CRANFIELD UNIVERSITY

BLANCA ÁLVAREZ ROS

OPTIMISATION OF ENERGY RECOVERY SYSTEMS FOR FORMULA E

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
Design of Rotating Machines

MSc
Academic Year: 2017 - 2018

Supervisor: Dr. Patrick Luk
September 2018

CRANFIELD UNIVERSITY

SCHOOL OF WATER, ENERGYAND ENVIRONMENT
Design of Rotating Machines

MSc

Academic Year 2017 - 2018

BLANCA ÁLVAREZ ROS

Optimisation of energy recovery systems for Formula E

Supervisor: Dr. Patrick Luk
September 2018

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

With the main purpose of reducing CO_2 emissions, in 2009 the first energy recovery system was designed and set in motion inside a Formula 1 (F1) single-seater. This marked a milestone within the motorsports field, since the first hybrid engines inside the F1 industry were born. Currently, Formula E vehicles, which are pure electric, are equipped with said system, which recovers kinetic energy from the braking process. It represents a crucial part, that needs to be accurately designed in order to optimise the energy availability.

The present project aims to study in detail the energy requirements under specific conditions and the FIA limitation, in particular in energy storage and power generation, which will determine the design strategy for the design of the propeller and transmission systems. Moreover, the energy storage system is also studied in detail, and several configurations from ultra-capacitors and NMC batteries are designed. Currently, Formula E is using exclusively Lithium-Ion batteries. However, hybrid systems are also object of study in order to compare their performances with the current ones and demonstrate their potential advantages for the present application.

Examining all the alternatives, with the help of an excel tool created for the study, the most optimal configuration identified, based on characteristic parameters such as weight, range, energy stored and power generation.

Keywords:

Battery management system, energy storage system, motorsports, Lithium-Ion NMC batteries, regenerative braking, ultra-capacitors.

ACKNOWLEDGEMENTS

This adventure would not mean anything without the people I met and with whom I shared every day. Firstly, I would like to thank my supervisor, Prof. Patrick Luk, for guiding me and giving me the opportunity to develop the present project. It was a pleasure to work next to him and to learn from a huge expert. I always wanted to test what I was capable of, and he gave me enough freedom to explore different possible options to carry out the project.

I would like to thank also, Dr. Leon Rosario, for advising me and helping me with all the issues I had to face. He is also a huge expert and transmits his passion in the electric field.

Finally, I would like to thanks my whole family for never limiting my dreams and supporting me in every decision. Thanks for never stop believing in myself. I became an engineer thanks to your daily motivation. I feel proud of you.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

BMS	Battery Management System
ERS	Energy Recovery System
ESS	Energy Storage System
FIA	Fédération Internationale de l’Automobile
ICE	Internal Combustion Engine
KERS	Kinetic Energy Recovery System
MGU-H	Motor Generation Unit – Heat
MGU-K	Motor Generation Unit – Kinetic
NCA	Nickel, Cobalt, Aluminium
NMC	Nickel, Manganese, Cobalt
SOC	State of Charge

1 INTRODUCTION

1.1 Background and scope

1.1.1 History of energy recovery systems in motorsports

In 2009, with the main purpose of increasing the energy efficiency, which can be expressed as reducing the fuel consumption and, as a consequence, CO_2 emissions (Bengolea and Samuel, 2016), Williams racing team was the first team which designed and manufacture entirely in-house their own energy recovery system officially used in Formula One.

This system, known as Kinetic Energy Recovery System (KERS), was based on the principle of regenerative braking (Mathews, 2013). An electric motor was connected to the wheels, so that when the braking process occurs, the rotor of the motor would rotate in the opposite direction relative to the rotating electromagnetic field within the airgap of the motor, thus acting effectively as a generator. The energy was stored in batteries, therefore, when extra energy was required, the recovery system would provide extra power to the engine. However, the mechanical-electrical energy conversions, which reduced the efficiency of the system, together with the additional weight that was installed in the F1 vehicle and the substantial cost, made these systems disappear in 2010. One season after, in 2011, a more efficient version was installed until 2013.

In 2014, the sophisticated powertrains were no longer referred as engines, but instead a new terminology, power units, was born (Ebbesen *et al.*, 2016). These are composed of different elements: the internal combustion engine (ICE), the energy recovery systems (ERS), the energy storage system (ESS) and the control system. The KERS developed to ERS, which is a combination of the following units:

- MGU-K (Motor Generation Unit – Kinetic)
- MGU-H (Motor Generation Unit – Heat)
- Turbocharger

The MGU-K acts like the KERS, obtaining electric energy from the braking process. This energy is stored in the storage systems (batteries and ultracapacitors). While the MGU-H produces energy from the exhaust gases, which are used to move the turbocharger connected to a motor in charge of the extra energy production.

1.1.2 Appearance of electric vehicles in motorsports

Although, currently, Formula One power units are extremely optimised, some limitations remain in the hybrid powertrains. Therefore, the necessity of new energy efficient propulsion systems led to the development of a new racing category based exclusively on electric vehicles. A promising Formula E was born in 2012 by the FIA (Fédération Internationale de l'Automobile) with a visionary look, considering the electric motor's high potential and the promising results that could be obtained (Thomas and Youson, 2014).

Initially, these vehicles could not be compared to Formula One single-seater cars, since their maximum speed was closer to Formula 3 and the vehicle's autonomy was limited, as a consequence of their energy storage systems. This limitation forced the drivers to switch the vehicle after 30 mins, should a race had to be completed (Thomas and Youson, 2014). Moreover, although electric motors have, in general, greater efficiency than internal combustion engines, their efficiency can be improved by using energy recovery systems (Lin *et al.*, 2016).

Maximising the amount of energy that can be recovered is vital to increase the competitiveness inside Formula E. Finding the right balance between maximising the regenerative braking through the motor and the friction brakes, is the main objective of every team, in order to optimise the available energy during every lap and, as a consequence, be thoroughly in command race after race.

However, the 'Generation-Two' was released in May 2018, with an improved and faster motor system and a more powerful battery systems which are designed to last a whole race without the necessity of being charged (Akres, 2018). These performance improvements mark the beginning of a new generation inside the motorsports field, with a vehicle that plans to be as competitive and innovative as

Formula One; and outside it, serving as a prototype of how pure electric vehicles will be designed in the future.

1.1.3 Scope

With formula E growing and developing at great strides, being able to regenerate energy from the braking process is of great importance in this type of vehicles, where the only energy available comes from an electric source. Optimising energy recovery systems together with the energy storage system is, currently, a daily task which happens inside the Formula E racing teams. These systems are not excessively complex, but they should be studied in detail, since they represent a key part inside these vehicles. Figure 1-1 shows a scheme about the functioning of these systems.

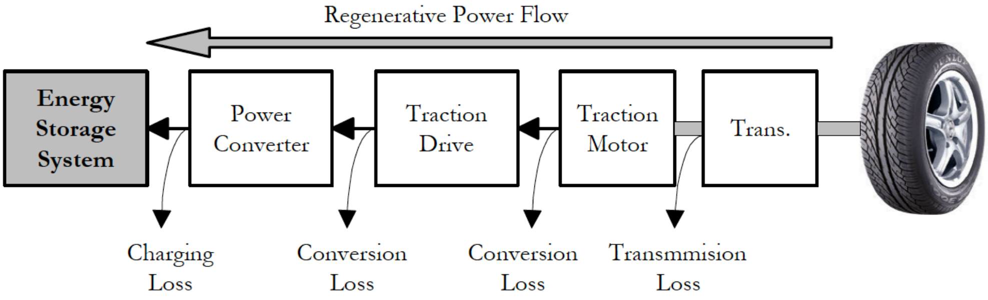


Figure 1-1. Regenerative power flow (Rosario, 2007)

1.2 Aims and objectives

The aims of the project are to study all the main energy recovery systems (ERS) for Formula E and optimise their use, in order to obtain greater amounts of energy. When studying the ERS, it is of great importance to know which systems are currently under use in these race cars, especially those presenting important limitations which should be improved. Moreover, an excel tool will be used for the study, in order to obtain the power and energy requirements in formula E races.

Several objectives have been established to achieve the aims as follows:

- Study the energy recovery systems (ERS) and energy storage systems (ESS) used in electric vehicles.

- Analyse the power and energy requirements for Formula E vehicles during a typical race, by using an existing excel tool.
- Select suitable drivetrains configurations according to the energy and power requirements and the maximum energy charge and discharge flow in the energy storage systems.
- Develop optimisation strategies to maximise the available energy in every lap during the race.

2 LITERATURE REVIEW

2.1 Energy Storage Systems

Energy Storage Systems (ESS) are the devices responsible for feeding the motor and, as a consequence, they determine its autonomy. Therefore, sizing them adequately is of great importance, especially in Formula E, since achieving optimum driving cycles, such as pole position or running the fastest lap, might depend on said fact (Burke, 2007). Currently, the most popular electric energy sources are batteries, fuel cells, ultra-capacitors and ultrahigh-speed flywheels (Trovão, Pereirinha and Jorge, 2009). There are several types of ESS and, generally, it is advisable to combine them in a synergistic configuration in order to obtain more competitive results, exploiting the use of power (Rosario, 2007). This configuration will contribute to exploit in a more efficient way the use of power required, while maximising the operation life of each Energy Storage System. Figure 2-1 shows the different ESS as a function of the specific power and energy.

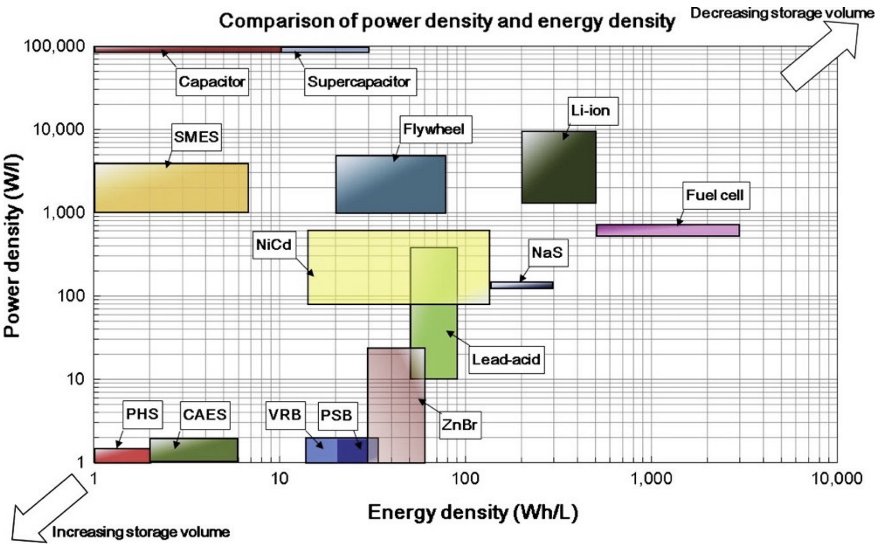


Figure 2-1. Specific power and energy ranges for each ESS (Luo et al., 2015)

Peak power is required to be delivered and transferred to the ESS in electric vehicles during rapid accelerations and decelerations. In the latter cases, the energy produced form the regenerative braking, generates substantially high currents, which should be mitigated. When having several energy storage systems, the power sharing should be coordinated. For the specific case of a Formula E, two types of energy storage systems have been used above others: rechargeable batteries and ultra-capacitors (Technical Department, 2017). The hybridisation of these systems creates an energy storage system with combined properties: the high energy density of the batteries together with the high power density of the ultra-capacitors.

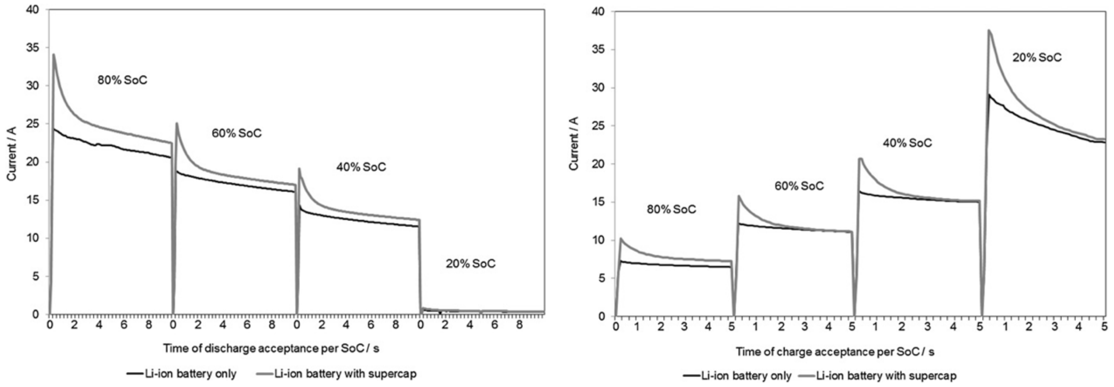


Figure 2-2. Discharge and charge comparisons for different states of Charge for Li-ion battery only and a hybrid system (Ferg, Rossouw and Loyson, 2013)

Figure 2-2 shows comparative studies of the discharge and charge ability for a hybrid system and a battery system itself. The results of the first study (discharge ability) showed that while the State of Charge (SoC) decreases, the amount of additional charge delivered also decreases. However, there are substantial differences between the different SoC that occur in the batteries. Whilst the 80%, 60% and 40% SoC showed that the batteries together with the ultra-capacitors were able to deliver slightly more current than the battery itself. The hybrid system with 40% SoC provided an additional 9% capacity during the 10s testing period.

In case of the charge ability, there is an increase in the maximum peak current that the system, composed of Li-ion batteries and ultra-capacitors, can accept for each SoC of the batteries. While the SoC decreased, the peak current in the hybrid system (Li-ion together with the ultra-capacitors) increased compared to the Li-ion battery itself. Particularly, said increase can be seen for a 20% SoC, where the hybrid system shows an increase of 7% in the charge capacitance over a period of 5s.

The hybridisation of a Li-ion battery with ultra-capacitors improved slightly the achievable power, meaning that the overall capacity is not necessarily being improved (Holland *et al.*, 2002). With the only purpose of achieving said improvement, managing the shared current between the different components is of great importance. It should also be noted that excessively large capacitors may increase the system weight significantly. Therefore, super-capacitors may have positive impact in said matter, since they are capable of providing the required capacity for charge and discharge.

2.1.1 Rechargeable Batteries (Electrochemical)

Electric vehicles batteries are required to handle high power and energy capacity with some limitations in weight and volume, whist the final cost should be affordable (Young *et al.*, 2013). Electrochemical batteries are devices that obtain electricity from chemical energy. The use of Lithium Ion batteries is becoming considerably popular in electric vehicles' applications. Actually, these cells are being employed by Williams Advanced Engineering to elaborate Formula E single-seater batteries (Art, 2018). The properties that characterise these batteries are: light weight, high specific energy, high specific power and high energy density (Tie and Tan, 2013). Table 2-1 shows a comparison between different rechargeable batteries.

Table 2-1. Electrochemical batteries comparison (Atmaja and Amin, 2015)

Type of battery	Specific energy (Wh/Kg)	Energy density (Wh/L)	Specific power (W/Kg)	Life cycle	Energy efficiency (%)	Production cost $(\$/kWh)$
Lithium-iron sulphide (FeS)	150	-	300	1000+	80	110
Lithium-iron phosphate ($LiFePO_4$)	120	220	2000-4500	>2000	80-95	150
Lithium-ion polymer (LiPo)	130-225	200-250	260-450	>1200	80-95	150
Lithium-ion	118-250	200-400	200-430	2000	>95	150
Lithium-titanate ($LiTiO/NiMnO_2$)	80-100	-	4000	1800	80-95	2000

Particularly, Formula E is currently using Lithium Ion cells, known as NMC (Nickel, Manganese, Cobalt). In said batteries, the Lithium ions rock between the anode and cathode during charge and discharge process (Niewiadomski, Gonçalves and Almeida, 2018). The anode is normally silicon-based, while the cathode is a combination of nickel, manganese and cobalt equally divided. Having a reduced rate of cobalt contributes to an important cut in its final cost.

Combining Nickel with Manganese enhances their strengths, the high specific energy of the Nickel with the low internal resistance of the Manganese. The efficiency in NMC batteries exceed 96% and considering their superior performance, reliability and safety features, they have competitive prices. Said batteries are recommended for applications which require either high specific energy or high specific power (Academy, 2000). Therefore, the combination of both types of NMC batteries (power and energy) in electric vehicles' powertrain is becoming a common practice inside the automotive field. As a consequence of said combination, battery management systems (BMS) need to be integrated inside the ESS, in order to control and manage the functions of the battery operation (Warner, 2015). For said combination, ultra-capacitors are substituted by power NMC batteries, which are able to provide large amount of energy during a very short period of time.

