H_2 and Oxygen. In the next years, this kind of technology is promising to become a competitive and environmentally friendly solution due to next-to-zero *TtW* (*Tank-to-Wheel*) emission and the possibility to produce Hydrogen from renewable energy source in order to have zero *WtW* (*Well-to-Wheel*) emission.

The aim of this thesis is, firstly, to analyse the different and the underdevelopment applications of Fuel Cell in Automotive field, understanding which can be the best candidates of electrolytes to be used as *Power Source* in vehicle and recognizing how the electric energy is produced by means of the different electrochemical reaction within the cells.

The second part of the proposal includes the design and the optimization of Series Hybrid Vehicle, developed in MATLAB/SIMULINK environment. The different component of vehicle, as Battery Pack, Driveline, Fuel Cell Stack and its auxiliaries, are sized with the final goal to optimize the *Balance of Plant* (*BoP*) of the Fuel Cell system, to design a proper *Control Logic* for *Energy Management System* and reach the best possible efficiency.

In conclusion, an energy prospective comparison between Series Hybrid REX (*Range Extender*) vehicle ICE-based and FC-Based, with *Well to Tank* (*WtW*) emission analysis for the production of Hydrogen, is proposed.

1. INTRODUCTION

1.1 Main goal of Activity

In Europe the transport sector is responsible of 30% of overall greenhouse gases emission of which 72 % is accountable by road transportation, that includes passenger cars, motorcycles, light and heavy-duty vehicles [1].

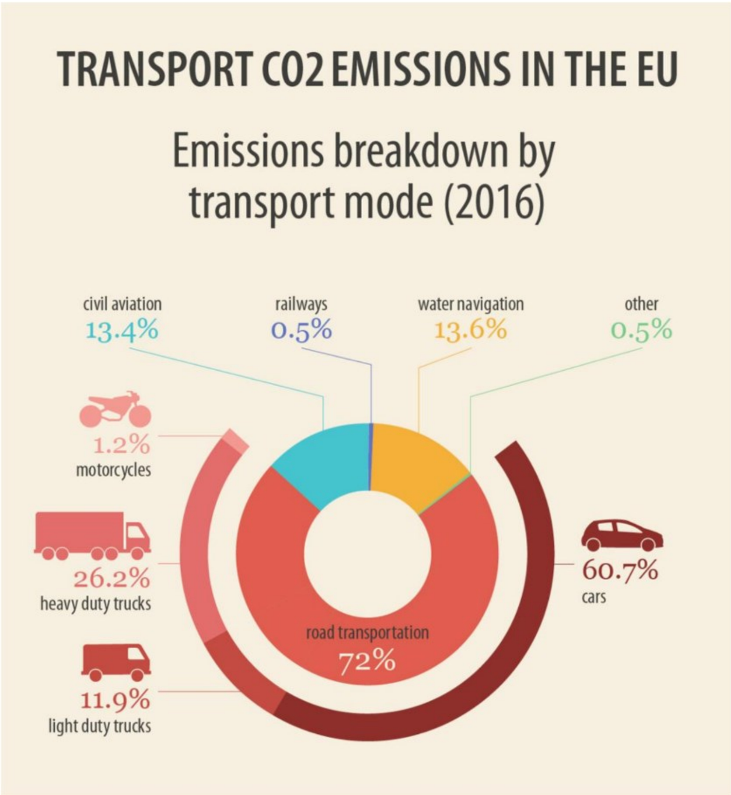

***Figure 1**: GHG emission share in Road Transport [1]*

As shown by the graph reported in the *Figure 1*, the highest contribution (60.7 %) of the emitted CO_2 is given by the passenger cars, therefore the main focus of European Commission is trying to force the car makers to find different ways to lower effectively the total GHG. In this scenario, the main actors are the ICE and its combustion process that causes the CO_2 production emitted by the pipeline. Consequently, the car companies are trying to meet the limitations imposed by EU introducing HEVs (ICE-based) and EVs.

Following the classification described by the professor *Joseph Beretta*, the HEVs are divided in two categories which are ***Simple Hybrid Vehicle*** and ***Complex Hybrid Vehicle*** [50]. The Simple Hybrid Architecture is further subdivided in two different group which are Series

Hybrid Vehicle and Parallel Hybrid Vehicle. In the former configuration ICE is not directly connected to the driveline, but it is used as an electric generation unit and the connection between the simple traction system (power generation module and E-motor) is done at energy source level. In the second solution the engine and the electric machine are both joined to the transmission line and these can give traction to the wheel, creating a mechanical linking between the ICE and E-motor.

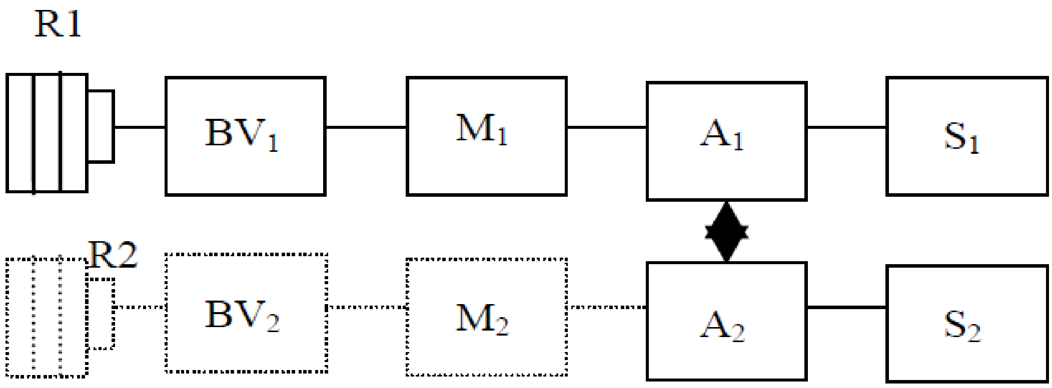

Figure 2: Series Hybrid Architecture according to Beretta Definition [50]

With the reference of *Figure 2*, the presented blocks represent different parts of the powertrain architecture; more in details:

- ***S_1***: is the energy storage system for the electric transmission, for instance the Battery Pack
- ***S_2***: is the energy storage system of the secondary power source, that can be fuel tank or Hydrogen Tank.
- ***A_1*** and ***A_2***: are the converter system between the two energy sources.
- ***M_1***: is the electric motor that gives traction to the vehicle.
- ***BV_1***: is the transmission unit, to connect the elementary traction unit to the wheel.
- ***R_1***: are the driven wheels.

The last drivetrain architecture is also called *Split Hybrid* and, according to the Beretta definition for the hybrid system, this kind vehicle has more than 2 elementary traction system, generally, at least 2 electric machine and one engine. One of the first car with this kind of system was the *Toyota Prius*, launched in the market since 1998 and, nowadays, it is being produced the third generation.

However, for all those layouts, the use of common internal combustion engine is only limited and, therefore, the effective reduction of pollutant can be achievable, mainly, in certain driving conditions, not eliminating completely the issue relative to CO_2 emission.
An EVs, instead, have the advantages to remove completely the pipeline emissions and also their overall efficiency is significantly higher with respect a baseline vehicle equipped with a common ICE: these are two of the main reason why electric vehicles are attractive products for OEMs to reduce of CO_2. On the other hand, an electric vehicle has some drawbacks among which:

- High cost of the battery pack to ensure a good range: for *Renault ZOE*, the price in 2018 was 180 euros/kWh and with a battery capacity of 52 kWh and overall distance covered in *WLTP* cycle (*Worldwide harmonized Light vehicles Test*) 395 km, it means that total price for the car maker was 9360 euros, with an overall market price around 26000 euro in 2021 [2].
- Strong dependency of the range on the temperature: a research shows how at -6°, the battery autonomy is decreased up to 41% [3].
- High weight of the vehicle: to ensure a long drivable range and good performance, it is necessary to increase heavily the number of cells for the battery pack and so its mass.
- Long charging phase: to recharge the battery from 0% to 80%:
    - the average time is from 30 minutes in DC Fast-Charging, with the drawback of degradation of Battery life
    - while in case of an AC Charging to some hours, but with the possibility con recharge the Battery through the domestic power grid.

In order to overcome the issues listed related to the electric vehicles, the main idea is to integrate an electric generation unit to produce the energy, as proposed by the Series Hybrid configuration. This allows to a decrease the frequency of recharging phase and downsize the battery pack, thus, lowering the its price, without renouncing to the benefits of electric drive.
In the recent years, some ICE-based examples of this kind of vehicle have launched in the market: for example, in 2014 *BMW* started the production *I3 REX*, which is a plug-in BEV equipped with a small motorcycle engine that is able to ensure an extra-range to the pure electric one, from 203 km, for the Pure Electric Version, to 320 km, for REX version (both with the same size of battery, 120Ah) [4]. The ICE is not connected directly to the driveline, but electric energy produced can drive the electric machine and, eventually, recharge the battery, with

penalties for a slightly increment of vehicle mass and, as previously described, the presence of an internal combustion engine that produce GHG emissions and pollutant. The idea to overcome these is change the power source, placing a Fuel Cell instead of a common thermal engine to produce the electric energy. The FC is a power plant that can generate electric energy from the simple electrochemical reaction between Hydrogen and Oxygen, with the possibility to completely eliminate the CO_2 at the pipeline.

The integration between the plant of an electric vehicle and the Fuel Cell system is modelled in MATLAB/SIMULINK environment. After a brief description of the different type of FCs and their performance, proper design for the Fuel Cell subsystem will be proposed.

1.1.1 Why a Fuel Cell System?

FCs is a device able to convert the chemical energy, without any combustion process, from the reactants, Hydrogen gas and Oxygen, into electricity. Unlike a common gasoline or diesel engine, which can be both adopted as a power generation unit, the Fuel Cell system has the advantages to have higher efficiency, from a maximum value around thermal efficiency 46% (in the best Scenario as for Nissan *E-Power* application [52]) for ICE to 60% for the FC technologies, and less impact from environment point of view. The level of the output power provided by the FC is at least equal to the one delivered by thermal engine and, meanwhile, the extra drivable range is ensured too.

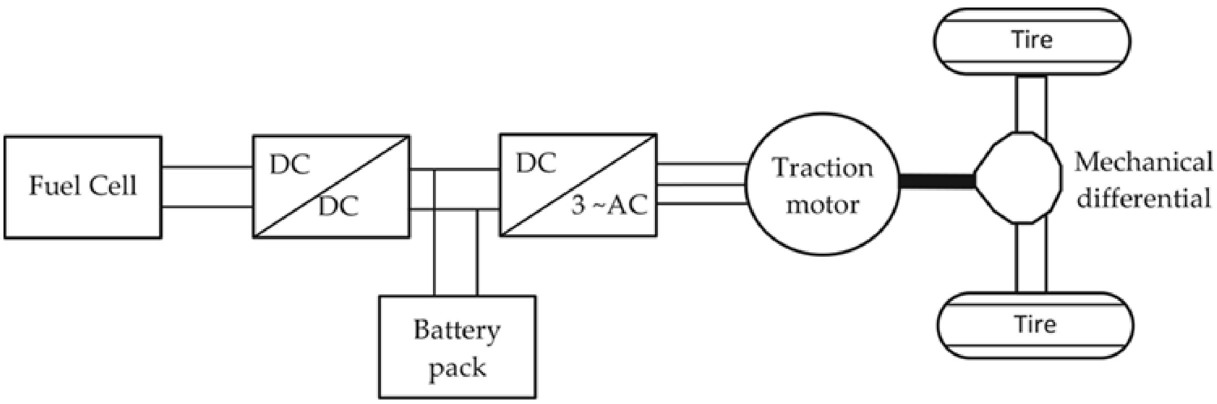

Figure 3: *Block Diagram of FCEV [51]*

In particular, the product of the reaction that produce electricity inside the fuel cell stack is water and so there are not pollutant substance emitted in atmosphere. Additionally, the fuels used to supply a FCs are generally Hydrogen or reformed-Hydrogen: these two have the potentialities to be zero-CO_2 WtT emission, in case of H_2 from renewable sources, or neutral-CO_2 *WtW* (*Well to Wheel*) emission, if the Hydrogen is internal or external reformed from fuel

as bio-ethanol or natural gases. Others benefits, with respect the ICE-based solution, are: dynamic performance, high modularity, good life cycle of the main components and possibility to enable cogeneration of power and heat for some types of fuel cell, better fuel economy compared with gasoline and diesel fuels.
The Fuel Cell behaviour is strongly dependent to the reaction enhanced and internal structure of Fuel Cell: nowadays, different types of electrolyte are available and these can be classified on basis of the operating temperature range and the main reaction that occur inside the cell.

1.2 Fuel Cell Basics

Fuel cells history started in the first half of the 19th century, when William Grove, a chemist, physicist and layer, had conducted a series of experiments during which he demonstrated that electricity could be produced by means the reaction between Hydrogen and Oxygen over a catalyst layer. Only in the 1950s, Francis Bacon, an engineering professor of the Cambridge University, exhibited the very first practical application of Fuel Cells with an output power of 5kW. Meanwhile, thanks to a partnership between NASA and General Electric, it begun the development of FC generator for space manner. Nowadays, the Fuel Cell system are used for a wide purposes and different type of cell has been developed.
In the previous chapter, it was explained shortly, how a Fuel Cell system works, which are the main advantages and why this technology can be used in Automotive field. More in deep, a FCs is device able to convert the chemical energy into electricity, water, heat and eventually CO_2 (for some electrolyte membrane application), through an electrochemical reaction of hydrogen and Oxygen. The FC structure is mainly composed by anode, cathode and an electrolyte exchange membrane in which the main reaction occurs: the reactants, supplied both at anode and cathode side, are fed by external supply systems whose design is strongly dependent of the type of Fuel Cell used.
In addition, a catalyst layer is used to split into electrons, which flow through an external circuit producing electricity, and protons. These migrate in the cathode generating water and heat from the reaction with Oxygen and further by-products of cathode side reaction [6]. Generally, to control the FC operation, it is possible to deal with the system temperature: indeed, raising it, the catalyst activity can be improved and a better efficiency can be achieved and, on the other side, an increment of temperature may lead to a reduction of functional life of different ancillary

components of the system. Indeed, a FCs is not only composed by electrodes (to draw the electric current), catalyst layer (to enhance the reaction) and membrane (in which the final electrochemical reaction occurs), but also by different auxiliaries, including pump, fuel storage system, blowers, muffler to exhaust the produced water and sophisticated sensors to handle and manage the operation of the system. In conclusion, to set a such important parameter as the operating temperature range, it is necessary to know the typology of fuel cell used, the reaction boosted and a proper trade-off between the overall efficiency and durability of components [7].

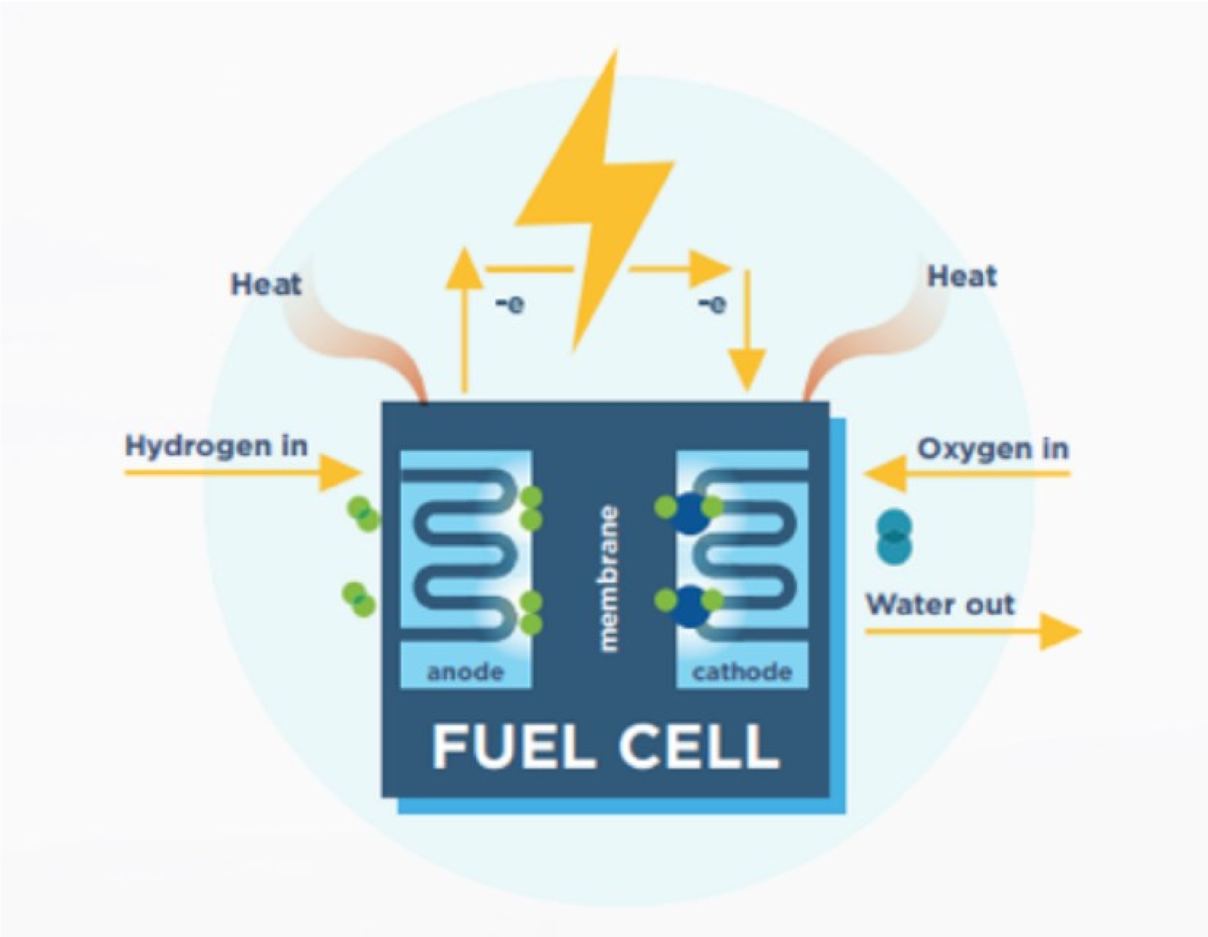

Figure 4: *Scheme of Fuel Cell behaviour [6]*

In this contest, a better distinction between the different type of Fuel Cell is needed: a first classification can be done on basis of the reaction at membrane level, temperature range and level of efficiency.

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluorosulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2; 40% reformed fuel	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Figure 5*: Different Typologies of FC [8]*

As reported in *Figure 5*, for each type of electrolyte membrane, it is possible to identify the possible application field, the benefit and cons.

- *PEM* (*Polymer Electrolyte Membrane*): the membrane is a proton-conducting polymer as electrolyte (Naflon is generally used). The two reactants are H_2 and O_2 and, respectively, the fuel (Hydrogen) is fed to the anode side, where the Hydrogen Oxidation Reaction (HOR) takes place, while air (pure Oxygen) is fed to the cathode, in which the Oxygen Reduction Reaction (ORR) occurs. The cells operate at low temperature, limiting the corrosion of the membrane and enabling quick warm-up phase, and have high dynamic performance, able to vary quickly the output as a function of power demand. Additionally, a high specific power is ensured, making PEM one of best candidate for the Automotive application.
  On contrary, the low possible temperature of PEM that is usually not higher than 120°, is a restriction for the co-generation of heat. Another parameter to control the membrane humidity, that displays the relative water content inside the *MEA* (*Membrane Electrode Assembly*). Having water inside the cell is fundamental to intensify the ionic conductivity. Since the total amount of water produced during the electrochemical

reaction is not sufficient, most of PEMFCs need a humidifier system to feed the correct amount of water at cathode side at the correct temperature, in order to avoid a possible reduction of cell voltage that implies a lower stack efficiency. Otherwise, an excessive amount of water is also detrimental since can cause the *flooding* of the membrane channels that, as a result, reduce the active area of MEA, worsening the performance. Another outcome of the temperature limitation is the low electrochemical activity and, to overcome this issue and ensure a good rate of reaction, the catalyst layer is made up by precious metal, such as platinum (*Pt*). Moreover, the catalyst layer is very sensitive to carbon dioxide contamination and, so, pure Hydrogen must be supplied to the anode side: this impedes the directly use hydrocarbon fuels without a reformer unit, combined with a proper filtering system [6].

$$Reactions = \begin{cases} Anode: H_2 \rightarrow 2H^+ + 2e^- \\ Cathode: \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \\ Overall: H_2 + \frac{1}{2}O_2 \rightarrow H_2O \end{cases}$$

- *AFC* (*Alkaline Fuel Cell*): this device has an aqueous alkaline or potassium hydroxide membrane as the electrolyte which allows to conducts hydroxide ions rather than protons. As in the previous type (PEM), the oxidizer is the Oxygen in the air. The main advantages are the fast cathode reaction in alkaline electrolyte, the use of a non-precious material as catalyst and the high theoretical efficiency (above 60%); while possible drawbacks are the requirement of pure H_2 and O_2, free form CO_2 and the high corrosion that affects the durability of the membrane itself and of the system auxiliaries [8].

$$Reactions = \begin{cases} Anode: H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \\ Cathode: \frac{1}{2}O_2 + 2H_2O + 2e^- \rightarrow 2OH^- \\ Overall: H_2 + \frac{1}{2}O_2 \rightarrow H_2O \end{cases}$$

- *PAFC* (*Phosphoric Acid Fuel Cell*): the electrolyte is a liquid phosphoric acid in which the protons kept inside a porous matrix may be conducted. Through this cell, it is possible to exploit a high level of efficiency, thanks to the co-generation of heat and electricity. Furthermore, PAFC are less sensitive to impurities in fossil fuel and, hence, hydrogen can be reformed. Backward, the dimension and the high loading of catalyst result in an increment of the cost and the temperature (up to 200°) along with the aggressive hot phosphate might produce design problems for pumps and sensors [7] [8].

$$Reactions = \begin{cases} Anode: H_2 \rightarrow 2H^+ + 2e^- \\ Cathode: \frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \\ Overall: H_2 + \frac{1}{2}O_2 \rightarrow H_2O \end{cases}$$

- *MCFC* (*Molten Carbonate Fuel Cell*): the membrane is molten potassium lithium carbonate and it operates at high temperature (above 600°). The cost of this technology is so high due to the possible use of non-precious metals as catalyst (Nickel is widely adopted) and inexpensive material for electrodes (metal based) and containment system (metal plus special plastic). In addition, methane or light hydrocarbons can be used to supply the cell without the need of an external reforming unit: thank to the high operating temperature, internal reforming process takes place. On the other side, the high temperature has some detrimental effect as corrosion of electrolyte and the long time to warm-up the system, making the use of MCFC not feasible for Automotive applications. In addition, the use of fossil fuel produces, as by product, carbon dioxide [7] [8] [9].

$$Reactions = \begin{cases} Anode: H_2 + \ CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^- \\ Cathode: \frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \\ Overall: H_2 + \frac{1}{2}O_2 \rightarrow H_2O \end{cases}$$

- *SOFC* (*Solid Oxide Fuel Cell*): this cell is built by solid-state non-porous material for the electrolyte as ion-conducting oxide such (for example zirconia treated with yttria). The operating temperature is, as for MCFC, high (up to 1000°) and this enable the possibility to exploit the co-generation of heat and necessity of precious material and, likewise, have a higher tolerance to carbon monoxide poisoning for the catalyst layers. From the performance point of view, the maximum possible fuel efficiency, combining the heat and electricity production, is up to 60%. Additionally, in this type of cell thanks to the high operating temperature range, the external reformer for the fuel is not needed, but the problems of corrosion and durability for the main sub-system are present [8] [9].

$$Reactions = \begin{cases} Anode: H_2 + O_2^- \rightarrow H_2O + 2e^- \\ CO + O_2^- \rightarrow CO_2 + 2e^- \\ Cathode: O_2 + 2e^- \rightarrow 2O_2^- \\ Overall: H_2 + O_2 + CO \rightarrow H_2O + CO_2 \end{cases}$$

In addition, other type of electrolyte membrane, not previously mentioned, is the *DMFC* (*Direct Methanol Fuel Cell*) which may be considered as a low-temperature Fuel Cell, since its range varies between 50° and 100°. The membrane, as for PEM, is a solid polymer and it is able to produce electric energy directly from the reaction of methanol (that is storage in liquid form), eliminating the need of hydrogen tank or/and of reformer unit to convert the fuel into Hydrogen. Otherwise, this system does not allow to clear completely the CO_2 at the pipeline and, moreover, to break the methanol bond, it is necessary to add to the common carbon supported catalyst not only the PT, also used for PEM, but also precious element (*Ruthenium*, *Ru*), leading to an increment of the overall cost for the system. Limitations also involved the crossover of methanol between anode and cathode, the poisoning to carbon monoxide for the catalyst layer and high polarization of the anode for the oxidation of methanol [10]. The reactions performed are:

$$Reactions = \begin{cases} Anode: CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \\ Cathode: \frac{3}{2}O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \\ Overall: CH_3OH + \frac{3}{2}O_2 \rightarrow 2H_2O + CO_2 \end{cases}$$

1.2.1 Performance of Fuel Cell

In order to characterize the efficiency of Fuel Cell Stack, it is necessary to study some particular functions and parameters, combining different equation with some input data. Considering that, calculate uniquely the overall performance for various type of FC is not a simple task to deal with, the idea is to find a proper set function which is able to determine the output voltage (one of the most important parameter) regardless the type operation enhanced by the membrane. Firstly, it is possible to distinguish the efficiency, between stack and system one: the former displays the effectiveness at membrane level, while the latter comprises also the power demanded by the auxiliaries. The two equations are:

$$\eta_{stack} = \frac{P_{stack}}{m_{fuel}LHV_{fuel}} \text{ and } \eta_{system} = \frac{P_{stack}-P_{auxiliaries}}{m_{fuel}LHV_{fuel}}$$

Another way to calculate the electric efficiency of a Fuel Cell Stack is to use the definition according to the voltage potential.

$$\eta_{stack} = \frac{V_{Actual-SingleCell}}{V_{Potential}} where\ V_{Potential} = 1.254\ V$$

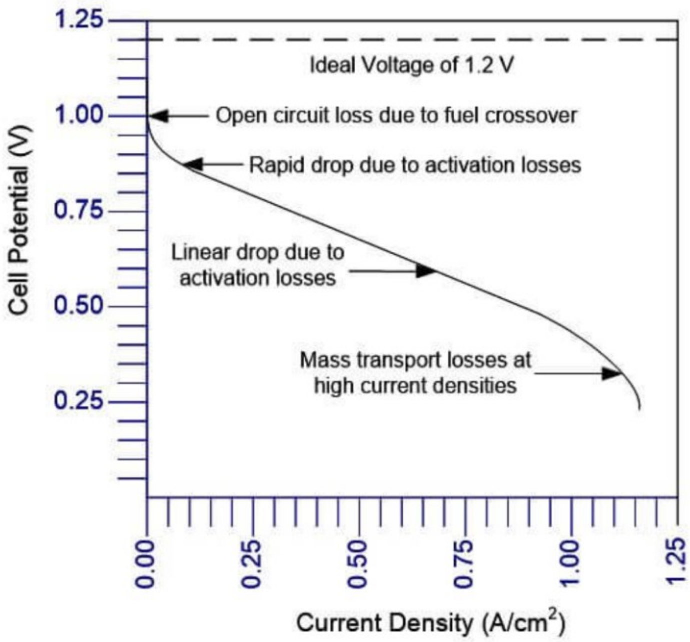

Figure 6: Polarization Curve [11]

A further performance indicator can be the *Polarization Curve* that displays the trend of DC cell voltage depending on current density [10].

As reported in the *Figure 6*, the Polarization Curve studies the stack DC potential that can be fluxed in an external load. The characteristic graph has on the *x-axis* the C*urrent Density* (usually measured in A/cm2) and on the *y-axis* the *Cell Voltage* (measured in V). The highest output voltage may be achieved in OCV (*Open Circuit Voltage*) condition, when no-load is connected. Increasing the current requested, the graph shows a reduction of the voltage, that is caused by three type of losses: *Fuel Crossover Losses*, *Activation Losses*, *Ohmic Losses* and *Concentration Losses*. The following describes the stack potential trend:

$$E = E_r - \frac{RT}{\alpha F}\log\left(\frac{i + i_{loss}}{i_0}\right) - \frac{RT}{nF}\log\left(\frac{i_L}{i_L - i}\right) - iR_i$$

- E_r is the *Nerst Voltage* and it is the ideal voltage at cell level, without any losses. It depends on the Gibbs Free Energy, actual operating stack temperature and partial pressure of the reactants. Through the Nerst equation it is possible to estimate this value:

$$E_r = -\frac{\Delta G_0}{2F} + \frac{RT}{2F}\log\left(\frac{p_{H_2} * \sqrt{p_{O_2}}}{p_{H_2O}}\right)$$

- *Fuel Crossover Losses*: these losses are due to the wasted fuel through the electrolyte. It is generally small, but for system with low temperature this term becomes more important.
- *Activation Losses*: these are the part of energy required to activate the electrochemical reaction on the catalytic surface. These losses are dominant at low current density in particular due to the slowness of Oxygen reaction. To describe this term, it is used the *Butler-Volmer equation*:

$$\Delta V_{act} = E_r - E = \frac{RT}{\alpha F}\log\left(\frac{i + i_{loss}}{i_0}\right),$$

$$where\ i_0\ is\ the\ reaction\ exchage\ current\ density$$

- *Ohmic Losses*: this term varies linearly with the current density, describes the voltage drop due to resistance to electrons flow to pass through the electrodes and it is remarkable at moderate load (or current densities). The cell components which contribute to this loss, are the electrolyte, the catalyst layer, the gas diffusion layer (also called *GDL*) and the bipolar plates. The equation that defines the amount of ohmic losses has two main parameters: the *electronic resistance* (R_{elec}) and the *ionic resistance* (R_{ionic}). The dominant part is the ionic one, which represents the resistance of the electrolyte, since it is more difficult to transport this charge with respect to electronic ones (that models the resistance of others subsystem of the cell) [10].

$$v_{ohmic} = i * (R_{elec} + R_{ionic})$$

- *Concentration Losses*: the mass transport loss is the result of a change in concentration of one of two reactants (fuel and Oxygen) and it is significant at high level of current density. Since the system has to be supplied continuously by fuel and oxidant to produce electricity and the products (generally, water) must be removed to have as lower as possible leakage, the term of concentration losses has to be minimized in order to obtain the maximum possible performance. The related equation is [10]:

$$v_{ohmic} = c * \log\left(\frac{i_L}{i_L - i}\right)$$
$$where\ \mathrm{c} = \frac{RT}{nF}\left(1 + \frac{1}{\alpha}\right)$$

1.2.2 Example of FCs in Automotive Field

In the previous paragraph, different types of electrolyte have been described, but not everyone are suitable for Automotive application. Indeed, FC are widely applied, not only in transport sector for passenger car, lorries and busses, but also in marine field, as portable generation unit or for power plant application. Notably, the MCFC and PAFC are currently use as power plant utilization due to features of these systems, while the typologies feasible for passenger cars, light commercial vehicles or, generally for road-transport sector are AFC, PEM and SOFC. The most use is the Polymer Electrolyte Membrane, but, for example, Nissan has an underdevelopment a Solid Oxide Membrane (with an external reformer), that may be the first application for this kind of electrolyte in a vehicle.
Nowadays, only few car makers have developed an integrate Fuel Cell system for a specific vehicle: Japanese and Korean OEMs, mainly, have launched Fuel Cell vehicles from the beginning of 2000s.

