POWER SYSTEM MANAGEMENT

Robotic Hardware System

Background

Power Management System

The Power Management System (PMS) is often provided as part of the IAS and provides control of electrical generators, switchboards and large consumers. The primary function of the Power Management System is to ensure that power capacity is in line with vessel power demand at any time. The PMS ensures that the load from main consumers does not overload power plant capacity, even if one of the generators should shut down unexpectedly. The PMS will automatically start-up and stop spare generators when required, and may sometimes shed load from large consumers to avoid overload.

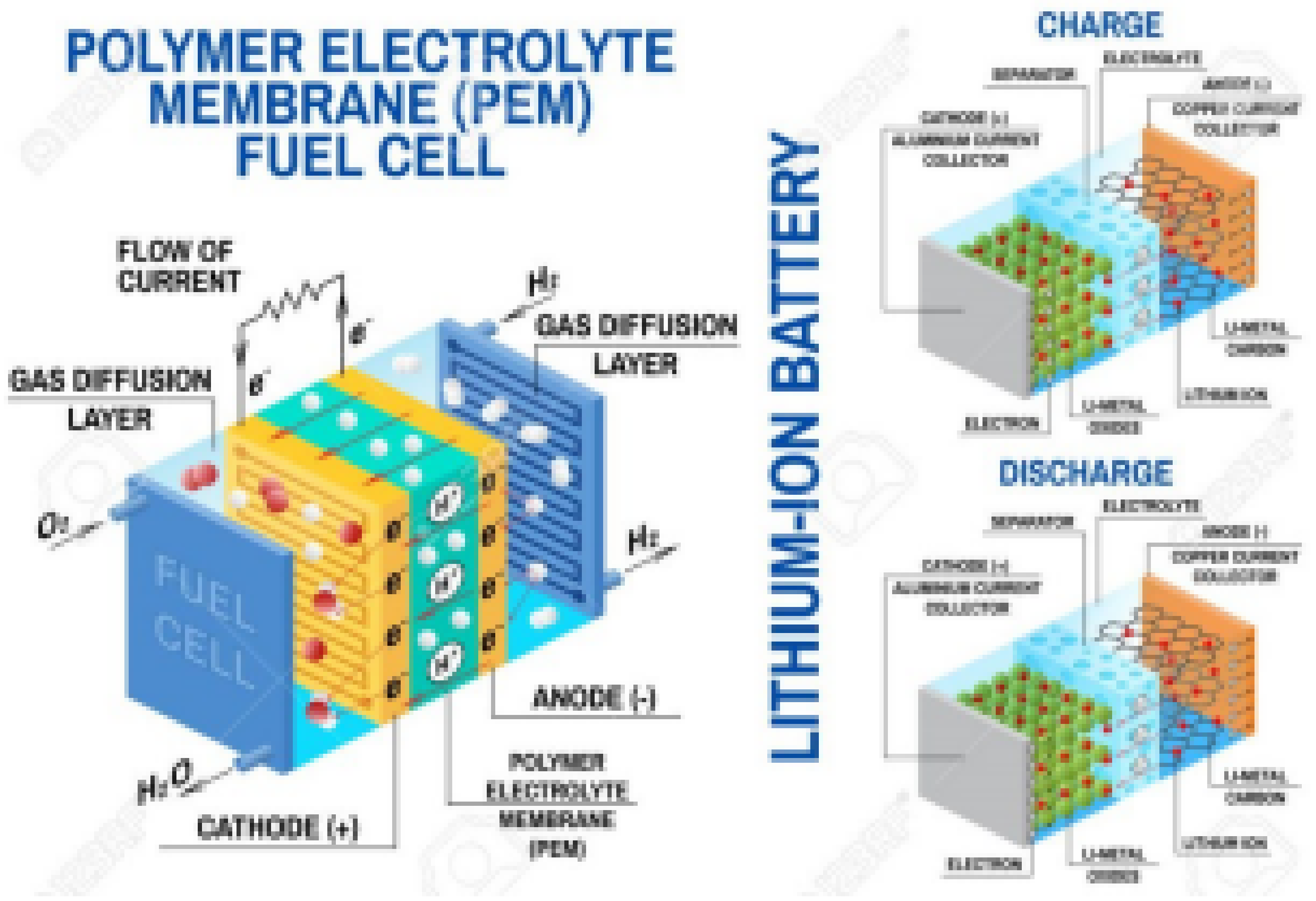


Figure 1 PEM Fuel cell and Li-ion battery diagrams

Batteries

A battery is a device that produces electrons through electrochemical reactions and contains positive and negative terminals. It is based on redox reactions: one of the components is oxidized (loses electrons) and the other one is reduced (gains electrons).

Batteries store chemical energy in one or more electrochemical cells and transform it into electrical energy. Each cell consists of an electrolyte (liquid or solid) together with a positive (anode) and negative (cathode) electrode. During discharge, the electrochemical reactions take place at the two electrodes and the electron current flows through the external circuit. This reaction is reversible, allowing the battery to recharge applying an extern voltage between both electrodes.

Some battery types include lithium-ion (Li-ion), nickel metal hydride (NiMH), nickel-zinc (NiZn), and nickel-cadmium (NiCd) cells. So far, Li-ion batteries have the highest market value and they are the most relevant ones for this project, as they are the ones used.

They consist of a Li metallic oxide cathode (in this case, $LiFePO4$), an electrolyte of lithium salts dissolved in organic carbonates, a carbon anode combined with lithium, and a separator.