Losing capacity over their lifetime is in the nature of Lithium-Ion batteries due to several factors such as high temperatures or an increase in the internal resistance. 'Self-discharge' is also a phenomenon that said batteries experiment. There are two forms of self-discharge: permanent and temporary, to the battery's aptitude to return to its initial energy storage capacity (Warner, 2015).

Regarding the shape of the batteries, several designs have been developed, as it is shown in Figure 2-3: cylindrical, prismatic and pouch-bag cells (Kermani and Sahraei, 2017). These cells are grouped, according to the amount of energy that is required to be stored inside them, forming battery packs. Prismatic and pouch cells, also known as laminate cells, favour batteries being compacted in a more efficient manner, due to their shape (Svens *et al.*, 2013). Controlling the temperature inside these devices is crucial to avoid damages and, as a consequence, a reduction in their lifetime. Optimising the cell format to reduce the resistance of the battery layers is the objective when designing a battery for a specific application (Ghalkhani *et al.*, 2017).

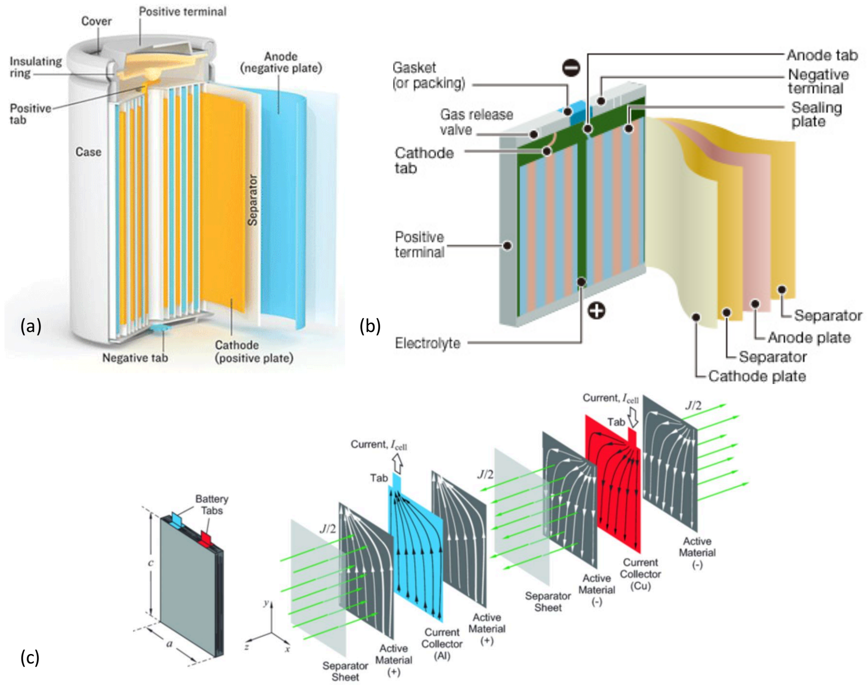


Figure 2-3. Types of battery cells. (a) cylindrical; (b) prismatic; (c) pouch-bag

Laminate pouch batteries, in special, are lighter, since they do not have a rigid container, unlike the rest of the cells. This fact maximises packaging density and, as a consequence, optimises the energy density inside the battery. Since one cell is not enough to store the whole amount of energy, these are assembled in cell packages. Several cells should be connected in series, in order to achieve the system voltage requirements, and in parallel, to achieve the required capacity. In order to avoid swelling, manufacturers oversize battery packs, so that excess gasses can escape (Maiser, 2014). Figure 2-4 shows a typical battery pack assembly.

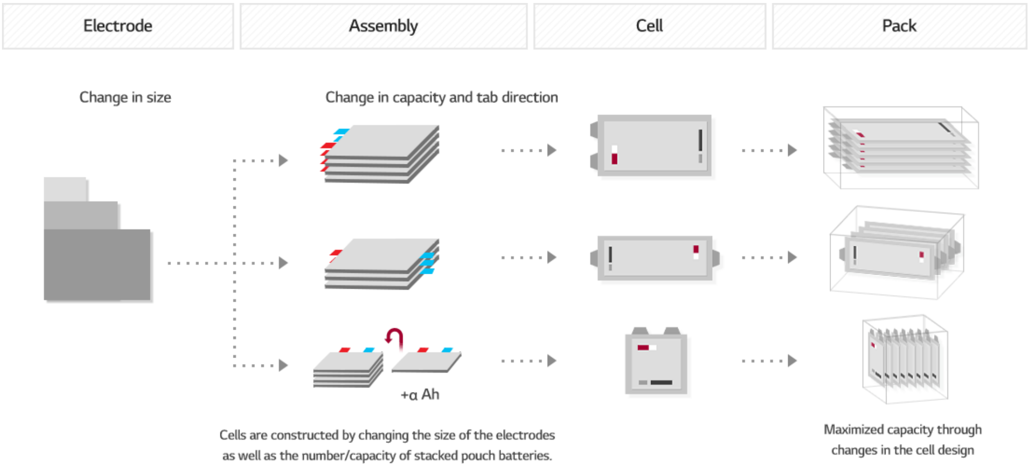


Figure 2-4. Battery pack assembly (LG Chem, 2018)

2.1.2 Ultra-capacitors

Ultra-capacitors are electrochemical energy storage devices, that differ from the batteries in the charge/discharge capability, having considerably greater rates, due to the fact that charges are physically stored inside the electrodes (Khaligh and Li, 2010). Said energy storage device, which has been under development since 90’s decade, is constructed similar to a battery, where two electrodes are immersed in an electrolyte using a separator between them (Burke and Zhao, 2015). Ultra-capacitors use dielectric materials with specific properties, such as: high permittivity, porous active carbon surface-edged electrodes, organic electrolyte and thin porous separator (Hannan *et al.*, 2017). Figure 2-5 shows a diagram of a typical ultra-capacitor.

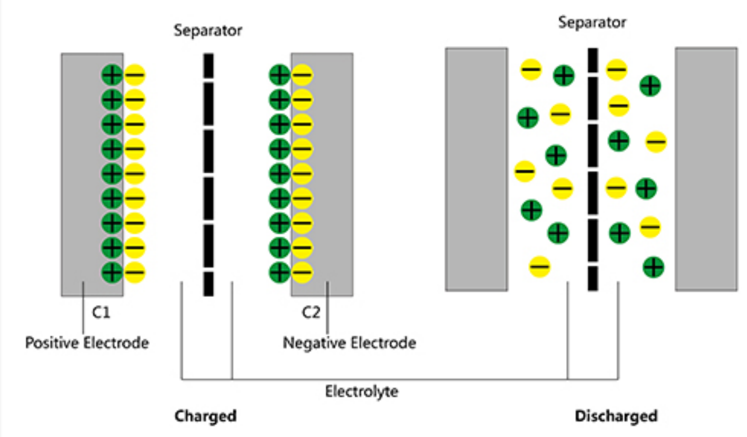


Figure 2-5. Diagram of a charged and discharged capacitor (GreenTech, 2018)

Although ultra-capacitors are characterised by its high power density, they cannot be used as the main power source, as a consequence of their low specific energy. Therefore, said devices are useful to absorb the peaks of energy that the battery is not capable of during short periods of time (Kouchachvili, Yaïci and Entchev, 2018). Said fact implies a reduction in the lifetime of the present devices, however, it remains higher than a normal capacitor (Tie and Tan, 2013).

Currently, these energy storage devices are classified in three classes (Hannan *et al.*, 2017):

- Electric double-layer capacitors (EDLC). These devices have higher power density than the rest of capacitors, but their specific energy is lower and the self-discharge rate is considerably high. Their high cost should also be noted.
- Pseudocapacitors. Similar to hybrid capacitors, the use of these devices is not extended due to their unavailability in the market.
- Hybrid capacitors. Relatively high power density, however, their power capability is not increasing proportional to the energy density.

Table 2-2 describes the typical specification for each type of ultra-capacitors explained above.

Table 2-2. Comparison of the different ultra-capacitors (Atmaja and Amin, 2015)

Ultra-capacitors	**Electrode material**	**Specific energy (Wh/Kg)**	**Power density (kW/Kg)**	**Life cycle (years)**	**Energy efficiency (%)**
Electric double-layer capacitors (EDLC)	Activated carbon	5-7	1-3	40	>95
Pseudocapacitors	Metal oxides	10-15	1-2	40	>95
Hybrid capacitors	Carbon/metal oxide	10-12	1-2	40	>95

Ultra-capacitors are recommended for applications where quickly delivery of power is needed, due to their fast charge and discharge rate (Khaligh and Li, 2010). As a consequence, several electric vehicles include ultra-capacitors as part of their regenerative braking system and energy storage devices. However, as it has been stated before, these energy storage devices are being replaced by batteries with high power density.

2.2 Battery Management System

The Battery Management System (BMS) is the main control unit of the battery pack and it is composed of several subsystems, such as: a master controller, ‘slave’ control boards or sensors. A special software integrates every subsystem and controls their correct functioning. The BMS provides protection against different failure modes: short circuiting, high or low temperatures, overcharging or overdischarging; therefore, it favours a safety life for the battery pack. Additionally, the BMS monitors the state of the battery at any time, contributing to the battery performance optimisation and maximisation (Warner, 2015). For said monitoring, several factors are estimated by the BMS: State of Health (SoH), State of Charge (SoC), maximum voltage…

There are two types of BMS: centralised and distributed system. In the first one, the main control board, together with the cell-monitoring control boards are located in one unit connected to every cell, minimising the amount of hardware, but increasing the required wiring inside the pack. In the second system, there is a master controller centrally located and several separate boards mounted directly in every battery module and monitors it. In contrast to the first system, it reduces the required wiring, but increases the costs, since larger amount of hardware is used. However, distributed systems offer great functionality and control of the batteries. Figure 2-6 shows both types of Battery Management System (BMS).

One of the main purposes of BMS is cell balancing, since, as it has already been stated, Lithium-Ion battery packs suffer ‘self-discharge’ phenomenon. When several cells are connected and one of them has a lower State of Charge (SoC), this cell will discharge before and the battery will stop delivering energy to avoid premature failure in the cell. The rest of the cells in the battery pack will never be fully discharge and, as a consequence, their lifetime will be higher than the lowest capacity cell. To avoid said failures and maximise the battery’s capacity, balancing the SoC of the cells in the same pack is of great importance. Figure 2-7 represents a battery pack composed of several cells with different SoC, where A is the lowest capacity cell and the stripped bars in the cells B and C represent the unusable amount of energy.

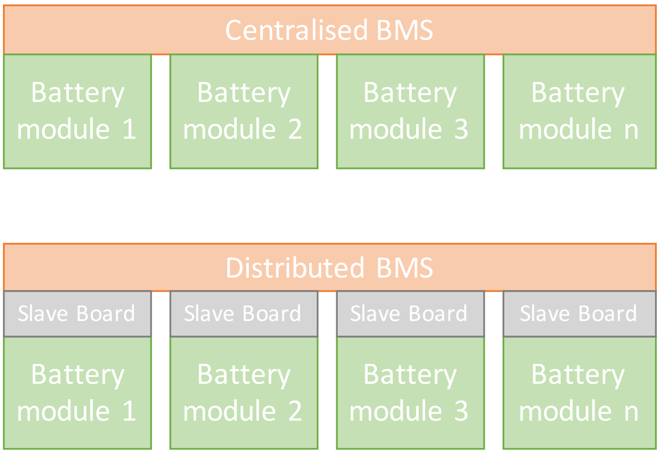


Figure 2-6. Centralised and distributed BMS

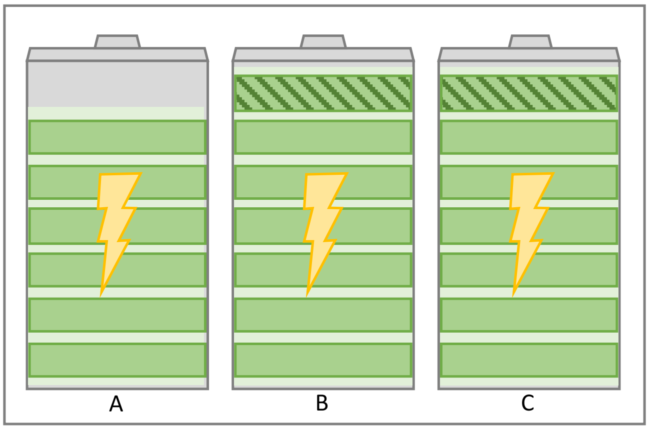


Figure 2-7. Example of an imbalanced battery pack

When imbalance cells are assembled in parallel configurations, they will self-balance, however, serial configurations need to be balanced by the BMS. There are two types of balancing: active and passive. In active balancing, the excess energy of the cells with greater SoC is transferred to the lower SoC cells, until the amount of energy in every cell is exactly the same. Although in this process, the excess energy is completely used, the required hardware is more expensive and may require extra space inside the pack. In passive balancing, the excess energy is converted into heat and dissipated by using a resistor. This process is less expensive, however, the excess energy is completely wasted. In this case, heat generation is an issue that should be also considered when designing BMS.

The process of balancing may take place during charging process or during a freeway drive when the battery is not being used (in hybrid electric vehicles). This is due to the amount of time that is required to carry out balancing and to the battery restrictions that bans their use while said process is taking place.

FIA Formula E regulations clearly specify that Lithium batteries must be equipped with Battery Management Systems (BMS), in order to ensure a safe driving (Art, 2018).

2.3 Electric motors

Electric motors are, essentially, governed by the electromagnetism laws, therefore, they highly depend on the materials from which they are made. When selecting the motor type for a certain purpose, several aspects need to be considered and studied in detail. Said features are (Hughes and Drury, 2013):

- Operating temperature and cooling. It usually limits the permissible output power and it is subjected to the class of insulation installed in the windings. Should the cooling system cannot be modified, then a higher class insulation can be used to increase the output power. On the contrary, an improved cooling system would require lower class insulation.
- Torque per unit volume. When the cooling system is similar, the motor torque might be directly proportional to its volume. Therefore, motors with roughly the same dimensions, may have similar torque.
- Power per unit volume and efficiency (related to the motor speed). The power directly depends on the rotor speed, increasing directly with the speed; whilst electrical losses usually experience a slower increase. Hence, it has been proved that the efficiency in the electric motors increases with speed. In practice, high speed motors connected to a speed reduction unit, are generally considered to be a better option from a cost point of view.

- Size effects (specific torque and efficiency). Large motors are more efficient and have a higher specific torque, since the specific electric loading and the specific magnetic loading are greater.
- Rated voltage. An electric motor can operate under a wide range of voltages, without compromising its integrity or its performance.
- Short-term overload. A wide range of electric motors can be overloaded during short periods, when the motor has been operating for a relatively long time with a reduced current, or from rest. The main factors that affect the permissible overload are the operating patterns and the thermal time constants.

2.4 Regenerative braking

One of the most important features of electric vehicles is their ability to recover energy while the vehicle is moving. Regenerative braking can be defined as the process of obtaining energy from the braking process by using the mechanical energy from the motor. The kinetic energy produced during the deceleration process, normally absorbed by the brakes and turned into heat, is converted into electrical energy by the motor (Erjavec, 2013). During this process of energy generation, the motor works as a generator instead. This amount of energy recovered, is stored in the vehicle's energy storage system, normally composed by a pack of battery cells and/or ultra-capacitors. By using regenerative braking, the driving range can be improved and brake's wear and maintenance costs decrease substantially.

The braking performance plays a vital role in the vehicle's safety, therefore, a successfully design system should guarantee stability in the vehicle's direction while reducing considerably the speed. In order to achieve said stability, the braking torque should be sufficiently high and the braking forces should be adequately distributed along every wheel. The electric motor should be designed and controlled to produce enough braking forces to maximise the recovered energy and decelerate the vehicle (Ehsani *et al.*, 2018). If the generator spins at high speeds, the regenerative braking is more efficient.

