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Drive Cycle Requirement Specifications

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“Customer Requirement: Feasibility study of a Tesla Model 3 Fuel Cell conversion.”

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Abstract – This report shows how a Tesla based vehicle would be converted for use with a fuel cell. The base vehicle was a 2019 Tesla Model 3 which was then modified to use a fuel cell. 66% of the battery was removed and replaced with a Type IV 2.1Kg hydrogen tank and a Toyota Mirai fuel cell and fuel stack.

Using WLTP drive cycles and a MATLAB code to simulate this, the range and efficiency for each vehicle was calculated. Following this, a cost analysis comparing a standard Tesla Model 3, the fuel cell modified Tesla and a BMW M340i was performed.

Overall, it was found that the fuel cell added 66.84km to the range, however the efficiency was reduced by 67.214 Wh/Km. For a full charge/ full fuel tank, the standard Tesla costing of £51.75 being the least expensive and the BMW costing of £82.60 being the most expensive. However, the fuel cell costs £59.36, but allows for quick refuelling, no greenhouse gas emissions and a weight reduction.

1. Introduction

Electrification for automotive transportation is currently considered the most sustainable future, moving the industry away from gasoline and diesel internal combustion engines (ICE). Cars such as the Tesla model 3 and Kia e-Niro are the top two best selling Electric Vehicles (EV) in the United Kingdom as of April 2022 (Herincx, 2022). These cars advertise a lower running cost, less maintenance and a more environmentally friendly alternative to their ICE counterparts. However limitations such as range, with many customers

reporting range anxiety, extensive charge times and a limited infrastructure, suggests that these vehicles may not be the best alternative.

Hydrogen powered fuel cell vehicles (FCEV) are another alternative to ICE cars, where they are again powered by electricity through a large lithium-ion battery and motors. However, rather than charge the battery up off the grid, whether at home or at a charging station, a fuel cell powered vehicle uses hydrogen as a fuel, to then convert it into electricity. This refuelling process takes the same amount of time as filling up an ICE vehicle, whilst the only by product is water, compared to harmful gases such as carbon monoxide and nitrogen oxides. This alternative appears to be the best solution due to the reduced refuelling time compared to EV's and emissions from ICE vehicles. However, these vehicles still have some downsides. For example, the refuelling infrastructure is declining, with around five stations across the UK, which means Hydrogen for these vehicles is expensive and very limited, reducing the incentive for manufacturers to continue to develop these vehicles. Similarly, carrying around a large tank of compressed,

highly flammable hydrogen does pose some obvious health and safety concerns.

1.1 WLTP drive cycle.

The test procedure used to calculate the range of any vehicle is called the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) and is an evolution of the New European Driving Cycle (NEDC) (WLTP Facts, n.d.). The WLTP vehicle test has been split up for vehicles in three different classes. This depends on the vehicle's power to weight ratio, with anything above 34 W/Kg classed as Class 3, see table 1. This means the test is split into four speed sections: low, middle, high, extra-high (Transport Policy, n.d.). For this report and investigation, class 3 will be the testing procedure and will be simulated in MATLAB. However, the WLTP drive cycle is not representative of real world driving as there is no representation for hard breaking or acceleration, poor road surfaces or traffic. It can also be seen that there is a lack of validation to the WLTP data and correlation to real-world data (Moldem, 2019).

Table 1: WLTP Class 3 Parameters (Transport Policy, n.d.)

WLTP Class 3 cycle: Selected parameters

Phase	Duration	Stop duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	s	m		km/h	km/h	km/h	m/s ²	m/s ²
Low	590	145	3095	24.6%	56.5	25.0	18.9	-1.47	1.47
Middle	433	47	4756	10.9%	76.6	44.4	39.5	-1.49	1.57
High	455	29	7162	6.4%	97.4	60.5	56.7	-1.49	1.58
Extra-High	323	6	8254	1.9%	131.3	93.7	92.0	-1.21	1.03
Total	1801	227	23266						

1.2 Overview

In this report, we will investigate the effect of modifying a Tesla Model 3 by removing at least 50% of the battery and adding a fuel cell in place, which will charge the remainder of the battery by using stored hydrogen whilst on the road. The weight of the vehicle will be calculated, with half the battery missing but the addition of a fuel cell, with all the electrical components and the hydrogen tank required. By using a MATLAB script to simulate a WLTP, the original range of the Tesla Model 3 will be attempted to replicate, therefore the amount of hydrogen to carry will be calculated based on the range requirement.

