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Hybrid Powertrain and control

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1. Abstract

In the previous coursework the WLTP drive cycle of Tesla Model 3 was studied using a dyno run data in multiple acceleration and velocity phases. These 4 phases are low, middle, high and extra high respectively. The methodology is to replace at least 50% of the Tesla Model 3's battery capacity with a fuel cell while attempting to achieve a similar WLTP range as the original vehicle concerned to meet the regulations of zero emissions by 2035. The steps that have used to accomplish this task are done by replacing the 50% energy storage by hydrogen fuel cell followed by the introduction of kinetic energy regenerative braking. The mass of the vehicle was then re-evaluated and new drive cycle of hybrid powertrain is studied with regards to energy consumption and conservation in this assessment.

2. Introduction

Hydrogen Fuel cells and batteries are both electrochemical devices that convert chemical energy into electrical energy. While batteries store energy chemically and release it through a reaction when required, Hydrogen fuel cells continuously convert chemical energy from hydrogen fuel source into electrical energy. There are several advantages for fuel cells over batteries. Fuel cells have a much higher energy density than batteries. This means they can provide more energy for the same weight or volume. For example, a hydrogen fuel cell has an energy density of 33.3 kWh/kg, while a lithium-ion battery has an energy density of 0.3-0.4 kWh/kg (National Renewable Energy Laboratory, 2021). Fuel cells can provide power for longer periods than batteries. This is because they can continuously convert fuel into electricity if there is a supply of fuel. In contrast, batteries will eventually run out of charge and need to be recharged. (U.S. Department of Energy, 2021).

Fuel cells have several advantages over batteries, including versatility of wide range of fuel, lower maintenance, higher energy density, longer run time, and lower environmental impact. However, batteries also have some advantages, such as lower upfront costs and faster charging times, which make them more suitable for certain applications. In this assessment, the drive cycle analysis of a Tesla Model 3 is done on a hybrid unit of hydrogen fuel cell and battery.

Meanwhile from a drive cycle perspective, it is essential to comment on what is unrealistic about the WLTP compared to real-world driving. the WLTP test is a laboratory-based test that does not account for factors such as driving style, weather conditions, and varying terrain conditions, which can significantly impact a vehicle's performance on energy storage systems. Moreover, the WLTP test does not consider the energy consumption of auxiliary systems such as air conditioning, which can also impact the vehicle's range.

The Tesla Model 3 is a highly efficient and high-performing electric vehicle that has garnered widespread popularity. However, there is growing interest in upgrading its capabilities by replacing at least 50% of its energy storage with fuel cell technology. This technical report aims to evaluate and reassess the initial drive cycle of the Tesla Model 3, highlighting any underlying assumptions and presenting approaches for improving it. Moreover, the report will provide an overview of the complete conversion of the powertrain or detailed sub-systems, focusing on listing the necessary major components sourced or design criteria specified. The report will also explore various methods such as mathematical modelling, industry research and the sub-systems.

3. Literature Review

3.1 Different hybrid fuel cell solutions

A hybrid fuel cell system is a power generation system that incorporates a fuel cell with other power sources such as batteries or combustion engines, providing benefits such as greater efficiency, an extended driving range, and increased power output (Yan, 2016). The configuration of the system can be tailored to suit the specific requirements and intended performance of the application.

- **1) Plug-in hybrid fuel cell electric vehicles (PHEFCVs):** PHEFCVs utilize both a rechargeable battery and a fuel cell and can be charged from an external power source. The benefit of this type of vehicle is an extended driving range, as they can operate on both battery power and fuel cell power. (Banerjee, 2018)
- **2) Hybrid fuel cell-battery electric vehicles (FCBEVs):** In these vehicles, an electric motor is powered by both a battery and a fuel cell. The battery supplies extra energy for acceleration and the regenerative braking process, while the fuel cell delivers continuous power for extended trips. (Yan, 2016)
- **3) Hybrid fuel cell-combustion engine vehicles:** This type of vehicle utilizes a fuel cell to produce electricity for an electric motor. A combustion engine is also employed to provide supplementary power for acceleration or to recharge the battery. This method is known as a range-extender hybrid. (Yang, 2020)
- **4) Fuel cell-hydrogen internal combustion engine (HICE) hybrid:** In this setup, an electric motor is powered by an electricity-generating fuel cell. An internal combustion engine that uses hydrogen provides supplemental power for acceleration or to charge the battery. (Yan, 2016)

3.2 WLTP cycle and its limitations compared to real world driving

The standardized testing procedure known as the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) gauges the fuel consumption, CO₂ emissions, and pollutant emissions of passenger cars and light commercial vehicles. However, despite its broad usage, there exist various restrictions with respect to the WLTP cycle.