- Toyota in 2015 presented the world-car *Mirai*, a PEMFC-based vehicle which was a huge breakthrough with respect the previous prototype *Toyota FCHV-adv* (manufactured in few units from 2008). Compared with the previous model, a huge increment of power density at Fuel Cell level is obtained, increasing the available power from 90 kW to 114 kW, with a lower loading of Pt (reduced by 2/3 compared to Toyota FCHV-adv) and a better fuel economy, up to 20%. As result, the cell voltage is 2.4 times higher with respect the model in 2008 and it has led to reduction about 24% of the overall volume occupied by the Fuel Cell Stack (the power density is 3.1 kW/L). Other innovations proposed are an innovative membrane, which is promising to raise the efficiency of overall system and to take out the need of Humidifier Unit. The membrane is able to perform *Self Humidification*, thanks to a new design flow field between anode and cathode. A new storage layout (*High-Pressure Hydrogen Tank*) also has allowed to reduce the overall cost of this component, boost the pressure (from 35 MPa to 70 MPa) and minimize the weight, and a *Fuel Cell DC/DC boost converter* enables to adjust the voltage fluctuation between inverter and motor, allowing to ensure the same level of reliability at lower cost and size for the overall motor system [12] [13].

In the last months of 2020, it has been launched a new version of Toyota Mirai. The main features are [53]:

1. An improved overall power, from 114 kW to 128 kW for the model year 2021.
2. An increased number of Hydrogen tank, from 2 to 3, to have a prefect weight distribution (50% on front axle 50% on rear).
3. An extended cruising range, from 650 km of the previous model to 750 km
4. A higher output density of the Fuel Cell system, from 3.5 kW/l to 5.4 kW/l.

In addition to the reported innovation, Toyota has developed a product that packages a fuel cell (FC) system into a compact module. The new module will be easily utilized by companies as FC module for wide variety of applications, including road transport such as trucks and buses, or trains and ships, as well as power generation purpose. The new module has a voltage range between 400 V and 750 V and can be connected to electric motor, inverter, battery and other electric instruments. The modularity and the facility of application is given by the use a built-in FC boost converter that simplifies the coupling with other external circuit [54].

- Honda, starting from 2008, has put in production *Honda FCX Clarity*, that was the first PEMFC production car. In 2017, a new version was presented with some updates, like a new cathode supply system in which the air compressor has been replaced by a motorize turbo-compressor unit that allows to reduce volume of the sound absorber equipment by 50% and to support a better air supply pressure (1.7 times, compared to the previous one) [14]. A further fuel economy is obtained, with a drivable range that has extended from 372 km to 589 km (according to *EPA*) [15].

- In 2018, Hyundai has introduced a hydrogen Fuel Cell powered SUV, *Tucson FCEV* the successor of *ix35 FCV*. Despite, the chassis of the previous version was directly based from the common combustion-engine platform, for the new model, a "*Fuel Cell-oriented design*" is implemented, in order to have a frame with the available space more suitable for the FCs. Moreover, evolution for humidity controller and the application different polar plates has been installed and it has permitted to extend the operating temperature range and enhance a better efficiency of the car (the overall value for this version has climbed to 60.4%) [16].

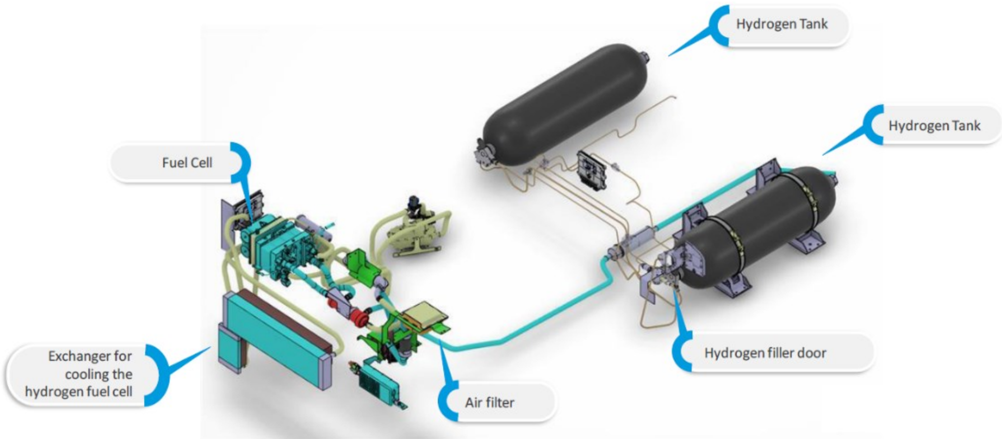

***Figure 7**: Fuel Cell System of Master Z.E. Hydrogen [17]*

In the last decade, also European companies have started to invest in Fuel Cell technologies, but, nowadays, only Renault (in 2019) in a partnership with PlugPower has added in its portfolio two light commercial vehicles (*KANGOO Z.E. Hydrogen* and *MASTER Z.E. Hydrogen*), FCHEV Range Extender based on PEM technology, a premiere for a Hydrogen LCV in Europe. The fuel cell may be activated automatically or by the driver when the *SOC* (*State of Charge*) of battery is at least 80%: the aim to maintain the level of charge or eventually recharge the battery during downtimes in driving condition. Furthermore, if the level of charge is under 2%, the vehicle can run only with electric energy produced by hydrogen. Compared to the electric version of the same vehicles, Renault claims that the FCs is able to provide additional range to cover a range up to 3 times higher (in WLTP cycle), with a drastic reduction of recharge time: from hours to 5-10 minutes for the Z.E Hydrogen version [17].

Meanwhile, other companies, whose business is not only the road-transport sector, (as for example, Ballard, Nuvera and Siemens) have realized different Fuel Cell system technology, with the final aim to produce flexible modules that may be used by different OEMs for wide applications.

Ballard has lunched in the market *FCveloCity®*, a line of PEMFC modules with multiple power size (30kW, 70 kW, 85 kW and 100 kW) designed to be integrate as range extender unit for light commercial vehicle, small transit busses and trucks [18].

Figure 8: *FCveloCity® - MD, 30 kW output Power [18]*

The main features of this system are: high performance, good fuel efficiency, flexibility to adapt the module to the final vehicle and durability of the components with a functional life ensured for at least 30000 hours of operation.

Nuvera, at the end of 2020, has introduced in its portfolio *E-Series Fuel Cell Engines* (*E-45* and *E-60*), a series of Fuel Cell units developed to be applied as power generation system in the transport field. According to the firm, these systems are able to ensure a high rate of flexibility in order to be easily integrated with existing electric vehicles [19].

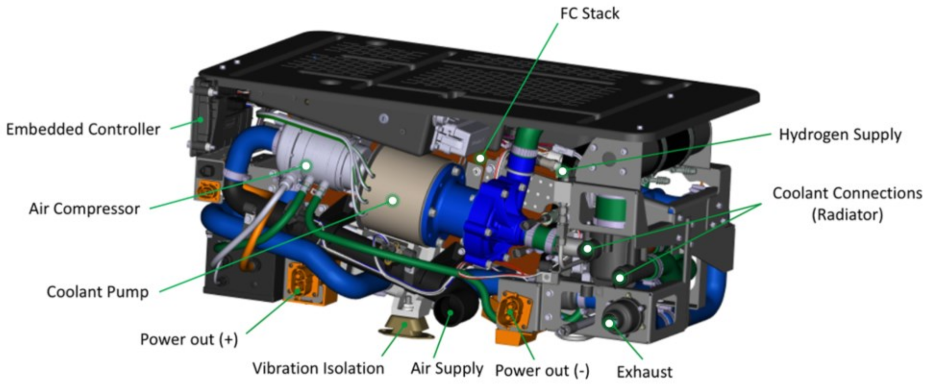

Figure 9*: Nuvera® E-Series Fuel Cell Engines [19]*

Bosch has an existing product line, which includes the main auxiliaries for the PEMFC, as sensor, Fuel Cell control unit, anode recirculation blowers, hydrogen gas injector and electric air compressor and, in partnership with the Sweden manufacturer *PowerCell Sweden AB*, has started to develop a FC stack powered directly by Hydrogen, based on the *PowerCell S3*. This prototype, produced by the Sweden Company, has a large scale of output power (from 30 to 120 kW) and the main features are the compact size and light weight. The final aim of Bosch, it to put in production a Fuel Cell stack that can be provided a good level of integrability with electric powertrain and integrable with the components manufactured by Bosch [20] [21].

Standard stack configuration

Max power	75 kW	92 kW	115 kW	125 kW
Cell count	275	335	419	455
Dimensions [i]	420 x 395 x 156 mm	420 x 457 x 156 mm	420 x 545 x 156 mm	420 x 582 x 156 mm
Weight	29 kg	34 kg	40 kg	42 kg

Figure 10*: Physical Data PowerCell S3 [19]*

1.3 Description of Series Hybrid Vehicle

Due to the actual cost of the battery pack, low autonomy and the long time required to phase recharge, the mass spread of *Pure Electric Vehicles* is limited to a slightly more than market niche. To overcome these problems, without renouncing to the huge benefits of electric drive, the Series Hybrid Vehicle may be the best possible alternative among the full electrified solutions. Compared to the Parallel Electric Vehicles and, above all, Split Hybrid layouts, the control system is generally simpler and the torque to the transmission line is directly feed by E-motor. Thus, the power generating module can be usable in the best possible operating condition in order to exploit the maximum possible efficiency according to the driver request. To do that, it is necessary to limit as much as possible the dynamic of hybridization unit, especially if a common ICE is used as secondary supply power source.

An indicator that provides an information about how much power is produced by the electric generation unit, is the ***Hybridization Ratio***: this shows the ratio between the generated power by the secondary unit and electric power delivered to electric motor. The formula that shows this parameter is:

$$R_{h\_Series} = \frac{P_{gen\_elect}}{P_{elect\_mot}}$$

According to the value of the Hybridization ratio, which ranges between 0 and 1, it is possible to classify the different configuration of a Series Hybrid Vehicle. To be specific, three possible layouts are identified, plus other two that represent the borders of R_{h_Series}.

- For a value equal to 0 of the Hybridization Ratio, the vehicle does not have any secondary power source and it means that all the requested power is drawn by the battery pack: therefore, this is a Pure Electric Vehicle, with the advantages and disadvantages previously discussed.
- On the other side, with a value equal to 1, all the power needed by the electric motor is produced by Hybridization Unit. In literature, this particular kind of vehicle is called "Electric Transmission": the electric drive, as in a conventional Pure Electric Vehicle, is always enabled, but the power source is not a battery pack. Indeed, the installed power source can an ICE or a Fuel Cell system, and it has continuously to follow the dynamic requests by the driver, producing the electric energy needed to cruise the vehicle. The only battery is the one devoted to the auxiliaries (generally a 12/24V battery). Despite, it is possible to enable to *optimal operating line* (in case of ICE application), the overall GHG emission are far from 0 and the high costs of all devices, along with their size and weight, have limited the use of this solution.

1.3.1 Series Hybrid Configurations

The other three configurations, mentioned in the previous paragraph, are function of hybridization ratio that furnishes a primary information about the sizing of the electric power-energy sources. In particular, it can be useful to define the *Hybridization Unit* (*HU*), that is composed by the secondary electric generation unit, an electric machine used as generator (in case the supply unit is an ICE), and, generally, power converter. Thus, it is possible to identified three main families:

- ***Range Extender***: HU power is equal to the average power requested in a reference cycle representative of the real driving condition. The supply unit works at the maximum possible efficiencies and the extended range depends on how much energy is available at tank level while the use of battery pack is restricted to *Buffer* operations.
- ***Load Follower***: the installed power of HU is set to the continuous maximum power and the supply power does not work at fixed point, not always exploiting the optimal efficiency, but follow the driver request up to the its maximum available power. In this layout, the battery pack is sized to cover the peaks power, adding up the maximum power from the HU and the remaining portion of requested power from the battery. Using a common ICE as a power supply, the noxious and GHG emission are worse, but in some cases, it is possible to exploit a higher overall efficiency and better performance.

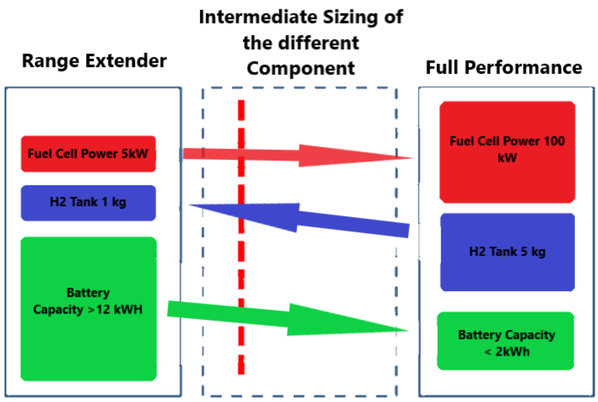

Figure 11: Power Source Sizing for Fuel Cell Series Hybrid Vehicle

- ***Full Performance***: the energy supply unit is sized to cover the maximum transient power condition. This configuration can be perfectly matched with the requirement of Fuel Cell system used as HU, since, in contrast with the internal combustion engine, the maximum power does not coincide with the maximum possible efficiency. Indeed, employing these sizing criteria, the overall installed power of the FCs can be significantly higher than the requested. Although the high power available at HU could not require the presence of a battery pack, for this strategy having a supplementary electric storage (a battery or even a supercapacitor) is meaningful, since enable different advantages as: limit the dynamic of HU, make possible the regenerative braking, ensure a fast start-up mode (both for FC and ICE) and allow different energy management approaches.

1.3.2 Range Extender Architecture

The Range Extender Series Hybrid vehicle is developed with the final aim to extend the range of the vehicle, eventually, narrow the capacity the battery, thus its cost, and reduce the frequency of the recharge phase at grid. The solutions adoptable for secondary power source are: common ICE-based (generally a low displacement is preferred), Rotary engine-based (a Wankel unit is used to generate current) or Hydrogen Fuel-Cell-based, with general adoption of PEMFC of SOFC.

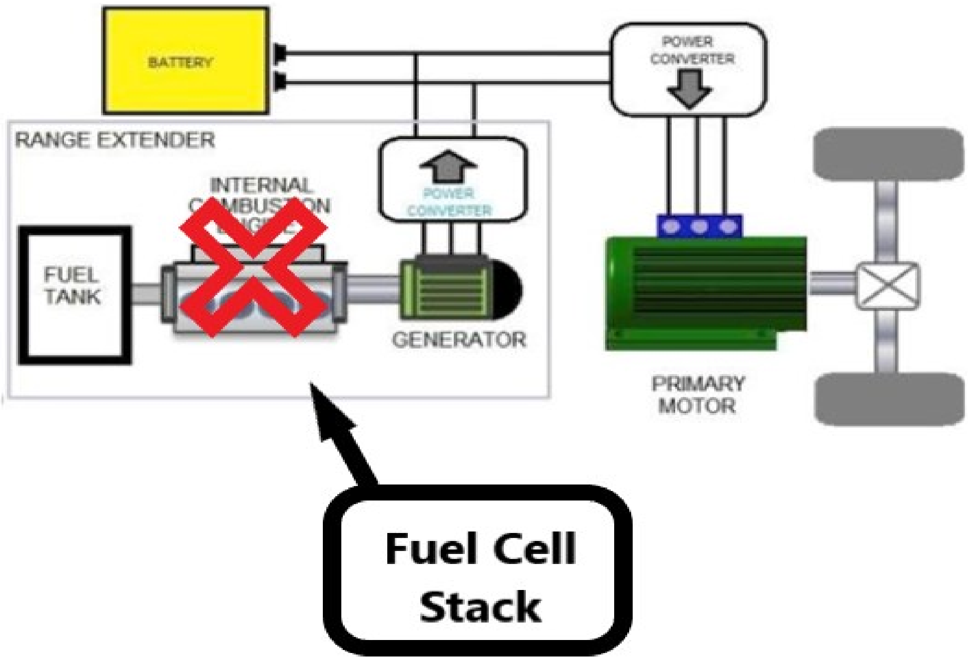

***Figure 12**: Range Extender Vehicle, Fuel Cell-based*

As reported in *Figure 12*, in case of the HU is ICE or Wankel engine, a second E-machine is employed as an electrical generator to convert the mechanical torque, at the output of the engine-shaft, into electricity. Instead, the Fuel Cell does not produce mechanical power and its output is an electric signal, avoiding the use of E-generator, eventually, replaced by a common DC/DC converter to regulate the voltage between FCs and vehicle system.

Particularly importance has the sizing of the HU, that should be tuned for a reference driving cycle: in this way, it is possible to not penalize the performance of the vehicle and to optimize the fuel economy. Indeed, with a proper control strategy and trade-off between the use of energy sources, it is possible to implement various energy management strategies, in order to exploit the maximum efficiency of the secondary supply unit and, at the same time, have the lowest possible fuel consumption. A huge relevance has the management of the battery pack: two main operating modes can be deployed depending on the actual SOC and these are *Charge Depletion* (*CD*) and *Charge Sustaining* (CS).

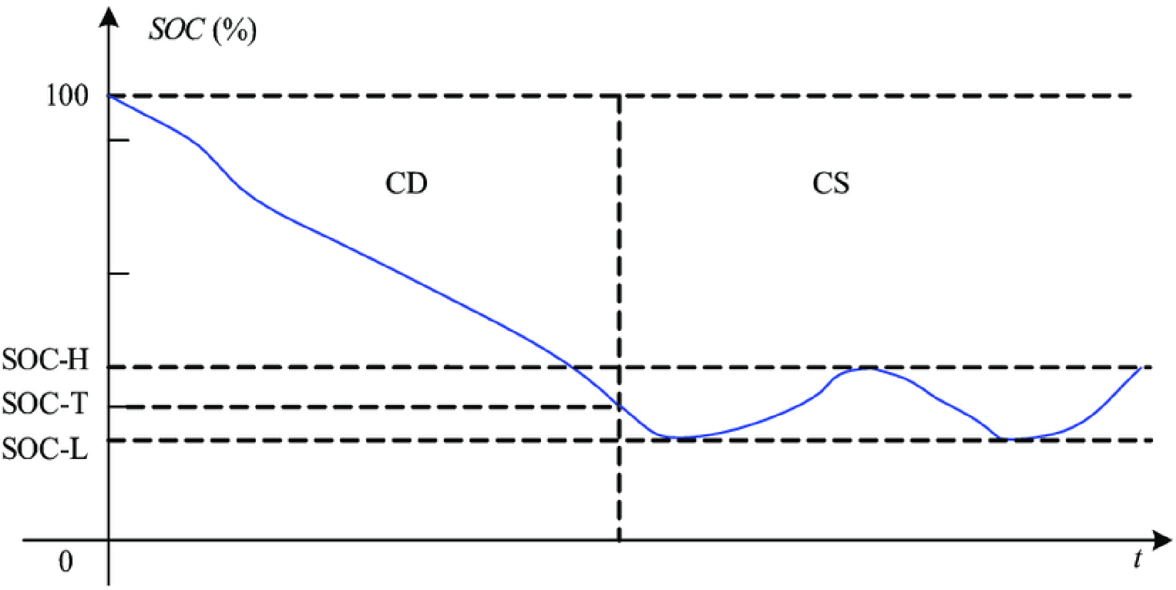

***Figure 13**: Charge Depletion and Charge Sustaining [23]*

The working principle of this mode is based on the idea that in CD mode the actual SOC is higher than certain threshold and only battery provides energy to the electric machine, while the secondary power source is OFF. Opposite, if the SOC is below a certain value, the CS mode is enabled: to maximize the fuel economy and, meanwhile, to minimize the charging-discharging inefficiencies of the batteries, the power produced by the range extender is used to meet the required wheel power, supplying directly the electric motor. Generally, in case of the required power is lower with respect the output power of the HU, it is possible to use the surplus power to recharge the battery. The typology of the supply energy source strongly affects the working modes that can be carried out: an optimal trade-off between fuel economy, warm-up phase and performance required have to be found in order to exploit the maximum possible efficiency and, eventually, the lowest noxious emissions, extending the *Zero Emission Drive*.

Another beneficial aspect of the REX Series Hybrid Vehicle is that can be possible to develop this kind of system, without increasing heavily the total mass or reducing the available space for the passengers. Furthermore, existing solutions on the market, as for example the abovementioned BMW i3, have Pure Electric Version, making possible a huge reduction of costs during the design phase. More specifically, BMW has manufactured a Range Extender ICE-based version of the B-segment Electric Vehicle, with only a modified version of the platform used for the Pure Battery Vehicle: the final result is a little increment of the overall weight due to the presence of motorcycle engine, its auxiliaries and the tank of the fuel (the mass grown up from 1195 kg for the Pure Battery Vehicle to 1315 kg for the REX version, both equipped with the same battery pack, 94 Ah) [4]. In addition, for what concern NVH issues, it is possible to achieve great result: for a REX vehicle equipped with a small displacement ICE (900 cm^2), it is demonstrated that, once the vehicle is travelling above 40 km/h, the engine starting is imperceptible to the vehicle's occupants, as road and wind noise become predominant [24]. Even better performances are obtained the with PEMFC system, since its noise is around 40dBA and it is significantly lower with respect to a common Diesel Engine (82 dBA) [25].

2. FC SYSTEMS: STACKS AND BALANCE OF PLANT

2.1 Existing and Underdevelopment solutions for PEMFC in Automotive Field

The widespread diffusion of FCEVs or FCHEV based on PEMFC is strongly limit by multiple factors, among which the most significant are availability of Hydrogen station for the refuelling operation, cost of the technology due to the requirement of precious metal for some types of cell and storage of high-pressure fuel (up to 700 bar) in the vehicle.

Around the world, different countries have established an integrated program to pave the way for the development of Hydrogen technologies. In USA, for instance, the central government settles that hydrogen and fuel cell technology are part of its national energy strategy to promote the decarbonization of the transport sector. Especially, California has become the most active federal state that pushed the spread of Fuel Cell: the imposed target is to have almost one thousand hydrogen refuelling stations and one million of FCEVs by 2030. Similarly, in Europe, Japan and China different proposals are deploying to sustain full-scale popularization the Hydrogen solution [5].

		Passenger vehicles	Buses and coaches	Trucks**	Forklifts	Refueling stations
US	Current	7,271 [44]	35 active, 39 in development	prototype test	>30,000 [335]	~42 online [37]
	Target		5,300,000 FCEVs on US roads by 2030 [337]		300,000 by 2030 [337]	7,100 by 2030 [337]
China	Current	0	2,000+ [64 83 84 85]	1,500+ [94]	2	23 [89]
	Target	3,000 by 2020 [87] 1,000,000 by 2030 [336]	11,600 commercial vehicles by 2020 [87]			100 by 2020 500 by 2030
Europe	Current	~1000+ [42]	~76 [42 73 86]	~100 [88]	~300 [42]	~152 [71]
	Target	3,700,000 by 2030 [34]	45,000 fuel cell trucks and buses by 2030 [34]			~3,700 by 2030[34]
Japan	Current	3,219 [44]	18	N/A	160	127; 10 in progress
	Target	40,000 by 2020 200,000 by 2025 800,000 by 2030 [24]	100 by 2020 1,200 by 2030 [24]		500 by 2020 10,000 by 2030 [24]	160 by 2020 900 by 2030 [24]

***Figure 14**: Targets for diffusion of the FCs in Road Transport Sector [5]*

2.1.1 Technical Solution in the Market

In the previous paragraph, it was shortly mentioned that the main technological problems related to the diffusion of the Fuel Cell system in the vehicle, are the catalyst loading and the tank to store the fuel: both are critical for what concerns the overall cost of the system, while the weight is significant influenced by the vessel dimension.

In order to reduce the content of precious metal to boost the reaction and, meanwhile, increase the fuel economy with benefit for the dimension of storage system, different way have been studied. Before it is fundamental to analyse the Plant of PEMFC: for Automotive application, the system is composed by the Fuel Cell stack and ancillaries to regulate the reactants and control the internal temperature.

- **Fuel Cell Stack**: in automotive application, the Fuel Cell stack is the core in which the electrochemical reaction occurs. The stack is also known as membrane electrode assembly (MEA) and it is made by a sequence of different layers that are devoted to perform different operations. These layers of single cell are: *End Plate*, *Gaskets*, *Bipolar Plates*, *Anode*, *Cathode* and *Proton Membrane*.

  To explain better the operation inside the stack, as briefly discussed in the introduction, it can be worth to describe how the reactants are fed and in which way the reaction occurs. Firstly, the Hydrogen is supplied to this porous anode and it passes over a negatively charged anode electrode, where, in the at catalyst level, is split into H+ (ions) and e^- (electrons), which are then transported through an external circuit to produce current. On the opposite side, the oxygen passes over a positively charged cathode electrode and, after this, the ions go through the electrolyte to the cathode and react with oxygen to produce H_2O and heat as by-products. Since oxygen will react with the protons, during this operation the main element of the air that diffuses from the cathode side to the anode once is nitrogen: for this reason, the N_2 has to be eventually discharged from fuel side. The two most important parameters at cell level are the cell potential and the output current: in order to have higher values of these quantities, it is necessary to connect in series a higher number of cells, up to the desired nominal or maximum power.

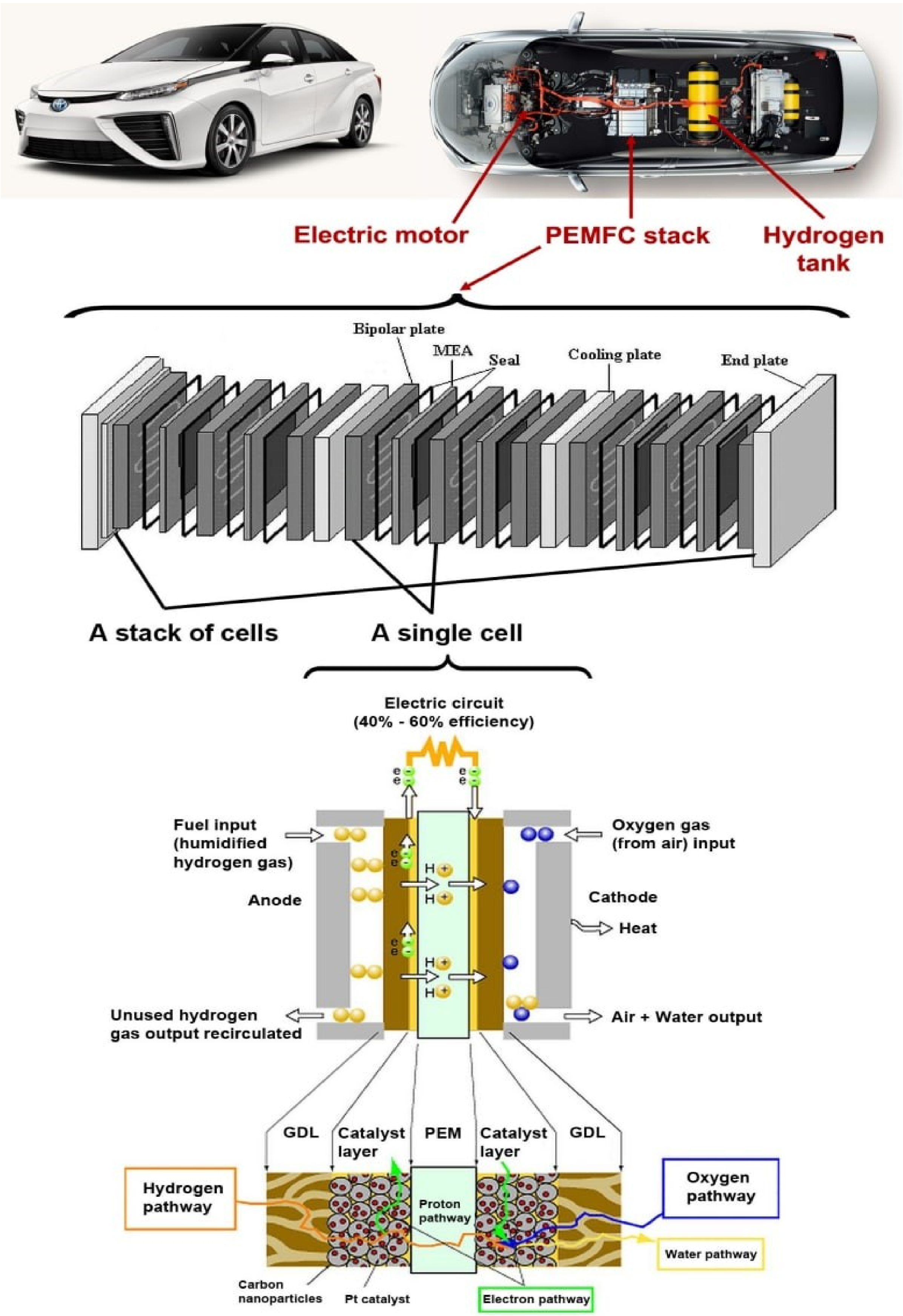

Figure 15: Fuel Cell Stack Description

- **Auxiliaries of the FCs Plant**: the FC is used to produce electricity and eventually heat, but to get this the stack needs to be supplied with the correct amounts of reactants, control the system temperature, having the optimal operating conditions, and provide the correct amount of water in order to enhance stable behaviour. The elements needed are mainly: *Air Compressor* (moved by an electric motor) to deliver the air flow rate o *Hydrogen Injector* that control the fuel stoked in the anode and connected to the *Tank* in series with a regulation valve*;* a *Recirculated Pump* to distribute the unused fuel at the inlet; an *External Humidifier* in order to manage the *Relative Humidity* (*HR*) and water content inside the membrane; an *External Cooling Circuit* made up by radiator, fan and cooling pump; *Muffler* to exhaust the water produced during electrochemical reaction; *Sensors* to provide signal to the Electronic Control Unit.