1.3 Fuel Cell

Decision matrices will be used to decide what type of fuel cell chemistry will be used, as well as the specific fuel

cell and stack which can be fitted into the car. Since there are a variety of fuel cell chemistry options, this will be the first decision to be made, so we can then choose between fuel cell options which use that chemistry. However, it is likely that the fuel cell used will likely be one taken from a Toyota Mirai (figure 1). This is one of the most common fuel cell production cars, as there is a wide amount of information and data regarding technology used and the car in general.

In general, a fuel cell converts the hydrogen chemical energy into electrical energy by splitting the molecules into electrons and protons. The hydrogen gas flows through tubes to an anode with a catalyst, this then splits the hydrogen into protons and electrons. The protons pass through the membrane and the negatively charged electrons flow to the cathode, where it reacts with air and the protons to form water. These fuel cells rarely

Table 2: Fuel Cell Technology Comparison (U.S Department of Energy, 2015)

Comparison of Fuel Cell Technologies							
Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	60% direct H ₂ ⁱ 40% reformed fuel ⁱⁱ	- Backup power - Portable power - Distributed generation - Transportation - Specialty vehicles	- Solid electrolyte reduces corrosion & electrolyte management problems - Low temperature - Quick start-up and load following	- Expensive catalysts - Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60% ⁱⁱⁱ	- Military - Space - Backup power - Transportation	- Wider range of stable materials allows lower cost components - Low temperature - Quick start-up	- Sensitive to CO₂ in fuel and air - Electrolyte management (aqueous) - Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbedded in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40% ^{iv}	Distributed generation	- Suitable for CHP - Increased tolerance to fuel impurities	- Expensive catalysts - Long start-up time - Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50% ^v	- Electric utility - Distributed generation	- High efficiency - Fuel flexibility - Suitable for CHP - Hybrid/gas turbine cycle	- High temperature corrosion and breakdown of cell components - Long start-up time - Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60% ^{vi}	- Auxiliary power - Electric utility - Distributed generation	- High efficiency - Fuel flexibility - Solid electrolyte - Suitable for CHP - Hybrid/gas turbine cycle	- High temperature corrosion and breakdown of cell components - Long start-up time - Limited number of shutdowns

produce more than 1v, so they are stacked to produce more voltage, known as a Fuel Stack (U.S Department of Energy, 2015). For transportation, Polymer Electrolyte Membranes are the most common type of fuel cell used, which have advantages of lack of electrolyte corrosion due to solid electrolytes and low running temperatures. Table 2 shows a comparison of different fuel cell technologies, with advantages and disadvantages for each, made by the U.S Department of Energy.

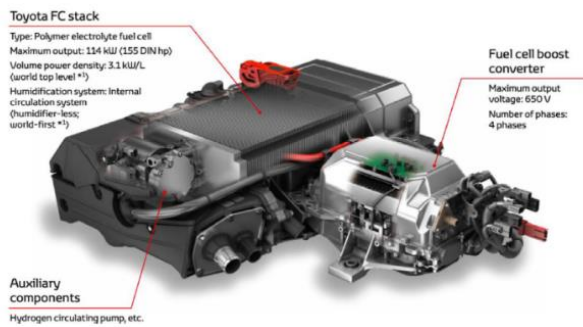


Figure 1: Toyota Mirai Fuel Cell (M.A. Aminudin, Lim, Majilan, Masdar, & Shaari, 2023)

1.4 Literature Review

From a review article published in 2022, (M.A. Aminudin, Lim, Majilan, Masdar, & Shaari, 2023); several challenges for FCEV were found. For example, the infrastructure surrounding these vehicles is limited compared to gasoline and EV vehicles. Similarly, the use of platinum for the catalyst poses an environmental concern and increases the overall cost of these vehicles.

In another comparison review article, the emissions of a FCEV and ICE vehicle were compared. This was done using a Well to Wheel (WTW) method and found that

FCEV use 5%-33% less fossil fuel emissions and 15%-45% less greenhouse gas emissions (Liu, et al., 2020).