Certain limitations of a WLTP cycle compared to real world driving conditions are as follows (Vojtišek, 2019) (International Council on Clean Transportation, 2018) (European Automobile Manufacturers Association, 2023)

- **1) Test Conditions or Lack of real-world driving conditions:** Critics of the WLTP cycle have argued that it does not accurately replicate real-world driving conditions due to the fact that the test is conducted in a controlled laboratory setting. This can lead to differences between the reported fuel economy and CO₂ emissions and the actual performance of the vehicle on the road.
- **2) Test Duration and Variation in testing procedures:** The WLTP test cycle is lengthier than the previous New European Driving Cycle (NEDC) test, resulting in a more time-consuming and expensive testing process.
- **3) Limited range of driving scenarios:** The WLTP cycle is intended to emulate a variety of driving conditions, however, it may not encompass all conceivable circumstances. For instance, the assessment excludes conditions of extreme weather or driving at high altitude, which may impact a vehicle's overall performance.

- **4) Influence of vehicle options:** The outcomes of the WLTP test could be impacted by the car's configurations, including the presence of air conditioning or the type of tires. Consequently, comparing the results of different vehicles with distinct options may present difficulties.

3.3 Hydrogen Fuel Cell

hydrogen fuel cell is an electrochemical device that uses hydrogen and oxygen to generate electricity, heat, and water. This occurs through the catalytic oxidation of hydrogen gas at the anode, which creates protons and electrons. While the protons pass through the electrolyte membrane, the electrons travel through an external circuit, resulting in electricity production. Finally, the electrons and protons recombine with oxygen at the cathode, forming water. (Larminie, 2017)

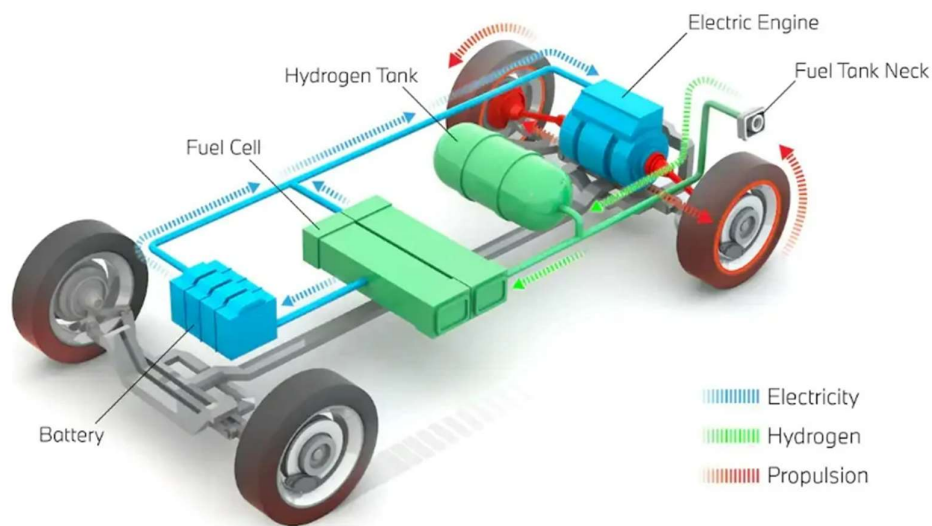


Figure 1 : Flowchart of Energy flow in a Hybrid fuel cell and battery system (PCMag, 2022)

Fuel cells have numerous advantages over traditional combustion engines, including lower emissions, higher efficiency, and quieter operation. They are also able to provide power continuously as long as fuel is supplied, making them suitable for a wide range of applications, including transportation and stationary power systems. (Kim, 2016)