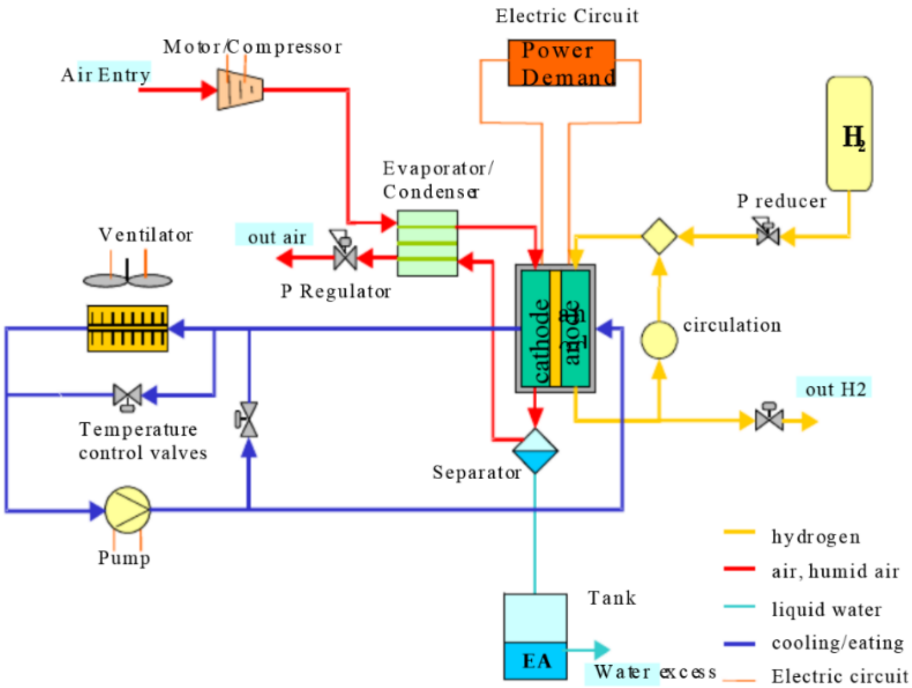

***Figure 16**: Auxiliaries of PEMFC [26]*

In particular, the Air Compressor, the Coolant Pump and the Recirculation Pump are driven by different electric motor: these are detrimental for what concern the overall efficiency of the FCs, because part of the electrical power produced by the electrochemical reaction is consumed to provide energy to those electric machines. Moreover, to conduct a better analysis and balance the plant, it is significant to study the single efficiency of the various subunits in different working modes: since this can lead to a huge complexity of the investigation, a further simplification can be introduced, taking into account only a single value of performance for any items.

All of the components previously described are fundamental for the proper operation of a PEMFC, but the Water Management plays a key role to have stable output power according with the system requests: lower value of hydration of the membrane will decrease the protonic conductivity, affect the resistive loss increasing its value, and, thus lower net fuel cell stack power. Another huge issue related to the lack of proper humidification is the life cycle of the MEA: local hot spots could be formed and it can lead to reduce the membrane duration. At the same time, the presence an excessive quantity of water in the membrane or in the gas diffusion layer introduce the opposite problem: flooding will occur and it causes the stoppage of the gas flow in the channels, electrodes, with major effects on the FC performance and duration. Therefore, it is essential to manage properly the membrane humidity and avoid dehydration or flooding, regardless the cost and the power demanded to the system for this component to ensure this correct amount of water as a function of the driving and environment conditions [27]. The importance of the correct Humidity Management is even more for automotive applications since requested current drawn the fuel cell can change rapidly, in accordance with driver demand.

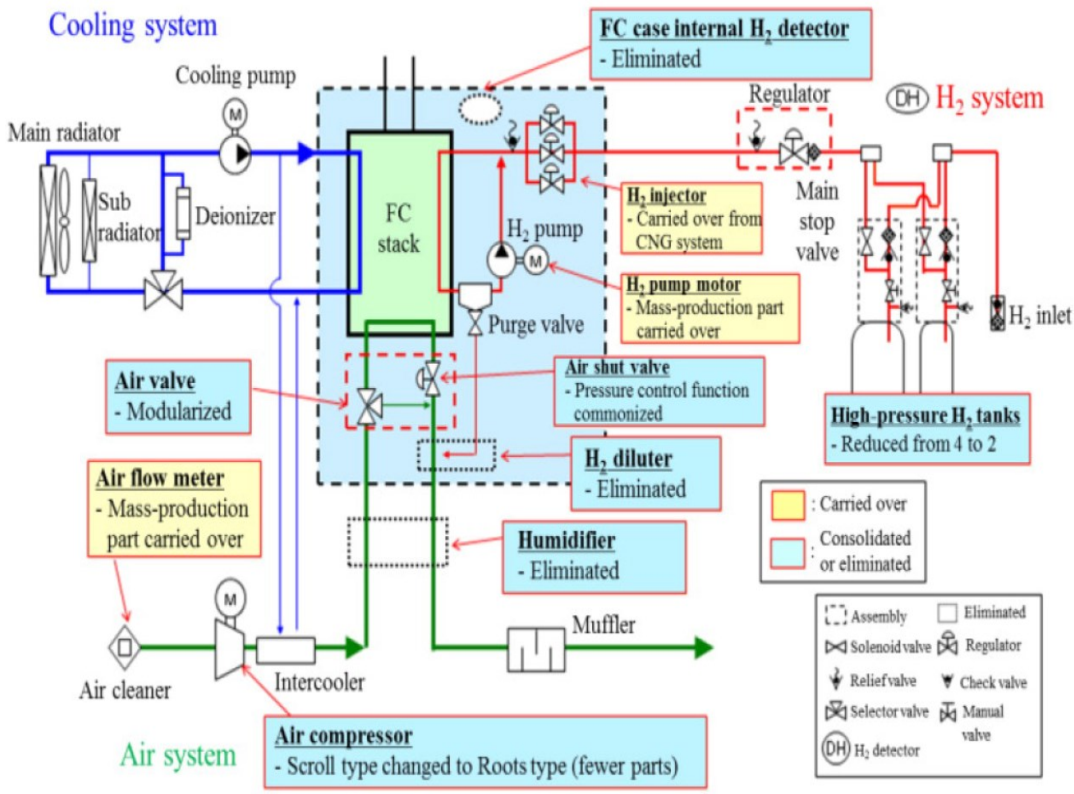

***Figure 17**: Mirai FCs vs FCHV-adv System [12]*

Up to now, the layout of a baseline system has been described, but in the recent year a huge step-forward has been made with the introduction of control unit and technologies able to mitigate, partially, the limits of the old PEMFCs and allow to exploit higher level of performance. In order to do a remarkable comparison between a "standard" configuration and an innovative system developed in the last decades, it is possible to take as reference the system introduced by Toyota in 2008 for the prototypal vehicle FCHV-adv and compare it with the innovative FCs presented in 2015: through the various innovation introduced, the PEMFCs became more reliable, efficient and a better fuel economy can be achieved.
As reported in the Figure 17, there was huge evolution of the plant between the version of the 2008 and the current design. The most significant improvement is the elimination of external humidifier: this component allows to control inside the membrane in order to reduce the losses inside the MEA, but it has the drawback that tends to increase air system pressure loss, raising up the load required to anode-cathode supply systems, and the complexity of the plant.

Therefore, the challenge is to adopt FC system without an external humidifier through improving water management inside the membrane and fulfil others technical innovations introduced for what concern the system temperature and reactants flux directions. To accomplish the goal of free-Humidifier operation, three structural countermeasures inside the membrane are adopted:

1. The first was to reduce the dimension of the electrolyte membrane thickness, thereby promoting the *back diffusion* of water generated downstream in the air system. Moreover, an innovative three-dimensional (3D) fine-mesh flow field has been proposed was developed for the cathode side. The flow field is designed as 3D micro-lattice that guides the air toward the MEGA and meanwhile favour the diffusion of the Oxygen in direction of the Catalyst Layer. Some countermeasures are set to the geometry and surface wettability of the 3D fine-mesh flow field to optimize the back diffusion of the water generated through the MEGA. In addition to that, a further aid is guaranteed thank to the prevention of the mass transportation loss due to flooding, with the final advantages to enable a more uniform power generation for each single cell surface and to reduce voltage difference cell by cell. Last improvement is made as result of the possible modification settled up at flow field level within each cell surface in favour of a reduction of air turbulence, that may lead to an additional drying action inside the MEA [13].

2. The second deployment is to enhance the humidification of the system, using the residual moisture at the anode. To do that, modifications were made in the anode level: the structure is build up as integrated channel-based fine-pitch flow field structure with the circulation of the H_2 flow on the front-side, while coolant is flowing on the back-side. This structure provides several important functions to intensify self-humidification at anode stage: firstly, the generated water is recycled from the air outlet path by the action of back diffusion that helps the humidification of the inlet anode. Secondly, the humidification of air inlet port is boosted by through back diffusion from water vapor in the anode. To exploit this function, the H_2 pump plays a critical support role by recirculating water. By means of Hydrogen recirculation pump, furthermore, it is possible to perform the humidification of the cathode inlet, which is susceptible to drying: the flow rate of H_2 circulation at the anode is increased as a function of the driver request. To have a good amount of water (or water vapor) at the outlet of then anode, the two reactants flow in counter directions and to efficiently migrate the water generated enhancing even more the back diffusion from the cathode outlet to the anode inlet. Another possible strategy is to reduce the anode pressure, with the benefit of ensuring the required amount of circulation can aid the movement of water into the anode surfaces [13].

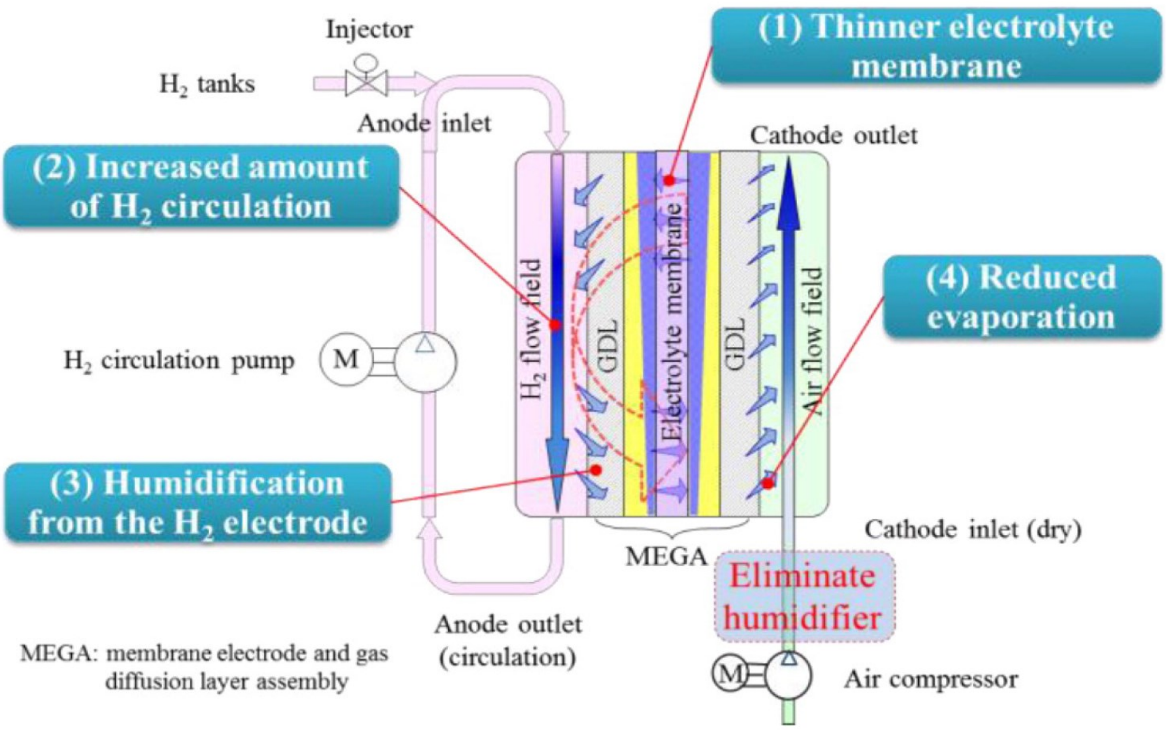

***Figure 18**: Innovative Membrane of Toyota Mirai [13]*

3. The third was to reduce evaporation thanks to the coolant flow and heat transfer at the cathode inlet that it is increased to diminish evaporation caused by possible temperature increment. One benefit is the improvement of cathode temperature distribution and it is favourable to prevent moisture evaporation from the membrane: applying these innovative control strategies (the flow field structures and water recirculation techniques), the FC stack can maintain the required performance with high system temperature even without a humidifier [13].

The absence of the humidifier has an impact for the cold start operation: indeed, to prevent the water for freezing and blocking, it is necessary to maintain a high level of the cell water balance. For this reason, it is particularly important to avoid the blockage of the fuel flow field, since lack of supplied Hydrogen to the system can produce a reverse potential, with detrimental effect for the cell.

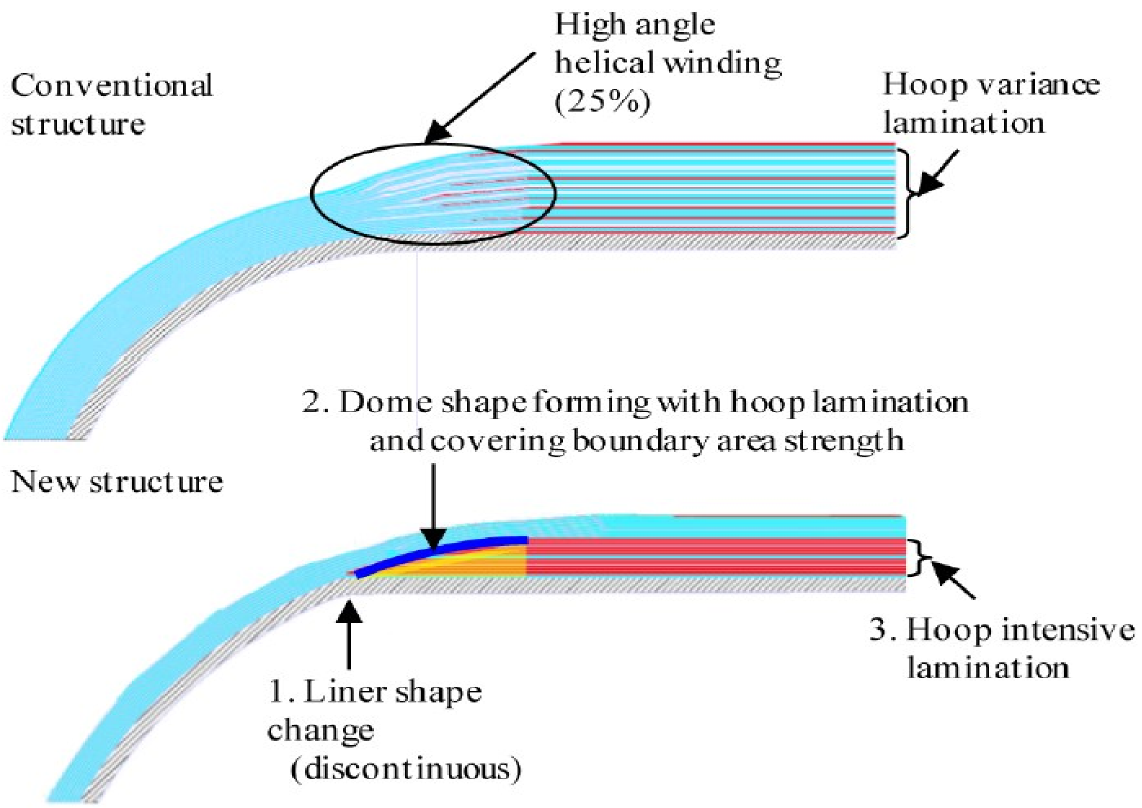

Figure 19*: Lamination Method for Hydrogen Tank, Conventional vs "Mirai" Structure [12]*

Another progress was the reduction in size, weight, cost and number of elements for the storage system. With respect to the previous version of a FCV developed by Toyota, the new Mirai has two larger diameter tanks at 700 bars, instead the four vessels present in the version lunched in

2008. The laminated structure of the tanks was realized in order to reduce weight, and meanwhile increase strength of the carbon fiber material. The high-pressure hydrogen tanks are composed of a plastic liner at the inner layer is composed by a plastic liner, used to secure in the hydrogen gas. Then, a sheet made by a strong CFRP, layer capable of withstanding high pressure, surrounds inner face and an additional a glass fiber reinforced plastic (GFRP) is used to reinforce the tank and to form a layer with high impact resistance to protect the tank from possible dangerous effects of impact. The aluminium bosses are adopted to form at both ends of the plastic liner, with one side design to be fit with the pressure reducing valve. A new lamination method for the CFRP layer was developed to increase the strengthen of the material. The three correctives adopted are: the shape of the liner was flattened to ensure the lamination by hoop winding in the external; in this region the section a dome shape is inserted to cover this are; the hoop winding lamination are intensified in direction of the inner layer, different with respect the earlier generation of tank.
The pressure system has changes significant developments, that have allowed to reduce the overall cost and size of high-pressure components. The gas flow paths inside the valve are simplified and the electrical also layout of shut-off valve is revised thanks to a reduced size.
These innovations in addition with a new generation of the pressure reducing valve have helped the reduction of overall weight by approximately 15%, and at the same time the lower number of parts by half has led to a significant cutting of the total cost for this unit [12].

In Automotive Field, not only Toyota has evolved their PEMFCs, but also others OEM introduced, during the last 10 years, different innovation both Stack level and for the Auxiliaries. For instance, Honda in 2017 launched a new version of Clarity FCV, presenting a new idea for the air supply system: instead to the common Lysholm compressor, which needs a high number elements to attenuate the noise produced and NHV, it was proposed a two-stage supercharging that allows to raise up the delivered air pressure up to 1.7 times with respect the old configuration. Thanks to this and others adjustments the FC power results increased, and it enables a reduction of the overall number of cells needed, with benefit for what concern the humidification operation and, therefore, the size of External Humidifier.

One of the main benefits, owing to the introduced innovations, is the lower volume used for the sound absorber: in order to ensure the quietness during the working mode of the Fuel Cell system, in the previous version of the Cathode supply system, the different element, as including a silencer and soundproofing cover, were needed, while in the new version of the

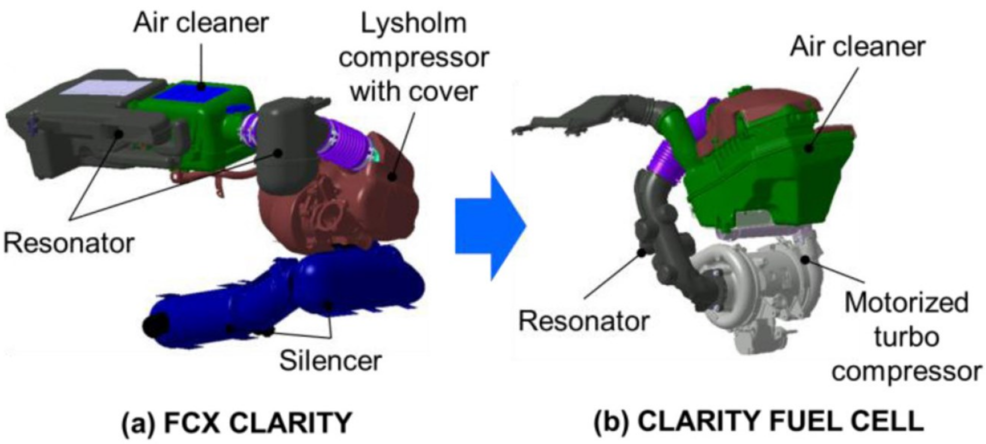

***Figure 20**: Resonant Dimension, FCX Clarity vs Clarity Fuel Cell [14]*

Two-Stage Turbocharger the lower pulsation at inlet and outlet allow to cut the dimension of resonant.

Using an alternative air compressor unit, not only has effect for the downsizing of the sound absorber, but also allow to play with a higher level of performances: raising air supply pressure to the partial pressure of the oxygen has increased and the voltage drop at high power output is scaled down. Moreover, the power consumed to achieve a high pressures level is reduced, since the power utilization in the Two-Stage Turbocharger is lower at the same level of net output power of the FCs [14].

The last implementation is related to the to the lubricant system for the air conditioner: since in FCV the catalyst layer can be poisoned by oil sulphur of the bearing, an oil-less system, as for aircraft, has been engineered for the first time in Automotive application. Thus, air bearings have been adopted: the rotor rotates, air is pushed into a wedge-like gap by the viscous action of the air at. Since in this condition the rotor becomes a floating element, the loads produced is through the air to the upper foil layer and bump one. This generates lots of pressure fluctuations that have to be absorbed by the bump foil and subsequently damped by frictional forces between the foils [14].

2.1.2 Future Development for FCPEMs in Automotive

Despite the first prototypical FC vehicle was introduced earlier during the beginning of 2000's, the PEM technology can be considered as an innovative solution, above all for Automotive powertrain. Indeed, the cost of this technology is still high and many improvements for what concern the overall efficiency, both at stack and ancillaries level, can be made.

Related to the cost, it is worth to underline how the critical point in this contest is the presence of precious material in the catalyst layer: since, the Pt requirement is still high (about 5 gr for each FCV), for PEM application, and, therefore an area of research is to develop a catalyst that requires a lower amount of platinum, that is more durable and sustainable and reduces the dependency of precious metal whose extraction has high environment impact.

At University of Copenhagen's Department of Chemistry, a new catalyst makes possible to produce more horsepower per gram of platinum, compared to a baseline catalyst used in the actual FCV. The surface of catalyst layer is generally made by platinum-nano-particles coated with carbon: one drawback of this solution is that the Pt becomes unstable if in contact with carbon. To overcome this issue, the new catalyst is developed to be carbon-free. While nano-particles solutions are highly applied for PEM, the purpose of this studies was to work up a new idea for the catalyst layer: instead of the abovementioned, the result was nanowires

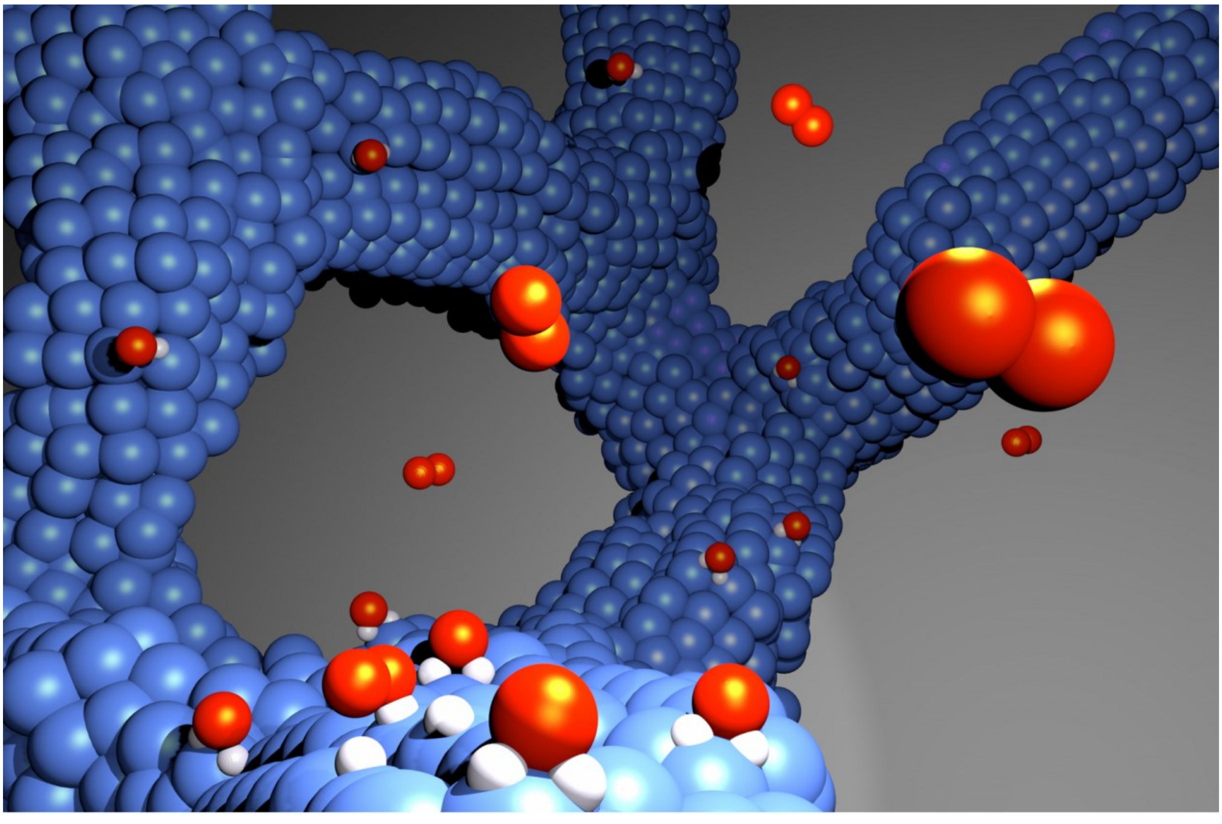

Figure 21: *Cathode Sputtering [29]*

characterized by higher efficiency, with respect of surface area, and high durability. The main benefit of this idea is less requirement of Pt for the catalyst without any detrimental on the performance [28].

Likewise, due to the importance of the catalyst layer which is the sheet that allows to achieve high performance and maintain stable FC operations even at higher temperatures and high current density, the researchers of University of Berna have been able to introduce new idea, called *Cathode Sputtering*, through which into reality thanks to a special process to boost the performance of the catalyst. In comparison with the adopted solutions, a single precious material is individually atomized by bombardment with ions in the layer. In this way, the gas is released, enhancing the formation of an adhesive surface and making unnecessary the use of carbon carrier: this can result in low corrosion effect, above all in traffic condition [29].

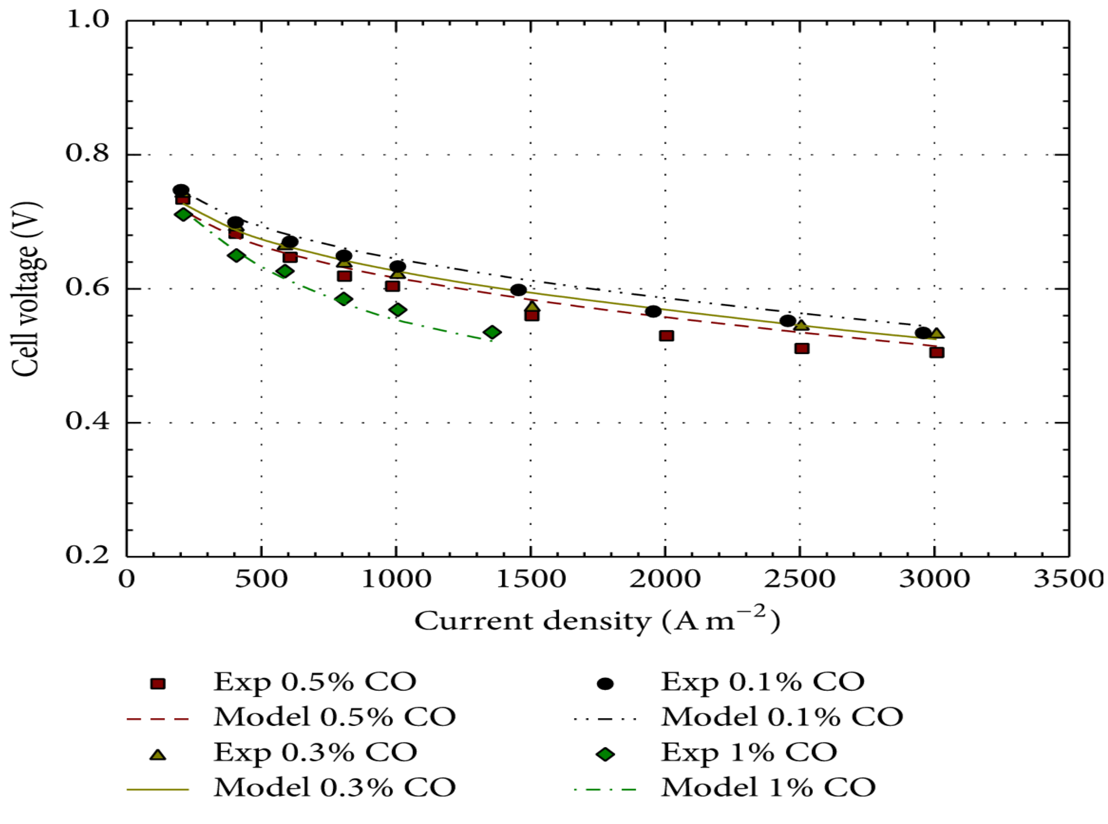

Figure 22*: Polarization Curve at different CO level [31]*

Develop innovative solution for the catalyst layer, in order to lowering the cost and increasing the performance, is one of the key points to force OEM, but not only. Another critical aspect for the water management inside the membrane: to overcome this issue, some HT-PEM (High Temperature PEM) are under development. Despite the low-temperature PEM, the assembly of this electrolyte is made by phosphoric acid doped poly-benzimidazole (PBI) membranes with a higher working temperature with respect the common design (between 120° - 200°). The high temperature operation not only allows to eliminate the complexity of the water management system, but also leads to an improvement of PEM performance: one of the main operational advantages is a higher tolerance to carbon monoxide (CO) level (CO of up to 3% in hydrogen at 0.8 A cm^{-2} and 200°C). This greater resistance to CO poisoning allows the use different synthetic gas from various fuel reformed in specific unit, reduce the need of a complicated system to filter the carbon monoxide, making the system more suitable for Automotive application. Moreover, the higher temperature of the membrane leads to exploit a greater efficiency of the Cogeneration of heat: for instance, a comparison between three different systems (based on HT-PEM and LT-PEM supplied by pure hydrogen,) has demonstrated better performance for pure hydrogen operation for the low temperature application (60°), while high cogeneration efficiency (up to 78%) for the HT stacks [30] [31].

