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Evaluating supercapacitors to improve electric motorcycles

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T452-24B

Project Report (EMA)

[5674 Words]

Contents

Executive Summary

This report looks at the various implications, potential benefits and drawbacks of implementing supercapacitors (SCs) into various popular electric motorcycle models.

A literature review identified potential areas to analyse, where benefits have been shown in other vehicle types. The analysis was therefore focused on:

- Using SCs to maintain peak power while reducing battery mass is achieved with a low mass of SCs – less than 5kg for a 25% reduction in battery mass. The biggest downside is range reduction.
- SCs can be added to the standard battery size to significantly improve peak power – at least 30% increase may be possible with an SC pack equivalent to 2.5% of vehicle mass.
- Discharge time at peak power would be under 5 seconds, while charge time is limited by infrastructure. Charge time when using current-limited charging infrastructure is just over 13s/kg, resulting in a maximum theoretical charge time in the results analysed of 85 seconds.
- Discharge rate can be reduced at the expense of power output to provide a longer duration of additional power, although at the mass of SCs analysed this was limited to <9% power of peak for 30 seconds or <4.5% for 1 minute.
- Costs of the SCs by mass ranged from £12 to £622, or £150/kg. This did not include cost of implementation or motor upgrades. This is a relatively small portion of the total cost of the vehicle, which in most cases is over £15,000.
- Battery lifetime can be improved with SCs by limiting current and discharge cycles.
- Energy density remains a key limiter for including SCs in the system.

Introduction

Electric vehicle sales are increasing year-on-year by roughly 35% (IEA.org, 2024). However, much of this market is car sales (see Figure 1); electric motorcycles are still a niche product with significant drawbacks to internal combustion engine (ICE) powered models. These drawbacks include cost (Wahab and Jiang, 2019) and increased mass (McLaren, 2023) due to heavy battery packs. Packaging heavy battery packs is difficult in a motorcycle frame due to the limited space and challenge in achieving a low centre of gravity.

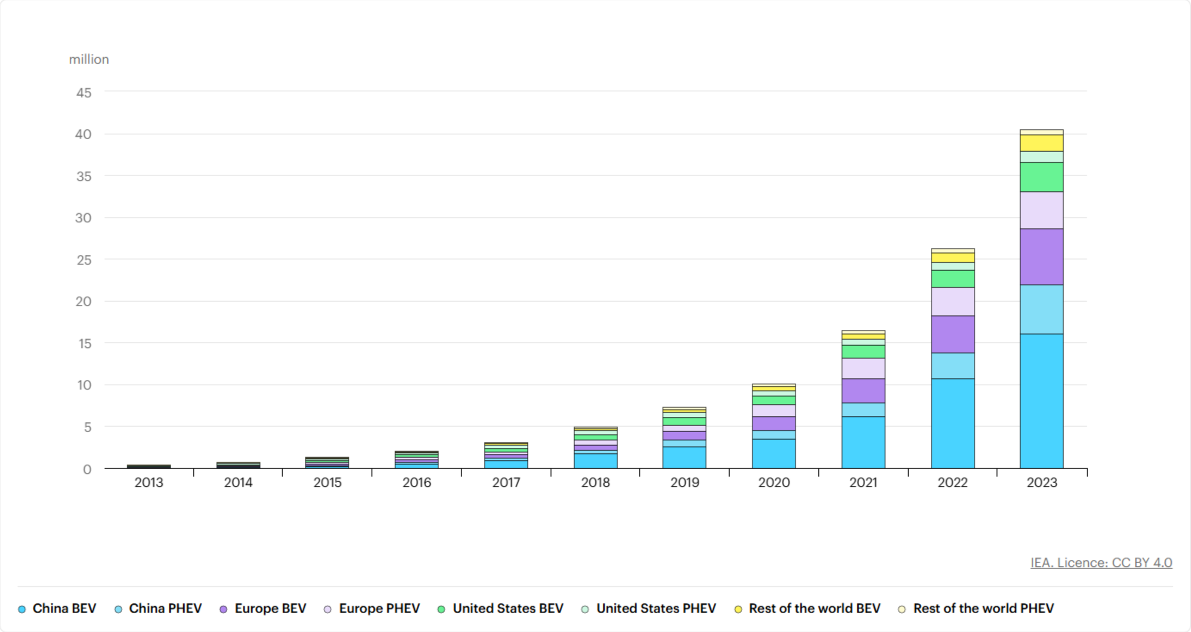

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Figure 1 - Global electric car sales 2013 - 2023

Motorcycles are currently lagging behind cars in adopting electric power. Currently few of the main manufacturers offer an electric option, despite bans on sales of new ICE vehicles being implemented from 2035.

Supercapacitors may be a good option for motorcycles, which are typically more limited in terms of weight increase and thus battery capacity than electric cars with current lithium-ion (li-ion) batteries. Issues with range and charge time could be more of an issue with a mode of transport that is often recreational in nature, with long waiting times for charging not practical.

Project Aims

The main aim of this project is to assess ***the feasibility of implementing supercapacitors into electric-powered motorcycles to improve power output, reduce battery degradation, cost, charge time and reduce mass.***

The key objectives consist of:

- Conduct literature review to include reliable sources discussing supercapacitors in the context of vehicles. This will include any present use cases and will include searches for literature that specifically address power output, battery degradation and charge time
- Use analytical techniques including calculations of power requirements, power density and charge currents to assess potential benefits of integrating SCs
- Calculate potential hardware costs using available products
- Identify any potential drawbacks, complications and risks from incorporating SCs
- Make conclusions and recommendations based on results from analysis and available research, discussing potential benefits

To achieve these objectives theoretical analysis of each aspect discussed in the project aim will be carried out to help quantify the potential advantage that SCs may bring to the electrical system.

Scope

The scope of this project is a theoretical analysis of the parameters set out in the objectives. Design of the electrical system will not be included in the report.

The remaining sections in the report consist of:

- A literature review that discusses existing knowledge and use cases for SCs in electric vehicles, specifically relating to the criteria set out in the project aim
- The methodology section discusses the analysis techniques used
- The results section presents the results of the analysis conducted
- A discussion on how might SCs best be utilised based on the results
- Conclusions and recommendations based on the discussion

Literature Review

Supercapacitors (SCs) use high surface areas to achieve a high energy density, occupying a middle ground between electrolytic capacitors and li-ion batteries (Kar, 2023).

Figure 2 shows a Ragone plot of energy vs power density for energy storage devices. It shows that while li-ion batteries have a relatively high energy density, their power density is generally lower than capacitors. SCs utilised on an electric motorcycle may be able to deliver higher power than batteries for a comparable mass, and will also charge faster (Vlad *et al.*, 2014).

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Figure 2 - Power density compared to energy density, with supercapacitors occupying a middle ground (Liew and Jun, 2022)

Power output

Peak power output and thus acceleration of an electric motorcycle could be increased by implementing SCs alongside the battery. SCs have significantly higher power density than li-ion batteries, so can be used to significantly increase peak power output to maximise acceleration. (Khaligh and Li, 2010) discuss SCs enabling battery packs to be reduced in size by providing the additional power bursts required, particularly in stop-start traffic, allowing the battery to be used more efficiently when maintaining speed.

Power requirements for an electric motorcycle will be analysed to assess how reducing battery size through use of SCs may also help reduce mass.

Efficiency and battery degradation

(Perrotta *et al.*, 2012) modelled the efficiency of a regenerative system for a bus during a standard duty cycle, noting a drawback of a battery-only system is the limited power density reducing the amount of energy that can be reclaimed during braking – only 57% of the reclaimed energy was put back into the battery. Using SCs to capture the braking energy, 97% was stored – this could then be fed into the battery at a lower charge rate. No similar study was found for a motorcycle powertrain; however, it can be assumed that at a minimum reduced charge currents to the battery would reduce temperature cycling and improve longevity of the battery.

Figure 3 shows the SCs in an SC/Battery powertrain being charged during deceleration. This charge can then be fed into the battery or used for acceleration. How the SCs use the charge could be dictated by the riding mode i.e. economical or 'sport'.

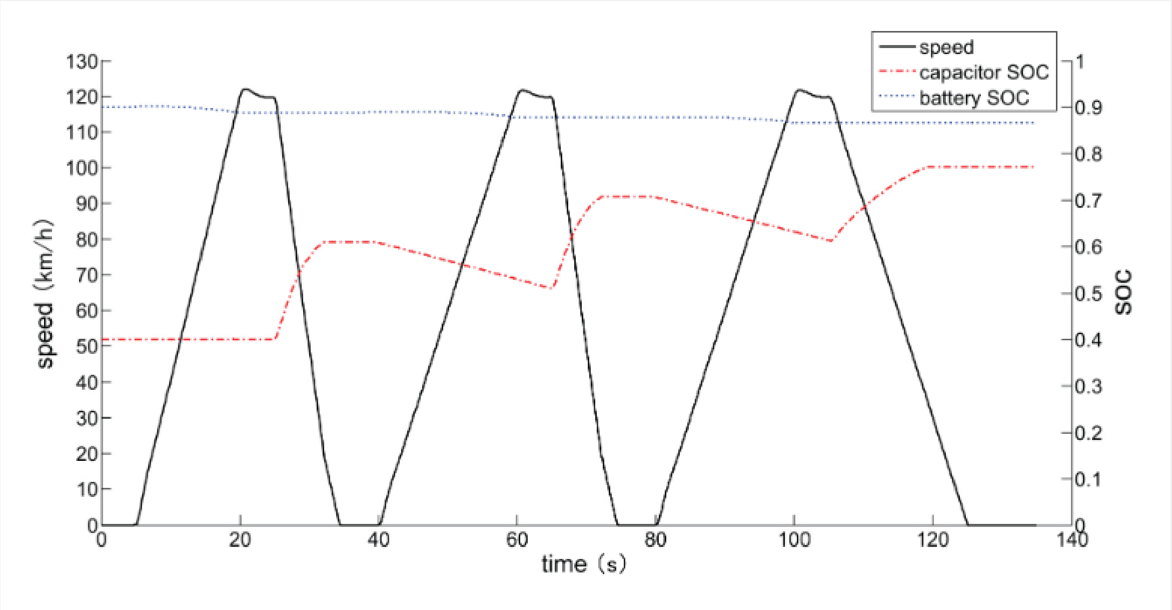

Figure 3 - State of charge (SOC) of an SC/Battery powertrain during acceleration/deceleration (Jin* et al.*, 2015)

Li-ion batteries degrade through use. This degradation often results in reduced charge capacity and power output (S. Edge *et al.*, 2021). The degradation rate is dependent on temperature, state of charge and power output (Birkl *et al.*, 2017). SCs could be utilised in a motorcycle to influence all these factors, therefore improving the longevity of the batteries. (Shen, Dusmez and Khaligh, 2014) modelled li-ion degradation using a model that was verified with experimental results and determined the battery lifetime be extended by up to 76% by optimising the use.

While ambient temperatures cannot be influenced, internal battery temperature is affected by discharge currents (Hussein, 2023). A 3°C increase can increase degradation by 300% (S. Edge *et al.*, 2021). Battery current and wear will peak during acceleration of the motorcycle, due to peak load from the motor. (Bopche, Deosant and Ahmad, 2016) discuss how SCs can be used to smooth the current from the battery by compensating for the additional load during acceleration, limiting battery temperature.

The battery management system could use SCs to maintain an optimum battery level to a greater extent than a battery-only system, as discussed by (Gharibeh *et al.*, 2019), reducing charge/discharge cycling. In this use case the SCs act as a filter, smoothing currents to and from the battery (Khan *et al.*, 2018).