Reducing costs and increasing durability are the primary engineering challenges associated with fuel cell technology development. Researchers are working on identifying new materials for catalysts and membranes, as well as developing more advanced manufacturing techniques to address these challenges. (Gottesfeld, 2019)

There are several advantages of a hydrogen fuel cell hybrid system (Deng, (2017))

- A hydrogen fuel cell hybrid system offers several benefits, which include high efficiency, zero emissions, quiet operation, and flexible design. The high efficiency of up to 60% is achieved through the electrochemical process used to convert hydrogen into electricity, which is more efficient than the combustion process of conventional engines.
- The only by-products of hydrogen fuel cells are water and heat, which makes them an environmentally friendly energy source that helps reduce greenhouse gas emissions and improve air quality.

- The silent operation of fuel cell hybrid systems makes them ideal for use in applications where noise pollution is a concern, such as residential areas and indoor environments.
- Fuel cell hybrid systems can be designed to fit a wide range of applications, from small portable devices to large stationary power plants, and can be integrated with other energy storage and conversion systems like batteries or solar panels.

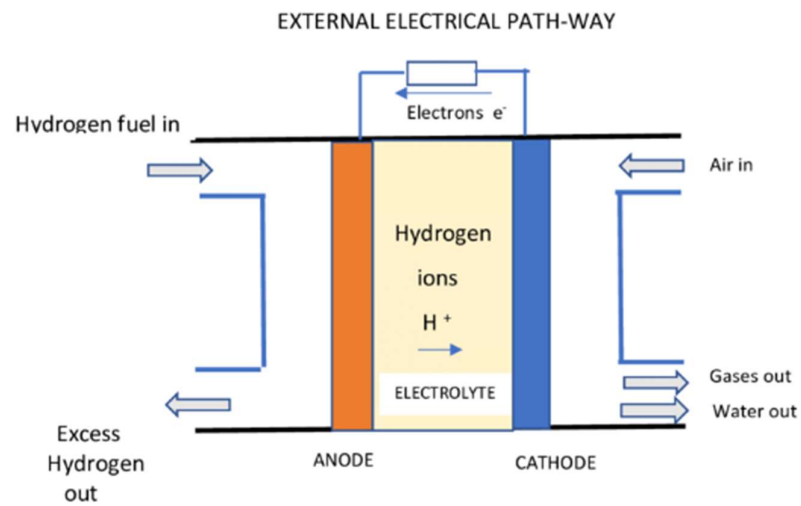


Figure 2: Working principal of a Hydrogen Fuel Cell (Murray Smith, 2019)

4. Methodology

4.1 Tesla Model 3 (100% EV)

To assess the battery performance of a Tesla Model 3 on a WLTP cycle, the forces that affect the vehicle's movement are initially determined using provided data. This data includes four distinct operating conditions that boost vehicle performance during a dyno run, categorized as low, middle, high, and extra high based on increased vehicle speed.

Calculating the forces that act on a test mass vehicle is crucial in determining the resistive forces, which include aerodynamic forces, rolling resistance, and acceleration resistance. The gradient resistance is a strong opposing force that affects a vehicle's movement, and it has a significant impact on battery energy storage performance. However, the gradient resistance is assumed to be zero for the WLTP cycle, as it cannot be technically considered during the dyno run.

The formulas for calculating the resistive forces are provided in the table below.

Resistive Forces		Unit
1. Aerodynamic Forces	$0.5 \times \text{Density of air} \times \text{Drag coefficient} \times \text{Frontal Area} \times \text{Velocity}^2$	Newton
2. Rolling Resistance	$\text{Mass} \times \text{Coefficient of road surface} \times \text{Gravity}$	Newton
3. Acceleration Resistance	$\text{Force} \times \text{acceleration}$	Newton
4. Total Tractive Effort	$\text{Aerodynamic Force} + \text{Rolling Resistance} + \text{Acceleration Resistance}$	Newton
5. Power Required	$\text{Total Tractive Effort} / 1000$	kW

Table 1: Calculation of forces and power required

Traction energy is the energy available at wheels and is classified into two types. The energy required to accelerate the vehicle and the energy regenerated when the vehicle is slowing down. The regenerated energy is the energy stored to the battery due the negative power available in the cycle. The regenerative energy is directly proportional to mass and velocity of the vehicle in the WLTP cycle.