2.2 Existing and Underdevelopment solutions for SOFC in Automotive Field

Up to now, the described hybrid systems for vehicle application are all base of PEMFC technology, but during the recent years, Solid oxide fuel cells (SOFC) have gained more and more interest in the transport sector for many reasons. In comparison with the conventional PEMFC, which has the advantages of low system weight, high dynamic and fast start-up phase, but the drawbacks of high costs due to use of noble metals and refuelling phases; the SOFCs can combine high electrical efficiency with the option of supply the system with choosing high density fuels, which can be available in the existing fuelling infrastructure, thanks to its structure, able to accept higher level of impurities. The fuel that can externally or internally reformed into Hydrogen and CO, are mainly CNG, LNG, LPG and biofuels, some of which can be based on renewable source. In addition to fuel flexibility, SOFCs can exploit a lower manufactured cost, without any detrimental on the electrical performances, making this membrane perfectly practical for Range Extender Application.

Regardless the several benefit of this type of FCs, different factors have limited the its widespread in transport field: the SOFCs, indeed, have low power density, long start-up time, and poor thermal behaviour. To make clear, during the star-up phase, the stack has to be heated up to the nominal operating temperature, over 600°, and this operation can take several minutes.

In case of the utilization of the system below the nominal temperature, the results are lower electrical power and heat generated.

2.2.1 State of Art of SOFC and Future Development in Automotive Field

As briefly mentioned, the Solid Oxide FC are a typology of membrane made by a ceramic material, as the electrolyte. SOFCs use a solid oxide electrolyte to drive negative oxygen ions from the cathode side to the anode, between which the electrochemical oxidation of the hydrogen occurs. The main application fields are for Power Plant purpose and for Cogeneration of heat, but, thanks to its features, a further utilization, as for Automotive, can be possible.

Owing to the very high temperatures, typically between 500 and 1,000 °C, the stack does not require expensive platinum catalyst material, as is generally necessary for lower temperature fuel cells such as PEMFCs, and, therefore the membrane is not affected by carbon monoxide poisoning: this a pivot point for what concern the comparison between a traditional PEM system with respect a SOFC, from cost point of view. By contrast, SOFC suffers but high vulnerability to sulphur poisoning that must be removed before entering the cell: specific filter, as adsorbent beds or other means, must be integrated in the FCs.

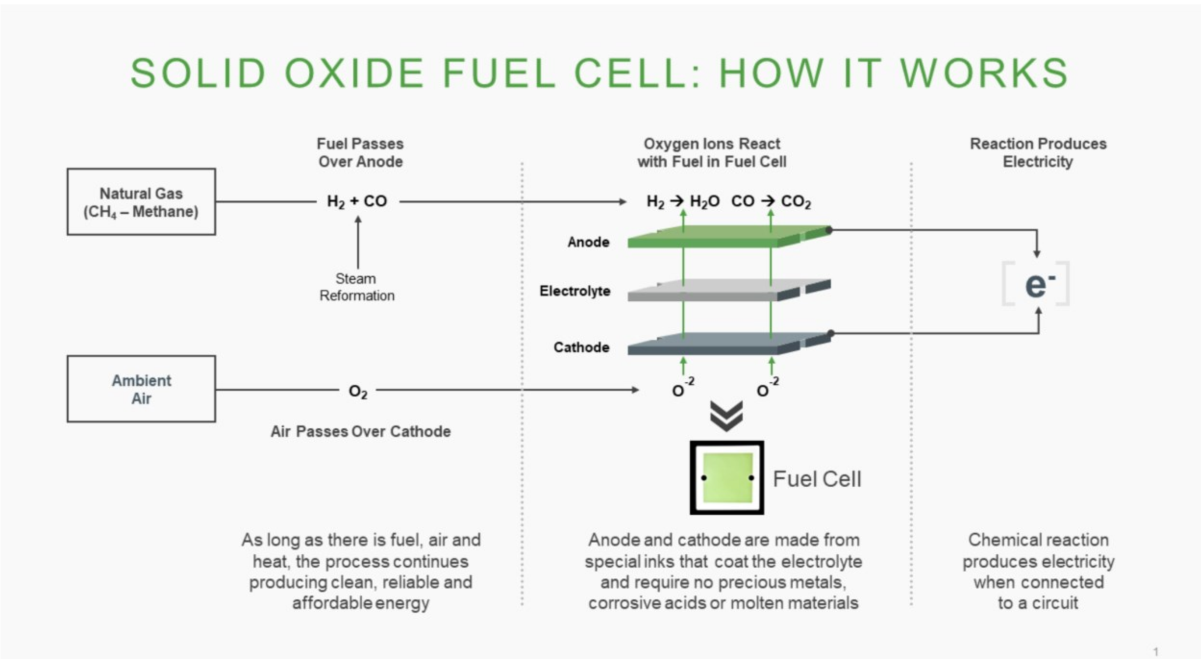

***Figure 23**: Solid Oxide Fuel Cell, Working Principle [32]*

The geometrical configuration of the stack presents differences: unlike many types of fuel cells, the layout of Solid Oxide are multiples. Generally, a planar design with the typical sandwich structure is employed (in this configuration the electrolyte is interposed between the positive and negative electrodes), but also tubular geometries are proposed: thanks to latter layout, it is possible to result in a better seal air from the fuel. Despite this configuration, the overall performance of the planar design is resulted to be better than tube one (lower internal resistance for the planner layout).

- **Stack Configuration:** the stack is design to feed Oxygen from the cathodes and fuel from anode. The FCs is composed by a set of layers including interconnects, air channel, electrodes, electrolyte and fuel channel gas. Different materials are used for the three main layers (Anode, Cathode and Electrolyte): the cathode can be used a material which provides high electrical conductivity and, meanwhile, good coefficient of thermal expansion (for example lanthanum nickel ferrite, or LNF, can be adopted); for the electrolyte it is possible to utilize scandia-alumina stabilized zirconia (SASZ) due to its high ionic conductivity; while for the anode it is generally applied a cermet of metallic nickel and SASZ.
  The geometrical configuration has a huge impact on the gas channel and gas flow direction: for instance, in planar SOFC, the main dimension corresponds to the gas channel and the direction is determined by the gas flow, while for tubular layout, the dimension is usually the tube axis and it corresponds with the direction of the fuel and oxidant flow. Another critical point for the design of the stack is the interconnect between two subsequent cells: this factor regulates the flow field of the Oxygen and Fuel between the cells, influencing the performance of the stack. Moreover, a sticking point that affects stack performance, is the gas seal necessary to prevent the escape of gas from the cell structure [33] [34].

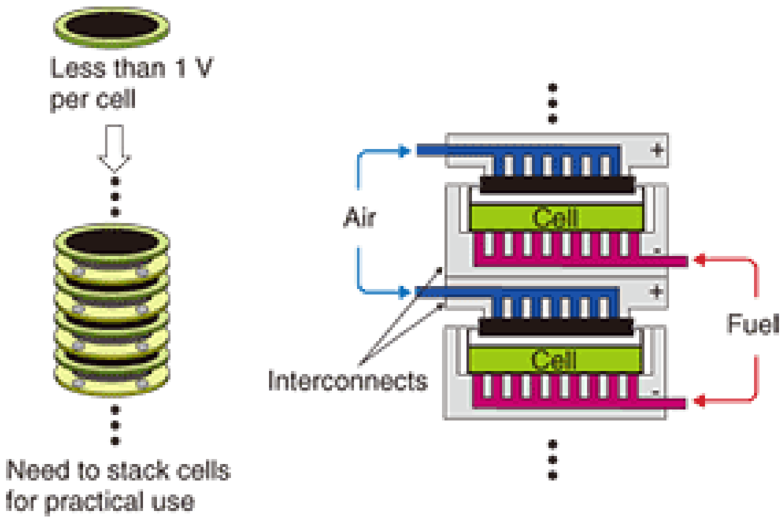

***Figure 24**: Stack Interconnection for SOFC [33]*

- **Auxiliaries**: due to the high temperature of the stack, the system components have to be selected to comply the resistance at great thermal load. The most important auxiliary component in the Solid Oxide Fuel Cell is the presence of external reformer: depending on the type of reforming unit used in the system, different ancillaries characterize the overall system. More in general, a typical system with external reformer for Power Plant application is made up by an *Air Preheater* to increase the temperature of the inlet air; a *Reformer* to transform the supplied fuel into to a hydrogen gas by either steam reforming or partial oxidation reforming; an *Afterburned* in which the anode off-gas, with residual unburned fuel, is fed to the afterburner and combusted with the outlet cathode providing the energy required to reform the input fuel; *Flow distributor* to distribute equally the anode and cathode flow through the stack and auxiliaries of the SOFC system, *Heat Exchanger* in which the hot cathode that exiting from the stack passed through the plates heat exchanger, where can heat up the reformed fuel before its ingress into the stack and, afterward, flows into afterburner [35].

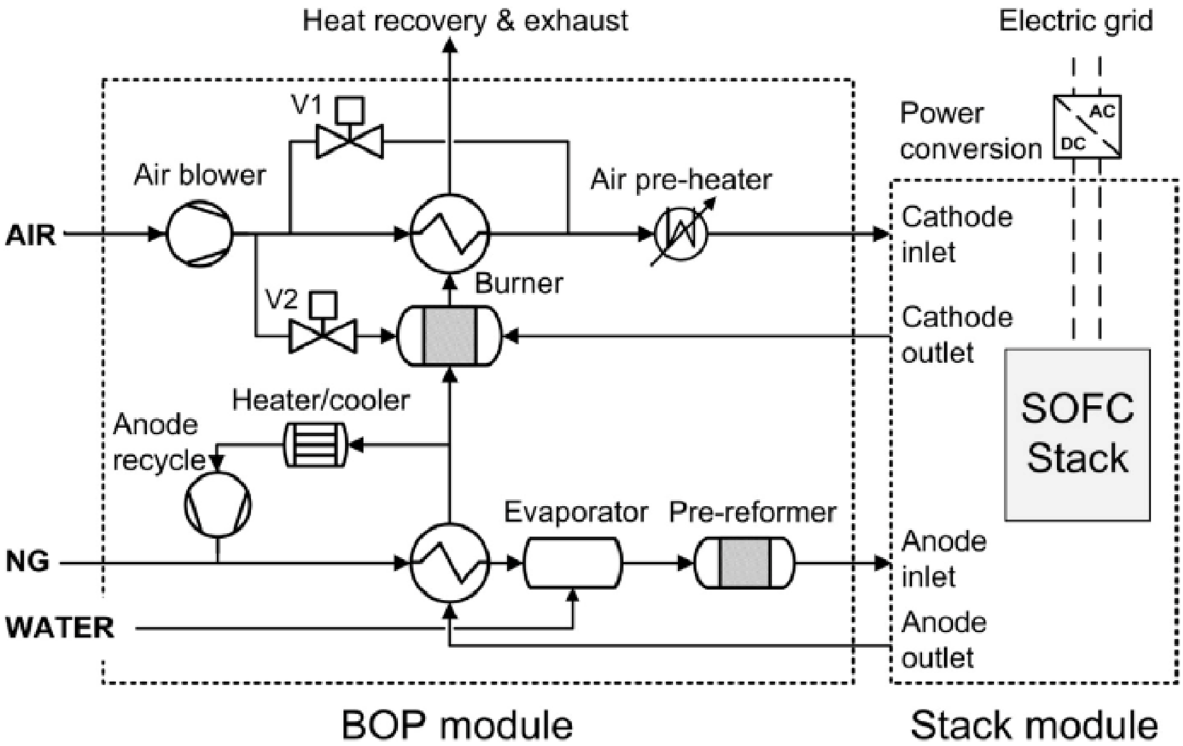

Figure 25: Auxiliaries of SOFC [35]

Nowadays, only one prototype vehicle, based on SOFC, is underdevelopment thanks to a system called by Nissan E-Bio Fuel Cell. The idea is to use a SOFC as a secondary power source, in order to extend the driving range of a Pure Electric Vehicle. The system is composed by HT Fuel Cell and an external Reformer supplied by ethanol-blended water (55% water, 45% ethanol), which can be obtained from sugarcane and corn. This fuel is converted in Hydrogen that is fed to the Fuel Cell stack that electrochemically reacts with the cathode gasses to produce electricity for battery system and drive electric motor. According to the conducted tests, with a battery pack size for 24 kWh, the combination with FCs can extend the autonomy of the vehicle more than 600 km.

One of the main asset is the availability of the fuel (especially in North and South America) and the existing refuelling stations. Furthermore, although the external reformer can produce greenhouse emissions, that can be recovered during the life cycle of the surgacane from which it is produced the fuel: in this way the target of carbon-neutral emission can be achieved [36].

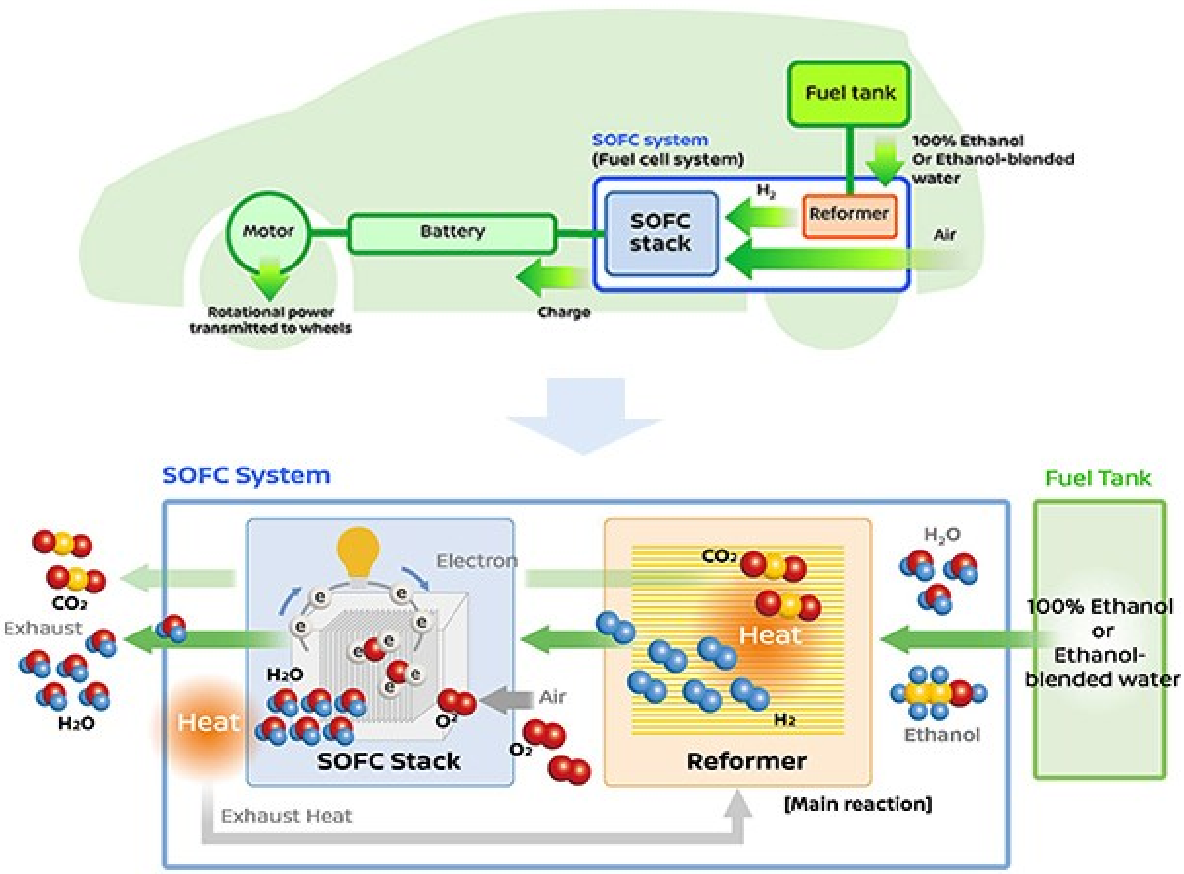

***Figure 26**: E-Bio Fuel Cell System, Nissan [36]*

To adapt the features of SOFC system to the needs for Automobile application, Nissan in partnership with Lawrence Berkeley National Laboratory has studied a new prototype of SOFC system, called ***Metal-Supported Solid Oxide Fuel Cell***. The aim is to develop and demonstrate at cell-level that MS-SOFC technology can be suitable for Automotive application, owing to an increased power density and reduction of start-up time. The metal based SOFC stack not only has a better performance in terms of fast start and power density, but also improves reliability and reduces the manufacturing cost of SOFC stacks. To achieve these goals, the researchers have integrated at stack level a high-performance catalysts and high-oxide-conductivity electrolyte. Unlike the previous version of ion conductor (Yttrium-doped zirconia), the new solution adopts a Gadolinium-doped ceria (GDC) which is a mixed ionic electronic conductor (MIEC) under the reducing conditions at the fuel electrode. The breakthrough is given by the features of material that is able to act as an excellent catalyst for the anodic fuel oxidation reaction. From this in-depth understanding of GDC's elementary properties and their effect in the electrochemical reaction, it is possible to deduce that the Ni phase is mainly necessary to maintain long range of electron transport and high mechanical stability of the overall system.

Several experiments have been conducted, feeding the system with different fuel including Pure Hydrogen, Ethanol and Water-Ethanol. As result a comparison, as a function of *Power Density* and operating temperature, has been made, in order to balance the impact of the innovative SOFC structure with respect the conventional one [37] [38] [39].

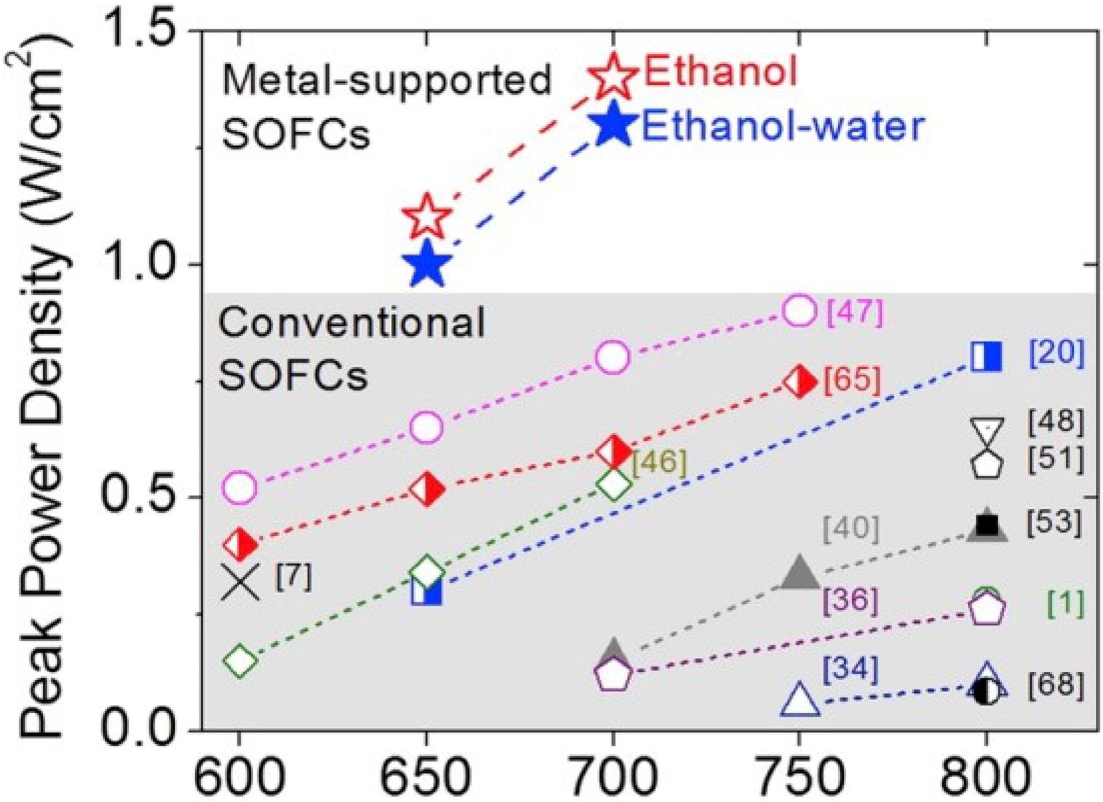

Figure 27: Conventional SOFC vs MS-SOFC [37]

As reported in the *Figure 27*, in the narrow range, between 650° and 700°, the innovative Metal-Supported SOFC can accomplish a higher level of the Power Peak, overcoming one of the main limits that has restrained the usage for transport field.

3. DEVELOPMENT OF SERIES HYBRID RANGE EXTENDER VEHICLE

3.1 Phase of FCV Development

The core of the thesis is to develop a Series Hybrid Fuel Cell Vehicle, design a proper Energy Management System and carry out different analysis in order to find the best trade-off between the H_2 consumption and the difference among initial and final State of Charge.

The first phase was entirely dedicated to the definition of layout of vehicle and the subsequent simulation of the calculated parameter in a baseline model of pure Battery Electric Vehicle (BEV). This step was fundamental to understand the required power and energy during the WLTP, with the aim to provide a reference for the future sizing of the different element of the powertrain. In following phase, the objective was to analyse and model the behaviour of Fuel Cell Stack in MATLAB/SIMULINK environment starting from the available data. Different tests were performed in order to acquire data useful for the modelling of Fuel Cell auxiliaries and to derive the parameters which influences the losses through the *Polarization Curve*.

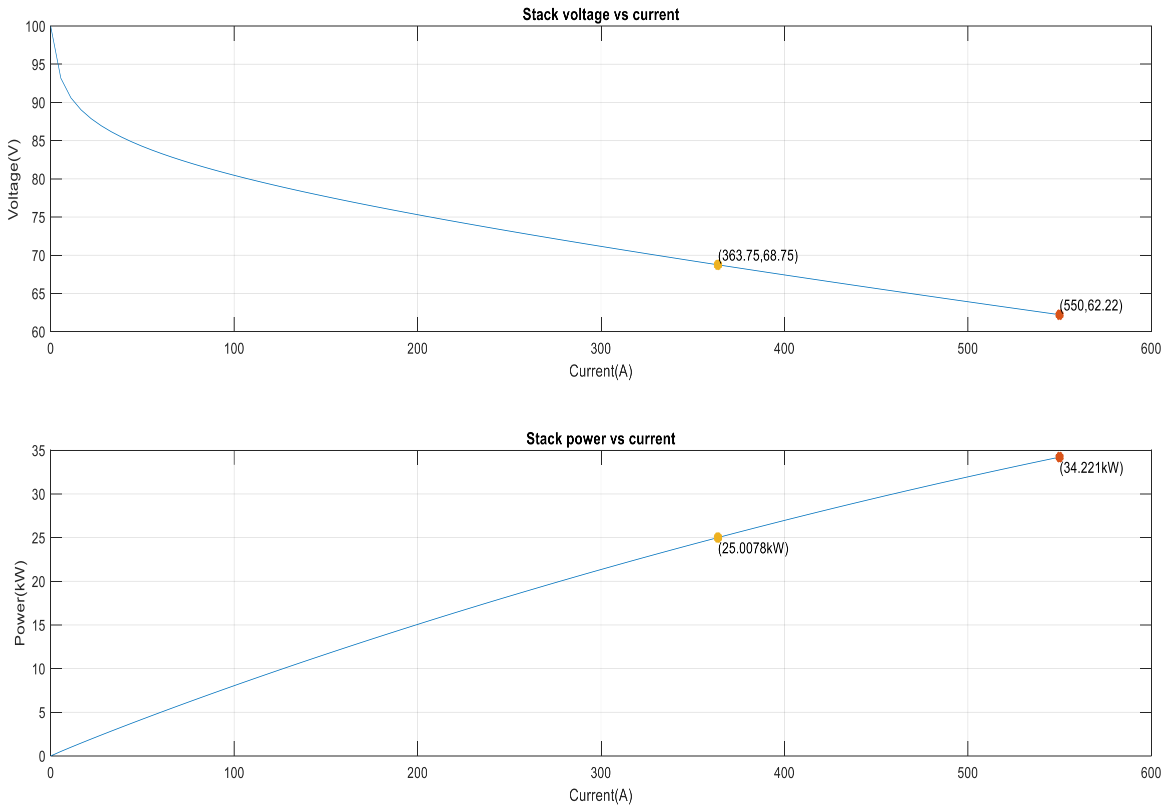

Figure 28: Polarization Curve and Stack Power of the FC used

During the development phase of the Powertrain, the main activity was to provide the connection between the two Energy Source (Battery Pack and Fuel Cell) and E-Motor and Inverter. Moreover, all Fuel Cell ancillaries (Cathode supply system, Anode supply system and Cooling system) have been modelled to ensure the correct operation during all possible working conditions: to do that different tests are simulated with a wide range of speed profiles and requested load.
The last part of the design phase for the Fuel Cell Vehicle was related to the design of a proper Control Logic able to "drive" in the smartest way the energy flux from/to the Battery Pack and from the Fuel Cell system. For all configurations, the two followed guidelines are: limit the dynamic of the Fuel Cell and distinguish the *Charge Depletion Phase* and the *Charge Sustaining Phase* for the Battery Pack.

Finally, starting from the designed Energy control unit, the results are obtained and studied varying the parameters which influence the action threshold of the FC during the working cycle. Specifically, the Fuel Cell output power is set to vary according to the actual *State of Charge* of the Battery Pack and to the Required Power by the vehicle.

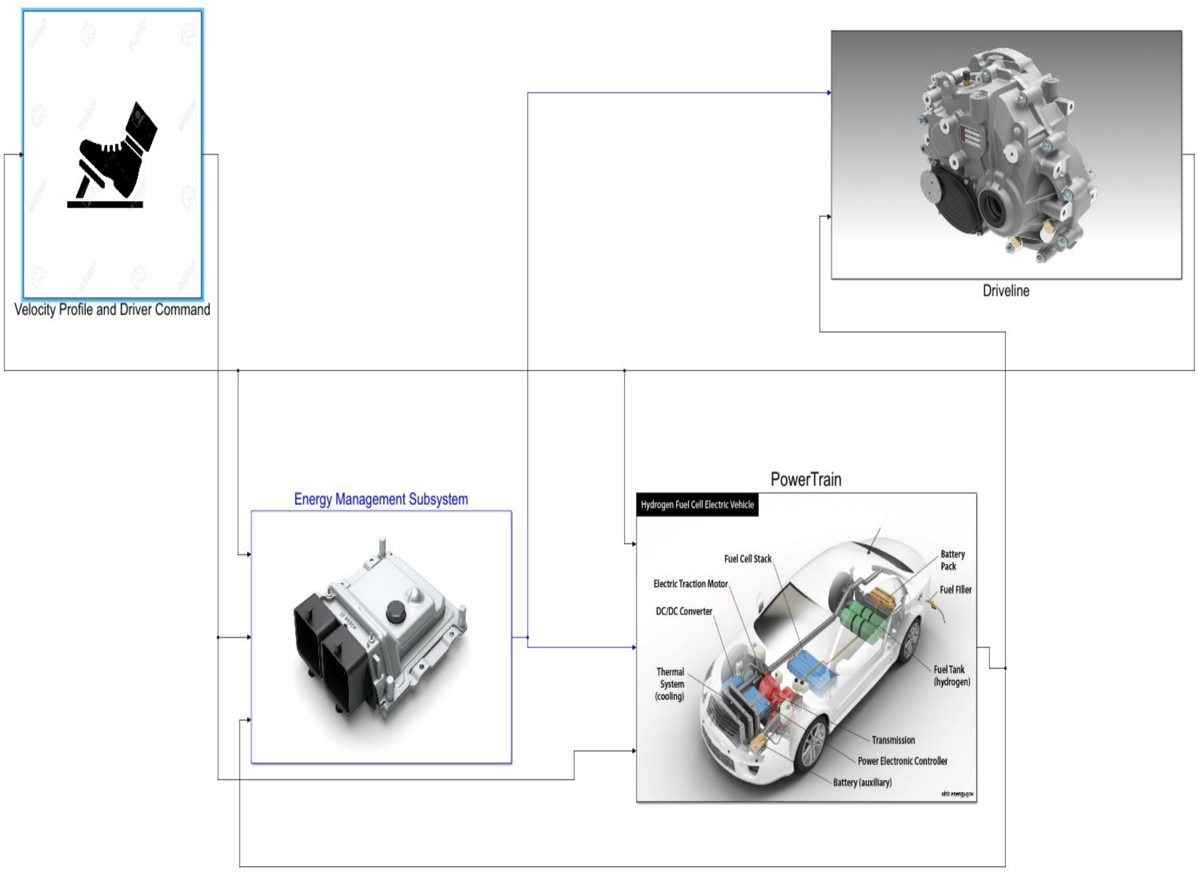

Figure 29: Topology Diagram of FCv implemented in SIMULINK

3.2 Powertrain Architecture and Balance of Plant

The Powertrain architecture is worked up around the two main Power Sources: Fuel Cell and Battery Pack are both studied in terms of sizing and technology in order to ensure a proper drivable range and a level of overall power able to meet the various driver requests. Since the output voltage of the FC covers a wide range, a Fuel Cell DC/DC converter is needed to give the reference value of BUS voltage that has to supplied to the Inverter/E-Motor assembly. In all driving condition, during which both Fuel Cell and Battery Pack work in combination, the DC/DC of Fuel Cell side helps to regulate and delivery the correct value for the BUS voltage according with the actual SoC of the Battery. Regarding the Fuel Cell system, the auxiliaries that are modelled through the *Simscape Library* of MATLAB/SIMULINK, are:

1. ***Cathode Supply System***: this subsystem includes an *Air Compressor* (Blower compressor) driven by an *Electric motor*, an *Intercooler* to lower the gas temperature and many *Connection Pipe* to supply the flow at Cathode inlet.
2. ***Anode Supply System***: The *High-Pressure Tank* (700 bar) is linked with a *Pressure Reducing Valve* able to reduce the inlet pressure up to 15 bar. The rail is connected with the injector which provides to the Anode inlet the correct amount of H_2 flow rate, according to the requested load.
3. ***Cooling System***: the aim of Cooling System is to maintain the designed temperature inside the FC Stack. The circuit is made up by a *Cooling Pump* commanded by an *Electric Motor*, a *Heat Exchanger* and *Connection Pipes* to the cooling fluid not only through the FC Stack, but also through the Intercooler.