Charge time

(Musolino, Tironi and di Milano, 2010) compare ‘state-of-the-art’ SCs and li-ion batteries (at the time of publication) and find the specific power of the battery was superior when discharging, but when charging was one-fifth of the SC charge power. It is unusual to see a study where a battery has higher specific power than an SC, however battery degradation and thermal effects are not considered. Cost of the modules tested were about €50/Wh for the SC and €200/Wh for the battery.

Mass

SAE conducted a test with three electric motorcycles (Phan *et al.*, 2023) to assess acceleration and braking characteristics. Kerb weights were comparable to an internal combustion engine (ICE) motorcycle for one model (190kg) but higher for the other two models (250kg and 275kg). The additional mass over ICE motorcycles is largely from the battery pack and is one of the largest drawbacks of current models.

A part of the report will focus on analysing what potential mass savings could be possible by reducing battery size by using SCs. This will need to be compared against the loss in range if battery size is reduced.

Methodology

Table 1 shows the most popular electric motorcycles of 2023 (Hancocks, 2023). The specifications for these models were used for comparison. The stated range from each manufacturer that conformed to EU 134/2014 was used to enable somewhat reliable comparison.

Table 1 - Popular Electric Motorcycles for 2023

Model	**Total Mass (kg)**	**Battery Capacity (kWh)**	**Charge Time (CCS Type 1, CCS Type 2), (hrs)**	**Range*(EU 134/2014 Drive Cycle) (km)**	**Peak Power Output (kW)**	**Starting Price (£)**
Livewire S2 Del Mar (Livewire, 2024)	198	10.5	8.4/2.36	111	63	16,990
Energica Experia (Energica, 2024b)	260	22.5	6.6/0.95	222	75	25,990
Zero DSR/X (Zero Motorcyles, 2024a)	247	17.3	2.7/1.6	172	75	20,950
Energica Eva Ribelle (Energica, 2024a)	260	21.5	6.3/0.95	180	126	27,540
Zero SR/F (Zero Motorcyles, 2024c)	227	17.3	2.7/1.6	188	84	20,200
Maeving RM1 (Maeving, 2024a)	111	2	4.16	48	4.4	4,995
Zero S (Zero Motorcyles, 2024b)	223	14.4	4.5/1.8	162	45	15,300

Literature Review

A literature review was conducted to determine the current ‘state-of-the-art’ for using SCs – this was not limited to research based on motorcycles due to lack of information; research based on cars and other vehicles was included. Relevancy of sources was assessed and discussed where relevant if the findings might have different implications for motorcycles. Research was grouped and discussed around each technical aim of the project, for example reducing battery degradation.

It was decided during researching this project that the project would focus on the practicalities of utilising current SC technology in the areas discussed in the key objectives. Other areas that were considered such as fabrication options, nanomaterial choice and what implications these have for SC performance were discounted based on the limited size of the project and thus the complexity of these subjects being out of scope.

Analysis

The analysis was conducted in separate parts to align with each technical aspect of the project aim.

Power output

SCs could be used to either maintain peak power output while reducing battery size or increase peak power output by maintaining battery size. These design choices would be dictated by the main use case of the vehicle.

Reduced battery size

Manufacturers do not generally release specific data on the battery packs used, therefore energy density for the specific bike models shown in Table 1 is not known except Maeving. (Liu *et al.*, 2018) state li-ion battery energy density ranges from 100 – 270 Wh/kg in electric vehicles. An average of 185 Wh/kg was used for subsequent calculations based on this data.

Battery mass for each model was estimated by using Equation (1):

$$Battery\ mass = \frac{Maximum\ Capacity}{Energy\ Density} \tag{1}$$

The battery mass for the Maeving RM1 was calculated at 11 kg (2 s.f.), using Equation (1):

$$M = \frac{2000}{185} = 10.81$$

$$M = 11\ kg\ (2\ s.f.)$$

Maeving states the removable battery pack total mass is 12 kg (Maeving, 2024b). Not including battery shroud and handle, 11 kg calculated using an energy density of 185 Wh/kg appears to be a reasonable assumption. Estimations of battery mass for each model is shown in

Table 2.

A figure of 835 W/kg for power density of li-ion batteries was used for calculations, based on the performance of the Panasonic battery in the Tesla Model Y (Batemo, 2023).

Table 2 - Battery Specifications of Each Model

Model	**Total Mass (kg)**	**Battery Capacity (kWh)**	**Battery Mass (kg)**	**Battery Mass as Percentage of Total Mass**
Livewire S2 Del Mar	198	10.5	57	29%
Energica Experia	260	22.5	120	46%
Zero DSR/X	247	17.3	94	38%
Energica Eva Ribelle	260	21.5	120	46%
Zero SR/F	227	17.3	94	41%
Maeving RM1	111	2	12	11%
Zero S	223	14.4	78	35%

All calculations shown in Appendix Section 1.

Table 3 shows SC models available from the leading manufacturers. Types were selected from different manufacturers to reduce reliance on a single manufacturer.

Table 3 - Selected Supercapacitor Types and Specification

Type	**Capacitance (F)**	**Voltage (V)**	**Mass (g)**	**Specific Energy (Wh/kg)**	**Equivalent Series Resistance (ESR) (mΩ)**	**Cost/cell (£)**	**Cost (£/kg)**
Maxwell BCAP0350 E270 T11/T12 (Maxwell Technologies, 2024)	350	2.7	60	5.9	3.2	£12.36 (*AllICData, 2024*)	206
Maxwell BCAP2000 P270 L04/05 (Maxwell Technologies, 2024)	2000	2.7	360	5.6	0.35	£50.01 (*Mouser Electronics, 2024a*)	139
Maxwell BCAP3400 P270 K04/05 (Maxwell Technologies, 2024)	3400	2.7	513	6.7	0.29	*Unknown*	-
Cap XX GY12R740070V807C (CAP-XX, 2024)	800	2.7	115	7.0	3.5	*Unknown*	-
Eaton XL60-R7308T-R (EATON, 2024)	3000	2.7	515	5.9	0.23	£85.54 (*Mouser Electronics, 2024b*)	166
Tecate TPLH-2R7/3000SL60X138 (Tecate Group, 2024)	3000	2.7	525	5.8	0.26	£44.66 (*Digikey Electronics, 2024*)	85
LS Materials LSUC 002R7C 3000F NH (LS Materials, 2023)	3000	2.7	515	5.9	0.20	*Unknown*	-

Specific energy was calculated to enable comparison between supercapacitors. Equation (2) was used to calculate maximum stored energy for each SC, and Equation (3) was then used to calculate specific energy to enable comparison.

$$Maximum\ Stored\ Energy, E_{max} = \frac{\frac{1}{2}CV^2}{3{,}600} \qquad (2)$$

$$Gravimetric\ Specific\ Energy\ (E_s) = \frac{E_{max}}{M} \qquad (3)$$

$$Where:$$

$$M = Mass$$

For the Maxwell BCAP0350 E270 T11/T12 cell, this was calculated as follows:

$$E_{max} = \frac{\frac{1}{2}(350 \times 2.7^2)}{3{,}600} = 0.354375\ Wh$$

$$\frac{0.354375}{60 \times 10^{-3}} = 5.90625\ Wh\ kg^{-1}$$

$$E_s = 5.9\ Wh\ kg^{-1}$$

The calculated figure corresponds to the manufacturer’s datasheet.

All calculations shown in Appendix Section 2.

It was also necessary to calculate power output of each SC type. Peak theoretical power output is given by Equation (4):

$$P_{max} = \frac{V_{max}^2}{4ESR} \tag{4}$$

$$Where:$$

$$V_{max} = Maximum\ theoretical\ voltage$$
$$ESR = Equivalent\ series\ resistance$$

For the Eaton XL60-R7308T-R cell, maximum theoretical power output was calculated as:

$$P_{max} = \frac{2.7^2}{4 \times (0.23 \times 10^{-3})} = 7923.913 \ldots W$$

$$P_{max} = 7900\ W\ (2\ s.f.)$$

The calculated figure corresponds to the manufacturer's datasheet.

All calculations shown in Appendix Section 3.

A more realistic estimate of maximum usable specific power is given by Equation 5 (IEC, 2006):

$$P_d = \frac{0.12 \times V^2}{ESR \times m} \tag{5}$$

For the Eaton XL60-R7308T-R cell, this gives a more conservative estimate of longer duration power delivery (<3 minutes) of

$$P_d = \frac{0.12 \times 2.7^2}{(0.23 \times -3) \times (515 \times 10^{-3})} = 7385.394681\ W\ kg^{-1}$$

$$P_d = 7400\ W\ kg^{-1}\ (2\ s.f.)$$

All calculations shown in Appendix Section 4

Table 4 shows the theoretical maximum power output and specific power output calculated for each cell.

Table 4 - SC Energy and Power Specification

Type	Specific Energy (Wh/kg)	Theoretical Maximum Power Output (Per Cell) (W)	Usable Specific Power (P_d) (W/kg)
Maxwell BCAP0350 E270 T11/T12	5.9	570	4600
Maxwell BCAP2000 P270 L04/05	5.6	5200	6900
Maxwell BCAP3400 P270 K04/05	6.7	6300	5900
Cap XX GY12R740070V807C	7.0	520	2200
Eaton XL60-R7308T-R	5.9	7900	7400
Tecate TPLH-2R7/3000SL60X138	5.8	7000	6400
LS Materials LSUC 002R7C 3000F NH	5.9	9100	8500

An average power density of 6000 W/kg was used to calculate subsequent results and reduce the quantity of calculations.

Table 5 shows the estimated figures for mass and range after battery mass was reduced by between 5% and 25% in 5% increments. The mass includes SCs added to maintain the peak power output of the vehicle. These additional masses are shown in Appendix Section 6.

Results for range were derived by multiplying the original stated range by the percentage reduction in battery size, assuming a linear relationship between battery mass and range.

Higher battery mass reductions were not considered due to the considerable reduction in range.

All results are shown in Appendix Sections 5 and 6.

Battery Size Retained, SCs Added

Table 6 shows the theoretical gains from adding an SC pack equivalent to 0.5 – 2.5% relative total mass for each specific model, in 0.5% increments. Previously results were calculated with 1 – 5kg in 1 kg increments, however this was revised to relative mass to be more appropriate for each model. The original battery capacity was used in this case, resulting in an increase to theoretical peak power output.

Battery degradation

As discussed, using SCs to limit peaks in battery currents during acceleration can reduce battery capacity and performance degradation.

No analysis was conducted on extending battery lifetime with SCs – conclusions were based on the literature review.

Cost

Cost implications were based on available SC module manufacturer datasheets and mass needed. Calculations were done on mass instead of number of SCs due to the average figures used, such as average power density. Cost implications of system design and testing were not analysed.

An average cost of £150/kg was used to calculate the cost of each module. This was based on the average specific cost of the SCs after calculating specific cost per kg of each type, based on their individual masses.

Full results are shown in Appendix Section 6.

Charge/Discharge Time

Equation (6) (RichardsonRFPD, 2021) was used to estimate charge/discharge times of the SC pack for each module size.

$$t = \frac{C(V_s - V_e)}{I} \tag{6}$$

$$\begin{aligned} &Where: \\ &t = Charge\ time\ in\ s \\ &C = Capacitance\ of\ SC\ pack \\ &V_s = Starting\ voltage \\ &V_e = Cut-off\ voltage \end{aligned}$$

The cut-off voltage was estimated at 1V. The actual cut-off voltage would depend on the system design and the battery management system.

The capacitance value used was an average specific capacitance value of 6000 F/kg.