2.1.1 Lithium-ion batteries

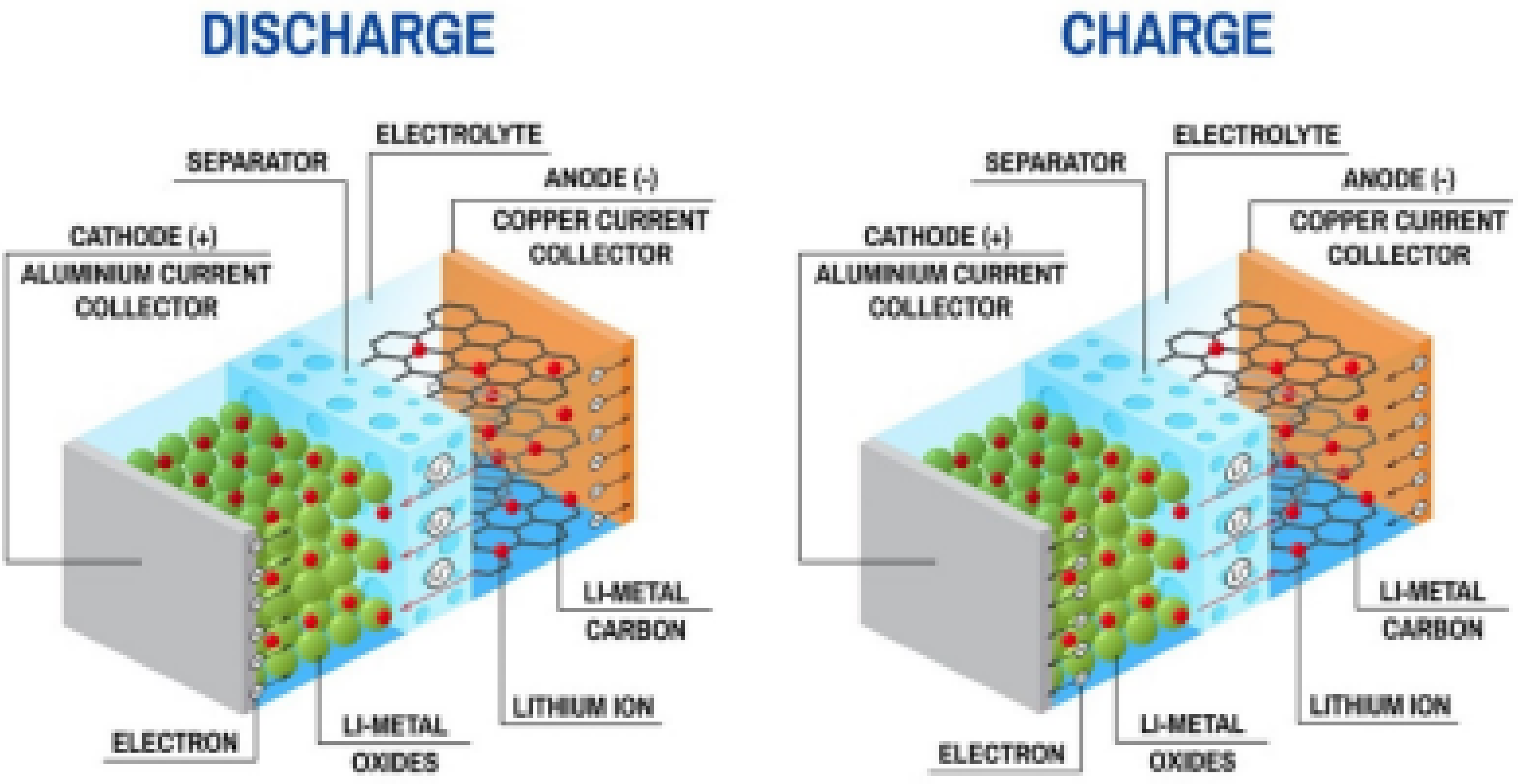


Figure 2 Lithium-ion battery diagram of charge and discharge

Lithium-ion batteries (LIB) are a family of rechargeable batteries having high energy density and commonly used in mobile or portable systems and in hybrid and electric vehicles.

Li-ion batteries are significantly lighter than other kinds of rechargeable batteries of similar size, that is why they are heavily used in portable electronics. These batteries can be commonly found in cell phones, laptops, etc.

When a LIB is discharging, lithium ions move from the negative electrode (anode) to the positive electrode (cathode). When a LIB is charging, lithium ions move in the opposite direction, and the negative electrode becomes the cathode, while the positive electrode becomes the anode.

Table 1 Advantages and disadvantages of Li-ion batteries [1].

ADVANTAGES	DISADVANTAGES
Higher energetical density (It can store 150 watt-hours electricity per kg).	LIBs start to degrade the moment they leave the factory. They usually last for only two to three years from the date of manufacture, regardless of whether used or unused.
Lower self-discharge rate. (They usually lose approximately 5% of their charge each month, against a 20% for NiMH).	LIBs are highly dependent to higher temperatures; this leads to a much faster degradation rate than normal.
LIBs do not require complete discharge prior to recharging.	If they are fully discharged, it gets totally damaged.
It can handle more charge/discharge cycles.	LIBs are comparatively expensive.
LIBs barely require maintenance.	There exists a small possibility that if the LIB pack fails, it may burst open into flame.

Fuel cells

A fuel cell (FC) is a device that converts chemical energy of a fuel into electricity. It consists of an electrolyte and two electrodes. Fuel cells generate the electrical power from a fuel (hydrogen) and an oxidant (oxygen). The fuel cell consumes oxygen from the air and hydrogen from a tank (or any other supplier). A chemical catalyst may be used to speed up the chemical reaction in the cell. It produces electricity without combustion and is hence less polluting.

The fuel cell was first devised by Sir William Grove in 1839. William Grove postulated that by reversing the electrolysis process, electricity and water could be produced. [2]

Fuel cells produce electricity by making use of chemical energy generated through a chemical reaction between positively charged ions and an oxidizing agent. They consist of an electrolyte and two electrodes. The positively charged electrode is called the anode and the negatively charged electrode is called the cathode. [2]

A fuel cell converts the chemical energy of the reaction between charged hydrogen and oxygen ions into electricity. The positively charged hydrogen cells move between the two electrodes to create a flow of electricity which is directed outside the cell to provide electricity. As long there is a flow of chemicals into the cell, it never goes dead, unlike conventional batteries which require recharging after a while. [2]

There are several types of fuel cells: alkaline, molten carbonate, methanol…However, in this work the FC used is Polymeter Electrolyte Membrane (PEM) due to their power density and low operating temperature.