The traction is demanded to an E-Motor based on IPMS interior permanent-magnet synchronous technology, able to provide a maximum power around 93 kW. The E-Motor is coupled with an Inverter to convert the DC voltage BUS into AC electric signal to supply the traction element. The driveline is designed as gearbox with a single speed, whose gear ratio is 7.2, coupled with an open differential to limit the overall cost of transmission line. For the design of the driveline, it has been taken the driveshaft compliance and the rotor inertia, to have a fine simulation of connection between E-motor and wheels.

3.2.1 Fuel Cell Modelling

The key element of the powertrain are the Fuel Cell Stack and its subsystems to perform the simulation of main ancillaries. The sizing criteria to select the FC is based on the mean power needed in WLTP cycle: for this reason, the choice for the Stack is a module manufactured by *Nuvera* with a nominal power of 25 kW and a maximum value of power around 34 kW.

As already mentioned in the previous chapters, one of the factors which heavily influence the behaviour of Fuel Cell system is the use of External Humidifier to ensure the correct amount of the humidity within the membrane: the model of Fuel Cell system selected for this application does not need an external element to enhance the humidification, since the water can circulate by the back-diffusion between anode and cathode and by means of the Hydrogen recirculation pump. In this way, with the water produced inside the membrane is used to humidify the membrane both at anode and at cathode side.

Starting from the experimental result of the used Stack, the input data to compute the calculation and determine the performance of the Fuel Cell are studied around the nominal point that in this case in placed at a value of power of 25 kW. Other data used to carry out the prediction related to the Polarization Curve and Power Curve of the FCs are the efficiency of the Stack at nominal point, the operating temperature, the value of inlet pressure (both for Hydrogen and Air), the nominal volumetric Air Flow Rate and overall number of cells. Moreover, parameters such as *Active Area* and *Maximum Current Density* (useful to find the *End-point* and therefore the Maximum value of Power) have been reported in order to outline the characteristics of FC.

Parameter	Value [unit]
Nominal Point	[363.75 A 68.75 V]
Stack Efficiency @ Nominal Point	52 %
Inlet Pressure H_2 @ Nominal Point	1.6 bar
Inlet Pressure Air @ Nominal Point	1.6 bar
Operating Temperature	348 K (75°)
Air Flow Rate @ Nominal Point	1173 lpm
Number of Cell	102
Active Area	360 cm^2
Maximum Current Density	1.53 A/ cm^2

Table 1: Main Parameters of Fuel Cell Stack

To better calibrate the main parameters, as *Exchange Current* (i_0), *Exchange Coefficient* (*alpha*), *Nerst* Voltage (E_n) and *Internal Ohmic Resistance*, which regulate the trend of Polarization Curve, different polarization curve are simulated in the used Simulink Block-set: in this way it has been possible to calculate mean values of the abovementioned constant.

Parameter	**Value [unit]**
Nerst Voltage	1.16 V
Internal Ohmic Resistance	0.027 Ω
Exchange Current	0.83 A
Exchange Coefficient	0.438

Table 2: Characteristic Parameter of Fuel Cell Stack

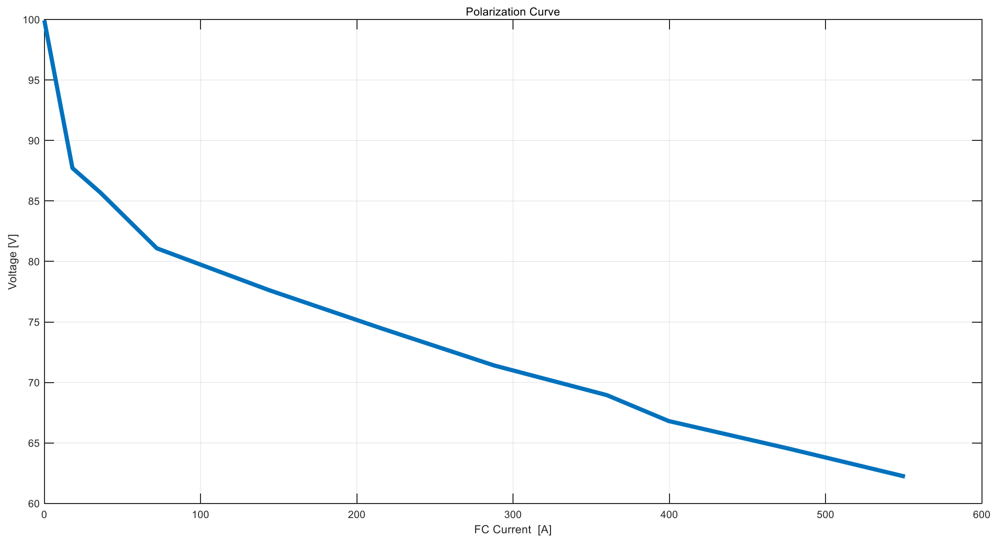

Figure 30: One Experimental Polarization Curve from given Data used to perform the calculation

In addition to the mentioned electric parameters, the other features of this kind of electrolyte are the following:

- 1.6 kWe/l power density at high pressure of Hydrogen and 1.3 kWe/l at low pressure.
- Overall low-pressure operation for cathode side: reason why the selected air compressor is a blower type.

- Repeatable freeze-start from -30º C with a capability to reach the 50% of power in 30 seconds.
- Greater than 1,500 hours steady-state operation with a decay rate 10 of mV/h/cell.
- 100000 cycles during operation without any measurable decay.
- Non-coated stainless steel bipolar plate construction. Metallic stacks offer resistance to shock and vibration and are lower in manufacturing cost than graphite stacks [40].

Going more in deep with the simulation of FC Stack in Simulink environment, it is worth to mention that to have a correct simulation it is necessary to link the Fuel Cell block with an electric variable resistor which has to be able to simulate the require load.

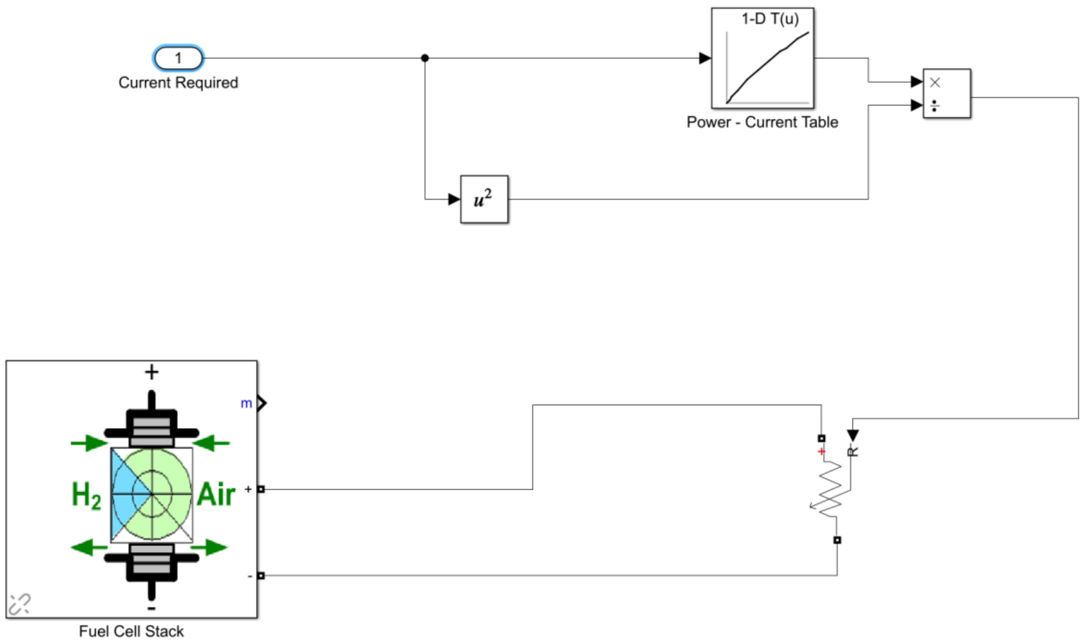

Figure 31: Simplified Scheme of Load Required at Electrical Ports of Fuel Cell Stack

With the reference at the topologic scheme in *Figure 29*, it is possible to mentioned that the required load is computed by means of the following equation:

$$R_{Load} = \frac{P_{Requested}}{I_{Requested}^2}$$

The current requested to the Fuel Cell is an output signal calculated in *Control Logic*, while the power is computed by using a *Look-Up Table* to predict the actual value of generated power. In case of no-load current the value of the variable resistor is set to be infinite.

3.2.2 Anode Supply System Modelling

In order to ensure the correct amount of H_2 flow rate at inlet of the anode, a proper design of anode supply system has been studied. The final aim is to calculate the correct amount of hydrogen according to the requested load of Fuel Cell. The main elements used to build this auxiliaries subsystem are:

1. A pair of High-Pressure tanks with a pressure level of 700 bar and an overall capacity about 5 kg of H_2 (in order to simplify the simulation, only one tank is used for the modelling).
2. A pressure reducing valve to lower the pressure from the high value (700 bar) to the rail one (around 15 bar).
3. A variable valve (ball type) which has the aim to simulate the behaviour of injector. This component is studied to deliver the correct amount of flow rate, as a function of the Fuel Cell current request, at predicted value of pressure (as previously mentioned, 1.6 bar).

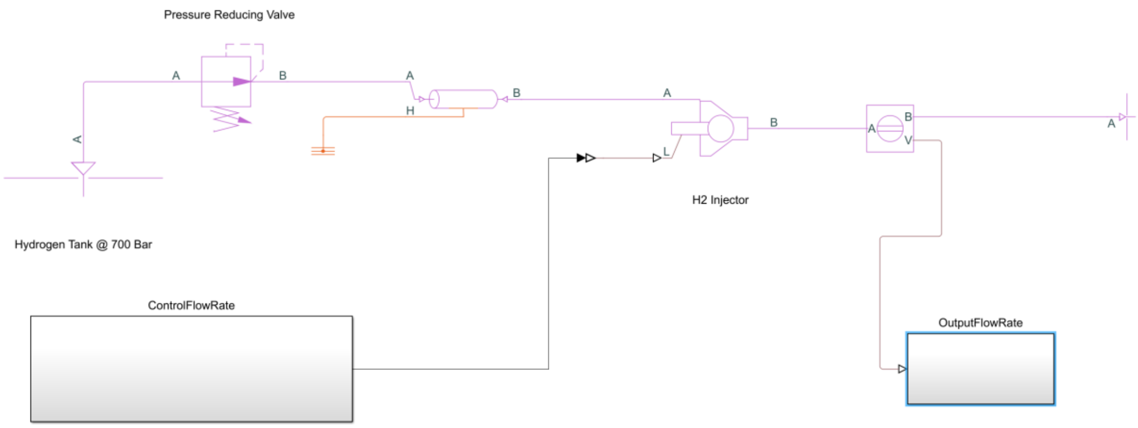

Figure 32: Topologic Scheme of the Anode Supply System

To command with good accuracy the requested amount of Hydrogen and therefore meet the load requirement, an external control has been designed. The key to predict the amount of Hydrogen that has to be supplied to the anode is given by the equation:

$$\dot{m}_{H2} = 60 * \frac{I_{Requested} * n_{cell} * M_{Mol\_H2}}{2 * F * \rho_{H2@700bar}} \text{ [lpm]}$$

Through the equation shown, it is possible to correlate the flow rate with the current requested: in this way, Hydrogen flow rate is computed and, subsequently, a discrete signal is driven to the external control of the ball valve in order to the lift.

One of the most important elements in the Anode supply system is the Hydrogen Recirculation Pump, that has the aim of refill the inlet supply line with the unused H_2. Since the Hydrogen consumed during the electrochemical reaction is not equal to the supplied one, a pump is required to feed at the inlet line of the anode the residual fuel at outlet anode. In order to optimize the *Balance of Plant* for the FC system, the pump, that is driven by a DC electric motor, is activated by a relay command when a certain amount of Hydrogen is “collected” at anode outlet.

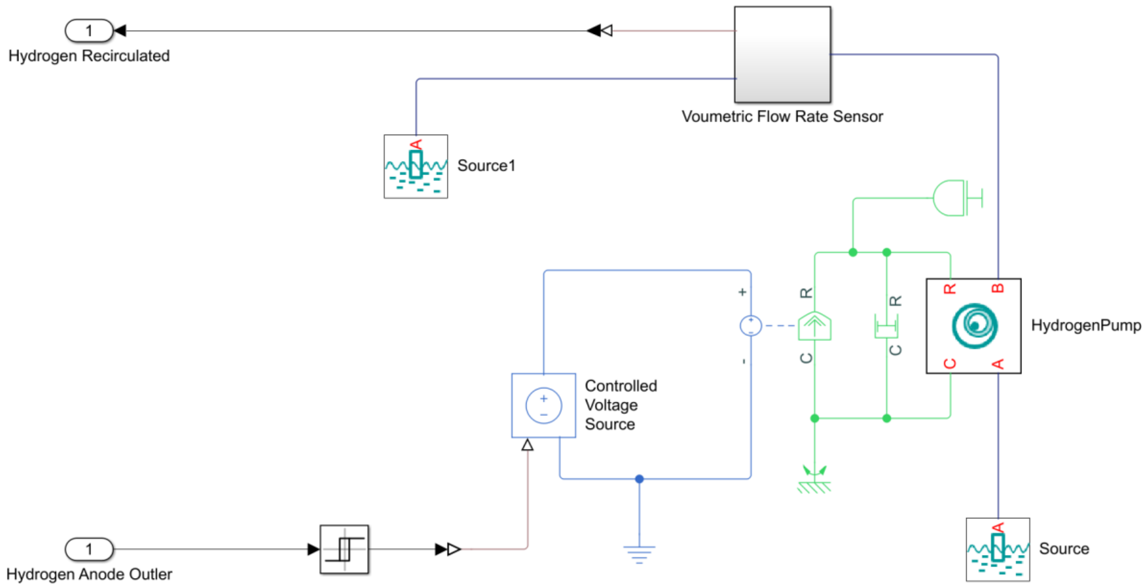

Figure 33: Functional Scheme of Hydrogen Recirculation Pump

The value of power consumed when the pump is activated is designed to be 200 W. During the phase of activation of the recirculation pump, a proper command has been studied in order to request the correct amount of the H_2 flow at tank level: indeed, since that part of needed Hydrogen is provided by the pump, a lower Hydrogen quantity will flow on the main supply line.

3.2.3 Cathode Supply System Modelling

To enhance the correct operation inside the cell, it is necessary to feed not only the H_2, but also Air, especially Oxygen broken up from the molecular of air at cathode catalyst layer level. The air is picked up from external environment and it is filtered by means of an air filter prior to be compressed by the blower. In this modelling, the air box is not simulated, while the others element simulated are:

1. Air compressor driven by a DC electric motor, able to compress the air from atmospheric pressure up to a mean value of 1.6 bar. The mean value of the power consumed by the assembly DC motor – Compressor is almost 400 W, with a peak value of 1000 W.
2. An Intercooler to cool down the air after the compression in order to stabilize the inlet temperature of the gas around up 303 K (the reference temperature for the simulation is 293 K).
3. A series of pipe to ensure the connection between the Air supply line and the inlet of the cathode of FC Stack.

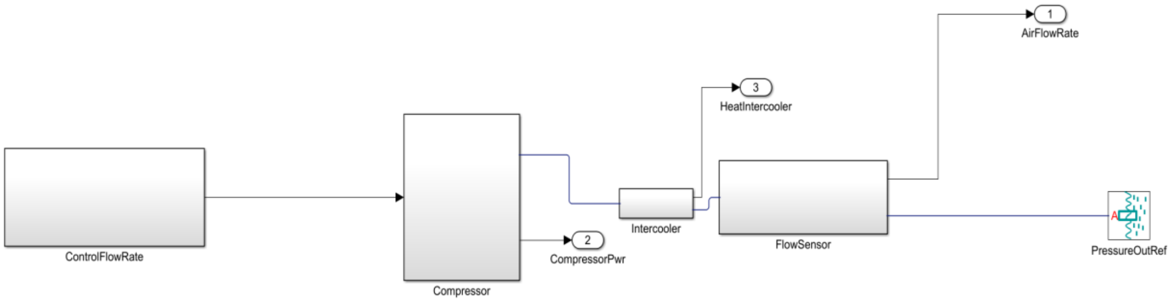

Figure 34: Functional Blocks of Cathode Supply System

As for the anode supply system, a proper control system is modelled to ensure the correct operation of the compressor, coupled with its DC motor. An electric signal has to provide to the motor in order to drive correctly the blower compressor. The amount of the air flow rate required to ensure the requested level of power.

$$\dot{m}_{Air} = 60 * SR * \frac{I_{Requested} * n_{cell} * M_{Mol\_Air}}{4 * F * \rho_{air}}$$

In the above expression, one important parameter is the *SR*, stoichiometric ratio, which displays the ratio between the mass flow rate of air and the mass flow rate of Hydrogen. To simplify the analysis, the SR is kept constant and in the specific case it is equal to 1.8.

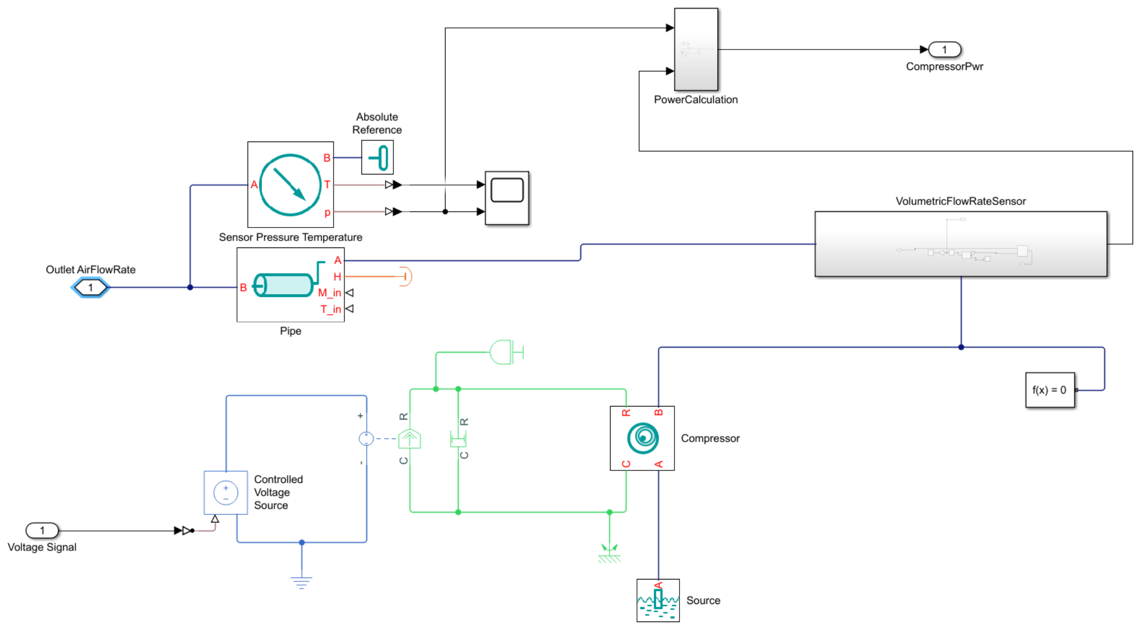

Figure 35: Detailed Scheme of Assembly Compressor - Motor

3.2.4 Cooling System Modelling

The objective of the cooling system is to remove the heat from the Fuel Cell Stack in order to keep the internal temperature of the stack almost constant around a value of 348 K. A the second of aim is to remove the heat generated by the intercooler, used to cool down the air flow. The modelled system is composed by different elements that are:

1. An electric water pump (driven by a DC motor) that is used to deliver the correct amount of Ethylene glycol and water mixture to Stack and Intercooler.
2. A pair of pipes with related heat source, that are used to simulate, respectively, the thermal load of Intercooler and Stack.
3. A Heat Exchanger used to remove heat from the cooling fluid. With the prospective of limiting the overall cost of radiator pack and due to the limited dimension of the FC stack, the radiator is cooled down only by the air of the vehicle in driving condition. For this reason, all assembly of the FCs is supposed to be placed at front end of the vehicle.

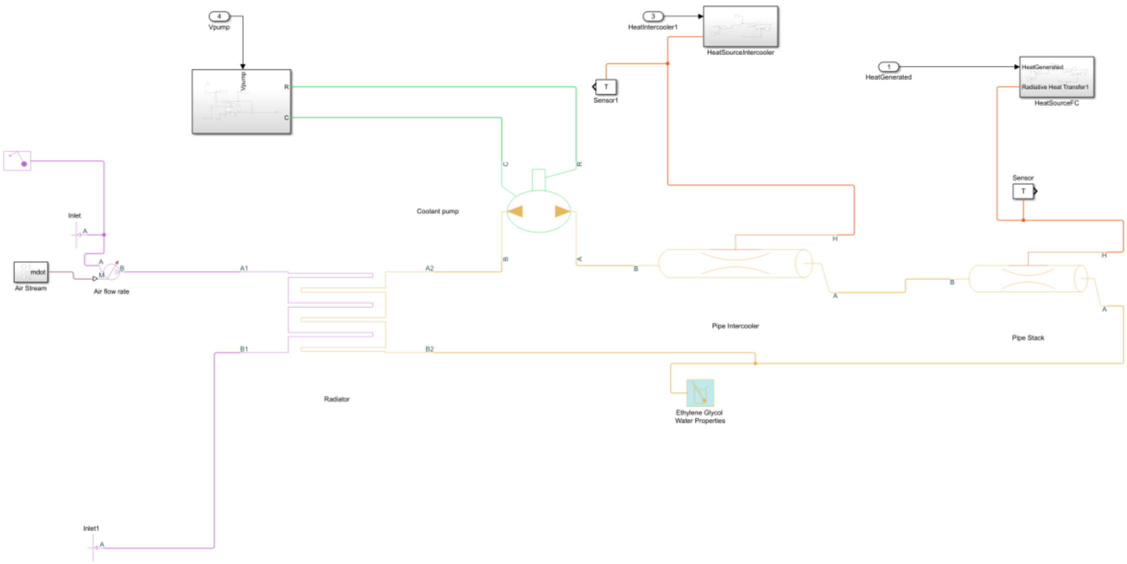

Figure 36: Modelling of Cooling System

Since the block-set used to model the Fuel Cell stack does not perform any calculation related the heat generated the electrochemical reaction, the idea is to calculate the heat released as difference between the power potential, as a function of the actual fuel consumption, and the effective generated electrical power:

$$Q = \dot{m}_{H2_{consumed}} * LHV_{H2} - P_{elect\_generated}$$

Through this expression, it is possible to derive the heat generated during the reaction within the Fuel Cell membrane. The heat is dissipated in adiabatic way by means of the cooling fluid that flows through the channel modelled as a pipe. Coherently with the real design of the Stack used, the passage for the cooling flow is shaped to have one inlet port and one outlet port.

Figure 37: Pierburg CWA400, Electric Water Pump [41]

Since the electric water pump is commanded by an electric DC motor, a strategy to optimize this power consumption is implemented:

- Up to the Fuel Cell temperature is below a certain value, the flow is stand still and it is heated up by the thermal load generated by the Fuel Cell. This phase occurs especially during the *Warm-Up Phase*.
- During the following mode, the pump is triggered and cooling fluid starts to flow to be cooled down by the radiator pack. The pump is moved by electric motor only when the Fuel Cell generates power: otherwise, it is shunt and the membrane cooled. The mean power consumed by the electric pump is 100 W.
- In case of the temperature exceed a certain threshold, the pump delivers higher flow rate in order to stabilize the internal temperature and maintain the optimal operating range. In this mode, electric water pump has a power consumption greater than 200 W

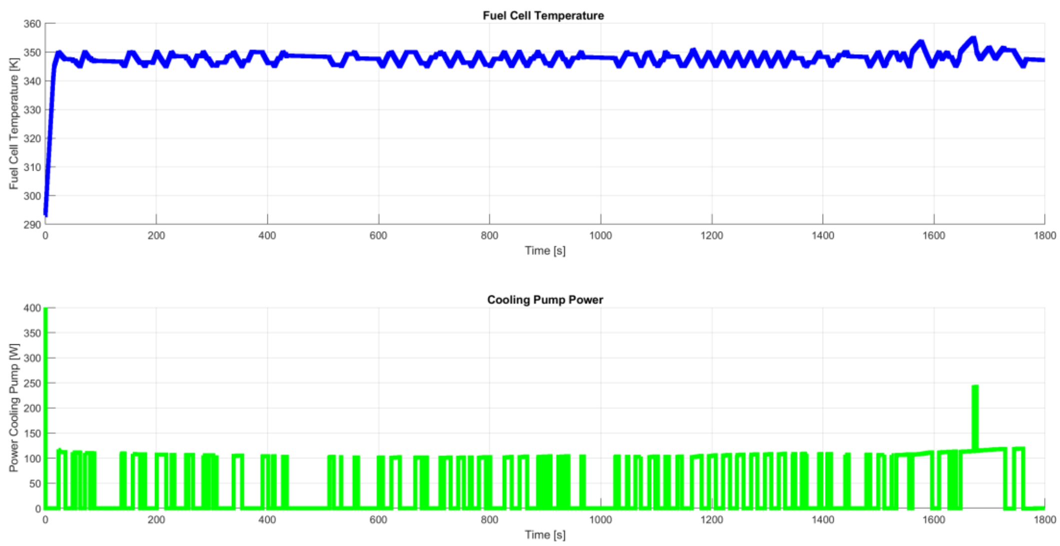

Figure 38: Fuel Cell Temperature and Power consumed by the Pump, Simulation in WLTP

As it is shown in the *Figure 38*, below a certain value of temperature, in particular 350 K, the power consumption for the pump is slightly higher than 100 W; while in case of higher thermal load which can lead to an increment of internal temperature of the Stack, the pump delivers higher flow rate of cooling in order to stabilize the temperature in a narrow range, according with the operating condition designed by manufacturer.

3.2.5 Battery Pack Modelling

Since the Fuel Cell is sized to meet the mean power requirement of the reference cycle (WLTP), the Battery pack has to be designed in order to ensure at the same time a good level of peak power, in order to cover the possible heavy requests by the vehicle in all driving condition, and to have a sufficient energy content able to ensure a drivable range in *Pure Battery Mode* (FC is OFF).

To satisfy the two requirements, the idea is to use a Battery Cell with medium value of peak power and high peak power. The selected cell has the following features [42]:

Parameter	Value [unit]
Capacity	15.5 Ah
Max Voltage	2.7 V
Nominal Voltage	2.3 V
Voltage Range	1.5 V – 2.7 V
Max Discharge/Recharge Current @ 10 sec	240 A
Internal Resistance	1 mΩ @ SoC 50% and 25°
Weight-Energy Density	96 Wh/kg
Volume-Energy Density	202 Wh/l
Number of Cell	148
Max Capacity	6.2 kWh

Table 3: Characteristics of the Battery Pack [42]

The cells are connected in series in order to ensure a level of maximum voltage that should be equal to the maximum DC voltage of the Inverter (400 Vdc). Furthermore, to satisfy one of the two requirements the selected design choice has taken into account the need of ensure a good level of power: with the abovementioned data, it is possible to calculate that the max Battery power at 100 % of SoC is equal to 54 kW. This level of power is needed due to the role of battery pack that has to provide enough power to cover heavy accelerations required by the vehicle. The necessity to have continuously a high level of potential power in the battery has influenced the way in which the *Energy Management Unit* has been made.

In particular three main working conditions are implemented and shortly reported:

1. ***Charge Depleting Mode***: for high SoC and up to a certain threshold the battery delivers all the needed power. In this mode the Fuel Cell is OFF.
2. ***Charge Sustaining Mode***: below a certain value of SoC and above a lower limit, the utilization of battery is reduced, or according to the required load the energy storge can be even recharged, while the Fuel Cell is ON.
3. ***High Recharge Mode***: below the lower limit of SoC, the FC provides its maximum value of power, regardless the possible low efficiency. In this way, the power contribution of the battery pack is strongly limited and the residual charge can be maintained constant or even incremented.

The needed power is only one of the two tasks that the energy storage system has to fulfil: the other is to provide a good drivable range in pure battery mode. The reason why this proper range has to be ensured are mainly two:

- The Refuelling Hydrogen Station are not widespread around the world, for this reason the battery sizing has to predict this eventuality in case of the Hydrogen at the tank is finished.
- Since for design and cost choices the Fuel cell is sizing to meet the requirement of mean requested power in the reference cycle (thus with a value of maximum continuous power, 25 kW), the battery pack has to be calibrated with the aim of ensure enough range at high requested load.