3 METHODS

The main purpose of Formula E can be defined as the development of a competitive car able to run faster than its competitors and to maximise the recovered and stored energy during each race. Formula E is currently under development, hence, new designs and strategies are being tested. Formula E technology will show the way to how future electric vehicles will be. The steps to design the energy recovery system (ERS) and the strategies to achieve an optimise one, are explained hereunder. Figure 3-1 shows the diagram of the project's methodology.

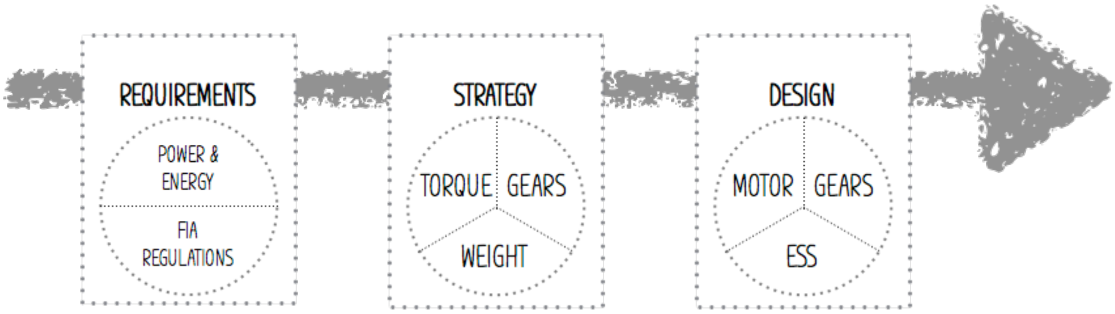


Figure 3-1. Scheme for the project's methodology

3.1 FIA regulations for Formula E

In order to ensure a safe driving and the competitiveness of every racing team intended to take part in Formula E, the FIA (Fédération Internationale de l'Automobile) establishes some regulations that should be considered when designing the single-seater. Said regulations define every aspect of the car, such as the materials to be used, the motor, energy storage system and battery management system's specifications, the vehicle's weight and dimensions or the emergency stop systems' specifications. For this specific project, several parameters have been extracted from FIA's technical regulations (Art, 2018) and they have been gathered together in Table 3-1.

In some cases, technical regulations are extremely restrictive and imply several challenges, however, they should be followed in detail, otherwise, the team would be penalised or expelled from the competition.

Table 3-1. Formula E FIA’s technical regulations

	Limitations	
Vehicle	Maximum speed (km/h)	280
	Min weight (kg)	900
	Max voltage per vehicle (V)	1000
Motor	Power (kW)	250
	Power race (kW)	200
Tyres	Max width (mm) [Front-Rear]	260 – 305
	Max diameter (mm) [Front-Rear]	650 – 690
	Rim diameter (inch)	18
Energy Recovery System (ERS)	Min battery weight (kg)	230
	Max energy delivered (kWh)	54
	Circuit voltage (V)	12
	Factor for losses in braking generation	0.7

3.2 Power and energy requirements

Formula E vehicles are subjected to different forces that the electric propulsion system should overcome in order to achieve the vehicle’s movement (acceleration or deceleration). Newton’s second law of motion has been used to obtain the parameters that influence the vehicle’s tractive efforts. The components of said forces are illustrated in Figure 3-2.

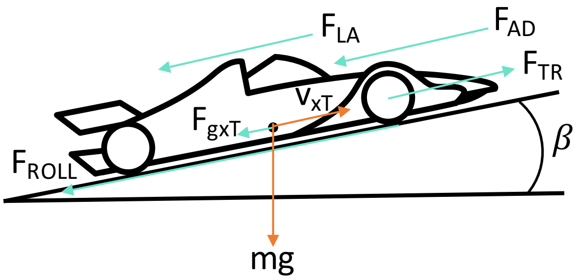


Figure 3-2. Formula E vehicle longitudinal dynamics

3.2.1 Vehicle dynamics

In order to understand energy losses related to braking systems, vehicle dynamics should be studied in detail. They can be classified in three categories according to their direction (Chau, 2016):

- Longitudinal dynamics describe the driving movement (acceleration and braking process) in the longitudinal direction. Forces included in this category were used for the calculation of power and energy requirements.
- Lateral dynamics are related to stability, in particular, during the vehicle's turns. The stability calculation was obtained from said forces.
- Vertical dynamics define the vertical vibration of the vehicle during the driving process and are related to the comfort and safe driving.

Lateral dynamics have been neglected for this study, since they are insignificant for a drive in straight line. However, they play an important role when the vehicle is travelling on a curved road. The decision of studying exclusively a straight road is based on the fact that maximum decelerations and accelerations will occur in said sections, before or after a corner respectively. The forces illustrated in Figure 3-2 are described hereunder.

Linear acceleration force (F_{LA})

This force represents the changes in velocity that the vehicle experiences during a period of time. It has been obtained from Newton's second law, and it can be defined according to (3-1):

$$F_{LA} = m\frac{d}{dt}v_{xT}\,(dt) = ma \tag{3-1}$$

Where m is the vehicle's weight, ν_{xT} is the tangential velocity (m/s) varying during a period of time t (s) and a is the vehicle's linear acceleration (m/s^2).

Slope frictional force (F_{gxT})

This force is dependent on the road slope angle and it is induced by gravity when the vehicle is traveling in a non-horizontal track. When the vehicle is moving upward, the resultant force has a positive sign, whist for downward driving, the force has negative sign. It can de expressed as:

$$F_{gxT} = mg\,sin\,\beta \tag{3-2}$$

Where m is the vehicle's weight (kg), g is the gravity acceleration (m/s^2) and β is the slope of the road (rad).

Rolling resistance force ($\mathbf{F_{ROLL}}$)

The rolling resistance force can be defined as the force acting against the motion of the vehicle, acting as a friction force between the wheels and the road. Due to said resistance, extra amount of energy is required to move in the forward direction, however, it facilitates the braking process. As a consequence, mechanical energy is turned into heat.

Since this force is dependent on the rolling resistance, it can be expressed as (Dhameja, 2002a):

$$F_{ROLL} = mg(C_o + C_1V)V \tag{3-3}$$

Where m is the vehicle's weight (kg), g is the gravity acceleration (m/s^2), C_o is the tyre rolling resistance, C_1 is the road rolling resistance and V is the tangential velocity (m/s).

Aerodynamic drag force ($\mathbf{F_{AD}}$)

The aerodynamic force that acts against the direction of travel of the vehicle and is due to aerodynamic resistance, measured in the plane of symmetry of the vehicle. In some cases, it can be defined as the force parallel to the vector of the relative wind.

It can be obtained with the following expression (Badin, 2013):

$$F_{AD} = \frac{1}{2}C_D\rho A_F V^2 \tag{3-4}$$

Where C_D is the aerodynamic drag coefficient, ρ is the air density kg/m^3, A_F is the vehicle equivalent frontal area (m^2) and V is the velocity (m/s). Typical value of the air density is $1.25\ kg/m^3$, however, this parameter depends on temperature, altitude and humidity. The velocity can be expressed as:

$$V = v_{xT} + v_0 \tag{3-5}$$

Where v_{xT} is the vehicle tangential velocity (m/s) and v_0 is the head wind velocity (m/s).

The vehicle's frontal area (A_F), considers the vehicle's surface that is in contact with the air and prevents the movement of the air in its direction, increasing the air resistance. The higher the frontal area is, the higher the air resistance is also. Therefore, racing vehicles such as Formula E are design to minimise said parameter. Typical value for the frontal area may be:

$$A_F = 1.212 \tag{3-6}$$

The aerodynamic drag coefficient (C_D) measures effectiveness of a body shape in reducing the air resistance to allow the forward movement of the vehicle. Low values of C_D implies that the shape of the body is designed to favour the movement with a minimum air resistance. On the contrary, high values of C_D are caused by body designs that oppose to the vehicle's motion and, as a consequence, increase the air resistance. Optimising this value is of great importance to minimise the effect of the air on the vehicle's motion. Drag coefficients for common vehicles and racing vehicles differ considerably. In case of Formula E, it has been assumed that the coefficient would be close to Formula One's aerodynamic drag coefficient (Balkwill, 2018).

$$C_D = 1.2 \tag{3-7}$$

Tractive force (F_{TR})

The required force to move the vehicle is known as tractive force. It is generated by the propeller and has to overcome the resistance forces that oppose to the vehicle's motion. It can be expressed as a combination of the previous forces:

$$F_{TR} = F_{LA} + F_{gxT} + F_{ROLL} + F_{AD} \tag{3-8}$$

It can also be expressed as a function of the engine torque and the transmission conditions (Badin, 2013):

$$F_{TR} = \frac{T_{eng} \cdot u_{trans} \cdot \eta_{trans}}{r_w} \quad \textbf{(3-9)}$$

Where T_{eng} is the engine torque (Nm), u_{trans} is the gear ratio, η_{trans} is the transmission efficiency and r_w is the wheel radius (m).

3.2.2 Axle torque

To generate the traction force (F_{TR}) the torque in the axle of the wheels should be:

$$T_{TR} = F_{TR} \cdot r_w \quad \textbf{(3-10)}$$

Where r_w is the tyre dynamic rolling radius (mm) and can be obtained from the following expression (Miller, 2010):

$$r_w = \frac{(D_{rim} + 2H_{sidewall})}{2} \quad \textbf{(3-11)}$$

Where D_{rim} is the diameter of the wheel rim (mm) and $H_{sidewall}$ is the sidewall height (mm). Both parameters have been obtained from the wheel manufacturer.

3.2.3 Tractive power

The propulsion system defines the vehicle capability to travel at a certain velocity, wind and terrain profile. Knowing the tractive force (F_{TR}) and the vehicle tangential velocity (v_{xT}), the tractive power has been obtained from the following expression:

$$P_{TR} = F_{TR} \cdot v_{xT} \quad \textbf{(3-12)}$$

The vehicle operating modes can be defined according to the results obtained in the tractive power:

- $P_{TR} > 0$. When having positive tractive power, the vehicle is in traction mode and it is moving forward. In this case, the traction force is greater than the resistance forces.

- $P_{TR} < 0$. For negative tractive power, the vehicle is in braking mode, therefore the tractive effort is also negative.
- $P_{TR} = 0$. In this case, two possible situations may occur: the vehicle is at rest (dwell mode) or the resistance forces equal the decrease in kinetic energy (coast mode).

3.3 Strategies

Two types of strategies have been considered to be important for the present study: design and driving strategies. Both affect directly the performance of the vehicle and, as a consequence, they influence the results in the race.

3.3.1 Design strategies

The design of the internal parts plays a crucial role in the high performance of the vehicle. The strategies are not related to which direction to follow for each race to achieve the team objectives, but they are related to what the vehicle's results are expected to be during the whole season. Next season, Formula E will experience an important improvement, where vehicle shifts will no longer occur during each race. This fact implies that only one car will be running during a whole race; and it will be possible as a consequence of the increase in the battery range from 28 kWh to 54 kWh and the increase in power from 200 kW to 250 kW (Taranovich, 2017).

In contrast, there are several parameters that affect the vehicle's powertrain efficiency performance and need further development. In order to obtain an optimised design of a Formula E single-seater, several strategies have been considered in the present project, which are explained hereunder.

3.3.1.1 Designing a power unit with high torque and a small gearbox

Acceleration is directly related to instant peak torque. There is an outstanding feature that should be considered when having to use electric motors, the fact that they can produce peak torque at 0 rpm. In other words, said motors are capable of achieving their maximum speed in a shorter period of time.

Since electric motors can be high revved and have suitable efficiencies along a wide range of revolutions, large motors can be used to produce the required force and power. Said fact would imply a simpler gearbox configuration to be used in the present strategy. The gear ratio for a simple gearbox configuration can be obtained as a function of the vehicle's maximum speed, v_{max}, (m/s), the maximum motor revving, n_{max}, (rps) and the tyre circumference perimeter, c_{tyre}, (m), according to the following expression:

$$u_{trans} = \frac{n_{max}}{v_{max}} \cdot c_{tyre} \qquad \textbf{(3-13)}$$

Two possible configurations may be designed for this purpose:

- One single large motor
- Twin small motors, each of them with low torque.

Although this strategy is thought to improve the vehicle's performance in the race, the additional weight that would be introduced in the single-seater should be also considered and studied in detail. Since these configurations imply using heavy motors or the combination of two small motors, the vehicle's total weight will increase substantially and, as a consequence the resistance forces will also increase, together with the required motor power. However, simplifying the transmission system will reduce the vehicle's weight and, as a consequence, it will compensate its increase due to the design motor.

Moreover, running the motor outside the peak efficiency may affect the number of laps available per battery, which may imply batteries oversizing in order to ensure that the race is finished without running out of battery.

3.3.1.2 Designing a power unit with low torque and a complex gearbox

Opposite to what has been aforementioned, low torque motors require longer periods of time to reach the motor maximum speed. However, this fact can be modified by using several gears to improve the torque at low speeds. In that case, reaching the maximum power can be achieved at lower motor revving. Figure 3-3 illustrates the power curve of two cases: (A) simple transmission (single gear) connected to a low speed motor and (B) complex transmission (few gears) connected to a low speed motor.

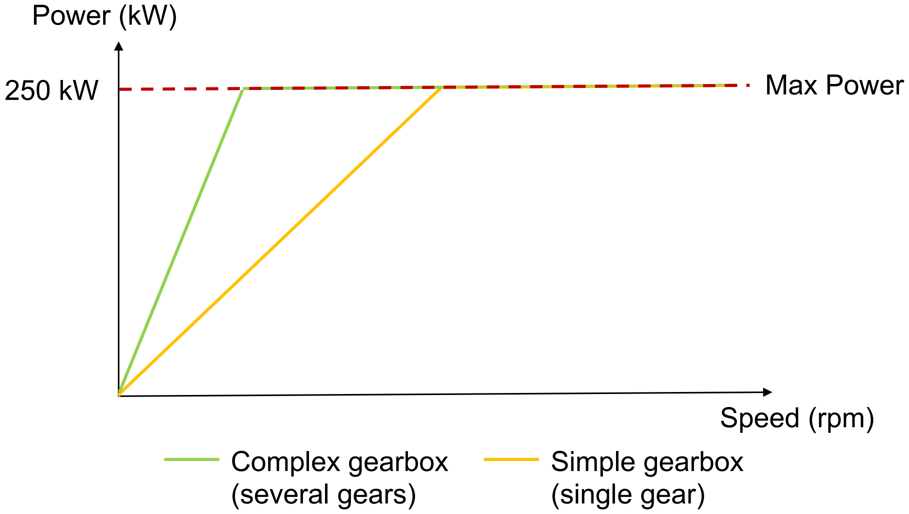


Figure 3-3. Power curve of a small motor for different number of gears

As it can be seen in the previous Figure 3-3, when the number of gears increases, it is possible to reach the maximum power at lower motor speed. This is due to the fact that torque can be easily modified by modifying the distance between the operational gears, which is related to modifications in the gears' size and the number of gears participating in the transmission process. This solution requires lighter motors, however, the weight of the transmission system will increase substantially. Therefore, finding a balance in weight for the motor and transmission system has been one of the main objectives of the present project.

3.3.2 Driving strategies

It may seem that the driving cycles do not affect the design of the driving system. However, the required power supplied by the engine is dependent on the vehicle speed. Said parameter can be obtained modelling a driving cycle, which depends on the driving strategy that the team is studying to accomplish during the race. Until next season (season 5), the drivers had to use two vehicles to complete one race, since the battery mileage was extremely limited. Therefore, the goal was to use the first car for the first half of the race and the second one to complete the race. How to optimise the use of both vehicles' batteries in each circuit was the key to succeed in the Formula E season.

However, the improvements in the vehicle's motor and batteries have led to improve the vehicle's autonomy and, hence, remove the second car. Therefore, the strategies will be slightly different, although they will be focused on the optimisation of the energy consumption. Said strategies have been defined as:

- **Equalise:** Control the race from the front and try to consume the same amount of energy during the whole race. The vehicle is not expected to be pushed to its limit, hence, the average speed will be lower than in other strategies.
- **Extend:** Save more energy at the beginning of the race and take advantage of it at the end of the race. The vehicle will be expected to run at extremely high speed at the end of the race, especially during the last laps.
- **Attack:** Decide to be more aggressive during the first part of the race in order to win positions. Once the objective has been reached, the strategy is based on maintaining the current position until the end of the race. In this strategy, the vehicle is expected to run at maximum speed and efficiency, therefore, the driving cycle will be more critical than in the rest of strategies.
- **Conserve:** This strategy is very similar to the extend strategy, however, they differ in the amount of energy that is saved at the beginning of the race. In this case, the vehicle will consume less energy, in order to be able to use said amount during the last laps and, hence, adopt a more aggressive attitude to gain positions. The present strategy can be defined as opposite to the attack strategy, however, both of them require vehicle's high performance.