2.2.1 PEM fuel cells

The polymer electrolyte membrane fuel cell (PEMFC), also known as proton exchange membrane fuel cell, takes its name from the type of electrolyte: a polymeric membrane with high proton conductivity when the membrane is conveniently hydrated. The operation of a PEM FC is briefly explained in **Figure 3**:

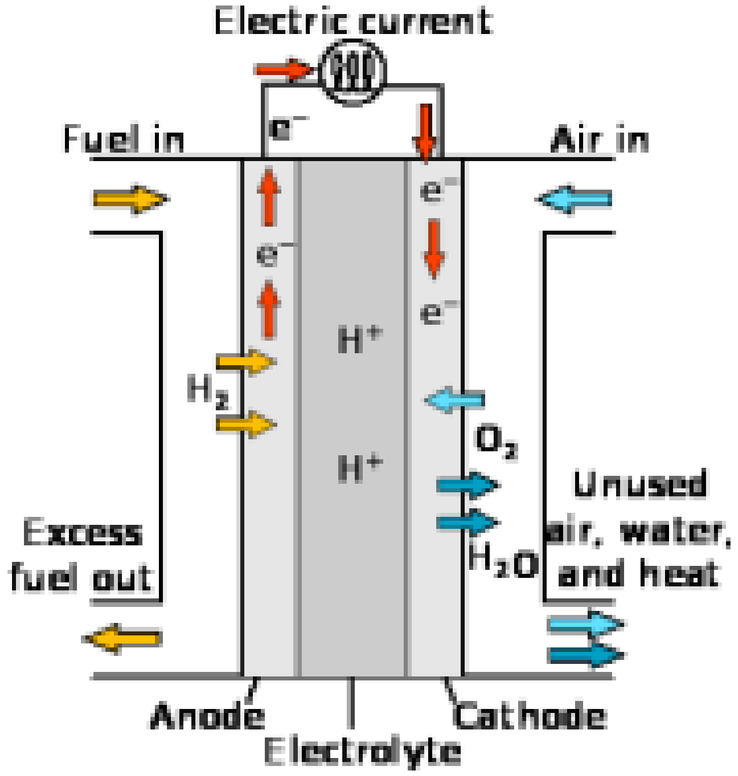


Figure 3 Simplified diagram of H_2 working PEMFC

In the anode, the hydrogen molecules are divided into protons (H+) and electrons. The protons pass the membrane to the anode, while the electron travel through the external circuit, producing current to the anode. In the anode, these protons and electrons react with the oxygen, producing water [3].

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \quad (1)$$

Table 2 Advantages and disadvantages of PEM FC [4].

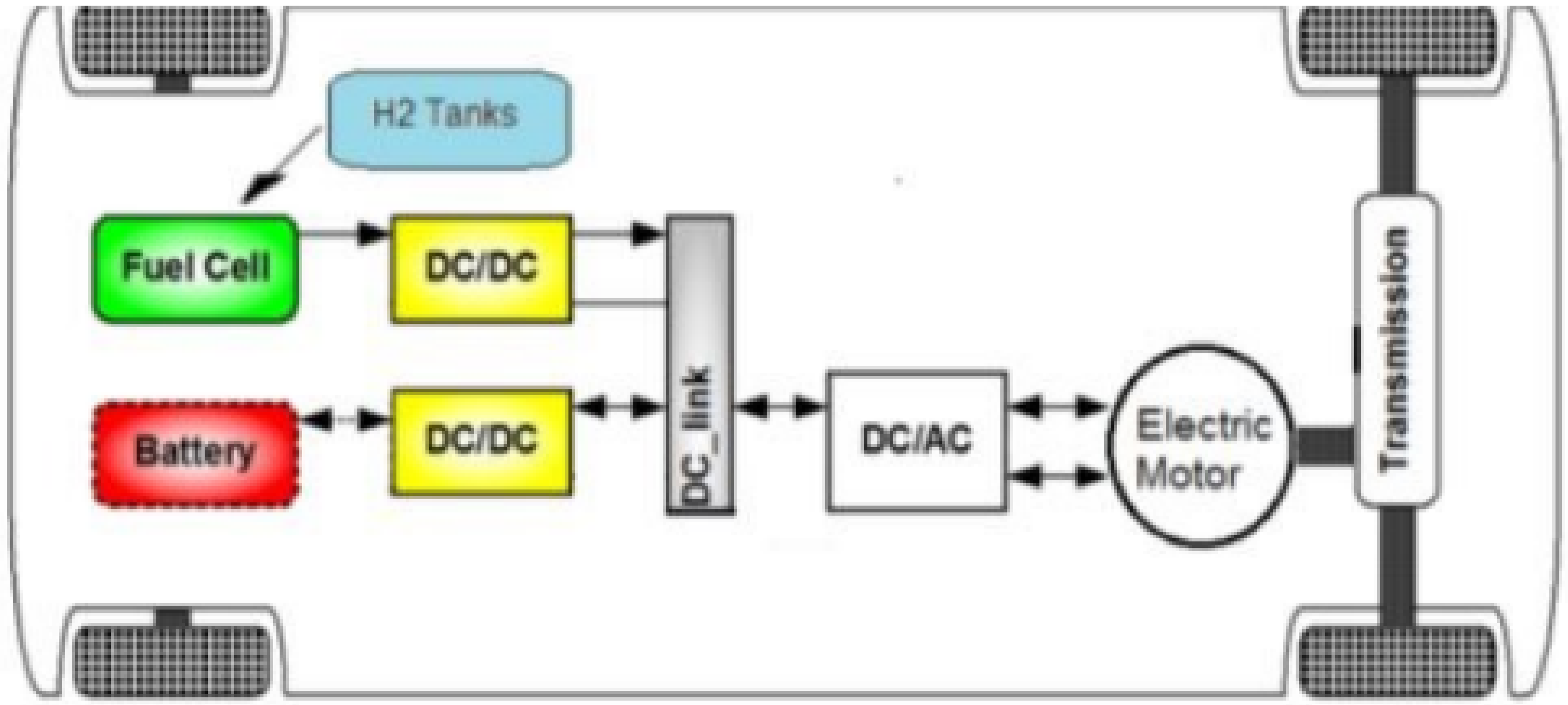
Table 2 Advantages and disadvantages of PEMFC [4].

ADVANTAGES	DISADVANTAGES
High efficiency compared with other energy conversion devices (Twice a gasoline vehicle's efficiency).	High cost of hydrogen.
Efficiency high with partial loads, unlike ICE.	High production cost of hydrogen.
Local emissions problem in densely urban areas can be eliminated.	
Low operation temperature (below 80ºC).	
Smaller cost of the materials (except for the catalyst, based on platinum).	
Operation is safer.	