4.2 Tesla Model 3 hybrid (50% EV + 50 % Fuel Cell)

Hydrogen Fuel Cell Stack	Power Output = 128 kW	Weight = 52 Kg
	For Power Output 37.5 kW (50 % output of Tesla Model 3)	Weight = 15.23 Kg
Tesla Model 3 Li-Ion	Number of Cells = 8000 (Power Output = 75 kWh)	
	Weight of one cell = 100 grams	
	Number of Cells = 4000 (Power Output = 37.5 kWh)	
	Total Weight = 400 Kg	
New Hybrid Test Mass =	Total weight of Tesla model 3 - 50 % weight of cell stack + 50 % weight of Fuel cell	New Test Mass= 1595.23 Kg

Table 2: Test mass calculation of hybrid powertrain (50% Fuel cell + 50% Battery)

Table 2 provides the assumptions used to compute the new test mass of the Tesla Model 3. During part 2 of the drive cycle, 50% of the powertrain is replaced with a hydrogen fuel cell system, while the remaining 50% provides a maximum power of 37.5 kW from the battery pack.

To determine the new test mass, the 50% reduction in the battery pack (4000 cells) is scaled and combined with a scaled hydrogen fuel cell system from the Toyota Mirai to achieve an overall performance output of 37.5 kW, which is comparable to the Tesla Model 3. Switching from a lithium-

ion battery pack to a hydrogen fuel cell system result in an approximate weight reduction of 385 kilograms.

4.3 Subsystem of the Hybrid Powertrain

The subsystem of the new fuel cell powered hybrid powertrain consists of the following parts to work together to provide efficient and effective power delivery.

- **Hydrogen fuel Cell:** The hydrogen fuel cell is a component of the powertrain that operates by converting hydrogen and oxygen into electrical energy within its fuel cell stack. The electricity produced is then used to drive the electric motor. Unlike traditional combustion engines, the fuel cell stack only produces water vapor as a by-product, which is emitted from the tailpipe.
- **Electric Motor:** In a hybrid powertrain, the main source of power is an electric motor that receives its energy from a battery and generates torque for the drivetrain. Additionally, the electric motor doubles as a generator during regenerative braking, whereby the energy produced by the vehicle's motion is transformed into electrical energy that can be accumulated in the battery.
- **Lithium Ion Battery**
- **Power electronics:** The power electronics are responsible for controlling the transfer of electrical energy between the battery, electric motor, and generator. Additionally, they regulate the process of charging the battery during regenerative braking.
- **Regenerative Braking:** The process of regenerative braking entails harnessing the kinetic energy generated during vehicle braking, which is then converted into electrical energy and subsequently stored in the battery.
- **Control system / Battery Management System:** The hybrid powertrain's control system oversees the functioning of all subsystems, which encompass the engine, electric motor, battery, transmission, and power electronics. Additionally, it supervises the performance of the vehicle and modifies power delivery to enhance both efficiency and performance.

5. Results

5.1 Tesla Model 3 (100% EV)

Based on the information presented in Figure 3, the Tesla Model 3 100% EV experiences various forces that affect its performance. The data indicates that the highest aerodynamic resistance is observed during phase 4 (extra high) when the vehicle is delivering maximum performance in the drive cycle. Specifically, the highest recorded aerodynamic resistive force is 436 N during this phase.

In addition to aerodynamic resistance, the rolling resistance of the 100% EV powertrain remains constant at 427 N throughout the entire drive cycle. A total tractive effort of 3545 N is the highest recorded net sum of resistive forces acting on the 100% EV vehicle.

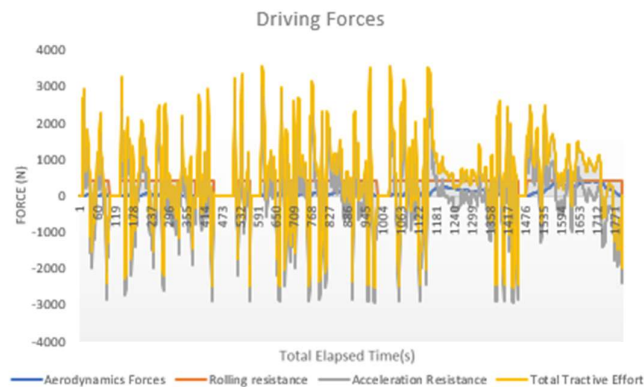


Figure 3: Driving forces acting on the Tesla Model 3

Figure 4 discusses about the power available at wheels throughout the drive cycle. Power goes negative while decelerating and can be used for the regenerative energy storage in the drive cycle. A maximum power of 40.94 kW is requested by the vehicle at a total elapsed time of 1724 seconds.