2. Procedure

2.1 Decision Matrix

To decide on the components used for the conversion and application of a fuel cell and battery combination, then decision matrices are a useful tool to help narrow down and create the optimal solution. For this investigation different fuel cell chemistries, electrical energy storage, hydrogen storage and current fuel cell and stacks are used, which can be bought and used in the car. The decision matrix will score each option on a range of criteria from 1 to 5 with 5 being the best and 1 being the worst. Each score will then be totalled with the option achieving the highest overall score being the optimal choice for this application.

2.11 Fuel Cell Chemistry

Table 3: Fuel Cell Chemistry Decision Matrix

Criteria	Fuel Cell				
	PEM	Alkaline	Phosphoric	Solid Oxide	Molten Carbonate
Operating Temp	4	5	2	1	3
Output Power	2	1	4	5	3
Startup Time	5	5	3	2	1
Efficiency	5	2	3	4	2
Power Density	5	4	3	5	2
Total	21	17	15	17	11

Table 3 shows a decision matrix which has been made, to assess the different fuel cell chemistry options available, with the majority of information used to score each option taken from table 2. As highlighted in green, PEM fuel cells are the best option for this use case, with ideal optimal operating temperatures, startup times,

efficiency and power density. The clear negative downside to a PEM fuel cell is the output power (Mekhilef, Saidur, & Safari, 2011). Meaning a large number of fuel stacks are required for an adequate output for the application, which could result in increased weight and a loss of efficiency. Phosphoric and solid oxide fuel cells offer a better alternative, however with more serious downsides. For example, a phosphoric acid fuel cells have a long start up time and poor operating temperatures (GenCell, n.d.). Similarly, looking at solid oxide fuel cells, they have even worse operating temperatures, meaning an increase in cell corrosion and a limited number of shutdowns of the fuel cell. Therefore, this is not suitable for a car application.

2.12 Electrical Energy Storage

Table 4: Electrical Energy Storage Options

Criteria	Energy Storage		
	Capacitors + Large Battery	Battery	Capacitors + Small Battery
Mass	5	3	4
Complexity	2	4	2
Cost	2	5	3
Charge Rate	5	3	4
Capacity	2	4	1
Total	16	19	14

Table 4 shows the decision matrix for the type of electrical energy storage options. The main three are single battery, capacitors and a large battery, for example the remaining portion of the battery after removing at least 50% of it, and the third option which is capacitors + a small battery. All batteries will be lithium ion, a size variation to the remaining original Tesla Model 3 battery.

Looking at the different options, it is clear that the standalone battery, the remaining at least 50% after the fuel cell conversion is the best option. This requires the least cost as no new components are required to wire in the battery. The charge rate will still be as fast as customers are expecting, whilst the fuel cell will top up the charge of the battery on the road. Increased the range of the vehicle, without increasing the charge time of the vehicle.

By comparing this to a larger portion of the battery with some added capacitors, this will increase the charge and discharge rate, meaning the fuel cell will be able to fill them up quickly, providing improved performance, however the increased mass, complexity and cost limits the worthiness of this option. Then looking at a capacitor only or with a small battery option, the vehicle would aim to run off the fuel cell alone, without a battery to also charge. Whilst this would reduce the mass, the customer could easily become stranded. Since hydrogen filling stations are uncommon around the UK and capacitors can quickly lose charge when stored for a short amount of time, if the customer was to use this in an area where hydrogen was limited, then the capacitors would not provide enough power, even if they could charge them up from the wall.

Therefore, using a fuel cell with a large EV battery would increase the range and reduce the charging times of the vehicle, without limiting the use to around areas with a hydrogen station.

2.13 Hydrogen Storage Options

Table 5: Hydrogen Storage Options (Li, et al., 2019)

	Hydrogen Storage			
	Gas	Liquid	Nanotube	Chemical
Cost	5	4	1	2
Weight	3	5	2	4
Density	5	5	3	4
Safety	3	2	4	5
Lifetime	5	4	3	1
Total	21	20	13	16

Table 5 compares four different hydrogen storage options, gas and liquid are more common and well researched options, whereas carbon nanotubes and chemical storage in the form of metal hydrides are promising but more unknown technologies which have had little industrial research.

Looking at storing hydrogen as either a gas or a liquid appears to be two suitable options, based on the decision matrix. Gas storage is the most common solution for fuel cell vehicles, where the hydrogen is highly compressed to around 700 bar and then stored in an adequately sized metal or polymer tank with a composite casing (Type III and Type IV respectively). This option offers the cheapest cost as the most common and is also one of the safest due to a high number of health and safety precautions (Li, et al., 2019).

