The University of Queensland

Energy Management of an Autonomous Electric Hauler

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Executive Summary

In this modern world where it is important to minimise emissions and effect on the environment diesel vehicles are becoming old fashioned and the mining industry needs to adapt. Electric haulers solve many of the environmental issues associated with surface and underground mines. However for them to be economically viable autonomy is required, as a result of this the mining industry has been focusing a lot of research in recent time to this development.

At Mining3 research is being conducted into this topic through the creation of an autonomous electric hauler that can navigate a mine without the need for a human operator. In order to make this idea even more economical this hauler is to be charged by wireless power transfer by powering a primary coil on the ground and having the energy received by a secondary coil on board the hauler. This will make the need of battery replacement much less frequent. Lastly electric haulers theoretically are able to climb steeper slopes than diesel haulers which would decrease the cost of mine construction. The project was first investigated by another group of students in 2018 who made some good findings but left many more opportunities for investigation available.

This report outlines the findings of a project to investigate the modelling the energy requirements of the autonomous electric hauler over haul routes, in terms of the energy required to complete them, the requirements of where coils need to be located and the storage technologies to be used to make this possible.

A literature review was conducted which investigated the current options available and what has been researched in these fields the methodology was outlined in terms of what simulations and experiments took place and justifications. The Appendices discuss the project management and professional development that took place during this placement.

From the results a fully active hybrid energy storage system interfacing between a Li-Ion battery and a supercapacitor was deemed to be a suitable choice of storage system. A model was devised for defining the relationship between velocity driven over coils and the length of coils and how this effects time and energy over haul routes, which needs to have a value model applied in order to obtain a conclusive solution. Then lastly, the energy usage was verified on a small scale using the developed prototype at Mining3, however a larger scale prototype is necessary to confirm that the large scale simulations are also accurate.

Acknowledgements

I would like to acknowledge Mining3 in particular my industry supervisor Erik Isokangas. I am thankful for all the help I received from Mining3 staff during this project and the other students I was alongside at Mining3 Alex Goodsell, Paul Sachse and William Hale.

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1 Introduction

1.1 Background

Currently in mining the vast majority of vehicles and machines are run from diesel which has many disadvantages associated with them. These could be addressed if electric power could successfully be implemented and replace diesel options. The disadvantages associated with diesel engines and corresponding advantages with electrically powered engines are summarised in Table 1. One thing mentioned in Table 1 is that

Issue	Diesel hauler	Electric hauler
Air quality	Poor due to emissions which leads to high ventilation costs	Good no emission of carcinogenic pollutants in particular
Noise	Loud	Quiet
Energy efficiency	Poor (25-45%)	Good (60-90%)
Slope climbing	Around 10%	Potentially 20%
Future	Declining	Large research investment

Table 1: Table showing disadvantages of diesel haulers and advantages of electric haulers

electric haulers are able to climb steeper slopes than those powered from diesel this is due to the fact that electric motors are able to achieve higher acceleration at low speeds [9]. The table also mentions the future this is regarding the future of all vehicle technology due to the growing presence and concerns surrounding global warming and emissions research is moving towards electrical options. These social and economical reasons have led to increased research into electric hauling in recent times.

In many mines there is already the use of electrical systems in the form of things like conveyors for constant, long distance transport of resources. But conveyors are not very flexible as they are difficult to move and require large initial construction followed by regular maintenance. Similarly trolley assisting systems have been used in an attempt to increase the ability of diesel haulers with electric drive systems to achieve higher torque while loaded and travelling up hills to reduce mine construction costs as pictured

Figure 1: Trolley assist system

in Figure 1. However this has similar difficulties in terms of flexibility and relocation.

Volvo has developed multiple autonomous battery electric vehicles such as the HX01 and HX02 in 2016 and 2017 [10] which aim to transform the way in which mine sites and quarries are run in an attempt to reduce emissions and costs. Through the use of these prototypes and other factors Volvo have predicted up to a 95% reduction in emissions and 25% reduction in the total cost of ownership. These are obviously very large steps in the move towards a more sustainable world as well as a more affordable mine.

Nouveau Monde Graphite in Canada is also moving towards using a zero emission mine fleet aiming to begin production in 2022 [11]. This is planned to be achieved with the use of 36.3t mining trucks and a mobile charging facility with fast-charging capability of up to 600kW.

Autonomous capabilities are something very valuable mines in order to reduce risks and expenses, due to the costs and safety concerns surrounding personnel in current mines. It is very unsafe to be working in a mine due to the possible avalanches and collapses that could be fatal, as a result of these risks people who work under these conditions are payed a substantial amount of money as well as the loss of equipment. However with an autonomous vehicle there is still the loss of equipment but much less risk of the loss of human life.

Figure 2: Vehicle built by 2018 students

Last year Mining3 began research in to the development of a completely electrically operated autonomous mining hauler that is unique in the sense that it is to be wirelessly inductively charged by driving over one or a series of powered coils with a secondary coil on board. In the hope that energy expended over a haul route can be regained through this and the combination of regenerative braking to hopefully remove the need of changing or charging a battery a long with the associated people that would need to do that. The prototype built by the students last year is shown in Figure 2. There was a lot achieved on this project but there is still a long way to go for this to be considered a viable for solution in a commercial mining application. The key aspect of this regarding the inductive charging last year it was shown that wireless power transfer could be achieved and was demonstrated by the lighting of LEDs when it was receiving power.

However none of the power was used to charge the battery and the transfer efficiency was quite low.

This year Mining3 has tasked placement students with continuing this project except moving the focus to the inductive charging functionality as that is what is seen as the innovation here not the ability to build a chassis for a mining vehicle. As a result of this an electric mobility scooter has been purchased and being transformed to be operated by similar electronics as the students implemented last year. One key factor to be noted is the intention of this system is 100kg hauler that is to be charged using 1kW power network while the goal for the end system is a fleet of 15 tonne haulers that will be charged with a 1MW system.

1.2 Purpose

The key purpose of this project is to harvest as much as possible of the energy transferred to the secondary coil. So to be able to do this effectively the most appropriate storage device must be used. Accompanying this to ensure that the energy is managed effectively it must charge in a smart and efficient way so that the hauler is able to sustainably travel many haul routes without the energy storage being depleted while completing haul routes in a consistent time that is comparable to diesel haulers. This project was created as it was something that was not addressed by last year's students but something they mentioned should be focused on for the progress of the overall project.

This is essentially one of many stages in the prototyping process for Mining3 with the eventual aim that the ideas discovered and research done by the students on this project eventually being applied to the development of a fleet of 15 tonne autonomous electric haulers that could be deployed in either open cut or underground mines.

Erik Isokangas also began work on a simulation to determine the energy consumption of a hauler around a haul route however this simulation requires some work in order to make it a more accurate representation of a real system.

Overall the goal is to determine the more effective storage device to be used for charging and the capacity required when considering many of the factors at play in a mining hauler scenario.

1.3 Project Scope

The project consists of a planning for the energy use of a fleet of electric haulers by developing models and a tool to estimate energy needs for a system of electric haulers, then use in conjunction with energy storage system to determine the best techonology for storage and the size required. The goals that pertain to this can be split into four areas

1. Given a haul route and the specifications of a hauler to model the energy consumption around the haul route.
2. Determine how charging coils should be located in a mine so that the haul routes can be completed, and the effect of this on the energy capacity requirements.
3. Determine how the energy should be stored and the distribution of this storage between batteries, supercapacitors etc.
4. Prototype the use of this energy storage system.

Table 2 outlines different aspects that are inside and outside of the area of scope.

Inside Scope	Outside Scope
Improve upon current MATLAB simulation	Tuning motor speed controllers
Research energy storage possibilities	Optimizing the vehicle speed over haul route
Develop strategy for managing energy from regenerative braking as well as inductive charging and distributing this effectively	Measuring losses in current prototype
Effect of coil spacing on storage capacity requirements	Large scale design
Present to Mining3 technical committee	Economic model implementation
Known haul route	Design of secondary coil harvesting of power

Table 2: Scope of Project

1.4 Deliverables

To ensure that this project is completed and the outlined goals in the project scope are achieved there are some deliverables to be submitted during the completion of this project. These include the following:

1. **Reflective Journals**
   During the placement monthly journals will be submitted to track development as a professional engineer and reflect on events that have been fostering this growth. There are still two of these remaining

2. **Energy Storage Literature Review**
   Research which technologies have been used for similar purposes before and how this applies of could be adapted to this project.

3. **Final Report**
   A document submitted when the placement is completed which records the progress and outcomes of the investigation.

4. **Energy Simulation**
   A tool that can be used to simulate the energy consumption of various types of hauling vehicles over different haul routes.

5. **Hauler prototype**
   The current group of students at Mining3 need to deliver and updated prototype this year by modifying a mobility scooter rather than beginning from scratch.

6. **Oral Presentation**
   Towards the completion of the project an oral presentation will be delivered at Mining3 and also at the University of Queensland regarding the work completed and the conclusions drawn from this project.

2 Literature Review

This section summarises the information that has been accumulated from different sources that is relevant to the understanding required so far for the completion and planned completion of this project.

2.1 Batteries

There are many types of battery technology available today, they all have different advantages and disadvantages which make them useful for different purposes and applications. Generally batteries have different base materials for the anode and then have many different other materials used this can also modify the properties.

The three most used batteries that have been used in industrial electric vehicles are lead acid, nickel metal hydride (NiMH) and lithium ion (Li-ion) batteries [12]. Lead acid batteries have a much lower specific energy, energy density and longer charge times than the other two options. NiMH batteries have large problems when it comes to self-discharge which can be up 12.5% per day which becomes much worse at high temperatures which can occur in vehicle applications.

Due to these reasons today the most common battery used in electric vehicles today is the lithium ion battery as it has very good specific energy, energy density as well as low self-discharge of 5% per month. However, nothing is free of potential problems and those associated with the lithium ion battery are that they are quite expensive and also have safety concerns. Thermal runway can occur which could cause vehicle fires and hence special consideration has to be taken when making designs that include Lithium ion batteries. It is important to know the process of charging Li-ion batteries also in Figure 3 it is depicted. The two main phases are first the constant current charging stage and then to avoid potential overcharging problems it is important to switch to a constant voltage stage. The charging then terminates and is occasionally topped back up to deal with discharge that can occur when fully charged. There is also sometimes a beginning stage where lower current is used if the battery is at a very low percentage although this can occur it is not that common.

Although the lithium ion battery is most common in commercial applications in the prototype being used currently a lithium ion polymer (LiPo) battery is being used as it can supply high currents at lower voltages. However it has even more safety issues when it comes to thermal runaway potential to catch fire.

2.2 Supercapacitors

A supercapacitor is a very high capacitance capacitor which possess a much higher volumetric and gravimetric energy density than electrolytic capacitors but lower voltage limits [13]. Conventional capacitors use solid dielectric but in the case of supercapacitors in order to achieve much higher capacitance electrostatic double layer-capacitance and electrochemical pseudocapacitance [14] which both play a part in achieving the much higher capacitance which allow supercapacitors to have a much higher energy density than electrolytic capacitors.

Supercapacitors are an emerging form of energy storage that are very different from Li-ion batteries in many ways Table 3 is a comprehensive summary of the differences between the two storage technologies over a plethora of different areas.

Generally supercapacitors have been considered a poor trade off due to the superior volumetric and gravimetric energy of Li-ion batteries. Although they have much better power density, life time and are easier to charge. The amount of space required and the

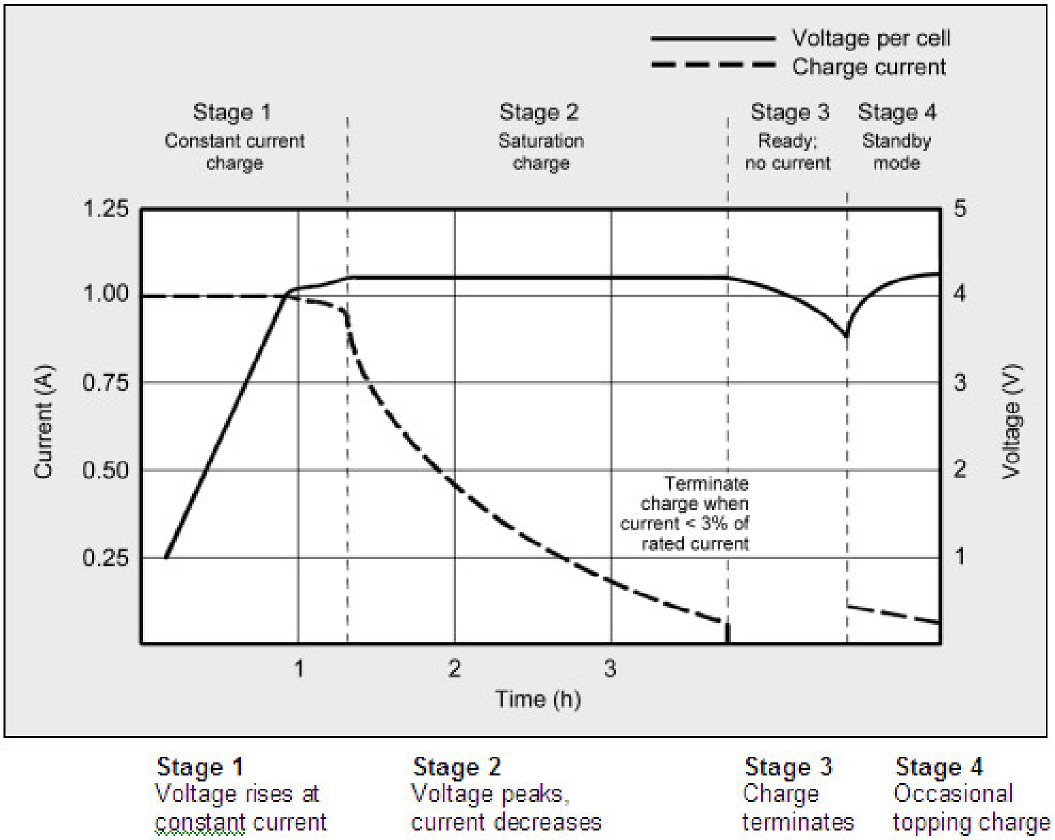

Figure 3: Charge States of lithium ion battery from [1]

cost of supercapacitors has made them unfavourable.

There was an article released in 2018 regarding the University of Surrey [15], and that they had made a breakthrough regarding supercapacitors which could drastically improve the energy density to that comparable with Li-ion batteries. As there are still patents pending on this technology not a whole lot of information has been released about this but it could be something very revolutionary to the progress of this project.

Supercapacitors are very simple to monitor as you can determine the energy stored and the current just by monitoring the current as expressed by the following equations.

$$E = \frac{1}{2}CV^2 \tag{1}$$

$$i = C\frac{dV}{dt} \tag{2}$$

The first equation demonstrates the trade-off when adding supercapacitors in series and parallel. As by adding them in series you will increase the voltage but also decrease the capacitance conversely adding them in parallel will increase the capacitance and decrease the voltage. But also as expressed in Table 3 charging supercapicators in series becomes complicated as cell balancing has to be done in order for the charging to happen safely.