Charge current was calculated using Equation (7). Capacitors are voltage limited, but can accept very high charge currents, allowing for rapid charging and discharging. SC modules can often accept >1 kA per capacitor (Maxwell Technologies, 2024). SCs are typically rated at <3V. All types used for this project are 2.7V.

$$I = \frac{SC\ P_d \times m}{V_R} \tag{7}$$

$$\begin{aligned} &Where: \\ &V_R = Rated\ voltage\ of\ SC\ (V) \\ &SC\ P_d = Averaged\ power\ density\ (W\ kg^{-1}) \\ &m = Mass\ of\ SC\ pack \end{aligned}$$

For the Livewire S2 Del Mar with 0.5% SC mass of the total motorbike mass added, this equated to:

$$I = \frac{6000 \times 0.4}{2.7} = 881\ A$$

Discharge time was then calculated as:

$$t = \frac{(6000 \times 0.40) \times (2.7 - 1)}{881} = 4.6311 \ldots\ s$$

$$t = 4.6\ s\ (2\ s.f.)$$

The theoretical discharge time of 4.6s is consistent for all SC masses, as while the voltage is constant, the current can increase significantly, a key differentiator between li-ion batteries and SCs.

Charge time for SC packs is likely to be limited by charging infrastructure. Fast chargers are currently limited to 500A (Spendiff-Smith, 2023). Therefore, theoretical charge times for the SC packs were calculated using this lower figure. Per kg of SC, this is just over 13 s.

For the equivalent SC mass as equation 7, charge time increased to 8.1 s when current limited.

Sustained power delivery of 1 minute was calculated using MS Excel's Goal Seek, to determine what current each mass of SC pack could deliver to supply one minute of power. A time of 3 minutes was originally used but the power supplied was minimal, under 1 kW for all SC sizes.

All results shown in Appendix Section 6.

Mass

Results for potential mass savings were calculated using the estimated average power density of 6000 W/kg previously calculated, and average specific capacitance value of 6000 F/kg which was based on manufacturer datasheets, of which the relevant data is shown in Table 3.

Capacitor energy capacitor is typically stated in Farads (F), whereas Watt-hours (Wh) is used for batteries.

To enable comparison, Wh/kg was used as a measure of specific capacity. This is an approximate way of comparing the energy density, and in practice the useable energy varies based on voltage required, and how the technology is used. Approximate capacities of both systems were estimated in the analysis, based on the quantity proposed and power output/voltage requirements of the motor.

A full analysis of the capacity implications would require design of the hybrid electrical management system, which was out of scope for this project.

Analysis of results

Results of the technical aspects were discussed separately based on the analysis done and research done on each topic.

The results were then discussed in context with the assumptions made, based on the requirement for further analysis and system design to verify potential benefits in a real-world scenario.

Results and Analysis

Reduced Battery Size

Table 5 shows estimations for range and total mass for each model after the battery mass was reduced between 5 – 25% in 5% increments.

This is visualised in Figure 4.

Table 5 - New Mass and Range Estimates - SCs Used to Maintain Peak Power

Model	**Original Total Mass (kg)**	**Range (EU 134/2014 Drive Cycle) (km)**	**New Total Mass After Battery Mass Reduced 5%-25%**					**New Total Range After Battery Mass Reduced 5%-25%**				
			5%	**10%**	**15%**	**20%**	**25%**	**5%**	**10%**	**15%**	**20%**	**25%**
Livewire S2 Del Mar	198	111	196	193	191	188	186	105	100	94	89	83
Energica Experia	260	222	255	250	245	239	234	211	200	189	178	167
Zero DSR/X	247	172	243	239	235	231	227	163	155	146	138	129
Energica Eva Ribelle	260	180	255	250	245	239	234	171	162	153	144	135
Zero SR/F	227	188	223	219	215	211	207	179	169	160	150	141
Maeving RM1	111	48	110	110	109	109	108	46	43	41	38	36
Zero S	223	162	220	216	213	210	206	154	146	138	130	122

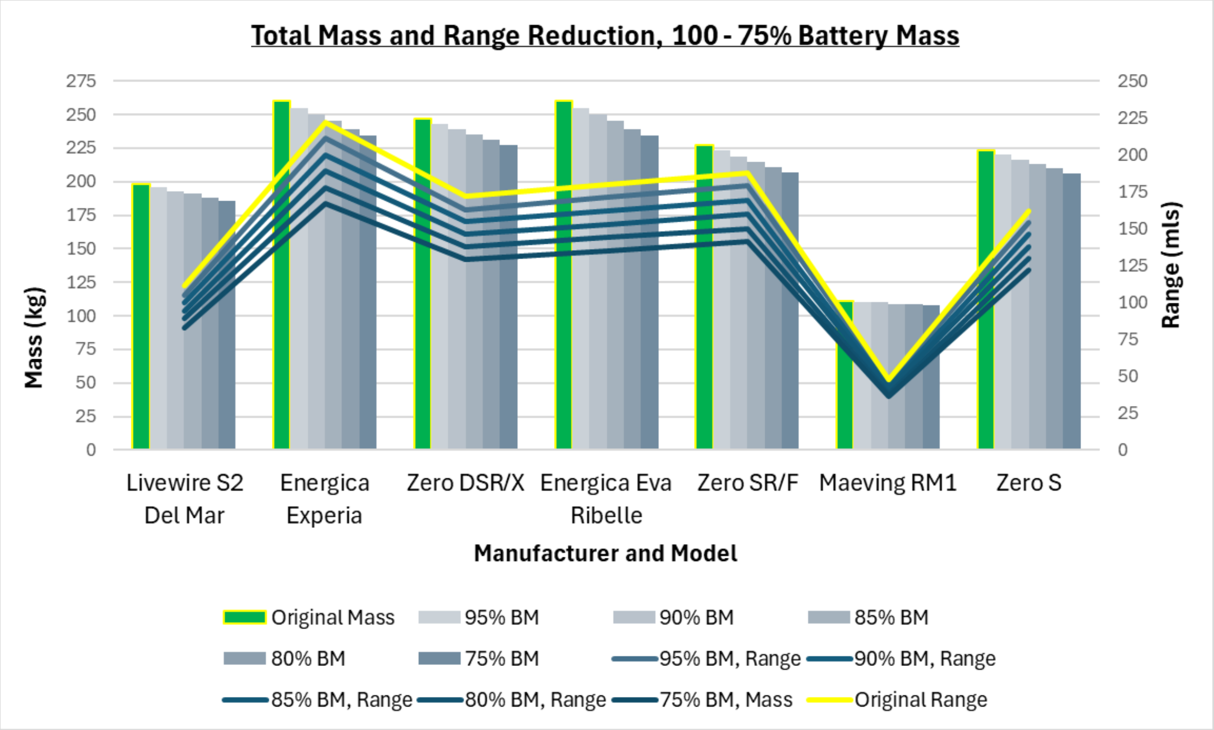

Figure 4 - Mass and Range Implications of Reducing Battery Mass

Battery Size Retained, SCs Added

Table 6 shows the theoretical gains from adding an SC pack equivalent to 0.5 – 2.5% relative total mass for each specific model, in 0.5% increments. This is visualised in Figure 5. The power increase of the Maeving RM1 appears to be unrealistic.

Table 6 - Peak Power Increase with 0.5% - 2.5% Relative Mass SCs added.

Model	Original Total Mass (kg)	Peak Power Output (kW)	Relative SC Mass Added, Revised Peak Power (kW)					Relative SC Mass Added, Power Increase (%)				
			0.5%	**1%**	**1.5%**	**2%**	**2.5%**	**0.5%**	**1%**	**1.5%**	**2%**	**2.5%**
Livewire S2 Del Mar	198	63	69	75	81	87	93	9%	19%	28%	38%	47%
Energica Experia	260	75	83	91	98	106	114	10%	21%	31%	42%	52%
Zero DSR/X	247	75	82	90	97	105	112	10%	20%	30%	40%	49%
Energica Eva Ribelle	260	126	134	142	149	157	165	6%	12%	19%	25%	31%
Zero SR/F	227	84	91	98	104	111	118	8%	16%	24%	32%	41%
Maeving RM1	111	4.4	8	11	14	18	21	76%	151%	227%	303%	378%
Zero S	223	45	52	58	65	72	78	15%	30%	45%	59%	74%

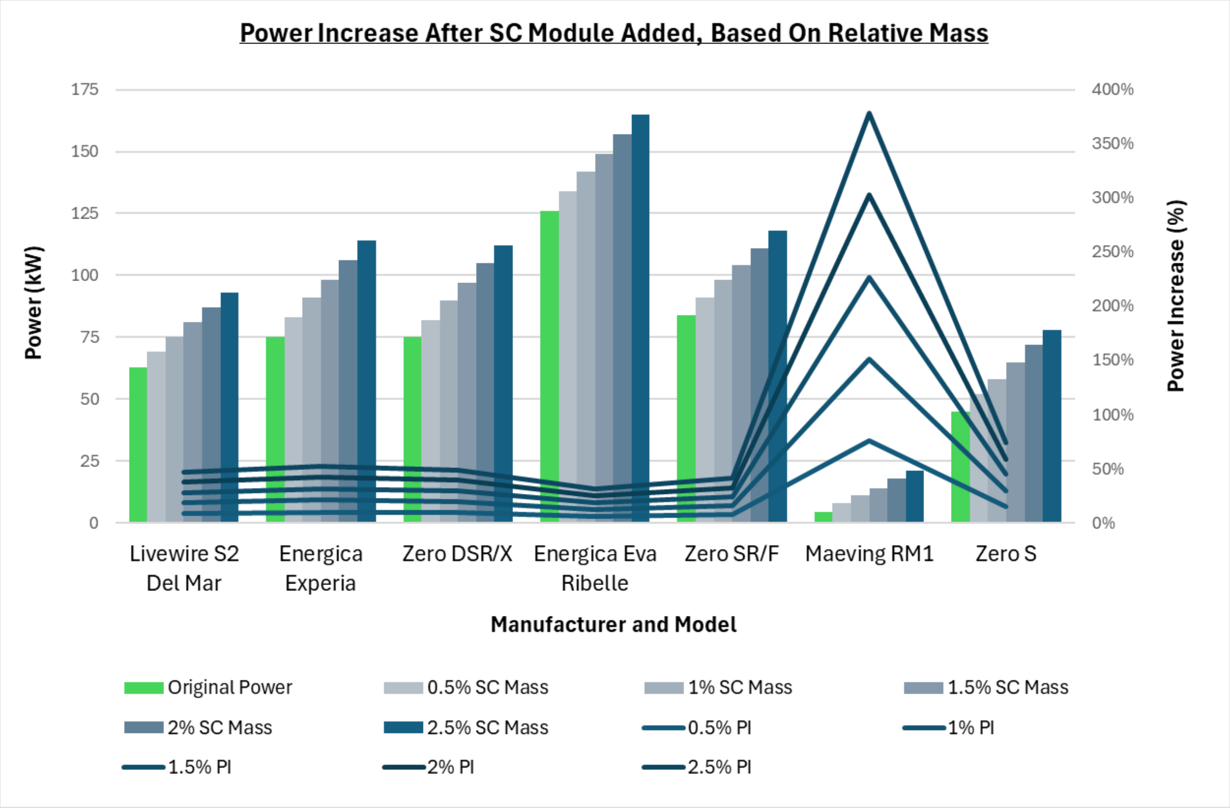

Figure 5 - Peak Power Output and Power Increase %

Charge time

Table 7 shows the estimated charge times of each relative SC mass, between 0.5 – 2.5% relative total mass of each model, when current limited to 500A.

Table 7 - Charge Time of SC Module, 0.5% - 2.5% of Motorcycle Mass

Model	**Relative SC Mass Added, Charge Time (s), Current Limited to 500A**				
	0.5%	**1%**	**1.5%**	**2%**	**2.5%**
Livewire S2 Del Mar	8.1	16	24	32	40
Energica Experia	17	34	51	68	85
Zero DSR/X	13	27	40	53	67
Energica Eva Ribelle	17	34	51	68	85
Zero SR/F	13	27	40	53	67
Maeving RM1	1.7	3.4	5.1	6.8	8.5
Zero S	11	22	33	44	55

Figure 6 visualises the increase in charge time as the SC module increases in mass.

