Vehicle Battery Pack Design and Considerations for Repurposing

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The market for hybrid and electric vehicles is expanding with the rise of gas prices and desires to curb climate change. With the creation of these complex systems comes the development of advanced battery systems which store and provide energy in the vehicle life stage. These batteries however have a limited lifetime in the vehicle, after which they can be used to provide energy in repurposed stationary energy storage applications. The objective of this thesis is to examine how electric vehicle batteries can be repurposed. The design of a hybrid vehicle battery pack, which uses mechanical topology optimization techniques to assist the designer in developing a weight-efficient design, is detailed. The battery pack under consideration is composed of Lithium-ion cells and the design techniques proposed can assist with the design of a lightweight repurposed energy storage system for a residential application. A design process for a repurposed battery pack is also proposed, which takes into account design steps from initial business/market predictions to installation of the assembly at a residence. This design process details a capacity fade model to predict battery state of health after the vehicle life stage, as well as a risk analysis which focuses on a design failure modes and affects analysis, fault tree analysis, and a code analysis. Finally, the design of two iterations of a repurposed battery pack bench test is documented with lessons learned for the design of future test benches and the full size repurposed pack. Lithium-ion battery packs are still relatively new to the vehicle market, and the ability for significant numbers of them to enter the repurposed market is a few years away. However, there are commercially available stationary battery packs that use this technology. As a result, there are a number of risks still evident in the design of a repurposed system as the relevant codes and legislation have not been written. Additionally, the nature of the collection, testing, and supply chain for the repurposed packs after vehicle use is currently unknown. It is recommended that more research be completed in the areas of battery state of health models as well as the business models for repurposed applications. Full-scale degradation research of packs is required in real-world vehicle settings, in order to understand exactly how the batteries degrade over a vehicle's lifetime. As well, re-manufacturing firms need to understand how they can feasibly take used packs of uncertain quality to build the newly proposed assemblies while minimizing risk to the consumer and their own liability.

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I would like to thank the entire technical steering committee and the sponsoring partners of EcoCAR. The experience through the Advanced Vehicle Technology Competition Series is unparalleled in academia, and not only trains the next generation of engineers, but also forms a basis to create friendships that will last for years. Thank you especially to the two headline sponsors, the U.S. Department of Energy and General Motors. GM has been instrumental in my schooling over the past three years and I am very excited to join the team in the coming months. A special thanks goes to Dan Mepham and Benjamin Beacock for helping to mentor the team while I was a member. Without your support, we would not be able to do what we do, and you are an inspiration for every team member moving through the program.

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Thank you as well to the members of my master's research group into battery repurposing, and my sponsors Mitsui and NSERC. Dr. Steven Young, Sean Walker, and Leila Ahmadi were very helpful in the development/editing of my content for my thesis and helping me to complete my master's degree. I look forward to seeing the progress of the group and installing a repurposed energy storage system in my future home!

Finally, I would like to thank my family for their support during my master's program. Long days and nights were tough sometimes. Thank you Mom, Dad, and Heather for supporting me no matter what and to push me to be better every day.

Dedication

To my family, friends, mentors, and teammates.

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List of Acronyms

Ah-Processed	Amp-hours Processed
AVTC	Advanced Vehicle Technology Competition
BEV	Battery Electric Vehicle
BMS	Battery Management System
C-Rates	Charge Rates
CAN	Controller Area Network
CO_2	Carbon Dioxide
COG	Centre of Gravity
CSM	Current Sense Module
DOD	Depth of Discharge
DET	Detection
DFMEA	Design Failure Modes and Effects Analysis
E&EC	Emissions and Energy Consumption
EMI	Electromagnetic Inteference
EOL	End of Life
EPA	U.S. Environmental Protection Agency
FEA	Finite Element Analysis
FDR	Final Design Review
FTA	Fault Tree Analysis
HC	Hydrocarbons
HEV	Hybrid-Electric Vehicle
HV	High Voltage
HWFET	Highway Fuel Economy Driving Schedule
ICE	Internal Combustion Engine
L-PEM	Linear Prediction Error Method
Li-ion	Lithium-ion
$LiFePO_4$	Lithium-Iron-Phosphate
LiMnO	Lithium-Manganese-Oxide
LV	Low Voltage
MIL	Model-in-the-Loop
NiMH	Nickel-Metal-Hydride
NO_x	Nitrogen Oxide
NVH	Noise, Vibration, and Harshness
OBD	On-board Diagnostics
OCC	Occurrence
OEMs	Original Equipment Manufacturers
O_3	Ozone
PDR	Preliminary Design Review
PHEV	Plug-in Hybrid-Electric Vehicle
PM10	Particulate Matter
RPN	Risk Priority Number

RUL	Remaining Useful Life
SEI	Solid Electrolyte Interface
SEV	Severity
SOC	State of Charge
SOH	State of Health
SO_x	Sulfur Oxides
SSR	Solid State Relay
UDDS	Urban Dynamometer Driving Schedule
UPS	Uninterruptable Power Supply
UWAFT	University of Waterloo Alternative Fuels Team
VTS	Vehicle Technical Specifications

Chapter 1
Introduction

With the rise of gas prices and the desire to curb climate change, there is a push to utilize alternative energy sources to provide for the needs of the future. Currently, non-renewable energy sources make up 29 percent of the energy used to meet the grid needs within the province of Ontario [1]. Within the automotive sector, the incorporation of new technologies and fuels is allowing consumers to offset emissions and decrease energy consumption in the vehicles they drive. Automakers are looking to capitalize on methods which decrease the use of fossil fuels to provide power to a vehicle; one of the biggest being the use of electrification [2].

Electrification allows automakers to use electric motors either in conjunction with, or in replacement of the conventional combustion engine to propel the vehicle's wheels. Electric motors have many advantages over combustion engines, including the availability of their full torque at a standstill, and the ability to contain vehicle tailpipe emissions to upstream sources exclusively. The pinnacle of electrification in a vehicle is the Battery Electric Vehicle (BEV) that uses full electric power without any burning of fossil fuels onboard. However, this type of vehicle is hampered by its low vehicle range compared to a conventional vehicle. An alternative is a hybrid-electric vehicle, which combines both a combustion engine and one or more electric motors to achieve the highest efficiency of both powertrains and increase the vehicle's usable range.

Both hybrid and full-electric vehicles use large batteries to provide storage of onboard electrical energy. These batteries are predominantly made up of Lithium-ion cells which can be heavy, and expensive. With the increased use of these batteries, there is an increased demand of minor metals, including lithium. Experts believe that this industry can be carried forward for future generations, with future growth being governed by the amount of recycling which occurs in the manufacturing process [3]. The current life cycle of these batteries is shown in Figure 1.

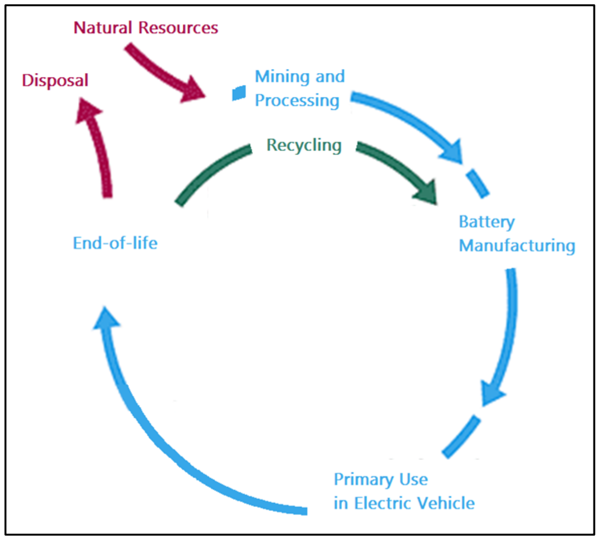

Figure 1: Original Battery Lifecycle [4]

Within automotive use, batteries see large current draws and state of charge swings in acceleration, deceleration, and prolonged driving periods. This environment degrades the battery, and can render it useless over a period of approximately eight years for this application, based on automotive manufacturer's warranties [4].

One way of modifying the life cycle of these batteries to increase sustainability is to add a second 'repurposing' phase to the battery's use. In this repurposing phase, the battery is reused in a second application, such as stationary energy storage, where it is gently cycled and able to be used again before going through the recycling process. The addition of the repurposing stage of the battery's life allows it to be fully utilized before being disassembled for recycling. The addition of the repurposing stage in the battery life cycle is shown in Figure 2.

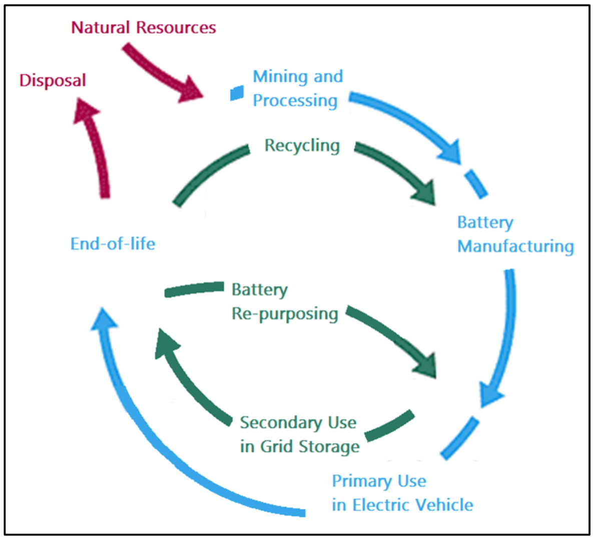

Figure 2: Modified Battery Lifecycle [4]

1.1 Objective and Contributions

The objective of this thesis is to outline the background, design considerations, and bench test setups of using a repurposed battery pack in a stationary energy storage application. Specific information is drawn from the design and fabrication of automotive batteries, used in a hybrid configuration in the context of the Advanced Vehicle Technology Competition (AVTC) series for the University of Waterloo Alternative Fuels Team (UWAFT) entry. Following this discussion, considerations for the design of a repurposed energy storage system will be outlined and a design process will be proposed. Finally, two revisions of a repurposed energy storage system test bench setup using a 1.3 kWh battery pack will be outlined. The design will be documented, along with the lessons learned from the setup for the next phase of testing. Both designs are in initial conceptual phases, and the use of the test bench setup allows for simulation of the pack with integration with the utility grid.

1.2 Thesis Outline

This thesis includes six chapters, including this introduction. The topics of each of the sections are as follows:

Chapter 1 outlines an introduction to the thesis, including a background on the push for electrification in vehicle design to offset vehicle tailpipe emissions and reduce operating costs. The introduction also discusses batteries, their life cycle process, and the addition of a second use stage known as ‘repurposing’ which is the focus of this thesis.

Chapter 2 discusses background and literature focusing on hybrid vehicles, batteries, vehicle design, and repurposing. Concepts discussed include the modifications required to implement a hybrid vehicle design, including aspects in terms of mechanical, electrical, and controls. The discussion also incorporates information about vehicle configurations, and overall design choices/considerations including drive cycles, and component sizing. Finally, batteries and literature focusing on fade mechanisms and degradation are discussed and how these factors correlate to battery use in initial use stages (vehicle) and repurposed stages (secondary storage).

Chapter 3 discusses battery pack design in a vehicle. This chapter focuses on the design of a battery pack for the University of Waterloo Alternative Fuels Team, which competes in Advanced Vehicle Technology Competitions. Design considerations and aspects of battery pack manufacturing are discussed to give a background on the areas of consideration when building a battery pack from the module level. The mechanical optimization techniques discussed are useful for the repurposed pack discussion as they can be employed in the design of the casement for the repurposed assembly.

Chapter 4 discusses considerations for design of a repurposed battery pack. A design process is outlined, which follows the repurposed pack from initial market research to installation at an application. Steps outlined include insight into battery state of health predictions following vehicle use, including a capacity fade model developed based on cycling results from studies on Lithium-ion half cells. A risk analysis is also performed for the pack assembly, including a design failure modes and effects analysis, fault tree analysis, and code analysis.

Chapter 5 discusses the repurposed battery pack bench test setup constructed at the University of Waterloo. Sections of discussion include the design, operation, and lessons learned in the construction of the setup. The documentation of its design is outlined as a starting point for further analysis into repurposed battery packs in the future, with the use of a newly available bi-directional inverter/charger system sourced from the solar energy industry.

Chapter 6 is a conclusion section, which will outline the main points covered in this thesis and outline recommendations for future work which builds upon this knowledge base in the areas of vehicle, battery, and repurposed energy storage system design.

Chapter 2
Background and Literature Review

2.1 Conventional and Hybrid Vehicles

There are three basic vehicle configurations used on the road presently: conventional vehicles, electric vehicles, and hybrid vehicles. Conventional vehicles utilize an Internal Combustion Engine (ICE) which performs a conversion between chemical and mechanical forms of energy to propel the vehicle in the form of combustion. These cars feature a driving range of around 500 – 600 km on a regular tank, and can be filled in only a few minutes at a convenient re-fueling station. The combustion process uses a source of ignition, air, and fuel which often produces harmful emissions into the environment. These emissions are in the form of Nitrogen Oxides (NO_x), Carbon Dioxide (CO_2), Hydrocarbons (HC), Sulphur Oxides (SO_x), Particulate Matter (PM10), or Ozone (O_3) [5].

Electric vehicles replace the combustion engine in the conventional vehicle with a battery pack and an electric motor. The battery pack provides an onboard storage area for electrical energy which can be used later by the motor. The biggest advantages of the use of an electric motor are the offsetting of vehicle tailpipe emissions and the ability to employ regenerative braking. Through the use of the motor, the vehicle will not create any emissions and leave all sources to upstream generation. For Ontario, this use of upstream energy is beneficial to the environment as 70.1 percent of the energy mix is made up of nuclear, hydro, wind, and solar energy; all forms of generation which do not pollute the air [1]. The biggest disadvantage to the use of electric vehicles is the limited range, lack of re-fueling infrastructure, and increased cost of the powertrain. The increased cost is mainly due to the incorporation of large Lithium-ion battery packs to store onboard energy [6]. Additionally, it can take up to twenty hours to charge an onboard pack; an aspect of an electric vehicle's design which inhibits consumer acceptance [7].

Hybrid vehicles attempt to combine the advantages of both the combustion and electric vehicles into one package. They traditionally feature a downsized combustion engine to burn less fuel to meet the consumer's desired vehicle range, in conjunction with one or more electric motors. There are two main variants of hybrids: Hybrid Electric Vehicles (HEVs), and Plug-In Hybrid Electric Vehicles (PHEVs). HEVs are designed with smaller battery packs, benefitting from the use of regenerative braking in city driving to charge the onboard battery. For a PHEV, the battery is often much larger and is a dominant source of propulsion power. In the PHEV, the electric powertrain of the vehicle is often designed to meet the average commuting requirements of the consumer of 40.55 km [8]. By meeting this target, consumers can achieve the daily benefits of driving an electric vehicle, using only electric energy, creating zero emissions, and saving up to $13,000 over the lifetime of the vehicle compared to driving a conventional vehicle [9].

2.2 Hybrid Vehicle Configurations

There are multiple types of hybrid vehicle architectures, depending on how each of the powertrain sources in the vehicle are connected to the wheels. By changing how the engine and motors connect, engineers are able to change the power delivery to the wheels and many performance and environmental characteristics as a result. There are three main types of hybrid architectures in the marketplace: series, parallel, and split-parallel.

2.2.1 Series Hybrid Architecture

In a series hybrid, the engine is not directly connected to the vehicle’s wheels. Electric motors are used to fully provide torque and propulsion for the vehicle. Instead of driving the wheels, the engine is directly coupled to a generator. This coupling allows engineers to tailor the operation of the engine-generator connection, independent of the speed at which the driver wishes to drive. Additionally the use of a full-electric drivetrain mitigates any Noise, Vibration, and Harshness (NVH) concerns made by using a loud, vibrating engine which requires the use of a multi-speed transmission to keep power operation in efficient ranges. The power flow of a series vehicle is seen in Figure 3.

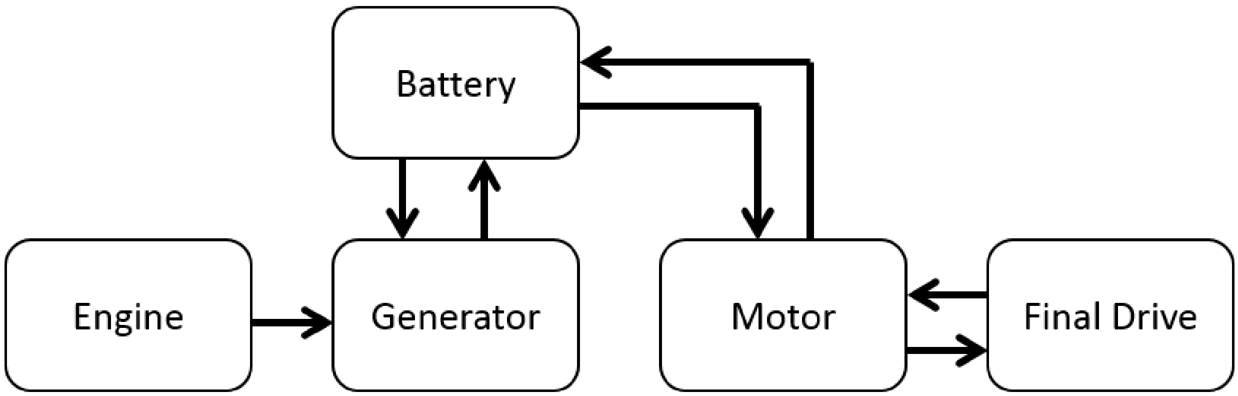

Figure 3: Series Power Flow

An example of a series vehicle put in to production in the automotive market is the *Fisker Karma* [10].

2.2.2 Parallel Hybrid Architecture

In a parallel hybrid, both the engine and the motors are connected to the vehicle's wheels to provide tractive force. Either powertrain, or both together, can provide torque, with the vehicle often relying on the electric motors to supplement the power-torque curve of the combustion engine at low speeds where they can provide their full amount of available torque. Parallel vehicles have decreased cost/weight compared to a series vehicle, but are unable to generate at optimal efficiencies at all times as all powertrain components are limited by the driver's desired vehicle speed. The power flow for a parallel vehicle is shown in Figure 4.

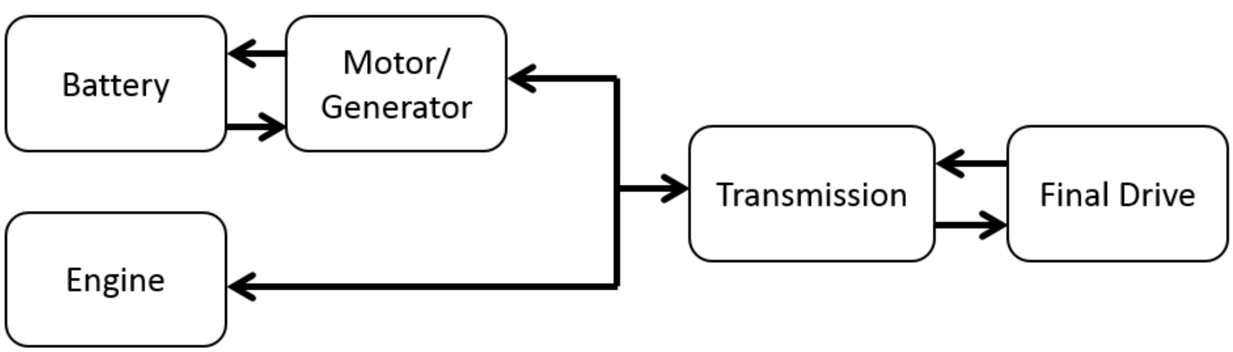

Figure 4: Parallel Power Flow

An example of a parallel vehicle put in to production is the *Honda Civic hybrid* [11].

2.2.3 Split-Parallel Hybrid Architecture

In a split-parallel vehicle, the vehicle can operate in either series or parallel modes depending on which is most efficient at the time. Vehicle characteristics such as battery State of Charge (SOC) and vehicle speed dictate which mode of operation would be best. Split-parallel vehicles combine the advantages of both series and parallel powertrains, but can often be complicated and difficult to build as they usually require complex planetary gear sets. The power flow for a split-parallel vehicle can be seen in Figure 5.

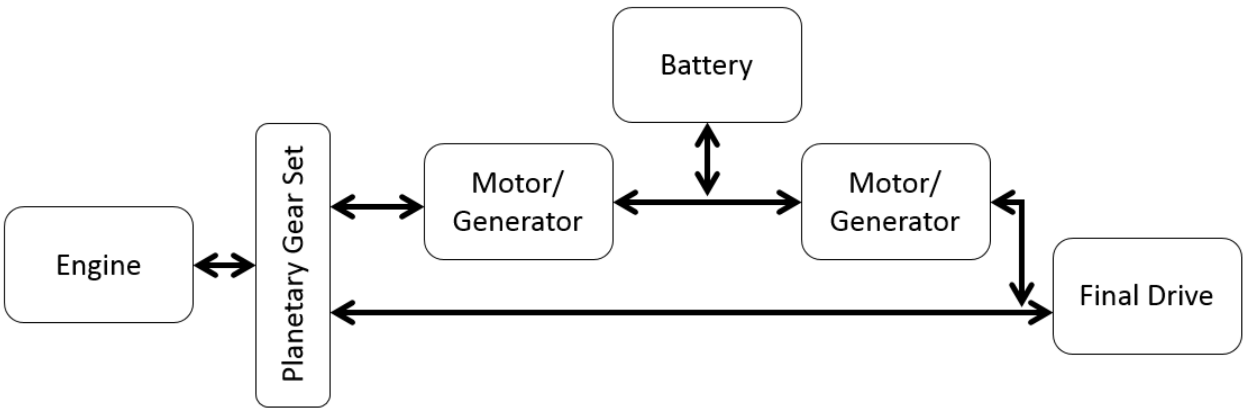

Figure 5: Split-Parallel Power Flow

Production examples of split-parallel vehicles include the *Toyota Prius* and the *Chevrolet Volt* [12] [13].

2.2.4 Benefits/Drawbacks of each Architecture

As alluded to earlier, there are some benefits/drawbacks of each of the series, parallel, and split-parallel vehicles mentioned. Table 1 shows these as they pertain to each architecture discussed.