To satisfy these specifications a simulation is carried out to verify the overall range in WLTP condition. Starting from a SoC of 90 %, final value of residual charge inside the battery is 15.7 %.

$$Charge_{Consumed} = (SoC_{Init} - SoC_{Fin}) * Cap_{BattPack}$$

$$Range_{Overall} = \frac{Range_{WLTP}}{Charge_{Consumed}} * Cap_{BattPack}$$

The result of the above expression is that, with reference of WLTP cycle the drivable range in Pure Battery Mode (with the FC shut OFF) is equal to 31 km, while for each WLTP cycle the total charge consumed is 4.6 kWh.

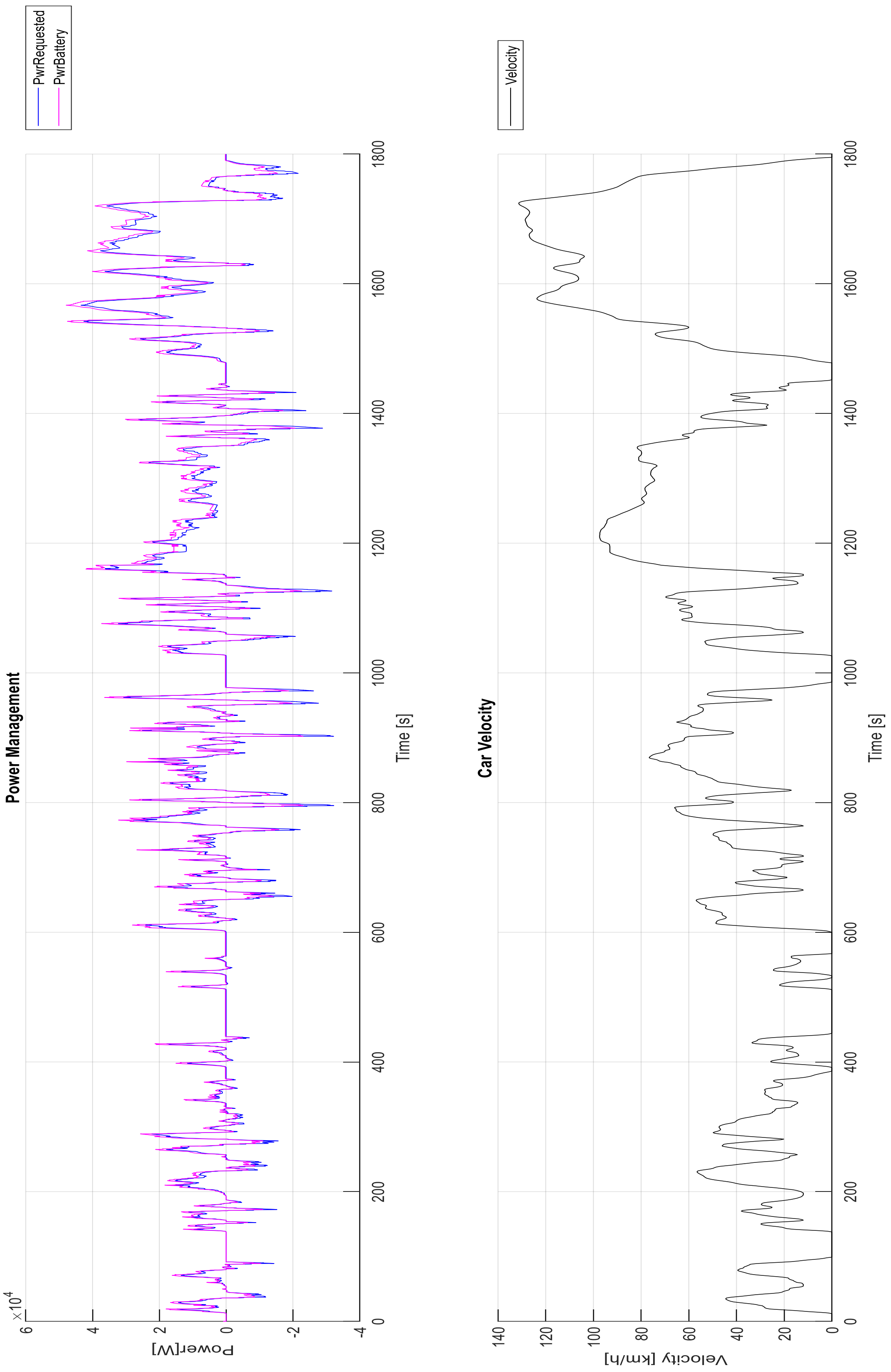

Figure 39: Simulation of Pure Battery Mode in WLTP

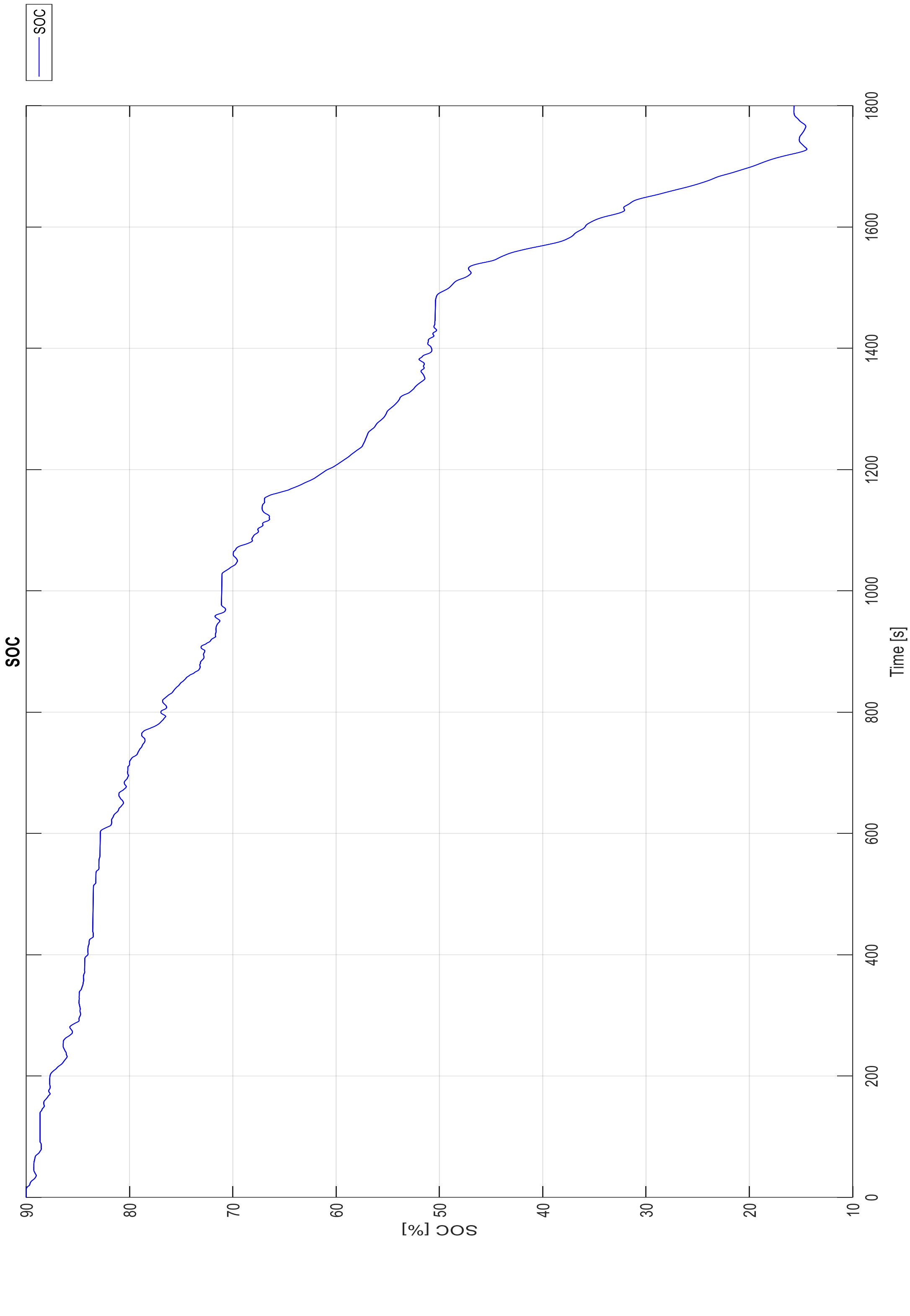

Figure 40: Trend of SoC with Pure Battery Mode in WLTP

3.2.6 E-Motor and Inverter Modelling

For this simulation, the choice is to model the assembly E-Motor – Inverter as unique block-set to simplify the analysis during the simulations and limit the computational time. In Simulink environment the used block-set allows to incorporate the actual map of motor as a function of the rotational speed and requested torque. The inverter is only simulated as a reference of efficiency with respect the actual requested motor power.

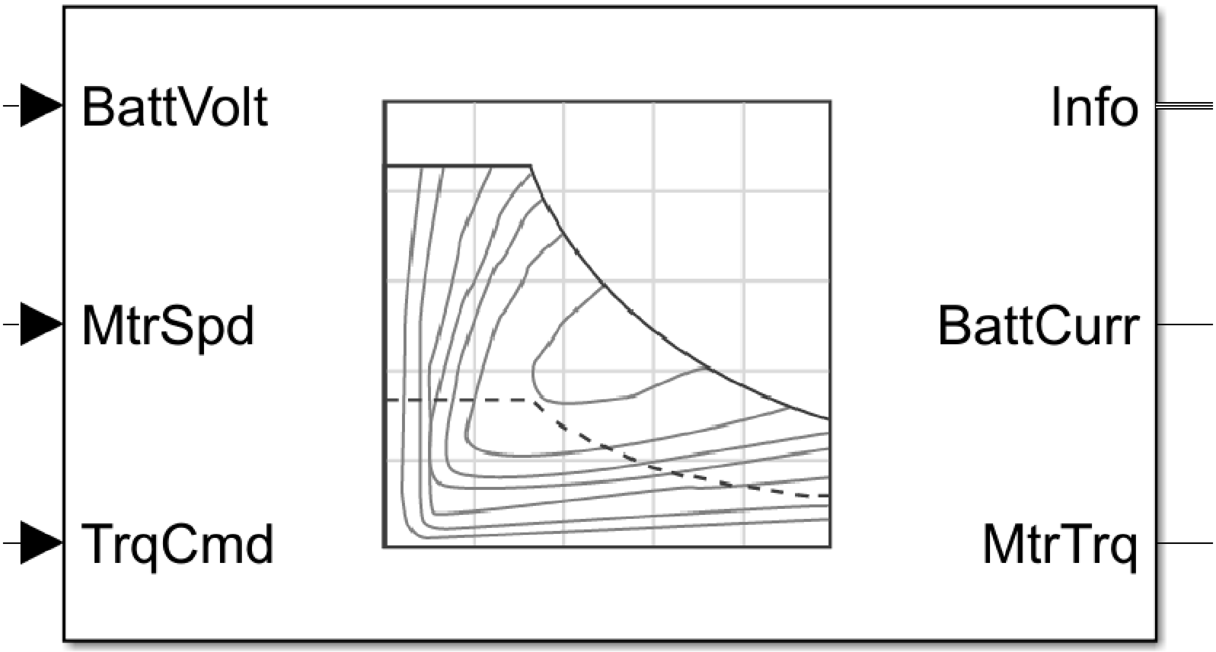

Figure 41: Modelling of E-Motor

As shown in *Figure 39*, the input ports are:

- ***Motor Speed***: computed in *Energy Management Unit* as a result of the requested pedal acceleration and speed profile.
- ***Motor Torque***: predicted at *Energy Management Level*.
- ***Bus Voltage***: the bus voltage is calculated considering the working mode used (with only battery as power source or with both battery and FC active) and on basis of the actual SoC of the battery, in order to give the correct signal BUS voltage at the Inverter.

The motor used is ***IPMS*** (Interior Permanent-Magnet Synchronous) with a maximum power of 93 kW at 5000 rpm. Value of torque of Maximum Transient Torque ranges between 0 and 210 for null motor speed, indeed, the rotor speed varies between 0 and 17000 rpm.

Figure 42: Actual Efficiency Map of E-Motor

The *Figure 42* displays the actual behaviour of the E-Motor: on the x-axis it is plotted the motor speed (in rpm), while on the y-axis the plotted quantity is the delivery torque by the motor to the driveline of the vehicle. Since the analysis of the Motor efficiency is carried out considering only few points (every 500 rpm and 10 Nm a point for the efficiency is calculated), the shape of the curve is not expected one: nevertheless, thanks to the *2D-Interpolation*, every single value of the efficiency can be estimated and, thus, the correct value of power (and torque) is measured.

As mentioned in the introduction of this chapter, to reduce the complexity of the model and, therefore, the computation time for the simulation, the Inverter is only simulated as an efficiency value as a function of the power request. The Inverter has a value of IGBT voltage of 600 Vdc max: it means that the maximum BUS voltage is 400 Vdc (2/3 of the power switch voltage). In particular the efficiency of this component is:

Level of Power [kW]	9.3	11.16	13.95	18.6	27.9	37.2	46.5	55.8	65.1	74.4	83.7	93
Efficiency of Inverter [%]	88.2	90.2	92.3	93.8	95	95.7	95.8	95.9	95.8	95.7	95.5	95.2

Table 4: Table of the Inverter Efficiency as Function of Power

3.2.7 Fuel Cell DC/DC Converter Modelling

To stabilize within a certain range the BUS voltage between the two power sources, the Inverter and E-Motor, a DC/DC converter is placed on Fuel Cell side. This choice is justified by the voltage range of FCs that is between 100 V and 62.6 V, while the BUS voltage for the traction system has a maximum voltage of 400 Vdc: in this way it is possible to exploit as function of different working conditions to step-up the voltage signal outgoing of the FCs:

1. If only FCs gives traction, the DC/DC is set to regulate supply a BUS voltage up to 350 V.
2. If both FCs and Battery Pack are activated, the DC/DC regulates is BUS voltage according to the actual SoC of the battery, to eliminate the differences between the voltage from Battery side and the Voltage of Fuel Cell side.
3. In case of Pure Battery mode, the DC/DC converter is shut OFF, since the FCs does not provide any value of power.

The modelling of the Fuel Cell DC/DC converter is simulated a single value of efficiency, with the following data:

Parameter	Value [unit]
Converter Response Time Constant	0.001 s
Converter Response Initial Voltage	0 V
Converter Power Limit	40 kW
Overall DC/DC Converter Efficiency	98 %

Table 5: Input Data of DC/DC Converter

The features of the selected DC/DC converter, manufactured by *Brusa*, are:

- Bidirectional capability allows wide applications among which there are Fuel Cell, Drivetrain or DC charging applications.
- Facility to control the operation that allows to implement a wide variety of applications.
- Easy to integrate due to high power density and with more than one power sources.

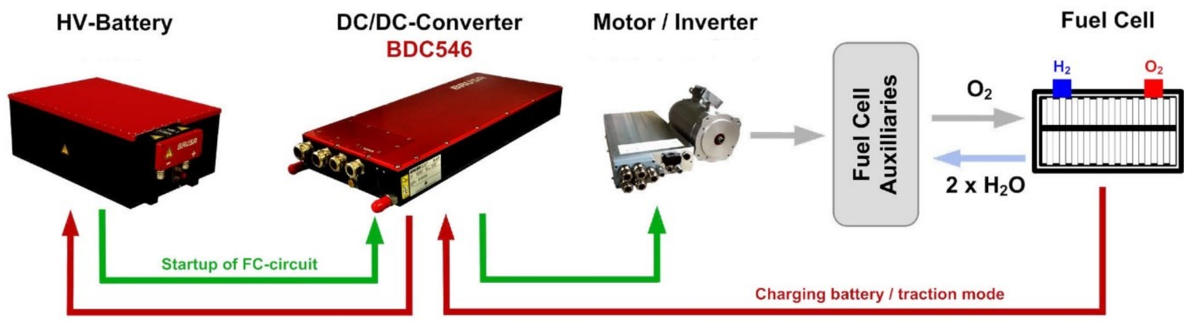

Figure 43: Functional Scheme of the Connection between the Battery, DC/DC, E-Motor and Fuel Cell System [43]

In the *Figure 43* a topologic chart of the connection between the different power source of the vehicle is reported: Fuel Cell Stack is connected to its auxiliaries and to the DC/DC Convert which is subsequently linked to the Inverter-Motor assembly and to the High voltage battery. This element, moreover, can feed energy through the DC/DC converter to the Fuel Cell system to start-up the Fuel Cell during the *Warm-Up phase*.

3.2.8 Control Logic in *State Flow Language* Modelling

To manage the two different energy from, respectively, Battery Pack and Fuel Cell System, an *Energy Management Unit* is design to optimize the Hydrogen consumption and the Discharge/ Recharge Phase of Battery Pack. The main output signals are: Current of Battery, Current Fuel Cell, DC/DC converter Voltage Signal and BUS Voltage for Inverter-Motor.

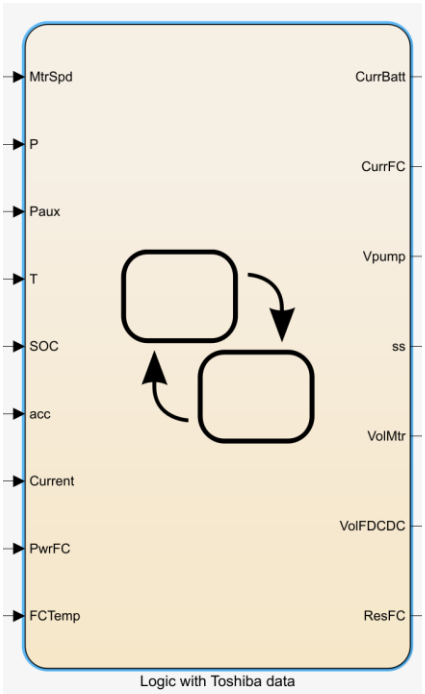

Figure 44: Logic with Input Signal and Output Signal

The guideline is to develop a flexible system able to perform the needed calculation in order to derive a set of output signals that are used to handle the energy flow between the two energy sources. The main features of the Control Unit are:

- Implement a State to simulate the *Warm-Up* phase during which the Battery provides the all power needed by the vehicle, while the Fuel Cell is heated up.
- When activated, the Fuel Cell has to supply a value of power as a function of the actual State of Charge of the battery. The aim is to limit the dynamic of the FCs in order to maintain stable operation and maximize the system efficiency.
- Others command, for example the one devoted for the input signal of cooling system of Fuel Cell system.
- The functions implemented are not designed only to satisfy the needed power in WLTP cycle, but also considering a plenty of working modes for daily driving requests.

More in deep, the main working modes are function of the State of Charge and are designed to, respectively, *Deplete the Charge of the Battery*, *Sustain the Battery Charge* and *Maximum Performance of the Fuel Cell* in order to utilise as much as possible the Fuel Cell. In particular the main *State* are:

1. ***Charge Depletion Mode***: if $SOC_{Actual} > SOC_{UpperLimit}$

$$\begin{cases} Battery\ ON\ and\ P_{Batt} = P_{Req} \\ Fuel\ Cell\ OFF \end{cases}$$

2. ***Charge Depletion Mode***: if $SOC_{UpperLimit} < SOC_{Actual} < SOC_{LowerLimit}$

$$\begin{cases} Battery\ ON\ and \begin{cases} Recharged\ if\ P_{FC} > P_{Req} \\ Provide\ Power\ if\ P_{FC} < P_{Req} \end{cases} \\ Fuel\ Cell\ and\ P_{FC} = f(SOC_{Actual}) \end{cases}$$

3. ***Maximum Performance of the Fuel Cell***: if $SOC_{Actual} < SOC_{LowerLimit}$

$$\begin{cases} Battery\ ON\ and \begin{cases} Recharged\ if\ P_{FC} > P_{Req} \\ Provide\ Power\ if\ P_{FC} < P_{Req} \end{cases} \\ Fuel\ Cell\ and\ P_{FC} = P_{FC}\_max \end{cases}$$

For each *Macro-State* a specific mode for the *Regenerative Braking* is implemented: the braking phase is divided in two contributions, one part for the regenerative stage and other for the pure mechanical braking.

Going more in depth on the ***Charge Depletion Mode*** and on the ***Maximum Performance of the Fuel Cell***, it is worth to mention that for a value of State of Charge lower than $SOC_{UpperLimit}$, the Fuel Cell is activated: in a first phase, up to the reaching of the Operating Target Temperature of the Fuel Cell, the system is modelled to behave as Pure Battery Vehicle, in which all the power request are provided by the Battery. After this time, which depends on environmental condition, the Fuel Cell starts to effectively supply energy and the output power depend on vehicle demands and on the actual SoC. The function that describes the generated power by the Fuel Cell is:

$$P_{FC} = \frac{a_1 - b_1 * (SOC_{Actual} - SOC_{LowerLimit})}{SOC_{Actual}}$$

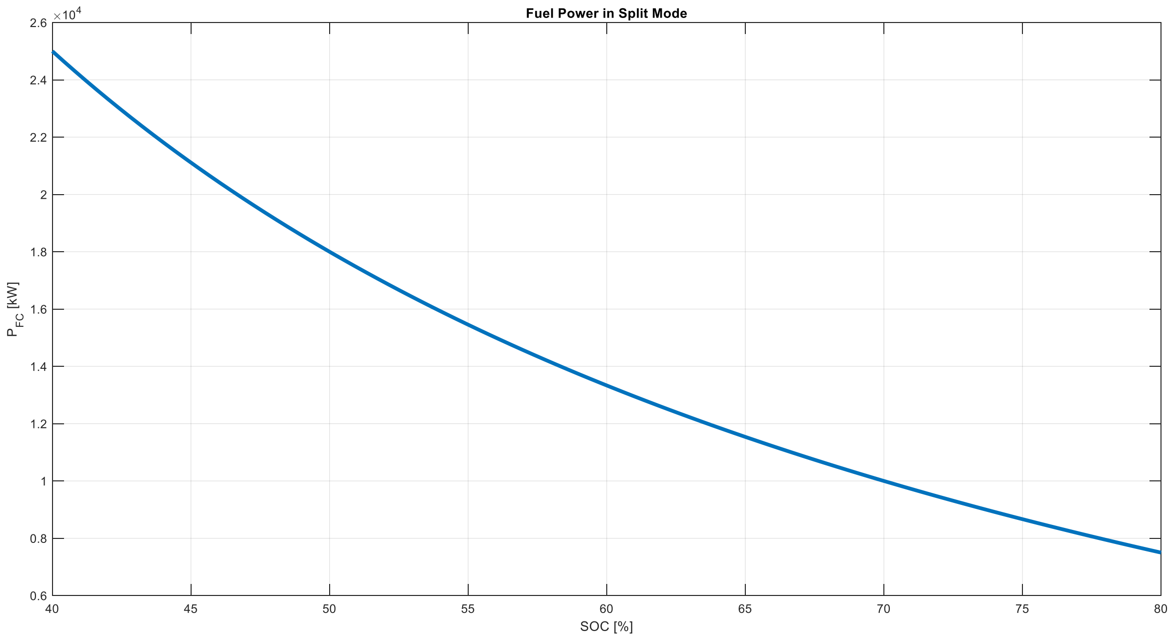

Figure 45: Fuel Cell Power as function of State of Charge

The different Trade-Off have been found varying the coefficients $\boldsymbol{a_1}$ and $\boldsymbol{b_1}$ and the range of action for the Fuel Cell, changing the *Upper* and the *Lower* limit of State of Charge.

One issue related to this type of function and intrinsic at the FCs in terms of power is that, also WLTP, the maximum power that the FC can ensure is not sufficient to satisfy the vehicle request: for this reason, it has been necessary to studies, also in ***Charge Depletion Mode*** some working mode in which the Battery Pack provides part or all needed power. In particular two different situations are analysed: heavy acceleration and high power requested. For these driving conditions, the idea is to limit the dynamic of Fuel Cell and use the Battey to follow the load.

- ***Heavy Acceleration***: for $acc_{vehicle} > acc_{threshold}$

$$\begin{cases} if\ t_{acc} < t_{Threshold} \begin{cases} Batt\ ON\ and\ P_{Batt} = P_{Req} \\ FC\ ON, P_{FC} = f(SOC_{Actual}), but\ does\ provide\ power\ to\ Motor \end{cases} \\ if\ t_{acc} > t_{Threshold} \begin{cases} Batt\ OFF \\ FC\ ON\ and\ P_{FC} = f(SOC_{Actual}) \end{cases} \end{cases}$$

- ***High Power Request***: for $P_{Requested} > P_{NominalFC}$

$$\begin{cases} if\ P_{NominalFC} < P_{Req} < P_{Max\_Ref} \begin{cases} Batt\ ON\ and\ P_{Batt} = P_{Req} - P_{NominalFC} \\ FC\ ON, P_{FC} = P_{NominalFC} \end{cases} \\ if\ P_{Req} > P_{Max\_Ref} \begin{cases} Batt\ ON\ and\ P_{Batt} = P_{Req} - P_{MaxFC} \\ FC\ ON\ and\ P_{FC} = P_{MaxFC} \end{cases} BOOST\ MODE \end{cases}$$

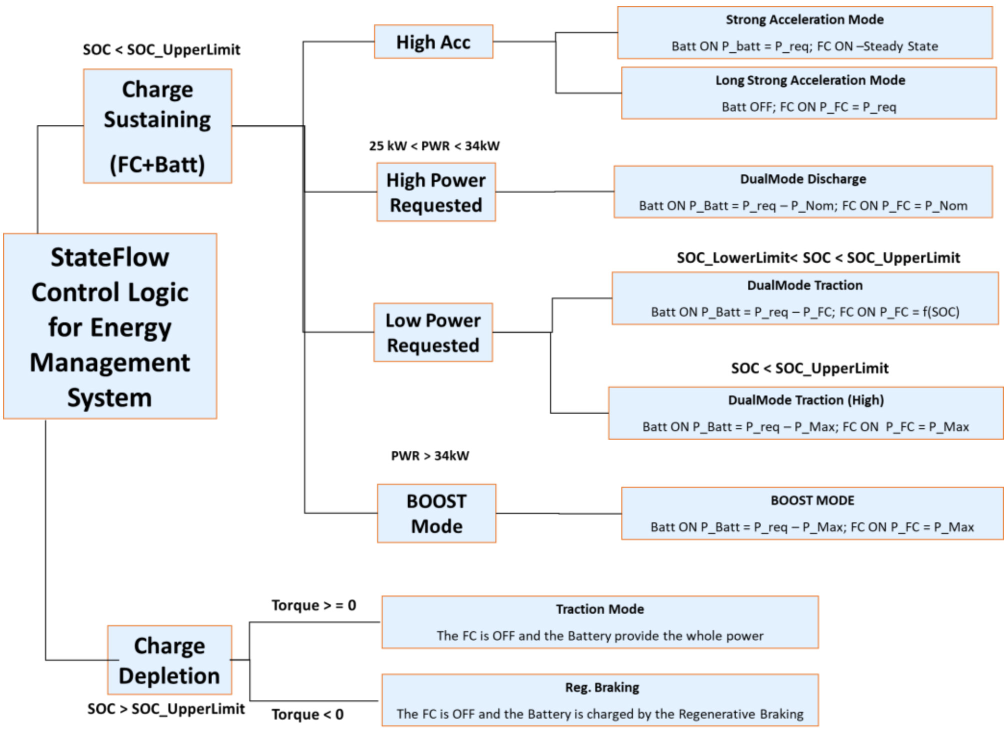

Figure 46: Summery of the Different Working Mode

4. ANALYSIS OF RESULTS

Due to the high number of simulations carried out and to have result, as much as possible comparable among them, the input data are kept constant. The focus is to fix environmental and vehicle conditions, maintaining them equal and analyse the obtained results.

Firstly, it is necessary to identify which are the parameters to be regulated and justified the choices. In a second phase, it will be shown the result obtained for the driveline simulation, in order to verify the correct operation of the drivetrain, regardless the source of power (from Battery or/and from Fuel Cell side). Finally, the different result achieved will be reported changing the parameters which influence the action threshold of the Fuel Cell and the *Initial SoC* of the Battery Pack.

After the last phase the relationship between the Hydrogen Consumed during the entire cycle and the variation of *SoC* between the start and the end of the cycle will be displayed in order to acquire the information about the real H_2 consumed: a corrective factor will be described in order to understand which is the actual Fuel Consumption.

4.1 Condition of the Simulation and Input Data of the Vehicle

The main parameters studied and kept constant during all simulations are the environmental conditions: in particular, changing the ambient Temperature has a huge impact on Fuel Cell *Warm-Up* Phase and on *Internal Resistance* of the Battery Pack. Moreover, the wind affects the dynamic of the vehicle and for this reason the is set to 0.

Parameter	Value [unit]
Ambient Temperature	293.15 K
Wind Velocity	0 m/s
Absolute Pressure	101325 Pa
Slope of the Road	0 %

Table 6: Environment Conditions

In the same way, many input data for the vehicle are set in order to maintain constant the value of ***Power Needed*** during the entire cycle and to have the same dynamic behaviour regardless the test done. For the instance, varying the data, such as suspensions parameters, testing mass of the vehicle, aerodynamic coefficient, vehicle-auxiliaries power and dimension of the wheels.

Parameter	Value [unit]
Kerb Weight	1300 kg
Test Load	200 kg
Overall Mass	1500 kg
Wheelbase	2700 mm
Wheel Rolling Radius	0.3 m
Frontal Area	2.27 m^2
Drag Coefficient	0.3
Tau Ratio of Single Speed Transmission	7.2
Transmission Efficiency	95 %
Vehicle Auxiliaries Power	400 W

Table 7: Table of Vehicle Parameter

4.2 Driveline Simulation

4.2.1 Torque Required and Torque

To simulate and verify that the required torque is effectively produced by the electric motor and transmitted to the transmission line, the two signals are plotted and compared each other.