Feature	Li-ion Battery	Supercapacitor
Gravimetric energy (Wh/kg)	100-265	4-10
Volumetric energy (Wh/L)	220-400	4-14
Power density (W/kg)	1500	3000-40000
Voltage of a cell (V)	3.6	2.7-3
ESR (mΩ)	500	40-300
Efficiency (%)	75-90	98
Cyclability (nb recharges)	500-1000	500 000 - 20 000 000
Life (years)	5-10	10-15
Self-discharge (% per month)	2	40-50
Charge Temperature (°C)	0 to 45	-40 to 65
Discharge Temperature (°C)	-20 to 60	-40 to 65
Deep discharge problem	yes	no
Overload problem	yes	no
Risk of thermal runaway	yes	no
Risk of explosion	yes	no
Single cell charging	complex	simple
Charging series cells	complex	complex
Voltage while discharging	stable	decreasing
Cost per kWh (€)	200 - 1000	10 000

Table 3: Table comparing statistics between Li-ion batteries and supercapacitors from [8]

2.3 Regenerative braking

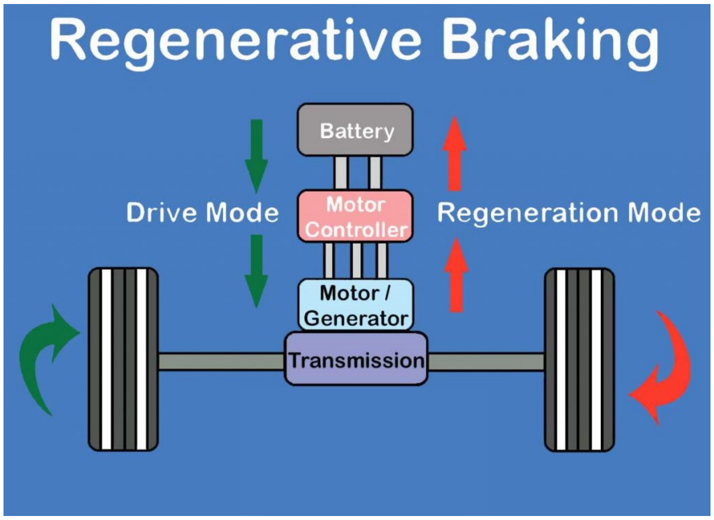

Figure 4: Visualisation of regenerative braking from [2]

In order to complete many haul routes over a long period of time it is important to harness every possible source of energy. Regenerative braking occurs during braking when the motor acts as a generator and converts the inertial energy from moving into electrical energy to be stored in storage devices for reuse as can be seen in Figure 4. However in electric vehicles it is not yet possible to regenerate all of the energy from braking, only the energy from the driving wheels which can propagate through the driving shaft. The amount of energy that can be recovered depends on the remaining power and maximum charging power of the storage device as well as the motor speed, braking strength etc. As a result regnerative braking cannot be solely relied on and must be combined with friction braking [16].

Given regeneration efficiency η_{regen} which considers the losses in the regeneration due to the motor, environment and other factors. There are two ways to look at the energy regenerated from regenerative braking the first is to consider what occurs when driving down a slope at constant speed and consider the change in potential energy as a result of this and the following is obtained in equation 3.

$$E_{regen} = \eta_{regen} mgh \tag{3}$$

The other option which is when driving to consider the change in potential energy as explored in equation 4 this displays what the change in energy of the system will be in the braking time and hence what maximum energy it is possible to regenerate if $\eta_{regen} = 1$.

$$E_{regen} = \eta_{regen} \frac{1}{2} m(v_1 - v_2)^2 \tag{4}$$

2.4 Hybrid energy storage systems

Due to the contrasting properties possessed by batteries and supercapacitors they have been combined in hybrid electric vehicles (HEV) to take advantage of both of their beneficial properties. Not all hybrid electric vehicles use batteries and supercapacitors but that is what is focused upon during this project and as a result will be discussed in this literature review. One analogy that is used to demonstrate the value of hybrid vehicle systems is that of the tortoise and the hare where the battery is the tortoise and the supercapacitor is the hare due to the contrasting charge and discharge rates as well as energy and power densities. But instead of them needing to compete they can be used in conjunction to make an overall better performing energy storage system.

The typical reasoning behind a hybrid electrical vehicle is that the higher power loads associated with quick acceleration and braking cause batteries life spans to deteriorate quicker than is desired. But by adding a DC - DC converter and charging a supercapacitor it is able to output the higher power for short periods of time when required or if it has a low state of charge it will be able to store all the energy input. This aids in the battery having an extended lifespan. As well as this reduced environmental impact due to less replacing of parts resulting in needing to dispose of old parts.

There are three different topologies of hybrid energy storage systems which will be outlined in these following sections.

2.4.1 Passive HESS

A passive hybrid energy storage system configuration is a topology where the supercapacitor and battery are connected directly in parallel as shown in Figure 5. In this HESS there are issues when it comes to the control of this system due to the direct connections, however the supercapacitor will be able to deal with the large transients during various stages of operation [17]. It is cheaper in terms of not using any DC - DC Converters however the supercapacitor generally has to be larger as there needs to be less variations in the supercapacitors state of charge.

2.4.2 Semi Active HESS

A semi active hybrid energy storage system is still a parallel connection but in this case the connection is made through a bidirectional DC DC converter. This is typically in series with the supercapacitor but can also be in series with the battery as shown in Figure 6. The bidirectional DC DC converter allows bidirectional flow of power in which one side is a low voltage level and the other side is a high voltage level. In this system is much easier to have some control over how the components are supplying power as one of the elements output can be controlled which indirectly dictates the output of the other storage technology [18]. If the bidirectional DC DC converter is in series with the supercapacitor it lessens the capacity requirement of the supercapacitor

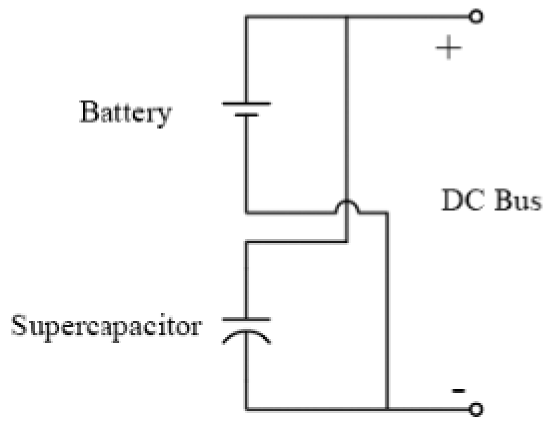

Figure 5: Passive HESS from [3]

as it can be operated at a wider range of voltage levels which has a direct relationship with the state of charge of the capacitor.

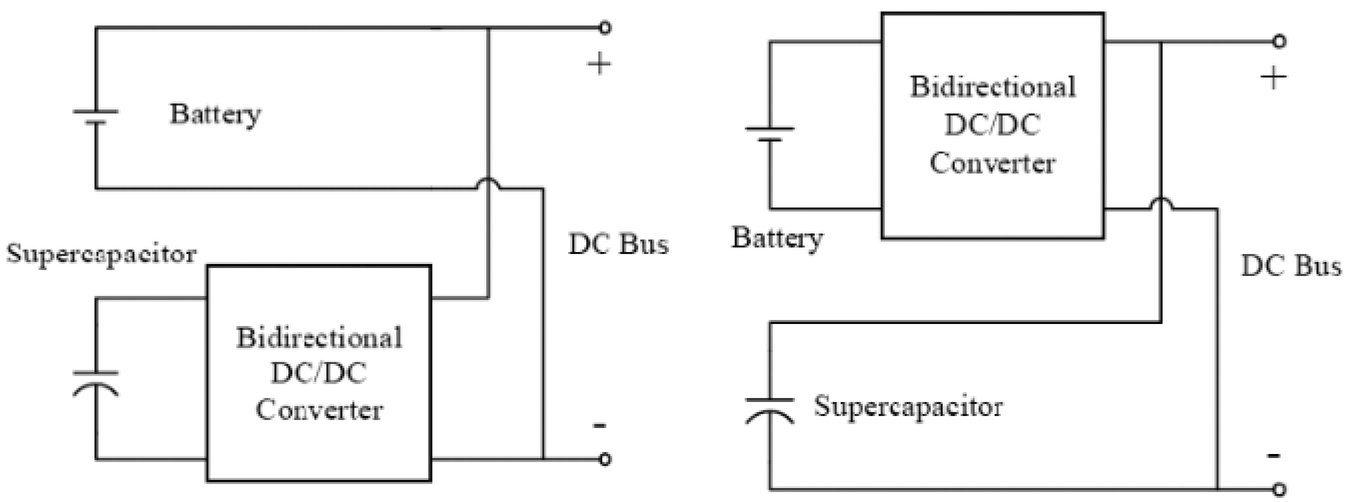

Figure 6: The two forms of semi active HESS from [3]

2.4.3 Fully Active HESS

The case of a fully active hybrid energy storage system is shown in Figure 7. This topology allows the most control as there is the ability to directly control the power output or input by both storage systems simultaneously and this allows for the most robust operation but it is also the most expensive initial cost due to the need to have two bidirectional DC DC converters [19]. However this will prolong the life most effectively allowing all of the high power loads to be handled by the supercapacitor. For example the regenerative braking and the wireless power transfer. Meanwhile the steady state less intensive loads can be taken by the battery which possesses the higher energy density.

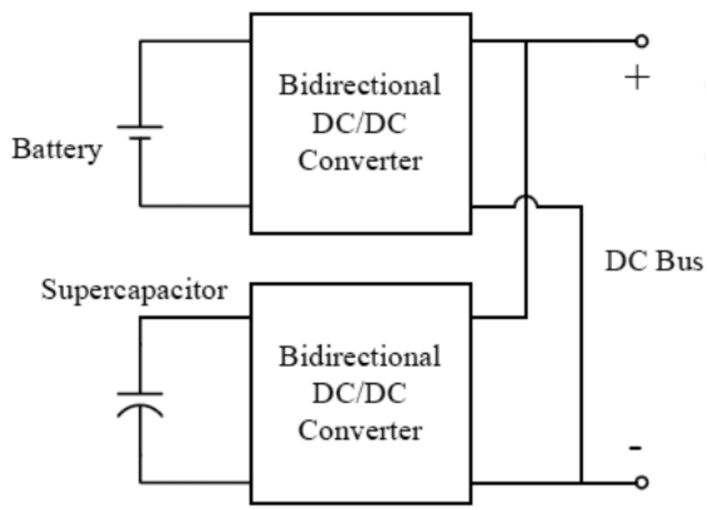

Figure 7: Active HESS topology from [3]

2.4.4 Bidirectional DC DC Converter

Essentially a bidirectional DC DC Converter allows power flow in both directions in which one is a low voltage side and the other is a high voltage side and this type of functionality is very beneficial to use in a hybrid energy storage system and allows for controllable energy management so that specific storage devices can be limited to the amount of power output or the rate of change in how much power output. It achieves this functionality by acting as a boost converter in the step up direction and a buck converter in the opposite direction [20]. It is also possible to buck and boost in both directions with the addition of more complexity to the circuit including the addition of two more FETs.

2.5 Energy Management System

There are a few different energy management techniques mentioned in the literature but the two main concepts that they come down to are [21]:

- Rule-based
- Optimisation-based

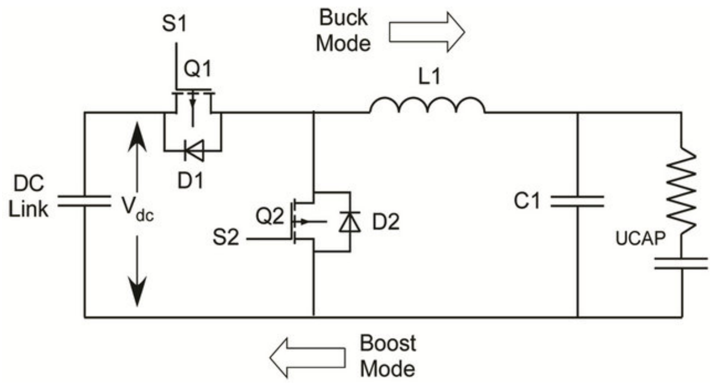

Figure 8: Typical Bidirectional DC DC circuit diagram

Rule-based implementation is most useful for real-time applications while optimisation-based can be adapted for either online or offline use. There is also examples of other techniques for energy management in the literature some notable ones include a fuzzy logic approach [22] and another study which attempted to train a neural network to find the most effective method energy expenditure [23].

It seems that the best way to address the energy management design determine what are potential constants or repeatability in the system and observe how these can be used to simplify the energy model and cause the energy to be used in a more efficient manner. In many automotive applications in the literature this involved looking at common drive trains in various cities as well as looking at the effect of traffic conditions [24].

2.6 Haul routes

Truck haulage and haulage related costs can account for up to 50% of the total operating costs incurred by an open-cut mine[4]. As a result of this it is extremely important to ensure that haulage is being done in the most effective way possible. The key piece of data used in the mining industry which determines the maximum speed at which a hauler can drive up a slope and based whether is is loaded or unloaded. Two things that need to be taken into account when determining rimpull are:

- Rolling resistance - a measure of the quality of the road and how difficult it is the drive over.
- Road grade - the steepness of the road the higher this is the cheaper the haul route is to build.

Figure 9 is an example of a rimpull curve for a 324t diesel powered mining hauler, so as you can see in the figure if it was to be loaded in order to generate enough force to be able to climb the slope it would only be able to travel at a max speed of approximately

14.8 km/h. It can be seen in the rimpull curve that the force created decreases very quickly at low speeds and then decreases slower at higher speeds however the damage has already been done by this as the slope climbing ability has decayed too far. These factors culminate to cause diesel loaders to be able to climb a max slop of 10-13% when taking into account rolling resistance and still maintain an efficient speed. This is where

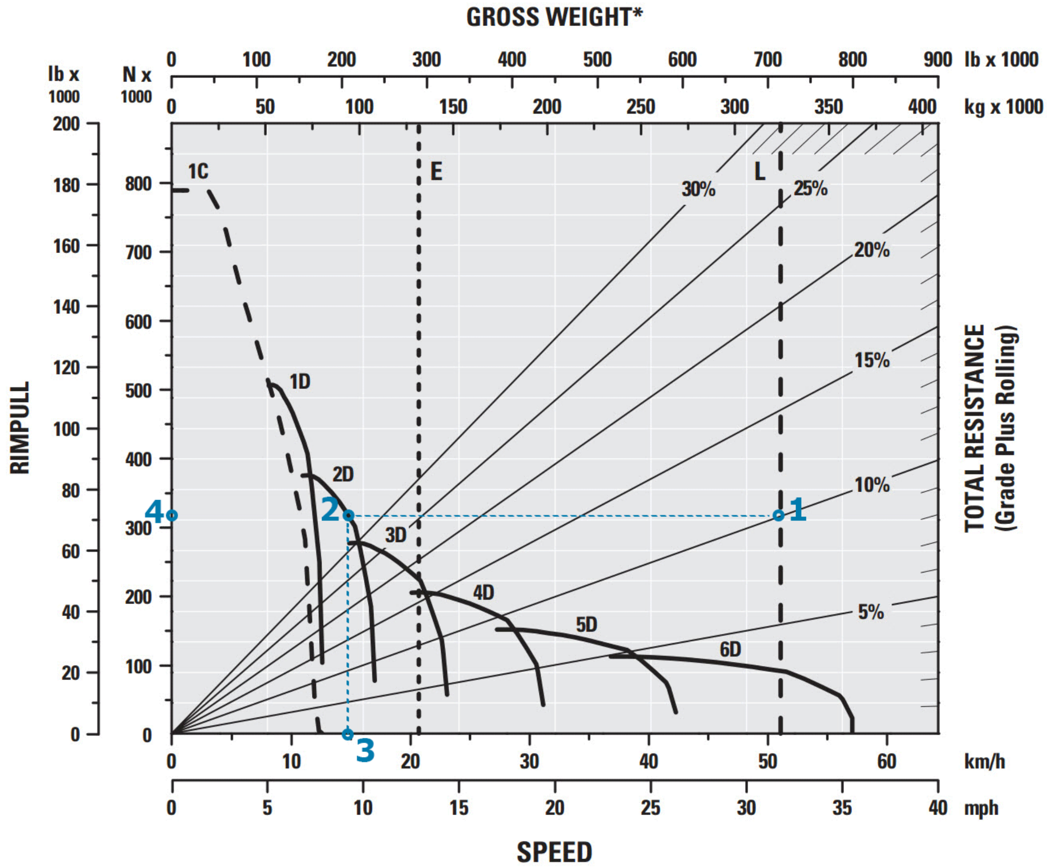

Figure 9: Example rimpull curve from [4]

electric haulers can progress the mining industry as they are able to generate higher torque at low speeds which will allow them to climb higher slopes and decrease mine costs. In Figure 10 a rimpull curve of a vehicle with electric drive is depicted although the vehicle sizes in these two examples are not the same it can be seen simply in the curves that the roll off for the electric drive vehicle is just not as extreme.