Table 1: Advantages and Disadvantages of Hybrid Architectures

	Series	Parallel	Split-Parallel
Advantages	• Generate at optimal efficiency at all times • Electric-only drive (NVH concerns)	• All components can provide torque to wheels	• Generate in series or provide torque in parallel operation
Disadvantages	• Engine unable to provide torque to road (heavy) • Space constraints (multiple components to do same job)	• Unable to generate at optimal efficiency	• Complex mechanical connections and control in powertrain

2.3 Vehicle Drive Cycles

In designing a vehicle, it is important to know how the driver may interact with the constructed product. As a guideline, the U.S. Environmental Protection Agency (EPA) has developed drive cycles which attempt to characterize a typical drive under differing conditions. These drive cycles are used to test new vehicles to determine fuel economy ratings, and are used as design targets by Original Equipment Manufacturers (OEMs). The typical drive cycles utilized include the US06 drive cycle which features high acceleration events that are typical of a more aggressive driver, a city cycle known as the Urban Dynamometer Driving Schedule (UDDS), and a high way cycle known as the Highway Fuel Economy Driving Schedule (HWFET). [14]

Although these drive schedules are made to describe a daily driver's cycle, many factors affect a person's unique driving profile. As a result, there can be differences between a vehicle's test performance under the EPA drive cycles and those found by a consumer. Differences can occur due to vehicle conditions, ambient environment, and variations in fuel. As a result, there is an importance in understanding each person's driving habits in order to best optimize a vehicle powertrain to a consumer. [15]

This push to categorize a consumer has created a number of technologies which can be deployed on vehicles to describe a driver's habits. One that has been used by the author is the use of the data loggers developed by *fleetcarma*, a division of *CrossChasm Technologies* [16]. *fleetcarma's* data loggers allow consumers to track On-board Diagnostic (OBD) signals to track their vehicle's performance, including vehicle speed and length of trips. *fleetcarma's* C5 logger can be seen in Figure 6.

Figure 6: *fleetcarma* Data Logger

With the use of the logger, consumers are able to enter their data into *fleetcarma's* database to generate reports on their driving profile. With the information provided, consumers can make better choices on their driving habits, and have new vehicles marketed to them which are best optimized to their profile. Not all HEVs or PHEVs are built for every user's drive cycle patterns, and the data from the logger can help vehicle designers. As a result, vehicle designers can best understand consumer driving habits and design vehicles to perform optimally in each environment. As OEMs use the results from modeling and simulation of vehicle designs on EPA or real-world drive cycles, they are able to establish targets known as Vehicle Technical Specifications (VTS) to benchmark their design. These specifications are goals which new designs of vehicles try to achieve. For HEV or PHEV design, the architecture, including the specifications/number of motors used to propel the vehicle in conjunction with the engine, can have wide variance on the VTS.

2.4 Component Sizing

Based on the understanding of consumer driving profiles and preferences, designers can make decisions on component requirements to meet these VTS. For a hybrid vehicle, this method of component sizing can be much more complex than that of a conventional vehicle. This added complexity is due to the fact that there are multiple variants of hybrids and many combinations of engines, motors, and batteries that can meet the vehicle requirements.

The University of Waterloo Alternative Fuels Team (UWAFT), a vehicle design team the author is a part of, uses a combination of mechanical, controls, and simulation techniques in the early stages of vehicle design to develop vehicle architectures. These tools allow students to simulate vehicle performance, without the need of actual components. One of the tools used to simulate vehicles through drive cycles is *Autonomie*, which is a software 'wrapper' which works over top of *MATLAB/Simulink*. *Autonomie* allows the simulation of multiple hybrid powertrains with different components, in a Model-in-the-Loop (MIL) context that allows for fast iterations between vehicles. The modeling environment in *Autonomie* is shown in Figure 7.

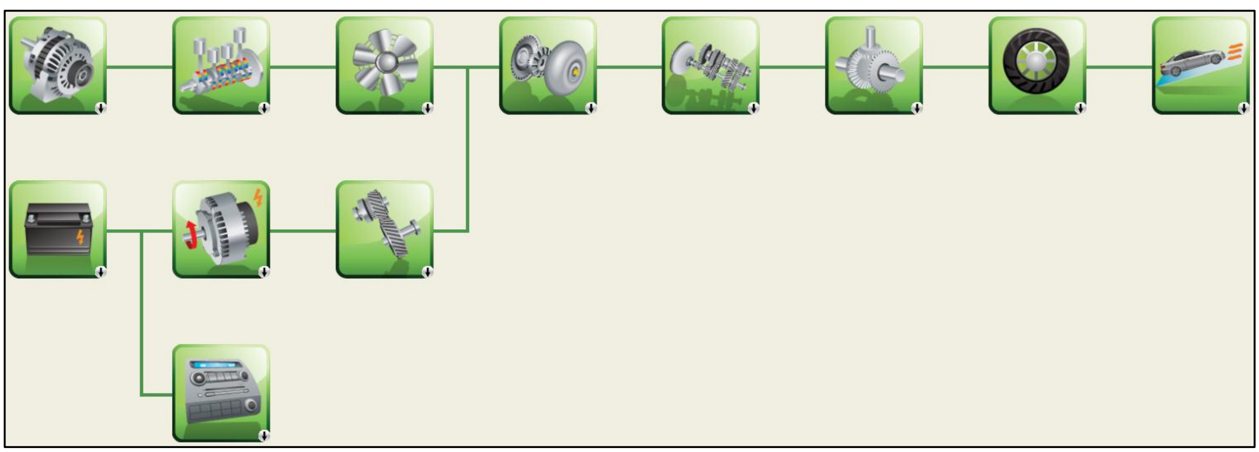

Figure 7: Sample Vehicle Architecture in *Autonomie*

In the entries into AVTCs by UWAFT, there has been a large emphasis of battery performance in previous competitions. As discussed previously, batteries allow consumers to offset emissions and drive on all-electric energy alone in many driving situations with the use of large batteries in a PHEV. However, battery technology is the reason why many hybrids have a large initial cost, and are heavy. It is research into this area that can allow hybrids to develop to take more of a market presence, and progress the automotive sector for generations to come.

2.5 Battery Fundamentals and Definitions

A battery is fundamentally defined as ‘a container consisting of one or more cells, in which chemical energy is converted into electricity and used as a source of power’ [17]. Batteries are used in many applications, to power systems which are disconnected from the utility grid during use. As technology progresses, battery technology has changed in order to maximize power and energy density. Currently, Lithium-ion (Li-Ion) technology is at the forefront and is utilized in applications ranging from computers to hybrid vehicles [18].

Through both their use and their calendar aging, batteries exhibit degradation mechanisms which affect their performance over time and operational use. The two main performance degradation mechanisms are referred to as ‘Capacity Fade’ and ‘Power Fade’ [19]. Capacity fade is a known degradation mechanism where the available capacity of the battery decreases during its life. Capacity fade can be attributed to both calendar aging and regular cyclic fade. Power fade is the loss of available power during a battery’s life time. As a battery ages, its ability to provide power to connected loads such as a motor decreases. A third degradation mechanism has been defined by the battery research group at the University of Waterloo [20]. This degradation mechanism has been referred to as ‘Charge Efficiency Fade’. During the charging/discharging process for a battery, internal resistances inherent in the battery cells lead to a loss converted to heat. This loss affects the efficiency of the charging/discharging process, and is predicted to increase during the lifetime of the battery as the internal resistance of the cells increases with use. The following section will discuss capacity, power, and charge efficiency fade further with references to the fade mechanisms in current literature.

2.6 Capacity Fade, Power Fade, Charge Efficiency Fade

2.6.1 Capacity Fade

During cycling of a battery pack, the usable amount of capacity may diminish as a result of degradation mechanisms. These mechanisms include increased impedance, Solid Electrolyte

Interface (SEI) build up, and degradation of the positive electrode [21] [22]. Spotnitz added a loss of active lithium at the negative electrode of the battery as another major fade mechanism [22]. Higher temperatures increase the rate of capacity loss according to the Arrhenius law, as well as high SOC. At high SOC, reactions within the battery's electrolyte are more prone to occur, degrading the material used for ionic transport [23]. These side reactions can occur during storage of the battery, with oxidation occurring on the positive cathode and reduction on the negative anode. This capacity loss can actually be reversed in the event that both reactions occur at the same time, and the lithium ions are able to be released by the negative terminal [23]. For Li-ion batteries incorporating a graphite anode, the degradation rate is increased at the start of a cell's life as build up occurs but is reduced once a layer is formed. Of note is that the Depth of Discharge (DOD), the amount of charge utilized in one battery cycle, does not affect capacity fade [24].
Capacity fade rate follows a trend of brief acceleration followed by an approximately constant slope. Figure 8 below shows data from the study completed by Lohmann et al for different types of Li-Ion cells.

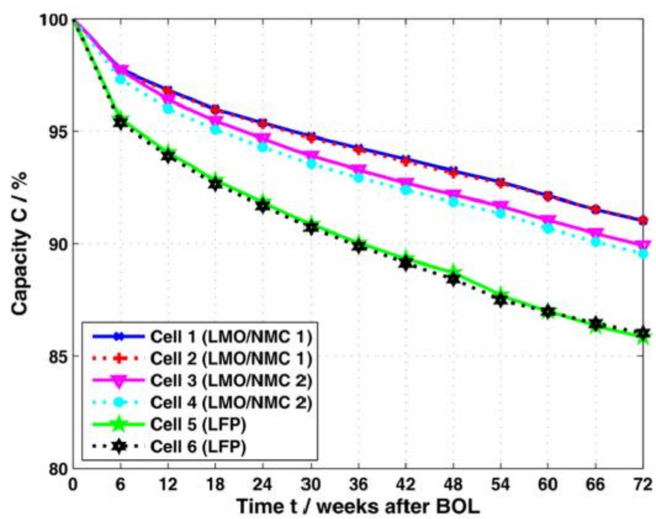

Figure 8: Capacity Fade Trend [25]

Lohmann concluded that the fade rates were similar for each of the cells tested based on their chemistry, with $LiFePO_4$ cells exhibiting the least acceleration at the beginning of life and the highest overall [25].

Spotnitz came up with the following conclusions regarding capacity fade in Li-ion batteries:

1. *Capacity loss on storage has reversible and irreversible components;*

2. *Capacity loss on storage or cycling increases with increasing temperature;*

3. *Capacity loss on storage increases with increasing cell voltage; and,*

4. *Cycling causes capacity loss at a greater rate than storage. [22]*

2.6.2 Power Fade

Power fade has been said to be due to the construction of a resistive layer on the cathode to the active material [26]. Lohmann et Al. used values of internal impedance throughout the life of a battery as an indicator of power fade. Lohmann found that internal impedance decreases during the early life of a cell, and then follows a period with approximately no change. The LiMnO cells in the study exhibited the highest acceleration of impedance at the start of life and highest over the entire life of the cell. However, the cells made up of $LiFePO_4$ showed the lowest change in impedance, attributed to stability with the $FePO_4$ cathode material. Figure 9 shows the internal impedance trend followed.

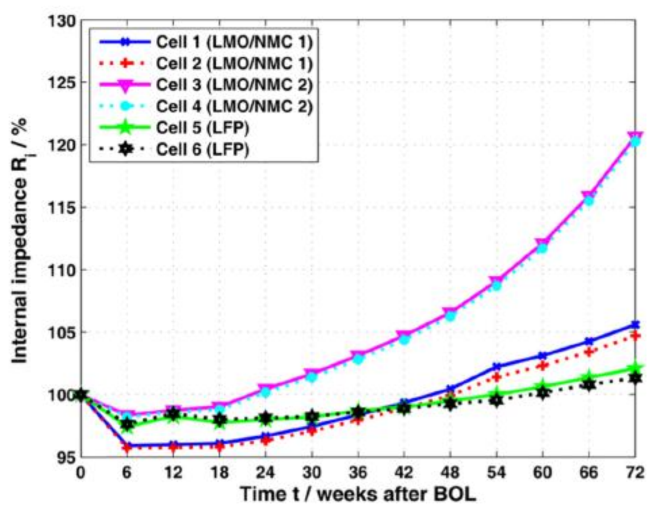

Figure 9: Internal Impedance Acceleration [25]

2.6.3 Charge Efficiency Fade

Charge efficiency is defined as the ratio between the energy used to charge the battery and what can be utilized for work after storage. Parasitic reactions cause inefficiencies between the charging and discharging periods, where some energy is lost in the battery as heat. Smith et Al. explain the concept of charge efficiency using Equation 1 [27].

Equation 1: Charge Efficiency

$$Charge\ Efficiency = \frac{Q_d}{Q_c} = \frac{Charge\ Out}{Charge\ In}$$

Charge efficiency is an important battery aspect in a repurposing application, as it should be ensured that the majority of the energy utilized off of the electrical grid can be harnessed at a later time instead of being lost in inefficiencies such as heat generation. More heat is generated in a battery system as more power is required for propulsion [28]. Miyamoto et Al. suggest that heat generation, G_{batt}, can be calculated using Equation 2 and is a result of three factors: internal resistance, entropy changes and secondary reactions [29].

Equation 2: Battery Heat Generation

$$G_{batt} = \frac{\int_0^T P_{in}dt - \int_0^T P_{out}dt}{T} = \frac{Q_c - Q_d}{T}$$

Studies on Li-ion cells show that this chemistry can reach near 100% charge efficiency [30]. However if this finding were true in all Li-ion applications, full size battery packs would not require large cooling systems. All batteries have a form of internal resistance which contributes to a loss in charge efficiency. One reason Li-ion batteries are preferred over NiMH batteries as they have lower internal resistance [31]. Entropy changes do not make up a significant amount of charge efficiency loss in HEV batteries as the power going in/out of the cell during charging is regulated by the battery's Battery Management System (BMS). The BMS monitors battery parameters, estimates battery SOC, and controls battery operation throughout the drive cycles of a vehicle [32]. In addition, in the case of Li-ion batteries, secondary reactions are absent during the charging/discharging times, leaving only internal resistance as a factor in charge efficiency loss [29]. These secondary reactions are used in conventional batteries as a form of load leveling. The water-solvent electrolyte induces secondary reactions where water will become dissolved and recombined [33]. During charging of Li-ion batteries, the BMS is responsible for leveling the amount of charge throughout the battery. This load leveling procedure is usually completed through electrical connections between the battery's cells. As one cell charges more than another, a resistor is placed between it and a neighbouring cell to discharge the excess power accumulated. Miyatake et Al. attempted to correlate how individual battery factors and their combinations, including the physical electrode material properties, ion concentration, and external control variables, affect internal resistance values of a pack [34]. It was found that for a small portion of charge rates, near 100% charge efficiency can be achieved; similar to those results found on Li-ion cells in a laboratory environment. However, as high discharge currents are used, as typical in an automotive environment, charge efficiency may decrease. Specifically, it was found that at a 10C rate some batteries will only be able to provide around 20% of their capacity [34]. This result is echoed in the experiments completed by Tanjo et Al., where a prototype Li-ion cell was cycled at rates between 1C and 40C. At a 20C discharge rate only 88% of the original capacity could be utilized, while at a 40C discharge rate approximately 80% could be used [33]. Results of the tests performed are included in Figure 10.

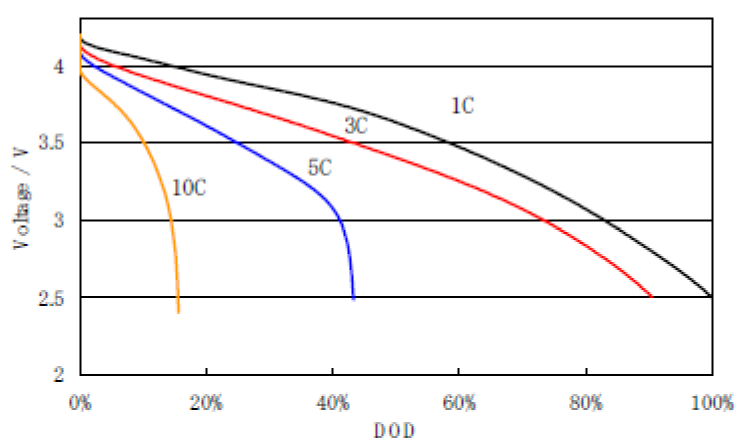

Figure 10: Energy Capacity available at Differing Charge Rates [34]

It has also been found that rates of heat generation in batteries may rise by approximately 35% by the end of their service life, indicating greater cooling practices may need to be implemented [35]. As a battery ages, its internal impedance may become higher and more losses will occur. This resistance may be the main contributor to any changes seen in the charge efficiency of a battery over its lifetime.

Charge efficiency fade and its effects on stationary repurposing applications was studied by Ahmadi et Al. [20]. The proposed capacity fade model is used to correlate to charge efficiency fade, as both fade mechanisms are predicted to degrade at the same rate; being primarily driven by SEI growth. The battery is predicted to have 80% of its original capacity remaining after its use in the vehicle, with a further 15% drop in capacity during its repurposing stage (resulting in 65% remaining at the end of its stationary use compared to new). A failure rate model was also introduced to study the effects of cell failures on battery health, but showed no significant effects in the expected life of the battery.

2.7 Fade Mechanism Contributors

There are a number of indicators which can be monitored throughout the life of a battery to indicate the amount of degradation which has resulted. In the degradation study completed by Lohmann et Al., available cell impedance and cell capacity were monitored. The statement regarding these two indicators is included below:

> *"Available cell capacity refers to cruising range while internal impedance affects the maximum available power. Cruising range is also affected by internal impedance, because higher voltage drop at increased internal impedance results in a decreased available energy before cell is discharged to minimal voltage defined by the cell chemistry" [25]*

Therefore, in the context of this review, available cell capacity and internal resistance would both contribute to capacity fade, while internal resistance would also be applicable to charge efficiency fade and power fade. With an increased internal resistance, more heat may be generated during the charging/discharging processes which may lead to a decrease in charge efficiency.

There are a number of techniques being discussed to be implemented in future 'smart' batteries. These batteries may have two forms of communication to communicate their State of Health

(SOH) during their use. Neural networks feeding back data from the battery including terminal voltage, battery temperature, and discharge current have been utilized in control systems to assess SOH and predict Remaining Useful Life (RUL) [36].

2.8 Stationary Energy Storage

In new 'smart grid' solutions for the utility grid, new technologies and energy storage solutions are being proposed to be integrated to help assist with varying loads and demands. Stationary energy storage technologies which have been researched include hydrogen, pumped hydro, and the use of batteries [37]. These technologies allow utilities to store energy for later use, in reference to the demand on the grid. A sample of a grid projected and actual demand for the province of Ontario can be seen in Figure 11.

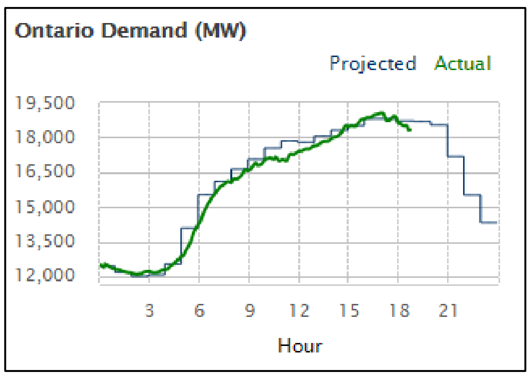

Figure 11: Sample Utility Demand in Ontario [1]

Stationary storage is critical in Ontario due to the nature of the grid mix, and its widespread use within the grid network would assist the utility due to the power generation sources which are predominant within the infrastructure. The energy sources making up Ontario's generation in order of largest to smallest percentage of generation are: nuclear, hydro, gas, wind, biofuel, and solar [1]. The use of stationary energy storage can shift generation from sources that cannot be easily turned on/off with demand, nuclear energy for example, and generation from sources which vary with nature, such as wind or solar energy.

2.9 Repurposed Battery Pack

Batteries show great promise in being able to meet the generation shifting within the grid, however they can be hampered by fade/degeneration mechanisms as well as high cost [38]. This application can be referred to as load shifting, demand management, or energy arbitrage (where the energy storage system is charged during periods of low cost electricity and discharged when grid electricity is at a high cost). One way of reducing the cost of this application is by using previously used batteries in repurposed stationary storage applications. Lithium-ion, being the lead energy storage technology at the moment, shows high costs for initial investment but low costs in a used context. Some predictions are on the order of 38 – 132 $/kWh of capacity (in 2020 USD) [39].

Currently, battery packs are designed, assembled, and installed with the idea that they are only to be used for one stage of their life cycle – in a vehicle. As a result, many of the components of a battery pack are designed to be assembled once, with any disassembly requiring heavy modifications to the pack. Some manufacturing methods used in battery packs have welded tabs and compression systems which connect the cells together; a one-time construction method which would require a high amount of labor to disassemble and re-assemble into the repurposed pack.

In a repurposed idea, the battery pack would initially have to be designed to incorporate the disassembly of the pack from the vehicle stage before being integrated into the stationary assembly. From previous findings within the author's research group, it is believed that repurposed packs should be integrated into a stationary application as a full assembly without any modification to individual cells or modules. If repurposing were to reuse batteries at the cell level, it would not be cost effective to dismantle the packs [20]. Some automotive manufacturers have demonstrated the repurposed application using battery packs at the pack level, including *General Motors* who used one at a demonstration setup at the Toronto 2015 Pan American games and as backup power at their proving grounds in Milford, Michigan [40].

Chapter 3
Battery Pack Design

3.1 Background

The design considerations for a hybrid battery pack are included here from the author's experience with designing a High Voltage (HV) Energy Storage System (ESS) for use in the University of Waterloo Alternative Fuels Team (UWAFT) entry to EcoCAR 3. At the time of writing, the battery pack's design has gone through the initial Preliminary Design Review (PDR) section of feedback from the competition, and is being progressed before the Final Design Review (FDR) is completed and pack construction takes place. An overview of the vehicle, the pack design, and considerations are included in the following chapter. The mechanical design optimization discussed is important to the repurposed battery pack discussion as the techniques can be used in the design and assembly of the repurposed pack assembly's casing. Additionally, it provides an overview of one battery pack setup which could be used in a repurposed application following its installation into a vehicle.

3.2 Vehicle Background

EcoCAR 3 is the current AVTC occurring from 2014 – 2018, which challenges 16 universities across North America to re-design a 2016 *Chevrolet Camaro*. The competition is open to undergraduate and graduate students, and challenges them to design a vehicle which reduces the environmental footprint of the stock vehicle while maintaining design aspects including safety and consumer acceptability. The competition is UWAFT's sixth participation since its inception in 1996, and the team is looking to build on its extensive history with an award-winning design.

In Year One of the competition (2014 – 2015), teams use software and model-based design to generate hybrid vehicle concepts/architectures that they would be willing to design and construct in the following three years of the competition. After an extensive process using tools such as *MATLAB/Simulink*, *Autonomie*, and *Unigraphics NX*, UWAFT selected a split-parallel architecture for construction. The powertrain architecture for the vehicle is included in Figure 12.