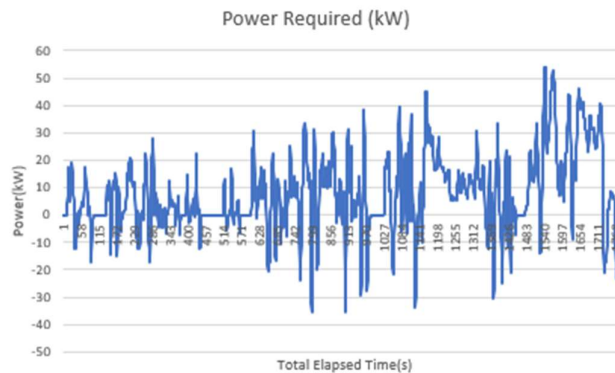


Figure 4: Power Required for Tesla Model 3 in WLTP cycle

Figure 5 discusses the battery state of charge of lithium-ion cell system of a tesla100%EV. The battery state of charge (SOC) is a way of quantifying the quantity of electrical energy that a battery can store compared to its total capacity. SOC is typically represented as a percentage and shows the available capacity of the battery. (Battery University., 2022).

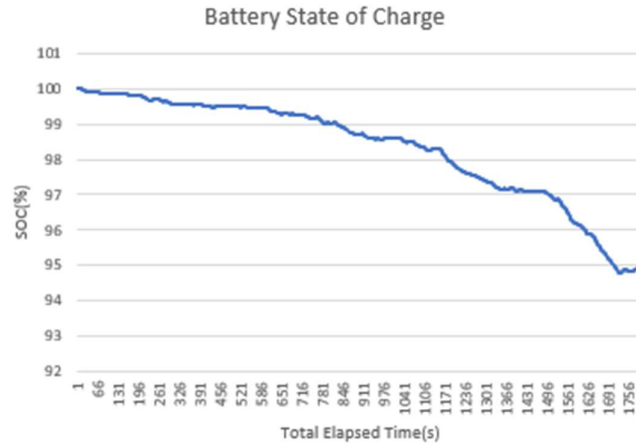


Figure 5: Battery State of charge for Tesla Model 3

Figures 5 and 6 illustrate the energy flow within the battery during the WLTP cycle, which comprises four performance phases and lasts 1800 seconds in total. At the end of the cycle, after accounting for both energy depletion and conservation, the State of Charge is recorded as 94.93%. The discharge rate was found to be the highest in phases 3 and 4. Based on these findings, it can be inferred that the battery would be fully discharged after approximately 20 cycles of the same drive cycle, with a total elapsed time of 10 hours (36000 S)

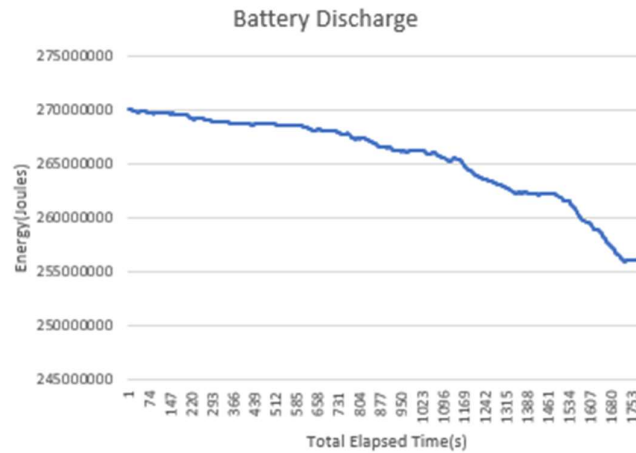


Figure 6: Energy flow in battery of given Tesla Model 3 100% EV

5.2 Tesla Model 3 (50% EV + 50 % Fuel Cell)

Based on the data presented in Figure 5, it can be concluded that there are certain resistive forces acting against the Tesla Model 3 100% EV. The highest aerodynamic resistance is recorded during phase 4 (extra high), which is the phase where the vehicle delivers the highest performance in the drive cycle. Specifically, the highest aerodynamic resistive force of 416 N for the 100% EV is recorded during phase 4 at a total elapsed time of 1724 seconds in the WLTP cycle. This value remains the same for the new test mass since aerodynamic forces are directly proportional to the frontal area of the vehicle.