Hybrid technology

A FCEV is a zero-emission vehicle with a fuel cell system that generates electricity to propel the vehicle and operate auxiliary equipment. Hydrogen fuel is consumed in the fuel cell stack to produce electricity, heat, and water vapor—no harmful pollutants are emitted from the vehicle. [5]

Like hybrid electric and battery electric vehicles, FCEVs also use traction batteries, inverters, and electric motors. FCEVs also require the use of electrified accessories, which are beginning to be developed to improve overall efficiency and reduce emissions. **Figure 4** FCEV basic configuration shows a basic representation of the major system components in a FCEV.



(Intechopen.com, undated)

Figure 4 FCEV basic configuration [5]

The energy storage system (batteries or capacitor) is connected via the converters to the electric motor that moves the vehicle. The fuel cell supplies energy to the electric motor and/or delivers power to the energy storage system.

The power conditioning requires power regulation and inversion. Fuel cells and batteries both produce direct current (DC) electricity, while the electric drivetrain may require alternating current (AC) or DC. A DC/DC converter regulates the fuel cell power. For AC electric drivetrains, the DC power must be inverted to power the electric motors, typically by using a DC/AC inverter.

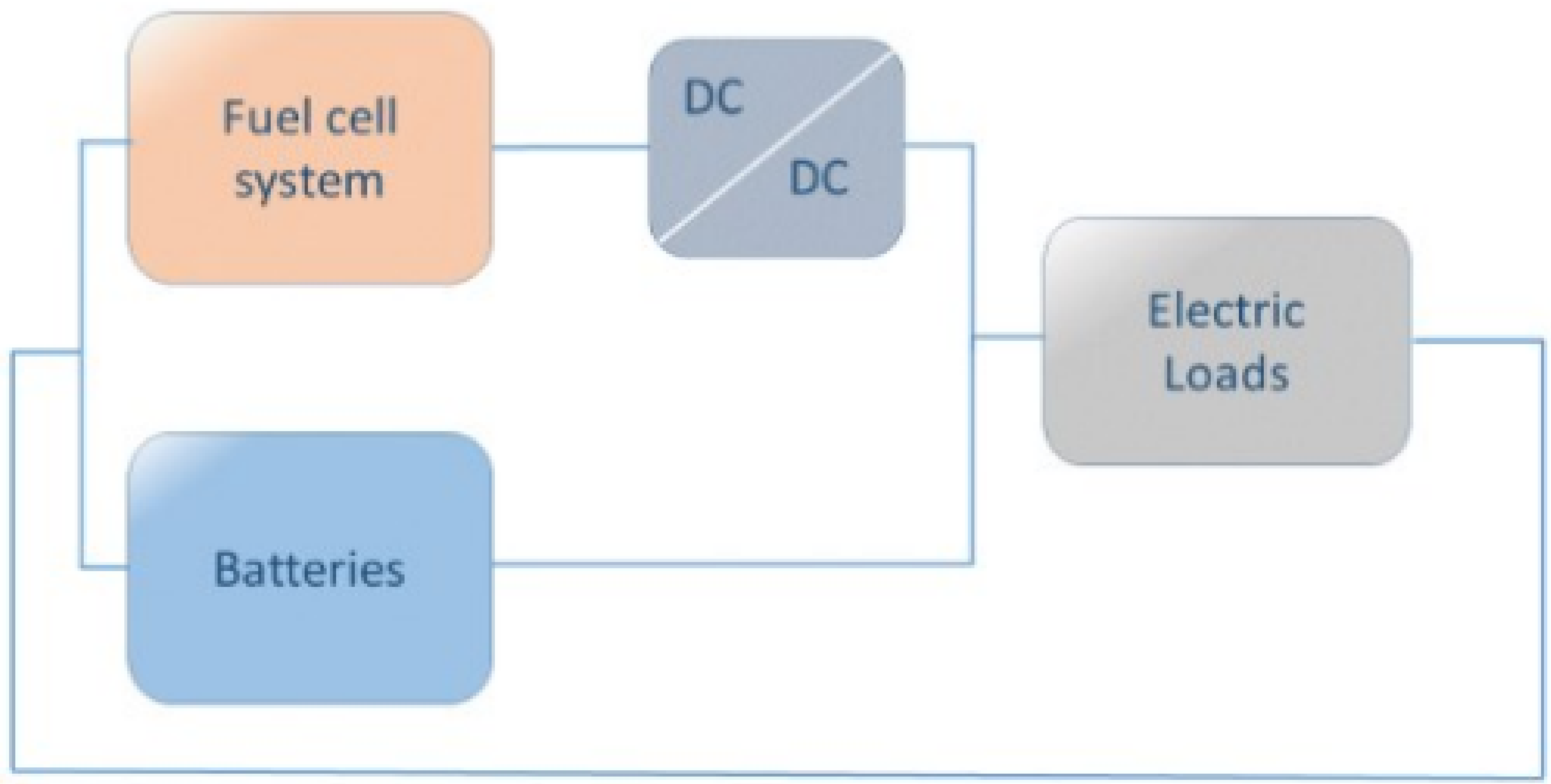


Figure 5 Active hybrid power system

Both batteries and fuel cells can power a charge (for example, an engine), but in real practise fuel cells are not used by their own. They are both combined in different configurations, as the ones shown in **Figure 5** and **Figure 6**.

The active configuration allows a decoupling of sizing and operating conditions in batteries and fuel cell, thanks to the DC/DC converters, allowing also a more precise control of the power system. The main disadvantages of indirect hybrids (active) are the more complex system topology, reduced efficiency due to losses at the voltage, system cost, and higher weight and volume [6].