Since the most critical strategies, where the vehicle is pushed to its limit, are attack and conserve, said driving cycles will be studied in the present project.

3.4 Design

In the present section, the process of designing the transmission system, the motor selection and the energy storage system is described in detail.

3.4.1 Motor and driving system

Taking into consideration the previous section, it has been assumed that the engine that best fits for the application, Formula E racing, is a permanent magnet motor. The main reason of this selection is that this type of electric motors can generate high torques for a more compact size than an induction motor. Moreover, for a simple gearbox, the speed and torque in the motor can be efficiently and cost-effectively over a wide operational range with advanced power electronic drives. Therefore, the strategy that has been selected for the design of the Energy Recovery System (ERS) is a large motor with a simple gearbox configuration.

The gearbox design depends on the strategy that has been previously selected and is extremely related to the motor design. Maximising the simplification of the gearbox, the transmission ratio has been defined according to (3-13), considering that the tyres imposed by the FIA to be used are: MICHELIN Bespoke 18”.

The parameters that characterise the permanent magnet motor can be obtained from the initial parameters calculated for the energy and power requirements of the vehicle. Said parameters are: motor torque, motor speed and motor power.

Motor torque

As it has been previously stated, this parameter is of great importance and can be obtained from the axle torque following the next expression:

$$T_M = \frac{T_{TR}/u_{trans}}{\eta_{trans}} \tag{3-14}$$

Where T_{TR} is the axle torque (Nm) explained in section 3.2.2, u_{trans} is the gearbox ratio and η_{trans} is the transmission efficiency.

Motor speed

The speed of the motor (rpm) at a certain vehicle velocity depends on the axle speed and the gearbox ratio, which depends also on the motor's maximum speed:

$$n_M = n_{axle} \cdot u_{trans} \tag{3-15}$$

The axle speed (rpm) can be obtained from the following expression:

$$n_{axle} = \frac{v}{2\pi \cdot r_w} \cdot \frac{1000}{60} \tag{3-16}$$

Where v is the vehicle speed (km/h) and r_w is the dynamic rolling radius explained in section 3.2.2.

Motor power

The motor power (kW) that the vehicle will require, according to the driving cycle, can be obtained as a function of the traction power or the motor torque and speed, following the next equation:

$$P_M = \frac{T_M \cdot 2\pi \cdot n_M}{6000} = \frac{P_{TR}}{\eta_{trans}} \tag{3-17}$$

Where T_M is the motor torque (Nm), n_M is the motor speed (rpm), P_{TR} is the tractive power explained in section 3.2.3 (kW) and η_{trans} is the efficiency of the driving system.

It should be noted that in this case, the FIA limits the maximum power delivered by the motor ($P_{M-max} \leq 250\ kW$), therefore, the driving cycle should be designed so that the motor fulfils said requirement.

Since the electric motor has been designed to act as a motor, and as a generator when the vehicle is under braking conditions, it is important to integrate an inverter that allows the current flowing in both directions. The power in the inverter will depend on its efficiency and the driving mode. Hence, said parameter under normal driving operation can be obtained according to the following expression (Dhameja, 2002b):

$$P_i = \frac{P_M}{\eta_M} \tag{3-18}$$

In case of regenerative braking operation, the power in the motor will be:

$$P_M = P_{TR} \cdot \eta_{trans} \tag{3-19}$$

And, as a consequence, the power in the inverter will be:

$$P_i = P_M \cdot \eta_M \tag{3-20}$$

3.4.2 Energy storage system

The devices responsible of feeding the motor are the batteries, therefore, they should be designed accounting the power required by the engine. Although they are called batteries, they may be a hybrid combination between Lithium-Ion batteries and other energy storage systems, such as super-capacitors. As it has been previously stated, the motor is connected to an inverter that allows the power generation. Hence, the power that said batteries need to produce should be obtained as a function of the inverter's efficiency. Two scenarios may occur during the vehicle's driving: normal driving operation and regenerative braking.

For the first scenario, the power in the batteries should be:

$$P_{batt} = \frac{P_i}{\eta_i} \tag{3-21}$$

In case of regenerative braking, the power in the batteries should be:

$$P_{batt} = P_i \cdot \eta_i \tag{3-22}$$

Knowing the power and the maximum energy that the energy storage system can store during the whole race, several options have been studied in detail to demonstrate the optimal configuration. Said alternatives are:

- Lithium-Ion NMC batteries exclusively
- Lithium-Ion NMC batteries together with ultra-capacitors.

3.4.2.1 Lithium-ion NMC batteries exclusively

According to section 2.1.1, Lithium-Ion NMC batteries have been proved to have high energy density, however, their specific power has been improved compared to other energy storage systems. Three different models of NMC battery cells will be studied to reach a more precise solution for the battery pack (Niewiadomski, Gonçalves and Almeida, 2018), Table 3-2 contains their technical specifications.

Table 3-2. Technical specifications of different NMC battery cells

Parameter	NMC1	NMC2	NMC3
Capacity (Ah)	37	60	95.6
Nominal Voltage (V)	3.6	3.65	3.68
Max Charging Current (A)	2 (74 A)	1 (60A)	-
Charge Cut-Off Voltage (V)	4.2	4.2	4.15
Max Discharging Current (A)	3 (111 A)	4 (180 A)	-
Discharge Cut-Off Voltage (V)	2.75	2.75	3.72
Maximum discharge current	333	720	413
Standard Current (A)	0.5 (18.5 A)	0.5 (30 A)	-
Dimensions (Thickness/Width/Length) (mm)	7.4/212/269	14/98/300	45/173/125
Volume (m3)	0.000422007	0.0004116	0.000973125
Model No.	IXP74/212/269PA	LG60AH-3.6 V/60 Ah	SAMSUNG SDI 94Ah
Maximum output Power (W)	1198.80	2628.00	1519.84
Weight (kg)	0.83	0.82	2.06
Volumetric energy density (kWh/m^3)	29196.18	104956.27	40573.20
Gravimetric energy density (kWh/kg)	14.84	52.69	19.17
Cell Energy (Wh)	133.20	219.00	351.81
Specific power density (kW/kg)	1444.06	3205.50	737.79

In this case, the most complex part of the pack design is minimising the number of NMC cells without compromising the vehicle's required power, since the specific power (kW/kg) of NMC battery cells, although competitive, is not as high as in other energy storage devices, such as ultra-capacitors. Obtaining the optimal battery configuration is an iterative process that consists in modifying the serial (n_{serial}) and parallel cells ($n_{parallel}$) until the power and energy obtained reach the required levels. The most important parameters to obtain, as a function of the number of cells, and that will define the battery characteristics, are explained hereunder.

Battery capacity (kWh)

The present parameter represents the amount of energy that can be stored inside the battery pack. It can be obtained with the following expression:

$$E_{batt-pack_1} = \frac{\left(E_{batt-cell} \cdot n_{parallel}\right) \cdot \left(V_{N-cell} \cdot n_{serial}\right)}{1000} \quad \textbf{(3-23)}$$

Where $E_{batt-cell}$ is the capacity in each NMC battery cell (Ah) and V_{N-cell} is the nominal voltage of the battery cells (V). The battery capacity should not exceed $E_{max} = 54\ kWh$, however, the calculation will give greater capacity. Therefore, the Battery Management System (BMS) will be programmed so that the maximum energy stored is always below the limit established by the FIA.

Power generation (kW)

The battery pack generated power can be obtained as a function of the maximum output power in each cell (W) and the number of cells arranged in series, according to the following equation (Dhameja, 2002b):

$$P_{out,batt-pack_1} = \frac{P_{out-cell} \cdot n_{serial}}{1000} \quad \textbf{(3-24)}$$

Similar to the case of the battery capacity, the effective power generation should never exceed 180 kW.

Discharge cut-off voltage (V)

The voltage at which the battery is considered fully discharge is known as the discharge cut-off voltage, and can be obtained from the next expression:

$$V_{DCO-pack_1} = V_{DCO-cell} \cdot n_{serial} \quad \textbf{(3-25)}$$

Where $V_{DCO-cell}$ is the discharge cut off voltage of each battery cell (V).

Charge cut-off voltage (V)

Opposite to the discharge cut off voltage, the charge cut off voltage is the voltage at which the battery is considered to be fully charged.

$$V_{CCO-pack_1} = V_{CCO-cell} \cdot n_{serial} \tag{3-26}$$

Where $V_{DCO-cell}$ is the discharge cut off voltage of each battery cell (V).

Battery nominal voltage (V)

The voltage at the battery pack in normal operating conditions can be obtained as a function of the nominal voltage in the battery cells (V) and the number of serial cells, according to section 2.1.1:

$$V_{N-pack_1} = V_{N-cell} \cdot n_{serial} \tag{3-27}$$

Weight (kg) and volume (m^3)

The weight and volume of the battery are key parameters to consider when designing the energy Storage System (ESS), since they need to fit properly inside the vehicle. On the other hand, the weight needs to be reduced to its minimum so that it has the lower impact on the vehicle's performance, in particular, on the energy and power requirements. Therefore, the magnitude of both parameters can be obtained according to the battery cell dimensions and weight:

$$m_{batt-pack_1} = m_{cell} \cdot n_{serial} \cdot n_{parallel} \tag{3-28}$$

$$Vol_{batt-pack_1} = \frac{(T \cdot W \cdot L) \cdot n_{serial} \cdot n_{parallel}}{10^9} \tag{3-29}$$

Where $\mathrm{m_{cell}}$ is the mass of the individual cells (kg) and T, W and L are the thickness, width and length of each cell (mm).

Energy density (Wh/kg) and specific power (W/kg)

As it has been previously stated, the weight plays an important role in the design of the ESS, therefore, the energy density and the specific power are two parameters which will define the performance of the battery pack. The following expressions define how to obtain them:

$$W_{batt-pack_1} = \frac{E_{batt-pack_1}}{m_{batt-pack_1}} \tag{3-30}$$

$$P'_{batt-pack_1} = \frac{P_{out,batt-pack_1}}{m_{batt-pack_1}} \tag{3-31}$$

Where $E_{batt-pack_1}$ is the battery pack capacity (Wh) and $P_{out,batt-pack_1}$ is the power generated by the battery pack (W).

Range (km)

The fulfilment of the energy and power restrictions should not be the only issue to consider. The optimal design of the Energy Storage System should be also related to the battery autonomy, since only one single-seater would be available in each race. Considering that the average distance that the vehicle will have to run in each race may exceed 100 km, it can be assumed that the minimum range distance of the battery pack should be at least said number. However, and with the main purpose of reducing the risks of uncompleting one race, a safety factor of about 10% has been applied in this specific case. Therefore, the minimum distance range of the Energy Storage System (d_{min}) has assumed to be 110 km.

In order to predict the battery range, the energy consumption during the race (E_{cons_1}) should be also obtained as a function of the nominal voltage (V_{N-pack_1}), the nominal current (I_{N-pack_1}) and the vehicle's average speed ($n_{avg-vehicle}$), as it is indicated in the following equation:

$$E_{cons_1} = V_{N-pack_1}\left(\frac{I_{N-pack_1}}{n_{avg-vehicle}}\right) \tag{3-32}$$

Once said value has been already obtained and considering the battery's energy capacity ($E_{batt-pack_1}$), the maximum distance at which the battery pack will be able to supply energy would be obtained with the following expression:

$$d_{batt-max_1} = \frac{E_{batt-pack_1}}{E_{cons_1}} \tag{3-33}$$

Finally, one verification should be done in order to guarantee that the vehicle will be able to finish the race without any difficulty:

$$d_{batt-max} \geq d_{min} \tag{3-34}$$

If (3-34) is not fulfilled, the battery pack design should be modified until the previous condition is satisfied.

3.4.2.2 Lithium-Ion NMC batteries together with ultra-capacitors

As it has been previously noted, hybrid batteries might be a proper solution to reduce weight without compromising the energy stored and power generated. In this specific case, a battery pack will be installed in parallel with pack of ultra-capacitors. The main function of the batteries will be to store the vast majority of the energy, whilst the super-capacitors will be in charge of the peaks of energy. Figure 3-4 illustrates a general scheme of an Energy Storage System using the present configuration.

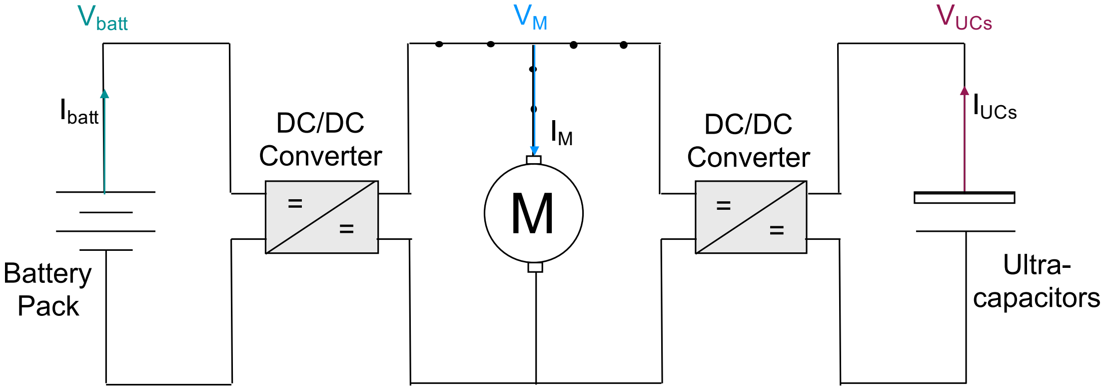


Figure 3-4. General scheme of an ESS composed of batteries and ultra-capacitors

Since two different types of energy storage devices are going to participate in the process of feeding the electric motor with energy, the amount of power and energy that each of them should be able to generate and store, has been adjusted considering the FIA's limitations (E_{max} and P_{M-max}). Figure 3-5 illustrates the diagram to obtain the theoretical amount of energy and power in each device and that will be used by the BMS to optimise the vehicle's performance.

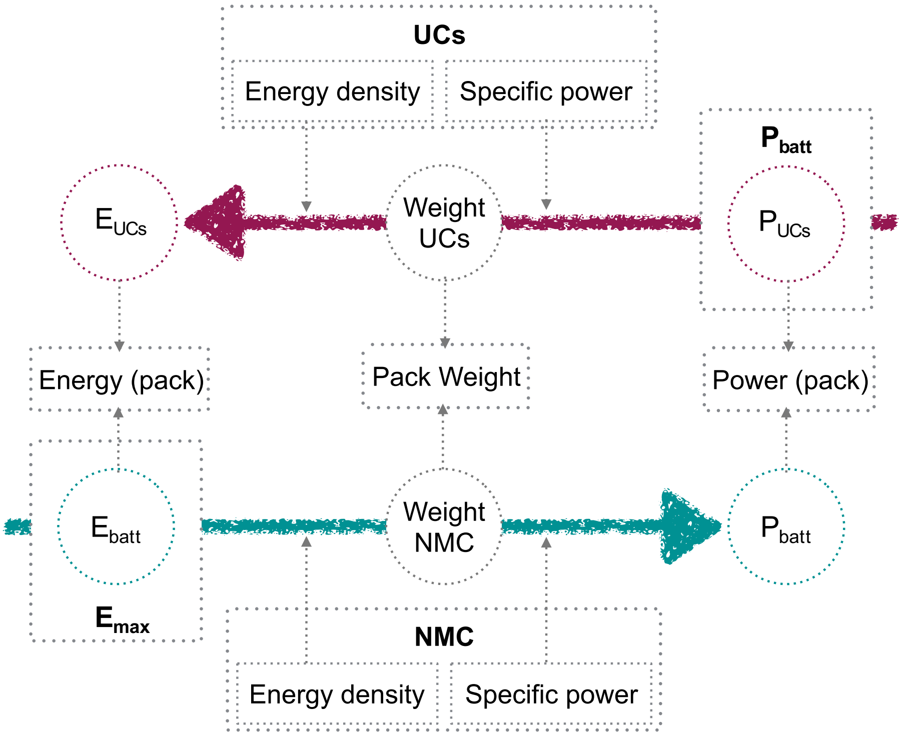


Figure 3-5. Theoretical power and energy in a hybrid ESS

As it can be observed in the previous Figure 3-5, the values that limit the design of the present ESS configuration are: the maximum energy allowed to be stored (E_{max}) and the maximum power to be delivered by the ESS (P_{batt}), obtained at the beginning of section 3.4.2. Two different criteria have been used to design both energy storage devices, however, said criteria explained hereunder are enormously linked.