This information about rimpull is interesting as taking into account the speed at which the hauler will be travelling at different points along a haul route is important in determining the capacity of energy storage required to sustain the haul route.

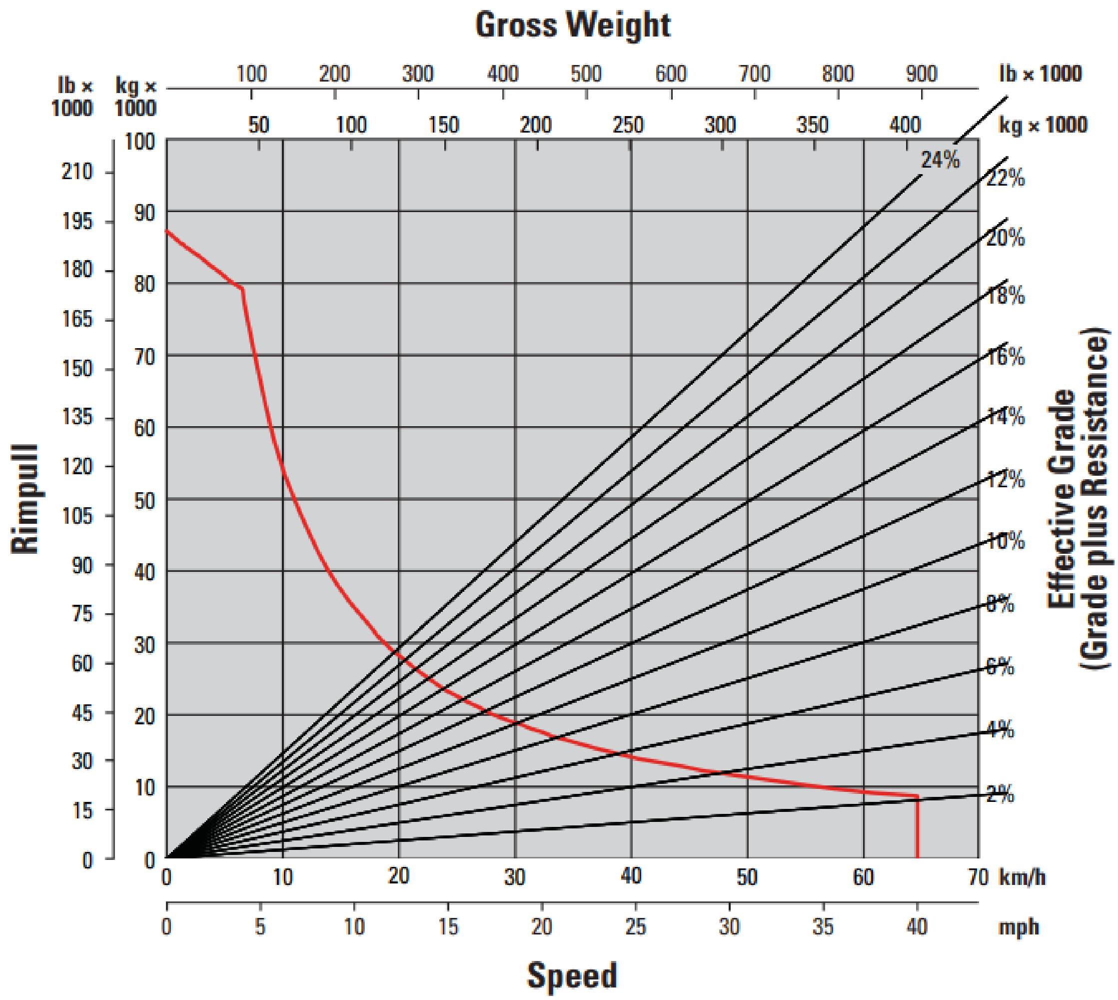

Figure 10: Rimpull curve for electric drive MTD440D from [5]

2.7 Wireless Charging

At KAIST a university in South Korea the shuttle bus around the campus operates as an on line electric vehicle (OLEV). This is essentially the major goal of this whole project but applied to a mining application. It is claimed that due to the on wire charging it is possible to reduce the battery capacity by $\frac{1}{5}$th. In Figure 11 it can be seen driving along its route, the line which it charges off can be seen on the ground in front of it in blue. This case is somewhat different to this project at the same time as it seems the charging mechanism is very permanent and would not be easily relocated.

The key features of an OLEV include the following [7]:

- Road-side power inverter to bring supply electricity to the transfer system.
- Road embedded transfer system

Figure 11: KAIST shuttle bus from [6]

- A system to receive and store the wireless power on board the vehicle.

In figure 12 these systems are depicted.

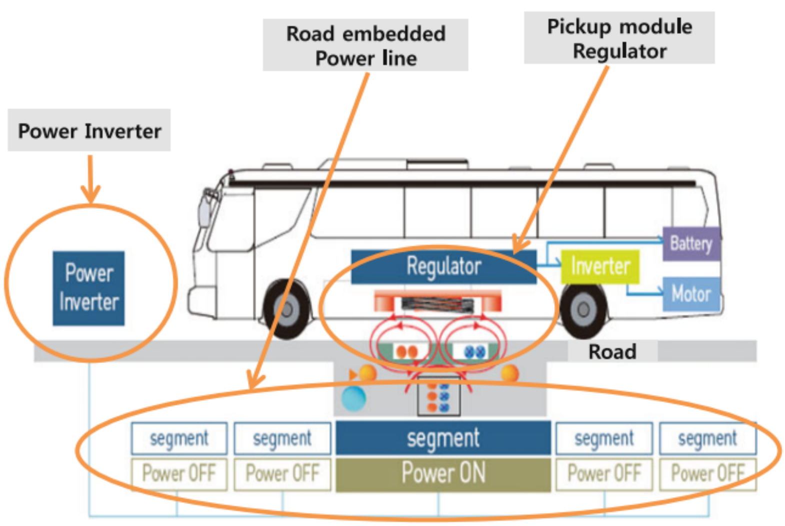

Figure 12: Diagram of an OLEV system from [7]

3 Project Methodology

3.1 Technical Approach

3.1.1 Haul Route Model

As has been referenced in the literature review an electric hauler is able to generate a higher rimpull at lower speeds than that of a hauler which operates off fuel. Erik Isokangas recently completed a case study for Mining3 investigating the grades and rolling resistances of haul routes in a mine he visited. The data collected from this case study is what has been adapted for a proposed haul route for an autonomous electric hauler. That is using a grade of 20% rather than the 10% used for fuel operated haulers these values can be seen in Table 4. For the purpose of this project it should be noted that the haul route is considered to be without variation and takes the same sequence with the starting location of little consequence as such the starting position was chosen to be in the mine while the hauler is waiting to be loaded.

Figure 13 shows a haul route with some comments overlaid which depict the locations from Table 4 from this it can be seen how the haul route has been approximated however it is important to know this image is not actually from the Mining3 case study but gives us the ability to understand the haul route model for this project.

Start	Finish	Distance (m)	Grade (%)	Rolling Resistance (%)
Load Pit	Ramp Bottom	260	0	3
Ramp Bottom	Ramp Top	150	20	3
Ramp Top	Ore Unload	4021	2.6	3
Ore Unload	Ramp Top	4021	-2.6	3
Ramp Top	Ramp Bottom	150	-20	3
Ramp Bottom	Load Pit	260	0	3

Table 4: Parameters used to define haul route for simulations

3.1.2 Vehicle Model

One of the most difficult aspects of this project has been modelling a 15 tonne electric vehicle. The key difficulty has been trying to find something similar in order to derive a rimpull curve for such a vehicle as there is little prior art for electric vehicles of this magnitude. So the rimpull curve that has been used for the purpose of the simulations has been derived from statistics of a Tesla that were collected online. Essentially data found on line regarding a Tesla SP 100D was used to generate a rimpull for this vehicle

Figure 13: Visualisation of haul route model

this was then tested on in a simulation using a straight road to determine if it the model accelerate similarly to how it does in real life. Once a satisfactory result was achieved in tweaking these values then this model tweaked by some factors regarding that ratios of rimpull and speed that would be expected in an up scaled version.

3.1.3 HESS Simulations

At this stage the different HESS topologies have had Simulink models created through the Simulink library of Simscape which allow them to be experimented with different loads and see how they react to these circumstances. The simulation has been based on the components which are available for use on board of the prototype at Mining3 which is a 22.2V 16000mAh battery and 16.2V 58F supercapacitor although for the purpose of investigating the feasibility of different HESS configurations this was not possible for all of the simulations.

Figure 14 shows the passive HESS model it clearly does not have any bidirectional DC DC converters present and also as a result this simulation has to be conducted with a supercapacitor with voltage rated to be higher or equal to that of the simulation battery used, this is simply the nature of a passive HESS due to loading effects that will be caused otherwise the general parameters used are displayed in Table 5. To see the contents of the load block see Figure 39 in Appendix C.

In Figure 15 the simulation model developed for the semi active HESS can be seen and this module uses one bidirectional DC DC converter which allows the supercapacitor to be operated at a voltage independent to the battery. Then in Figure 16 the fully active Simulink model which runs off of the same battery and supercapacitor values which can be observed in Table 6.

Battery Voltage	Battery Capacity	Capacitance	Supercapacitor Voltage
22.2 V	355 Wh	58 F	24 V

Table 5: Passive HESS Simulation parameters

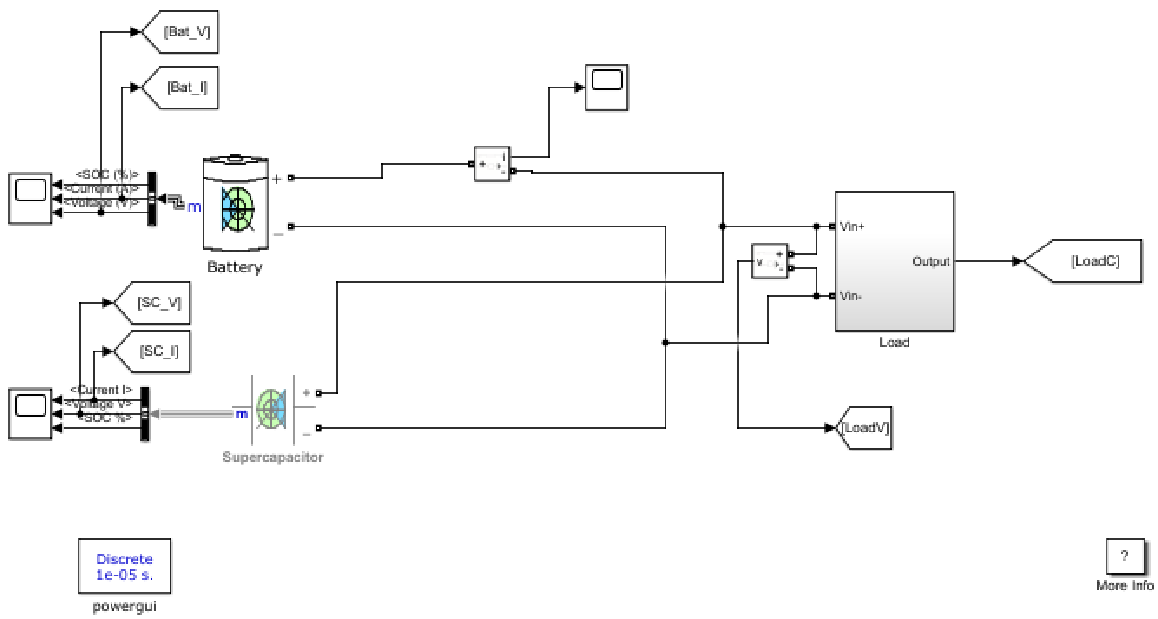

Figure 14: Simulink Model of Passive HESS

Battery Voltage	Battery Capacity	Capacitance	Supercapacitor Voltage
22.2 V	355 Wh	58 F	16.2 V

Table 6: Semi Active and Active HESS Simulation parameters

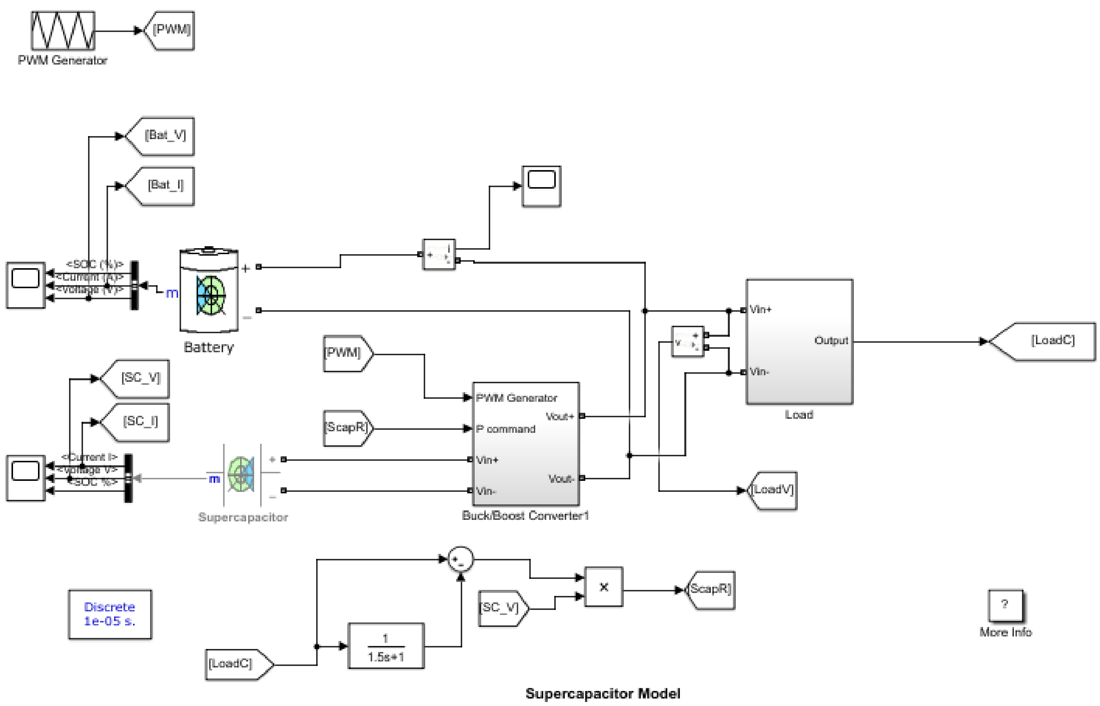

Figure 15: Simulink Model of Semi Active HESS

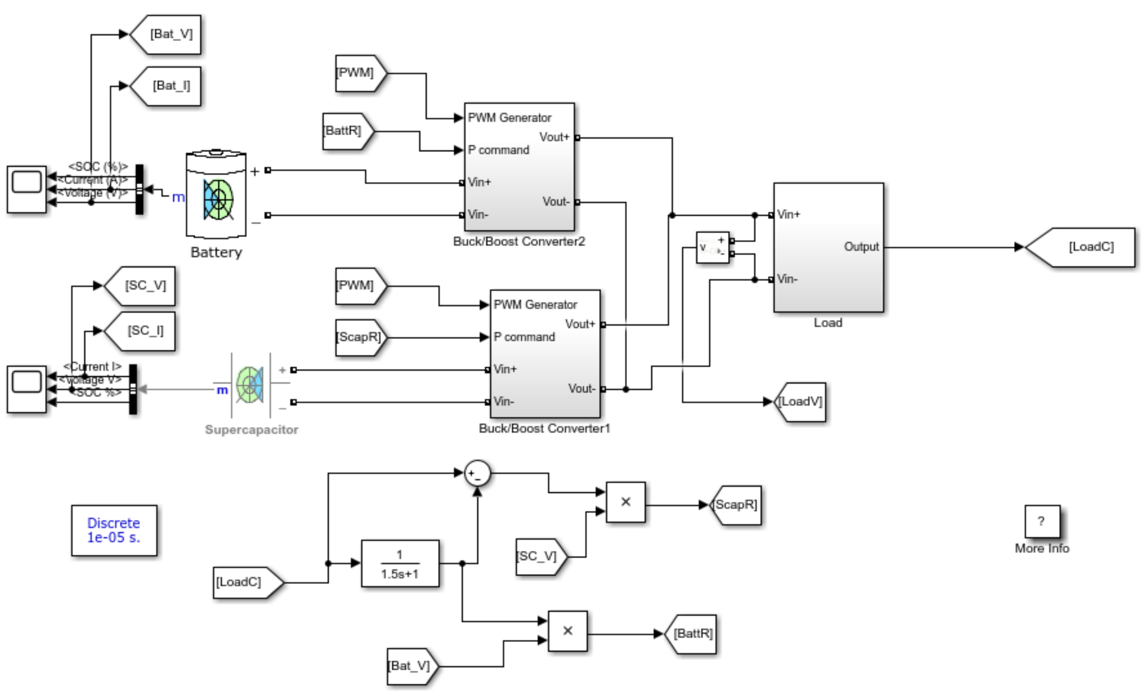

Figure 16: Simulink Model of Fully Active HESS

3.1.4 Energy Management System

It seems in many ways logical to consider a rule-based approach for energy management in this application. There are three clear stages in the ascent and similarly three clear stage in the descent. However there is something that can be quickly seen is that some of the states will have similar objectives. But the main control objective is in the state of charge of the supercapacitor. But also an objective to control the rate of change of the output current of the battery at all times

A summary of the supercapacitor state of charge goals is shown in Table 7. In this table and in the haul route there are six stages so a state machine could be used to model this in six states. However the six states can be simplified to two and this leaves a state machine with two states as shown in Figure 17. In this Figure some variables are present in the state transitions G is simply the grade of the slope on which the hauler is traveling. Each state governs how the supercapacitor and battery behaves at that point in the haul route. More information on the specific behaviour and power outputs can be seen in the charge and discharge flow charts in Figure 18 and Figure 19.