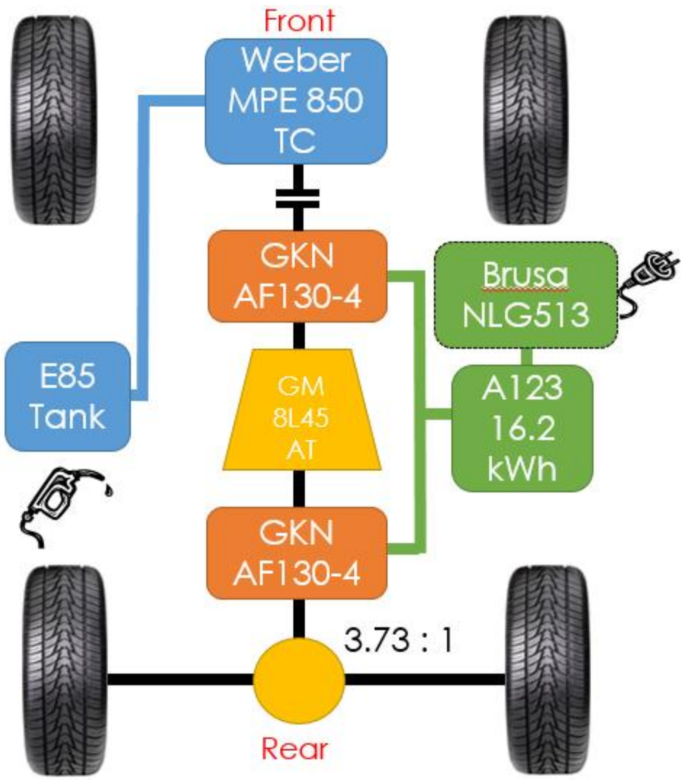

Figure 12: UWAFT EcoCAR 3 Powertrain Architecture

The selected vehicle features an 850cc turbocharged *Weber* engine which has been converted to run on E85, and two *GKN* axial flux motors. The vehicle can run in series, parallel, or split operation depending on a number of factors including driver torque demand, and battery SOC.

The development of the EcoCAR 3 battery pack began with the selection of the appropriate battery pack for use in the vehicle. UWAFT focused on the battery packs made available through the competition, as finding outside sponsors for this specific component has proven to be difficult. Two battery pack suppliers are sponsoring the EcoCAR 3 competition, with their specific packs included in Table 2 below.

Table 2: EcoCAR 3 Battery Pack Options

Manufacturer	Model	Capacity (kWh)	Peak Current (A)	Continuous Current (A)	Nominal Voltage (V)
A123	6x15S2P	10.8	350	115	292
A123	7x15S2P	12.6	350	115	340
A123	6x15S3P	16.2	520	175	292
A123	7x15S3P	18.9	520	175	340
Enerdel	PE 350-394	12.1	105	70	317
Enerdel	PP 320-394	11.2	320	125	317

The selection of the battery is based on a combination of both EcoCAR 3, and UWAFT-specific goals. The design and development of the vehicle is done with a 'model-based design' methodology without a real vehicle in accordance with the given drive cycle profiles that the vehicle should perform to in the latter years of the competition [41]. Specifically, the first step in the design process of 'simulation' of the vehicle is completed. The two biggest factors for battery sizing are the acceleration events, and the Emissions and Energy Consumption (E&EC) event. The battery should be able to provide sufficient energy to the vehicle's motors to meet acceleration targets, but also be able to provide energy during hybrid operation.

The chosen battery for the vehicle is a 16.2 kWh *A123* pack, which uses six 15S3P modules that are connected in series. The pack runs at a nominal voltage of 292 V, and can provide a peak current of 400 A to the two electric motors. These 15S3P modules were used in the team's EcoCAR 2 *Chevrolet Malibu,* which had an 18.9 kWh pack installed. The modules are chosen due to the team's familiarity with the system and accompanying research into the *A123* cells which is performed by graduate students working with the team. For construction of the pack, as part of the competition agreement, *A123* will provide UWAFT with the battery modules, the Current Sense Module (CSM), the BMS, the battery contactors, and limited technical support to help the team integrate the unit in to their vehicle.

Particularly, the 16.2 kWh pack is chosen as it is the largest battery that the team feels it can manageably fit into the vehicle's trunk, without adding large amounts of weight to the structure and inhibiting passenger or cargo capacity. The 16.2 kWh pack, in conjunction with UWAFT's own battery control scheme, is able to provide the user with up to 69 km of all-electric range, meeting the daily driving range of North Americans of 40.55 km [42]. This fact allows regular consumers driving the UWAFT-designed *Camaro* to be able to make their daily commutes on all-electric power alone, generating zero vehicle tailpipe emissions and using grid energy which is much cheaper than burning gasoline.

The design of the vehicle's battery pack is a joint effort made by the multiple sub-teams which make up the technical team for UWAFT. Mechanical, electrical, and controls considerations are all required to design a complete pack which works well in the vehicle. The design of the pack is based on the experience of the team in previous competitions as well as background documentation from *A123*, and is outlined in the following sections.

3.3 Structural Considerations

The structural design of the battery pack is key in order to ensure that the assembly, servicing, and installation of the components work well within the vehicle's structure. As mentioned previously, *A123* will be providing UWAFT with the battery modules, and auxiliary control modules for construction of the pack. UWAFT will be required to design, build, and integrate the structure for holding the modules in place, as well as the battery enclosure around the pack.

The design of a battery pack in the trunk of the *Camaro* is regulated by the rules enforced by the EcoCAR competition [43]. The first consideration is placement of the pack within the vehicle's structure. The modules and accompanying components should be placed within the vehicle such that they are not within the vehicle's crash structure. Much of the areas in the engine bay and trunk are eliminated from ESS placement as they are designed to crush in the event of a collision. Placement of the ESS in these selected areas would therefore cause a significant safety hazard to the driver and passengers in the event of an accident. In order to optimize both passenger, and cargo capacity as well as allow for the installation of other powertrain components, the vehicle's battery pack will be situated in the front of the vehicle's trunk.

Once placement is set, the team must design the frame to support the modules during vehicle operation as well as a finger-proof enclosure which can protect users from the battery's lethal electrical potential. The battery frame is to be designed to withstand the following loading conditions from the competition [43]:

- 20g Loading in the Front – Rear Longitudinal Direction;
- 20g Loading in the Left – Right Lateral Direction; and,
- 8g Loading in the Up – Down Vertical Direction.

These loading conditions are understood to be the 'worst case' basis for loading that the pack could experience in vehicle motion, or under large impacts in a collision. It is this loading which will verify whether the UWAFT-designed battery frame will be strong enough to be installed in the vehicle.

UWAFT's EcoCAR 3 battery pack is built on the knowledge gained primarily through the design of the battery pack in the team's EcoCAR 2 *Chevrolet Malibu* and the re-design of the team's custom rear subframe in Year Three of the EcoCAR 2 competition. The EcoCAR 2 pack was known through the competition to be a well thought out design, which was relatively easy to assemble, install, and service. An image of the battery pack in the rear of the *Malibu* in CAD and the pack installed in the vehicle can be seen in Figure 13 and Figure 14.

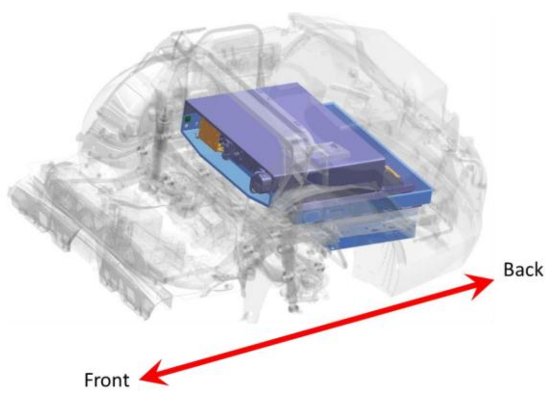

Figure 13: EcoCAR 2 Battery CAD Image

Figure 14: EcoCAR 2 Assembled Battery Pack

Through the design of the structural aspects of the pack, it became evident that the Camaro's trunk would prove significant hardship in fitting a full-sized hybrid battery. The trunk is large enough to fit the modules, however the trunk opening is small and inhibits entry and access. The team used multiple space claims within the trunk space, fitting modules in different arrays to find the best fit. The following images, Figure 15 and Figure 16, show two of the preliminary module configurations in the vehicle trunk. The overall vehicle CAD is scrubbed due to confidentiality reasons.

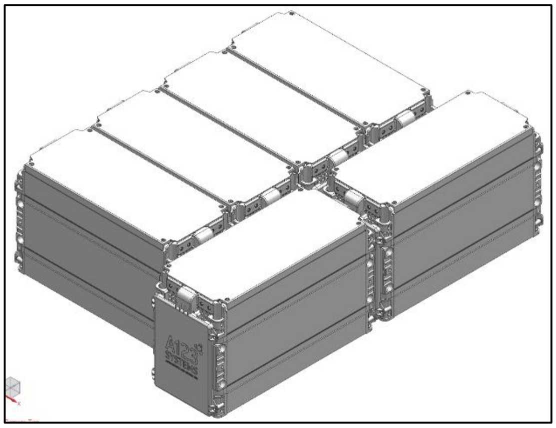

Figure 15: Module Configuration One

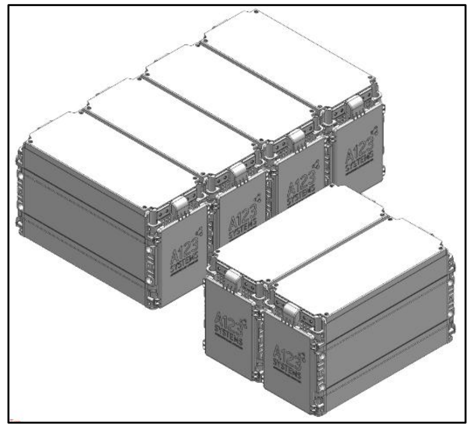

Figure 16: Module Configuration Two

After the space claim analysis, Figure 15 is chosen for construction due to its small volume and weight considerations required in its design. The structure is designed such that it can be easily manufactured, add minimal amount of the weight to the vehicle, and be assembled/serviced during use. Previous iterations of UWAFT battery packs have used steel in their construction, and aluminum or carbon fibre enclosures to isolate the high voltage energy source from the vehicle. Through development of UWAFT's custom rear subframe in Year Three of EcoCAR 2, new geometry optimization techniques were acquired by UWAFT engineers which are used in the design of the battery pack. These techniques allow the designer to understand where the load paths are in the structure in the final iteration, and where to best put material to meet the structural demands. This technique results in designs which can optimize overall assembly structures, based on lightweight materials. The following sections detail the geometry optimization and Finite Element Analysis (FEA) techniques used to come up with the first iteration of UWAFT's EcoCAR 3 battery pack. All design is completed using *Siemens Unigraphics NX 9* software, and all optimization/FEA is completed using *Altair Hyperworks 13*.

The initial battery concept is to mount the batteries to the vehicle's frame rails in the trunk, using the rails as a mounting point to the chassis. The pack will be made in two halves allowing UWAFT to bolt the two in place once assembled in the vehicle, and accommodate the small trunk opening. In order to help assembly further, the modules will be assembled outside of the vehicle on 'module mounting plates' which will be bolted to the main assembly in the vehicle.

3.3.1 Geometry Optimization

The geometry optimization techniques used by UWAFT in the construction of the battery pack are based on topology optimization in the *Hyperworks* software suite. There are a multitude of optimization methods available, and the topology optimization is used as a starting point to understand where material should be assembled to take the loads of the pack once constructed.

The battery pack is initially set up in *NX*, understanding the space claim where the team wishes to mount the battery modules and how. The geometry from *NX* is imported to *Hypermesh*, where two-dimensional shell elements and three-dimensional solid elements are made to represent the geometry for analysis. The designer initially sets up the design and non-design spaces where the optimization solver can and cannot place material to meet the loading conditions. The design and non-design spaces for the battery frame specifically are shown in Figure 17 below.

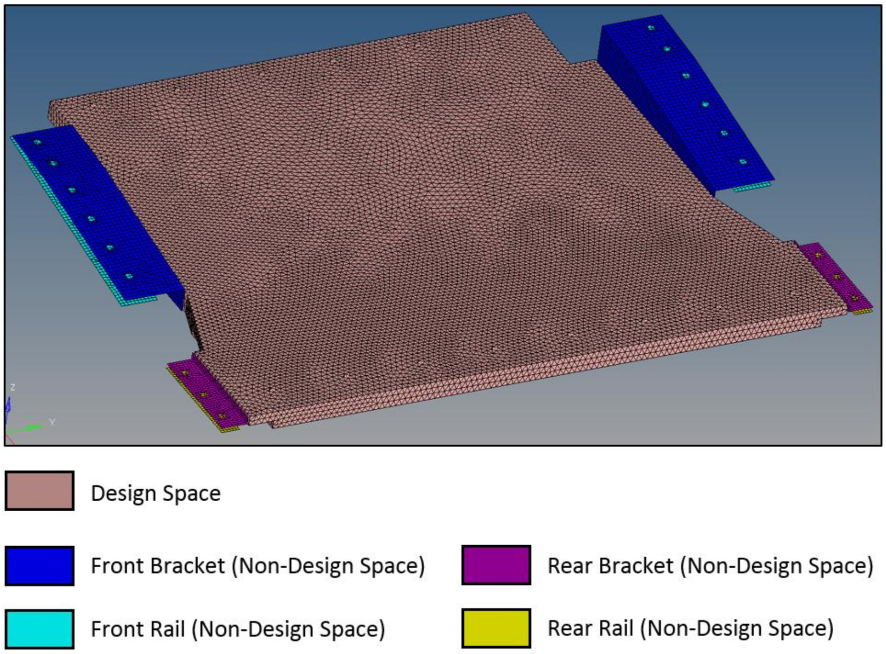

Figure 17: Optimization Setup with Design and Non-Design Space for Battery Frame

As can be seen, the optimization is set up by first defining the space, known as the 'design space', where the battery frame can exist. Building upon the design that was used by UWAFT in EcoCAR 2, the team proposes that the frame be secured to the frame rails by bolting to steel rails which will be welded to the vehicle chassis through the front/rear brackets/rails. The rails allow threaded bolts to go through the frame to attach to the vehicle, with the frame being made potentially of a different material than the base chassis as it will not require welding directly to a steel vehicle. These rails and the points which attach to them are non-design space, as they are required for attachment in the end design and cannot be modified. Within the design space, the optimization solver will understand where load paths form and where the most efficient use of material is in the structure.

An optimization will also be performed on the module mounting plate to minimize the overall mass of the entire structure. The module mount plate will not need to support the majority of the load in the structure, rather, it will act as a sub-assembly which transfers loading from the areas where the modules are bolted to the plate to the base battery frame. The design space setup for the module mounting plate is shown in Figure 18.

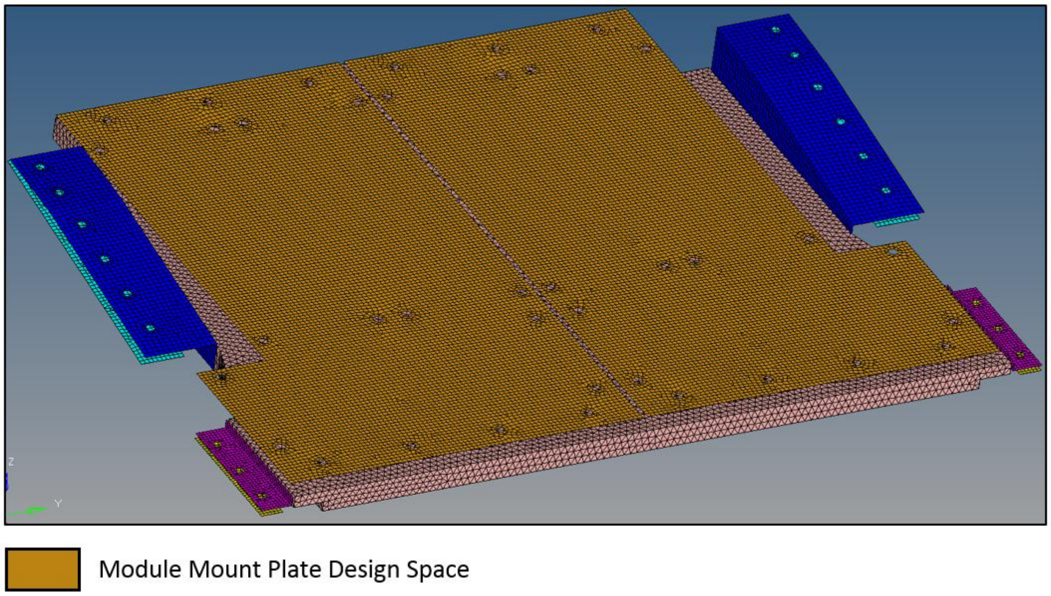

Figure 18: Optimization Setup for Module Mounting Plate with Design Space

Once the design spaces are set up, the loading conditions are applied that the frame will need to withstand. Based on the 20g, and 8g loading conditions outlined in Section 3.3, the loads are calculated and placed at the Centre of Gravity (COG) of each battery module. These COGs are then connected to the base module mounting plate at bolt hole locations where they would be connected during pack construction. These connections are made up of RIGID connectors in *Hypermesh*, which distribute the load within the frame and are denoted in red in the images. Similar RIGID connectors are used in the setup to simulate the bolts which hold the module mounting plate to the base battery frame, and the battery frame to the steel rails which will be welded to the vehicle chassis. The final setup for the optimization is shown in Figure 19.

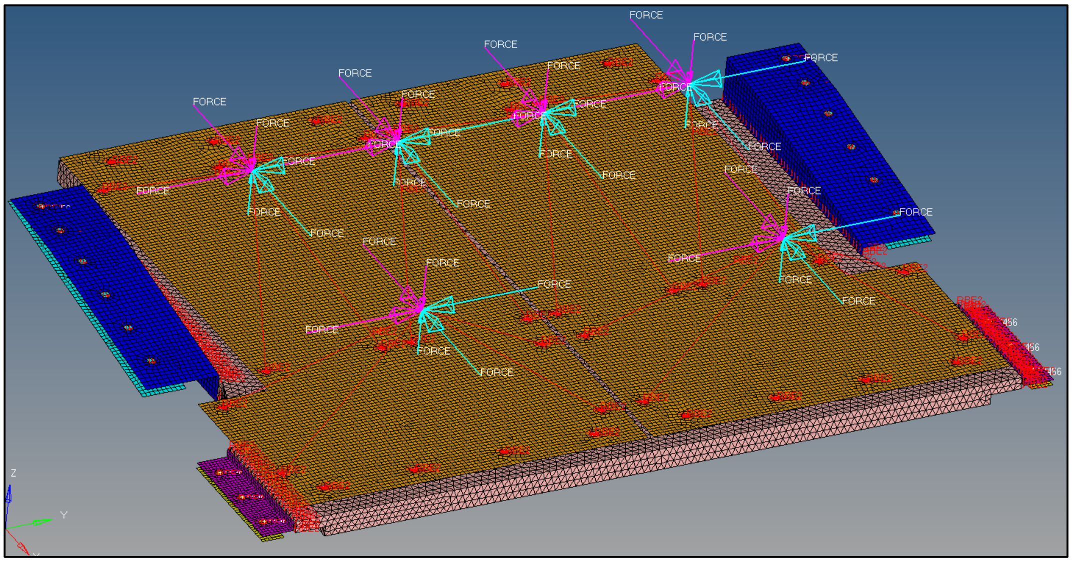

Figure 19: Final Optimization Setup with Loading Conditions

Through the use of optimization, there may be a trade-off in properties of the end result. If a material is desired to be the stiffest that it can possibly be, it may also be the heaviest. Alternatively, the lightest material will be nothing at all; which has zero stiffness. Therefore, when performing optimization processes, a 'Design Objective', a 'Design Constraint', and 'Optimization Responses' need to be defined for the solver.

The optimization is set up and ran in multiple iterations to achieve the best result. As the frame is required to withstand multiple loading conditions at once, including longitudinal, lateral, and vertical loading, the optimization is set up to take into account compliance with all three load cases at the same time. Compliance, within the context of structural physics, is defined as 'the ability of an object to yield elastically when a force is applied' [44]. During the time of optimization, the solver does not know which material the end assembly may be made of, or exactly how thick members of the assembly should be. Thus compliance is used, instead of a geometry specific term such as stress. The specific details of material and geometry will be found out later during the FEA stage.

To begin the optimization, the design objective is set to a 'Weighted Compliance' objective, which measures how much compliance is within the design space. The weighted category allows the designer to bias the optimization solver based on a specific loading condition. For the longitudinal, lateral, and vertical loads, a weighting of '1' is given to each to ensure that the conditions are evaluated equally. In order to constrain the objective, a volume fraction design constraint is applied to the frame design space. This constraint allows the solver to find the maximum stiffness of the design space, while only using a fraction of the material within it, reducing the resulting frame's overall weight. The volume fraction set up for the analysis is 30%, ensuring the solver eliminates 70% of the initial material based on input from *Altair* engineering support. This volume fraction, combined with the weighted compliance will be the two responses output by the optimization solver. The first run of the optimization process can be seen below in Figure 20.

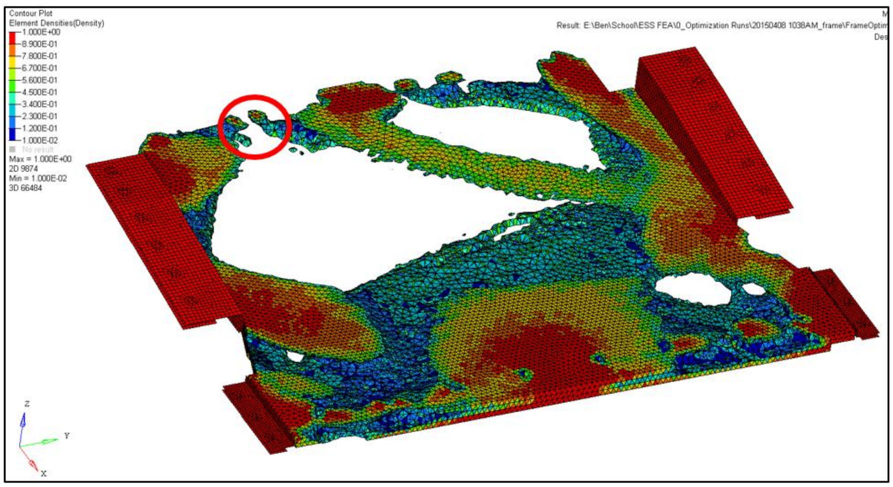

Figure 20: Frame Optimization First Iteration

The result of the topology optimization is a map which shows the elements of the design space which are holding load during the loading conditions. The elements have varying densities, as shown by the differing colours, with a density of '1' being a full element which carries load. The non-design spaces result in a density of '1' as they are not optimized through the process.

Iteration one of the optimization shows a viable result, but there are areas which can be improved upon. The optimization is showing load paths, but they are not mirrored across the design space and there are also holes in between the connection points as seen in the front of Figure 20 and highlighted by the red circle. It is predicted that the result should be symmetrical, as the loads and the design space are mirrored. Additionally, the manufacturing of a battery frame which is based on this optimization would prove hard as the material in the optimization has been removed from both the top and the bottom of the assembly requiring multiple setups during construction. Refer to Figure 21 below showing material removed from the same iteration.