The maximum power to be delivered would limit the amount of power to generate by the ultra-capacitors, and it could be determined following the next expression:

$$P_{UCs} = x_{P-UCs} \cdot P_{batt} \tag{3-35}$$

Where x_{P-UCs} is the rate of power generated by the ultra-capacitors, determined by an iterative process. In a similar manner, the power in the NMC batteries is obtained in the present design criterion:

$$P_{NMC} = x_{P-NMC} \cdot P_{batt} = (1 - x_{P-UCs}) \cdot P_{batt} \tag{3-36}$$

Where x_{P-NMC} is the rate of power generated by the NMC batteries.

For the estimation of the super-capacitors' weight (m_{UCs}), the specific power of said energy storage devices has been assumed to be $P'_{UCs} = 2\,kW/kg.$ The following expression describes how to obtain the required weight for the ultra-capacitors:

$$m_{UCs} = \frac{P_{UCs}}{P'_{UCs}} \tag{3-37}$$

Knowing the ultra-capacitors' weight, and since their energy density has been assumed to be $W_{UCs} = 8.33\,Wh/kg$, the real amount of energy that would be stored in said devices can be obtained from the following expression:

$$E_{UCs-real} = W'_{UCs} \cdot m_{UCs} \tag{3-38}$$

Opposite to what has been developed for the ultra-capacitors, the NMC batteries have been modelled according to the maximum amount of energy that can be stored (E_{max}), limited by the FIA. Therefore, the energy in said devices would be:

$$E_{NMC} = x_{E-NMC} \cdot E_{max} \tag{3-39}$$

Where x_{E-NMC} is the rate of energy stored in the NMC batteries, equal to the previous rates, an iterative process is required to obtain said value. As a consequence, the energy in the ultra-capacitors obtain would be:

$$E_{UCs} = x_{E-UCs} \cdot E_{max} = (1 - x_{E-NMC}) \cdot E_{max} \tag{3-40}$$

Where x_{E-UCs} is the rate of energy stored in the ultra-capacitors. Although the value obtained in (3-40) may be valid, the real energy stored by the super-capacitors has been obtained from expression (3-38), since their weight has been designed according to the first criterion.

In order to obtain the NMC batteries' weight, the energy density has been assumed to be $W_{NMC} = 0.26712\,kWh/kg$. Hence, said value would be:

$$m_{NMC} = \frac{E_{NMC}}{W_{NMC}} \tag{3-41}$$

Once the weight has been obtained, it is possible to calculate the real power generated by said device, considering that the specific power has been assumed to be $P'_{NMC} = 1.0685\ kW/kg$. Hence, the value object of interest would be:

$$P_{NMC-real} = P'_{NMC} \cdot m_{NMC} \tag{3-42}$$

To sum up, two different strategies have been developed to obtain the real performance of each device that composes the energy storage system. The ultra-capacitors can be defined with expressions (3-35) and (3-38), whilst the NMC batteries can be defined with equations (3-39) and (3-42). Therefore, the values for the whole battery pack would be:

$$m_{batt-pack_2} = m_{UCs} + m_{NMC} \tag{3-43}$$

$$E_{batt-pack_2} = E_{UCs-real} + E_{NMC} \tag{3-44}$$

$$P_{batt-pack_2} = P_{UCs} + P_{NMC-real} \tag{3-45}$$

$m_{batt-pack_2}$ in kg, $E_{batt-pack_2}$ in kWh and $P_{batt-pack_2}$ in kW.

Finally, the energy density ($W_{batt-pack_2}$) and the specific power ($P'_{batt-pack_2}$) for the hybrid pack would be:

$$W_{batt-pack_2} = \frac{E_{batt-pack_2}}{m_{batt-pack_2}} \tag{3-46}$$

$$P'_{batt-pack_2} = \frac{P_{batt-pack_2}}{m_{batt-pack_2}} \tag{3-47}$$

The range, in km, for the energy storage under study has been obtained following expressions (3-32) and (3-33).

It should be noted that, once the theoretical power and energy required is known, said values should be used as order of magnitude in order to estimate the real values using manufactured ultra-capacitors and NMC battery cells. These last ones could be modelled following section 3.4.2.1 instructions, whilst the design process for the first ones is explained hereunder. Table 3-3 contains technical specifications for several ultra-capacitor models, used for the present design.

Table 3-3. Technical specifications of different ultra-capacitor cells

Parameter	UC1	UC2	UC3
Capacitance C (F)	600.00	400.00	300.00
Nominal Voltage (V)	2.70	2.70	2.70
Max Charging Current (A)	33.00	26.00	20.00
Peak current (A)	316.41	236.84	172.34
Leakage current (microA)	1.3 (72h)	0.85 (72h)	0.6 (72h)
Dimensions (Thickness/Width/Legth) (mm)	87.5/D35	63/D36	53/D37
Model No.	XV3585-2R7607-R	XV3560-2R7407-R	XV3550-2R7307-R
ESR (mOhm) – 1kHz	2.60	3.20	4.50
Maximum output Power (W)	790.00	570.00	410.00
Weight (g)	108.00	72.00	62.00
Energy Stored (Wh)	0.61	0.41	0.30
Gravimetric energy density (Wh/g)	0.01	0.01	0.00
Specific Power (W/g)	7.31	7.92	6.61

Similar to the process described in section 3.4.2.1, the parameters that accurately describe the ultra-capacitor pack should be obtained as a function of the cells' technical specifications and the number of serial and parallel ultra-capacitors ($n_{serial-UCs}$ and $n_{parallel-UCs}$). Said number will be obtained in an iterative process considering that the power generation and the energy capacity should be extremely closed to the values obtained in expressions (3-35) and (3-38). Hence, the value for the nominal voltage in the ultra-capacitor bank would be:

$$V_{N-UCs-pack} = V_{N-UC} \cdot n_{serial-UCs} \tag{3-48}$$

Where V_{N-UC} is the nominal voltage in each ultra-capacitor (V).

Moreover, the power and energy in the bank could be obtained from the following expression:

$$P_{UCs-pack} = P_{UC-cell} \cdot n_{serial-UCs} \approx P_{UCs} \tag{3-49}$$

$$E_{UCs-pack} = E_{UC-cell} \cdot n_{serial-UCs} \cdot n_{parallel-UCs} \approx E_{UCs-real} \tag{3-50}$$

Where $P_{UC-cell}$ is the power generated by each cell (kW) and $E_{UC-cell}$ (kWh) is the energy stored in each ultra-capacitor.

Finally, the weight in the bank, in kg, would be:

$$m_{UCs-pack} = \frac{m_{UCs-pack} \cdot n_{parallel-UCs} \cdot n_{serial-UCs}}{1000} \quad \textbf{(3-51)}$$

Where $m_{UCs-pack}$ is the weight of each individual cell (g).

The real energy stored, power generated and weight of the battery pack composed of NMC cells and ultra-capacitors would be obtained following expressions (3-43), (3-44) and (3-45).

4 RESULTS

In this section, one case study is explained in detail in order to avoid redundancy, however, several studies were done to demonstrate the final conclusions. Said case studies are analysed in depth in Appendix A.

4.1 Power and energy requirements

The methodology hereinabove requires some previous calculations, related to the FIA limitations. The vehicle's technical data calculated and used to obtain the power requirements is detailed in the following table. The design criteria chosen in this case was a permanent magnet motor with a basic transmission system.

Table 4-1. Vehicle's data

VEHICLE'S DATA		
Parameters	**Units**	**Value**
Vehicle weight, m	kg	900
Acceleration, a	m/s^2	9.92
Gravity, g	m/s^2	9.81
Gradient, β	radians	0
Tyre Rolling Resistance, C_0	-	0.03
Road Rolling Resistance, C_1	-	0
Air density parameter, ρ	kg/m^3	1.25
Vehicle equivalent frontal area, A_F	m^2	1.212
Aerodynamic drag coefficient, C_D	-	0.85
Tyre radius, r	m	0.35
Gearbox ratio u_{trans}	-	10.88
Sidewall height, $H_{sidewall}$	mm	122.00
Diameter of the wheel rim, D_{rim}	mm	457.20

Furthermore, the driving criterion that was chosen for this specific purpose was the attack strategy, since it is the most critical and requires peaks of energy to be delivered. Figure 4-1 illustrates the speed that the vehicle is expected to reach in a long straight line of about 600 m, considered to be the maximum distance that the vehicle will be able to run in any circuit. It should be noted, that the present driving cycle has been designed specifically for this purpose, however, it could be modified considering how does the acceleration in the vehicle may affect the motor required power. For that purpose, and for the design of the ESS, an excel file has been developed in order to optimise the results.

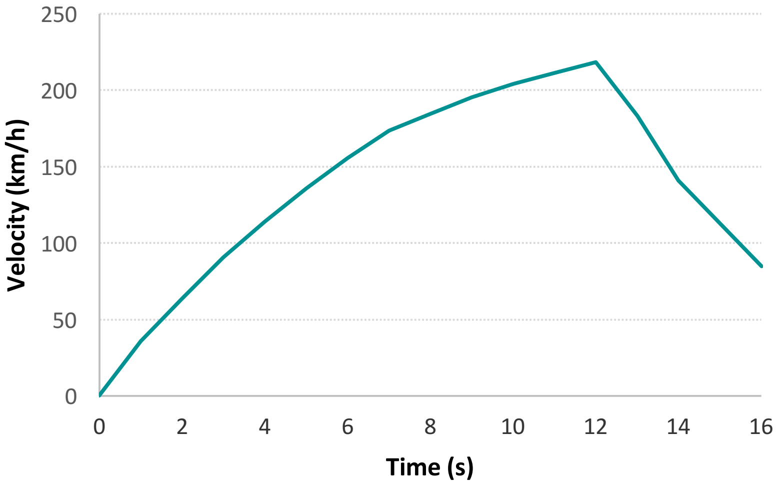


Figure 4-1. Driving cycle

Once the crucial values are known, it is possible to obtain the power and energy requirements. Table 4-2 contains the real values of the vehicle power requirements, power and torque in the axle and motor and, as a consequence, power in the inverter and battery. For this specific case, the head wind has been considered to be $0\ m/s$.

As it can be seen in Table 4-2, the maximum speed that the vehicle would reach under the present conditions would be approximately $220\ km/h$, whilst the maximum tractive power would be $258\ kW$ – which slightly exceeds the maximum allowed by the FIA, $250\ kW$. The BMS would limit the power so that the threshold is never exceeded.

Table 4-2. Values for the vehicle power requirements

Time (s)	Velocity (km/h)	Acceleration (m/s^2)	Tractive Force (N)	Tractive Power (kW)	Axel Torque (Nm)	Axel speed (rpm)
0	0.0	9.921	8928.6	0.0	3130.4	0.0
1	35.7	7.800	7348.2	72.9	2576.3	270.2
2	63.8	7.500	7217.1	127.9	2530.3	482.7
3	90.8	6.500	6524.4	164.6	2287.5	686.9
4	114.2	6.000	6312.7	200.2	2213.2	864.0
5	135.8	5.500	6131.0	231.3	2149.5	1027.4
6	155.6	5.000	5967.6	257.9	2092.3	1177.2
7	173.6	3.000	4462.0	215.2	1564.4	1313.4
8	184.4	3.000	4654.1	238.4	1631.7	1395.1
9	195.2	2.500	4407.8	239.0	1545.4	1476.8
10	204.2	2.000	4136.4	234.6	1450.2	1544.9
11	211.4	2.000	4285.0	251.6	1502.3	1599.4
12	218.6	-9.800	-6181.2	-375.3	-2167.1	1653.8
13	183.3	-11.800	-8685.6	-442.3	-3045.2	1386.9
14	140.8	-7.800	-5769.7	-225.7	-2022.9	1065.5
15	112.8	-7.800	-6123.5	-191.8	-2146.9	853.1
16	84.7	0.000	621.1	14.6	217.7	640.6

Although the main force is the tractive force, the longitudinal dynamics should be also obtained, in order to have an order of magnitude of which forces influence most the tractive force. Table 4-3 contains the values of the longitudinal dynamics.

According to Table 4-3, the gravitational force has no effect on the traction force, since it has been assumed that the vehicle is running in a completely horizontal plane; and the rolling resistance is constant through time. Therefore, the linear acceleration force is the dominant resistive force, which contributes most part of the tractive force.

Table 4-3. Values for the vehicle longitudinal dynamics

Linear acceleration Force (N)	Gravitational Force (N)	Rolling resitance Force (N)	Aerodyn. drag Force (N)
8928.6	0.0	0.0	0.0
7020.0	0.0	264.9	63.4
6750.0	0.0	264.9	202.2
5850.0	0.0	264.9	409.6
5400.0	0.0	264.9	647.9
4950.0	0.0	264.9	916.1
4500.0	0.0	264.9	1202.8
2700.0	0.0	264.9	1497.2
2700.0	0.0	264.9	1689.2
2250.0	0.0	264.9	1892.9
1800.0	0.0	264.9	2071.5
1800.0	0.0	264.9	2220.2
-8820.0	0.0	264.9	2374.0
-10620.0	0.0	264.9	1669.5
-7020.0	0.0	264.9	985.4
-7020.0	0.0	264.9	631.6
0.0	0.0	264.9	356.2

4.2 Propeller system

As it has been previously stated, the design strategy selected for this specific case was the criteria explained in section 3.3.1.1. Hence, the propeller selected in the present study was the permanent magnet motor, since the relationship between the torque and the motor weight is optimal for the present application. Considering that the transmission efficiency is $\eta_{trans} = 1$, the motor torque, power and speed are detailed in Table 4-4.

From said table, it is possible to observe that the motor chosen has a maximum rotating speed of $18000\ rpm$, which is reached at the vehicle's maximum speed. In this case, the motor power coincides with the traction power, assuming the unitary value of the transmission efficiency.

Table 4-4. Values for the motor power requirements

Motor Torque (Nm)	Motor Speed (rpm)	Motor Power (kW)
287.6	0	0.0
236.7	2941	72.9
232.5	5253	127.9
210.2	7476	164.6
203.4	9403	200.2
197.5	11182	231.3
192.2	12812	257.9
143.7	14295	215.2
149.9	15184	238.4
142.0	16073	239.0
133.2	16814	234.6
138.0	17407	251.6
-199.1	18000	-375.3
-279.8	15095	-442.3
-185.9	11597	-225.7
-197.3	9285	-191.8
20.0	6972	14.6

4.3 Energy Storage System

In the present study, two different energy storage systems were designed according to section 3.4.2, however, only one has been proved to be the optimal design solution. In order to obtain the maximum power delivered by the ESS, a constant value of 0.95 was assumed for the efficiency in the motor and 0.98 for the inverter's efficiency. Table 4-5 contains the values of the power in the inverter and the ESS.

According to said table, the maximum power delivered by the ESS would be $277\,kW$, whilst the maximum power at which the system would be under regenerative braking would be $410\,kW$ approximately. Said last value, would be limited by the BMS up to a maximum of $150\,kW$.

Table 4-5. Values for the inverter and battery power requirements

Motor Power (kW)	Inverter Power(kW)	Battery Power (kW)
0.0	0.0	0.0
72.9	76.7	78.3
127.9	134.6	137.4
164.6	173.2	176.7
200.2	210.8	215.1
231.3	243.4	248.4
257.9	271.5	277.0
215.2	226.5	231.1
238.4	250.9	256.1
239.0	251.6	256.7
234.6	247.0	252.0
251.6	264.9	270.3
-375.3	-356.6	-349.4
-442.3	-420.2	-411.8
-225.7	-214.4	-210.1
-191.8	-182.2	-178.6
14.6	15.4	15.7

Once the value of the maximum power to generate by the ESS is known, it is possible to calculate both configurations:

- Lithium-Ion NMC batteries exclusively
- Lithium-Ion NMC batteries together with ultra-capacitors

4.3.1 Lithium-Ion NMC batteries exclusively

Following the methodology described in section 3.4.2.1, and considering the NMC cells detailed in Table 3-2, the values obtained for each characteristic parameter are detailed in Table 4-6. The three models have been calculated maximizing the energy stored and the power generated, 54 kWh and 270 kW respectively. As it can be seen in said table, although the NMC2 battery produces the lowest amount of power, its weight and range makes easy the NMC cell model selection.