Start	Finish	Supercapacitor Goal	Load
Load Pit	Ramp Bottom	Charge	Loaded
Ramp Bottom	Ramp Top	Discharge	Loaded
Ramp Top	Ore Dump	Discharge	Loaded
Ore Dump	Ramp Top	Discharge	Unloaded
Ramp Top	Ramp Bottom	Charge	Unloaded
Ramp Bottom	Load Pit	Charge	Unloaded

Table 7: Different cases during haul route

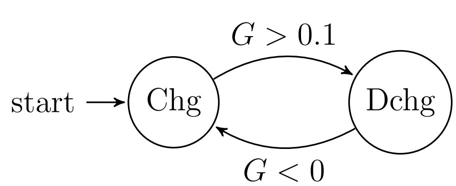

Figure 17: Initial energy management state machine.

In Figure 20 the Simulink model that was used to simulate the behaviour of the HESS being interfaced by the EMS under the power load results obtained from the haul route and vehicle model in the energy simulation. These are ported into Simulink through the "Haul Route" and "Power Gen" blocks in the model these generated signals

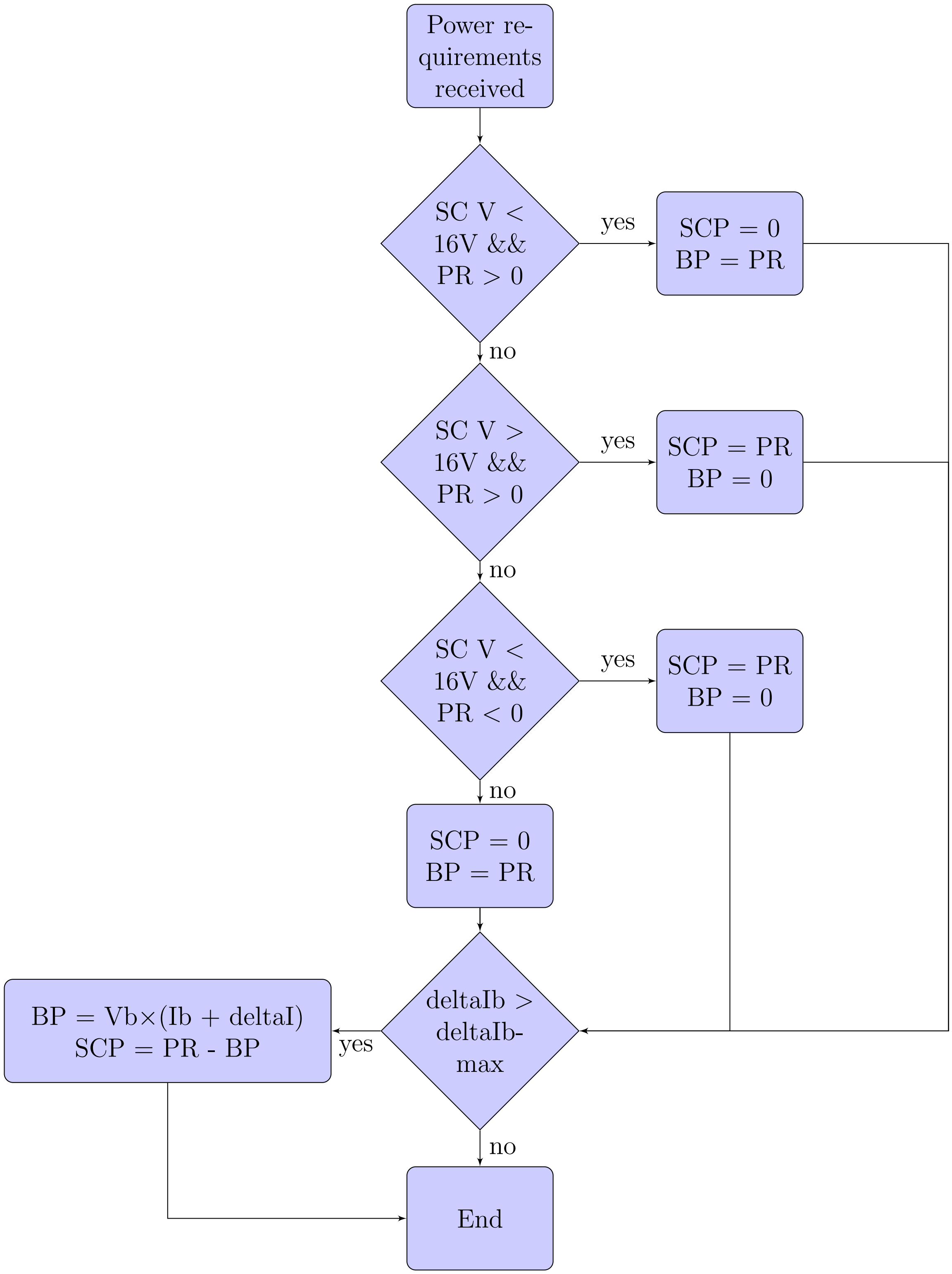

Figure 18: Charging decision flow chart

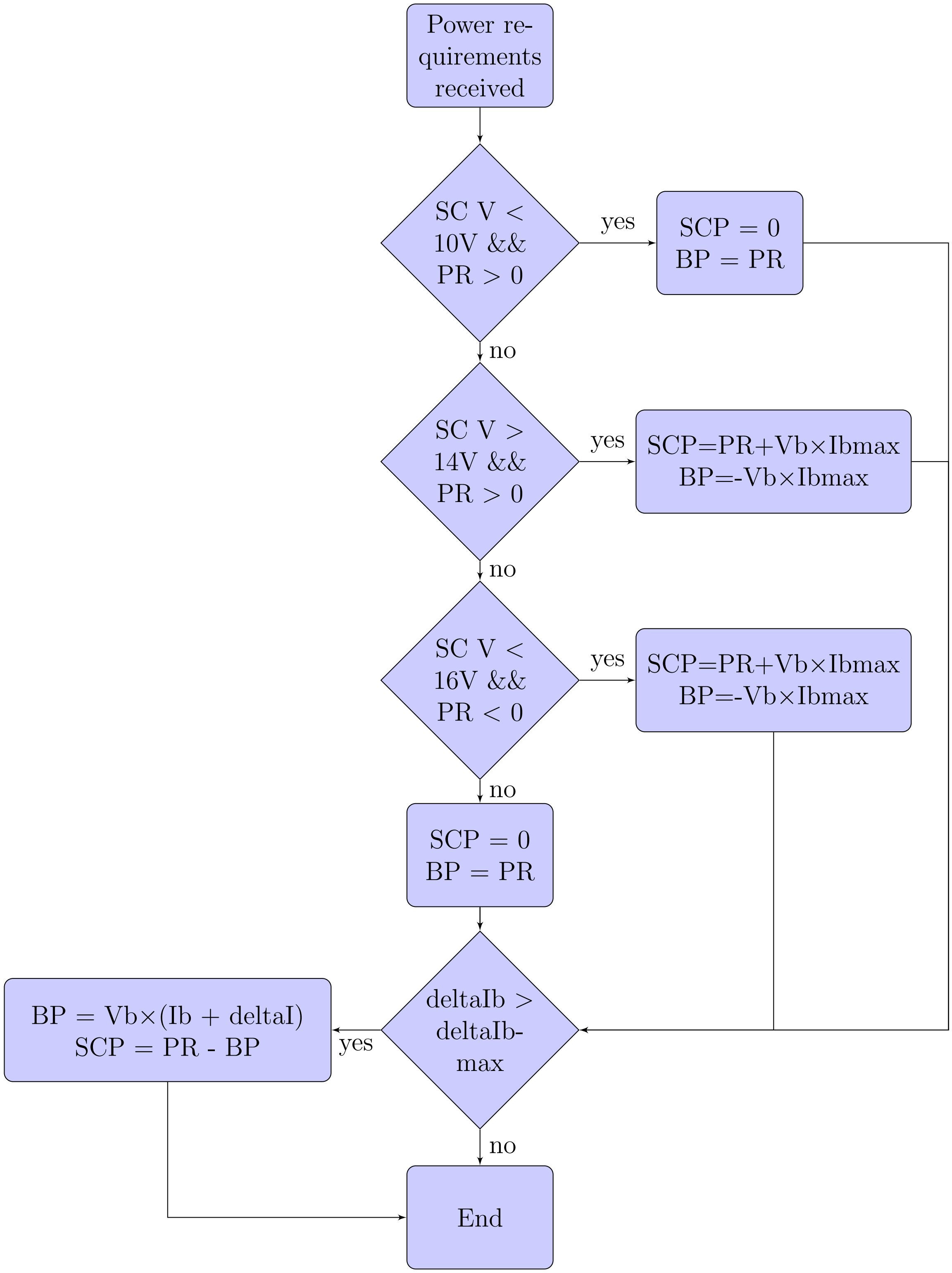

Figure 19: Discharging decision flow chart

are then sent to the EMS which controls inputs to the bidirectional DC DC converters interfacing the battery and the supercapacitor. Obviously the supercapacitor and battery power outputs are based off the state machine in 17 and the flow chat **??**.

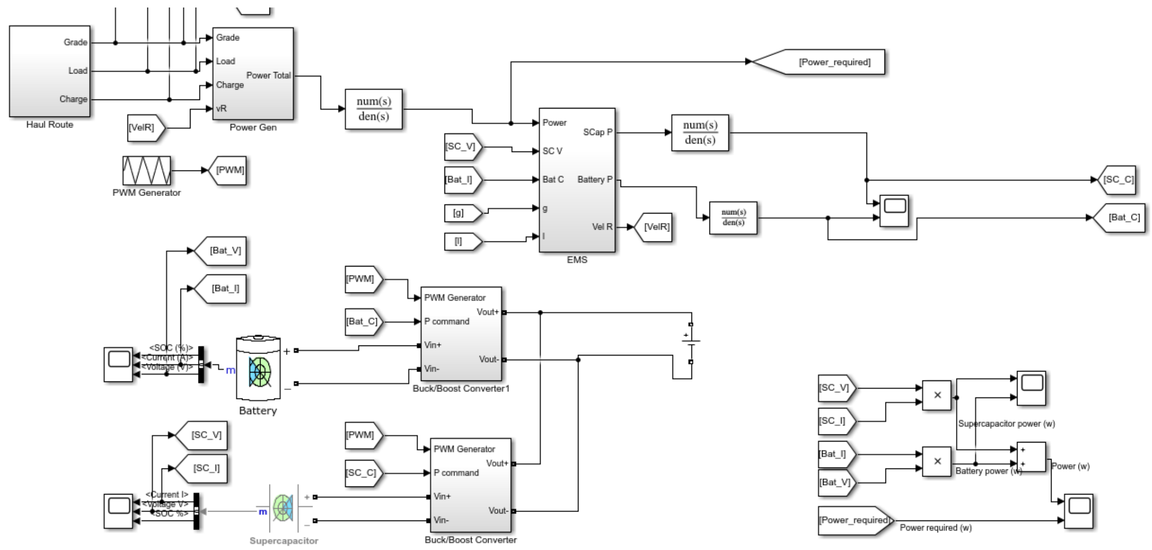

Figure 20: Simulink Model of Fully Active HESS with EMS

3.1.5 Charging

In order to fully determine the energy requirements of this autonomous electric hauler it needs to be investigated how the dynamic wireless charging and regenerative braking over the haul route effect the power and energy as a result part of the scope regarding this project has been to develop a relationship between how much distance of coil will be required in order to charge the hauler. Which involves how much the hauler may need to slow down while it is charging.

This has been experimented with by adding in ratio scaling factors for the ratio of how much of the haul route is covered with charging coils and at what ratio of the regular maximum speed the hauler drive over these coils. In Figure 21 this is represented graphically the interval is an amount that the a specific section of the haul route is segmented into for example the 4021m section was segmented into 400m intervals. The interval ratio then defines how much of each of these intervals has a charging pad an interval ratio of 1 would mean that the entire interval contains charging coils while 0 would mean no charging at all. Meanwhile the velocity ratio defines the ratio at which the hauler will drive over the coils relative to the regular speed it would be driving if there was no reason to slow down.

An assumption that was made regarding this is that the efficiency of the wireless power transfer remains the same regardless of what speed the hauler is travelling. Which is most likely not the case. Also as the vast majority of energy is used on the inclining parts of the haul route charging coils will only be placed on the up hill segments of the haul route.

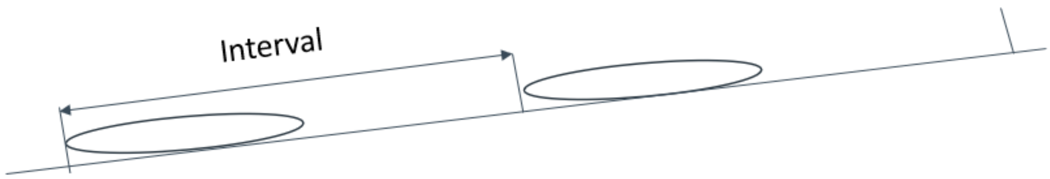

Figure 21: Visualisation of coil interval concept

3.2 Model Verification

In order to determine the usefulness of the model it is valuable to compare it with some real data. In Figure 22 the first test track is depicted as a 9 metre 13% slope this was chosen as a short test slope of higher grade and it was easily accessible at the Mining3 site. The essence of the test in this situation was to drive the hauler up the slope and then back down attempting to mainly go straight as the model does not account for power used while steering. The hauler motor speed controllers log battery supply voltage level, current draw and total energy used. There was also an inertial measurement unit on board the AEH which made it possible to record slope and velocity data.