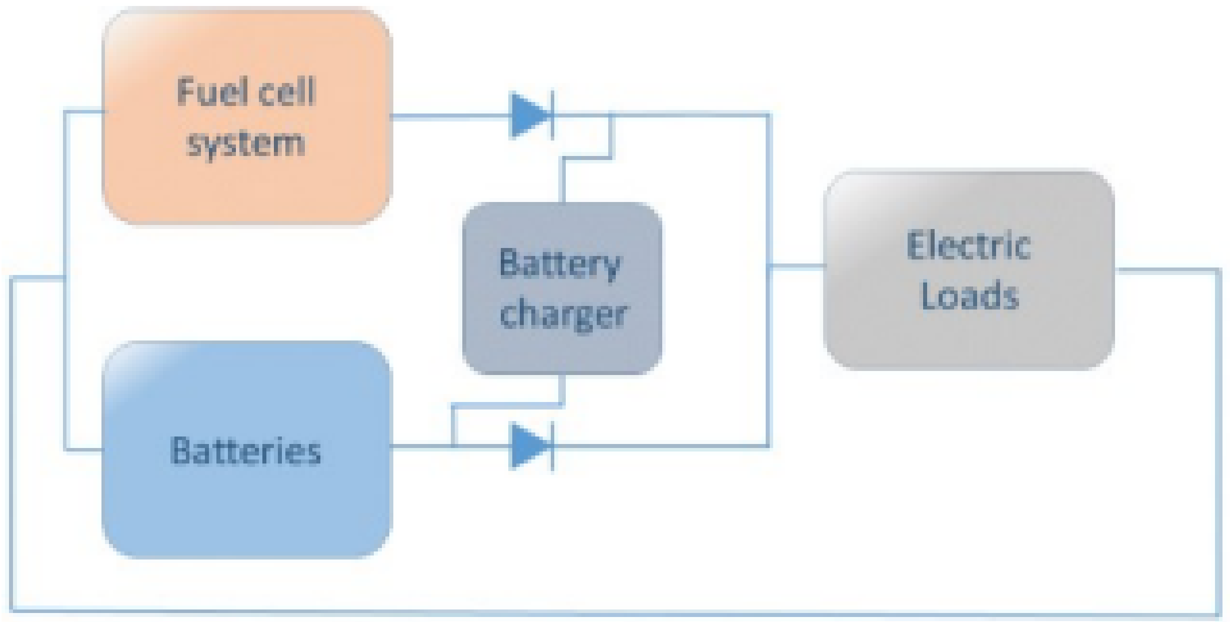
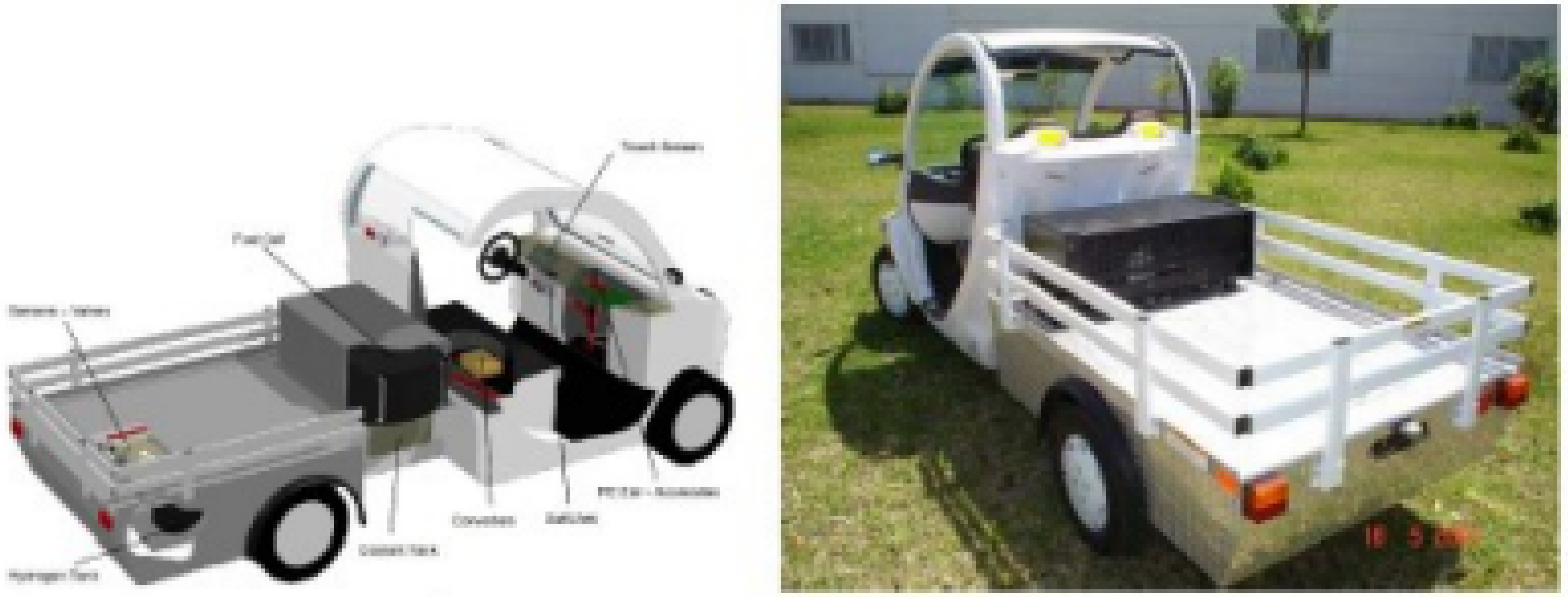


Figure 6 Passive hybrid power system

On the other hand, the passive configuration with direct connection to DC bus offer the advantages of lower losses, reduced cost and simple architecture. However, active power control is not possible, and a careful design and integration of fuel cells and batteries is required to ensure a similar voltage range operation and proper charging conditions of the batteries from fuel cell if this option is considered [5].

Table 3 Advantages and disadvanteges of hybrid configurations [6].

	Active configuration	**Passive configuration**
Advantages	Decoupling of sizing and operating conditions in batteries and fuel cell	Lower losses
	More precise control of the power system	Reduced cost
		Simpler architecture
Disadvantages	More complex system topology	Active power control is not possible
	Reduced efficiency due to losses at the voltage	Careful design and integration of fuel cells and batteries
	Higher system cost	
	Higher weight and volume	



(a) Delfin I scheme. (b) Delfin I (vehicle).