Full results are shown in Appendix Section 6.

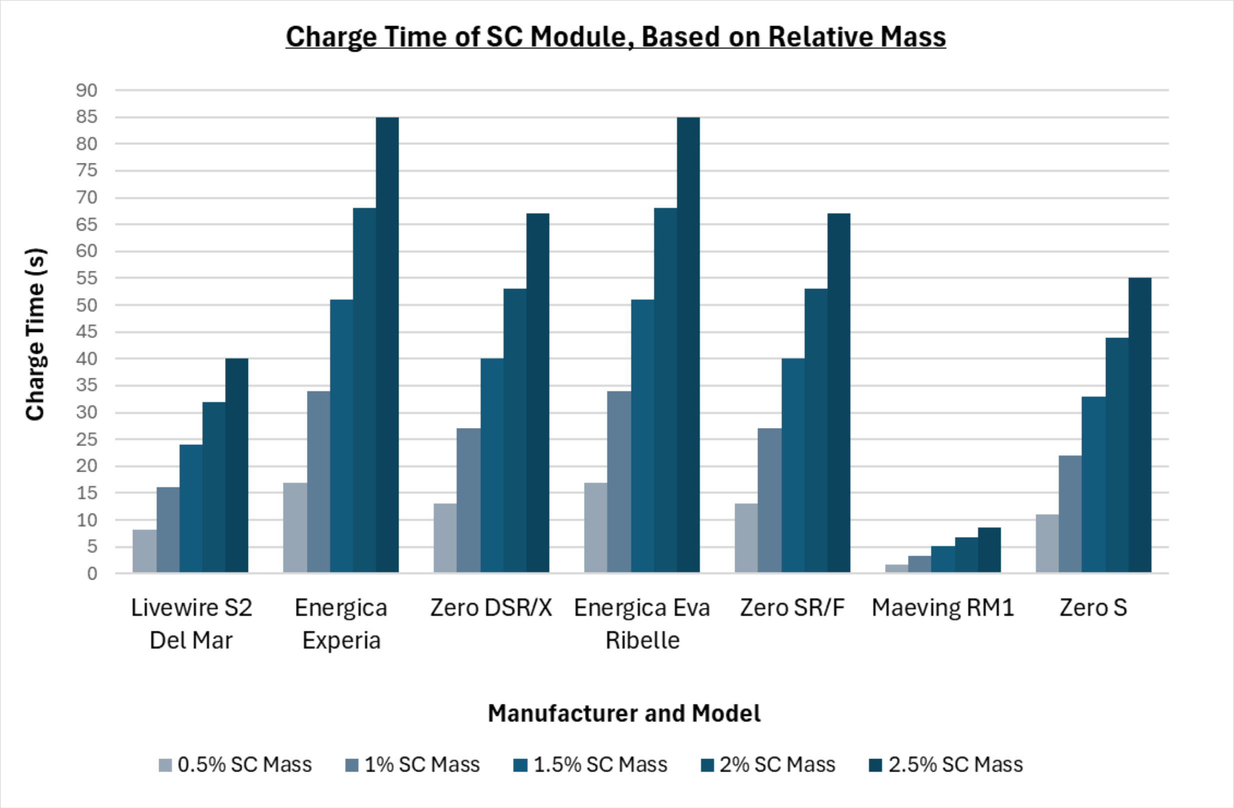

Figure 6 - Increase in Charge Time Relative to SC Module Size

Discharge – Sustained Power

By reducing the current during discharge, the SCs can be used for a sustained amount of time. Power output is maintained for a longer duration, for example for 30 seconds or a minute as calculated in Table 8 and Table 9, but at a reduced power output.

Table 8 - Additional Power Available as a Percentage of Peak Power for 30 Seconds

Model	**30 s Discharge, SC Mass Relative to Total Mass, Percentage of Peak Power Delivered (kW)**				
	0.50%	**1%**	**1.50%**	**2%**	**2.50%**
Livewire S2 Del Mar	0.58%	1.16%	1.73%	2.31%	2.89%
Energica Experia	1.02%	2.04%	3.07%	4.09%	5.11%
Zero DSR/X	0.80%	1.60%	2.40%	3.20%	4.00%
Energica Eva Ribelle	0.61%	1.22%	1.83%	2.43%	3.04%
Zero SR/F	0.71%	1.43%	2.14%	2.86%	3.57%
Maeving RM1	1.74%	3.48%	5.23%	6.97%	8.71%
Zero S	1.11%	2.21%	3.32%	4.43%	5.54%

Table 9 shows the power available for a 1 minute duration, as a percentage of total peak power.

Table 9 - Additional Power Available as a Percentage of Peak Power for 1 Minute

Model	**1 Minute Discharge, SC Mass Relative to Total Mass, Percentage of Peak Power Delivered (kW)**				
	0.50%	**1%**	**1.50%**	**2%**	**2.50%**
Livewire S2 Del Mar	0.29%	0.58%	0.87%	1.16%	1.44%
Energica Experia	0.51%	1.02%	1.53%	2.04%	2.56%
Zero DSR/X	0.40%	0.80%	1.20%	1.60%	2.00%
Energica Eva Ribelle	0.30%	0.61%	0.91%	1.22%	1.52%
Zero SR/F	0.36%	0.71%	1.07%	1.43%	1.79%
Maeving RM1	0.87%	1.74%	2.61%	3.48%	4.36%
Zero S	0.55%	1.11%	1.66%	2.21%	2.77%

Figure 7 and Figure 8 visualise the potential additional power available for 30 seconds and 1 minute respectively.

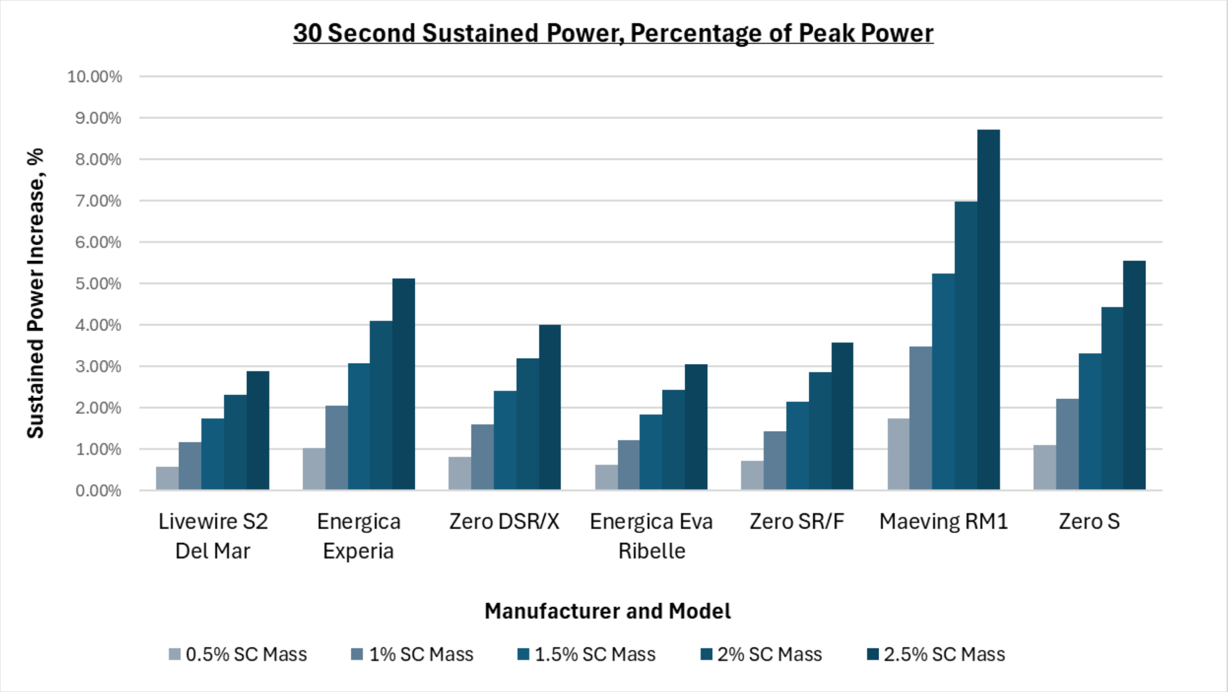

Figure 7 - Available Power as a Percentage of Peak Power for 30 seconds

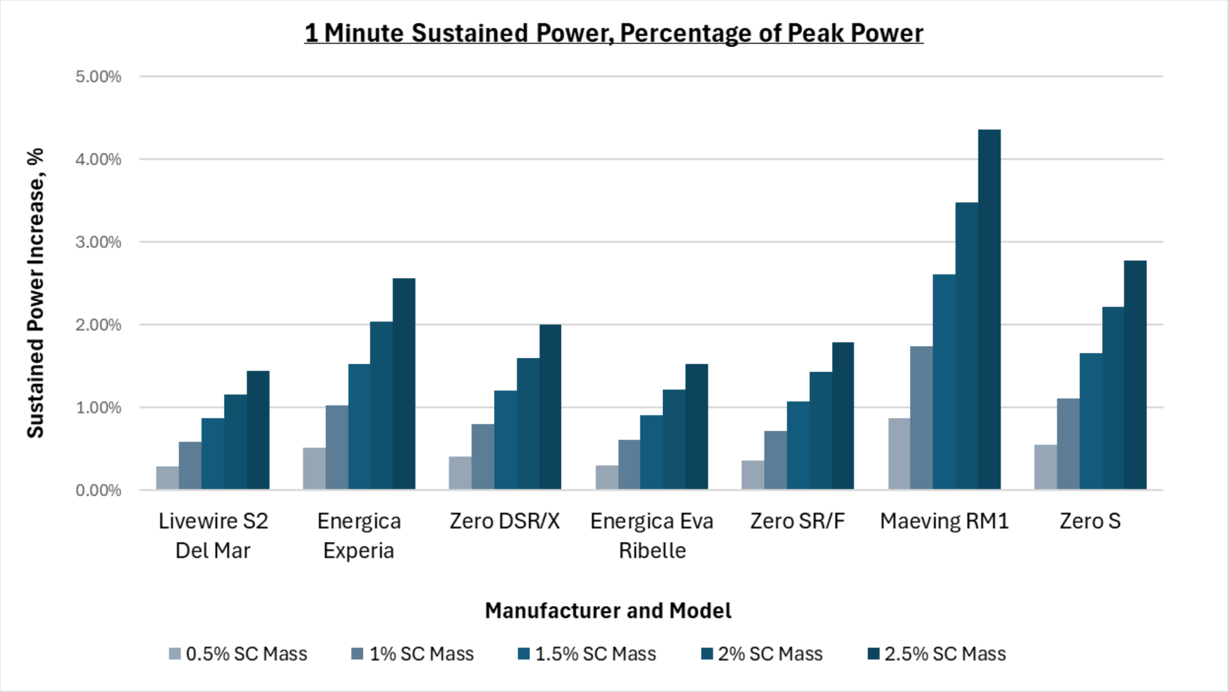

Figure 8 - Available Power as a Percentage of Peak Power for 1 Minute

Cost

Table 10 shows the estimated cost of the SC module added to each motorcycle, based on the relative mass added.

Full results are shown in Appendix Section 6.

Table 10 - Cost of SC Module, 0.5% - 2.5% of Motorcycle Relative Mass

Model	**Relative SC Mass Added, Estimated Cost (£)**				
	0.5%	**1%**	**1.5%**	**2%**	**2.5%**
Livewire S2 Del Mar	59	118	177	236	296
Energica Experia	124	249	373	498	622
Zero DSR/X	97	195	292	390	487
Energica Eva Ribelle	124	249	373	498	622
Zero SR/F	97	195	292	390	487
Maeving RM1	12	25	37	50	62
Zero S	81	162	243	324	404

Figure 9 visualises the cost of the SC modules.