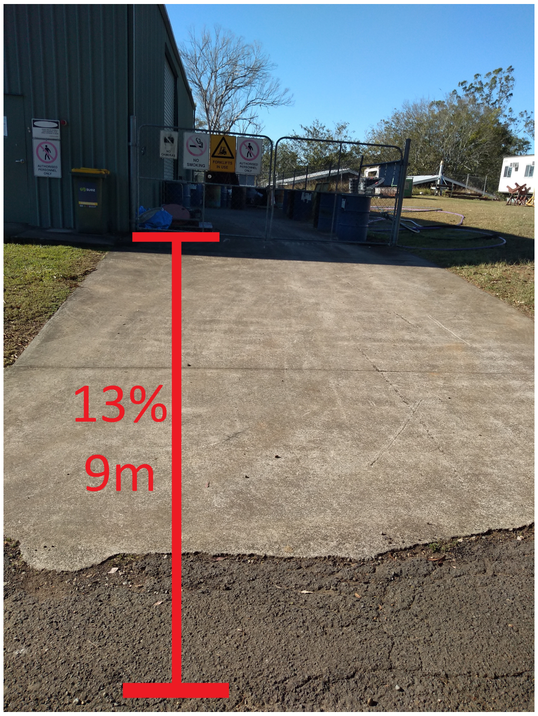

Figure 22: First test track

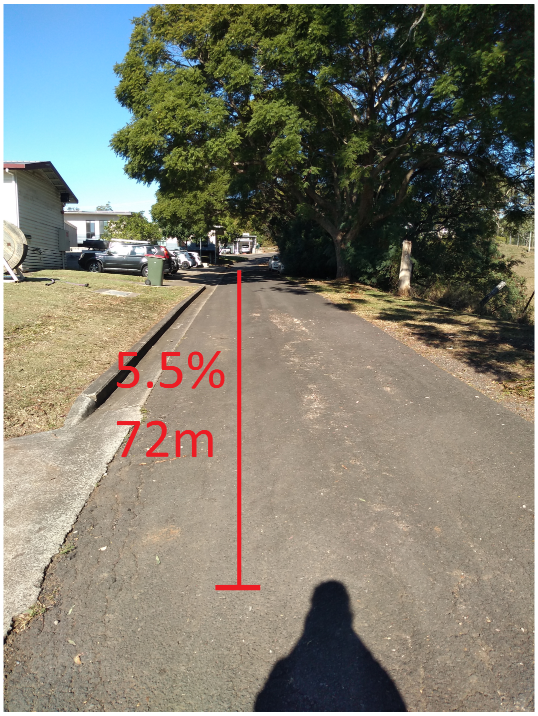

Figure 23: Second test track

4 Results and Analysis

4.1 Project Findings

In Figure 24 the final version of the prototype of the autonomous electric hauler is depicted it can be noted that it uses the same tipper as last year but also it can noted that this was originally a mobility scooter and has now be converted to this state.

It seems as though designing a scaled down version of what may be used as a storage solution on the full scale 15 tonne hauler is not feasible and instead the prototype implementation explored in this project along with simulation findings would be able to provide some recommendations of what is to be considered when designing the full scale hauler. As well as mentioned above this hauler can be used to verify the small scale of energy consumption and increase confidence in the accuracy of the large scale model.

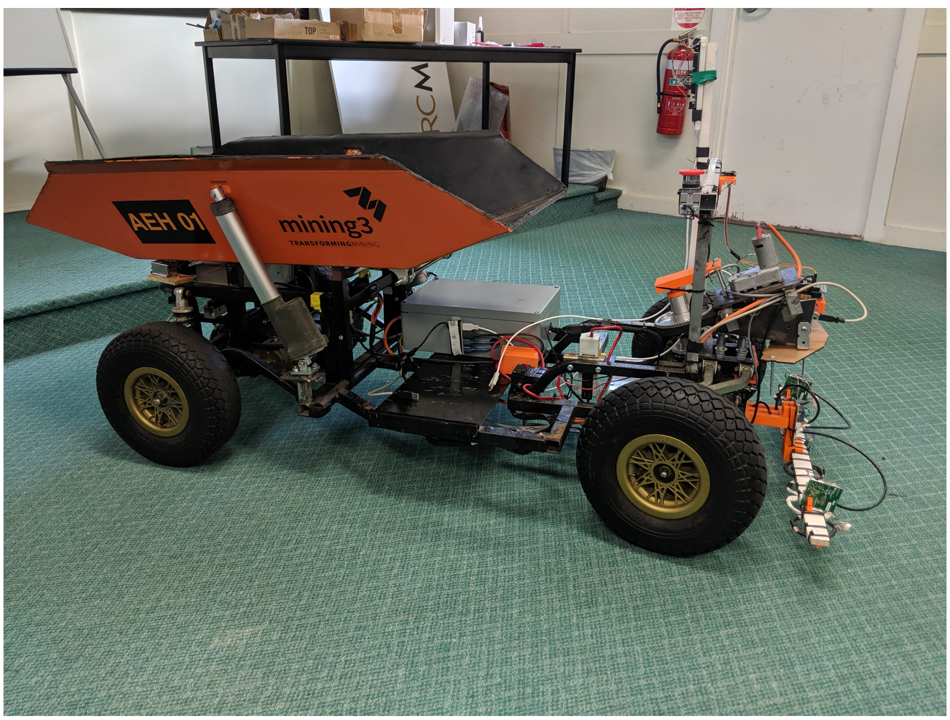

Figure 24: Final photo of the hauler prototype

4.1.1 Storage

As this prototype is just a prototype and is not going to be put under rigorous testing and is simply to prove concepts in more than just a simulation the storage system for the prototype will be designed with the components already available here at Mining3 which consists of a 58F 16.2V 6 cell supercapcitor and a 24V 16000mAh 6 cell LiPo battery.

The battery by itself is more than capable of powering this prototype in order for other students to test their concepts more easily however it should still be sufficient to demonstrate the usefulness of the addition of the supercapacitor using these storage devices.

4.1.2 Storage - Full Scale

In terms of the full scale a few things have been deduced simply from the requirements of the system of some of the needs of the storage system on the large scale. As it will be charged by a 1MW module if the wireless power transfer efficiency is 80% a very feasible number based on the literature then based on Table 3 some values can be calculated for parameters of firstly the requirements of an approximate system using only supercapacitors and then another which uses batteries in conjunction. These are based off requiring a capacity of 6400Wh which has at this stage been taken from the simulation results discussed below as a feasible capacity to complete haul routes.

From this table of two using two different methods to meet the same requirement

Feature	Supercapacitor	HESS
Capacity (Wh)	6400	6400
Power (MW)	12	1.24
Mass (kg)	640	128
Volume (L)	450	98.8
Cost (€)	64000	10800

Table 8: Comparison of requirements of different energy systems

and this can really exemplify the issues when it comes to supercapacitors versus using a HESS. The main advantage the supercapacitor has is the high power output however for this application this is just overkill. Apart from this the HESS dominates in every other category. This analysis firmly strengthens the decision of choosing to use a HESS in the large scale hauler.

4.1.3 Supercapacitor Charging circuit

In Figure 25 the current design of the charging system for the prototype is drawn. The AC voltage source represents what will be received on the secondary side of the

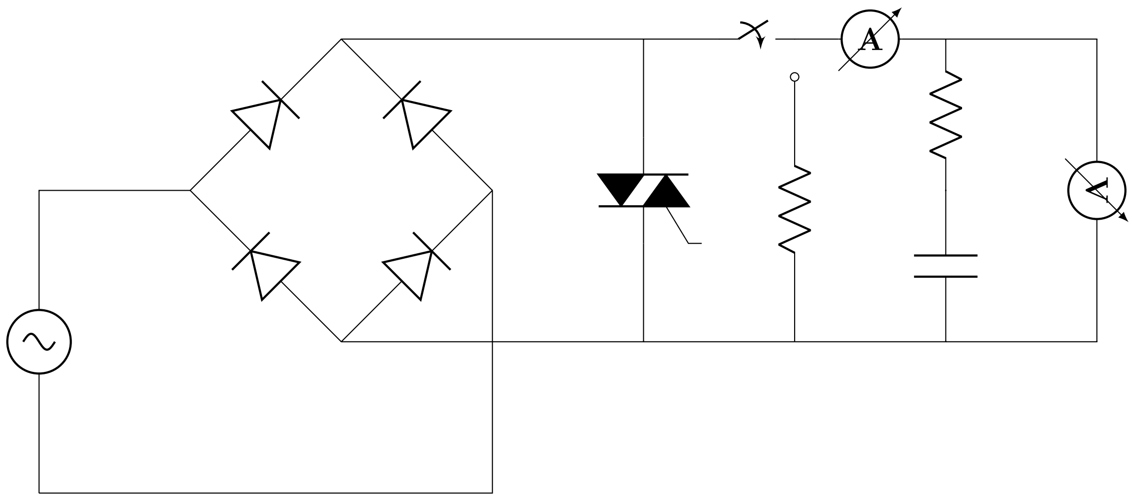

Figure 25: The current supercapacitor charging ciruit

wireless power transfer. This is then rectified to a DC voltage where TVS diodes are present to suppress any potentially harmful transients. There is then a switch which has the purpose of turning of the capacitor charging to prevent overcharging, however the transferred power still needs to be dissipated in some way so there is the connection of a resistive network. There is then in in series ammeter to monitor the supercapacitor current and a voltmeter so that the voltage of the supercapacitor is measured so that the switch can be controlled. All of this functionality has been practically tested on a smaller scale except that of the ammeter and TVS diodes.

4.1.4 Simulation

Figure 26 shows the rimpull curve that was derived and used to generate simulations results thus far in this project. This was derived from the aforementioned data of the Tesla and eGolf acceleration data and scaled to a curve of what could be considered feasible behaviour for the large scale model.

Meanwhile Figure 27 shows the typical power output over a haul route during a simulation in this case the interval ratio was 0.095 and the velocity ratio was 0.25 in this plot you can clearly see the different stages of the haul route firstly the flat part that comes from the loading pit and then the high fluctuations as the hauler moves up the hill it is important to note here that this is due to there being a smaller interval and something that needs to strongly be considered here is to resort to a constant speed on the hill to avoid this fluctuation which is probably a source of unnecessary power loss. Then then hauler progress along the long steady incline to the ore dump before returning to the loading pit.

Then Figure 28 shows energy over the course of the haul route this high fluctuation is as a result of the interval length and is partially an attempt to reduce the capacity requirements of the storage system.

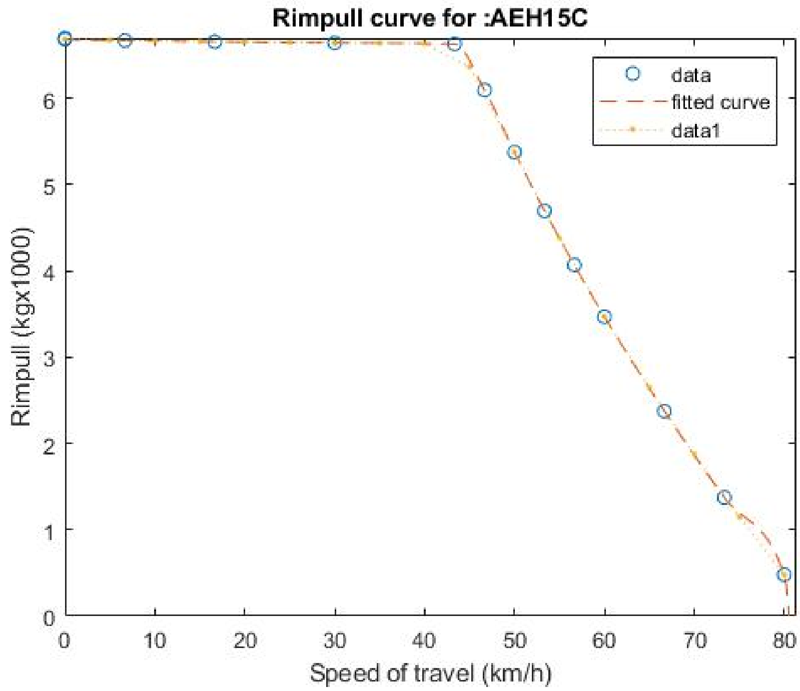

Figure 26: Generated rimpull curve for 15t hauler

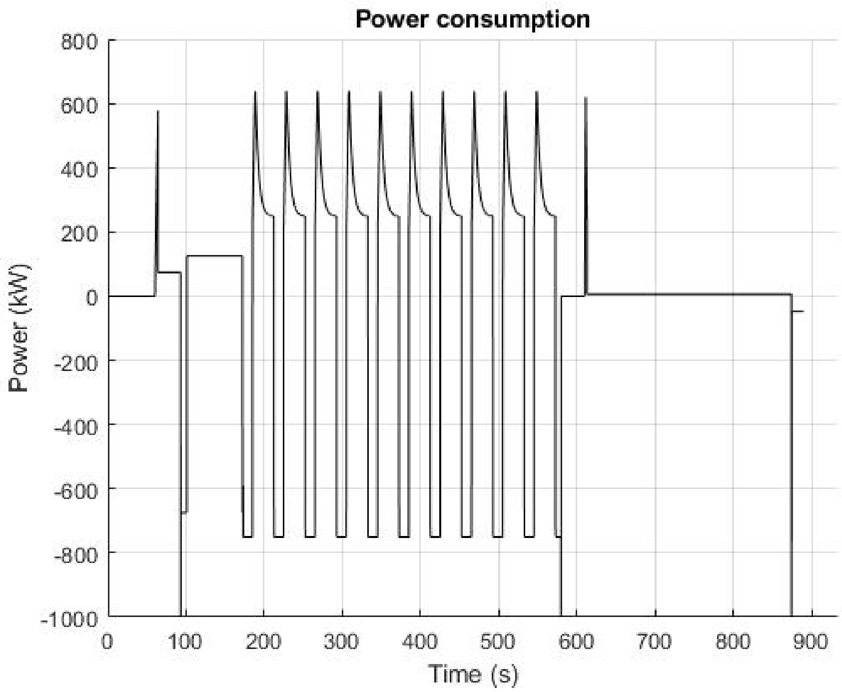

Figure 27: Power output over simulated haul route of 15t hauler

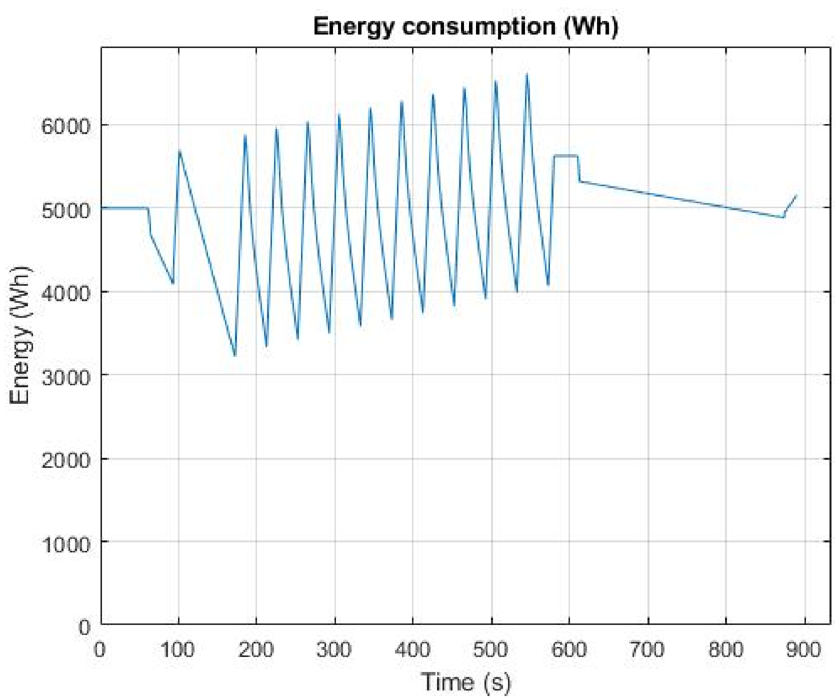

Figure 28: Energy consumption of the haul route

4.1.5 Charging

One of the key aspects that can be taken from these results is the trade off between time taken and amount of coil required in order to sustain travel for long periods of time using the rudimentary model of the haul route. To find something completely decisive these results should be applied to an economic model which takes into consideration the times required to complete haul routes so that the flow resources is not interrupted, due to no haulers being available. Then on the same note couple this trade off with the expense of having many charging coils. Essentially finding the cost minimum between these two factors is the next step in this section of the project. As it stands this is not considered a part of the scope of this project and there is no plan to explore the economic viewpoint at this stage.