Table 4-6. Characteristic values for NMC exclusively battery design

Parameter	NMC1	NMC2	NMC3
Serial cells	230	102	180
Parallel cells	2	3	1
Energy stored (kWh)	61.27	67.01	63.33
Power (W)	275.72	268.06	273.57
Discharge Cut-Off Voltage (V)	632.5	280.5	669.6
Charge Cut-Off Voltage (V)	966	428.4	747
Nominal Voltage (V)	828	372.3	662.4
Weight (kg)	381.87	250.87	370.80
Volume (m3)	0.19	0.13	0.07
Energy density (Wh/kg)	160.45	267.12	170.78
Specific power density (W/kg)	722.03	1068.50	737.79
Energy consumption (kwh/km)	0.64	0.47	0.63
Range (km)	84.64	116.08	85.10

4.3.2 Lithium-Ion NMC batteries together with ultra-capacitors

Considering the ultra-capacitors presented in Table 3-3, and according to the process described in section 3.4.2.2, the first estimation of the hybrid ESS is contained in the following tables. As it has been illustrated in Figure 3-5, two parallel design processes were implemented to obtain the power in the ultra-capacitors and NMC battery and, simultaneously, their stored energy. Table 4-7 contains the theoretical values for the power in the ultra-capacitors and the NMC battery pack. In this case, the results were obtained considering the maximum power allowed to be delivered by the ESS and obtaining, from an iterative process, the values of x_{P-NMC} and x_{P-UCs} – which represent the power rate for each energy storage device.

Table 4-7. Theoretical values for the power in a hybrid ESS

Parameter	Units	Value
Maximum battery system power, P_{batt}	kW	277.04
NMC power rate, x_{P-NMC}	-	0.78
Ultra-capacitors power rate, x_{P-UCs}	-	0.22
Power in NMC battery, P_{NMC}	kW	216.09
Power in Ultra-capacitors, P_{UCs}	kW	60.95
Ultra-capacitors weight, m_{UCs}	Kg	30.47
Real power in NMC battery, $P_{NMC-real}$	kW	213.41

Furthermore, Table 4-8 represents the theoretical values for the energy in the NMC battery pack and ultra-capacitors bank. From said table, it can be seen that the vast majority of the energy is stored in the NMC batteries, as a consequence of the low energy density in the ultra-capacitors. For this process, the maximum stored energy allowed by the FIA was defined as the threshold and, implied the start point to obtain the theoretical stored energy in both energy storage devices.

Table 4-8. Theoretical values for the energy in a hybrid ESS

Parameter	Units	Value
Maximum battery system stored energy, E_{max}	kWh	54
NMC energy rate, x_{E-NMC}	-	0.99
Ultra-capacitors energy rate, x_{E-UCs}	-	0.01
Energy in NMC battery, E_{NMC}	kWh	53.35
Energy in Ultra-capacitors, E_{UCs}	kWh	0.65
NMC battery weight, m_{NMC}	Kg	199.73
Real energy in Ultra-capacitors, $E_{UCs-real}$	kWh	0.25

Integrating both energy storage devices, the values for the whole hybrid system were estimated. Following expressions (3-43) to (3-47), the values contained in Table 4-9 were obtained.

Table 4-9. Theoretical values for the power and energy in a hybrid ESS

Hybrid ESS (NMC & UCs)		
Parameter	Units	Value
Hybrid battery pack weight, $m_{batt-pack_2}$	kg	230.20
Real power in hybrid battery pack, $P_{batt-pack_2}$	kW	274.36
Real energy in hybrid battery pack, $E_{batt-pack_2}$	kWh	53.61
Range, $d_{batt-max_2}$	Km	115.23
Energy density in hybrid battery pack, $W_{batt-pack_2}$	kWh/kg	0.23
Specific power in hybrid battery pack, $P'_{batt-pack_2}$	kW/kg	1.19

Once the theoretical values of power and energy were known, it was possible to estimate the real values, on the basis of the manufacturers datasheets for each energy storage device.

Firstly, the NMC battery pack for the hybrid system was designed following the steps described in section 3.4.2.1, considering the theoretical energy and power obtained in Table 4-7 and Table 4-8. In said case, the values for the basic parameters for the NMC models are represented in Table 4-10.

Table 4-10. Power and energy in the NMC battery inside the hybrid ESS

Parameter	NMC1	NMC2	NMC3
Serial cells	200	80	150
Parallel cells	2	3	1
Energy stored (kWh)	53.28	52.56	52.77
Power (W)	239.76	210.24	227.98
Discharge Cut-Off Voltage (V)	550	220	558
Charge Cut-Off Voltage (V)	840	336	622
Nominal Voltage (V)	720	292	552
Weight (kg)	332.06	196.76	309.00
Volume (m3)	0.17	0.10	0.06
Energy density (Wh/kg)	160.45	267.12	170.78
Specific power density (W/kg)	722.03	1068.50	737.79
Energy consumption (kwh/km)	0.55	0.36	0.53
Range (km)	96.03	144.05	99.79

For this case, exactly equal to the Lithium-Ion ESS, the NMC2 model offers the most optimal performance under the present conditions. The balance between weight, range, energy and power makes said model the optimal to meet best the project needs.

Moreover, for the design of the ultra-capacitors bank, the models described in Table 3-3 were used. According to section 3.4.2.2 and considering the amount of energy to store and power to deliver, the design configuration for each model is contained in Table 4-11.

Table 4-11. Power and energy in the ultra-capacitors inside the hybrid ESS

Parameter	UC1	UC2	UC3
Serial cells	76	80	150
Parallel cells	5	3	1
Nominal Voltage (V)	205.20	238.5	391.5
Energy stored (kWh)	0.23	0.26	0.26
Power (kW)	60.04	59.85	59.45
Weight (kg)	41.04	45.36	53.94

Finally, combining both results, the real design of the hybrid system was obtained. Following expressions (3-43), (3-44) and (3-45), said values were estimated and represented in Table 4-12.

Table 4-12. Real power and energy in the hybrid ESS

Hybrid system		
Parameter	Units	Value
Weight	Kg	237.80
Power	kW	270.28
Energy	kWh	52.79
Specific power	W/kg	1136.58
Energy density	Wh/kg	222.00
Range	Km	144.05

5 DISCUSSION

5.1 Current design proposal

In the previous section, two different energy recovery systems (ERS) were designed for one case study. The motor and transmission systems were assumed to be the same for both configurations, however, the energy storage system (ESS) differ from one to another. The alternative which provides better results regarding power generation, energy stored, weight and distance range would be assumed to be the most optimal configuration to be installed in Formula E vehicles.

Concerning the motor generation unit (MGU), the propeller selected for the present case study was a permanent magnet motor of $18000\,rpm$ operating at around $1000\,V$ –maximum voltage allowed by the FIA–. Maximising the voltage is a design strategy focused on reducing the wires' section and, as a result, their weight. Since permanent magnet motors are able to produce relatively large torques at low speed, the transmission system required in the vehicle can be simplified, reducing, at the same time its weight. Although permanent magnet motors are not light, their weight can be balanced by running at high speed with the gearbox, obtaining the optimal drive and transmission system for the present application.

Moreover, and accounting the battery type currently under use in Formula E, a Lithium-Ion battery was designed. According to the results obtained in Table 4-6, the cells that were selected for the design of the present ESS configuration were NMC2. Said decision was made on the basis of the number of cells together with the entire system weight required to reach the power and energy that the vehicle demands. Although the battery built from NMC3 had the lowest number of cells to meet the requirements, this design had to be dismissed as a consequence of its high weight. Since NMC2 was the lightest one, although having installed more than 300 cells, it was considered to be the most appropriate model to be installed in a Formula E vehicle.

Due to the large amount of problems in the homogeneous battery, as a consequence of the peak usage during the race (Kouchachvili, Yaïci and Entchev, 2018), and with the main purpose of improving the battery performance and the energy availability, a hybrid ESS was proposed as an alternative design. Said configuration had to be carefully designed to fulfil the vehicle's requirements, similar to what Frenzel, Kurzweil and Rönnebeck (2011) suggested for a Formula Student vehicle. In the same direction, Hamidi, Manla and Nasiri (2015) recommended hybrid configurations for high pulsed power applications where deep battery discharges occur.

On the basis of the NMC cells previously chosen, NMC2, additional energy storage devices were installed in order to absorb the current peaks during the battery charge and discharge process. The ultra-capacitor model was selected according to the same criteria previously used: the number of cells and their total weight. In this case, UC1 was the model with lower number of required cells and, as a consequence, lower weight. Therefore, the design of the hybrid system was made from NMC2 and UC3 cells. As it has been previously stated, the ultra-capacitors are extremely useful for the production and absorption of the peaks in power. Hence, the power and energy that each device will need to produce and store is detailed in Figure 5-1.

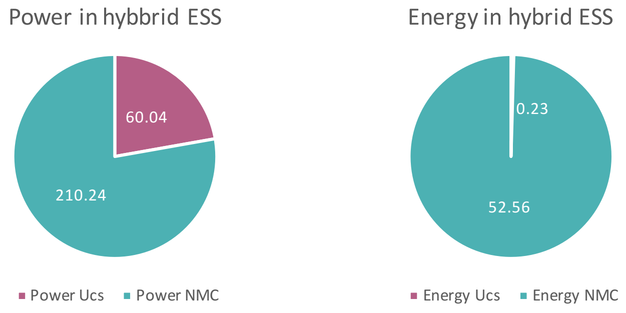


Figure 5-1. Power and energy in NMC and ultra-capacitors inside the hybrid ESS

The results obtained in the previous section, for the two energy storage systems designed, showed different vehicle performances for the same initial energy and power requirements. The main differences between the Lithium-Ion NMC pure battery and the hybrid ESS have been represented in Figure 5-2. The comparison explained hereunder is based on the homogeneous battery built from NMC2 batteries and the hybrid system elaborated with NMC2 cells and UC1 ultra-capacitors.

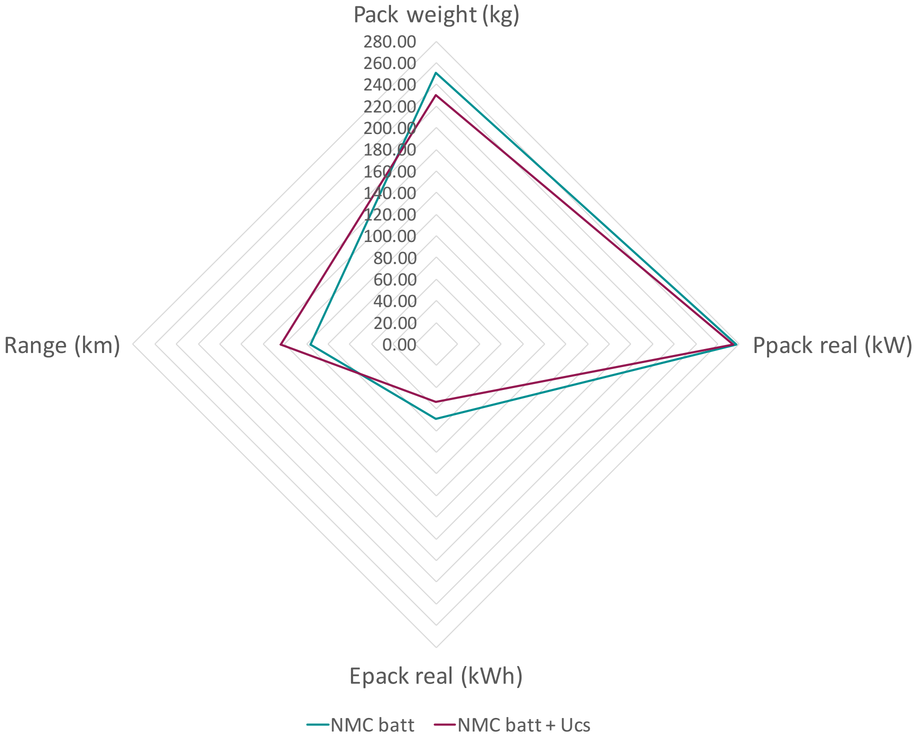


Figure 5-2. Performance comparison between NMC battery and hybrid ESS

From the previous figure, it can be noted that the hybrid energy storage system provides better results. In particular, the weight has been minimised and the range has been increased substantially, up to $140\ km$ approximately. This last fact is of extreme importance, since a Formula E battery is expected to be charged and discharged during a large number of cycles, which may affect the energy consumption. Essentially, the driving strategy is what will determine how much energy is available at the end of the race. For next season, said vehicles should be equipped with a battery that should last, at least, the entire race, which is approximately $100\ km$, when considering pit stops. Therefore, with such a great range in the hybrid design, the energy availability for one whole race would be ensured, no matter the driving strategy the driver is considering to follow.

Regarding the weight in the energy storage system, it is of great importance to minimise its value, since the mass in the batteries will directly affect the total vehicle weight and, as a consequence, increase the required tractive force and power in the motor. Vehicle dynamics play a crucial role in Formula E, since being faster than the competitors can be achieved by decreasing the resistive forces, which highly depend on the vehicle's weight. In the hybrid system, since the NMC battery's power production has been decreased, the number of required cells has also been reduced and, as a consequence, their weight is $13\ kg$ less. Although the vehicle dynamics have been calculated for the minimum weight, reducing the weight in the batteries would imply installing a heavier and more efficient propeller or cooling system, according to the vehicle's needs. In addition, Schupbach and Balda (2003) showed how ultra-capacitors can contribute to an improvement in the vehicle's acceleration by reducing the battery weight in a hybrid private vehicle. Although having different power and energy requirements, both cases strongly demonstrate how incorporating ultra-capacitors in a hybrid system can contribute to a weight reduction.

The power generation in both configurations is essentially the same, $270\ kW$ approximately. However, higher number of cells are needed in the NMC batteries to produce said amount of power and, as a result, the energy that can be stored is considerably higher than in the hybrid system. Despite of being able to store $67\ kWh$, the FIA stablishes a threshold in $54\ kWh$ –under the BMS control in order to never be exceeded–, which is approximately the energy stored in the hybrid ESS. Although storing greater amounts of power might be a positive feature in any other application, in this case, it is useless, since the cells will never be at full capacity. Therefore, energy and power are not key factors used for the selection of the type of energy storage system that best fits in the present application. Nevertheless, said parameters might be used as selection criterion for other purposes where energy is placed before power, such as, in urban private vehicles; or vice versa. As Hannan *et al.* (2017) suggested, the issues and challenges of the design are subjected to the electric vehicle application, which will demand certain power and energy requirements which should be accurately fulfilled.

Another feature that should be also considered, but does not appear on Figure 5-2 is reliability. NMC batteries are considered as moderately reliable in normal working conditions, however, Formula E requires high peaks of energy to be delivered instantaneously, discharging brusquely the ESS. Since Lithium-Ion cells are not suitable for producing said current fluctuation, they need to work under fatigue conditions, what has a negative effect on its reliability. Ultra-capacitors, nevertheless, are devices characterised by absorbing said peaks of power, without compromising its integrity. Therefore, they contribute to facilitate the operating conditions in the NMC batteries to which they are connected. Hence, the reliability in the whole system would increase and, as a consequence, the risk of a motor braking during a race is minimised. This stream of thought is supported by Kouchachvili, Yaïci and Entchev (2018), who demonstrated that ultra-capacitors prolonged Lithium-Ion operational time by reducing the detrimental effect of current fluctuation on the battery.

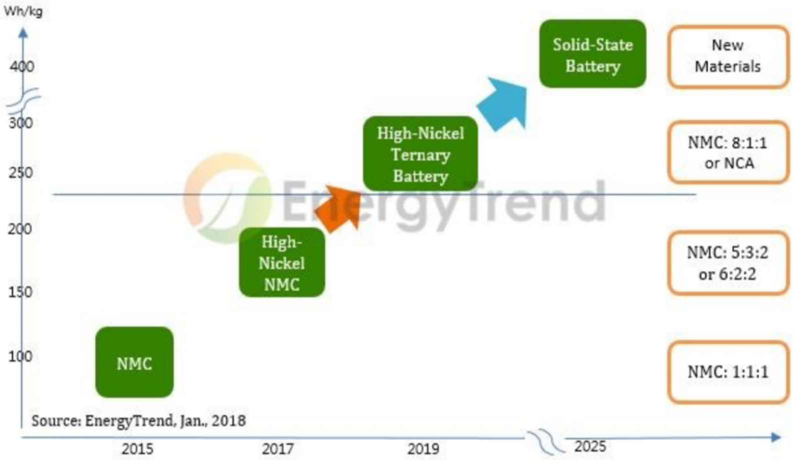
Moreover, the configuration designed for the hybrid system, presented in Figure 3-4, allows the BMS to switch on the connections between the Lithium-Ion batteries and the ultra-capacitors, in order to control the amount of power and energy supplied to the motor without having to balance the voltage in each device. Meaning that, since both ESS are coupled to a DC/DC converter, no matter the value of the voltage in each of them, since it would be transformed to the nominal voltage in the motor, helping the BMS to operate. A similar configuration was thought for the NMC exclusively battery.