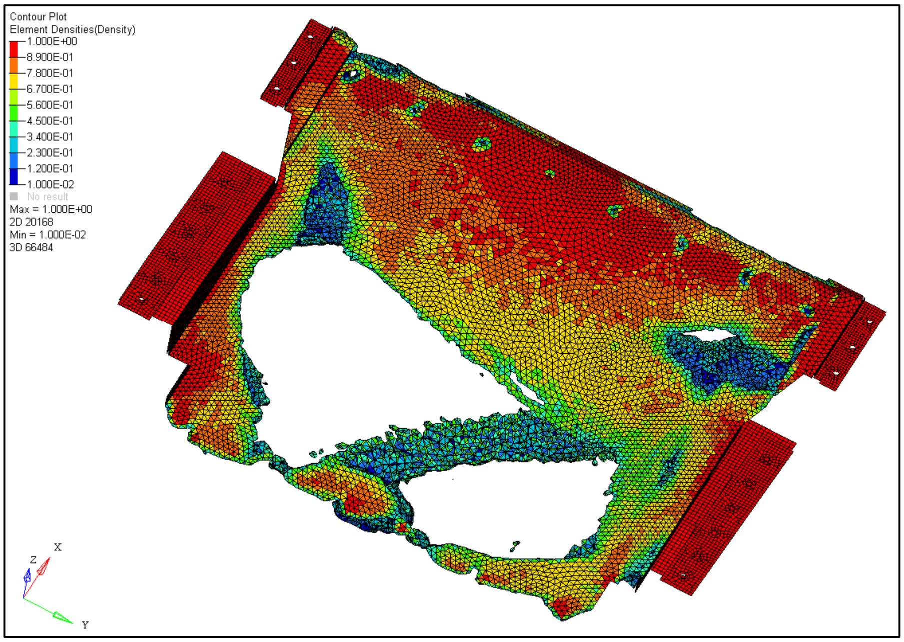

Figure 21: Frame Optimization First Iteration (From Bottom View)

This iteration is the most unconstrained, and it allows the designer to see the routes at which the solver would like to place material. Based on the results, the designer applies more constraints to come closer to a finished product which can be iterated through FEA at a later stage. The two largest changes made between this iteration and the final iteration include the integration of a 'Symmetry' constraint, ensuring both sides of the frame are symmetrical to one another, and a 'Draw Direction' constraint, ensuring that the solver only removes material from the top of the assembly. The 'Draw Direction' constraint is important, as the team uses basic, standard machining processes to make the majority of the structures in the vehicle. If there is material removed from both the top and bottom of the assembly, this construction would require multiple setups and increase the cost of manufacturing. If material is only removed from the top, manufacturing may be much simpler. The final iteration of the optimization process is seen in Figure 22.

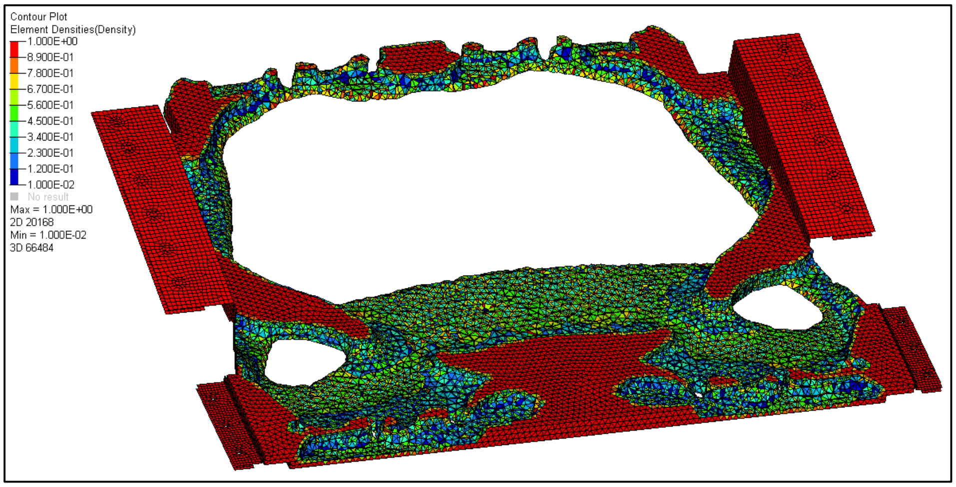

Figure 22: Frame Optimization Final Iteration

Figure 22 shows a symmetrical design which can now be imported into a CAD software program in order to start the mechanical design process. The optimization software shows load paths which connect the bolt areas from the modules to the welded frame rails, in an efficient manner. More material is shown to be required to be at the front and rear of the structure, with the majority of the frame being used to connect the front and rear mounting points. Of note is that no material is shown to be needed in the centre of the structure, below the four vertical modules.

The same optimization process is performed for the module mounting plate, in order to minimize the amount of material used overall. The mounting plate is a much simpler optimization, and it is predicted that the solver will show the majority of the material being required between the areas where the modules mount to the plate, and to the bolt holes which connect it to the main battery frame. Loading conditions are not used at this time to simulate the team assembling the battery and installing it in a vehicle, and the designer understands that more material may be required in the final iteration of the plate design to accommodate these tasks. The first iteration of the optimization process on the module mounting plate is shown in Figure 23.

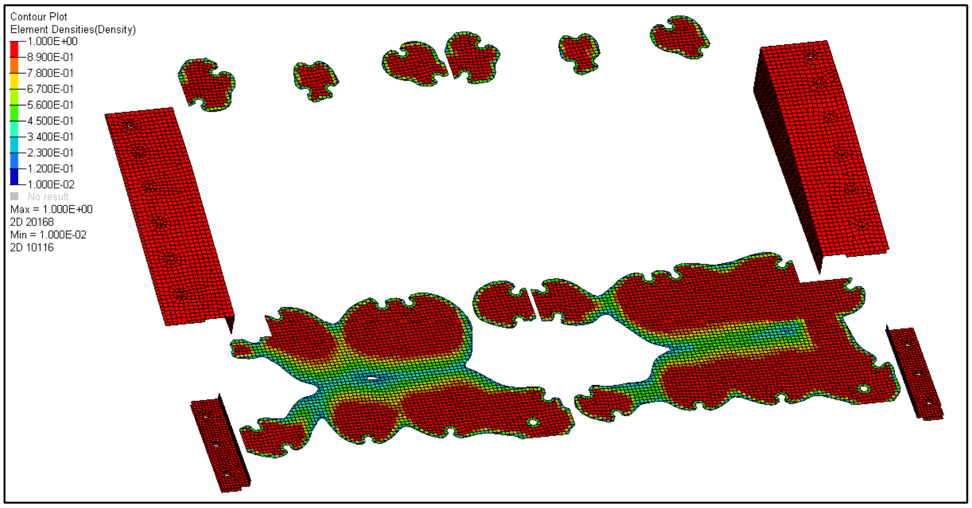

Figure 23: Plate Optimization First Iteration

The first iteration of the optimization of the plate shows similar areas to improvement as the first iteration of the battery frame optimization. The solver did not come up with a symmetric design, which would be the easier design to construct and assemble. There are also some constraint locations which show large amount of material around them, which is not repeated in other locations, showing a biased zone of material especially on the right hand side of the assembly. A symmetric constraint is imposed on the solution and the final iteration is included in Figure 24.

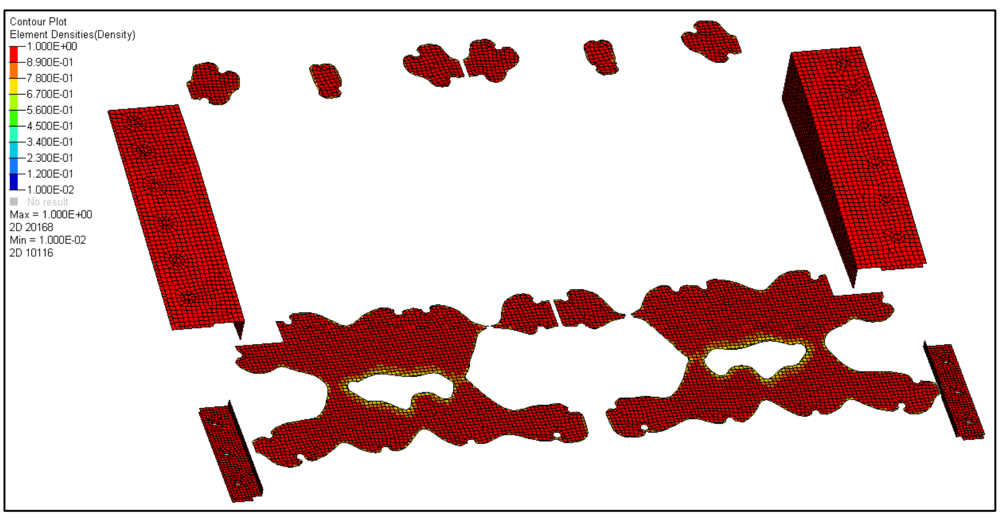

Figure 24: Plate Optimization Final Iteration

In the final iteration, the optimization has shown that the best use of material is between the module mounting bolt locations and the locations that mount the plate to the frame. There is no material in the centre of the assembly, given that the load paths would be directed towards areas of constraint. This iteration along with the final iteration are imported into CAD software in order to begin iteration in the design phase of the battery pack. Through iterations on the design, manufacturing, assembly, and joining methods can be taken into account. The final design of the battery frame is seen in Figure 25.

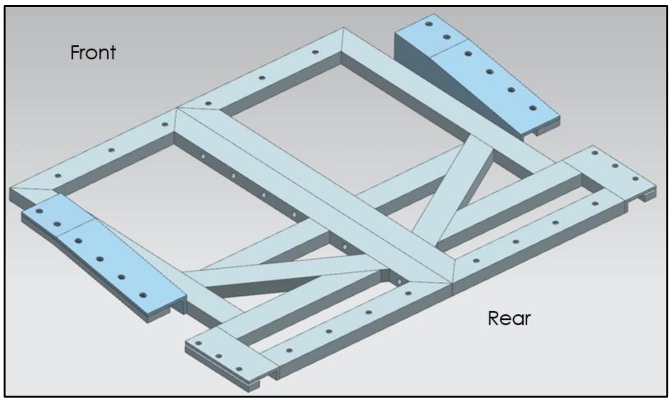

Figure 25: Final Battery Frame Design

The structure is based upon the optimization that took into account the load paths, however there are changes made to it to accommodate manufacturing, and assembly. The optimization also does not tell the designer the size, material, or shape of the members which make up the structure, and these design decisions are evaluated through FEA. The structural frame is made up of two primary pieces, which are bolted together at the centre by six bolts. This division of the structure into two halves allows easier assembly into the vehicle, given the small trunk opening. The frame is held to the vehicle frame rails via aluminum brackets, which are bolted in place to the frame rail. The final design for the module mount plate is shown in Figure 26.

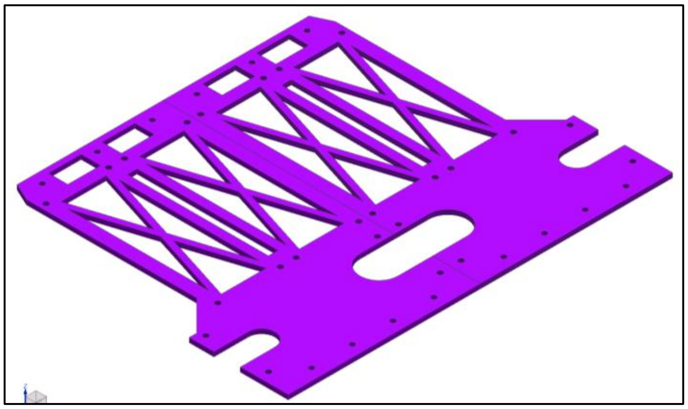

Figure 26: Final Module Mount Plate Design

The module mount plate is also primarily made up of material from which the optimization showed, but there are changes up front from the analysis. As the loading conditions in the optimization solver did not take into account any loads due to assembly or installation, the designer added the ‘X’ webbing to the front of the structure to support the modules during construction. The material is minimized in this area however, as the solver showed that this area of the structure will be subjected to minimal load in the conditions required by the competition.

In order to minimize the weight of the overall frame, 6061 Aluminum is proposed as the material to make up the structure. 6061 aluminum is approximately three times lighter compared to the 4130 steel used to make up the EcoCAR 2 battery pack, and can be welded by one of UWAFT’s suppliers. This aluminum was also used in the team’s EcoCAR 2 subframe, which displayed the ability to decrease weight of the entire assembly by almost 60 %. The use of 2” x 1” x 0.125” 6061 aluminum tubing is considered, as the tubing is easier to weld based on discussions with welders during the assembly of the subframe compared to solid material. Additionally, the tubing has optimal bending properties compared to a solid material. Figure 27 shows the FEA setup of the battery assembly and the materials which make up the structure.

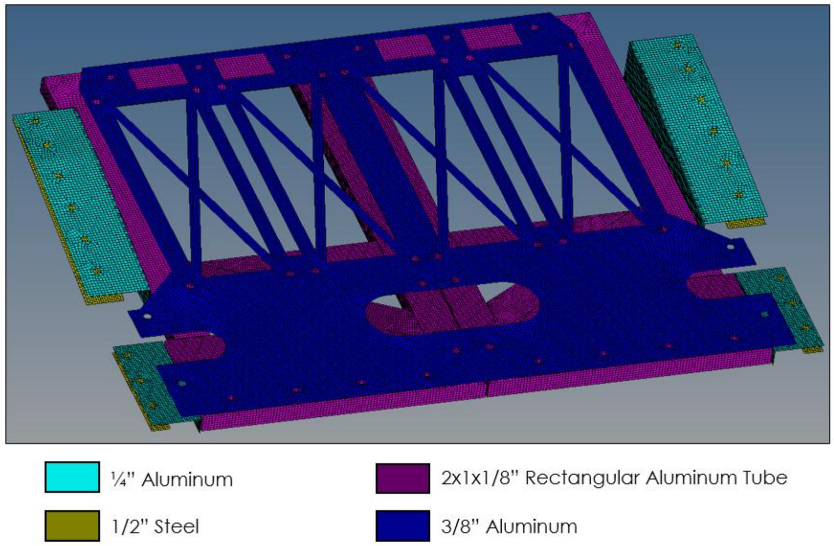

Figure 27: Battery Assembly Material Makeup

3.3.2 Finite Element Analysis

Structural FEA is completed on the final design of the structure to ensure that it can withstand the loading conditions. These loading conditions are the same as those used during the optimization, and are placed at the COG of each battery module. The FEA setup on the assembly is shown in Figure 28.

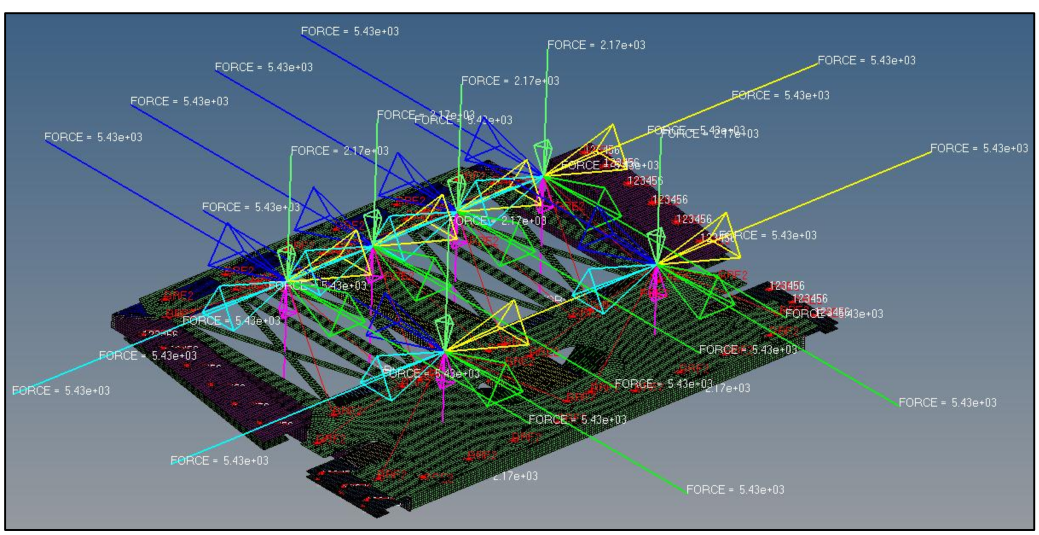

Figure 28: Battery Assembly FEA Setup

The setup is made in accordance with the *GM CAE Statement of Requirements* [45]. The statement of requirements details how the part should be meshed in order to obtain correct FEA results. Details are included on mesh quality, as well as element types which make up the model. The battery assembly is primarily made up of shell elements, simulating the aluminum tubing and plate which the structure is made up of. Shell elements are used as they best represent the bending that may occur in the frame members, which are thin.

Iterations are made on the exact design of the frame based on FEA results. The results show weak areas of the frame which need to be further supported to withstand the load. The final FEA results made by the author before the battery frame underwent the Preliminary Design Review for the EcoCAR 3 competition are shown in Figure 29.

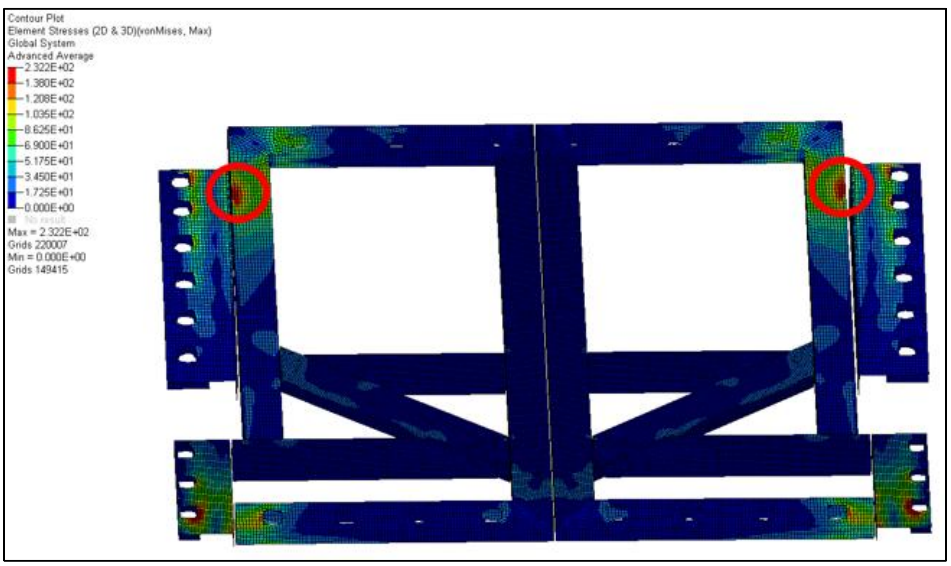

Figure 29: Final Battery Frame FEA Results

These results show the frame being minimally loaded in most areas, with the blue colour showing minimal stresses being applied to the material. There are two areas of weakness and failure in the structure in particular, near the front of the assembly that are outlined with red circles. During load, these two stress concentration areas are supporting the front of the first four battery modules, and the aluminum breaks in this loading condition.

3.3.3 Structural Recommendations

Based on the FEA results outlined in the PDR for UWAFT in EcoCAR 3, it is recommended that the team continue to iterate on the battery frame design to create a structure which can withstand the provided loading conditions. Currently the frame and mounting plate have been designed around the optimization results, which show the load paths within the structure. It is recommended that the team look at different geometries and material thicknesses which may increase the strength of the structure prior to the FDR.

3.3.4 Electrical Design

The battery pack has a complex electrical design which is made up of both Low Voltage (LV) and High Voltage (HV) components. The low voltage components in the assembly are primarily for the control of the pack, and include the control boards on each battery module as well as the battery pack's BMS. The high voltage components include the wiring from each module to the vehicle's HV bus, the battery pack contactors, the battery pack current sense module, and the battery pack manual service disconnect.

In EcoCAR 3, UWAFT will base the majority of its battery pack electrical design on documents provided by the battery manufacturer, *A123*. The manufacturer outlines the wiring schematic of the pack, and provides the base materials required for the team to make its LV control harness. UWAFT is tasked with the job of wiring the pack, routing cables, and sizing the wiring/fuses. The electrical work performed by the author in the design of the pack is based on recommendations from *A123* as well as knowledge gained through working with previous UWAFT pack designs. The LV harness will not be discussed in this document as the harness details have not been released to the author at the time of writing. It is recommended that during the design of the harness that the team takes great care in the construction, as many control issues have been experienced in the past from errors in the harnesses of key vehicle components. As well, all LV wires should be kept away from HV wires as much as possible to reduce impacts of Electromagnetic Interference (EMI). In the case that a LV wire must cross a HV wire, the crossing point should be done at a 90° angle to reduce EMI issues. The overall view of the electrical setup in the assembly is shown in Figure 30.

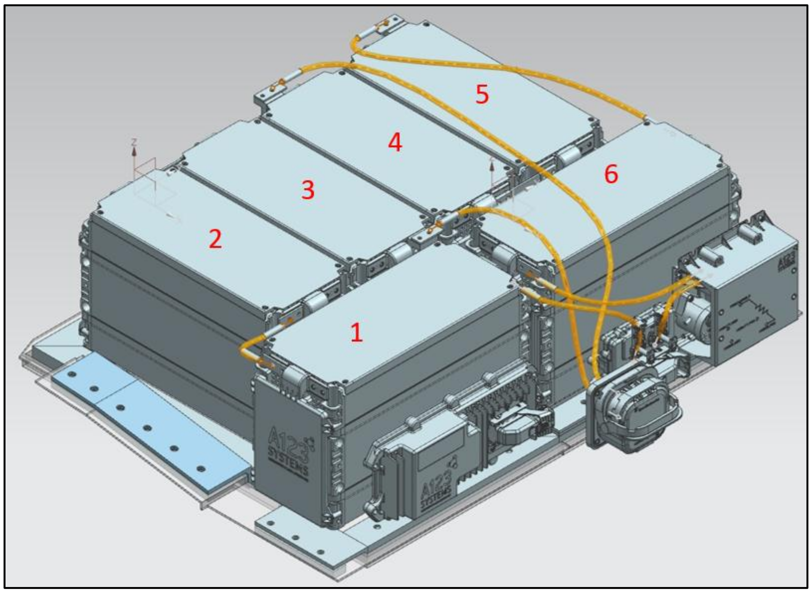

Figure 30: Battery Pack Electrical Setup

The numbers in the figure represent how the battery modules are set up in the circuit. The HV harness begins with the current sense module, which is connected to module ‘1’. All six battery modules are then connected in series to add to the overall pack voltage of 292 volts. The manual service disconnect is placed in between modules ‘3’ and ‘4’, which divides the battery potential when it is removed. This division reduces the safety risks involved with working on the pack, reducing the nominal voltage of each side to 146 volts. The battery pack contactors are the final part of the HV circuit, and the contactors will close in order to energize the vehicle’s full HV bus. The cable routing within the pack structure is shown by the orange cabling seen in Figure 30. EXRAD XLE 2/0 cable is suggested for construction of the pack based on the wire size table shown in Figure 31.