Figure 29 and Figure 30 show the effect that changing the velocity and interval ratios of the coils has on the energy consumed and the amount of time taken to complete haul routes respectively. The graphs look very similar simply due to the fact that they are with some small differences. The key take away from this is that the energy and time of haul routes is very co dependent of one another and hence the economical model would aid in determining the optimal solution.

In Figure 31 is plot which displays the values of interval and velocity ratio for which the energy over the haul route was a positive but not too extreme of a positive and then from these values the ones that were quicker than the overall mean time. One thing that is interesting from these results is that there are valid options for many combinations of velocity and interval ratios which can give quite a bit flexibility when it would come to building the full scale implementation.

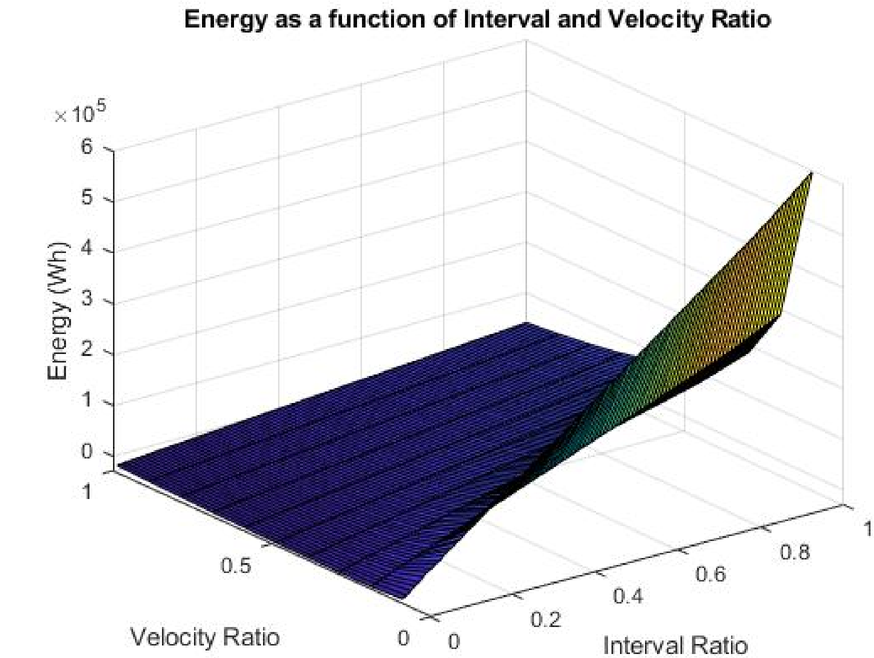

Figure 29: Energy consumption with different ratios

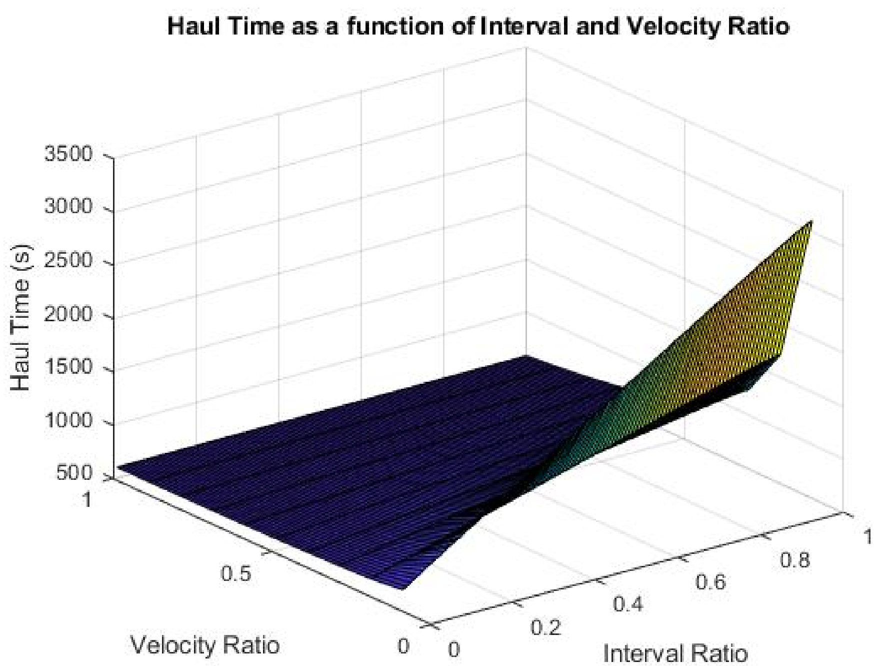

Figure 30: Haul times for different ratios

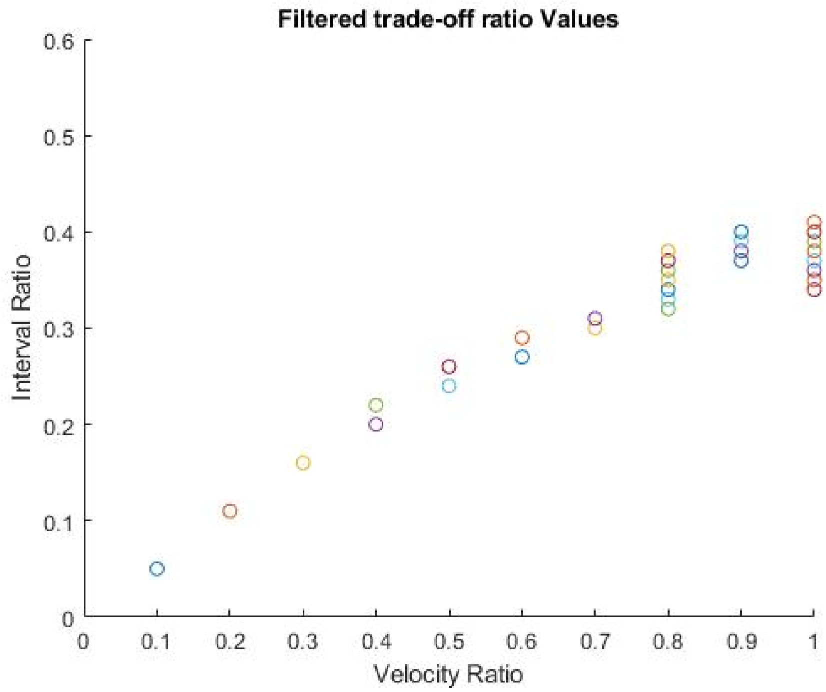

Figure 31: Efficient interval and velocity ratios from data used above

4.1.6 Model Verification

In this section the results of the model verification will be discussed. For the first test track the hauler was driven up and down the slope twice for testing in order to examine the error propagation over more than one trial. In Figure 32 the results of the energy simulation are depicted it can be seen that the model predicts the energy use pretty closely while the hauler is climbing the slope however there is some deviation when the hauler is going down the slope which is mainly due to some errors in the regenerative braking simulation but apart from this the model follows the collected data with a satisfying level of accuracy the incline results are particularly satisfying.

Due to the second haul route being considerably longer the data for this test track was only collected over a single return trip. The results of this comparison are shown in Figure 33 during the incline the values are very closely matched but slowly drift apart and similarly to the first test track there are issues with the model during the down hill phase due to unforeseen losses in the prototype and possibly some issues regarding the regenerative braking however overall these results are still pleasing due to the accuracy during the uphill. Although the regenerative braking modelling was tweaked with there is not much to be done to fix this simply due to the fact there is still positive energy consumption during the down hill section.

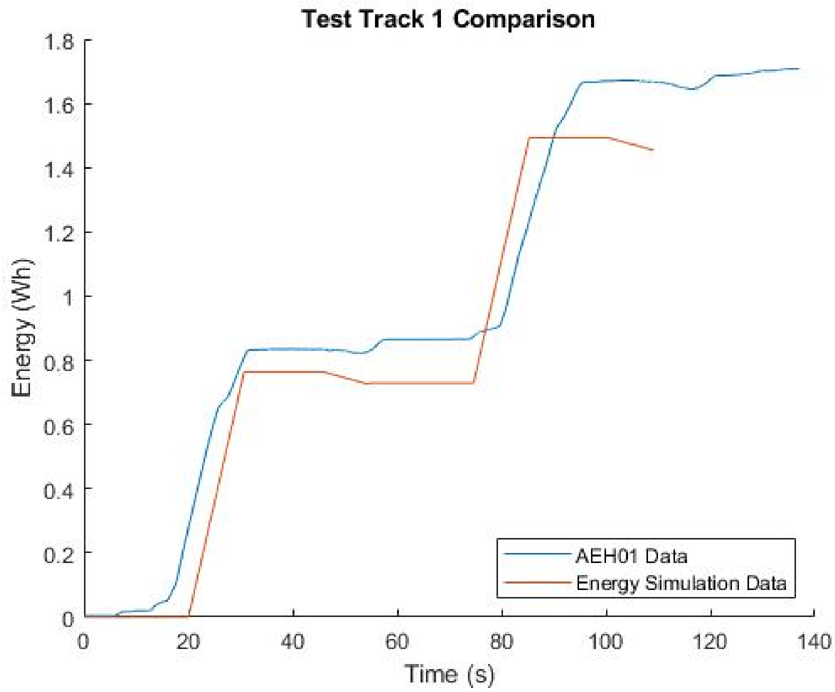

Figure 32: First test track comparison with model predicted result

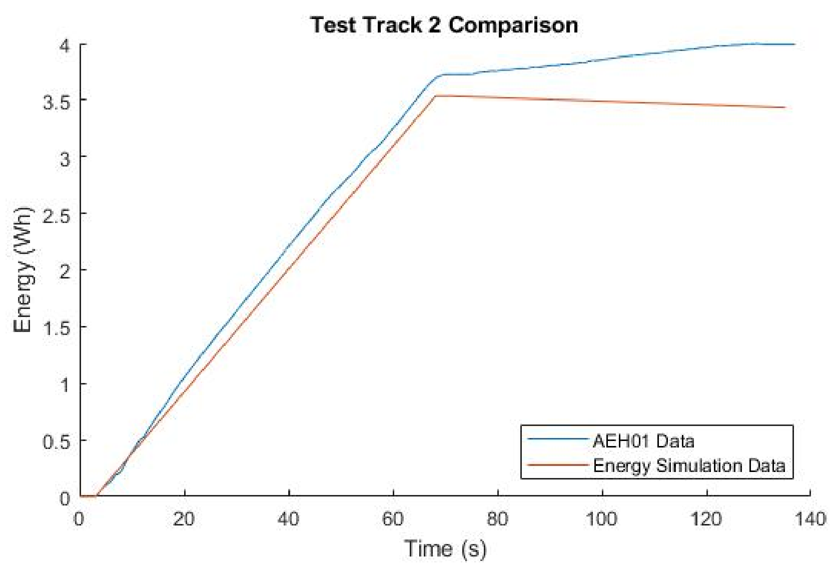

Figure 33: Second test track comparison with model predicted result

4.1.7 HESS Simulations

From the Simulink models shown in the project methodology and the requirements to have the best results for the system with the energy management system there were two main things that needed to be considered ability to control the rate of change of the battery current and the ability to control the state of charge of the supercapacitor these are essentially the two requirements for a large improvement in life span of the storage system.

As can seen in Figure 34 there is an adequate responses in terms of the power output. However in the passive case there is no ability to control either of these properties and they need to have the same voltage level.

Meanwhile in Figure 35 the semi active topology clearly also has an adequate response but only one aspect is necessarily directly controlled at one time depending on the location of the bidirectional DC DC converter. The other can be indirectly controlled for example when the bidirectional DC DC converter is interfacing the supercapacitor if the battery current is being sensed then action can be taken by the supercapacitor to attempt to keep that rate of change minimal. But in order to have a more robustly controllable system it is going to be beneficial to use the fully active HESS topology due to these reasons. In Figure 36 The results of the fully active test simulation are displayed and it can be seen the output is achieved while being to have control constraints on the supercapacitor power and also the rate of change of the battery current.

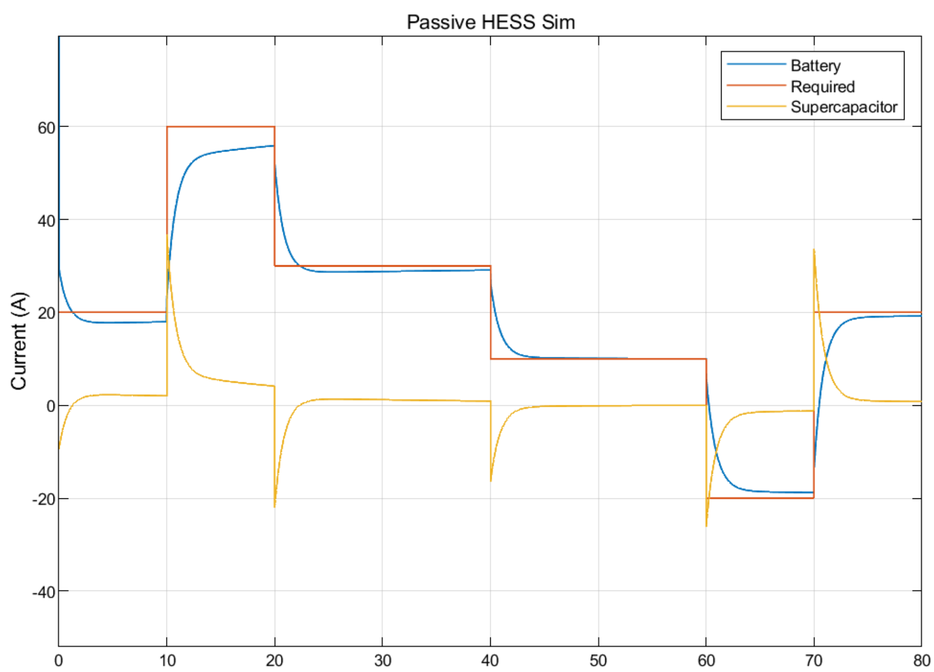

Figure 34: Passive HESS Test Simulation result

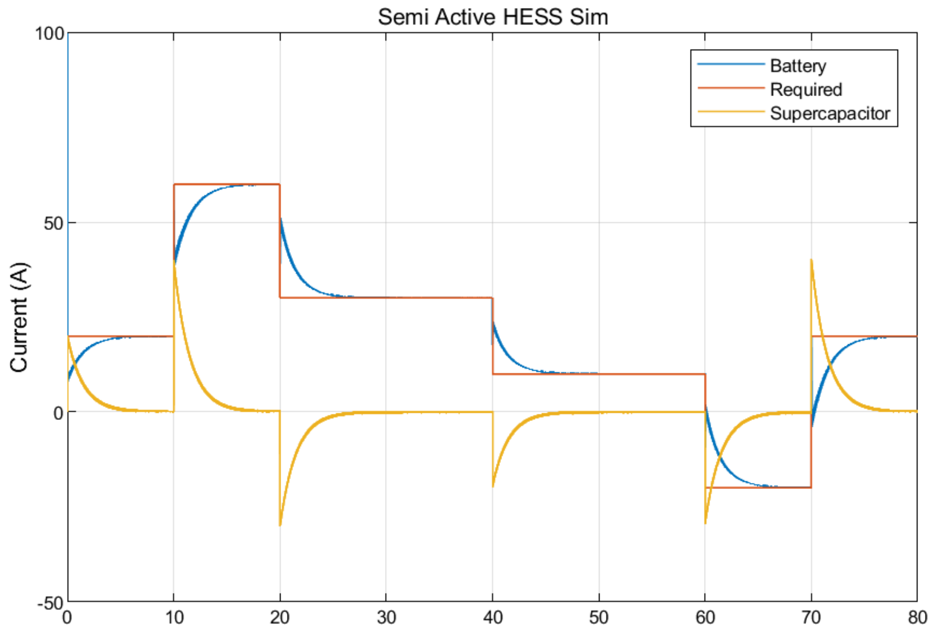

Figure 35: Semi Active HESS Test Simulation result

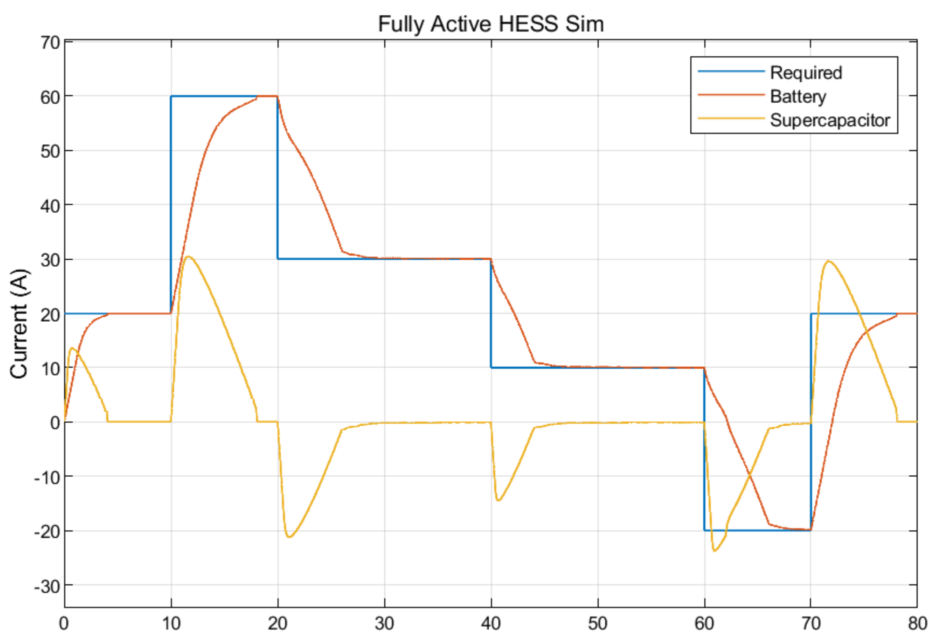

Figure 36: Active HESS Test Simulation result

4.2 Energy Management System

This section looks at the results of the HESS with EMS simulation. There were some issues that arose when running the simulation in which it took very long amount of time to complete the simulations. This problem was mitigated by condensing the time of the HESS simulations relative to the above energy simulations in particular down decreasing the amount of time by a factor of 3. Also the power used for this simulation is that expected for the small scale model rather than the large scale as these were values that had more confidence associated with them due to the model verification.