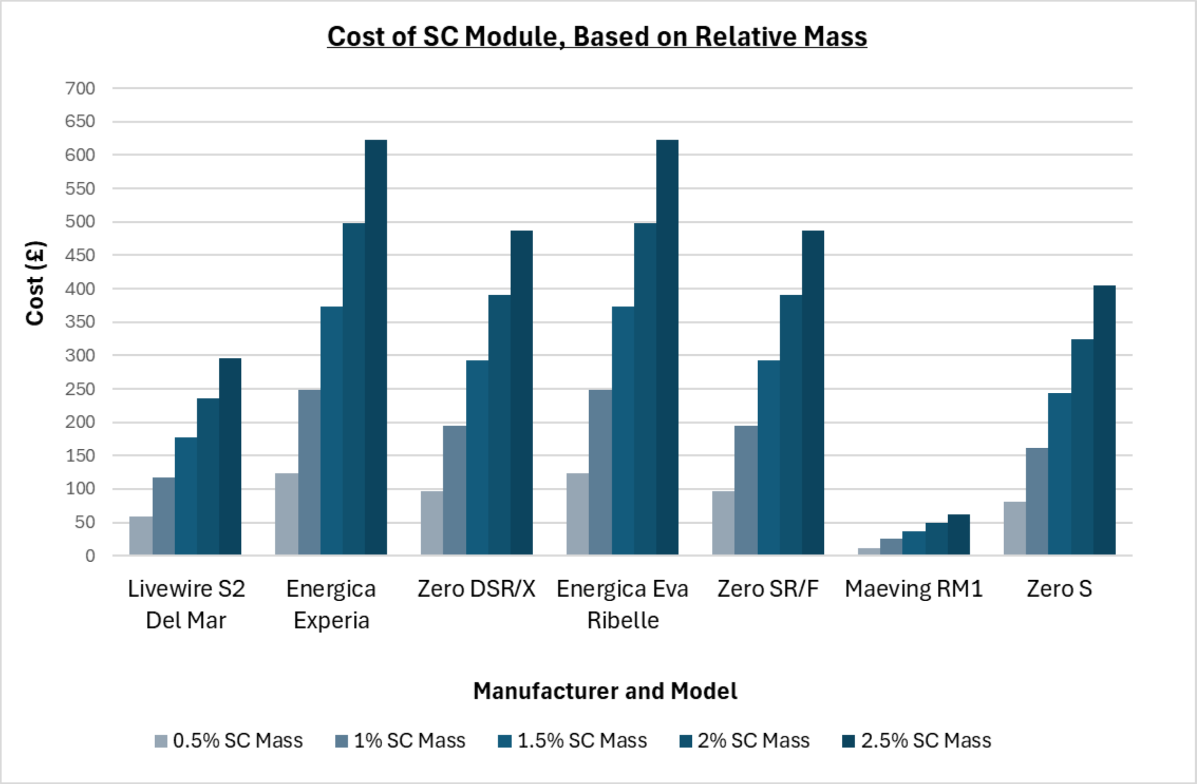

Figure 9 - Cost of SC Module Sizes

Discussion

Reduced Battery Mass

Reducing battery mass between 5 – 25% resulted in a theoretical mass saving of between 0.5% and 10%, while maintaining peak power output. Greater opportunities for mass reduction were seen on the models where the battery was a higher ratio of the total mass compared to other models – the Energica Experia and the Energica Eva Ribelle. Due to the smaller size and modular nature of the SCs compared to a li-ion battery pack, it might be possible to improve weight distribution by placing the SCs low in the frame – this is more difficult with a large battery pack.

However, any battery mass reduction inevitably reduced the total range by 5 – 25%, although this figure did not include additional energy put into the system by the SCs. Whether the reduction in range of up to 56km would be justified may be dependent on the use case of the vehicle. For a touring model this would not be acceptable, but a reduction in mass of 20 kg is significant for sports models and could significantly improve handling. This might be suitable for a track-focused variant where maximum range is less critical, and the motorcycle could be charged frequently between sessions.

Table 11 - Mass Savings and Range Loss

Model	**Mass Reduction (5 -25% battery mass removed) (kg)**	**Range Loss (5 – 25% Battery Mass Reduction) (km)**
Livewire S2 Del Mar	2.5 – 12	6 – 28
Energica Experia	5.2 – 26	11 - 56
Zero DSR/X	4.0 – 20	9 – 43
Energica Eva Ribelle	5.2 – 26	9 – 45
Zero SR/F	4.0 – 20	9 – 47
Maeving RM1	0.5 – 2.6	2 – 12
Zero S	3.4 - 17	8 - 41

Battery mass preserved, SCs added

All models saw a large potential increase in peak power output. The Energica Eva Ribelle power increase was the lowest at 6% at 0.5% SC relative mass to 31% at 2.5% relative mass (6.5kg).

The results for the Maeving RM1 suggest up to a 378% peak power increase. This is an unrealistic result – this is a low-powered model with a normal peak power of 4.4 kW. Adding just 1% of the motorcycle’s mass as SCs theoretically improves power by 150%. This is due to the power density of the SCs quickly surpassing the capabilities of the vehicle, and would require major changes to the motor, chassis and suspension. This would increase mass, cost and significantly reduce the already short range.

The theoretical peak powers observed would be unlikely to be achieved due to limitations of the motor and electrical system. A higher power output motor would likely be higher mass; the range reduction due to this has not been accounted for.

Peak power delivery would be short (<5s) based on unlimited discharge current (as discussed on page 17). A more realistic use case might be to limit peak output from the SCs so that peak power can be used for multiple accelerations, such as 30 seconds and 1 minute as shown in Figure 7 and Figure 8. The results show a modest increase in power for these extended power bursts – approximately between 1.5 – 4.5% when the discharge is extended to a minute and between 3 – 9% when reduced to 30 seconds. This power delivery duration may be sufficient for several starts from traffic lights. This would also reduce the performance requirements of the motor and the electrical system, and the associated costs compared to a higher peak power output.

While the peak power increase figures are impressive, the low energy density remains a significant drawback of SCs, and might limit their application to specific use cases, such as where acceleration is a priority. This could be decided at the design stage of a model or selected via riding modes.

Battery Degradation

There is ample research to suggest that battery lifetime can be optimised with SCs by limiting currents and thus limiting heat build-up, reducing battery use and number of cycles due to improved capture of regenerative energy.

Successful implementation requires an intelligent battery management system that can manage the battery/SC system while detrimentally affecting the function of the vehicle.

Charge Time

Charge time is between 1.7 and 85 seconds for all SC masses, at a current limited at 500A. Current infrastructure and usage habits mean using cable charging the SCs might only receive one or two charges a day. Recharge during use of the vehicle is feasible. This could be done in several ways including:

- Regenerative power from the motor during engine braking
- Regenerative braking
- Power from the battery during periods of lower power demand
- Wireless charging from infrastructure

Regenerative power from the motor or brakes recoup energy otherwise lost to heat, so are often used for EVs. Handling of the vehicle could be affected negatively. Good handling is often a priority for motorcycles as they are often a recreational vehicle; testing and development would be required to ensure energy recovery without significantly affecting the performance. SCs would enable higher efficiency if used with regenerative braking; batteries cannot capture all braking energy due to the restricted charge rate (Perrotta *et al.*, 2012).

The battery could also be used to slowly recharge the SCs during periods of lower power demand such as during cruising (Nielson and Emadi, 2011). This would impact range but make peak power consistent.

Current infrastructure does not currently allow for non-contact grid charging. However, wireless charging could be used to charge SCs in cities where traffic is often stationary.

Cost

Potential costs of implementing SCs between 0.5% and 2.5% relative vehicle mass range from £12 to £622. However, this is an unrealistically low cost due to:

- Price based on average specific cost, not number of modules. The cost would increase due to the nearest number of whole modules being required
- Not including the battery management system and equipment needed to implement SCs
- Cost of higher performance motor not included

However, costs do not appear to be prohibitive based on the current costs of electric motorcycles. Of the models analysed, the Maeving RM1 was the outlier at a starting cost of £4,995 at the time of writing (Maeving, 2024a). The other models range from £15,300 to £27,540 as of September 2024.

Further Work

Modelling of the battery/SC system would be needed to test the results and verify what kind of performance might be achievable.

A test-bed prototype could then be built to develop the battery/SC management system and perform tests.

Conclusions

- Moderate mass savings are potentially possible when reducing the battery mass – A battery mass reduction of 25% results in a mass saving of up 10% total mass of the motorcycles analysed. This has a significant negative effect on range, so use case must be considered.
- Peak power output could be increased significantly with a relatively small mass of up to 2.5% SC mass, relative to the specific vehicle mass. The smallest increase at 2.5% was 31% peak power increase, by adding 6.5kg of SCs (does not include mass of upgraded motor). Results suggested that <1.5kg of SC added could add 6 – 15% output.
- Charging of the SCs could be done via the grid (fast - <85s) or on-board through regenerative energy or the battery. Peak power would drain the SCs very quickly (<5s), but reduced power could give significant performance benefits for a reasonable duration if used in short acceleration bursts (<1 mins total).
- SC discharge rate can be reduced to provide a modest additional power output over a minute of between 1.5 – 9 % depending on the SC mass used.
- Costs to implement SCs are difficult to estimate due to the additional costs. Compared to the total cost of the vehicle, the cost of the SCs appears to be relatively small.
- Battery lifetime can be improved when coupled with SCs. This requires a sufficient battery management system.
- Energy density is the main limiter for the practicality of implementing SCs.

[5674 words]

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Appendix

1. Estimated battery masses:

Model	Total Mass (kg)	Battery Capacity (kWh)	Battery Mass	Battery Mass as Percentage of Total Mass
Livewire S2 Del Mar	198	10.5	$M = \frac{10500}{185} = 56.756$ $M = 57\ kg\ (2\ s.f.)$	$\frac{57}{198} = 28.7\%$ $29\%\ (2\ s.f.)$
Energica Experia	260	22.5	$M = \frac{22500}{185} = 121.621$ $M = 120\ kg\ (2\ s.f.)$	$\frac{120}{260} = 46.2\%$ $46\%\ (2\ s.f.)$
Zero DSR/X	247	17.3	$M = \frac{17300}{185} = 93.513$ $M = 94\ kg\ (2\ s.f.)$	$\frac{94}{247} = 38.1\%$ $38\%\ (2\ s.f.)$
Energica Eva Ribelle	260	21.5	$M = \frac{21500}{185} = 116.216$ $M = 120\ kg\ (2\ s.f.)$	$\frac{120}{260} = 46.1\%$ $46\%\ (2\ s.f.)$
Zero SR/F	227	17.3	$M = \frac{17300}{185} = 93.513$ $M = 94\ kg\ (2\ s.f.)$	$\frac{94}{227} = 41.4\%$ $41\%\ (2\ s.f.)$
Maeving RM1	111	2	$M = \frac{2000}{185} = 10.81$ $M = 11\ kg\ (2\ s.f.)$ **(Official figure 12 kg)**	$\frac{12}{111} = 10.8\%$ $11\%\ (2\ s.f.)$
Zero S	223	14.4	$M = \frac{14400}{185} = 77.837$ $M = 78\ kg\ (2\ s.f.)$	$\frac{78}{223} = 35.0\%$ $35\%\ (2\ s.f.)$