Liquid storage is another more research option that looks suitable for this application based on table 5. It offers a weight saving as a smaller tank is required since liquid hydrogen takes up less space than gaseous and has the greatest density of hydrogen out of all the options.

However due to the extremely low temperature, which is required, this option is expensive meaning the tradeoff for decreased weight would not be worth it. Similarly, hydrogen stations for vehicles in the UK output gaseous hydrogen, meaning a new network would need to be built to use liquid hydrogen. Then after previous reading within the field, it becomes apparent that a tank for this application smaller than 50L is not available at these extreme pressures (700bar), therefore this would be the ideal tank to use for a complete and production ready conversion.

2.14 Fuel Cell Components

Table 6: Fuel Cell Component Options

Criteria	Fuel Cell Options		
	Toyota Mirai	Ballard Fcgen-HPS	Loop s1200
Mass	5	4	1
Power	4	5	2
Consumption	5	3	2
Ease of Installation	1	1	5
Efficiency	4	4	4
Total	19	17	14

Once the type of fuel cell and storage options have been chosen, the actual fuel cell component to be fitted needs to be decided. Looking at table 6 shows three main options which have been found and can be easily sourced for fitting. The fuel cell out of the Toyota Mirai offers the best solution, with it being the least mass, most efficient and have the most data available online (Toyota). The Ballard Fcgen-HPS is an alternative which is not much worse than the Mirai cell. However, from the specification sheet it is less efficient and slightly heavier

(Ballard). However, both of these options are very difficult to retrofit to the Tesla model 3 as they require a custom cooling, wiring and mounting process. The Loop s1200 offers a complete package which negates many of these problems, hence the increased weight (Loop Energy, n.d.). However at a production and consumer scale these installation issues will become less of a problem.

2.2 Component List

After the use of the decision matrixes a component list can be formed:

- PEM Toyota Mirai Fuel Cell (figure 1).
- Reduced size Tesla Model 3 lithium-ion battery, 25kW.
- 50L 700 bar Type IV compressed hydrogen tank (HyFindr, n.d.).

2.3 Calculations

Several calculations need to be done to understand how much hydrogen needs to be stored and used to create a similar driving range to the standard Tesla model 3 car.

Since deciding on using a 2.1kg hydrogen tank, the amount of energy in that much hydrogen can be calculated and therefore the amount of battery energy that will be replaced using this hydrogen.

Tesla Battery = 75kW, at 480Kg (Arcus, 2018).

2.1Kg Hydrogen = 178MJ ((142MJ = 1Kg at 700bar) (Air Liquide, n.d.).

178MJ = 49.667kW (1kW = 3.6MJ)

Therefore, need to replace 49.667kW using Hydrogen.

Remaining battery = approximately 25kW

Hydrogen conversion is approximately 60% efficient so usable energy will be less than the total energy within the tank.

Overall to replace the battery with hydrogen, we will need 2.1Kg of H₂ to be used with a fuel cell.

Weight is the biggest factor between the efficiencies of these cars:

- Battery: 163.2Kg
- Fuel Cell: 52kg
- Hydrogen: 2.1Kg
- Tank: 36kg
- Fuel Cell and Battery Total = 253.3Kg
- New Tesla Mass: 1753.3Kg
- Mass Reduction = 226.7Kg
- Old cd = 0.278
- New cd = 0.247

A weight reduction of 226.7Kg occurs by removing the majority of the original Tesla battery and this effects the coefficient of drag from 0.278 to 0.247.

2.4 MATLAB Code

MATLAB can be used to simulate the WLTP drive cycle, where we can then compare the range, efficiency and overall cost of the car, before and after the conversion. The code then plots the battery depletion of both runs and the velocity and acceleration of the car during the test. The coefficient of drag is the main difference between the inputs which effects the range and efficiency. The battery total input remains the same, as the fuel cell has enough energy to replace the missing battery, which is then converted to joules for the code.