5.2 Further research

In recent years, the development and improvement of Lithium-Ion batteries has caused the electrification of the transport market, including high performance vehicle sector, which exploitation is expected to increase abusively (Kellner *et al.*, 2018). Hence, it is expected that the characteristics of each type of Lithium-Ion battery will improve in the recent future.

Currently, a large number of ultra-capacitors, Lithium-Ion and Lead Acid batteries are being used in the automotive field, however, each electric vehicle manufacturer uses a different battery configuration according to their priorities.

NMC (Nickel, Manganese and Cobalt) and NCA (Nickel, Cobalt and Aluminium), are the most extended batteries, nevertheless, the high cost of cobalt is pushing Korean and Japanese manufacturers to minimise the quantity of this component, modifying their chemical composition from a rate of 6:2:2, in case of the NMC, to 8:1:1 (Wu and Li, 2018).



Source: EnergyTrend, Jan., 2018

Figure 5-3. Lithium-Ion batteries development (Wu and Li, 2018)

Future research can be done in the development of new materials to create new solid-state batteries with better performance, that can help electric vehicles to be in the top of the transport market. However, Formula E will be always subjected to FIA’s regulations, which will determine the limits of the research and development that can take place inside said competition.

6 CONCLUSIONS

From season 5, in Formula E, where teams can use exclusively one vehicle per race, which limits the total energy available during the time it lasts, the energy recovery system plays a crucial role inside said competition. Since the vehicles are pure electric, the main source for recovering energy comes from the braking process, where the electric motor is forced to run in the opposite direction, acting as a generator. Therefore, energy storage systems (ESS), are the main component inside energy recovery systems (ERS) and their design needs to be extremely accurate to maximise the available energy in every race.

The FIA stablishes different limitations regarding energy stored in the ESS and power generation in the motor. However, the design and configuration criteria are not limited and depend on the strategy each team is studying to follow. The main purpose of every team should be designing a ESS that maximises said values – energy and power–, while minimising the total weight in the vehicle, in order to be the fastest team and gain advantage against their competitors.

Currently, Formula E is employing Lithium-Ion NMC batteries, which are characterised by its considerably high energy density. However, their power density is relatively low compared to other energy storage devices, such as ultra-capacitors. Said feature, allows NMC cells to store large amounts of energy inside them. Nevertheless, in order to reach the maximum power allowed by the FIA, the number of cells installed in the battery pack, should increase and, as a consequence, the battery weight will also increase.

Ultra-capacitors, opposite to Lithium-Ion cells, have extremely high power density, whilst their energy density is practically insignificant. Therefore, when combining ultra-capacitors with NMC cells, the first ones can contribute to the generation of extra power, helping the second ones to operate in normal conditions, reducing the number of NMC cells required to optimise the energy and power available. Hybrid ESS have been considered to have greater reliability, as a consequence of the inclusion of ultra-capacitors in the NMC power generation. Hence, it has been proved that hybrid energy storage systems contribute positively to the reduction of the energy storage system’s weight. As a result, the resistive forces in the Formula E vehicle will be also reduced and the maximum speed that the single-seater will be able to reach will increase considerably.

Moreover, the driving cycle has been demonstrated to affect the energy consumption, therefore when designing the ESS it is of great importance to consider a case study where said value is maximised. The NMC batteries designed in the present study, specially in the hybrid system, ensure with absolute certainty the energy availability during an entire Formula E race.

With regard to the driving and transmission systems, weight minimisation has been considered to be the design criterion to follow. Therefore, the optimal configuration, that ensures the required power generation and an efficient torque and speed transmission, is composed of a permanent magnet motor together with a simple gearbox. The powertrain simplification affects, additionally, the transmission system’s centre of gravity height, reducing it and, as a consequence, facilitating the vehicle’s driving in the circuit.

To sum up, the energy recovery system that has been designed, with the only purpose of optimising the energy availability and improve the vehicle’s performance, meets the objectives. Moreover, it demonstrates that hybrid energy storage systems, although being more complex, are extremely useful in applications where energy and power are limited and weight plays a crucial role.

7 REFERENCES

Academy, I. (2000) ‘Comparison Common-Lithium-Technologies’, pp. 1–6.

Akres, I. (2018) ‘AUTO #22’, *International Journal of the FIA*, (22), p. 945.

Art, A. J. A. J. (2018) ‘Article 253 Equipements de Sécurité / Safety Equipment (Groupes N , A , B , SP / Groups N , A , B , SP)’, pp. 1–15. doi: 10.1002/pi.4339.

Atmaja, T. D. and Amin (2015) ‘Energy storage system using battery and ultracapacitor on mobile charging station for electric vehicle’, *Energy Procedia*. Elsevier B.V., 68, pp. 429–437. doi: 10.1016/j.egypro.2015.03.274.

Badin, F. (2013) ‘1.1.1 Balance-of-Forces Equation’, in. Editions Technip. Available at: https://app.knovel.com/hotlink/pdf/id:kt00TY1M72/hybrid-vehicles-from/balance-forces-equation.

Balkwill, J. (2018) ‘4.3.4.1 Aerodynamic Drag’, in *Performance Vehicle Dynamics - Engineering and Applications* -. Elsevier. Available at: https://app.knovel.com/hotlink/pdf/id:kt011G71N6/performance-vehicle-dynamics/aerodynamic-drag.

Bengolea, F. and Samuel, S. (2016) ‘Technology Choices for Optimizing the Performance of Racing Vehicles’. doi: 10.4271/2016-01-1173.Copyright.

Burke, A. (2007) ‘Batteries and Ultracapacitors for Electric, Hybrid, and Fuel Cell Vehicles’, *Proceedings of the IEEE*, 95(4), pp. 806–820. doi: 10.1109/JPROC.2007.892490.

Burke, A. and Zhao, H. (2015) ‘Present and Future Applications of Supercapacitors in Electric and Hybrid Vehicles’, *2015 IEEE 82nd Vehicular Technology Conference (VTC2015-Fall)*, (April), pp. 1–5. doi: 10.1109/VTCFall.2015.7391093.

Chau, K. T. (2016) ‘6.1.2 Vehicle Dynamics’, in *Energy Systems for Electric and Hybrid Vehicles*. Institution of Engineering and Technology. Available at: https://app.knovel.com/hotlink/pdf/id:kt01129S91/energy-systems-electric/vehicle-dynamics.

Dhameja, S. (2002a) '3.9.4 Transmission Inefficiencies', in *Electric Vehicle Battery Systems*. Elsevier. Available at: https://app.knovel.com/hotlink/pdf/id:kt00BJO5S5/electric-vehicle-battery/transmission-inefficiencies.

Dhameja, S. (2002b) *Electric Vehicle Battery Systems*. Elsevier. Available at: https://app.knovel.com/hotlink/toc/id:kpEVBS0001/electric-vehicle-battery/electric-vehicle-battery.

Ebbesen, S. *et al.* (2016) 'Time-optimal Control Strategies for a Hybrid Electric Race Car', 25(6), pp. 1921–1934. doi: 10.1109/TCST.2016.2642830.

Ehsani, M. *et al.* (2018) *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles*. 3rd Ed. Chapman and Hall/CRC. Available at: https://ebookcentral.proquest.com/lib/cranfield/detail.action?docID=5264494.

Erjavec, J. (2013) *Hybrid, Electric and Fuel-Cell Vehicles*. 2nd Ed. Cengage Learning, Inc. Available at: https://app.knovel.com/hotlink/pdf/id:kt00B90Q91/hybrid-electric-fuel/basic-diagnosis.

Ferg, E., Rossouw, C. and Loyson, P. (2013) 'The testing of batteries linked to supercapacitors with electrochemical impedance spectroscopy: A comparison between Li-ion and valve regulated lead acid batteries', *Journal of Power Sources*. Elsevier B.V, 226, pp. 299–305. doi: 10.1016/j.jpowsour.2012.10.087.

Frenzel, B., Kurzweil, P. and Rönnebeck, H. (2011) 'Electromobility concept for racing cars based on lithium-ion batteries and supercapacitors', *Journal of Power Sources*, 196(12), pp. 5364–5376. doi: 10.1016/j.jpowsour.2010.10.057.

Ghalkhani, M. *et al.* (2017) 'Electrochemical–Thermal Model of Pouch-type Lithium-ion Batteries', *Electrochimica Acta*. Elsevier Ltd, 247, pp. 569–587. doi: 10.1016/j.electacta.2017.06.164.

Hamidi, S. A., Manla, E. and Nasiri, A. (2015) 'Li-ion batteries and Li-ion ultracapacitors: Characteristics, modeling and grid applications', *2015 IEEE Energy Conversion Congress and Exposition, ECCE 2015*, pp. 4973–4979. doi:

10.1109/ECCE.2015.7310361.

Hannan, M. A. *et al.* (2017) ‘Review of energy storage systems for electric vehicle applications: Issues and challenges’, *Renewable and Sustainable Energy Reviews*. Elsevier, 69(September 2015), pp. 771–789. doi: 10.1016/j.rser.2016.11.171.

Holland, C. E. *et al.* (2002) ‘Experimental characterization of hybrid power systems under pulse current loads’, *Journal of Power Sources*, 109(1), pp. 32–37. doi: 10.1016/S0378-7753(02)00044-7.

Hughes, A. and Drury, B. (2013) *Electric Motors and Drives - Fundamentals, Types and Applications*. 4th Ed. Elsevier.

Kellner, Q. *et al.* (2018) ‘Duty-cycle characterisation of large-format automotive lithium ion pouch cells for high performance vehicle applications’, *Journal of Energy Storage*. Elsevier, 19(July), pp. 170–184. doi: 10.1016/j.est.2018.07.018.

Kermani, G. and Sahraei, E. (2017) ‘Review: Characterization and modeling of the mechanical properties of lithium-ion batteries’, *Energies*, 10(11). doi: 10.3390/en10111730.

Khaligh, A. and Li, Z. (2010) ‘Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art’, *IEEE Transactions on Vehicular Technology*, 59(6), pp. 2806–2814. doi: 10.1109/TVT.2010.2047877.

Kouchachvili, L., Yaïci, W. and Entchev, E. (2018) ‘Hybrid battery/supercapacitor energy storage system for the electric vehicles’, *Journal of Power Sources*. Elsevier, 374(June 2017), pp. 237–248. doi: 10.1016/j.jpowsour.2017.11.040.

Lin, Z. *et al.* (2016) ‘A Study of Energy Recovery System during Braking for Electric Vehicle’, (Icaset), pp. 8–13.

Luo, X. *et al.* (2015) ‘Overview of current development in electrical energy storage technologies and the application potential in power system operation’, *Applied Energy*. Elsevier Ltd, 137, pp. 511–536. doi: 10.1016/j.apenergy.2014.09.081.

Maiser, E. (2014) ‘Battery packaging - Technology review’, 204, pp. 204–218. doi: 10.1063/1.4878489.

Mathews, T. (2013) ‘Flywheel Based Kinetic Energy Recovery Systems (KERS) Integrated In Vehicles’, *International Journal of Engineering Science and Technology*, 5(09), pp. 975–5462. Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.392.7247&rep=rep1&type=pdf.

Miller, J. M. (2010) ‘1.5.1 Components of Road Load’, in *Propulsion Systems for Hybrid Vehicles*. 2nd Ed. Institution of Engineering and Technology. Available at: https://app.knovel.com/hotlink/pdf/id:kt0098ODX6/propulsion-systems-hybrid/components-road-load.

Niewiadomski, W., Gonçalves, A. and Almeida, P. (2018) ‘Li-NMC Batteries Model Evaluation with Experimental Data for Electric Vehicle Application’, pp. 1–16. doi: 10.3390/batteries4010011.

Rosario, L. (2007) ‘Power and energy management of multiple energy storage systems in electric vehicles’, *Department of Aerospace Power & Sensors, Cranfield University, DCMT Shrivenham*, (June), p. 96.

Schupbach, R. M. and Balda, J. C. (2003) ‘The role of ultracapacitors in an energy storage unit for vehicle power management’, *2003 IEEE 58th Vehicular Technology Conference. VTC 2003-Fall (IEEE Cat. No.03CH37484)*, p. 3236–3240 Vol.5. doi: 10.1109/VETECF.2003.1286246.

Svens, P. *et al.* (2013) ‘Li-ion pouch cells for vehicle applications-studies of water transmission and packing materials’, *Energies*, 6(1), pp. 400–410. doi: 10.3390/en6010400.

Taranovich, S. (2017) ‘Formula E : The electric vehicle moves to the’.

Technical Department, F. S. (2017) ‘FIA Formula E Championship Technical Regulations Règlement Technique du Championnat de Formule E de la FIA’, pp. 1–56.

Thomas, T. and Youson, M. (2014) ‘Auto #7’, *Internationa Journal of the FIA*, (7).

Tie, S. F. and Tan, C. W. (2013) ‘A review of energy sources and energy management system in electric vehicles’, *Renewable and Sustainable Energy Reviews*. Elsevier, 20, pp. 82–102. doi: 10.1016/j.rser.2012.11.077.

Trovão, J., Pereirinha, P. and Jorge, H. (2009) ‘Design Methodology of Energy Storage Systems for a Small Electric Vehicle’, *World Electric Vehicle Journal*, 3, pp. 1–12. Available at: http://www.evs24.org/wevajournal/php/download.php?f=vol3/WEVJ3-5010505.pdf%5Cnhttp://www.evs24.org/wevajournal/vol3/title.html.

Warner, J. (2015) *Handbook of Lithium-Ion Battery Pack Design - Chemistry, Components, Types and Terminology.* Elsevier. Available at: https://app.knovel.com/hotlink/toc/id:kpHLIBPDC3/handbook-lithium-ion/handbook-lithium-ion.

Wu, J. and Li, G. (2018) ‘Development of NMC Battery May Ease the Tight Supply of Cobalt in 2018 , Says EnergyTrend’, 17, pp. 17–19.

Young, K. *et al.* (2013) *Electric Vehicle Integration into Modern Power Networks*. doi: 10.1007/978-1-4614-0134-6.

APPENDICES

Appendix A Case studies

In the present appendix, two alternative case studies are described, in order to demonstrate that the results obtained in section 4 are not accidental and, moreover, they can be used to demonstrate the final conclusions. Each case study is calculated using the same Formula E vehicle running in different circuits –different driving cycles–. Therefore, the importance of the driving strategy is also a matter of interest in the present appendix.

A.1 Case study 2

Considering a straight line in a circuit with a length of 300 m, approximately, the driving cycle designed in the present case is represented in Figure A-1.

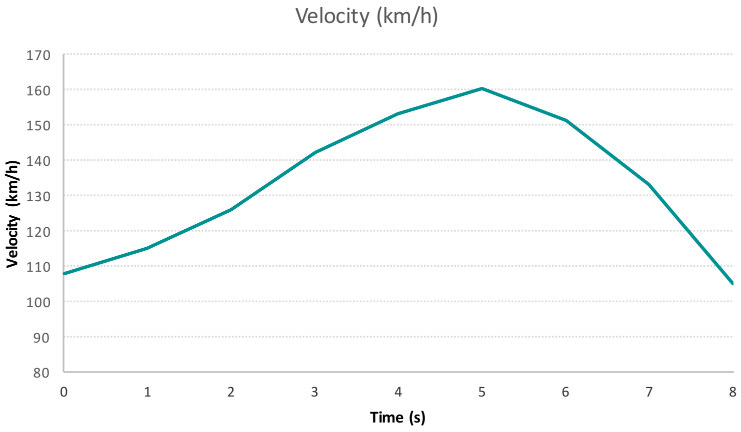


Figure A-1 Driving cycle for case study 2

Although the vehicle is the same as in case study 1, the tractive force, power and torque differ from the results obtained in said conditions, due to the modification in the driving cycle. In this case, the vehicle is not pushed to its limits, therefore, the maximum speed in the present circuit is 160 km/h, considerably lower than in the main case study. Table A-1 contains the vehicle's power requirements for case study 2, while Table A-2 contains the resistive forces in the vehicle. It should be noted that all the results were obtained following the same methodology used in case study 1.