Figure 37 depicts this power reference at the bottom and the corresponding power output by the HESS at the top and overall the reference is followed closely and the HESS performs as desired. Figure 38 shows the results of the battery and the supercapacitor when simulated with the EMS when first looking at these results they may seem strange but overall it has been expected to have the supercapacitor being the more dominant supply of power with the battery being more of a back up in allowing the supercapacitor to support the high changing power loads of the electric hauler. Although there are some impulse looking responses from the battery these are taking place over considerable amounts of time when the the scale of the time axis is considered.

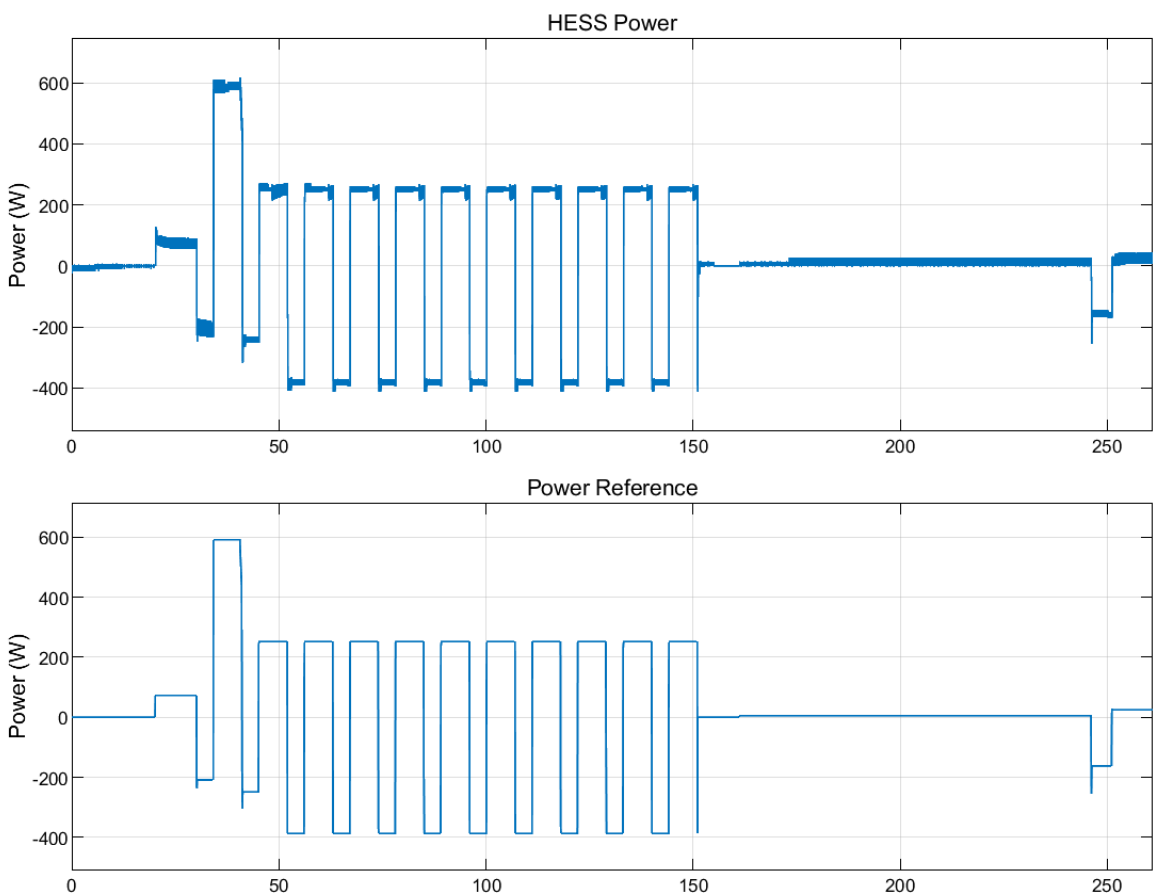

Figure 37: HESS with EMS on simulated haul route result

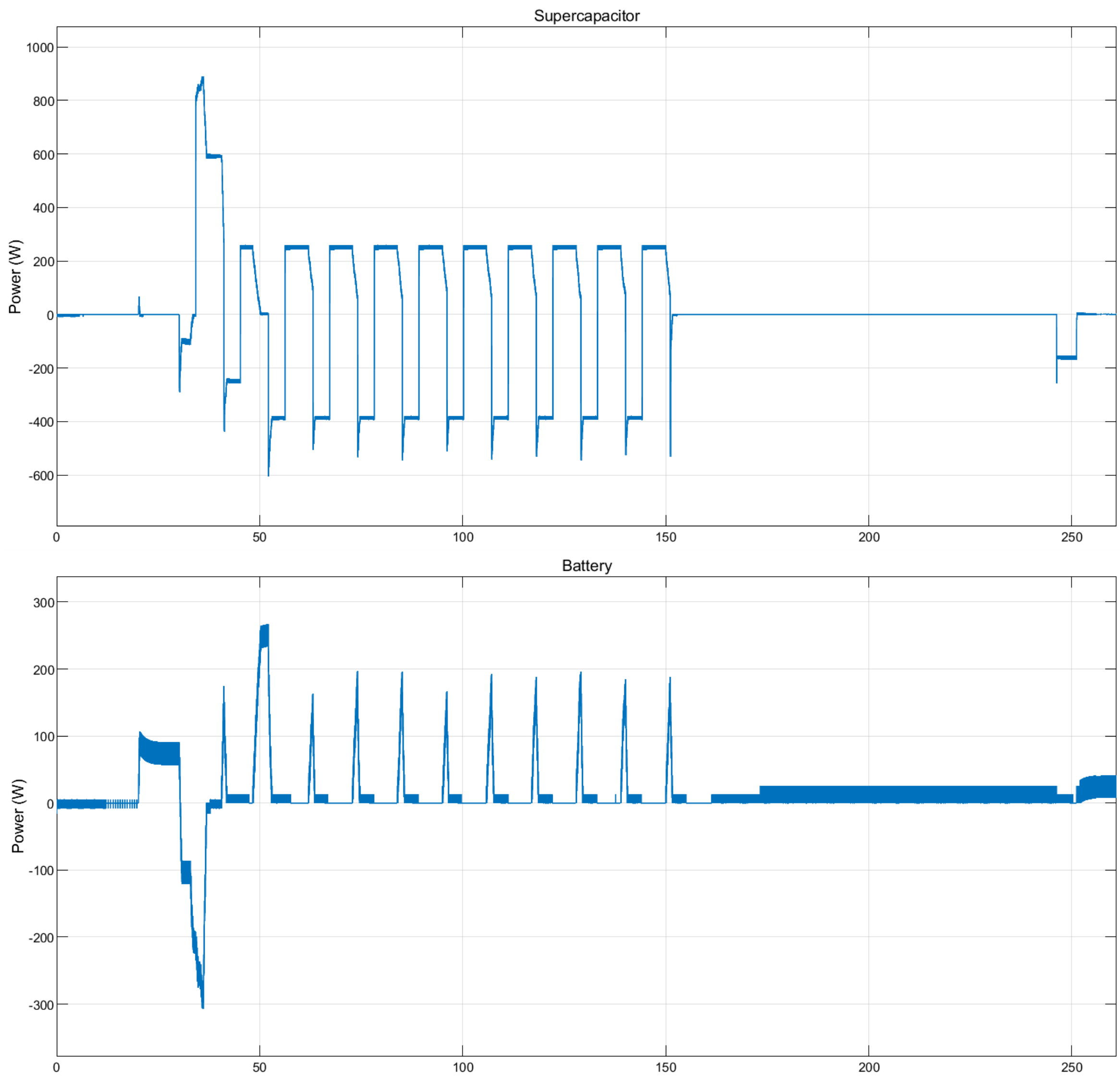

Figure 38: Distribution of Battery and supercapacitor power over haul route

5 Conclusion and Recommendations

It can be concluded that overall the project completed the core objectives that were set out and from this point of view the project can be considered useful. Firstly, the energy use of different vehicles over haul routes was modelled and the data was verified with the use of the physical prototype. Secondly, a model for interpreting the effect of different quantities of coils and different amounts of time spent charging on them affected the energy and time to complete haul routes. Then lastly, these pieces of information were used to determine that a viable storage option to support the high power requirements while minimising energy capacity and size was to use a hybrid energy storage system and in order to meet the control objectives of supercapacitor state of charge and battery power rate of change a full active topology with a rule-based energy management system was used. These goals were achieved with a systematic approach and effective time management which allowed deliverables to be completed.

However there are still some areas in which the work done in this project can be furthered and improved upon which will now be outlined. The first of being that most of that this project was completed on the basis of having a model of the haul route and the hauler available. The case of having a model for the hauler will likely always be true in the case of the autonomous electric hauler but not necessarily a model for the haul route. In order for this work to be more adaptable the use some kind of sensor implementation to detect haul route grade, velocity etc. In addition to use a more adaptable form of energy management system for example a model predictive controller could be feasible however it requires a considerable amount of CPU power to solve large prediction horizon equations.

Accompanying this it would be very useful to have an economic value model applied to the information regarding coil spacing and time taken to complete haul routes analysed in this project. That is devising a way to determine the cost of a certain distance of coil and the cost of taking an extra amount of time to complete haul routes. These pieces of analysis will allow an effective placement of coils and time to spend over the coils to be devised which is a very important part of this project to be addressed.

In terms of prototyping it would be very useful to firstly move towards a larger prototype vehicle in order to verify the haul route energy simulations further, as at the moment although there has been some verification but this still does not necessarily mean the large scale model is correct. The other form of prototyping that would be beneficial to this project would be the development of a bidirectional DC DC converter this would provide some further insights into the viability of a hybrid energy storage system.

Lastly, it is very important to stay up to date with modern day advancements in storage technology in particular regarding supercapacitors and hybrid capacitors a prime example of this is the advancements made recently at the University of Surrey to considerably increase the energy density of supercapacitors to some comparable with batteries [15].

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7 Appendices

7.1 Appendix A (Project Management)

This Appendix explores the management of the project with the risks Tables 10 and 9 were used to develop the risk assessment in 11. Also in this Appendix there is the gantt chart that was followed in order to complete this project.

7.1.1 Risk Management Guide

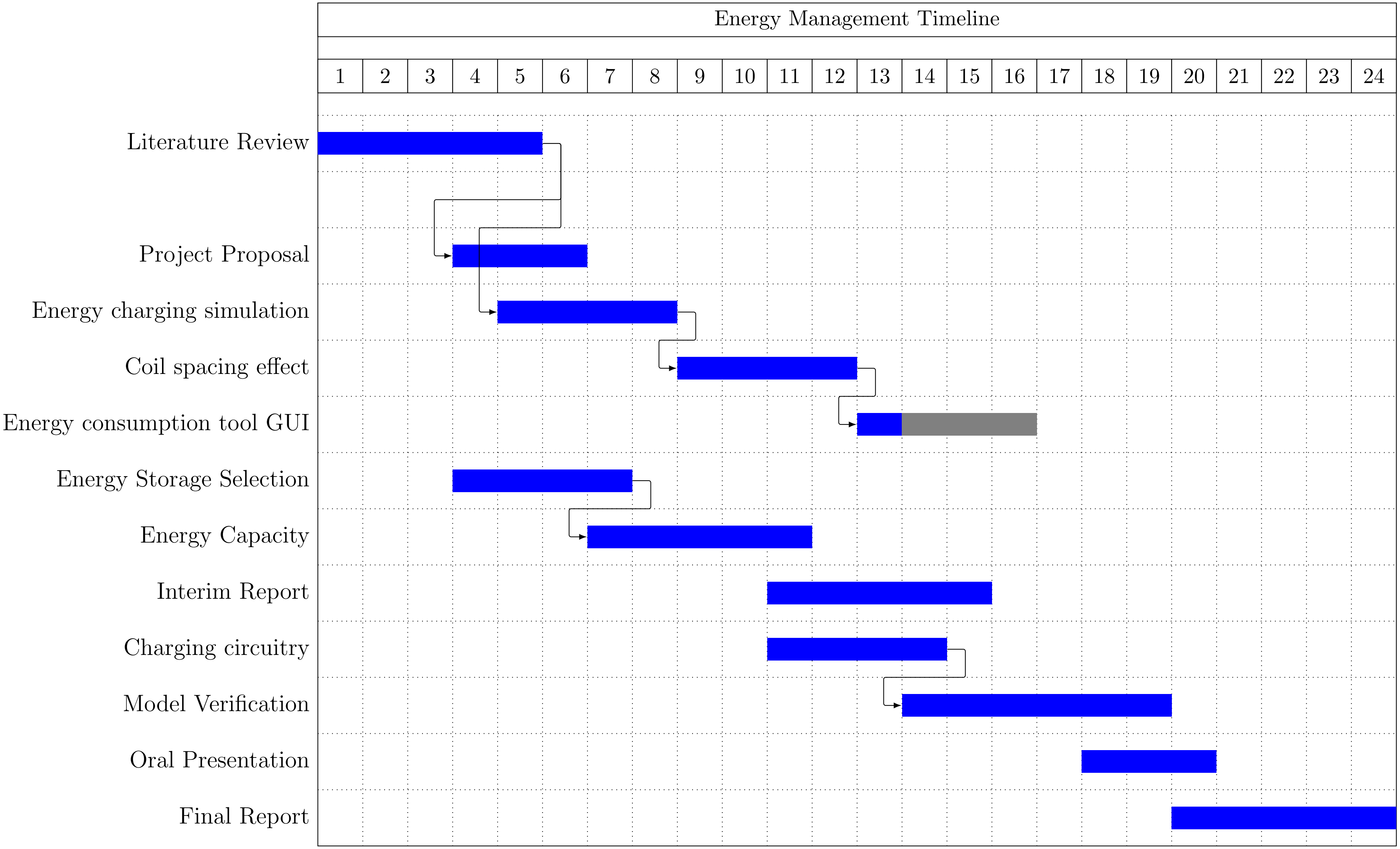
Risk Matrix Rating	**Risk Level**	**Mining3 Risk Management control guide**
1 to 5	(Ex) - Extreme - Immediate correction required - Eliminate, avoid or implement specific plans/ Standard to manage & monitor	Recommend implementation - minimum of 2 hard control Barriers and 2 soft controls
6 to 13	(H) - High - Should receive attention as soon as possible - Proactively manage.	Recommend implementation - minimum of 2 hard control Barriers and 2 soft controls
14 to 20	(M) - Medium - Should be dealt with as soon as possible but situation is not an emergency - Proactively manage.	Recommend implementation - minimum of 1 hard control Barrier and 2 soft controls
21 to 25	(L) - Low - Risk is normally acceptable Monitor & manage as appropriate	Monitor and manage