3. Measurements and Data Collection

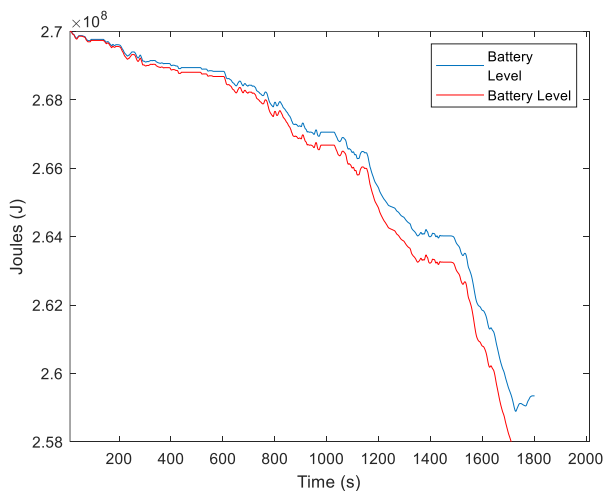


Figure 2: Battery Level vs Time

Figure 2 shows the battery depletion graph for the Tesla (red) compared against the Fuel Cell conversion (blue). The red line represents the cycle before the fuel cell was added, and the blue line indicates the cycle once the fuel cell was added. As you can see, without the fuel cell the stored energy is used more quickly and appears to

increase over time. This can be seen at 600s where the difference in energy is around 0.01J, however by 1700s, the difference is around 0.2J. This point within the WLTP test is the High Speed Section and as the name suggests, the car travels the quickest it will over the entire test. This explains the increase in energy depletion as well as why the difference in energy between the two vehicles has increased compared to the beginning of the test; higher speeds mean more force and energy is required to maintain or increase that velocity, due to the increase in drag and wind resistance.

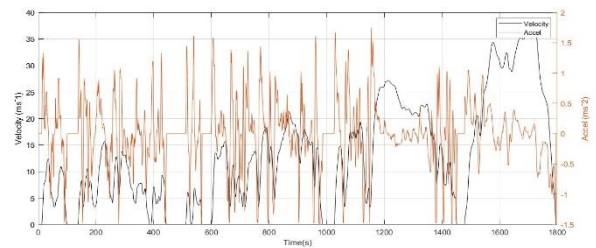


Figure 3: WLTP Drive Cycle Graph (with fuel cell)

Figures 3 and 4 show the WLTP drive cycles with the fuel cell added and without the fuel cell. Looking at table 4, the range and consumption before the fuel cell was calculated as 522.6Km and 143.5Wh/Km respectively. It can then be seen that with the fuel cell added, the range increased by 66.8Km (12.8%) and consumption decreased by 16.3Wh/Km (11.4%). The plots for both the drive cycles are identical which ensures that the contributing factor for the increase in range and efficiency is down to the addition of the fuel cell.#

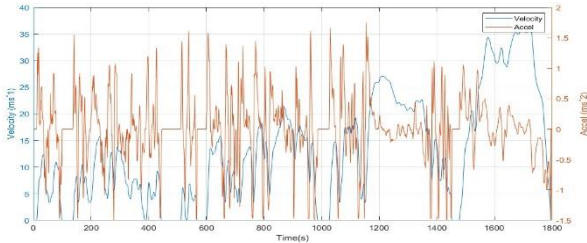


Figure 4: WLTP Drive Cycle Graph (without fuel cell)

4. Results and Discussion

4.1 Vehicle Performance and Efficiency

Table 7: Comparison between 3 vehicle options

	MATLAB Calculation			Stated WLTP (34MPG)
	2019 Tesla Model 3 (best case)	2019 Tesla Model 3 (worst case)	Tesla + Fuel Cell	BMW M340i
Efficiency (Wh/Km)	140.711	140.711	207.925	739.633
Range (Km)	522.5748	522.5748	589.4124	709.978
Cost (£)	25.5	51.75	33.7	86.57

Table 7 shows a range, efficiency and cost comparison between three different vehicle options. The 2019 Tesla Model 3 is the standard electric car which the fuel cell conversion is based around, the WLTP range and efficiency has been calculated using MATLAB, which allows for a fairer comparison to the fuel cell Tesla. However, based on the 530 Km stated WLTP range by Tesla, (Huntingford, 2022), the MATLAB test is adequately close, therefore validating the code. The original Tesla is the most efficient with using 140 Wh/Km compared to 207 in the fuel cell conversion. However due to the fuel cell allowing for more energy stored, the range has increased in the Fuel Cell Tesla from 522.57 to 589.41 Km. I have chosen to compare these vehicles to a 2019 BMW M340i as this car has a comparable cost, size, performance and all-wheel drive. This vehicle with a 3.0L

inline 6 single turbocharged engine claims a WLTP of 34-36MPG (BMW, n.d.) however for the purposes of this comparison, I have taken a more realistic 34MPG.