Table A-1 Vehicle's power requirements for case study 2

Time (s)	Velocity (km/h)	Acceleration (m/s^2)	Tractive Force (N)	Tractive Power (kW)	Axel Torque (Nm)	Axel speed (RPM)
0	108.0	2.000	2644.4	79.3	927.1	817.1
1	115.2	3.000	3624.2	116.0	1270.6	871.6
2	126.0	4.500	5103.6	178.6	1789.3	953.3
3	142.2	3.000	3969.5	156.8	1391.7	1075.9
4	153.0	2.000	3227.9	137.2	1131.7	1157.6
5	160.2	-2.500	-710.1	-31.6	-249.0	1212.0
6	151.2	-5.000	-3099.3	-130.2	-1086.6	1144.0
7	133.2	-7.800	-5873.7	-217.3	-2059.3	1007.8
8	105.1	-8.500	-6836.1	-199.6	-2396.7	795.3

Table A-2 Vehicle's dynamics in case study 2

Linear acceleration Force (N)	Gravitational Force (N)	Rolling resistance Force (N)	Aerodyn. drag Force (N)
1800.0	0.0	264.9	579.5
2700.0	0.0	264.9	659.3
4050.0	0.0	264.9	788.7
2700.0	0.0	264.9	1004.6
1800.0	0.0	264.9	1163.0
-2250.0	0.0	264.9	1275.0
-4500.0	0.0	264.9	1135.8
-7020.0	0.0	264.9	881.5
-7650.0	0.0	264.9	549.0

The power and torque required in the motor are detailed in Table A-3.

Table A-3 Motor requirements in case study 2

Motor Torque (Nm)	Motor Speed (rpm)	Motor Power (kW)
62.4	12135	79.3
85.6	12944	116.0
120.5	14157	178.6
93.7	15978	156.8
76.2	17191	137.2
-16.8	18000	-31.6
-73.2	16989	-130.2
-138.7	14966	-217.3
-161.4	11811	-199.6

The power that the ESS needs to generate in order to feed the motor is detailed in Table A-4.

Table A-4 Required power generation in the battery for case study 2

Motor Power (kW)	Inverter Power (kW)	Battery Power (kW)
79.3	83.5	85.2
116.0	122.1	124.6
178.6	188.0	191.9
156.8	165.0	168.4
137.2	144.4	147.4
-31.6	-30.0	-29.4
-130.2	-123.7	-121.2
-217.3	-206.5	-202.3
-199.6	-189.6	-185.8

In the present case study, the theoretical values are not shown in the report, in order to summarise the results. Therefore, the values in both ESS designs – homogeneous and hybrid– are the real values. The characteristic values for the homogeneous ESS are contained in Table A-5.

Table A-5 Characteristic values for NMC battery design in case study 2

Parameter	NMC1	NMC2	NMC3
Serial cells	160.00	73.00	126.00
Parallel Cells	3.00	4.00	1.00
Capacity (Ah)	111.00	240.00	95.60
Energy Stored (KWh)	63.94	63.95	44.33
Power (kW)	191.81	191.84	191.50
Discharge Cut-Off Voltage (V)	440.00	200.75	468.72
Charge Cut-Off Voltage (V)	672.00	306.60	522.90
Nominal Voltage (V)	576.00	226.45	463.68
Weight (kg)	398.48	239.39	259.56
Volume (m3)	0.20	0.12	0.05
Energy density (Wh/kg)	315.63	532.07	854.73
Specific power density (W/kg)	481.35	801.37	737.79
Energy consumption (kWh/km)	0.5	0.37	0.5
Range (km)	108.85	145.11	108.76

On the other hand, the values for the NMC battery inside the hybrid system in case study 2 are detailed in Table A-6.

Table A-6 Characteristic values for NMC batteries inside the hybrid ESS for case study 2

Parameter	NMC1	NMC2	NMC3
Serial cells	134.00	61.00	106.00
Parallel Cells	3.00	4.00	2.00
Capacity (Ah)	111.00	240.00	191.2
Energy Stored (KWh)	53.55	53.44	74.58
Power (kW)	160.64	160.31	161.10
Discharge Cut-Off Voltage (V)	368.50	167.75	394.32
Charge Cut-Off Voltage (V)	562.80	256.20	439.90
Nominal Voltage (V)	482.40	222.65	390.08
Weight (kg)	333.72	200.04	436.72
Volume (m3)	0.17	0.10	0.09
Energy density (Wh/kg)	315.63	532.07	854.73
Specific power density (W/kg)	481.35	801.37	368.89
Energy consumption (kWh/km)	0.42	0.31	0.42
Range (km)	128.88	171.84	178.56

Moreover, the real values for the ultra-capacitor are represented inTable A-7.

Table A-7 Real values in ultra-capacitors inside the hybrid ESS for case study 2

Parameter	**UC1**	**UC2**	**UC3**
Serial cells	40.00	56.00	78.00
Parallel Cells	5.00	6.00	6.00
Nominal Voltage (V)	108.00	151.20	210.60
Power (kW)	31.60	31.92	31.98
Capacity (kWh)	0.12	0.14	0.14
Weight (kg)	21.60	24.19	29.02

Finally, the real power and energy that defines the entire hybrid energy storage system is defined in Table A-8.

Table A-8 Real power and energy in the hybrid ESS in case study 2

Hybrid system		
Parameter	Units	Value
Weight	Kg	221.64
Power	kW	191.91
Energy	kWh	53.56
Specific power	W/kg	865.85
Energy density	Wh/kg	241.64
Range	Km	171.84

Equal to section 5 for case study 1, both ESS designs are compared in Figure A-2, in order to illustrate the possible advantages of a hybrid battery system.

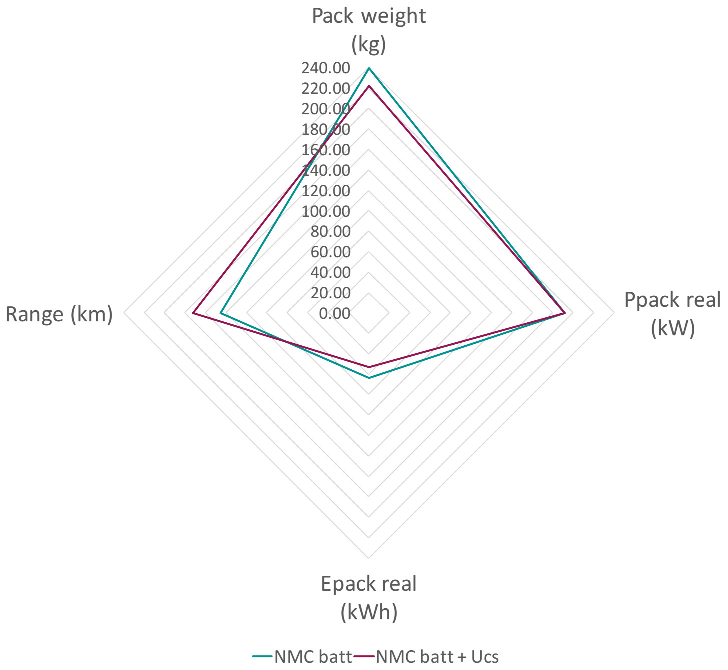


Figure A-2 Comparison of the results in case study 2

A.2 Case study 3

Considering a straight line in a circuit with a length of 330 m, approximately, and an initial velocity of $72\ km/h$ the driving cycle designed in the present case is represented in Figure A-3.

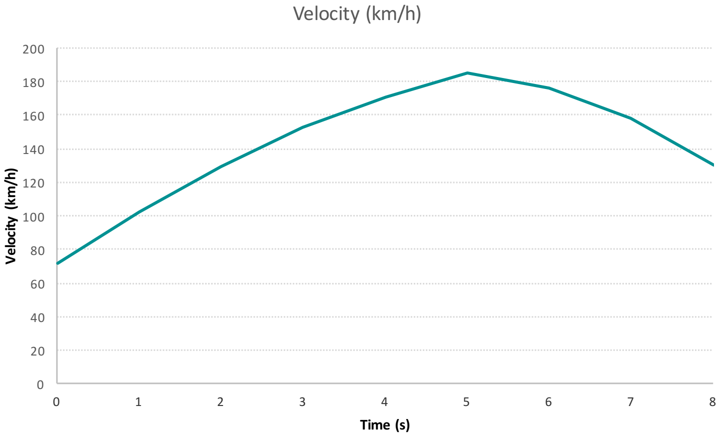


Figure A-3 Driving cycle for case study 3

Although the vehicle is the same as in case study 1, the tractive force, power and torque differ from the results obtained in said conditions, due to the modification in the driving cycle. Table A-9 contains the vehicle's power requirements for case study 3, while Table A-10 contains the resistive forces in the vehicle. It should be noted that all the results were obtained following the same methodology used in case study 1.

Table A-9 Vehicle's power requirements for case study 3

Time (s)	Velocity (km/h)	Acceleration (m/s^2)	Tractive Force (N)	Tractive Power (kW)	Axel Torque (Nm)	Axel speed (rpm)
0	72.0	8.500	8172.4	163.4	2865.3	544.7
1	102.6	7.500	7537.9	214.8	2642.8	776.3
2	129.6	6.500	6949.3	250.2	2436.4	980.5
3	153.0	5.000	5927.9	251.9	2078.3	1157.6
4	171.0	4.000	5317.6	252.6	1864.4	1293.8
5	185.4	-2.500	-277.4	-14.3	-97.3	1402.7
6	176.4	-5.000	-2689.2	-131.8	-942.8	1334.6
7	158.4	-7.800	-5508.6	-242.4	-1931.3	1198.4
8	130.3	-8.500	-6541.4	-236.8	-2293.4	986.0

Table A-10 Vehicle's dynamics in case study 3

Linear acceleration Force (N)	Gravitational Force (N)	Rolling resistance Force (N)	Aerodyn. drag Force (N)
7650.0	0.0	264.9	257.6
6750.0	0.0	264.9	523.0
5850.0	0.0	264.9	834.5
4500.0	0.0	264.9	1163.0
3600.0	0.0	264.9	1452.7
-2250.0	0.0	264.9	1707.7
-4500.0	0.0	264.9	1545.9
-7020.0	0.0	264.9	1246.5
-7650.0	0.0	264.9	843.8

The power and torque required in the motor are detailed in Table A-11.

Table A-11 Motor requirements in case study 3

Motor Torque (Nm)	Motor Speed (rpm)	Motor Power (kW)
223.3	6990	163.4
205.9	9961	214.8
189.9	12583	250.2
162.0	14854	251.9
145.3	16602	252.6
-7.6	18000	-14.3
-73.5	17126	-131.8
-150.5	15379	-242.4
-178.7	12652	-236.8

The power that the ESS needs to generate in order to feed the motor is detailed in Table A-12.

Table A-12 Required power generation in the battery for study 3

Motor Power (kW)	Inverter power (kW)	Battery power (kW)
163.4	172.1	175.6
214.8	226.1	230.8
250.2	263.3	268.7
251.9	265.2	270.6
252.6	265.9	271.3
-14.3	-13.6	-13.3
-131.8	-125.2	-122.7
-242.4	-230.3	-225.7
-236.8	-225.0	-220.5

In the present case study –equal to case study 2–, the theoretical values are not shown in the report, in order to summarise the results. Therefore, the values in both ESS designs –homogeneous and hybrid– are the real values. The characteristic values for the homogeneous ESS are contained in Table A-13.

Table A-13 Characteristic values for NMC battery design in case study 3

Parameter	NMC1	NMC2	NMC3
Serial cells	226.00	103.00	178.00
Parallel Cells	2.00	3.00	1.00
Capacity (Ah)	74.00	180.00	95.60
Energy stored (KWh)	60.21	67.67	62.62
Power (kW)	270.93	270.68	270.53
Discharge Cut-Off Voltage (V)	621.50	283.25	662.16
Charge Cut-Off Voltage (V)	949.20	432.60	738.70
Nominal Voltage (V)	813.60	375.95	655.04
Weight (kg)	375.23	253.33	366.68
Volume (m3)	0.19	0.13	0.07
Energy density (Wh/kg)	160.45	267.12	170.78
Specific power density (W/kg)	722.03	1068.50	737.79
Energy consumption (kWh/km)	0.70	0.53	0.70
Range (km)	76.95	102.69	76.88

On the other hand, the values for the NMC battery inside the hybrid system in case study 2 are detailed in Table A-14.

Table A-14 Characteristic values for the NMC batteries inside the hybrid ESS for case study 3

Parameter	NMC1	NMC2	NMC3
Serial cells	200.00	80.00	150.00
Parallel Cells	2.00	3.00	1.00
Capacity (Ah)	74.00	180.00	95.60
Energy Stored (KWh)	53.28	52.56	52.77
Power (kW)	239.76	210.24	227.98
Discharge Cut-Off Voltage (V)	550.00	220.00	558.00
Charge Cut-Off Voltage (V)	840.00	336.00	622.50
Nominal Voltage (V)	720.00	292.00	552.00
Weight (kg)	332.06	196.76	309.00
Volume (m3)	0.17	0.10	0.06
Energy density (Wh/kg)	160.45	267.12	170.78
Specific power density (W/kg)	722.03	1068.50	737.79
Energy consumption (kWh/km)	0.62	0.41	0.59
Range (km)	85.79	128.69	89.15

Moreover, the real values for the ultra-capacitor are represented in Table A-15.

Table A-15 Real values in ultra-capacitors inside the hybrid ESS for case study 3

Parameter	UC1	UC2	UC3
Serial cells	76.00	105.00	145.00
Parallel Cells	5.00	6.00	6.00
Nominal Voltage (V)	205.20	283.50	391.50
Power (kW)	60.04	59.85	59.45
Capacity (kWh)	0.23	0.26	0.26
Weight (kg)	41.04	45.36	53.94

Finally, the real power and energy that defines the entire hybrid energy storage system is shown in Table A-16.

Table A-16 Real power and energy in the hybrid ESS in case study 3

Hybrid system		
Parameter	Units	Value
Weight	Kg	237.80
Power	kW	270.28
Energy	kWh	52.79
Specific power	W/kg	1136.58
Energy density	Wh/kg	222.00
Range	Km	144.05

In the same way as in case studies 1 and 2, both designs are compared in Figure A-4, in order to illustrate the possible advantages of a hybrid energy storage system.

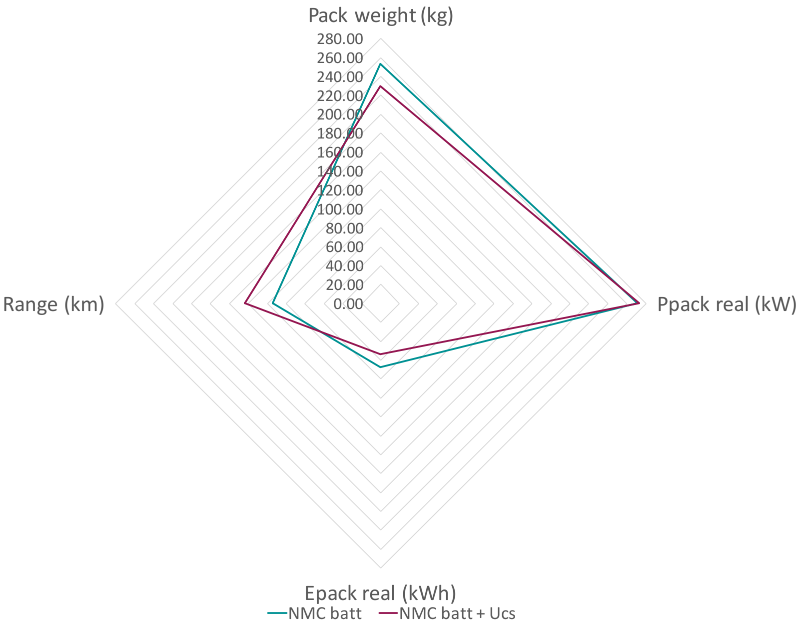


Figure A-4 Comparison of the results in case study 3