2. Capacitor Specific Energy

Type	Capacitance (F)	Voltage (V)	Mass (g)	Specific Energy (Wh/kg)
Maxwell BCAP0350 E270 T11/T12	350	2.7	60	$E_{max} = \frac{\frac{1}{2}(350 \times 2.7^2)}{3,600} = 0.354375\ Wh$ $E_s = \frac{0.354375}{60 \times 10^{-3}} = 5.90625\ Wh\ kg^{-1}$ $E_s = 5.9\ (2\ s.f.)\ Wh\ kg^{-1}$
Maxwell BCAP2000 P270 L04/05	2000	2.7	360	$E_{max} = \frac{\frac{1}{2}(2000 \times 2.7^2)}{3,600} = 2.025\ Wh$ $E_s = \frac{2.025}{360 \times 10^{-3}} = 5.625\ Wh\ kg^{-1}$ $E_s = 5.6\ (2\ s.f.)\ Wh\ kg^{-1}$
Maxwell BCAP3400 P270 K04/05	3400	2.7	513	$E_{max} = \frac{\frac{1}{2}(3400 \times 2.7^2)}{3,600} = 3.4425\ Wh$ $E_s = \frac{3.4425}{513 \times 10^{-3}} = 6.7105\ \ldots.Wh\ kg^{-1}$ $E_s = 6.7\ (2.s.f.)\ Wh\ kg^{-1}$
Cap XX GY12R740070V807C	800	2.7	115	$E_{max} = \frac{\frac{1}{2}(800 \times 2.7^2)}{3,600} = 0.81\ Wh$ $E_s = \frac{0.81}{115 \times 10^{-3}} = 7.0434\ \ldots.Wh\ kg^{-1}$ $E_s = 7.0\ (2.s.f.)\ Wh\ kg^{-1}$
Eaton XL60-R7308T-R	3000	2.7	515	$E_{max} = \frac{\frac{1}{2}(3000 \times 2.7^2)}{3,600} = 3.0375\ Wh$ $E_s = \frac{3.0375}{515 \times 10^{-3}} = 5.8980\ \ldots.Wh\ kg^{-1}$ $E_s = 5.9\ (2.s.f.)\ Wh\ kg^{-1}$
Tecate TPLH-2R7/3000SL60X138	3000	2.7	525	$E_{max} = \frac{\frac{1}{2}(3000 \times 2.7^2)}{3,600} = 3.0375\ Wh$

				$E_s = \frac{3.0375}{525 \times 10^{-3}} = 5.7857 \ldots .\,Wh\,kg^{-1}$ $E_s = 5.8\ (2.s.f.)Wh\,kg^{-1}$
LS Materials LSUC 002R7C 3000F NH	3000	2.7	515	$E_{max} = \frac{\frac{1}{2}(3000 \times 2.7^2)}{3{,}600} = 3.0375\ Wh$ $E_s = \frac{3.0375}{515 \times 10^{-3}} = 5.8980 \ldots .\,Wh\,kg^{-1}$ $E_s = 5.9\ (2.s.f.)\ Wh\,kg^{-1}$

3. Peak Theoretical Power Output

Type	Voltage (V)	Equivalent Series Resistance (ESR) (mΩ)	Theoretical Maximum Power Output (Per Cell) (W)
Maxwell BCAP0350 E270 T11/T12	2.7	3.2	$P_{max} = \frac{2.7^2}{4 \times (3.2 \times 10^{-3})} = 569.53125\ W$ $P_{max} = 570\ W\ (2\ s.f.)$
Maxwell BCAP2000 P270 L04/05	2.7	0.35	$P_{max} = \frac{2.7^2}{4 \times (0.35 \times 10^{-3})} = 5207.142857\ W$ $P_{max} = 5200\ W\ (2\ s.f.)$
Maxwell BCAP3400 P270 K04/05	2.7	0.29	$P_{max} = \frac{2.7^2}{4 \times (0.29 \times 10^{-3})} = 6284.4827 \ldots W$ $P_{max} = 6300\ W\ (2\ s.f.)$
Cap XX GY12R740070V807C	2.7	3.5	$P_{max} = \frac{2.7^2}{4 \times (3.5 \times 10^{-3})} = 520.7142 \ldots W$ $P_{max} = 520\ W\ (2\ s.f.)$
Eaton XL60-R7308T-R	2.7	0.23	$P_{max} = \frac{2.7^2}{4 \times (0.23 \times 10^{-3})} = 7923.913 \ldots W$ $P_{max} = 7900\ W\ (2\ s.f.)$

Tecate TPLH-2R7/3000SL60X138	2.7	0.26	$P_{max} = \frac{2.7^2}{4 \times (0.26 \times 10^{-3})} = 7009.6153 \ldots W$ $P_{max} = 7000\ W\ (2\ s.f.)$
LS Materials LSUC 002R7C 3000F NH	2.7	0.20	$P_{max} = \frac{2.7^2}{4 \times (0.20 \times 10^{-3})} = 9112.5\ W$ $P_{max} = 9100\ W\ (2\ s.f.)$

4. Usable Specific Power (P_d)

Type	Voltage (V)	Equivalent Series Resistance (ESR) (mΩ)	Mass (g)	Usable Specific Power (P_d) (W/kg)
Maxwell BCAP0350 E270 T11/T12	2.7	3.2	60	$P_d = \frac{0.12 \times 2.7^2}{(3.2 \times -3) \times (60 \times 10^{-3})} = 4556.25$ $P_d = 4600\ W\ kg^{-1}\ (2\ s.f)$
Maxwell BCAP2000 P270 L04/05	2.7	0.35	360	$P_d = \frac{0.12 \times 2.7^2}{(0.35 \times -3) \times (360 \times 10^{-3})} = 6942.8571 \ldots$ $P_d = 6900\ W\ kg^{-1}\ (2\ s.f.)$
Maxwell BCAP3400 P270 K04/05	2.7	0.29	513	$P_d = \frac{0.12 \times 2.7^2}{(0.29 \times -3) \times (513 \times 10^{-3})} = 5880.2177 \ldots$ $P_d = 5900\ W\ kg^{-1}\ (2\ s.f.)$
Cap XX GY12R740070V807C	2.7	3.5	115	$P_d = \frac{0.12 \times 2.7^2}{(3.5 \times -3) \times (115 \times 10^{-3})} = 2173.4161 \ldots$ $P_d = 2200\ W\ kg^{-1}\ (2\ s.f.)$
Eaton XL60-R7308T-R	2.7	0.23	515	$P_d = \frac{0.12 \times 2.7^2}{(0.23 \times -3) \times (515 \times 10^{-3})} = 7385.394681\ W\ kg^{-1}$

				$P_d = 7400\ W\ kg^{-1}\ (2\ s.f.)$
Tecate TPLH-2R7/3000SL60X138	2.7	0.26	525	$P_d = \frac{0.12 \times 2.7^2}{(0.26 \times -3) \times (525 \times 10^{-3})} = 6408.7912 \ldots$ $P_d = 6400\ W\ kg^{-1}\ (2\ s.f.)$
LS Materials LSUC 002R7C 3000F NH	2.7	0.20	515	$P_d = \frac{0.12 \times 2.7^2}{(0.20 \times -3) \times (515 \times 10^{-3})} = 8493.2038 \ldots$ $P_d = 8500\ W\ kg^{-1}\ (2\ s.f.)$

5. Excel Figures

Type	**Mass/ cell (g)**	**Capacitance**	**Specific Capacitance (F/kg)**	**Cost/ cell (£)**	**Cost /kg (£/kg)**	**Specific Energy (Wh/ kg)**	**Theoretical Maximum Power Output (Per Cell) (W)**	**Usable Specific Power (P_d) (W/kg)**
Maxwell BCAP0350 E270 T11/T12	60	350	5833	12.36	206	5.9	570	4600
Maxwell BCAP2000 P270 L04/05	360	2000	5556	50.01	139	5.6	5200	6900
Maxwell BCAP3400 P270 K04/05	513	3400	6628			6.7	6300	5900
Cap XX GY12R74007 0V807C	115	800	6957			7	520	2200
Eaton XL60-R7308T-R	515	3000	5825	85.54	166	5.9	7900	7400
Tecate TPLH-2R7/3000SL6 0X138	525	3000	5714	44.66	85	5.8	7000	6400
LS Materials LSUC 002R7C 3000F NH	515	3000	5825			5.9	9100	8500
Averages			6000	48.1425	149			5985.714286
Average 2 SF(Used in formulae)			6000	48	150			6000

Energy Density (kWh/kg)	0.185
Li-ion Power Density (kW/kg)	0.835
SC Pd (kW/kg)	6
SC Pd (W/kg)	6000
SC Charge Current (A)	500

6. Excel Results

95% Battery Mass

95% Battery Capacity							
95% Battery Mass (kg)	**95% Battery Energy**	**95% Battery Range**	**Power required from SCs**	**SC Mass Added**	**SC Cost (£)**	**New Mass (kg)**	**Total Mass Reduction (%)**
54	10	105	2.38	0.40	59	196	-1.24%
114	21	211	5.01	0.84	124	255	-1.99%
89	17	163	3.92	0.65	97	243	-1.64%
114	21	171	5.01	0.84	124	255	-1.99%
89	17	179	3.92	0.65	97	223	-1.78%
11	2	46	0.50	0.08	12	110	-0.47%
74	14	154	3.26	0.54	81	220	-1.51%

90% Battery Mass

90% Battery Mass							
90% Battery Mass (kg)	**90% Battery Energy**	**90% Battery Range**	**Power required from SCs**	**SC Mass Added**	**SC Cost (£)**	**New Mass (kg)**	**Total Mass Reduction (%)**
51	9	100	4.76	0.79	118	193	-2.48%
108	20	200	10.02	1.67	249	250	-3.97%
85	16	155	7.85	1.31	195	239	-3.28%
108	20	162	10.02	1.67	249	250	-3.97%
85	16	169	7.85	1.31	195	219	-3.56%
11	2	43	1.00	0.17	25	110	-0.93%
70	13	146	6.51	1.09	162	216	-3.01%

85% Battery Mass

85% Battery Mass							
85% Battery Mass (kg)	**85% Battery Energy**	**85% Battery Range**	**Power required from SCs**	**SC Mass Added**	**SC Cost (£)**	**New Mass (kg)**	**Total Mass Reduction (%)**
48	9	94	7.14	1.19	177	191	-3.72%
102	19	189	15.03	2.51	373	245	-5.96%
80	15	146	11.77	1.96	292	235	-4.91%
102	19	153	15.03	2.51	373	245	-5.96%
80	15	160	11.77	1.96	292	215	-5.35%
10	2	41	1.50	0.25	37	109	-1.40%
66	12	138	9.77	1.63	243	213	-4.52%

80% Battery Mass

80% Battery Mass							
80% Battery Mass (kg)	**80% Battery Energy**	**80% Battery Range**	**Power required from SCs**	**SC Mass Added**	**SC Cost (£)**	**New Mass (kg)**	**Total Mass Reduction (%)**
46	8	89	9.52	1.59	236	188	-4.96%
96	18	178	20.04	3.34	498	239	-7.95%
75	14	138	15.70	2.62	390	231	-6.55%
96	18	144	20.04	3.34	498	239	-7.95%
75	14	150	15.70	2.62	390	211	-7.13%
10	2	38	2.00	0.33	50	109	-1.86%
62	12	130	13.03	2.17	323	210	-6.02%

75% Battery Mass

75% Battery Mass							
75% Battery Mass (kg)	**75% Battery Energy**	**75% Battery Range**	**Power required from SCs**	**SC Mass Added**	**SC Cost (£)**	**New Mass (kg)**	**Total Mass Reduction (%)**
43	8	83	11.90	1.98	295	186	-6.20%
90	17	167	25.05	4.18	622	234	-9.93%
71	13	129	19.62	3.27	487	227	-8.19%
90	17	135	25.05	4.18	622	234	-9.93%
71	13	141	19.62	3.27	487	207	-8.91%
9	2	36	2.51	0.42	62	108	-2.33%
59	11	122	16.28	2.71	404	206	-7.53%