Figure 7 Delfin I

Table 4 GEM eL specifications [3]

Curb Weight	1,285 lb
GVW	2,300 lb
Payload Capacity	1,015 lb
Length	144"
Height	70"
Width	55"
Wheelbase	114"
Cubic Feet of Cab	47 ft³
Turning Radius	17 ft
Tires	12-inch
Top Speed	25 mph
Ground Clearance	8"

Table 5 Hydrogenics HyPM-12XR specifications [3]

Maximum output power	12.5 kW
Output voltage range	37-57 V
Maximum current	350 A
Dimension	90x50x32 cm
Volume	153.61
Weight	90kg

2.4.1.2 Delfin II

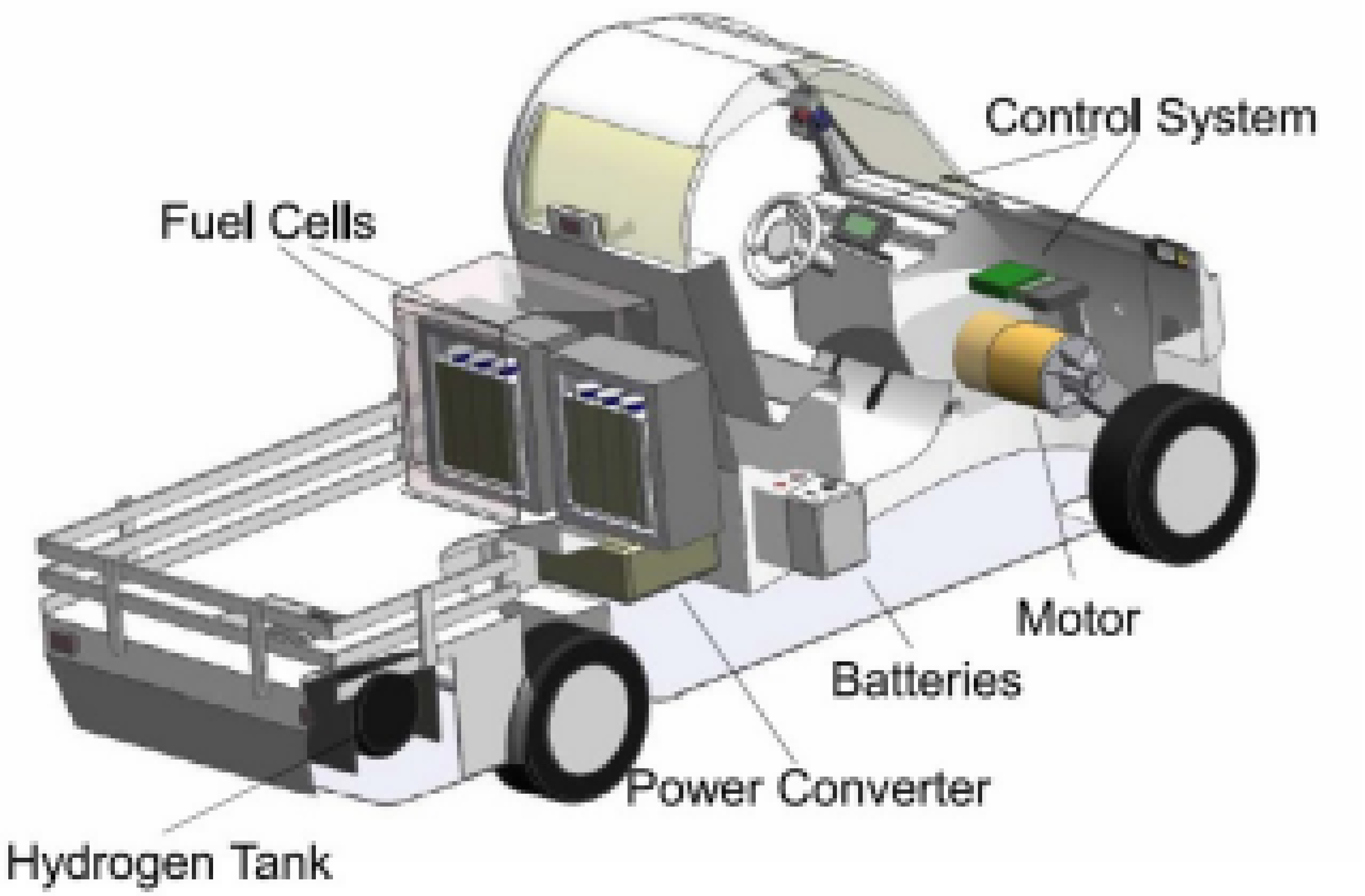


Figure 8 Delfin II

Based on the same vehicle as the Delf ın I project (a GEM eL electric car), the motor and the hydrogen storage system are the only elements remaining from the previous project.

Figure 8 shows the new disposition of the devices of the vehicle.

2.4.2 Hercules project

Figure 9 Hercules vehicle.

The vehicle is based on a commercial Santana 350 SUV. In this vehicle the engine and its auxiliary devices have been removed. In their place, the following devices have been installed:

- A PEM fuel cell: Nuvera with a maximum peak power of 56kW.
- A pack of Lithium-ion Batteries: four modules of 13 Li-ion 3.7 V cells in series, model Kokam SLPB 125255255H.
- A PermanentMagnet SynchronousMotor (PMSM): the nominal power is 66 kWand the maximum torque is 460Nm.
- A hydrogen storage system: it consists of two tanks of 33l and one of 24l, the three of them with a

maximum pressure of 350 bar. This system could store up to 2.4kg of hydrogen.

The possibility of substituting the batteries for UCs or combining both types of sources is also studied. In the first case, two modules in parallel of 126 Maxwell BCAP 2000 capacitors in series would substitute the pack of batteries. For the second, only two of the four modules of batteries and one of the two modules of UCs would be used [3] [7] [8].

A scheme of the Hercules vehicle is shown in **Figure 10**. The fuel cell and the lithium ion batteries feed an electrical motor through DC/DC converters to connect the different systems to the DC bus. The DC/DC converter which connects the fuel cell to the DC bus is unilateral and rises the fuel cell voltage to the DC bus voltage. The other two converters are bidirectional, allowing regenerative braking and battery recharging.