Product Number	Standard Conductor Bare Copper	Nom. Dia Cond. in.	Nom. Dia Cond. mm.	Nom. Dia. Primary insulation in.	Nom. Dia. Primary insulation mm.	Nom. Dia Shield in.	Nom. Dia Shield mm.	Nom. Dia. Outside in.	Nom. Dia. Outside mm.	Shield Coverage	Min. Static Bend Radius	Finished Weight (lbs/mft)	Ampa -city
EXRAD-XLX10X	10 (105/30)	.112	2.84	.162	4.11	.184	4.67	.234	5.94	95%	30mm	59.0	80
EXRAD-XLX8X	8 (133/29)	.166	4.22	.236	5.99	.254	6.45	.304	7.72	95%	39mm	92.0	106
EXRAD-XLX6X	6 (133/27)	.195	4.95	.265	6.73	.283	7.19	.333	8.46	95%	42mm	126.0	155
EXRAD-XLX4X	4 (133/25)	.242	6.15	.312	7.92	.330	8.37	.390	9.91	95%	50mm	187.0	190
EXRAD-XLX2X	2 (665/30)	.318	8.08	.388	9.86	.410	10.41	.490	12.45	95%	60mm	295.0	255
EXRAD-XLX1X	1 (779/30)	.346	8.79	.446	11.33	.469	11.91	.529	13.44	95%	95mm	335.0	293
EXRAD-XLX1/0X	1/0 (1007/30)	.390	9.91	.500	12.70	.528	13.41	.588	14.91	95%	105mm	412.0	339
EXRAD-XLX2/0X	2/0 (1254/30)	.438	11.13	.558	14.17	.586	14.83	.666	16.92	95%	115mm	534.0	390
EXRAD-XLX3/0X	3/0 (1615/30)	.475	12.07	.595	15.11	.623	15.82	.703	17.86	95%	125mm	620.0	451
EXRAD-XLX4/0X	4/0 (2107/30)	.602	15.29	.722	18.34	.750	19.05	.830	21.08	95%	150mm	876.0	529

Figure 31: EXRAD Sizing Table [46]

The 2/0 sized cable is selected based on the 390 ampacity rating for the cable. Through simulations of drive cycles of the UWAFT *Camaro*, it is estimated that the average current draw on the pack will be approximately 350 amps and can be accommodate by the selected wire.

For the smaller gaps between the modules, the 2/0 cable's bend radius will not allow the poles of the modules to be attached. In these circumstances, it is recommended that UWAFT connect the modules with the module-to-module jumper connectors suggested by *A123*. The connectors are included in the battery assembly as shown in Figure 32, with one connecting module '2' to '3' and one connecting module '4' to '5'.

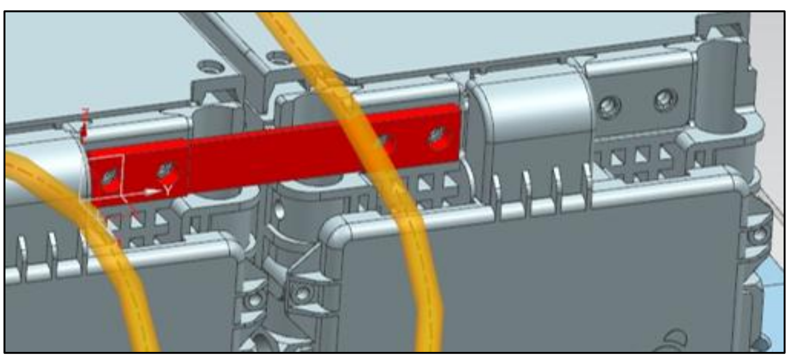

Figure 32: Module-to-Module Jumper

The jumpers are ideal in the battery pack as they allow some movement between the modules in case of a large loading on the pack that could be seen in the event of a collision. In the third year of EcoCAR 2, *A123* engineers recommended that UWAFT re-design the solid busbars used in the Malibu's pack to flexible ones which can allow the movement and decrease risk of catastrophic failure of the modules. The use of the jumpers early in the EcoCAR 3 design will mitigate these potential re-design issues in the future.

3.4 Thermal Management

Through the cycling of the battery in the charge and discharge portions of a drive cycle, or during stationary charging, inefficiencies in the battery cells will cause temperature fluctuations. The most aggressive drive cycle that the UWAFT vehicle will experience is the US06 city cycle, which makes up the E&EC event. The US06 city cycle is defined as a 'high acceleration aggressive driving schedule' that will demand a large amount of power from the battery [14]. Developed through *MATLAB/Simulink* models of the vehicle, the current draw on the UWAFT *Camaro* during the US06 city cycle is shown in Figure 33

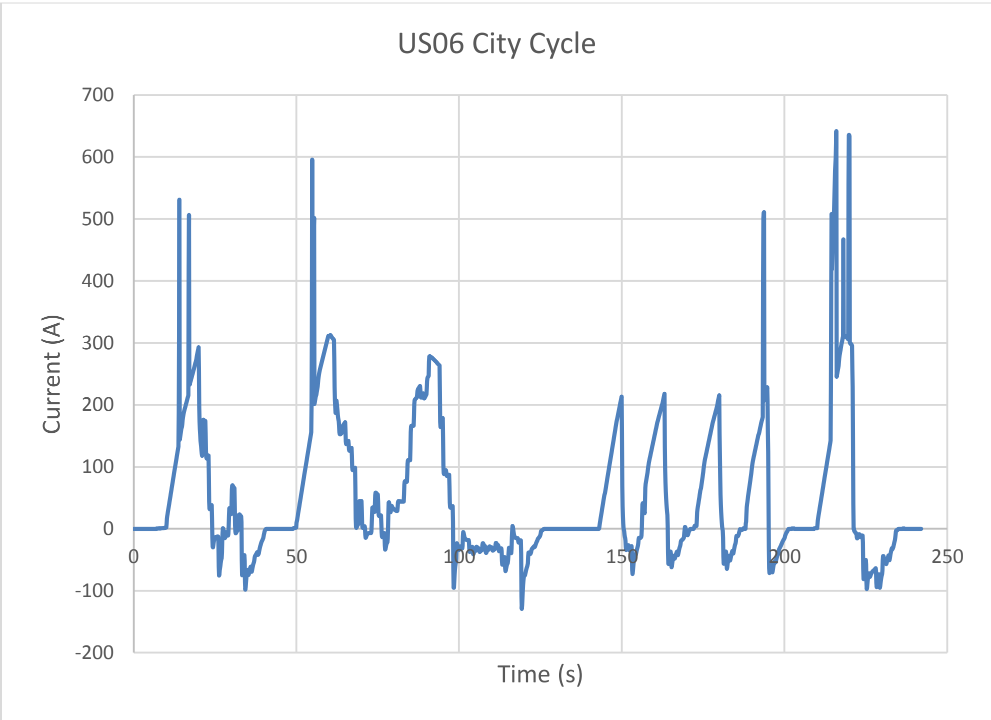

Figure 33: US06 City Battery Current

From the simulated data, UWAFT believes the total power to be discharged from the battery to be 215.5 W, based on a basic R_{int} model of a battery. The R_{int} model assumes the battery behaves as a simple resistor within a circuit, as seen in Figure 34.

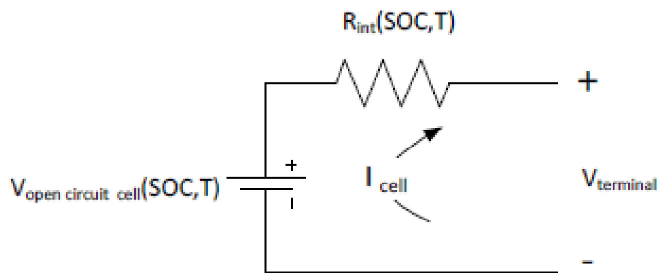

Figure 34: R_{int} Battery Model

The power calculation is made based on the root mean square current being drawn, as both the charge and discharge swings in the drive cycle will produce heat. The charge swings in the drive cycle are a result from regenerative braking which can cause higher current input than the motor draw. In order to dissipate the heat in the battery, a liquid cooling system is proposed. A liquid system was utilized in both the UWAFT EcoCAR and EcoCAR 2 packs, with varying success, but the liquid system shows the best promise to dissipate generated heat over an air cooled system. The liquid cooling system will use cold plates manufactured by *Dana Holding Corporation* in Oakville, Ontario, who have been long time sponsors of the team. The team plans on placing the cold plates on the bottom of the modules, where they have a large contact area and do not inhibit module placement. The layout of the pack with the cooling plates can be seen in Figure 35, with the cooling plates shown in green being placed between the module mount plate and the module.

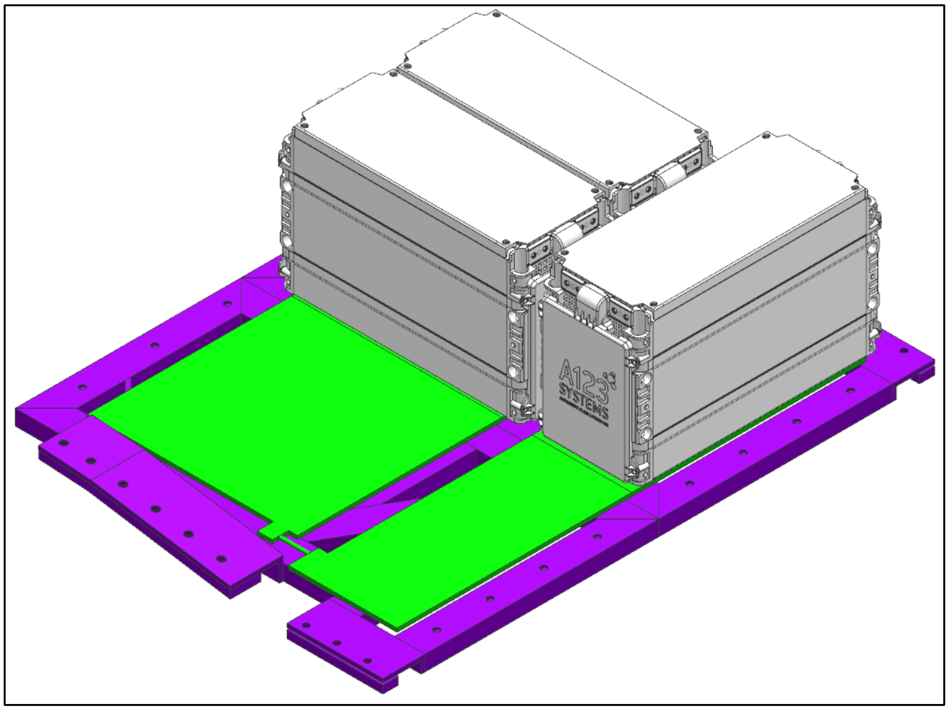

Figure 35: Cooling Plate Conceptual Design (Left Hand Side Modules Hidden)

Optimal placement of the cooling plates would be on the sides of the module, however routing of the liquid lines and the thickness of the modules did not allow for it. However, there is a major advantage given to UWAFT for the placement of the plates at the bottom of the modules. One of the innovation topics being focused on for the team over the course of EcoCAR 3 is the design and construction of a PHEV which can perform optimally in colder climates. It is a known issue that electric and hybrid vehicles perform poorly in colder weather, as the battery is not working at its optimal temperature [47]. Heat rises, and the placement of the bottom plates will allow UWAFT to best heat the batteries in the winter. By tying the engine and an electric heater in to the cooling loop, the control systems on board the vehicle can limit motor torque at colder ambient temperatures; relying on the engine to propel the vehicle primarily. At the same time, the heater and engine cooling loops can add heat to the battery loop to warm it. Once the battery is at its operating temperature, it can provide its full amount of energy to the system.

3.5 Chapter Summary

In this chapter, the design of a hybrid battery pack is outlined based on the author's experience with the design of a pack for the UWAFT *Camaro* in the EcoCAR 3 competition. Mechanical optimization techniques are used to create a starting point for mechanical design, and show great advantages in being able to make efficient designs which minimize vehicle weight and can be employed to design the assembly for a repurposed energy storage system. The pack is made in two halves, and features a base battery frame and module mounting plates which assist in assembly. This pack is developed for a split-parallel vehicle, with a 16.2 kWh *A123* pack which supplies power to two *GKN* AF 130-4 motors that power the wheels in conjunction with an 850cc turbocharged *Weber* engine. The pack's electrical design is made in accordance with guidelines from the battery manufacturer, and the cooling system is designed to accommodate both the heating and cooling of the battery. The cooling system is designed to provide cooling based on the worst case conditions the vehicle could face in competition: the US06 aggressive drive cycle.

Chapter 4
Repurposed Battery Pack Design Considerations

4.1 Introduction: Repurposed Battery Pack Design Process

Stationary energy storage can be used in multiple scenarios to provide energy, including for peak shifting in residential/industrial applications, intermittent power delivery for renewable energy sources, energy arbitrage, demand management, provision of ancillary services, or as power backup for grid interruptions. Once a repurposed battery pack is selected for use as stationary energy storage, the following design process is suggested for design of the overall pack assembly. The algorithm is based on a thesis published by Shahab Shkrzadeh, and is modified based on the business, risk analysis and degradation work completed by the author and the research group at the University of Waterloo [48] . The design process is included in Figure 36.

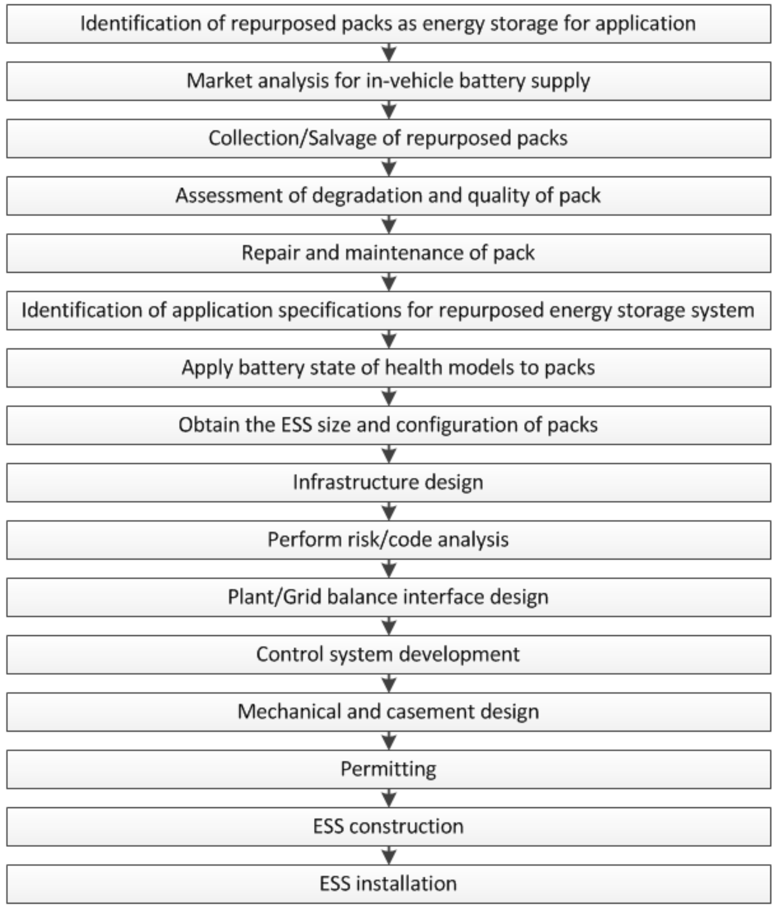

Figure 36: Repurposed Energy Storage System Design Process

4.2 Repurposed Pack Business Development

4.2.1 Repurposed Packs for Application

Initial market analysis may be required to be completed to determine the applicability of repurposed battery packs to an application. Currently, there are a number of energy storage systems which are used in the market, including pumped hydro, compressed air, and power-to-gas storage. For this work, the application is the provision of electrical services in a residential facility where the ESS is placed at the user's site, with the provision of services to this facility. Note that such a facility may also include the onsite generation of electricity by renewable means, including wind and solar energy. One example of the demand profile for a residential application that uses a repurposed energy storage system to peak shift energy is shown below in Figure 37 from

Heymans et Al, illustrating the differences between the demand for a house with or without a repurposed ESS installed.

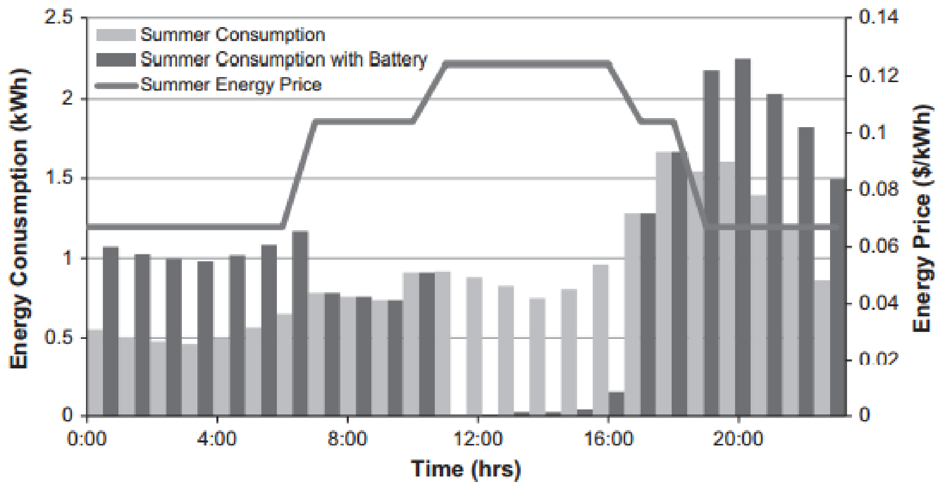

Figure 37: Example Residential Demand Profile [49]

Repurposed battery packs show advantages in low initial cost estimates of $2475 for the pack and its installation, with payback periods as low as two years based on the battery pack used in the system [39]. The packs have lower initial costs compared to a new Li-ion battery pack, and can be used in smaller applications such as a residential home.

4.2.2 Market Analysis of In-Vehicle Battery Supply

Once a repurposed pack energy storage system is selected for installation, the current in-vehicle battery supply should be analyzed to determine the number of batteries available for repurposing. Hybrid and electric vehicles sales have increased over the past years, due to the market penetration of new models and the use of incentives by the government. Figure 38 shows the increase in sales in the United States market.

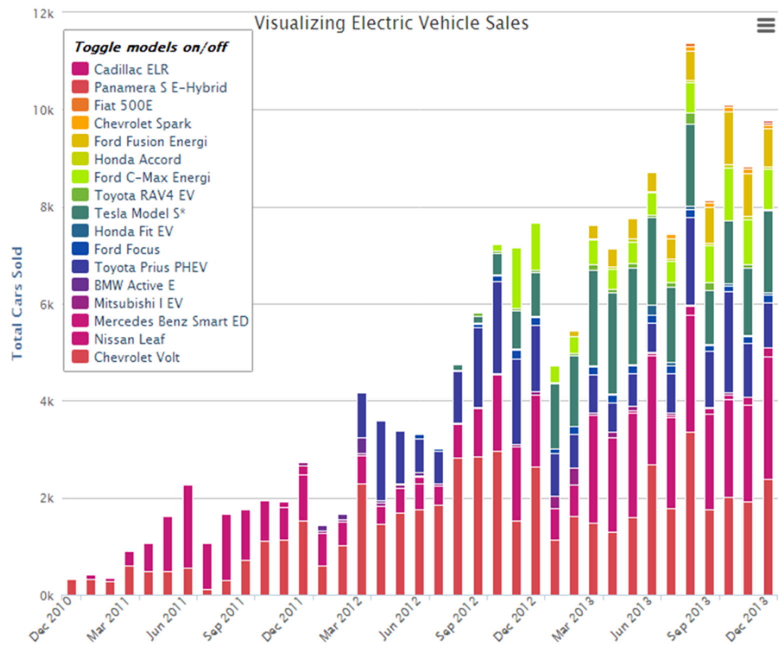

Figure 38: U.S. Electric and Hybrid Vehicle Sales [39]

It is predicted that after a period of eight years in the vehicle that these batteries will no longer be useful and can be released to the market for repurposing [20]. This estimate is consistent with the OEM's warranty of such battery packs [50]. The timeline for the majority of Li-ion battery systems which would be useful in the repurposed packs discussed in this thesis is around 2018, at which point multiple packs would be available from vehicles being removed from service.

4.3 Repurposed Pack Condition Assessment

4.3.1 Collection/Salvage of Repurposed Packs

One of the biggest uncertainties with the use of repurposed battery packs in stationary, second-use applications is the collection and salvaging of the packs after they are integrated into the vehicle. As the number of electric and hybrid vehicles with valuable Li-ion batteries increase on the roads, the batteries that power them are beginning to be collected by automotive recyclers as vehicles are damaged in an accident or ownership is transferred. A report from the author's research group attempted to predict how manufacturers of repurposed packs could obtain the batteries after vehicle life through interviews with OEM dealers and surveys with automotive recyclers [51]. Although there was a small response rate of 10%, the surveys gained information on the hazards and policies the recyclers have on the batteries. Of note is that the majority of recyclers are currently obtaining batteries from insurance companies and auctions, and not necessarily from the overall vehicle. This finding indicates that automotive recyclers see the value in the packs, but the survey also finds that many do not know what to do after obtaining the batteries. As well, it emphasizes the trend that large numbers of hybrid batteries will not be ready for repurposing from vehicles nearing the end of life period for a few years.

Many recyclers also noted that they re-sell the batteries in an approximate two month timeframe, but some hold on to them for prolonged periods [51]. For collecting of the batteries by a re-manufacturer, they would need to implement a supply chain which encompasses all of the available salvaging network. This network includes insurance companies, automotive recyclers, garages, dealers, auctions, and consumers themselves [51].

4.3.2 Assessment of Degradation/Quality of Pack

From the responses of the automotive recycler survey, many recyclers are concerned about the hazards associated with the battery pack and the author's experience believes that many do not have the specialized knowledge that the OEM and its dealer network have with safe servicing practices of the system. Additionally, it is found that many recyclers do not understand how to properly test the battery and understand its SOH after coming out of the vehicle [51]. Re-manufacturing firms may need to take batteries once acquired and test for degradation and quality to establish baselines for each pack. Currently, only vehicle manufacturers and dealers are able to check the diagnostic codes displayed by the packs to check their quality. Each pack can vary widely based on its vehicle use, how aggressive it was cycled, and the environment in which it was operated. This assessment may take into account fade mechanisms associated with capacity, and power as well as the testing for cells which have catastrophically failed. Any cell failures in the author's opinion may render an entire pack useless for repurposing, due to the labor-intensive operation that would be required to replace the broken cell.

The author proposes a five level system to categorize battery packs based on their SOH after the vehicle use phase. Batteries could be sorted based on a diagnostic process completed by the vehicle manufacturer or dealer and decisions on the battery's future can be made with the level categories as shown below in Figure 39.