0.5% SC Relative Mass

0.5% SC Mass						
0.5% SCs Added, Total Mass	**0.5% SCs Added, Total Power (kW)**	**0.5% SCs Added, Mass Change (%)**	**0.5% SCs, Power Increase (%)**	**Discharge Current (A)**	**Discharge Time (s)**	**Charge Time (s)**
198.99	69	0.50%	9%	881	4.59	8.09
261.30	83	0.50%	10%	1856	4.59	17.03
248.24	82	0.50%	10%	1454	4.59	13.34
261.30	134	0.50%	6%	1856	4.59	17.03
228.14	91	0.50%	8%	1454	4.59	13.34
111.56	8	0.50%	76%	186	4.59	1.70
224.12	52	0.50%	15%	1206	4.59	11.07

1.0% SC Relative Mass

1% SC Mass						
1% SCs Added, Total Mass	**1% SCs Added, Total Power (kW)**	**1% SCs Added, Mass Change (%)**	**1% SCs, Power Increase (%)**	**Discharge Current (A)**	**Discharge Time (s)**	**Charge Time (s)**
199.98	75	1.00%	19%	1763	4.6	16.2
262.60	91	1.00%	21%	3711	4.6	34.1
249.47	90	1.00%	20%	2907	4.6	26.7
262.60	142	1.00%	12%	3711	4.6	34.1
229.27	98	1.00%	16%	2907	4.6	26.7
112.11	11	1.00%	151%	371	4.6	3.4
225.23	58	1.00%	30%	2412	4.6	22.1

1.5% SC Relative Mass

1.5% SC Mass						
1.5% SCs Added, Total Mass	**1.5% SCs Added, Total Power (kW)**	**1.5% SCs Added, Mass Change (%)**	**1.5% SCs, Power Increase (%)**	**Discharge Current (A)**	**Discharge Time (s)**	**Charge Time (s)**
200.97	81	1.50%	28%	2644	4.59	24.3
263.90	98	1.50%	31%	5567	4.59	51.1
250.71	97	1.50%	30%	4361	4.59	40.0
263.90	149	1.50%	19%	5567	4.59	51.1
230.41	104	1.50%	24%	4361	4.59	40.0
112.67	14	1.50%	227%	557	4.59	5.1
226.35	65	1.50%	45%	3618	4.59	33.2

2.0% SC Relative Mass

2% SC Mass						
2% SCs Added, Total Mass	**2% SCs Added, Total Power (kW)**	**2% SCs Added, Mass Change (%)**	**2% SCs, Power Increase (%)**	**Discharge Current (A)**	**Discharge Time (s)**	**Charge Time (s)**
201.96	87	2.00%	38%	3526	4.59	32.4
265.20	106	2.00%	42%	7422	4.59	68.1
251.94	105	2.00%	40%	5814	4.59	53.4
265.20	157	2.00%	25%	7422	4.59	68.1
231.54	111	2.00%	32%	5814	4.59	53.4
113.22	18	2.00%	303%	742	4.59	6.8
227.46	72	2.00%	59%	4824	4.59	44.3

2.5% SC Relative Mass

2.5% SC Mass						
2.5% SCs Added, Total Mass	**2.5% SCs Added, Total Power (kW)**	**2.5% SCs Added, Mass Change (%)**	**2.5% SCs, Power Increase (%)**	**Discharge Current (A)**	**Discharge Time (s)**	**Charge Time (s)**
202.95	93	2.50%	47%	4407	4.59	40.46
266.50	114	2.50%	52%	9278	4.59	85.17
253.18	112	2.50%	49%	7268	4.59	66.72
266.50	165	2.50%	31%	9278	4.59	85.17
232.68	118	2.50%	41%	7268	4.59	66.72
113.78	21	2.50%	378%	928	4.59	8.52
228.58	78	2.50%	74%	6031	4.59	55.36

7. Sustained Discharge Results

Discharge Current and Power, 30 Second/1 Minute Sustained Power, 0.5% SC Mass

0.5% Mass							
Discharge Current, 1 min of Power (A)	**1 min discharge**	**Power, 1 min discharge (kW)**	**Percentage Increase**	**Discharge Current, 30s of Power (A)**	**30s discharge**	**Power, 30s discharge (kW)**	**Percentage Increase**
67	60	0.18	0.29%	135	30	0.36	0.58%
142	60	0.38	0.51%	284	30	0.77	1.02%
111	60	0.30	0.40%	222	30	0.60	0.80%
142	60	0.38	0.30%	284	30	0.77	0.61%
111	60	0.30	0.36%	222	30	0.60	0.71%
14	60	0.04	0.87%	28	30	0.08	1.74%
92	60	0.25	0.55%	185	30	0.50	1.11%

Discharge Current and Power, 30 Second/1 Minute Sustained Power, 1.0% SC Mass

1.0% SC Mass							
Discharge Current, 1 min of Power (A)	**1 min discharge**	**Power, 1 min discharge (kW)**	**Percentage Increase**	**Discharge Current, 30s of Power (A)**	**30s discharge**	**Power, 30s discharge (kW)**	**Percentage Increase**
135	60	0.36	0.58%	270	30	0.73	1.16%
284	60	0.77	1.02%	568	30	1.53	2.04%
222	60	0.60	0.80%	445	30	1.20	1.60%
284	60	0.77	0.61%	568	30	1.53	1.22%
222	60	0.60	0.71%	445	30	1.20	1.43%
28	60	0.08	1.74%	57	30	0.15	3.48%
185	60	0.50	1.11%	369	30	1.00	2.21%

Discharge Current and Power, 30 Second/1 Minute Sustained Power, 1.5% SC Mass

1.5% SC Mass							
Discharge Current, 1 min of Power (A)	**1 min discharge**	**Power, 1 min discharge (kW)**	**Percentage Increase**	**Discharge Current, 30s of Power (A)**	**30s discharge**	**Power, 30s discharge (kW)**	**Percentage Increase**
202	60	0.55	0.87%	405	30	1.09	1.73%
426	60	1.15	1.53%	852	30	2.30	3.07%
334	60	0.90	1.20%	667	30	1.80	2.40%
426	60	1.15	0.91%	852	30	2.30	1.83%
334	60	0.90	1.07%	667	30	1.80	2.14%
43	60	0.11	2.61%	85	30	0.23	5.23%
277	60	0.75	1.66%	554	30	1.49	3.32%

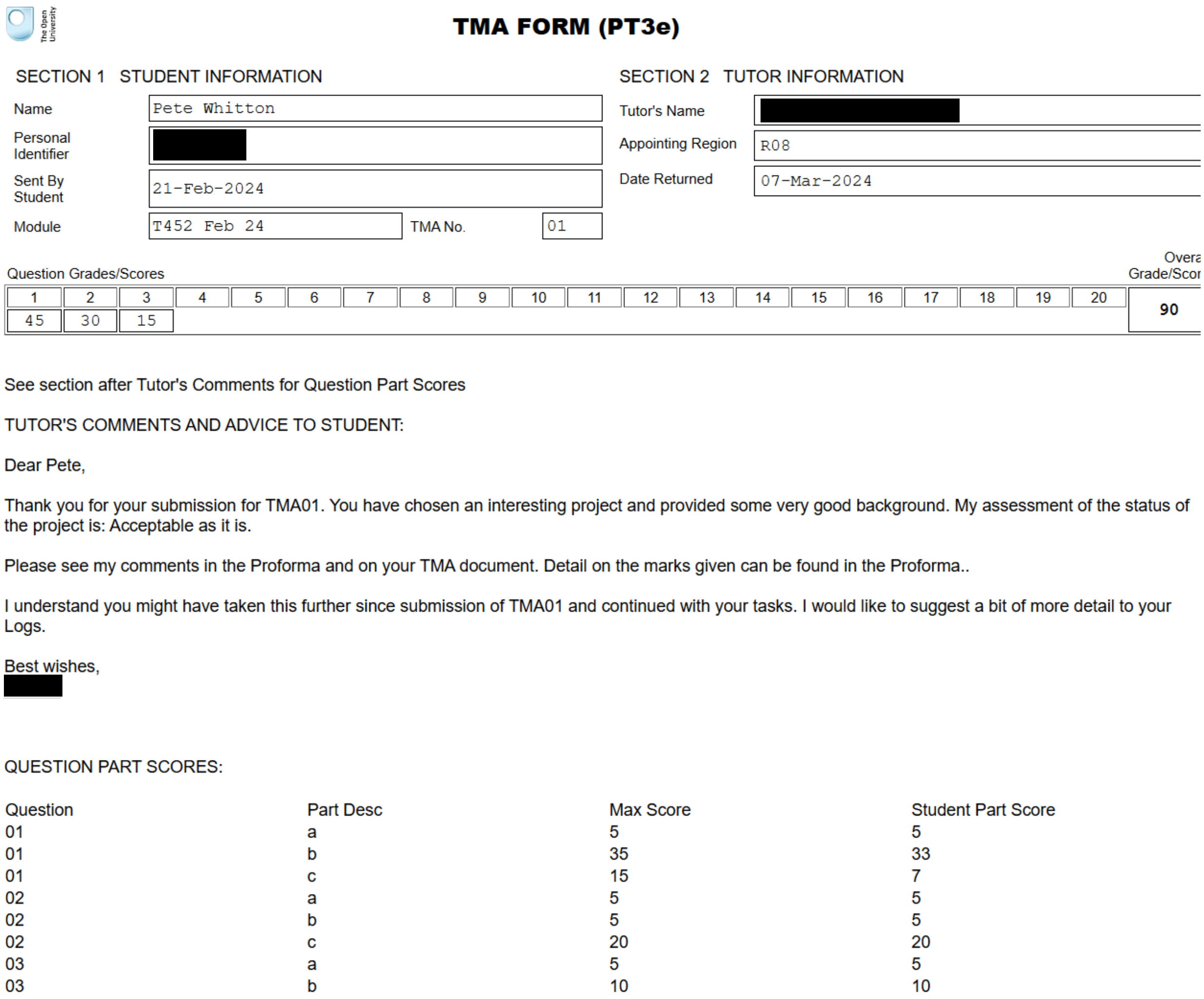
Discharge Current and Power, 30 Second/1 Minute Sustained Power, 2.0% SC Mass

2.0% SC Mass							
Discharge Current, 1 min of Power (A)	**1 min discharge**	**Power, 1 min discharge (kW)**	**Percentage Increase**	**Discharge Current, 30s of Power (A)**	**30s discharge**	**Power, 30s discharge (kW)**	**Percentage Increase**
270	60	0.73	1.16%	539	30	1.46	2.31%
568	60	1.53	2.04%	1136	30	3.07	4.09%
445	60	1.20	1.60%	890	30	2.40	3.20%
568	60	1.53	1.22%	1136	30	3.07	2.43%
445	60	1.20	1.43%	890	30	2.40	2.86%
57	60	0.15	3.48%	114	30	0.31	6.97%
369	60	1.00	2.21%	738	30	1.99	4.43%

Discharge Current and Power, 30 Second/1 Minute Sustained Power, 2.5% SC Mass

2.5% SC Mass							
Discharge Current, 1 min of Power (A)	**1 min discharge**	**Power, 1 min discharge (kW)**	**Percentage Increase**	**Discharge Current, 30s of Power (A)**	**30s discharge**	**Power, 30s discharge (kW)**	**Percentage Increase**
337	60	0.91	1.44%	674	30	1.82	2.89%
710	60	1.92	2.56%	1419	30	3.83	5.11%
556	60	1.50	2.00%	1112	30	3.00	4.00%
710	60	1.92	1.52%	1419	30	3.83	3.04%
556	60	1.50	1.79%	1112	30	3.00	3.57%
71	60	0.19	4.36%	142	30	0.38	8.71%
461	60	1.25	2.77%	923	30	2.49	5.54%

8. Tutor Feedback TMA1



TMA FORM (PT3e)

SECTION 1 STUDENT INFORMATION

Name	Pete Whitton
Personal Identifier	[redacted]
Sent By Student	21-Feb-2024
Module	T452 Feb 24
TMA No.	01

SECTION 2 TUTOR INFORMATION

Tutor's Name	[redacted]
Appointing Region	R08
Date Returned	07-Mar-2024

Question Grades/Scores

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Overa Grade/Scor
45	30	15																		90

See section after Tutor's Comments for Question Part Scores

TUTOR'S COMMENTS AND ADVICE TO STUDENT:

Dear Pete,

Thank you for your submission for TMA01. You have chosen an interesting project and provided some very good background. My assessment of the status of the project is: Acceptable as it is.