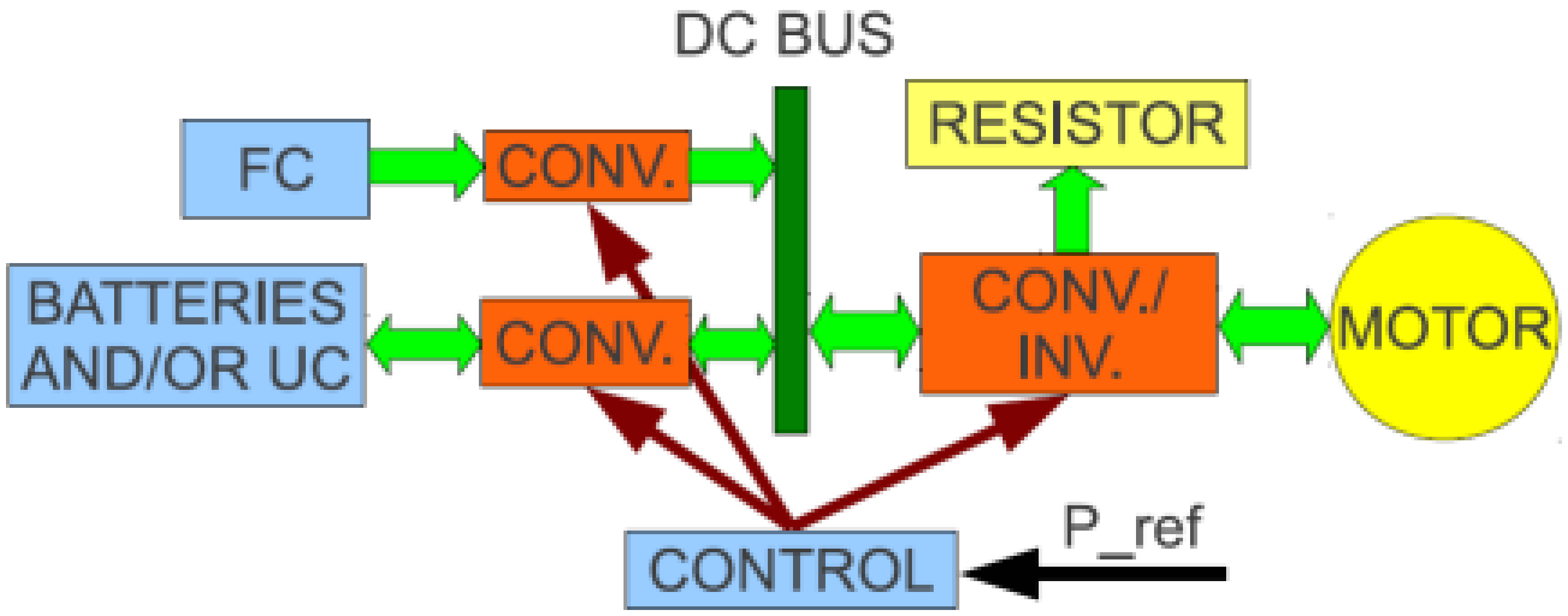


Figure 10 Hercules scheme.

Table 3. Power consumption in the proposed robotic system.

Name of the Component	Rated Voltage and Current	Number of unit	Power consumption / unit (watt)	Net Power (watt)
DC gear motor	12 V, 500 mA	4	6 W	24 W
Servo motor	5 V, 200 mA	12	1 W	12 W
Camera and wireless video transmitter	12 V, 150 mA	1	1.8 W	1.8 W
Temperature, Humidity and ping sensor	5 V, 35 mA	3	0.175 W	0.525 W
Gas sensors	5 V, 150 mA	2	0.75 W	1.5 W
GSM module	3.3 V, 800 mA	1	2.64 W	2.64 W
Transceiver	3.3 V, 200 mA	1	0.66 W	0.66 W
Arduino Microcontroller	5 V, 35 mA	3	0.175 W	0.525 W
Emergency light power	_	1	5 W	5 W
Miscellaneous passive loss / resistive loss	_	_	5 W	5 W

So, gross power consumed by the robotic system ≈ 50 Watt

Table 4. Power consumption in control unit.

Name of the Component	Rated Voltage and Current	Number of unit	Power consumption / unit (watt)	Net Power (watt)
Arduino Microcontroller	5 V, 35 mA	2	0.175 W	0.35 W
Video display unit	12 V, 1 A	1	12 W	12 W
LCD display	5 V, 100 mA	1	0.5 W	0.5 W
Joystick	5 V, 50 mA	2	0.5 W	0.5 W
Transceiver	3.3 V, 200 mA	1	0.66 W	0.66 W
Wireless video receiver	12 V, 150 mA	1	1.8 W	1.8 W

So, Total consumption ≈ 16 Watt

Calculation of Power Consumption in Robotic unit and Contro unit:

At first we need to calculate the power concumed by different components of the robotic unit as shown in Table-3.

In this proposed prototype, the robot was planned to keep active for 3 hours under single charging of battery,

So, Total Watt-Hours required = 50 * 3 WH = 150 Wh

Assuming depth of discharging of battery is 60%

$$\text{Battery Amp Hour required} = \frac{\text{Total Watt Hour Rating}}{\text{Depth of discharging*battery volatage}} = \frac{150}{.6*12} = 20.83 \text{ Amp-Hour} \approx 21 \text{ Amp-Hour}$$

$$\text{No of 7.5 Ah battery required} = \frac{\text{Total Ampere Hour rating}}{\text{Battery rating under use}} = \frac{21}{7.5} = 2.8 \approx 3$$

Accordingly, total three 7.5 Ah batteries were used for the proposed robot mounted in its body. Among them two are SLA or sealed Lead acid battery and one of it is Lipo for reduced weight. Lipo battery has high discharging rate whereas mechanical arm's servos need high ampere when 8 servos become functional or full load. So, all three batteries should not be Lipo though it will reduce weight further.

Now, we need to calculate the power consumed by Control unit as shown in Table-4.

Total Watt-Hours = 16*3 Wh = 48 Wh

$$\text{Battery Amp Hour required} = \frac{\text{Total Watt Hour Rating}}{\text{Depth of discharging*battery volatage}} = \frac{48}{.6*12} = 6.7 \text{ Amp-Hour} \approx 7 \text{ Amp-Hour}$$

$$\text{No of battery required} = \frac{\text{Total Ampere Hour rating}}{\text{Battery rating under use}} = \frac{7}{7.5} = .933 \approx 1$$

2.4.3 IUFCV project

The project "Improving efficiency and operational range in low-power unmanned vehicles through the use of hybrid fuel-cell power systems (IUFCV)" aims to demonstrate and evaluate the technical feasibility of hybrid power systems, based on batteries and fuel cells, in existing unmanned vehicles.