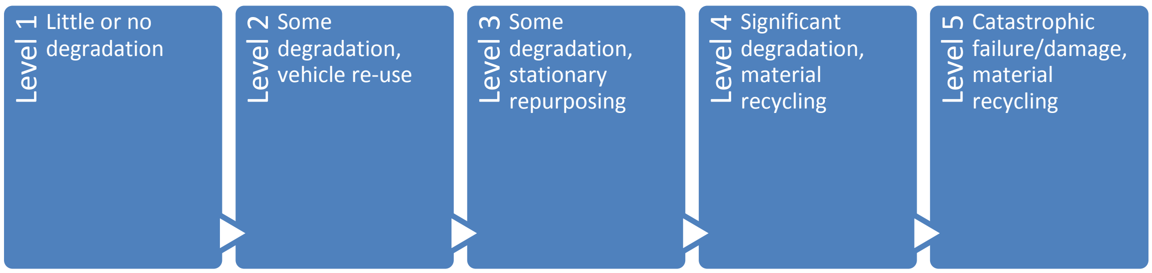

Figure 39: Battery Pack Level Classification

After the vehicle life stage, batteries can be placed in one of the five categories based on their state of health. Level One and Level Two batteries have experienced a minimal amount of degradation during their vehicle use, and have more than 80% capacity remaining. These batteries could continue to be used in the vehicle before being taken out for use in a repurposed application. Level Three batteries have degraded to below the 80% threshold for capacity remaining, but still have enough life to be used in a repurposed application. In this scenario, a second battery could be installed in the vehicle to extend its life and the original battery can be taken out for stationary storage. Level Four and Five categories are for batteries which have been significantly degraded or suffered catastrophic damage. In this state, the batteries are unable to provide energy for either the vehicle or stationary use, and should be recycled.

4.3.3 Repair/Maintenance of Pack

Extensive repair or maintenance of the pack would make the pack unsuitable for use in repurposing, due to the labor-intensive process that would be required for servicing. However, some packs may be able to enter a repurposed application with limited repairs or maintenance being required. For example, the author with the help of undergraduate students was able to construct a repurposed pack with limited damage from a collision (results included in Chapter 5). This pack only had minor damage to the case, leaving the battery cells fully functioning.

4.4 Repurposed Energy Storage System Application Specifications

After an application is deemed as a fit for a repurposed energy storage system, specifications for the system may need to be collected prior to design. A repurposed pack in the context of this thesis is to be designed to primarily offset peak electricity usage and/or energy arbitrage, but the packs are also able to help store energy from renewable, intermittent sources, or provide energy during grid blackouts in a back-up power function. Each application may have specific properties which affect the repurposed ESS design including:

- Time-of-use and/or grid electricity pricing;
- Variability in grid dependence;
- Congestion in the distribution and transmission systems;
- Integration of renewable energy sources; and,
- Charge/discharge profiles of the facility.

The combination of these factors may help designers to understand how much capacity is required to meet demands of the application, and the charge/discharge capabilities required.

4.5 Battery Pack State of Health

4.5.1 Background

In order to understand how a vehicle battery can be repurposed into a secondary, stationary application, one should understand how they are affected during the initial vehicle stage. Through aggressive drive cycles and various use profiles, batteries can be damaged and degraded during vehicle life. The initial vehicle life puts a large strain on batteries, which can lead to capacity fade, power fade, charge efficiency fade, and catastrophic failure of individual cells within the pack. In order to understand the available capacity for repurposing, a capacity fade model is developed which builds upon lab experiments on Li-ion half cells to understand how their degradation is affected in the two stages of the battery's life.

4.5.2 Capacity Fade Model

As discussed, the capacity fade model is based on the cycling of Li-ion half cells. The model is developed to understand fade over two life stages of the battery: vehicle, and repurposed stationary use. The first assumption in the model is that the battery has a useful in-vehicle life span of eight years, based on manufacturers' warranties [20]. Currently, manufacturers do not claim a specific lifetime of the battery as many factors including drive cycle aggression and ambient temperature can affect the overall life. The author states that End of Life (EOL) of the battery in the vehicle is defined as 20% capacity fade, at which point the battery would be repurposed for a stationary application. At this stage, the battery can no longer meet the daily drive demands of the driver, and it still retains enough residual value to be able to provide energy in a secondary use. This capacity fade over the vehicle lifetime occurs as a result of both calendar aging, a decomposition of the electrolyte over the battery's lifetime, and cycling which contributes a larger portion of the overall capacity fade in the battery. $LiFePO_4$ cells are focused on, due to their environmental effectiveness, cost, and availability [20]. These cells have been researched extensively to understand their capacity fade based on charge rates (C-rates), temperatures, and DOD. A large issue found by the author in developing a capacity fade model for the entire lifetime of the battery is that many studies only cycle the cell for a small amount of time. This fact makes it hard to establish predictions for fade rates over the entire lifetime. The chosen studies which are used for the correlation are those completed by Song et Al., Lam et Al., Dubarry et Al., Safari et Al., and Peterson et Al. [52] [53] [54] [55] [56]. All of these studies cycle $LiFePO_4$ cells to different amounts of time, to establish capacity fade trends as a result of different environments. The model developed normalizes the results of the previous studies, and extrapolates them from their relatively low number of cycles processed to achieve results in a practical application. At the start of the trend, all five study results are averaged to find a capacity fade trend, and they are gradually phased out as they are extrapolated. [20]

The capacity fade of the battery is correlated to the number of Amp hours-processed (Ah-processed). This correlation allows for the normalization of many experiments, where cycles range in the amount they utilize the energy in the battery based on differing DOD. The battery's capacity fade is found for its 18 year life, which includes the initial eight years of vehicle use and an additional ten years of repurposed stationary life. The ten years are estimated for full repurposed life, at which point the battery can be re-assessed for further cycling or replaced.

Through the normalizing of the cycling occurring in the aforementioned five studies, the following capacity fade trend developed as part of this work is found in Figure 40.

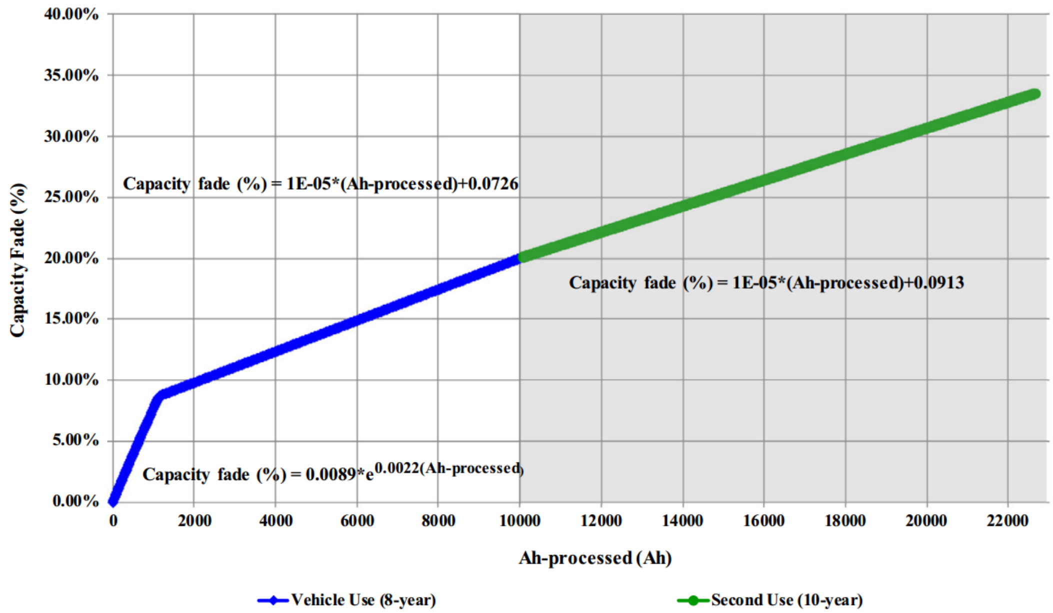

Figure 40: Capacity Fade Model (Assumes no cell failure) [20]

The model is broken up into three distinct capacity fade stages. The first stage, which has an exponential capacity fade, occurs over the first 300-350 cycles of the battery; resulting in an 8% capacity loss. The exponential loss is seen in the five independent studies, as the battery is 'broken in', and begins its cycling life. This exponential loss would correlate to approximately 20,000 km of driving in the average vehicle. The five study results are shown in Figure 41.

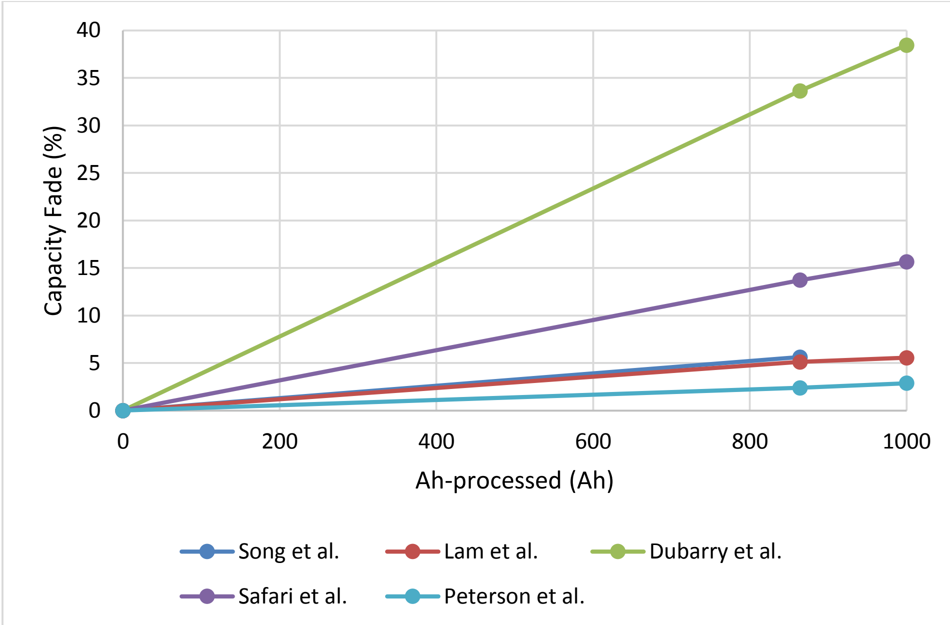

Figure 41: Initial Study Capacity Fade Loss

For the remaining vehicle life in the second and third stages of the capacity fade model, the battery will degrade in a linear fashion. The trend in the second stage is based on the initial assumption of 20% loss of capacity over the first eight years of service in the vehicle. After the 8% initial loss, the trend is normalized to achieve the 20% at its conclusion of the battery's lifetime in the vehicle.

In the repurposed application, the third life stage, capacity fade loss is also assumed to be linear. However, the rate at which the capacity degrades is assumed to be less than the linear fade as seen in the second stage of vehicle life. This decreased capacity fade rate in the repurposed stage is due to the fact that the stationary pack can be gently cycled, thus reducing fade during this application. Through the many potential applications of the repurposed pack, designers of the battery control system can limit current draws on the battery and regulate its performance as its design is no longer constrained by the volume/space limitations of the vehicle and its aggressive drive patterns. The reduced capacity fade rate in the stationary application results in a 15% decrease in capacity overall in the repurposed stage of life, resulting in approximately 35% capacity fade loss over the entire 18 year life.

Capacity fade is important in the context of a repurposed application, as the available amount of capacity diminishes over the vehicle life. However, of particular importance is also the charge efficiency fade over the battery's lifetime. Specific studies for charge efficiency fade over long cycling life has not been completed at this time, most likely due to the fact that it is an unimportant characteristic to many OEMs. Due to the cost difference between running a vehicle on conventional gasoline or grid electricity, inefficiencies in charging can be overcome during vehicle operation. In a repurposed application this charge efficiency loss represents a significant decrease in overall efficiency (and thus effectiveness, especially for economics) of the system, as the packs need to be charged and discharged again in order to provide energy at a later point in time [49]. It is currently estimated that the rate at which charge efficiency decreases over a battery's lifetime is approximately the same at which capacity fades, marking the importance of being able to predict this battery characteristic through its life cycle. This assumption is likely generally correct since the predominate material degradation mode is likely to be the growth in the SEI layer, which may lead to an increase in resistance of the cell, which in turn may result in capacity and charge efficiency fade.

4.6 Energy Storage System Conceptual Design

4.6.1 Energy Storage System Sizing and Pack Configuration

ESS sizing and configurations of packs within the assembly may be dictated based on each application and the packs chosen for construction. As indicated in Section 4.4, each application may have specific needs which will be addressed by the repurposed ESS. The specific design may depend heavily on the selected vehicle pack for assembly, as each have differing capacities which may degrade over time in the vehicle. Table 3, included in a report from the author's research group, shows currently available vehicle battery packs and their capacities assuming 20% degradation over the vehicle's lifetime.

Table 3: Available Vehicle Battery Packs [39]

Vehicle	New Capacity (kWh)	Repurposed Capacity (kWh)
Toyota Prius PHEV	4.4	3.5
Ford C-Max Energi	7.6	6.1
Ford Fusion Energi	7.6	6.1
Chevrolet Volt	16	12.8
Mitsubishi i-MiEV	16	12.8
Ford Focus	23	18.4
Nissan Leaf	24	19.2
Toyota RAV4	41.8	33.4
Tesla Roadster	56	44.8
Tesla Model S	60	48

These packs can be connected in parallel to add capacity, or in series to increase the potential of the repurposed system. Higher rates of return are seen with the larger *Tesla* packs in a repurposed setting, as they are able to offset more power on each charge cycle [39].

4.6.2 Infrastructure Design

Infrastructure of the repurposed pack assembly may depend heavily on the size and pack configuration of the unit. Some sizing of components in the repurposed bench test setup is outlined in Chapter 5. Nominal voltage of the pack, as well as the desired charge/discharge rates will determine specifications required of the charger/inverter that is used, with costs increasing quickly with increasing performance. Larger capacities of packs may be able to offset longer periods of peak power, but may require high capacity charge circuits to be able to charge the battery during daily cycling. Additionally, control systems may need to be developed which integrate with the smart grid network and can control the charge/discharge of the ESS.

4.7 Battery Pack Risk/Code Analysis

One of the biggest inhibitors to widespread integration of repurposed battery packs into the market is the risks involved in installing, servicing, and insuring this high potential device. As the repurposed packs are new, there is little literature and codes that are in place to regulate their incorporation on to the grid and into residential homes or businesses. In order to understand the risks that the battery packs create, the author performed a Design Failure Modes and Effects Analysis (DFMEA), a Fault Tree Analysis (FTA), and a code analysis. The details from each of these analysis techniques are included in the following sections [57].

4.7.1 Design Failure Modes and Effects Analysis

The DFMEA risk technique approaches a problem from the user function down to a potential cause of an issue [58]. The DFMEA for the repurposed pack looks at each component in the bench test setup outlined in Chapter 5, and the functions that the component should achieve. Each function and the associated risk is assigned a number from 1-10 for the following three categories:

Severity (SEV): Defined as the severity of an incident that is caused by the risk
Risk of Occurrence (OCC): Defined as the chances of an incident being caused by the risk
Probability of Detection (DET): Defined as the chances that once an incident occurs that it is detected before risk to people

The SEV, OCC, and DET are then multiplied together to find the Risk Priority Number (RPN) using the following formula, Equation 3:

Equation 3: Risk Priority Number

$$RPN = SEV * OCC * DET$$

The higher the RPN, the greater risk that each risk poses on the entire assembly. The greatest risks are targeted as those need the most attention during the design phase to be mitigated prior to installation and assembly. The DFMEA discussed is based on the revision one bench setup of the repurposed battery pack, focusing on the charger, battery pack, controller, inverter, and protective case which would be installed in a home setting, refer to Chapter 5. The DFMEA is included in the Appendix A and the top risk, included in Table 4, from the analysis for each component are discussed further here. Note: The charger and inverter displayed the same risks in the analysis and are included in the same line number.

Table 4: Top DFMEA Risks

Item/Function of Part	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	DET	RPN
The charger/inverter shall convert power to charge/discharge the battery pack	Overheating	Personnel injury: Burns (10) Wire damage (8) Loss of charge capability (8) Degradation of charge capability (7) Component internal damage (7)	10	Loss of control input (2) Power surge (3)	3	6	180
The battery pack shall store and deliver energy	Overheating	Damage to cells (7) Loss of charge capability (8) Degradation of charge capability (7) Thermal runaway (10)	10	Charger/inverter degradation (3) Loss of control input (3) Wire degradation (2)	3	6	180
The controller shall direct pack components (charger/inverter)	Overheating	Personnel injury: Burns (10) Wire damage (8) Loss of charge capability (8) Degradation of charge capability (7)	10	Incorrect control input (3) Physical damage (3) Power surge (3)	3	6	180
The battery pack casing shall protect personnel from electrical components	Case damaged	Personnel injury: Shock, burns (10) Component internal damage (7) Loss of charge capability (8)	10	Corrosion (3) Physical damage (3)	3	6	180

With every line item in the DFMEA, there are multiple effects or causes of an associated failure. The highest number in each category is used to evaluate the risk in the function. Overheating is a common high risk to each component in the assembly, as it is anticipated that the assembly may heat up during operation which could cause damage to the components. Overheating is understood to be one of the biggest risks associated with Li-ion packs due to the risk of thermal runaway in a potential breakdown situation. As a result, the design team recommends the installation of multiple fans in the case which protects the assembly, with a perforated enclosure which can allow for sufficient air flow to cool the pack. The battery used in the bench test setup is an air cooled pack, and may require additional cooling under heavy loading scenarios.

4.7.2 Fault Tree Analysis

The Fault Tree Analysis (FTA) risk technique looks at a risk which is posed to personnel, and attempts to break it down to the root causes which can lead to it. The technique approaches the risk analysis for the repurposed battery pack from the opposite side of the DFMEA, to find if there are different risks which can be posed to the user. The FTA for the repurposed battery pack focuses on the following five major safety risks: electrocution, slips/falls, inhalation, cuts/scrapes, and burns/explosions. Faults are connected through 'And' or 'Or' gates to suggest the combination of faults which can arise with the risk in question. The full FTA for the five risks is included in Appendix B. The 'Burns/Explosions' FTA is included in Figure 42 for discussion.

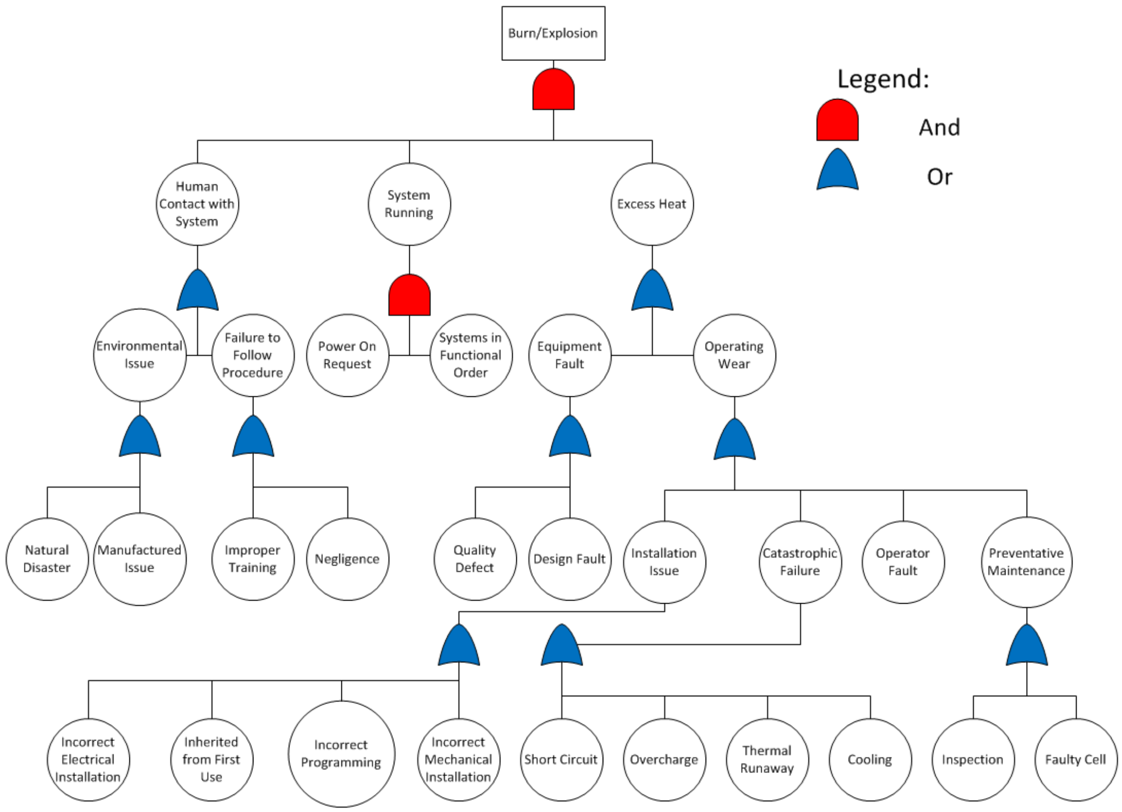

Figure 42: Burn/Explosion Fault Tree Analysis

Through the use of the FTA, designers can understand where an end risk to the user began. The biggest root causes leading to burns/explosions in the repurposed pack arise from installation issues, improper preventative maintenance, and catastrophic failure of the battery pack. The installation issues can be mitigated in the implementation of the pack through the use of qualified technicians who are specially trained in HV apparatus. These same technicians should also be employed to do routine maintenance on the assemblies, especially early in their use in the market as issues are sorted through the cycling of the packs. Finally, catastrophic failure is always a risk in an assembly, but the integration of a well-designed assembly/enclosure which has a thorough control system in place that can monitor the pack as it is cycled should mitigate any issues of overheating or thermal runaway.

4.7.3 Repurposed Battery Pack Code Analysis

To understand the safety measures that need to be included in the design of a repurposed pack in a grid storage context, all applicable safety codes for construction may need to be adhered to. Stationary energy storage, especially with Li-ion cells, is a relatively new concept and codes are currently being developed which address the safe design, installation, and operation of these projects. In the United States, it is anticipated that new codes may take approximately six years before they are ready for enforcement in the market [59].

A report by the *Pacific Northwest National Laboratory* outlines the codes and standards in the United States for energy storage systems [60]. Table 5 and Table 6 display the codes outlined which are applicable to the repurposed packs outlined in this report. Table 5 focuses on codes which are specific to the battery pack used in the stationary assembly, while Table 6 focuses on codes which outline design considerations for the repurposed pack assembly.