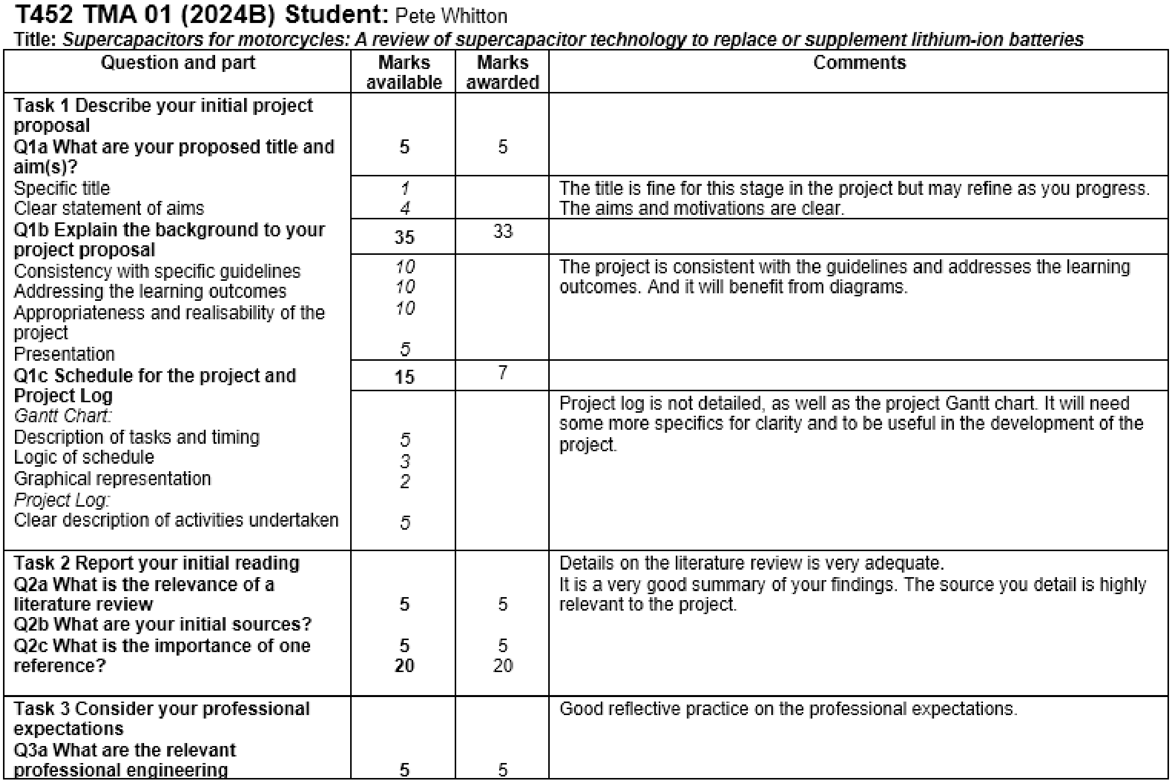
Please see my comments in the Proforma and on your TMA document. Detail on the marks given can be found in the Proforma..

I understand you might have taken this further since submission of TMA01 and continued with your tasks. I would like to suggest a bit of more detail to your Logs.

Best wishes,
[redacted]

QUESTION PART SCORES:

Question	Part Desc	Max Score	Student Part Score
01	a	5	5
01	b	35	33
01	c	15	7
02	a	5	5
02	b	5	5
02	c	20	20
03	a	5	5
03	b	10	10

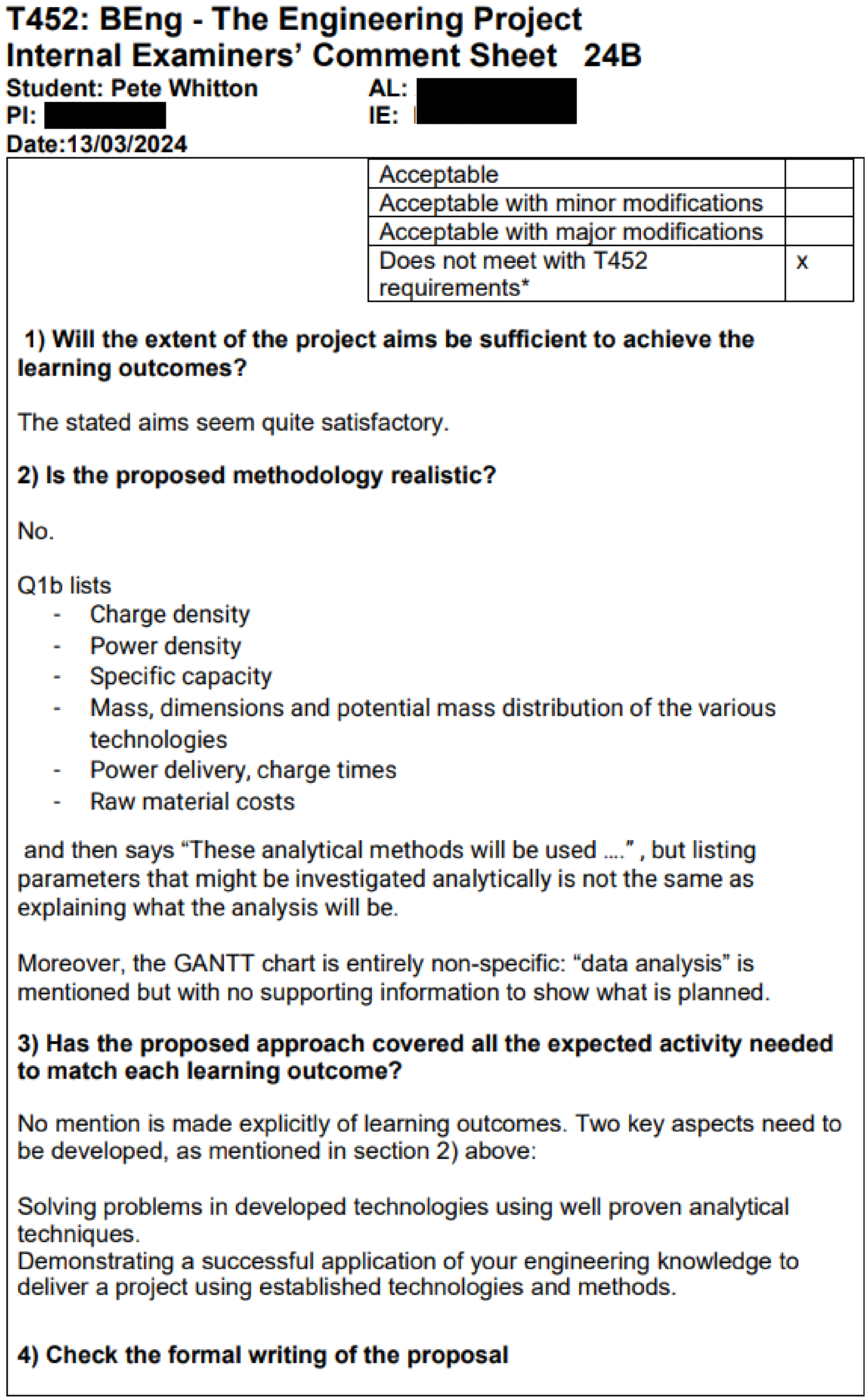



T452 TMA 01 (2024B) Student: Pete Whitton

Title: ***Supercapacitors for motorcycles: A review of supercapacitor technology to replace or supplement lithium-ion batteries***

Question and part	Marks available	Marks awarded	Comments
Task 1 Describe your initial project proposal **Q1a What are your proposed title and aim(s)?**	**5**	5	
Specific title Clear statement of aims	*1* *4*		The title is fine for this stage in the project but may refine as you progress. The aims and motivations are clear.
Q1b Explain the background to your project proposal	**35**	33	
Consistency with specific guidelines Addressing the learning outcomes Appropriateness and realisability of the project Presentation	*10* *10* *10* *5*		The project is consistent with the guidelines and addresses the learning outcomes. And it will benefit from diagrams.
Q1c Schedule for the project and Project Log	**15**	7	
Gantt Chart: Description of tasks and timing Logic of schedule Graphical representation *Project Log:* Clear description of activities undertaken	*5* *3* *2* *5*		Project log is not detailed, as well as the project Gantt chart. It will need some more specifics for clarity and to be useful in the development of the project.
Task 2 Report your initial reading **Q2a What is the relevance of a literature review** **Q2b What are your initial sources?** **Q2c What is the importance of one reference?**	**5** **5** **20**	5 5 20	Details on the literature review is very adequate. It is a very good summary of your findings. The source you detail is highly relevant to the project.
Task 3 Consider your professional expectations **Q3a What are the relevant professional engineering competences/skills?**	**5**	5	Good reflective practice on the professional expectations.
Q3b **What is personally relevant about one competence?**	**10**	10	
Total	100	90	

9. IE Feedback, TMA1



T452: BEng - The Engineering Project
Internal Examiners' Comment Sheet 24B
Student: Pete Whitton **AL:** [redacted]
PI: [redacted] **IE:**
Date:13/03/2024

Acceptable	
Acceptable with minor modifications	
Acceptable with major modifications	
Does not meet with T452 requirements*	x

1) Will the extent of the project aims be sufficient to achieve the learning outcomes?

The stated aims seem quite satisfactory.

2) Is the proposed methodology realistic?

No.

Q1b lists
- Charge density
- Power density
- Specific capacity
- Mass, dimensions and potential mass distribution of the various technologies
- Power delivery, charge times
- Raw material costs

and then says "These analytical methods will be used ….", but listing parameters that might be investigated analytically is not the same as explaining what the analysis will be.

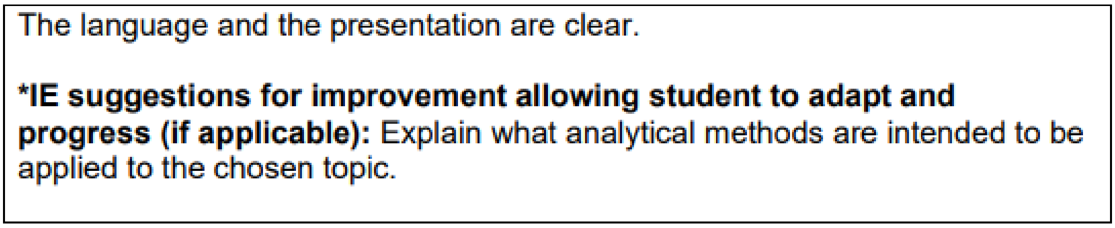
Moreover, the GANTT chart is entirely non-specific: "data analysis" is mentioned but with no supporting information to show what is planned.

3) Has the proposed approach covered all the expected activity needed to match each learning outcome?

No mention is made explicitly of learning outcomes. Two key aspects need to be developed, as mentioned in section 2) above:

Solving problems in developed technologies using well proven analytical techniques.
Demonstrating a successful application of your engineering knowledge to deliver a project using established technologies and methods.

4) Check the formal writing of the proposal



The language and the presentation are clear.

***IE suggestions for improvement allowing student to adapt and progress (if applicable):** Explain what analytical methods are intended to be applied to the chosen topic.