It is a current project developed by the Laboratorio de Energía de CEDEA, in Instituto Nacional de Técnica Aeroespacial (INTA), from Huelva, Spain; the Autonomous Systems Lab, in Commonwealth Scientific and Industrial Research Organization (CSIRO), from Brisbane, Australia; and the Departamento de Ingeniería de Sistemas y Automática, in Universidad de Sevilla (DISA-US), from Seville, Spain. It is supported by The NATO Science for Peace and Security Programme.

The proposed hybrid power systems are designed and developed according to the specifications of three existing unmanned platforms, one autonomous underwater vehicle (AUV), also called unmanned underwater vehicle (UUV), and two unmanned ground vehicles (UGVs). These power systems will be integrated and evaluated in real operating conditions. The chosen criteria for success is the one shown in **Table 6**. [6]

Table 6 Criteria for success [6]

CRITERIA FOR SUCCESS
Specific energy of the fuel cell hybrid power systems > 180 Wh/kg (without O2 storage in the AUV)
Endurance of the fuel cell UGVs (in runtime-nominal usage) > 7 hours
Endurance of the fuel cell UUV > 10 hours
Recharging time < 5 minm (for hydrogen compressed gas)
Availability of the power system > 95%
Achievement of end user requirements
Application of existing RCS related to the safe use of hydrogen and fuel cells

This project involves three platforms: the underwater (UAV) Starbug which is placed in the CSIRO Laboratory, in Brisbane, Australia, as well as one of the ground devices (UGVs), called Husky; the last robot is called Summit XL and it is a commercial platform, from Robotnik, currently placed in the Universidad de Sevilla Department.

The objective of DISA-US with this last robot is to design the control for the energy management, making it efficient. This Project is about to design the controllers to optimize the power management of the battery and the fuel cell.

Figure 11 Husky [5]

Figure 13 Starbug X ROV [5]

Figure 12 Summit XL [5]

Figure 13 Starbug X ROV [5]

Figure 12 Summit XL [5]

The main characteristics of this platform are as follow [9] [10] [11] [12].

- Size: 722x613x392 mm
- Weight: 45 kg
- Max. payload: 20 kg
- Enclosure class: IP54
- Speed: 3 m/s
- Drive system: 4 wheel, 4x250W brushless motors
- Driver motor: DZCANTE 020L080 and MC1DZC board
- Camera: AXIS p5514 PTZ Dome Network Camera
- Sensor: Stick laser range Finder, amplitude 270°, 10m range
- Motherboard: Mitac PD10B1 MT con Quad core Intel Bay Trail J1900
- Autopilot: Pixhawk FPU PX4 (gyroscope and accelerometer)
- Controller: PS3 Bluetooth remote controller
- Batteries: 8x3.3V LiFePO4
- Router: Belkin N300 Wi-Fi N
- Autonomy: 5 hours (continuous usage), 20 hours (standard laboratory usage)

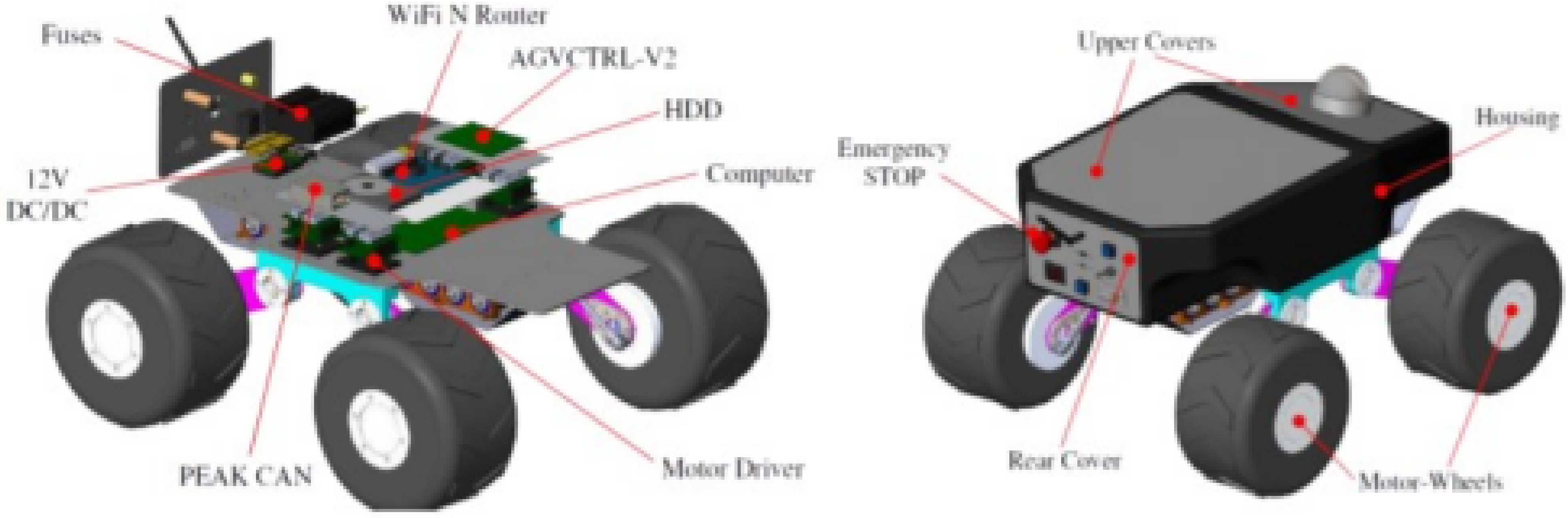


Figure 14 Summit XL scheme

(a) Front view.

(b) Back view.

(c) Lateral view.

Figure 15 Summit XL unmanned ground vehicle [13]

One of the innovations for the Summit XL in IUFCV Project would be to increase the autonomy up to seven hours of continuous usage, maintaining its core capabilities in terms of payload. It would have a power system based on open cathode and air cooled PEMFCs and Li-ion batteries. Besides, compressed hydrogen and metal hydrides will be the hydrogen storage technologies used in the platform. It would also have a passive hybrid configuration, with direct coupling between batteries and fuel cells [6].

The Summit XL has an embedded computer where runs the Ubuntu 14.04 LTS OS from Linux. In that computer ROS is installed in its version 2019 ROS Indigo. For compatibility reasons the same OS and version of ROS were installed in the DISA computer in order to monitor the transmitted data [9].