Comparing this to the two Tesla based vehicles, a full tank (59L) gains around 709Km of range and an efficiency of 739Wh/Km:

$$2019 \text{ BMW M340i} = \text{WLTP } 34\text{mpg} = 8.31 \text{ l/100km}$$

$$1\text{L petrol} = 8900\text{Wh}$$

$$0.0831\text{L per Km}$$

$$0.0831\text{L} = 739.633\text{Wh}$$

$$\text{BMW} = 739.633\text{Wh/Km}$$

$$59\text{L fuel tank} = 709\text{kM based on stated WLTP}$$

This is clearly a significant amount more energy used when compared to the electric and hydrogen powered vehicles. The main difference to the efficiencies and range between the two Tesla based vehicles was due to the mass difference. Adding the fuel cell reduced the mass by 226.7Kg and therefore changed the coefficient of drag from 0.278 to 0.247.

4.2 Cost Analysis

Looking at cost in Table 7, the standard Tesla proves to be the cheapest to fill up from empty. The calculations are as follows:

Hydrogen = £12 per kg (Kristan, 2022)

Electricity (from rapid chargers) = £0.69 per kWh (RAC, 2023).

Electricity (standard home rate) = 0.34p/kWh (ERIN YURDAY, 2023)

Petrol = 146.73p per litre (RAC, 2023).

Tesla + 66% fuel cell = **£33.7**

Tesla (fast charger) = **£51.75**

Tesla (home charger) = **£25.5**

48.9799l for 589.41 km * 146.73p = 6857.195p = **£71.87**

On average hydrogen for use in road vehicles is around £12 per Kg, electric within the home = 0.34p/kWh and 0.69p/kWh for rapid car chargers. For the pure battery Tesla, a worst-case and best-case scenario have been undertaken. For the worst-case scenario it has been assumed that the full 75kWh battery was charged at a rapid charger which would cost £51.75. However, this would be unrealistic during ownership of the vehicle and so the best-case scenario would be to charge the battery at home and this would cost £25.5 on average. However, this could further drop depending on individual tariffs and the time of day the battery was charged.

For the fuel cell Tesla conversion, I have assumed that the only time the vehicle would be charged would be at home, therefore the total fill up cost would be £33.7. The reason the cheaper electricity cost was used is due to the suggested use case of the vehicle. Ideally the vehicle would be charged up overnight and then filled up with

hydrogen at a station. This will allow for the cheapest running cost, quick refill time and extended range over the standard Tesla Model 3.

Comparing this to the petrol ICE BMW alternative a significant cost increase can be seen. To achieve the same amount of range as the fuel cell Tesla, it would cost £71.87 and to totally fill up the 59L fuel tank the cost would be £86.57. Therefore either the full electric or hydrogen alternative have been shown to be a more cost effective choice

5. Conclusion

Overall, it can be seen that converting a Tesla Model 3 vehicle to use a Toyota Mirai fuel cell in conjunction with a 25kWh does provide benefits. Similarly, this idea could be easily used on a new car, where a fuel cell and larger lithium ion battery are used, rather than just a small battery like found in the Toyota Mirai or Hyundai Nexo.

This alternative allows for quick refuelling, much cheaper than petrol or diesel ICE, less strain on the national grid, and, due to the large battery, the concern of having limited places to refuel with hydrogen is removed. Instead, the vehicle can be charged from the grid either at home or at a charging station which are becoming more popular options compared to hydrogen. Personally, I believe that a hydrogen future would be more sustainable compared to a fully electric future, with less strain on the grid and less rare earth metals used due to the smaller battery required. However, the

car needs to be compatible with the current infrastructure as well.

The MATLAB code provided an accurate representation of the WLTP code, validated by the provided Tesla Model 3 range. However, in the first iteration the efficiencies were estimated to be too high. This is due to the fact I had already accounted for the 60% efficiency of the fuel cell, meaning more energy was put into the system than could physically be possible. Therefore, the system is now set at a 60% efficiency with the correct amount of energy stored in the tank which had been selected.

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