Additionally, it is noted that the rolling resistance of the drive cycle has changed to 344 N, approximately 19.8 % decrease as the rolling resistance is directly proportional to vehicle test mass. This significant change in rolling resistance will have a significant impact on the net tractive effort and power required to accelerate the vehicle. A total tractive effort of 2857 N is the highest recorded net sum of resistive forces acting on the hybrid vehicle, 19.41 % less than the previously simulated 100%EV model.

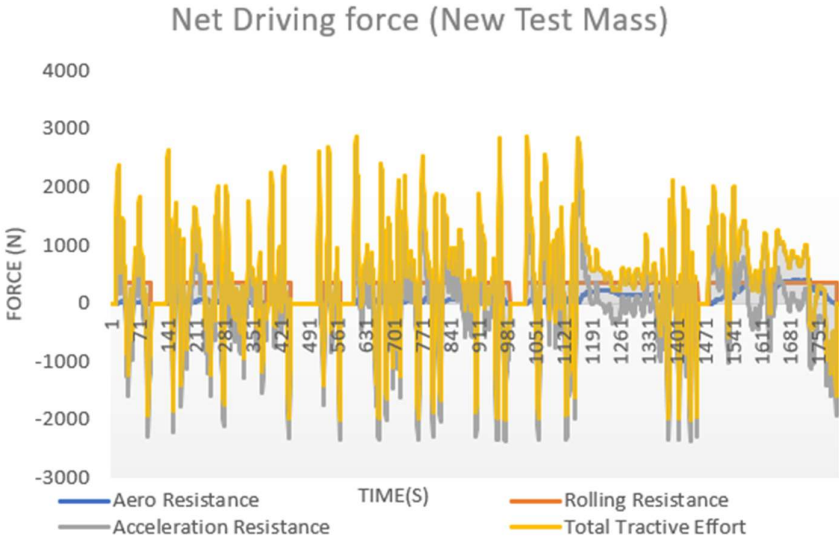


Figure 7: Forces acting on the hybrid test mass (Fuel cell + Battery)

A maximum power of 40.94 kW is requested by the 100% electric vehicle at a total elapsed time of 1724 seconds whereas a maximum power output of 35.85 kW is the maximum power required to drive the vehicle at the same elapsed time. There is a performance advantage of 12.46 % compared to that of the 100% battery pack which have a strong influence on battery state of charge.