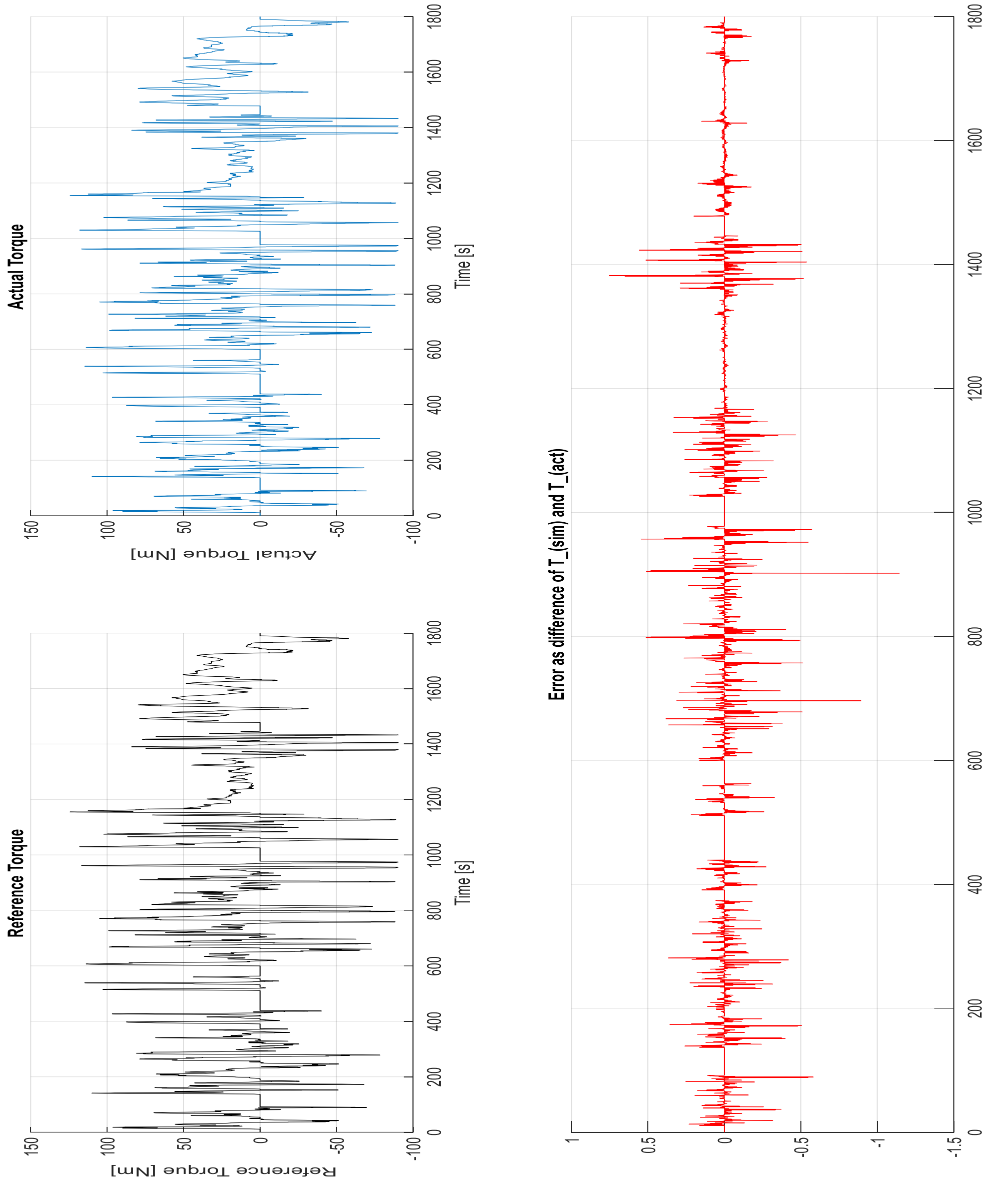

Figure 47: Torque Simulated vs Torque Resulted

4.2.2 Speed Profile in WLTP vs Actual Speed

The speed profile selected for all simulation is the WLTP cycle that is composed in four different sub-cycle. The WLTP that has replaced replaces the standard NEDC based procedure for type approval testing of light-duty vehicles, is justified by many arguments, among which:

- A greater range of driving situations (urban, suburban, main road, motorway) with higher average and maximum speeds and higher average and maximum drive power.
- Longer test distances covered with respect the NEDC: enable to have a better prediction of the real driving range of the vehicle.
- More dynamic and representative accelerations and decelerations, with shorter stop phase
- Allows to evaluate best and worst-case values on consumer information, reflecting the options available for similar car models.
- Because of all these improvements, WLTP will provide a more accurate basis to compute a car's fuel consumption and eventual emissions profile (in this case only the Fuel Consumption is considered since the Fuel Cell does not emit any pollutant or GHG substances). This will ensure that lab measurements better reflect the on-road performance of a car. [45].

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	s	m		km/h	km/h	km/h	m/s²	m/s²
Class 3b (v_max ≥ 120 km/h)									
Low 3	589	156	3095	26.5%	56.5	25.7	18.9	-1.47	1.47
Medium 3-2	433	48	4756	11.1%	76.6	44.5	39.5	-1.49	1.57
High 3-2	455	31	7162	6.8%	97.4	60.8	56.7	-1.49	1.58
Extra-High 3	323	7	8254	2.2%	131.3	94.0	92.0	-1.21	1.03
Total	**1800**	**242**	**23266**						

Figure 48: Subdivision of the WLTP cycle for a Vehicle Class 3b [44]

As reported in *Figure 48*, for each sub-cycle is reported the duration and the different values of speed: both factors influence heavily the power required by the vehicle during the driving condition.

In the following analysis, it is worth to underline the error between the predicted speed profile according to the driving condition in WLTP cycle and effective speed profile calculated at wheel level.

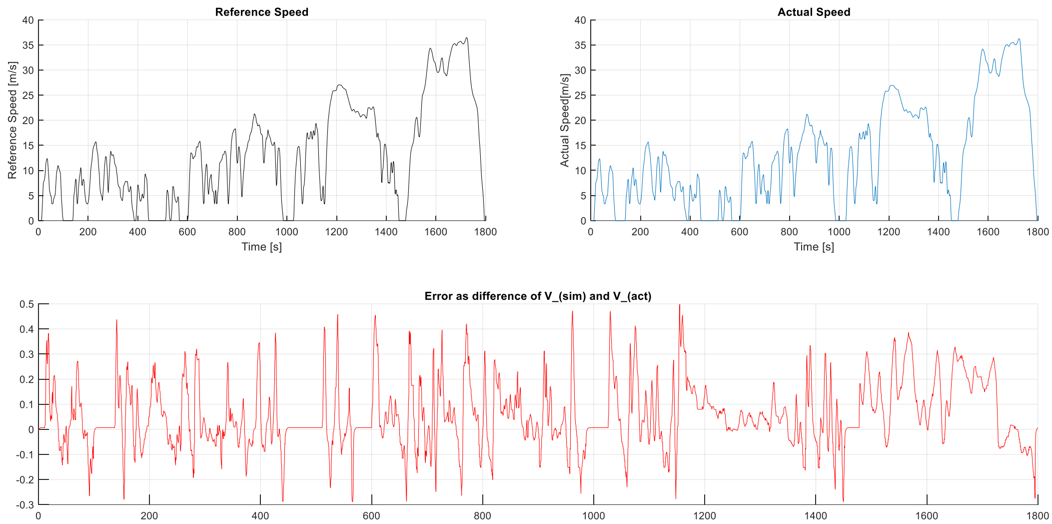

Figure 49: Speed Profile of WLTP vs Actual Speed Profile

The final result of the two simulation is that the driveline is simulated with a good level of accuracy as it is show in these two paragraphers. For the modelling of transmission, including the wheel and the braking system, a possible future development could be to design an automatic gearbox with two speeds and make a comparison in terms of efficiency and accuracy between the two different architectures.

4.3 Obtained Results and Comments

In this section, there will be plotted and analysed the results obtained during the simulation, changing the different variables which regulates the threshold action of the Fuel Cell. The two criteria adopted during the different analysis are the following:

1. Change the coefficient which regulates the output power of Fuel Cell (a_1 and b_1): in this way, it is possible to vary the range of power in *Charge Sustaining Mode*.
2. The second variation adopted is to modify the $SOC_{UpperLimit}$ in order to extend or reduce the duration of *Charge Depleting Mode*, phase during which the Fuel Cell is OFF and only the Battery pack provides power to the vehicle.

The different simulations are carried out to display the different power contribution along the entire cycle and to studied the influence of many parameters on the overall Fuel Consumption: firstly, considering a single *Scenario*, so maintaining equal the coefficients and $SOC_{UpperLimit}$ and changing only the $SOC_{Initial}$, and a second analysis is performed to compare different *Scenario* keeping constant the $SOC_{Initial}$.

For what concern the calculation of the Hydrogen consumption, that is a key parameter for these analyses, some explanations have to be done:

- Since the FCs does not follow the load according to the driver request, but generally provides a value of power related to the actual SoC, the final SoC is generally different with respect the initial value: it means that the Fuel Cell can deliver an excessive (or a lower) value of energy that can be storage (or discharged) in the battery during the cycle.
- To compensate this the delta, a proper function is studied to correct the predicted Hydrogen consumption at the end of driving cycle.

$$m_{H2\_corrected} = m_{H2\_end} - \frac{\Delta SOC * Cap_{max}}{\eta_{DC/DC} * P_{FC\_Nom}} * \dot{m}_{H2_{Nominal}}$$

4.3.1 Analysis of the Power Contribution in WLTP Cycle

The firstly conducted analysis is to study the power contribution from the two energy sources along the sub-cycle of the WLTP. Taking into account that the $P_{FC} = f(SOC, a_1, b_1)$, the *Scenario* set in *Control Logic* is the baseline:

Parameter	Value [unit]
a_1	10^6
b_1	-10^4
SOC Range for the *Charge Sustaining Mode*	[40 80] %
Output Power Range of FC @ 40 %	25 kW
Output Power Range of FC @ 80 %	7.5 kW

Table 8: Main Parameters of Scenario 1

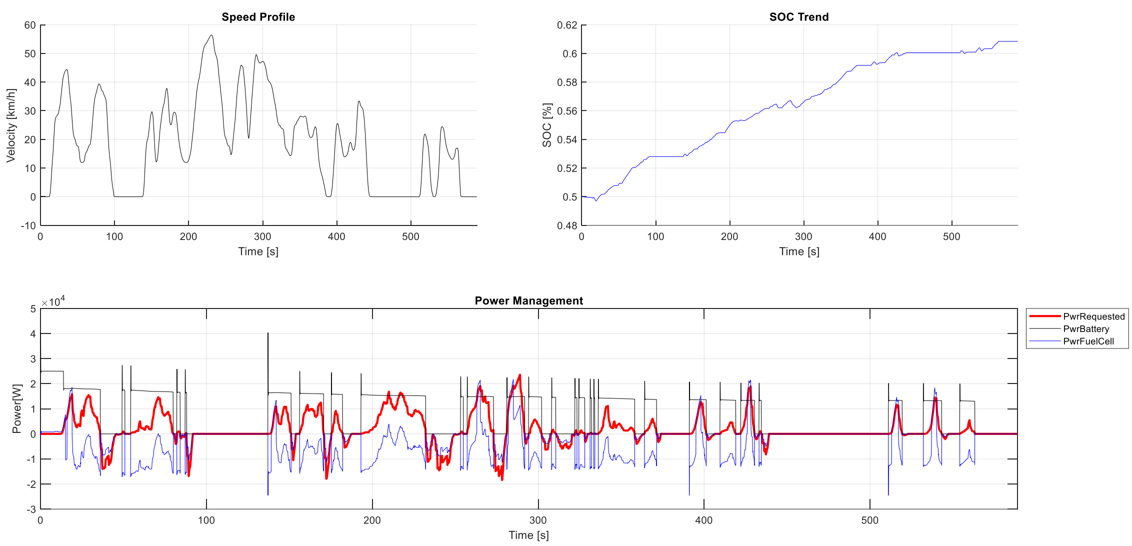

Figure 50: Sub-Cycle Low 3, SOC_{Int} = 50%

In the *Figure 50*, it is reported the sub-cycle *Low 3* of WLTP with an initial State of Charge of the battery equal to 50 %. The main outcomes for this part of the driving cycle are:

1. Up to time equal to 19 s, the Fuel Cell provides a value of power equal to $P_{FC\_Nominal}$ to perform the *Warm-Up Phase*. During this period, the Battery Pack feeds all the power

needed by the Vehicle (Reference Power, according to WLTP condition, Vehicle Auxiliaries and Fuel Cell Ancillaries).

2. When Fuel Cell starts to provide power to the Vehicle, it is possible to verify that, even in traction condition, for most of the time the FC is able to satisfy the driver requests and the Battery Pack is recharged by the difference between the P_{FC} and P_{Req}.
3. Since the above point, the actual SOC tends to increase (up to 60 % at the end of sub-cycle) and therefore the output level of power provided by the Fuel Cell starts to decrease.

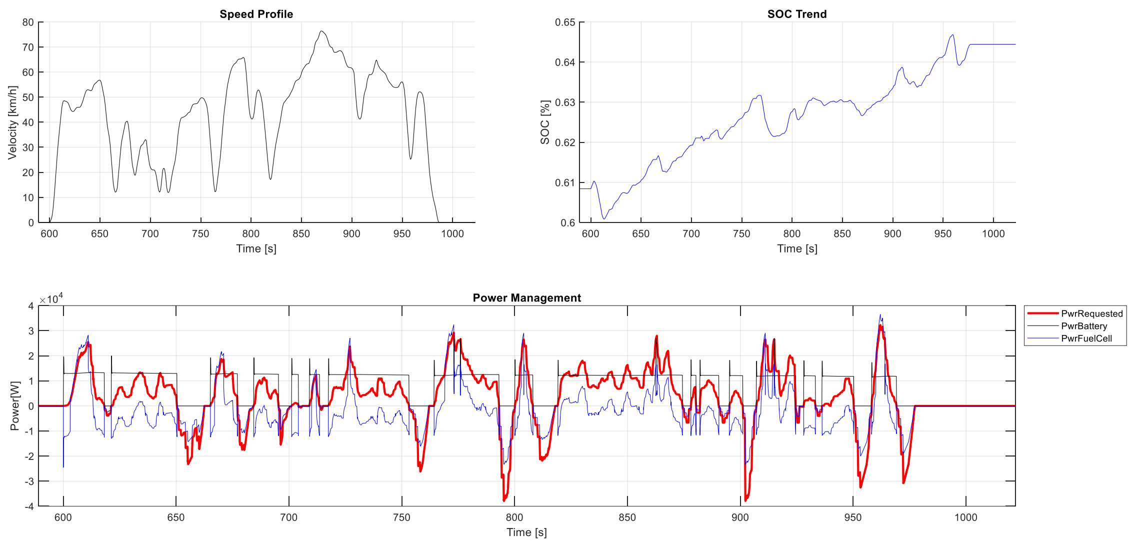

Figure 51: Sub-Cycle Medium 3-2, SOC_{Int} = 50%

The subsequent cycle is the *Medium 3-2*, as reported in *Figure 51*, and it is possible to notice how the overall stopping time is lower, while the load starts to increase. With the reference at these considerations, the Power Management chart shows these trends:

1. The heavy accelerations are multiple, reason why it is possible to see how the load is effectively supplied by the Battery Pack, while the Fuel Cell is maintained in Steady State condition (according to the actual State of Charge) in order to limit the its dynamic behaviour
2. Since the load required during this sub-cycle tends to increase and, meanwhile, the P_{FC} slightly decreases, in some conditions (take as reference the period between 820 s and 870 s), the FC is unable to cover all the power required and, therefore, the Battery pack has to provide the remaining part of Power.
3. For the situation mentioned above, the SOC has only a little increment.

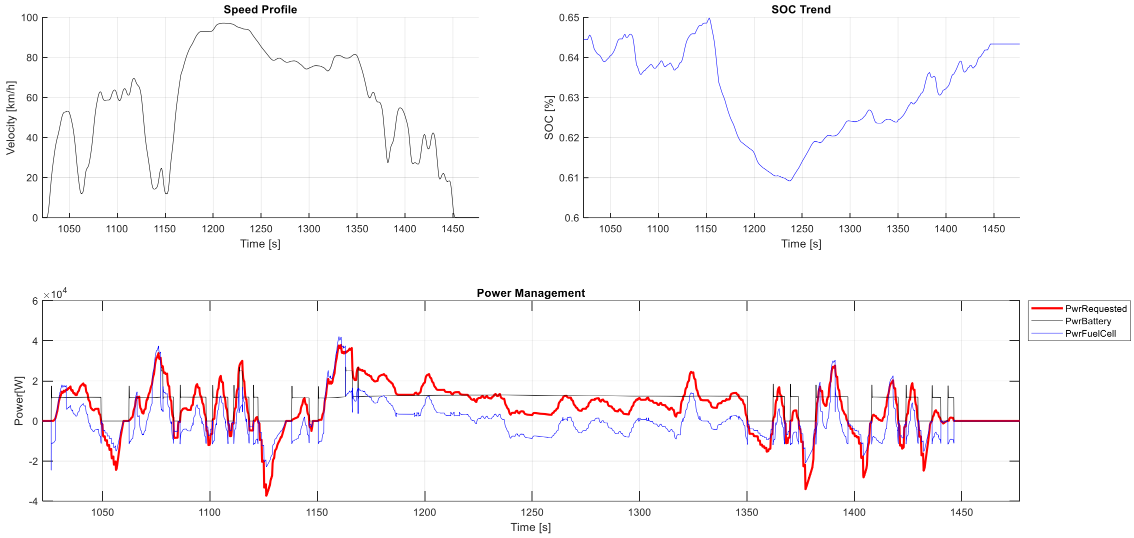

Figure 52: Sub-Cycle High 3, SOC_{Int} = 50%

In the second-to-last sub-cycle, the load is even more increased (*Figure 52*) and the power generated by the Fuel Cell is not sufficient to meet requirements (the velocity reaches a value around 100 km/h) and, thus, the Battery Pack has to supply part of the power, reason why the SoC tends to decrease. At the end of the *High 3-2*, the load required goes down and the Charge inside the Battery grows up to the value at the beginning of this sub-cycle.

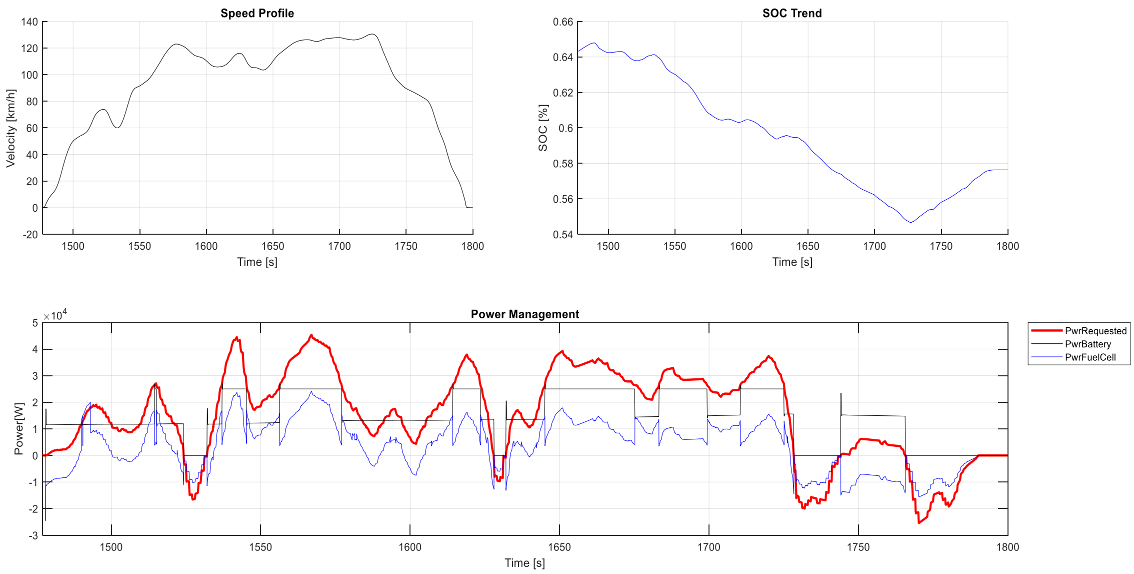

Figure 53: Sub-Cycle Extra-High 3, SOC_{Int} = 50%

In the last sub-cycle (*Figure 53*), the Vehicle Power overcomes the value of $P_{FC\_Nominal}$, the Fuel Cell is set to feed a level of power equal to the its nominal value, while the difference between P_{Req} and $P_{FC\_Nominal}$ is given by the Battery: indeed, along this sub-driving cycle the SoC of the Battery decreases constantly and only during the last part of the cycle, when the braking phase occurs the Battery is marginally recharged.

Thanks to these analyses, in which the entire driving cycle is subdivided in different parts, it is possible to derive some conclusions about the *Energy Management Unit*:

- Reduce the *Warm-Up Phase* can have benefit both in terms of power consumed by the Battery and Hydrogen Fuel Consumption earlier in the driving cycle.
- During the *Low* and *Medium* sub-cycles, the power generated by the Fuel Cell is enough to meet the vehicle requests and part of the generated power is used to recharge the Battery.
- For higher values of needed power (*High* and *Extra-High*), the Fuel Cell does not meet the vehicle requirements and, therefore, the Battery has to provide the remainder part of power, with the drawback of lowering the State of Charge.
- The Fuel Cell is optimized in order to have a high overall Stack efficiency.

4.3.2 Mean Fuel Consumption for *Scenario 1*

To have a better view of the real Fuel Consumption of the vehicle in WLTP cycle, different simulations are performed, considering the conditions of the *Scenario 1* and changing for each plot the initial SoC: in this way, it should possible to understand which are the best condition to minimize the overall Hydrogen Consumption.

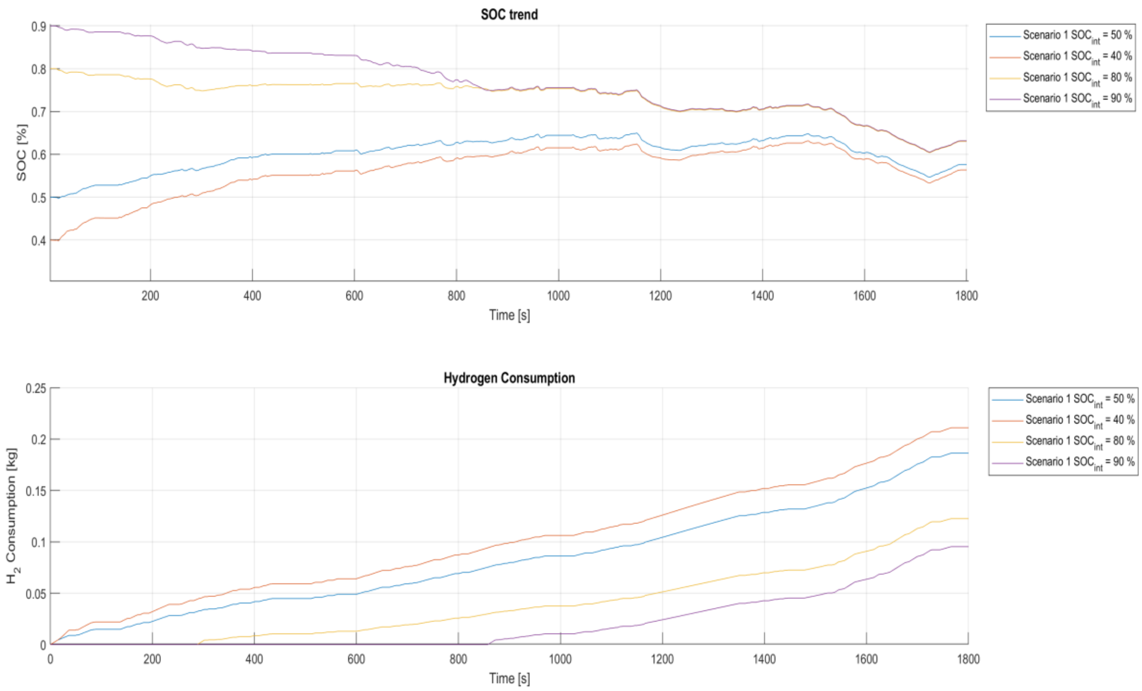

Figure 54: SOC Trend and Fuel Consumption for Scenario 1

As it is possible to see in *Figure 54*, higher is the State of Charge at the beginning of simulation lower will be the effective H_2 Consumption, but, nevertheless the greater apparent final consumption, starting from SOC_{Init} equal to 40 % (or even 50%), the final internal Charge of the battery is greater the initial one and, hence, a possible corrected factor for the Fuel Consumption can introduce. This operation can be made both in case the SOC_{Final} is greater than SOC_{Init} and vice-versa: the aim is to “transform” in a Fuel Contribution (positive or negative, as a function of the SOC difference) to convert the electric energy stored (or used) in the battery in chemical quantities.

Fuel Consumption	**SOC_{Init} = 50%**	**SOC_{Init} = 40%**	**SOC_{Init} = 80%**	**SOC_{Init} = 90%**
Resulted	0.186 kg	0.211 kg	0.123 kg	0.095 kg
Corrected	0.166 kg	0.167 kg	0.168 kg	0.168 kg

Table 9: Resulted Fuel Consumption and Corrected for Scenario 1

With the reference on *Table 9*, it is understandable how the resulted consumption is lower increasing the initial State of Charge, but performing the calculation for the corrected factor, the situation is completely different: indeed, the lower fuel consumption is for an initial SOC equal to 50%, since at the end of the cycle, the final energy content inside the battery in higher. In this way the difference between these two values is converted in a term of mass of Hydrogen Consumption and it is subtracted to the final reference value of H_2.

Another consideration is that the abovementioned difference between the different Fuel Consumption is very small (order of 2.5 gr), reason why it is possible to calculate a mean value and compute an effective Range for this vehicle in Hybrid mode, according to the WLTP simulation.

$$m_{H_2 mean} = 0.167\ kg\ to\ cover\ the\ distance\ of\ WLTP\ cycle$$

It means that, considering the WLTP condition, the consumption is:

$$m_{H_2} = \frac{m_{H_2 mean} * 100\ km}{distance_{WLTP}} = 0.718\ kg/100km$$

Since the tank has been designed to have a capacity of 5 kg, the overall range is 696 km.

4.3.3 Analysis of Hydrogen Consumption with different *Scenario*

As briefly explained during the previous paragrapher, the idea is to vary continuously the different parameters which regulates the threshold action of the Fuel Cell in order to study the variation in terms of Fuel Consumption. In the following analysis, different scenario will be described and simulated: the results will be discussed in order to define which is the best strategy to minimize the Hydrogen Fuel consumption and which can be the improvement that can be done to have a better regulation for the Energy Management System.

The different *Scenario* are set in Control Logic, by modifying the key parameters which regulates the Fuel Cell impact of the generated power.

Moreover, to have more comparable results, the initial State of Charge is maintained constant (60 %): in this way a comparison can be shown, understating which is the best strategy for the H_2 consumption point of view.

Parameter	***Scenario 1***	***Scenario 2***	***Scenario 3***	***Scenario 4***	***Scenario 5***	***Scenario 6***
a_1	10^6	5*10^5	5*10^5	10^6	10^6	10^6
b_1	-10^4	-2*10^4	-10^4	-2*10^4	-10^4	-10^4
SOC Range for the *Charge Sustaining Mode*	[40 80] %	[40 60] %	[40 80] %	[40 80] %	[40 60] %	[40 70] %
Output Power Range of FC @ 40 %	25 kW	12,5 kW	12,5 kW	25 kW	25 kW	25 kW
Output Power Range of FC @ 80 %	7.5 kW	1.67 kW @ 60 %	1.25 kW	2.5 kW	13.3 kW @ 60%	10 kW @ 70 %

Table 10: Parameters for the Different Scenario

Those parameters are used just to have different reference values for the simulation with respect the analysed case with *Scenario 1*: a future development could be to arrange a *Loop-simulation* in which the parameters and the range of action are continuously changed in order to find the optimal *Trade-Off*. Indeed, the selected numbers are used mainly to understand which are the conditions that has to be avoided due to the overall poor system efficiency, evaluated by means of Corrected Hydrogen Fuel Consumption.