Table 9: Mining3 Risk management guide

		Hazard Effect/ Consequence				
Loss Type		**1** **Insignificant**	**2** **Minor**	**3** **Moderate**	**4** **Major**	**5** **Catastrophic**
(P) **Harm to People**		Slight injury or health effects -first aid/ minor medical treatment level	Minor injury or health effects – restricted work or minor lost workday case	Major injury or health effects – major lost workday case/ permanent disability	Permanent total disabilities, single fatality	Multiple fatalities
(E) **Environmental Impact**		Environmental nuisance	Material environmental harm	Serious environmental harm	Major environmental harm	Extreme environmental harm
(A) **Asset Damage**		Slight damage < $5000. No disruption to operation	Minor damage $5000 to $50 000. Brief disruption to operation	Local damage $50 000 to $500 000. Brief disruption to operation	Major environmental harm	Extreme environmental harm
(R) **Impact on Reputation**		Slight impact - public awareness may exist but no public concern	Limited impact - some local public concern	Considerable impact - reasonable public concern	National impact - national public concern	International impact - international public attention
Likelihood	**Likelihood Examples** (use only as a guide for evaluation of uncontrolled hazards)	**Risk Rating**				
A **(Almost certain)**	Likely that the unwanted even could occur several time per year at this location	**15 (M)**	**10 (H)**	**6 (H)**	**2 (Ex)**	**1 (Ex)**
B **(Likely)**	Likely that the unwanted event could occur several times per year in Mining3, or could happen annually	**19 (M)**	**14 (M)**	**9 (H)**	**4 (Ex)**	**3 (Ex)**
C **(Possible)**	The unwanted event could well have occurred in the mining industry at some time in the past 10 years	**22 (L)**	**18 (M)**	**13 (H)**	**8 (H)**	**5 (Ex)**
D **(Unlikely)**	The unwanted event could well have happened in the mining industry at some time; or could happen in 100 years	**24 (L)**	**21 (L)**	**17 (M)**	**12 (H)**	**7 (H)**
E **(Rare)**	The unwanted has never been known to occur in the mining industry; or it is highly unlikely that it could ever occur	**25 (L)**	**23 (L)**	**20 (M)**	**16 (M)**	**11 (H)**

Table 10: Mining3 Risk Assessment Matrix

7.1.2 Gantt Chart



7.1.3 Updated Risk Management

See Figure 11 for the Risk Assessment Matrix used to determine the following risk assessment. Overall the workplace health and safety risks of the project remained the same throughout the project.

Hazard	Controls	Type	Score	Additional Controls	New Risk
Solder in eyes	Safety glasses	P	20 (M)	Solder Training, Eye wash station	23 (L)
Soldering iron burn	Appropriate solder station, Do not leave on while not in use	P	23 (L)	-	23 (L)
Muscle injury	Reduce lifting. Do not lift items that are too heavy (>20kg without help).	P	18 (M)	Heavy items training	22 (L)
Electric shock	Earth leakage circuit breaker, Low voltage design, PPE.	P	18 (M)	Design evaluated by electrical engineer	22 (L)
Asbestos Inhalation	Informed of building condition, many cautions inside office.	P	16 (M)	Be careful when driving prototype inside, Ensure care is used when performing any construction in office.	21 (M)
LiPo or supercapacitor fire	Exercise care to not short circuit when working with such items	P,E	17 (M)	Safe circuit design to ensure safe charge and discharge, use if fire proof storage bags, Electrical engineer verifies designs	21 (L)
Falling behind schedule due to illness	Attempt to work ahead to account for possible schedule delays	A	22 (L)	Work extra time to catch back up if necessary	22 (L)
Wireless Power Transfer system is unable to deliver power	Find another source to simulate how the Wireless power transfer should hopefully be able to transfer	A	21 (L)	-	21 (L)

Table 11: Risks to be faced during project

7.1.4 Opportunities

There are many opportunities in this project if a successful outcome is reached.

- The possibility of continued work at Mining3 if there is still relevant objectives to be worked towards.
- If the proof of concept during the iteration of the project is successful then it is likely it may be transferred to a larger electric vehicle.
- In the event of this project being successful it is possible to be granted with more funding within Mining3 or externally for continued research.
- If promising results are reached the opportunity to continue with a larger prototype could be achieved.

7.2 Appendix B (Professional Development)

This project and placement at Mining3 as given me the opportunity to undergo personal and professional development from various learning events which were recorded and submitted as reflections as a part of this project. The development from the events was categorised by the Engineers Australia Stage 1 learning competencies. This section will cover what I consider to be some of the key learning events during this project. These will be addressed using the situation, effect, action and learning format that was used for the reflections throughout the placement.

Overall I feel as though I have undergone tremendous professional development during this project in terms understanding the expectations of a professional workplace and where I fit into that at this point in my career. As well as this how I should conduct myself in specific situations in order to achieve the best outcomes.

7.2.1 SEAL Analysis of Learning Event – Attending a 'Lunch and Learn'

EA Stage 1 Competencies Developed

EA 1.2 - Conceptual understanding of the mathematics, numerical analysis, and statistics which underpin the engineering discipline.
EA 1.4 - Knowledge development within the engineering discipline
EA 1.6 - Understanding the principles and norms of contemporary engineering practice

Situation

On the 1st of February Mining3 had a Lunch and Learn session this particular one was hosted by Byron Wicks, a new member of the company who had been working here for one month. The purpose of this session was for him to inform the company about past projects he had worked on at other companies in relation to mining. This was a great opportunity to learn more about the opportunities and challenges regarding engineering in the mining industry.

Effect

In Byron's presentation one of his big projects was wireless detonation of mine blasting and this eliminates some safety concerns of wires but introduces a whole new plethora of safety concerns regarding human error which really made me think about the different advantages and disadvantages regarding improvements in safety when trying to improve technology. I did not really feel a personal impact from this situation.

Action

I know now to be careful when taking action to reduce safety concerns in a given project as to think about new safety concerns that may rise as a result and take this into consideration. As for this being a new situation it was quite similar to a lecture setting at university and due to this it was quite a normal situation for me.

Learning
I have firstly learnt about some of the different directions that can be taken when being an engineer in the mining industry. This gives me a greater understanding of where I may want to eventually take my career one day. It has also, as mentioned given me some safety precautions to take in to consideration in my future developments or innovations that I may be involved in and that minimising one risk may cause another safety concern to increase tremendously.

7.2.2 SEAL Analysis of Learning Event – Filling out a 'Take 5'

EA Stage 1 Competencies Developed
EA 3.6 - Effective team membership
EA 3.3 - Creative, innovative and pro-active demeanour.

Situation
The mobility scooter that we have using to prototype here at Mining3 had an issue where the front and back of it had come a part and it needed to be lifted in order to be put back together as there is some potential risk involved I asked Bill to help me. But it is protocol at Mining3 to fill in a 'Take 5' risk assessment to evaluate risk involved with certain activities the could cause injuries.

Effect
Filling out the Take 5 allowed me to more easily see the risk associated with the activity I was performing and to understand that if done in the correct way all will be fine. Knowing this helped me feel at ease and more relaxed when performing the task. It was nice feeling to know I had followed the protocol as well.

Action
I guess the action here was filling out the take 5 but then based on that when you write out the risk associated with the task that you are performing and then in this case I made best attempt to mitigate these factors. This allowed me to know that I am working in the safest way that I could be.

Learning
I have learnt that in any professional environment safety is paramount to success. I apply this in of course in future situations that I encounter which may have risk associated with them as I am sure this is not the last time that I will be doing something with potentially bad outcomes, for example the activities that occurred in learning event 1 where burns were experienced.

7.2.3 SEAL Analysis of Learning Event – Supervisor leaving the country

EA Stage 1 Competencies Developed
EA 3.5 - Orderly management of self, and professional conduct.
EA 3.3 - Creative, innovative and pro-active demeanour.

Situation
My industry supervisor at Mining3 was required to present mining research convention in Canada and as a result was not on site at Mining3 for over a week. The only way I had of contacting him during this time was via email which he had very limited time to reply what I might inquire about.

Effect
Personally, I was much more dependent on myself and needed to be more organised so that I always knew what task to work on. This was a good feeling as it has made me feel more competent and less dependent on my superiors and that I can be productive on my own.

Action
I planned out my week of work so that I could remain productive and throughout the whole time and remain on track with my project. This was very useful for me and I believe a successful and proactive approach to dealing with this situation which I can use in the future when I am more than likely to be in similar situations again.

Learning
I have learnt that in any professional environment it is important to have a high amount of responsibility on yourself so that projects can be completed and micro managing is not necessary. It is especially good in maintaining autonomy of work within a company which can be a very powerful thing when everyone is working as they should be. I will be sure to apply this in any industry jobs in the future and remain proactive in my completion of work and communicating with my supervisor beforehand to understand my expectations.

7.2.4 SEAL Analysis of Learning Event 5 – Visit from engineering professionals

EA Stage 1 Competencies Developed
EA 3.2 - Effective oral and written communication in professional and lay domains.
EA 3.4 - Professional use and management of information.

Situation
An engineer from Maclean Engineering was visiting Mining3 as Maclean Engineering has developed some autonomous mining haulers, there are some key differences between their designs and what we have in mind for example they only use batteries instead of

in conjunction with another type of technology. Basically, he was visiting to give us some insight on what they had done as they had actually deployed full size haulers in some mines.

Effect
This made this project feel real and that even though what we are doing at the moment is at the early stages one day it may be employed in a mine somewhere and improved my view of the project.

Action
There was a dialogue opened now with the possibility of obtaining some data collected from their haulers to be used to improve simulations and other tests.

Learning
For me the learning here is that in some situations for some projects another company could be working on a similar idea and rather than competition collaboration could be the best way to approach the situation.

7.2.5 SEAL Analysis of Learning Event 1 – Safescape mining vehicle showcase

EA Stage 1 Competencies Developed
EA 2.2 - Fluent application of engineering techniques, tools and resources.
EA 1.3 - In depth understanding of specialist bodies of knowledge within the engineering discipline.
EA 3.2 - Effective oral communication in professional domains.

Situation
Our supervisor Erik Isokangas was invited to a showcase in Mt Cotton where the company Safescape were having a showcase of two vehicles one being the Agrale Marruá and the other being the Bortana EV. They were both intended as light vehicle use in mines but the Bortana EV is essentially an electric version of the diesel Agrale Marruá. The showcase was at Mt Cotton and we had the pleasure of going there in Erik's Tesla.

Effect
I was able to see firsthand things that we have spent a lot of time talking about and hearing about and researching during our time at Mining3. It gave me some more motivation to continue working on projects like this now that I could experience the motivation of observing an end product.

Action
I spoke with the representatives from different companies involved with this project, asking them about the challenges involved in the project. How long they had been

working on it and what they enjoyed the most about it, just really trying to get more of an insight in to the completion of the project.

Learning
I have learnt that seems really rewarding to see the project all the way through to a finished product although it may take many years it really is something that will allow you to look back at something really impressive that you accomplished for the rest of your career.

7.3 Appendix C (Simulink)

7.3.1 Contents of load block

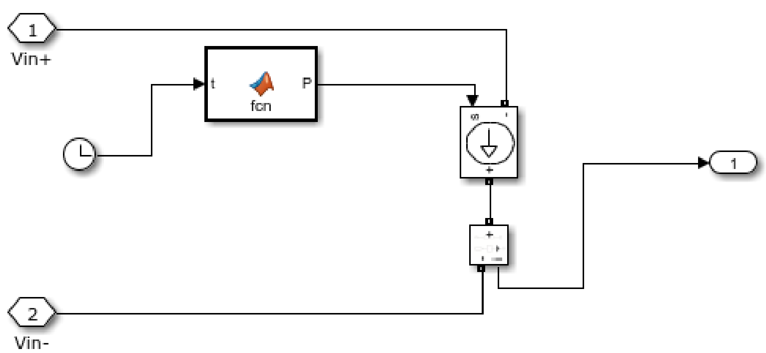


Figure 39: Contents of load block use for HESS test simulations

7.3.2 EMS Code

```
function [vR, Sp, Bp] = fcn(Pt, scV, bI, g, l)
%% Constants
Vb = 24;
deltaImax = 10;
Ichargemax = 15;


%% FSM

persistent state;
if(isempty(state))
```

```
    state = 4;
end


switch state

     case 1 %Charging

          if(scV < 16 && Pt > 0)
               Sp = 0;
               Bp = Pt;
               vR = 0;
          elseif(scV > 16 && Pt > 0)
               Sp = Pt;
               Bp = 0;
               vR = 0;
          elseif(scV < 16 && Pt < 0)
               Sp = Pt;
               Bp = 0;
               vR = 0;
          else
               Sp = 0;
               Bp = Pt;
               vR = 1;
          end

          if(g > 0.1)
               state = 2;
          end

     case 2 %Discharging

          if(scV < 10 && Pt > 0)
               Sp = 0;
               Bp = Pt;
               vR = -1;
          elseif(scV > 14 && Pt > 0)
               Sp = Pt + Ichargemax * Vb;
               Bp = - Ichargemax * Vb;
               vR = 0;
          elseif(scV > 10 && Pt > 0)
               Sp = Pt;
               Bp = 0;
```

```
            vR = 0;
        elseif(scV < 15 && Pt < 0)
            Sp = Pt;
            Bp = 0;
            vR = 0;
        elseif(scV < 16 && Pt < 0)
            Sp = Pt / 2;
            Bp = Pt / 2;
            vR = 0;
        else
            Sp = 0;
            Bp = Pt;
            vR = 1;
        end

        if(l == 0)
            state = 3;
        end

    case 3 %Discharging

        if(scV < 10 && Pt > 0)
            Sp = 0;
            Bp = Pt;
            vR = -1;
        elseif(scV > 10 && Pt > 0)
            Sp = Pt;
            Bp = 0;
            vR = 0;
        elseif(scV < 15 && Pt < 0)
            Sp = Pt;
            Bp = 0;
            vR = 0;
        elseif(scV < 16 && Pt < 0)
            Sp = Pt / 2;
            Bp = Pt / 2;
            vR = 0;
        else
            Sp = 0;
            Bp = Pt;
            vR = 1;
        end
```

```
        if(g < -0.1)
            state = 4;
        end

    case 4 %Charging

        if(scV < 16 && Pt > 0)
            Sp = -Ichargemax * Vb;
            Bp = Pt + Ichargemax * Vb;
            vR = 0;
        elseif(scV > 16 && Pt > 0)
            Sp = Pt;
            Bp = 0;
            vR = 0;
        elseif(scV < 16 && Pt < 0)
            Sp = Pt;
            Bp = 0;
            vR = 0;
        else
            Sp = 0;
            Bp = Pt;
            vR = 1;
        end

        if(l == 0)
            state = 1;
        end

    otherwise

        disp('Sumtin wong');
        Sp = 0;
        Bp = 0;
        vR = 0;
end

deltaI = Bp/Vb - bI;

%%Ensure battery current does not change to extremely
if(deltaI > deltaImax/10)
    Bp = Vb*(bI + deltaImax/10);
    Sp = Pt - Bp;
elseif(deltaI < -deltaImax/10)
```

```
    Bp = Vb*(bI - deltaImax/10);
    Sp = Pt - Bp;
end

end
```