Table 5: Applicable Codes for Repurposed Li-ion Battery Packs in a Stationary Application [60]

Code Category	Code Title	Connection to Repurposed Packs
Battery Pack	IEC 61960 Ed 3: Secondary lithium cells and batteries for portable applications	Covers criteria for the selection of secondary lithium cells for remanufacturing
	IEC 62485-2: Safety requirements for secondary batteries and battery installations – Part 2: Stationary batteries	Covers protections from hazards with stationary battery packs with nominal voltages less than 1500 V
	IEC CD 62619: Secondary cells and batteries containing alkaline or other non-acid electrolytes. Safety requirements for secondary lithium cells and batteries, for use in industrial applications.	Under development, covers requirements on all aspects of stationary application use of Li-ion batteries including erection, use, inspection, maintenance, and disposal of cells
	IEC CDV 62620: Secondary cells and batteries containing alkaline or other non-acid electrolytes – Secondary lithium cells and batteries for use in industrial applications	Covers tests and requirements for Li-ion cells to be used in a stationary application
	IEC 62620 Ed 1: Large format secondary lithium cells and batteries for use in industrial applications	Covers specifications for cells in secondary industrial applications
	IEEE 1660: Guide for Application and Management of Stationary Batteries Used in Cycling Service	Covers battery management strategies, with changes relative to cycling for stationary applications
	UL 1642: Lithium Batteries	Covers requirements for lithium batteries in stationary applications for safety of technicians, users, and other design features

Table 6: Applicable Codes for the Repurposed Battery Pack Assembly [60]

Code Category	Code Title	Connection to Repurposed Packs
Entire Assembly	ANSI C84.1: Electric Power Systems and Equipment – Voltage Ratings (60 Hertz)	Standard covers nominal voltage ratings and operating conditions for 60-hertz systems above 100 volts
	IEC 62257-9-2: Recommendations for small renewable energy and hybrid systems for rural electrification – Microgrids	Standard covers requirements for how microgrids can be maintained and safety upheld
	IEC 62897: Stationary energy storage systems with lithium batteries – Safety requirements (under development)	Covers hazards that need to be mitigated for the use of a stationary pack with Li-ion cells
	IEEE 1375: Guide for the protection of stationary battery systems	Covers guidelines for options of protecting stationary battery systems
	NFPA 111-2013: Standard on stored electrical energy emergency and standby power systems	Covers safe operation of stationary energy storage systems with the grid in the event of service disruptions
	UL 9540: Outline for investigation for safety for energy storage systems and equipment	Covers safety for all energy storage systems, being charged and discharged at a later point in time to shift demand

As many Li-ion codes are still in development, the author analyzed codes that have been developed for lead-acid battery stationary storage setups to determine the direction that would be followed for the Li-ion legislation. Two codes that are applicable for the installation of a lead-acid system in Canada are the *CSA Electrical Code 2012* and *IEEE 484* [61] [62]; key findings from both codes for the casing and assembly of the ESS are included below [61]:

- The assembly should be installed on a level plane, with sufficient storage strength to protect against electrolyte corrosion;

- Batteries with nominal voltage >150 V should be sectionalized into groups;
- Storage of the batteries should be only accessible by authorized personnel;
- Storage of the batteries should be kept at an ambient temperature of approximately 25°C; and,
- Installation should be performed in a protected area, isolated from vibration.

4.8 Assembly Conceptual Design

4.8.1 Plant/Grid Balance Interface Design

The interface between the ESS (plant) and the grid may need to be designed for each application. For maximum utility of the ESS, control may need to be established with the utility, to understand changes in price, supply, demand, and grid mix to integrate intermittent renewables. This interface may require HV access for the ESS to be integrated, as well as the communication infrastructure for the unit to communicate.

4.8.2 Control System Development

The development of the control system in the repurposed ESS may require the careful monitoring of changes in the usage profile of the application, the grid mix, and the SOC/SOH of the pack. Each battery pack used in the assembly should be integrated with its own BMS, which can monitor and control the differences in voltage and charge between the individual cells in the pack. There may be a supervisory controller in place which can control the whole system, and interact with the auxiliary components in the assembly. Figure 43 shows the overview of the proposed control system that could be implemented in a repurposed ESS.

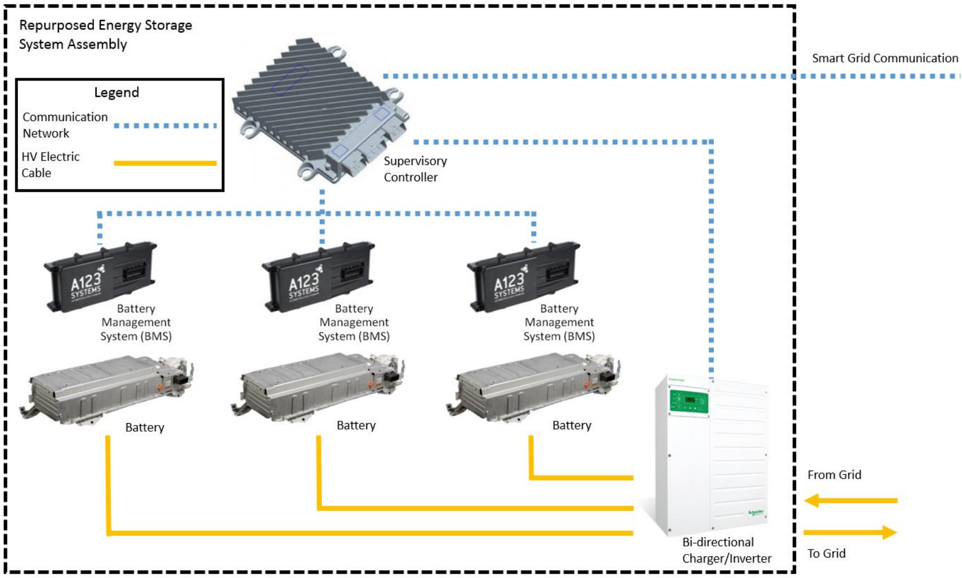

Figure 43: Control System Overview

The supervisory controller monitors the assembly, controlling the charger/inverter in accordance with grid and application needs. The controller should be monitoring communication with each individual BMS, to understand if there are degradation or failure issues with each pack. This communication may be a challenge to set up, given the differences in controllers between each individual vehicle. As a result, it is recommended that only similar packs are used in each application. All communication is anticipated to be completed via a Controller Area Network (CAN), similar to those that are implemented in a vehicle.

4.8.3 Mechanical and Casement Design

The design of the mechanical aspects of the ESS and the casing may need to achieve two main purposes. The first is to protect the internals of the case from the ambient environment. To protect the internals, the case may need to be designed to allow for cooling, while protecting against moisture which can degrade and corrode the batteries and electrical connections. A system which is mounted to a wall may be optimal, keeping the assembly out of the potential path of any floods which could occur in the area of the installation. In this case, mechanical optimization techniques such as those discussed in Chapter 3 may help to decrease the associated weight with the construction. The second purpose is to protect users and technicians who are interacting with the pack. The pack may be working at high voltages (likely 48 – 300 V), which may need to be protected in a secure case to protect against shock hazards. The lower end of this voltage range is anticipated for use in an industrial application, as many commercially available chargers and inverters could be used in the repurposed setup from the solar energy industry. To achieve this low working voltage using the 50 V modules discussed in the battery pack design in Chapter 3, each module would need to be connected in parallel to form the repurposed pack. Another example of achieving this low working voltage is outlined in Chapter 5, which uses four smaller modules from a Prius battery pack to reach a nominal voltage of 28 V.

4.9 Energy Storage System Grid Integration

4.9.1 Permitting

Permitting is currently a large unknown for repurposed energy storage systems. As in the code analysis outlined previously, Li-ion repurposed energy storage is a new concept. As a result, the legislation that regulates the installation of these systems is not currently written. Permits may need to first be issued to the designers/installers of the system to implement it in the market. Some studies have found that the introduction of renewable technologies into the market can be more difficult than introducing fossil-fueled technologies, and call for reforms to the system [63] [64].

4.9.2 ESS Construction

Once designed, construction of the ESS is anticipated to be simple, requiring the construction of Low Voltage (LV) harnesses and High Voltage (HV) cabling. Any remanufacturing facilities and their employees may need to be sufficiently trained in HV procedures however, and many training procedures differ based on each manufacturer. Safe practices will need to be employed, to ensure that the packs can be assembled and delivered to the customer in a safe manner. Incoming battery packs may first need to be sorted based on their degradation and SOH status into one of the five levels discussed in Section 4.3.2, and repaired if small amounts of damage are evident. There is the potential for one or more of the cells within the pack to be beyond useful application, requiring this cell to be physically removed from the pack or, more likely, the pack being reconfigured to bypass the nonfunctioning cells. Once the design has been completed for a specific application, viable packs can be assembled with a custom harness to a supervisory controller that has been programmed to work with the chosen charger/inverter and BMS specific to the packs in use. The control networks such as CAN can then be wired, and the battery modules connected together to form the system's HV bus. It is anticipated that the entire assembly may have its own service disconnect that can be installed/uninstalled to allow service procedures and shipping to occur in a safe manner.

4.9.3 ESS Installation

The installation of the ESS may require changes to the application's electrical network to allow for the integration of the unit. Installation is predicted to be simple, with the assembly acting as an independent unit with only HV and control connections required to integrate it. Installation may require certified technicians, to complete the task in accordance with the codes specific to the area of installation to ensure that the risks outlined in the FTA and DFMEA in this report are mitigated.

4.10 Pack Design with a 16.2 kWh Battery

Chapter 3 of this thesis discusses a 16.2 kWh battery pack, made up of six 15S3P battery modules from *A123*. These modules each operate at a nominal voltage of approximately 49 V, which are connected in the vehicle in series to achieve an operating voltage of 292 V. Assuming a 20% capacity fade through the vehicle, the full battery pack could be uninstalled from the *Chevrolet Camaro* with 12.96 kWh remaining.

To implement this pack in a repurposed setting, the modules could be disconnected in their series configuration within the vehicle, and connected in a parallel setting to achieve a nominal operating voltage of 49 V. At this range, chargers/inverters from the solar energy industry including the *Conext XW+* discussed in the design of the bench test setup in Chapter 5 could be implemented off-the-shelf to integrate the pack into the grid network.

Based on assumptions regarding charging from Heymans et Al., the following chart is created using this pack to understand the maximum amount of energy that can be offset during a single day for a residential application in a repurposed setting, Table 7. The numbers included are based on an assumption that the repurposed pack is charged/discharged at a charge efficiency of 80% for each charge, resulting in a 64% efficiency 'round-trip'.

Table 7: 16.2 kWh Battery Pack Energy Ratings

	Energy (kWh)
Rated Pack Capacity - New	16.2
Rated Pack Capacity – After Vehicle Use	12.96
Total Discharge Available – After Charge Efficiency	10.37
Maximum Energy Available for Discharge	8.3

Thus, only 8.3 kWh of energy is available for discharge in the repurposed pack, down from the newly rated capacity of 16.2 kWh. However, a given North American home will use on average 3 - 4 kWh of energy during a day [65]. Therefore, this pack has the potential to offset a full day worth of energy for a home, and can offset peak power use for the end consumer.

4.11 Chapter Summary

In this chapter, a design process is proposed which should be followed in the application of a repurposed battery pack in a stationary energy storage situation. Repurposed packs offer an alternative to more expensive energy storage solutions, which require new packs or specific infrastructure such as pumped hydro. There are many areas of research which still need to be sorted, in order to develop supply chains which can distribute used batteries to a re-manufacturer. The exact supply of vehicle batteries nearing end of life is still uncertain, as Li-ion technology is new to the market.

Once collected, assessments of the degradation and quality of the pack are needed to determine if they are viable for repurposing or require minor amounts of repair or maintenance. Packs with a large amount of degradation or large numbers of cell failures would deem packs as useless for repurposing, due to the large investment required in capital to fix packs at the cell level. This quality assessment can only be completed currently by dealers and OEMs; a fact which may inhibit the third party repurposing market.

Applications may benefit most from custom solutions made to the charge/discharge profiles of the user, with packs that have been designed and configured based on their state of health following vehicle use. Infrastructure of the specific pack can then be designed, in accordance with the codes applicable to the application and grid. Once constructed, the ESS can be integrated into the application to provide a relatively inexpensive option for storage.

Chapter 5
Repurposed Battery Pack Testing

5.1 Introduction

Two revisions of a repurposed battery pack are designed as part of this work. Both test setups are based on a 1.3 kWh battery pack from a donated *Toyota Prius*. This battery pack is made up of a NiMH chemistry, and runs at a nominal voltage of 201.6 V. The overall nominal voltage is attained by connecting 28 battery modules in series, each running at a nominal voltage of 7.2 V and made up of six NiMH cells. The battery pack used in the test bench setup is shown in Figure 44.

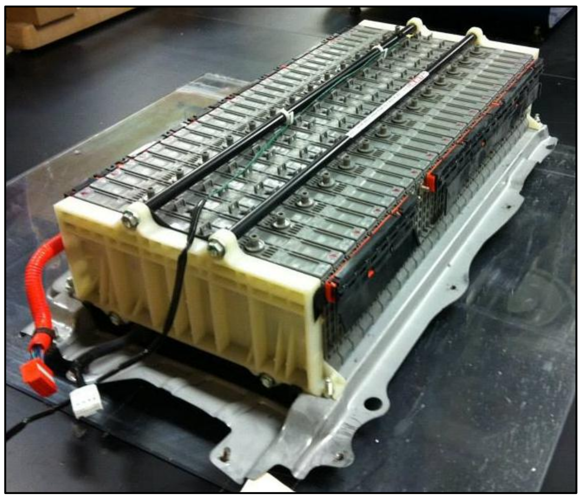

Figure 44: Test Bench Battery Pack

Revision one and two will be discussed in this chapter, which use a 28.8 V battery pack in conjunction with an AC/DC battery charger, a DC/AC inverter, and a Uninterruptable Power Supply (UPS) to simulate a load from the grid on the system. The setup is made to simulate one which would power an individual home, instead of a larger pack which may be used in a commercial application. The use of commercially available components are emphasised in the design to reduce overall costs, with much of the chosen equipment originating from the solar industry which works at nominal voltages similar to the repurposed battery setup. The revision one setup is designed and constructed with the author’s guidance by four fourth year Chemical Engineering students at the University of Waterloo for their fourth year design project: Mark

Merocchi, Alex Rak, Eric Wierdsma, and Corey Lavigne. Results of the project and the report are summarized in the following sections [66].

5.2 Design Criteria and Constraints

There are four major design criteria to be considered in the design of the test bench setup: functionality (size), safety, energy, and economics [66].

Functionality: As the repurposed pack would be used in a home, the equipment used should be of a size that is modular and could be installed in a basement or in a backyard. The equipment should show the ability to be scaled, such that components could be developed for use in the home. Additionally, they should be able to work with standard household nominal voltage (110V AC), and be reliable so that a user can depend on the pack on a daily basis to provide cost savings.

Safety: The safety of the end user should be considered in the development of the pack. As regular consumers will have the pack installed in their home, care should be taken to ensure that voltages of the pack are low to reduce any safety risk. Additionally, the pack's encasement should be designed to eliminate any potential sharp points and barricade against entry by unauthorized users to 'always energized' components.

Energy: For a residential application, the average full amount of energy used in a given day for a home in North America is 3-4 kWh [65]. A design constraint on the test setup is that the pack should be designed so that it can be charged the full 3-4 kWh capacity during off-peak times, and deliver this energy during on-peak hours. This use of the pack may allow consumers to shift the entirety of their on-peak energy use.

Economics: Costs should be minimized as much as possible to enable a shorter payback period for the end consumer. The residential pack's primary purpose is intended to be to load shift energy between off-peak periods to on-peak periods, thus reducing load on the grid. In Ontario, electricity prices are regulated based on time-of-use measures. For example, off-peak hours during the summer occur for a 12 hour period between 7 P.M. and 7 A.M. The prices and peak times for the province of Ontario is shown in Figure 45.

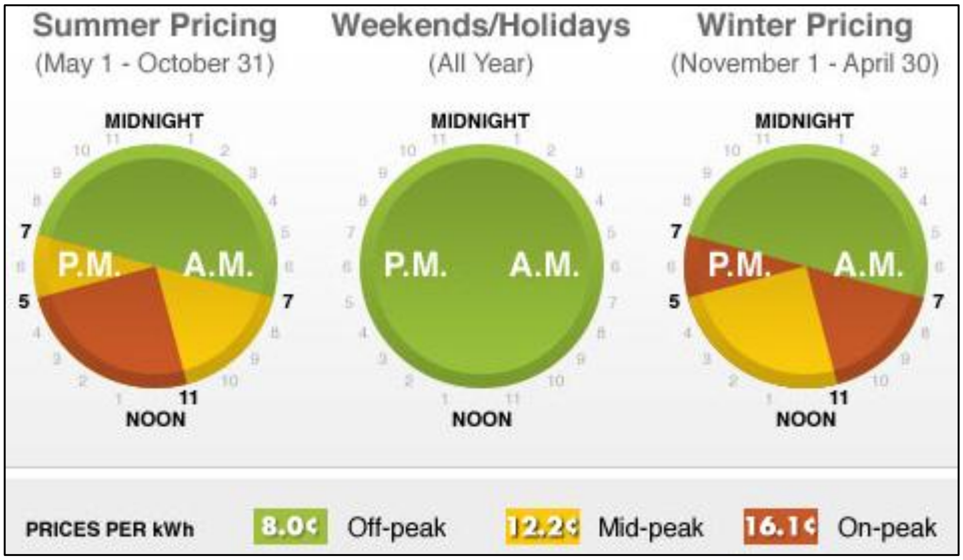

Figure 45: Time-of-use pricing in Ontario [67]

These cost savings will need to make up for the initial cost of design, construction, and installation of the setup. The battery pack will be charged over the 12 hour off-peak period, and the chosen charger should meet this requirement. Commercial components should be used as much as possible to reduce the potentially large costs of using custom components in the design.

5.3 Proposed Designs

There are three proposed designs in revision one for the test bench setup which are evaluated using the aforementioned design criteria. The first uses the entire 201.6 V, 1.3 kWh pack. In this design, three full battery packs would be connected in parallel to maintain the standard nominal voltage and increase the capacity to 3 kWh. In order to charge the full pack, the charger would need to provide 1.2 A over a period of 12 hours. Due to the high operating voltage of this design, a specialized inverter is required to convert the DC energy in the pack to AC energy for use in the grid. The *Schneider Conext RL 3000E* is selected, which can withstand input voltages ranging between 90 and 550 V DC [68]. However, this inverter will only output to 230V AC, and an additional transformer would be needed to reduce the voltage to 110 V. These two components cost $4,387. [66]

The second proposed design is based on a 64 V system. By breaking the battery modules within the pack into sections of nine, the 7.2 V (6.5 Ah) modules can be connected in series to reach a nominal operating voltage of 64.8 V. The connection of ten of these smaller packs will yield a total capacity of 3.2 kWh, enough to cover the entirety of energy used by a typical residential application. Due to the lower operating voltage, the capacity of this system is now 49.2 Ah and would require a charge current of 4 A to fully charge in 12 hours. The chosen inverter for this setup is bidirectional, allowing the charging and discharging of the energy storage system. The chosen inverter is the *Schneider Conext XW 4548 120*, and the entire setup would cost $2,350. [66]
The third proposed design is based on a 28V system, made up of four battery modules connected in series. With the small capacity of this system, 22 full battery assemblies would be required to be connected in parallel to achieve the operating energy of 3.13 kWh (with a capacity of 108.68 Ah). The connected charger in the setup would need to provide a current of 9 A to charge the pack in a 12 hour period. At the operating voltage of 28 V, the setup will be charged with an *Iota DLS-27-15* charger and discharged with a *Cotek S300-124* inverter. The total cost for the system is $925. [66]

A summary of each of the three proposed designs is shown below in Table 8.

Table 8: Revision One Proposed Design Summary

	Design One	**Design Two**	**Design Three**
Operating Voltage (V)	201.6	64.8	28.8
Parallel Units	3	10	22
Overall Capacity (Ah)	14.8	49.4	108.7
Overall Energy (kWh)	3	3.2	3.13
Charge Current (A)	1.2	4.1	9.1
Cost ($)	4,387	2,350	925

For safety, complexity, and cost purposes, design three is chosen for construction. The test bench is designed to work at low voltages of approximately 30 volts, thus limiting many electricallyassociated safety concerns. As well, the setup may not require the purchase and integration of additional transformers or the control of a bi-directional charger.

5.4 Repurposed Battery Pack Operation

The revision one setup relies on five major components for operation: the battery pack, a controller, a charger, an inverter, and a UPS. Figure 46 and Figure 47 show the test bench setup, with the proposed casing which would be integrated if the setup were to be installed in a home.

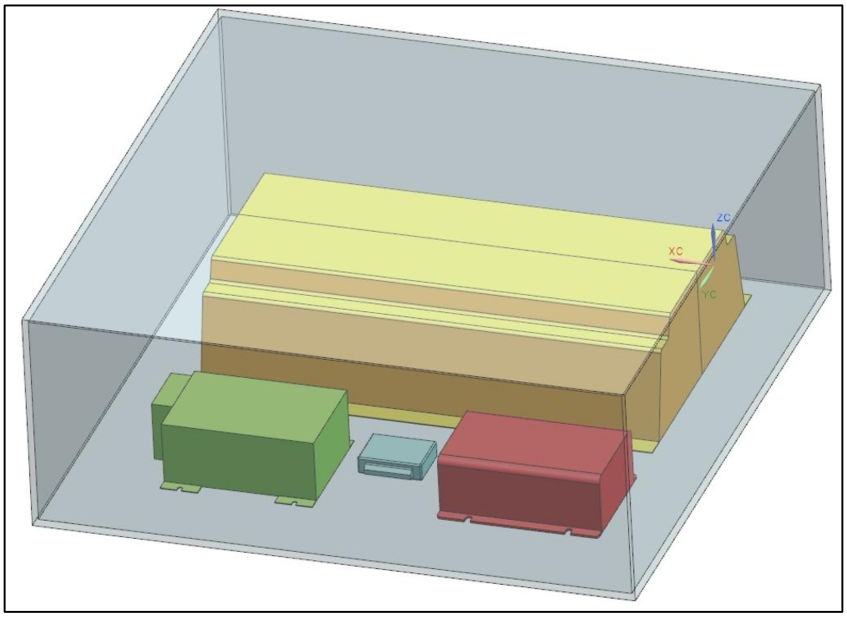

Figure 46: Bench Setup Isometric View

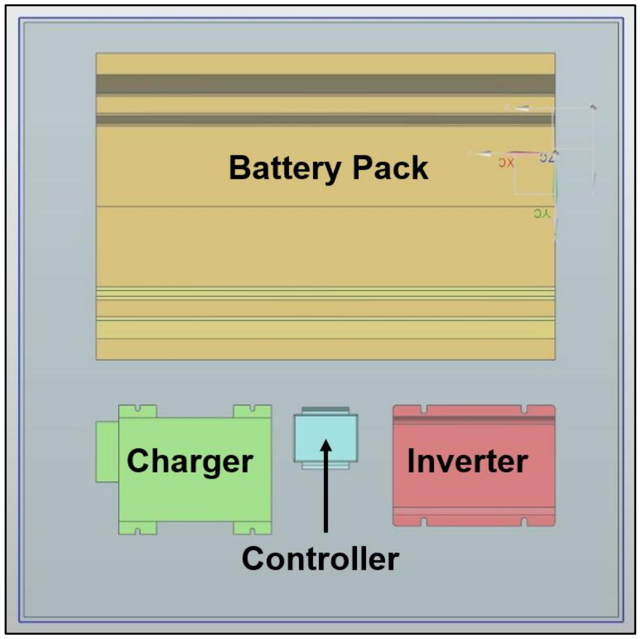

Figure 47: Bench Setup Top View

The diagram below shows the components and their electrical connections, Figure 48.