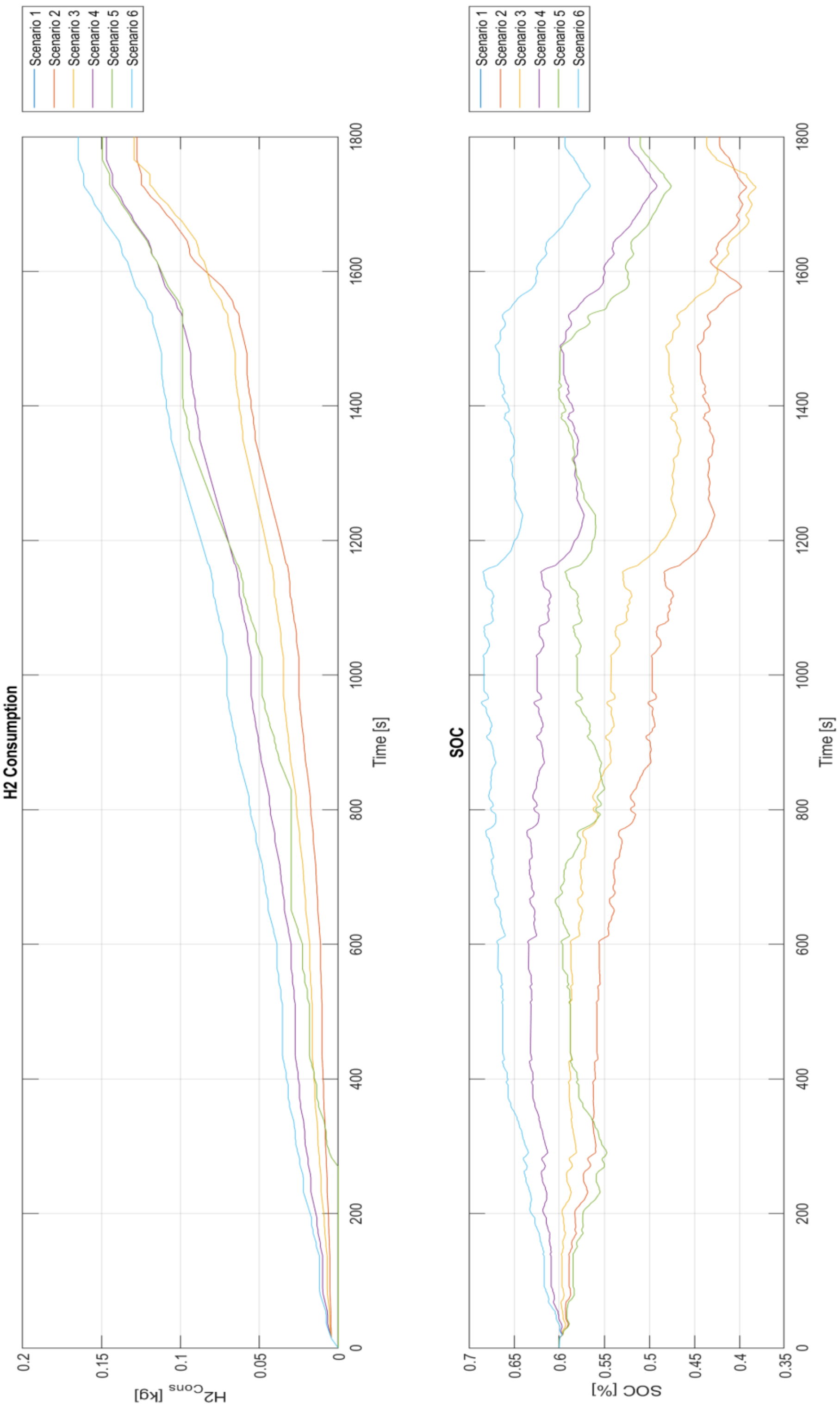

Figure 55: H_2 Consumption and SOC Trend for the Different Scenario

On basis of the plotted *Figure 55*, some remarks are necessary:

- The curves of the *Scenario 1* are superimposed with the ones of *Scenario 6*, because with the selected SOC interval for the *Charge Sustaining Mode*, the initial State of Charge and Power Needed by the vehicle along the cycle, the Battery is unable to overcome the limit of 70 % of SoC and in this way the State Logic does not pass in *Charge Depletion Mode*. This statement is valid both for the condition of Scenario 6 and, above all, for *Scenario 1*.
- The sequent comparison between the different Scenario is made only considering the SOC and Fuel Consumption: for a better analysis, it should be possible to study the behaviour of Fuel Cell under *Transient Load* (not taken into account for this test)

Fuel Consumption	***Scenario 1***	***Scenario 2***	***Scenario 3***	***Scenario 4***	***Scenario 5***	***Scenario 6***
Resulted	0.165 kg	0.128 kg	0.129 kg	0.147 kg	0.15 kg	0.165 kg
Corrected	0.167 kg	0.178 kg	0.175 kg	0.169 kg	0.175 kg	0.167 kg

Table 11: Resulted and Corrected Fuel Consumption with the different Scenario in WLTP

In the *Table 11* the final results in terms of Fuel Consumption are reported; the main interesting outcomes are:

- Reducing the range of action for the *Charge Sustaining Mode* (acting only on the range of SOC, without changing the coefficient a_1 and b_1) does not have any benefit in terms of the corrected fuel consumption. This is clear comparing, for instance, the consumption of *Scenario 5* with one of *Scenario 6*.
- Lowering the Range of Power, by acting on the two coefficients a_1 and b_1, for the *Resulted Consumption* seems a good solution, but taking as reference the *Corrected Consumption*, the results is totally different: restrict the range of the output power for the Fuel Cell leads to a heavy depletion of the Battery whose energy consumption must be recalculated by means of *Corrective Factor*.

Considering the analysis performed, the best *Trade-Off* found is for *Scenario 1*, in which the lowest Fuel Consumption is found. In addition, by using an extended Range for *Charge Sustaining Mode* it is possible to use the Fuel Cell in a wide driving condition, with the aim of maintaining charged the Battery Pack that can be used as *Power Buffer*.
The others analysed solutions can have some benefit in terms lower output power for the FC due to the possible lower thermal load (and thus for the cooling pump) and auxiliaries' power of the reactants supply systems, but these advantages are not compensated by the Corrected fuel consumption.

4.4 Future Development for the Model

The modelled vehicle, designed in Simulink/*Simscape* Environment, has been developed to be flexible in way that different sizing for the Battery Pack and Fuel Cell system can be provided. Despite this outcome, a future implementation can be done, among which it is possible to mention:

1. Study the dynamic of Fuel Cell stack, in order to have the possibility to design a better *Control Strategy* for the *Energy Management Unit*.
2. Improve the modelling of the Auxiliaries System, to have a better reference in term of power consumed and system efficiency.
3. Provide a modelling of External Charged for the Battery Pack and design the Battery Management System.
4. Model the Inverter unit to be coupled with the E-Motor.

5. COMPARISON BETWEEN THE FCV AND *BMW i3 REX*

One of the main questions about the use of Fuel Cell could be why prefer this system as a secondary power source instead of a common ICE for a *Series Hybrid Vehicle*. As initially mentioned in the previous chapters, the Fuel Cell, in particular the one based on the PEM technology as in the designed model, has zero pipeline emissions, while an internal combustion engine, despite its efficiency in a Series Hybrid Vehicle can be optimized, the noxious emission and the GHG are not null. This is only one analysis that can be carried out: indeed, while the combustion engine technology is widespread and the availability fuel is ensured around the World, to promote the development of Hydrogen-based solutions for the vehicle, an integrate infrastructure network for the Refuelling Station has to be built. Moreover, nowadays the cost of the FC is still high and it is another factor which has limited the diffusion of this kind of vehicles.

Regardless these considerations, to make a "*fair*" comparison between the overall emission profile, it is worth to compare the *Well-to-Wheel* greenhouse gas emission for the two different type of Series Hybrid Vehicles, one PEMFC based (as the model previously described) and another on ICE-base (*BMW i3 REX*), equipped with engine from the BMW K75 motorcycle [47].

The BMW i3 Rex (the model analysed is the one with a battery capacity of 120 Ah) is selected due to the dimensions, weight and segment comparable with respect to the modelled vehicle and why it is one of the main applications in Automotive market for a Series Hybrid Vehicle.

Parameter	BMW i3 REX	FCv Series Hybrid
Kerb Weight	1365 kg	1300 kg
Wheelbase	2570 mm	2700 mm
Frontal Area	2.38 m^2	2.27 m^2
Drag Coefficient	0.29	0.3
Tau Ratio	9.67	7.2
Wheel Radius	0.326 m	0.3 m
Maximum Installed Power for the Secondary Power Source	35 kW	34 kW

Table 12: Comparison between the Modelled vehicle and BMW i3 [46]

To have comparable results between the corrected Fuel Consumption of the two vehicles in WLTP cycle and, only for the BMW i3 REX, the actual pipeline CO_2 emissions, the simulations are carried out in *Charge Sustaining Mode*: in this way, regardless the different strategies implemented for the *Energy Management* for the two vehicles, it is possible to draw the advantages and the drawbacks of the two different systems.

FCv Series Hybrid	
Hydrogen Consumption	0.718 kg/100km
Scenario	1
Mode for the Simulation	Charge Sustaining Mode
BMW i3 REX	
Gasoline Consumption	0.88 l/100 km
CO_2 Emission	20.4 g/km

Table 13: Hydrogen Consumption and Gasoline Consumption [47]

The energy pathway to produce the Hydrogen are different and, as a function of the way in which the H_2 is produced and storage, there are a different emission profile to take into account. The Hydrogen can be produced by means of different process among which it is possible to consider *Electrolysis of Water* or *Steam Methene reforming*: for each of this case a value of GHG emission for the production.

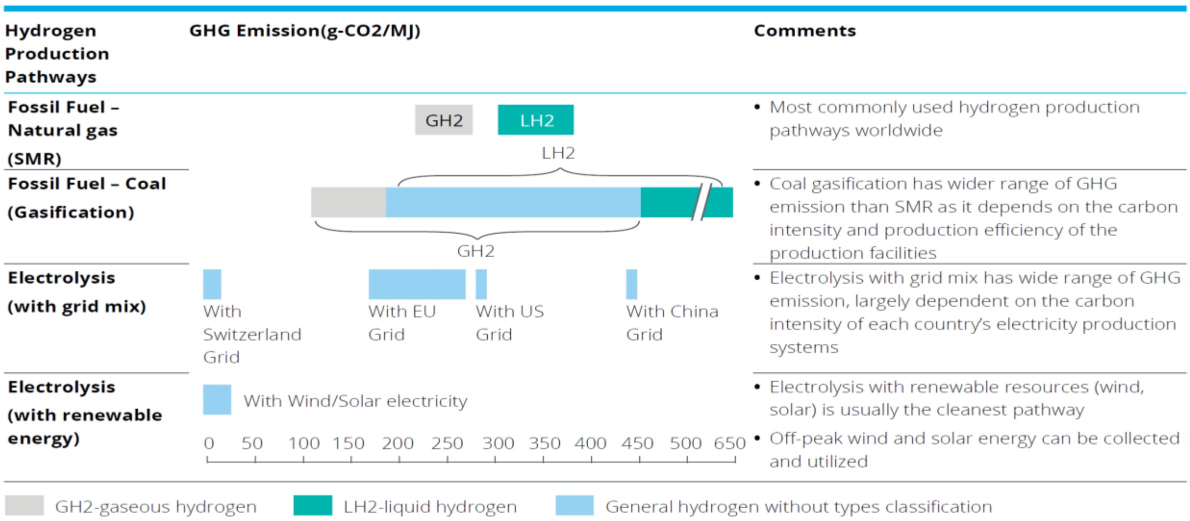

Figure 56: Different Pathway for the Hydrogen Production [5]

- If the Hydrogen is produced by means of *Electrolysis of Water* the *Well-to-Tank* emission are equal to 1452 g_{CO2}/kg_{H2} [48] and using electric energy from wind power. Regardless the renewable source of the electric energy, the CO_2 emissions reported 2 are due to the energy used for compressing and dispensing the hydrogen at a retail site. The final result will be

$$WtT_{H_2\_CO_2} = \frac{1452_{g/kg_{H2}} * \ 0.718 \ kg_{H2}}{100 \ km} = \ 10.42 \ \frac{g_{CO_2}}{km}$$

- In the other case, it is supposed that the Hydrogen is produced by means of *Steam Methene reforming*. For this scenario the equivalent emissions are 12863 g_{CO2}/kg_{H2} [48].

$$WtT_{H_2\_CO_2} = \frac{12863_{g/kg_{H2}} * \ 0.718 \ kg_{H2}}{100 \ km} = \ 92.35 \ \frac{g_{CO_2}}{km}$$

Likewise, the contribution of the *WtT* emission for the gasoline application has to be computed and finally added to the pipeline emission during the reference driving cycle. This contribution takes into account the *Oil Production*, *Oil Refining* and *Fuel Distribution* to the final gas station: considering these three phases to produce gasoline, the mean overall *Well-to-Tank* emissions are the 30 % of the exhausted GHG [49].

$$WtT_{Gasoline\_CO_2} = 20.4_{gCO_2/km} * 0.3 = \ 6.12 \frac{g_{CO_2}}{km}$$

With these calculations it is possible to derive the final contributions in terms of emission for the two vehicles (Fuel Cell based and BMW i3).

Parameter	**BMW i3 REX**	**FCv Series Hybrid – Water Electrolysis**	**FCv Series Hybrid – Steam Reforming**
Well-to-Tank Emission	6.1 g/km	10.4 g/km	92.4 g/km
Tank-to-Wheel Emission	20.4 g/km	0 g/km	0 g/km
Well-to-Wheel Emission	26.5 g/km	10.4 g/km	92.4 g/km

Table 14: GHG emission for the two vehicles

From the *Table 14*, it could appear that from the *WtW* emission point of view, the Fuel Cell vehicle can appear less “Environmentally Friendly” with respect the common Series Hybrid Vehicle with Range Extender unit based on gasoline engine if the Hydrogen is produced by *SMR* (*Steam Methane Reforming*). On the other side, the Hydrogen produced with the *Electrolysis of the Water* has a lower GHG impact than traditional system based on combustion engine. Moreover, if the Hydrogen production and storage is directly on site with a proper power plant for the electricity generation from renewable sources, as for the future generation of Refuelling station, the potential the *WtT* GHG emission can be *zero-CO_2-emission*. This kind of Hydrogen production pathway is called *Green Hydrogen*. Regardless these statements, nowadays the part of the Hydrogen that is produced through the electrolysis is only the 4 % with respect the overall [5].

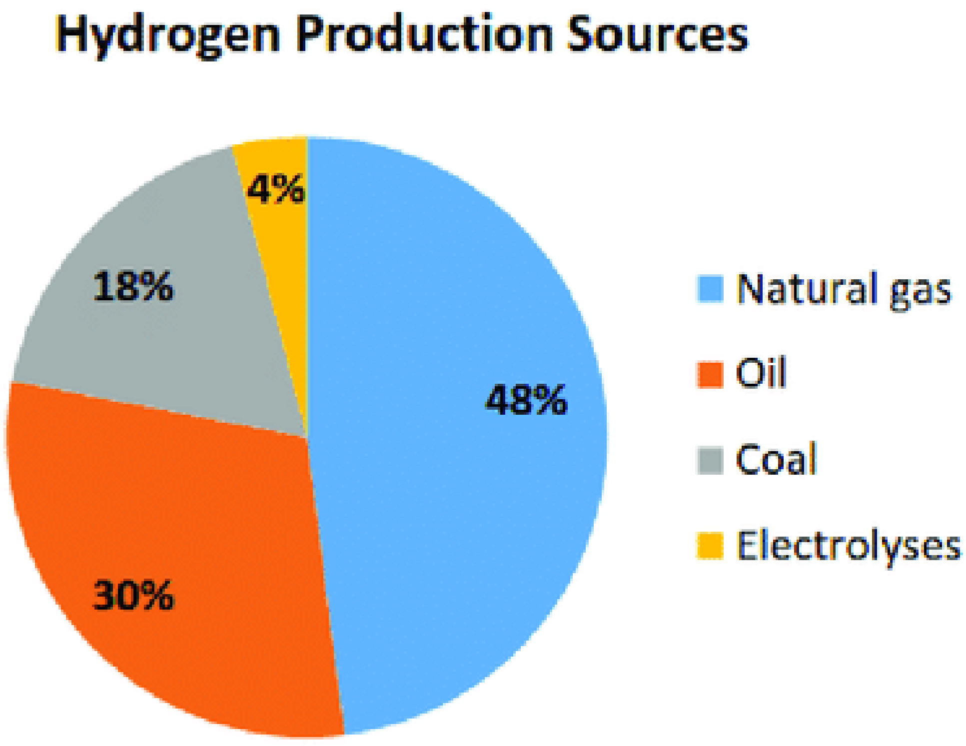

Figure 57: Global Energy source of pure hydrogen production [5]

By contrast, the CO_2 emitted by a gasoline engine, looking at both fuel production process and pipeline emission, can only reduce, increasing the efficiency of combustion cycle and production process, but not completely eliminated as for the Hydrogen-based solution.

To sum-up, the reported emission comparison between the two vehicles takes into account only two types of Hydrogen production (by electrolysis and SMR): to have a better view of the issue related to the *WtW* emission of GHG, the different energy pathway for the Hydrogen-Generation should be considered. Moreover, a possible future reduction in terms of CO_2 emission for the generation of electric energy has to be considered, since it could allow to reach a better overall efficiency for the H_2-based powertrains.

The emission profile is only a parameter to be compared for a deeper analysis of the two different propulsion system: other parameter that can be evaluated is the running cost of the two system and the future prospective in terms of overall cost of the system, maintenance cost and fuel cost. Moreover, to have a finer analysis between the two vehicles, it should be necessary knowing the logic with which the Energy Management Unit of the BMW i3 is built.

6. CONCLUSION

6.1 Final Comment on Obtained Results and Fuel Cell Analysis

The aim of thesis was to provide a flexible "platform" able to simulate not only B-Segment Vehicle based on the Fuel Cell, as for this project, but also others types of vehicle segment and typologies of vehicle. For the initial design choice, it was decided that the presented Simulink model of Vehicle, based on PEMFC, has a fixed powertrain architecture, but allows to change the sizing of the single elements that compose the traction system and vehicle body. Moreover, regardless the reported case in which all simulations were conducted according to the WLTP Cycle, the model was built up to perform others driving cycle and multiple speed profiles set by the user.

A secondary scope is to study and model the needed auxiliaries' systems for a PEMFC and present a functional design to simulate the influence of these subsystem on the Stack performance. Then a significant part of the project was related to create a proper *Energy Management System* in order to couple the energy contribution from the different Power Source (Battery Pack and Fuel Cell System) to the traction element (E-Motor).

Last objective was to verify the designed model by simulating a driving cycle used for type approval test (in this case WLTP): in this project the different simulations were carried out in order to estimate the behaviour of the FCs under various load condition and to study the actual fuel consumption along a specific driving cycle and making a further comparison with a Series Hybrid Vehicle based on ICE.

As reported in the previous chapter, the best result obtained is for the *Scenario 1*, in which the *Charge Sustaining Mode* is extended between value of $SOC_{LowerLimit}$ 40% and $SOC_{UpperLimit}$ 80% and the Output Power of FC ranges between 7.5 kW (@ SOC 80%) and 25 kW (@ SOC 40%). In this condition the resulted Hydrogen Consumption is 0.718 kg/100 km and an overall cruising range of 694 km in *Charge Sustaining Mode*.

For what concern the study of Fuel Cell, the application of FCs has become relevant in the recent years to replace the common Hybridization Unit based on common combustion engine. The main type of electrolyse used for Automotive purpose is the Proton Membrane Exchange Fuel Cell, while some solutions underdevelopments are based on Solid Oxide Fuel Cell, but only for specific market. The main advantages of the Hydrogen technologies and reasons why these Fuel Cell can be potentially helped a further reduction of emission in transport field are:

- Higher overall efficiency with respect a common Hybrid Vehicle based on internal combustion engine.
- Zero pipeline emission, both in terms of GHG and pollutant emission, if compared with a traditional system based on ICE
- Possible reduction of Battery Pack sizing, in comparison with Pure Battery Electric Vehicle, for which the only energy source is the electric accumulator and it has to provide sufficient energy to ensure a good drivable range and a high-power level.
- Possible zero *WtW* emission, if the Hydrogen is produced, compressed and storage from renewable electric source (for instance Wind or Solar power).

6.2 Future Development for the Fuel Cell Vehicle

Nowadays the Fuel Cell vehicles are slightly more than a market niche in Automotive field: the main reason behind this trend is that the running cost of the Fuel Cell is still high in comparison with traditional propulsion system and the availability of the Refuelling Station for vehicles is strongly limited.

In order to overcome these issues, the research field from technical point of view should be concentrated on the reduction of price and increment of lifecycle.

1. Since to enhance the electrochemical reaction within a Fuel Cell a catalyst layer is needed and the material used is generally a precious metal with high cost: for this reason, it is expected that the continuous advancement of R&D can be led to a lower use of platinum on the catalyst in order to lower the price of Stack per kW.

2. Another key point is the improvement of lifecycle of Fuel Cell: the catalyst layer and, more in general, all components of a Fuel Cell system are subjected to degradation phenomena during its operational life.

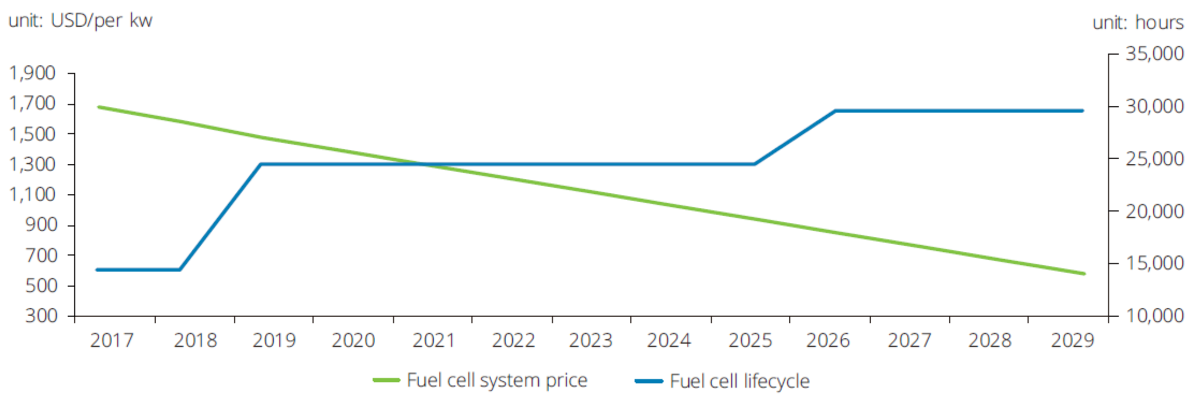

Figure 58: Fuel Cell System price and Fuel Cell lifecycle trends [5]

Meanwhile, to solve the lack of Refuelling Station of Hydrogen an integrated infrastructure network has to be created in order to meet the possible growth of the Fuel Cell Vehicles widespread. The method and cost of hydrogen delivery is highly related to where hydrogen is produced, which can be classified into centralized, semi-centralized or distributed ways and how it is produced: as claimed before, the *cleaner* way to produce the Hydrogen is by means of *Electrolysis of Water* from renewable energy source. To explain the previous concept:

- Centralized production refers to large central hydrogen facilities, which requires transportation to the final Refuelling station [5].
- Distributed production pathway refers to production near the Refuelling facility. This could be an optimal solution to produce H_2 in site by means of *Electrolysis of Water* with solar or wind energy.
- Semi-centralized production refers to intermediate sized hydrogen production facilities located in close proximity to the point of use [5].

REFERENCE

[1] European Environment Agency, “CO_2 emissions from cars: facts and figures (infographics)” in europarl.europa.eu, (2019)

[2] The Editorial Team, “The price of an electric car battery” in easyelectriclife.groupe.renault.com, (2020)

[3] “Auto elettriche: con il freddo l'autonomia cala del 41%”, in sicurauto.it, (2019)

[4] BMW Group, “BMW i3 Brochure” in bmw.com, (2019)

[5] Deloitte and Ballard, “Fuelling the Future of Mobility: Hydrogen and fuel cell solutions for transportation” in deloitte.com, (2020)

[6] Fuel Cell & Hydrogen Energy Association, “Fuel Cell Basics” in fchea.org/fuelcells

[7] Brooke Schumm, “Fuel Cell” in britannica.com/technology/fuel-cell, (2020)

[8] U.S. Department of Energy, “Comparison of Fuel Cell Technologies” in energy.gov/eere/fuelcells, (April 2016)

[9] Department of Chemical Engineering and Biotechnology of Cambridge University, “Types of Fuel Cell” in ceb.cam.ac.uk

[10] Dr. Colleen Spiegel, “Direct Methanol Fuel Cell Improvements” in fuelcellstore.com, (2018)

[11] Dr. Colleen Spiegel, “How to Predict Fuel Cell Performance” in fuelcellstore.com, (2019)

[12] Akira Yamashita, Masaaki Kondo, Sogo Goto, and Nobuyuki Ogami, “Development of High-Pressure Hydrogen Storage System for the Toyota Mirai” in SAE International, (2015)

[13] Norishige Konno, Seiji Mizuno, and Hiroya Nakaji, “Development of Compact and High-Performance Fuel Cell Stack” in SAE International, (2015)

[14] Tatsuya Sugawara, Takuma Kanazawa, Naoki Imai, and Yu Tachibana, “Development of Motorized Turbo Compressor for Clarity Fuel Cell” in SAE International, (2017)

[15] Honda, “Clarity Fuel Cell Specification” in honda.com, (2020)

[16] Chris Pickering for The Engineer, “The Engineer drives: Hyundai Nexo – a glimpse into the hydrogen future?” in theengineer.co.uk, (2019)

[17] Groupe Renault Press Release, “RENAULT RUNS ON HYDROGEN WITH MASTER Z.E. HYDROGEN AND KANGOO Z.E. HYDROGEN” in en.media.groupe.renault.com, (2019)

[18] Ballard, “Datasheet of FCveloCity® - MD” in ballard.com, (2018)

[19] Nuvera, "Nuvera® E-Series Fuel Cell Engines: Today's answer to an emission-free future" in nuvera.com, (2020)

[20] PowerCell, "PowerCell S3: Powerful and Compact" in powercell.se/en/products, (2021)

[21] Bosch Mobility Solution, "Fuel-cell stack: the heart of fuel-cell system" in bosch-mobility-solutions.com, (2020)

[22] Tabbi Wilberforce, Zaki El-Hassan, F.N. Khatib, Ahmed Al Makky, Ahmad Baroutaji, James G. Carton and Abdul G. Olabi, "Modern Technologies in Automobiles" in researchgate.net, (2018)

[23] Diju Gao, Wei Zhang, Aidi Shen and Yide Wang, "Parameter Design and Energy Control of the PowerTrain in a Hybrid Electric Boat" in researchgate.net, (2017)

[24] Mahle PowerTrain, "MAHLE Range Extender Demonstrator Vehicle" in mahle-powertrain.com, (2017)

[25] Maya Payne Smart, "Hydrogen Fuel Cells Backup Infrastructure Cleanly and Quietly" in energy.gov

[26] D. HISSEL and Ch. TURPIN, "A review of the existing modelling methodologies for PEM Fuel Cell System" in researchgate.net, (2008)

[27] Dongmei Chen and Huei Peng, "A Thermodynamic Model of Membrane Humidifiers for PEM Fuel Cell Humidification Control" in researchgate.net, (2005)

[28] Professor Jan Rossmeisl and Professor Matthias Arenz, "Hydrogen vehicles might soon become the global norm" in eurekalert.org, (2020)

[29] Prof. Dr. Matthias Arenz, "Hydrogen fuel cells last longer thanks to innovative electrocatalyst" in unibe.ch, (2020)

[30] F. Millo, S. Caputo, A. Piu "Analysis of a HT-PEMFC range extender for a light duty full electric vehicle (LD-FEV)" in sciencedirect.com, (2015)

[31] Daniel Ikhu-Omoregbe and Ademola Rabiu, "Parametric Analysis of a High Temperature PEM Fuel Cell Based Microcogeneration System" in hindawi.com, (2016)

[32] BloomEnergy, "Everything You Need to Know About Solid Oxide Fuel Cells" in bloomenergy.com, (2019)

[33] Katsuya Hayashi, Masayuki Yokoo, Yoshiteru Yoshida, and Hajime Arai, "Solid Oxide Fuel Cell Stack with High Electrical Efficiency" in ntt-review.jp/archive, (2009)

[34] Ing. Dario Marra, "Development of Solid Oxide Fuel Cell stack models for monitoring, diagnosis and control applications", (2012)

[35] Wen-Tang Hong, Tzu-Hsiang Yen, Cheng-Nan Huang, Hsueh-I Tan, Yu Chao "Design and development of major balance of plant components in solid oxide fuel cell system" in INTERNATIONAL JOURNAL OF ENERGY AND ENVIRONMENT, (2013)

[36] Nissan Motor Corporation “A fuel cell system that generates electricity from bioethanol to power a vehicle” in nissan-global.com, (2016)

[37] Advanced Research Projects Agency – Energy “LBNL, Nissan researchers explore ethanol internal reforming in SOFCs for vehicle applications” in greencarcongress.com, (2020)

[38] Dr. Michael Tucker “Metal-Supported SOFC for Vehicles” in arpa-e.energy.gov, (2018)

[39] David Udomsilp, Jurgen Rechberger, Raphael Neubauer “Metal-Supported Solid Oxide Fuel Cells with Exceptionally HighPower Density for Range Extender Systems” in cellpress.com, (2020)

[40] Green Car Congress “Nuvera Puts Next-Gen Andromeda II Fuel Cell Through its Paces” in greencarcongress.com, (2005)

[41] Tecomotive “Pierburg CWA400, Electric Water Pump” in tecomotive.com, (2010)

[42] Toshiba, “SCiB cell characteristic”, (2018)

[43] Brusa “BDC546 – Bidirectional DC/DC Converter” in brusa.biz/en/products/dcdc-converter, (2021)

[44] DieselNet “Worldwide Harmonized Light Vehicles Test Cycle (WLTC)”, in dieselnet.com/standards/cycles/wltp, (2018)

[45] WLTPFACTS “What are the benefits of WLTP?” in wltpfacts.eu/wltp-benefits, (2020)

[46] BMW Group “Technical specifications. BMW i3 (120 Ah).” in bmwgroup.com, (2018)

[47] F. P. Brito, Jorge Martins, Francisco Lopes, Carlos Castro, Luís Martins and A. L. N. Moreira “Development and Assessment of an Over-Expanded Engine to be Used as an Efficiency-Oriented Range Extender for Electric Vehicles” in mdpi.com/journal/energies, (2020)

[48] Stuart Chubbock and Ralph Clague “Comparative Analysis of Internal Combustion Engine and Fuel Cell Range Extender” in sae.org, (2016)

[49] Auke Hoekstra “Producing gasoline and diesel emits more CO2 than we thought” in innovationorigins.com, (2020)

[50] Beretta method: J. Beretta, "Automotive Electricity: Electric Drives" ed. Wiley, (2013)

[51] Javier De La Cruz Soto and Ulises Cano Castillo “Fuel Cell as Range Extender in Battery Electric Vehicles for Supply Chain Fleets” in intechopen.com, (2016)

[52] Nissan Motor Corporation “Nissan’s Powertrain Strategy”, (2020)

[53] Toyota Motor Corporation “Toyota Launches the New Mirai” in global.toyota, (2020)

[54] Toyota Motor Corporation “Toyota Develops Packaged Fuel Cell System Module to Promote the Hydrogen Utilization toward the Achievement of Carbon Neutrality” in global.toyota, (2021)