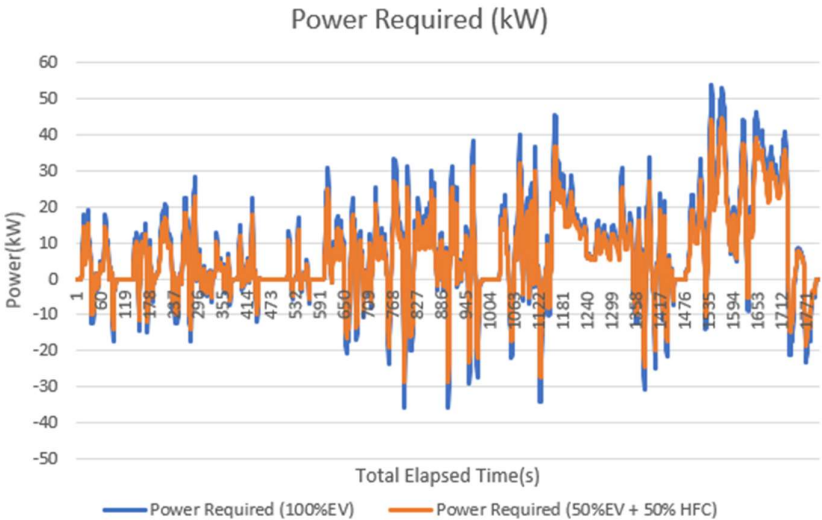


Figure 8: Power required for the new test mass

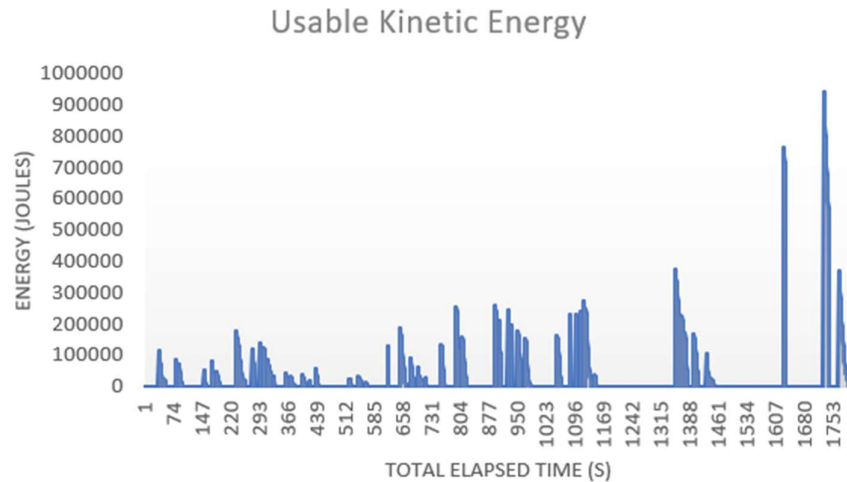


Figure 9: Kinetic energy available for regenerative braking

The available energy at the wheels can be harvested using regenerative braking, as demonstrated in Figure 9, which shows the time elapsed during which kinetic energy is stored when the power at the wheels becomes negative (during deceleration or braking). It has been observed that at phase 4, where high performance is required, the rate of energy storage increases with vehicle speed. However, the WLTP cycle does not account for factors such as gradient resistance, which can lead to inaccuracies in the energy harvested through regenerative braking when traveling downhill. As a result, the kinetic energy obtained from regenerative braking during downhill travel may exceed that indicated by the data in Figure 9. Kinetic Energy consumed throughout the total elapsed time is 4.24×10^7 joules.

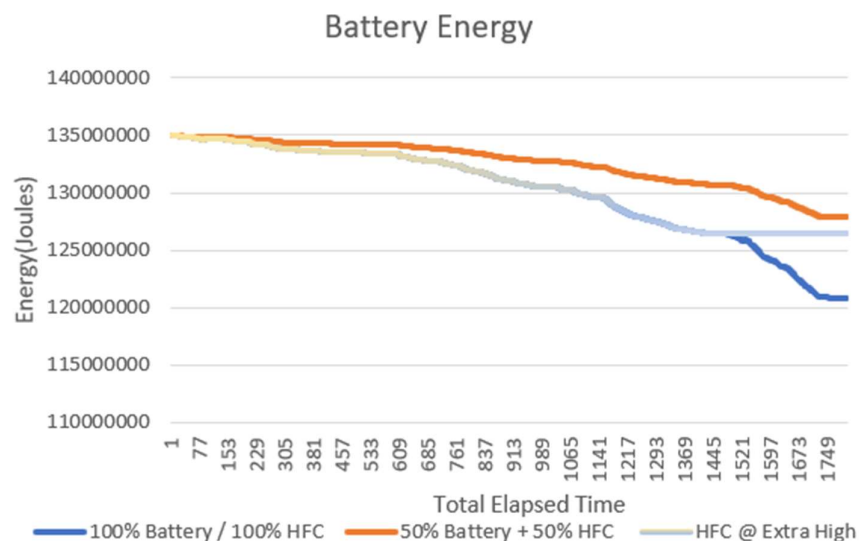


Figure 10: Battery energy flow rates in varying operating techniques

As seen on Table 3 the state of charge of battery when battery and fuel cell is operating at the same time, the hybrid version have less battery energy consumption to that of 100% EV. Several methodologies with data from figure 10 conclude that the power delivery using fuel cells at high and extra high-performance phases can save battery energy whereas at low phases, this energy can be used directly from battery to ensure the sustainability and reliability in performance.

	Battery State of charge(%)	Low	Middle	High	Extra-High
		(1-590)	(591-1022)	(1023-1477)	1478-1800
100%EV	Beginning SOC	100	99.47	98.6	97.11
	End SOC	99.47	98.6	97.11	94.93
50% Battery + 50% FC	Beginning SOC	100	99.39	98.33	96.81
	End SOC	99.39	98.33	96.81	94.74

Table 3: Battery SOC for 100%EV and hybrid powertrain at end of each drive cycle phases

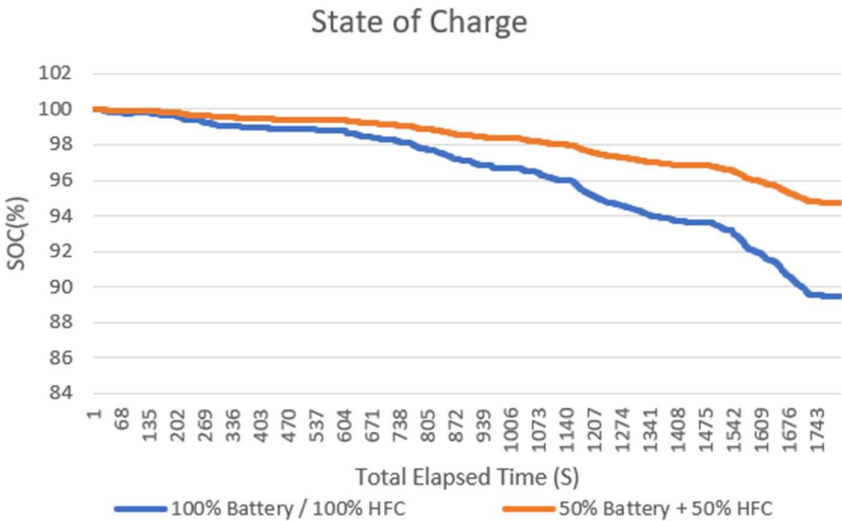


Figure 11: Battery state of charge in different applications

Figure 11 depicts the battery state of charge for 100% EV powertrain and Fuel cell Hybrid powertrain. The battery management works under the principle of energy storage while braking or decelerating. The power electronics system considered in the above graph is an integration of fuel cell and battery working at the same time. The battery state of charge has been on higher levels for phase high and extra high. Utilization of fuel cell systems using power electronics to operate at higher speeds can help to optimise and improve battery efficiency with less energy

6. Conclusion

The aim of this study was to investigate the impact of a fuel cell hybrid system on the net energy storage of an electric vehicle, using data from the WLTP cycle. A simulated analysis was conducted on both a 100% electric powertrain and a hybrid powertrain that integrated 50% fuel cell and 50% battery, to compare the two systems. Additionally, the study analysed the effects of a new hybrid powertrain, which assumed a 23% reduction in vehicle mass. The study found that the state of charge at the end of the WLTP cycle was 94.74% for the hybrid powertrain, while the Tesla Model 3 electric powertrain recorded 89.48%. This 5% improvement in the hybrid powertrain was attributed to the use of fuel cells to provide 50% of the power required at the wheels.

The application of a kinetic energy recovery system, such as regenerative braking, can help conserve energy by capturing negative power. As the WLTP cycle does not consider gradient resistance, the kinetic energy conserved was estimated based on deceleration. The results showed that the total amount of conserved kinetic energy was 15% of the maximum energy capacity of the battery for the 100% EV powertrain, and 31% for the hybrid powertrain.

Considering the development in the research of batteries, switching from lithium-ion battery cells to alternative lightweight solutions, such as solid-state batteries, zinc-air batteries, sodium-ion batteries, and lithium-sulphur batteries, can significantly impact the weight and efficiency of energy storage systems, particularly for larger applications. Improving the durability and reducing the cost of fuel cell components is also critical to the viability of fuel cell powertrains, which currently have a shorter lifespan and are more expensive than other powertrain options. Furthermore, the sensitivity of fuel cells to low temperatures poses a significant challenge to their performance in cold weather conditions and must be addressed for the future success of fuel cell technology.

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