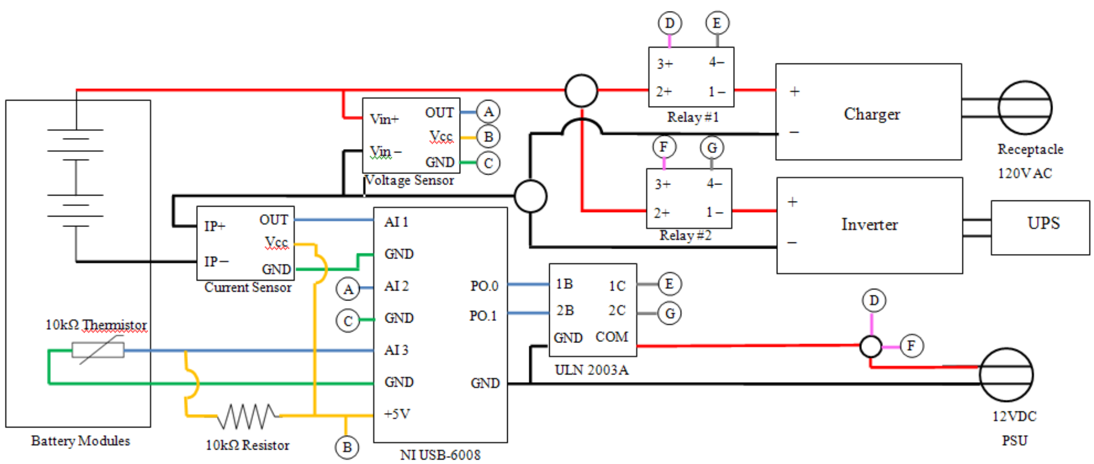

Figure 48: Revision One Setup [66]

In order to accommodate the choice of four battery modules to make up the ESS in the design, the battery needed to be dismantled in order to separate each component from the stock design. This process is documented step-by-step in order to allow future groups to use the additional stock batteries provided to the project from the sponsoring company. As stated earlier, the battery is made up of 28 battery modules which are ‘sandwiched’ together and use four lateral bars to hold them in operation. The modules each have terminals on opposing sides of the structure, and are connected using a copper bus bar which is protected from accidental short circuit through the use of a piece of custom orange conduit. Of note is that the stock battery uses passive cooling during operation, and there are small vent ports on the top of each module to allow ventilation of built up gases in the event of an emergency. The dismantling of the battery is shown below in Figure 49, Figure 50, Figure 51, and Figure 52.

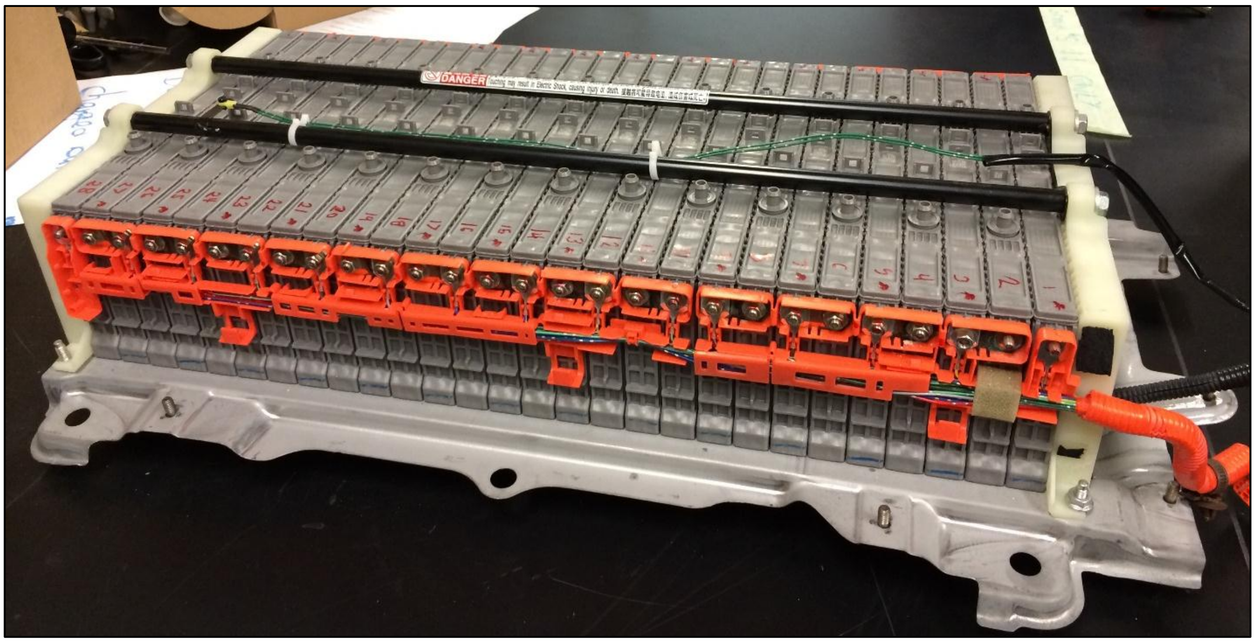

Figure 49: Pack without Case

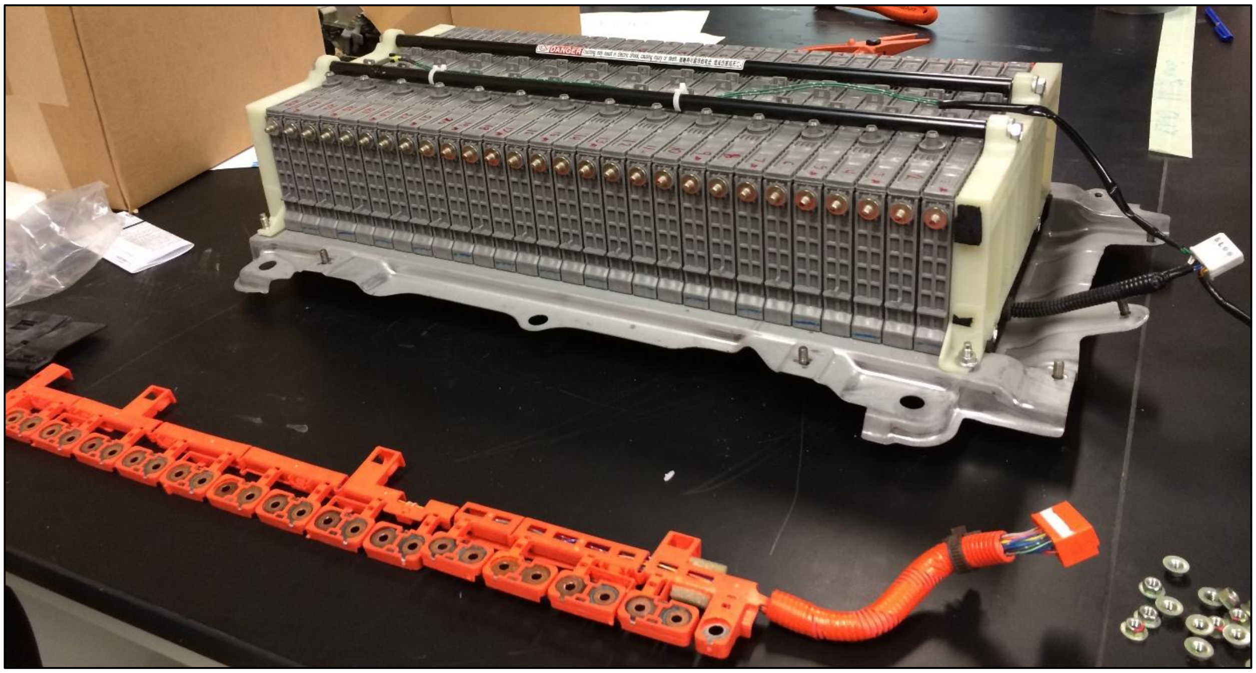

Figure 50: Pack Bus Bars Uninstalled

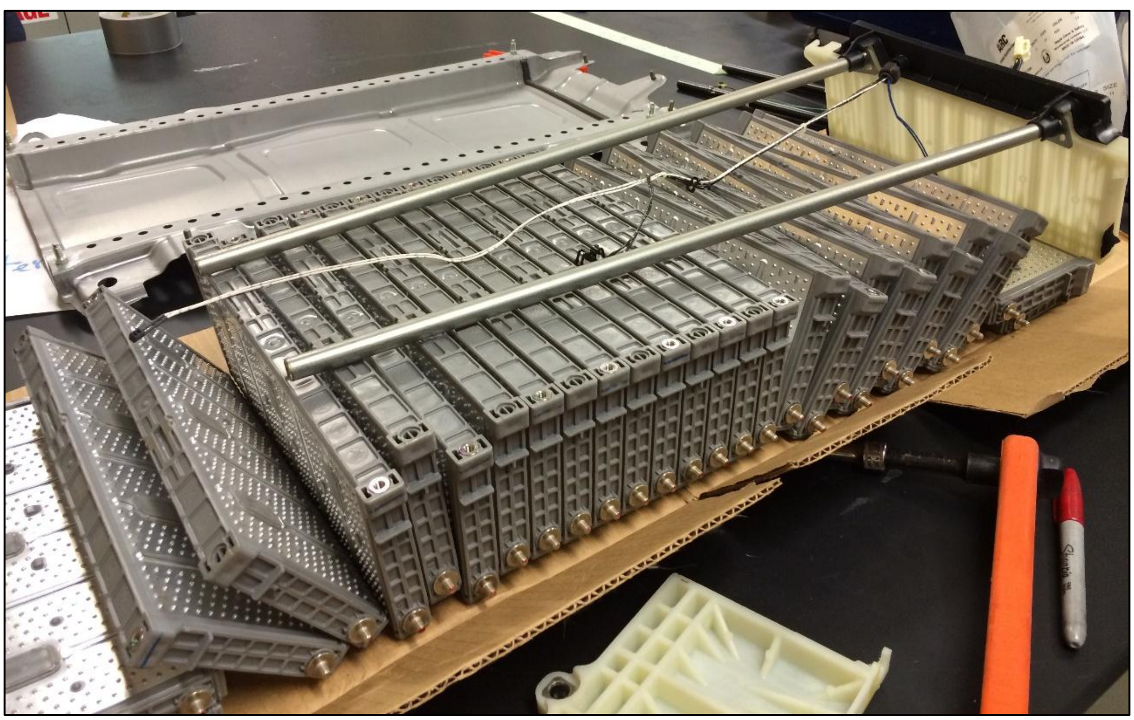

Figure 51: Retaining Bars Uninstalled

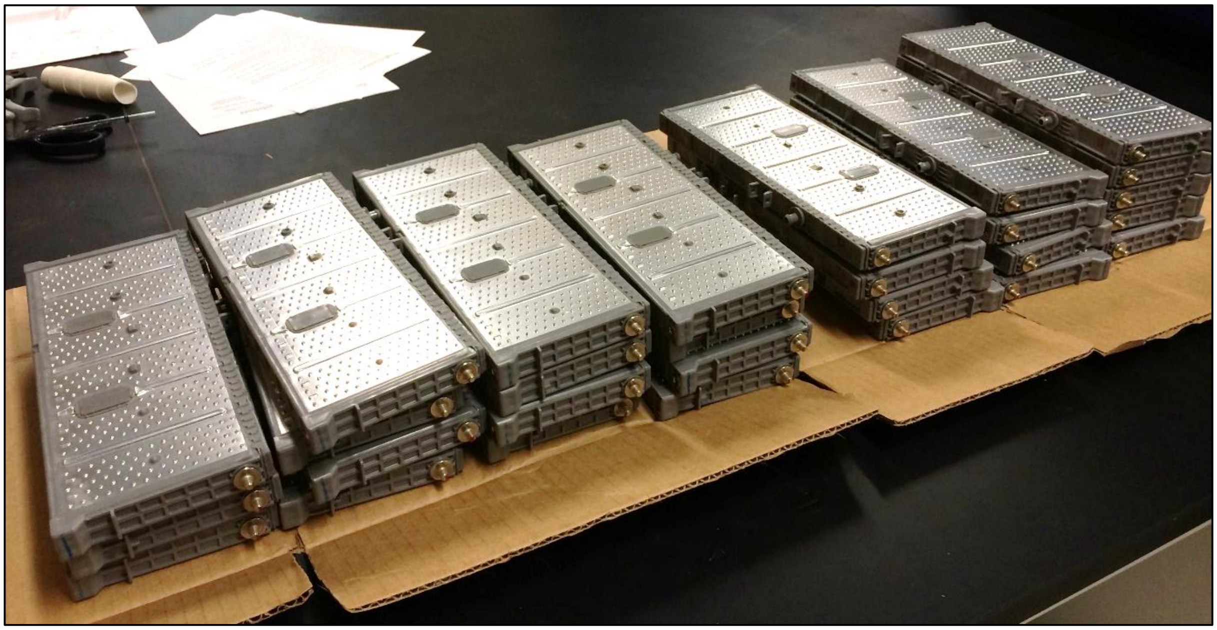

Figure 52: Disassembled Battery modules

Table 9 shows the selected inverter and charger in the setup and their design specifications. Both the inverter and charger are purchased from the solar energy market, and are designed to work at the operating voltage of 28.8 V.

Table 9: Inverter/Charger Design Specifications

	Inverter	**Charger**
Make/Model	*Cotek S-Series 28*	*Iota DLS-27-15*
Power (W)	300	400
Cost ($)	311	164
Efficiency (%)	85	85

One drawback of the selected charger is its inability to be directly controlled during operation. The inverter has a controller input which can turn it on/off during operation remotely by the chosen controller. The charger lacks a controller input pin, and other measures are required in order to control its operation. In order to control the charger, a *PowerSwitch Tail* is purchased which interfaces between the charger and the wall. The tail is able to be activated on/off using a 5V output on the controller, eliminating the need for manual charging of the setup.

A controller is needed in order for the test bench to charge and discharge given the time of day to offset peak power use. In order to safely control the pack, three measured variables are needed: voltage, current, and temperature. The controller will need to monitor the battery's SOC in order to determine how much current should be discharged/charged at a time. The SOC may need to be kept in a nominal operating range, to ensure that the battery will not be degraded from over charging/discharging which could affect its lifetime and its SOH. Additionally, large amounts of overcharging could result in a fire or catastrophic failure of the pack.

The controller will monitor the SOC and stop charging once the pack has reached its full SOC, with the opposite operation occurring when discharging. Three controller options are identified for use in the system: a *Mototron* 24 pin General Control Module, a *National Instruments USB-6008* controller, and a *National Instruments PCIe-6321* controller. The controller should have three analog inputs, one analog output, and two digital outputs to be compatible with the setup. All three controllers are compared based on their functionality, cost, and compatibility with the system. The *National Instruments USB-6008* controller is selected due to its intuitive controls software which the project group is familiar with using. [66]

In order to interface the controller with the pack to monitor operation, the *Phidget 1135* voltage sensor, *Allegro ACS-712-10B* current sensor, and a thermistor are selected. The voltage and current sensors are able to be connected to one of the 12 analog inputs on the controller, and the controller is able to provide enough power to drive them. The thermistors are attached to the tops of the modules in order to monitor any heat generated during cycling. [66]

For the cycling of the battery, two Solid State Relays (SSRs) are used to allow current to flow to either the charger or the inverter. The controller is not able to provide enough power to drive the relays alone, and interfaces with a *ULN2003A* relay driver and an external 12 V power supply in order to drive the selected *Phidget 3951* DC SSRs. [66]

5.5 Operation and Results

The team was able to charge the constructed 28.8 V pack using the charger and a wall plug independently of using the controller. Once the pack was charged, the charger was manually disconnected, and the system was connected to the inverter and UPS as a load. Once connected, the small pack was able to charge the UPS and deliver energy. This manual process was repeated to prove the ability of the setup to function correctly.

During cycling, control code was written in order to be able to integrate the *National Instruments* controller into the setup. Unfortunately, the accidental reversal of polarity on one installation of the inverter in the test bench setup damaged the *Cota* inverter to the point that it could not properly function. This damage caused the setup to be nonoperational for the remainder of the project, inhibiting the testing of the bench with the controller and all components fully functioning. It is anticipated that if the inverter were to still be functioning, that the setup would have proven fully functional with the documented control code written during the project.

5.6 Lessons Learned

Some positive lessons learned from the first test bench setup included the fact that charging and discharging was implemented manually using the chosen charger and inverter. The use of the four battery modules to create a small ESS allowed the team to reduce any safety considerations with using a high voltage pack, and commercial off-the-shelf components were integrated reducing cost of the setup. The pack was safely disassembled through the use of basic HV tools and the *Toyota* maintenance manual for the car.

For future installations, diodes should be installed on expensive components to ensure that damage does not occur. As well, proper fusing should be integrated into the circuits to protect against a short circuit or current spike which could damage sensitive components.

5.7 Revision Two Background

In order to build on the knowledge gained through revision one of the repurposed battery pack design, a second test bench is designed in order to understand how to design around the lessons learned from the previous setup. Revision two focuses on the use of a new bi-directional charger/inverter, the *Conext XW+*, which is made available through the University of Waterloo's new partnership with *Schneider Electric*. This charger/inverter is capable of working with the grid, and tying in additional energy sources/storage devices including photovoltaic panels and Lead-acid or Li-ion batteries. It can additionally be tied in with other *Conext XW+* systems, in order to scale the operation from one model, capable of providing from 5.5 kW - 102 kW with multiple systems attached [69].

This revision two setup is designed and constructed with the author's guidance by four fourth year Mechatronics Engineering students at the University of Waterloo for their ME 599: Hybrid Vehicle Design independent project: Jaesik Kim, Jae Seung Kweon, and Mingu Kwon. Results of the project and the report are summarized in the following sections [70].

5.8 Design

Revision two built off of the components and design from revision one. The setup is a 28.8 V test bench, using the four module configuration. Changes to the revision two setup include the use of an *Ardiuno Uno* board to control the system instead of the *NI* controller due to familiarity of the group members with the product, a real-time clock to sync the system with the charge profile, a bi-directional charger/inverter from *Schneider Electric* (replacing the *Cotek* inverter and *Iota* charger), and a new voltage sensor which interfaces with the newly chosen controller. [70]

The *Arduino Uno* controller is selected for revision two as the controller allows for development of code using C/C++, a language more familiar to the group than the *LabVIEW* software required for the *NI USB-6008* used in revision one. Both controllers are deemed sufficient to power the setup given the number of inputs/outputs available on each controller, but development time was short thus making the selection of the familiar controller. The real-time clock is used with the controller, as the *Arduino* does not have a stock method of keeping track of time as it progresses. The real-time clock is chosen over the use of an Ethernet or WIFI shield due to cost constraints and, once set, will track the time in order to switch the battery pack on/off in accordance with time-of-use electricity prices. The overall setup of revision two of the test bench is seen in Figure 53. [70]

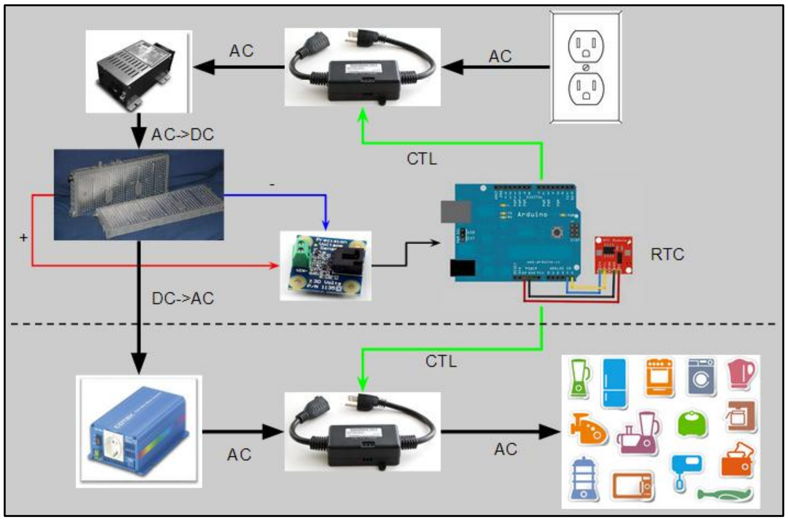

Figure 53: Revision Two Setup [70]

5.9 Operation and Results

Revision two was never fully tested before the writing of this report. Due to the complexity of the bi-directional charger/inverter, the team was not able to integrate it fully during the time constraints of the project. However, simulations of the newly written control code show that the new setup with the *Arduino* controller would be able to integrate with the fully completed setup. It is anticipated that with the results of developments with the battery pack in revision one and the controller selection in revision two that a fully functioning test bench could be made easily over the coming terms.

5.10 Chapter Summary

Through this chapter, two setups of a repurposed battery pack test bench are designed. Revision one focuses on the use of off-the-shelf commercial components, which are relatively inexpensive to incorporate into the setup. The *Toyota Prius* battery pack is dismantled into its 28 battery modules, of which four are connected to create a small pack which operates at 28.8 V. This low voltage decreases safety concerns with the setup, and allows the team to use components from the solar energy industry to connect the pack to the grid. The manual charging/discharging process using the chosen *Cotek* inverter and *Iota* charger is able to charge the pack, and provide energy to the UPS load. Unfortunately, the accidental reversal of polarity on the inverter irreversibly damaged it.

Revision two focuses on the use of the small 28.8 V pack as well, only with the addition of a donated *Schneider-Electric* bi-directional charger/inverter. The setup uses an *Arduino Uno* as a controller, due to the team's familiarity with the controller in the time constrained project. Unfortunately, the team did not manage to have the system fully functioning, as the bi-directional charger/inverter's control mechanism is complex.

Chapter 6
Conclusions and Recommendations

6.1 Conclusions

The objective of this thesis is to outline battery pack design for a vehicle application while taking into account considerations for repurposing in a stationary application, and to suggest setups and lessons learned from the construction of a repurposed pack bench test setup. The conclusions illustrate the advances made in each section of the work, with recommendations following on how the work can be further advanced in the future.

Mechanical design optimization techniques show advantages in designing complex systems and can be implemented in the design of the repurposed energy storage system casement. The battery pack designed by UWAFT for the EcoCAR 3 competition is based on a topology optimization performed in *Altair Hyperworks* which shows load paths in the assembly prior to mechanical design. These load paths allow the designer to have a starting point to create members in the final assembly prior to finite element analysis. This process, in turn, allows for a weight-efficient design which reduces the assembly's final mass. With this complex design integrating the battery into a vehicle being completed, the task of creating an assembly for the simpler repurposed pack for a residential application is within reach.

A design process for a repurposed battery pack is proposed, displaying the current research in design methods and steps. The design process takes into account business aspects including market analysis of in-vehicle batteries which are suitable for repurposing, state of health models which take into account degradation, and applicable risks/codes which may affect the end assembly design.

Repurposed battery packs are currently prohibited from mass market penetration, due to associated risks, an uncertain supply chain, and a lack of regulation. The incorporation of this new technology into the grid is currently not regulated, with applicable codes coming in the next six years. There are additionally many concerns on the state and number of batteries which may be uninstalled from the vehicles and used for repurposing.

Repurposed battery pack codes are still in development, with Li-ion technology being newly introduced in the market. Lead-acid stationary storage legislature shows some proxies which can be used for Li-ion technology, however Li-ion technology has its own issues which may need to be addressed in new codes. One of the biggest risks of the use of Li-ion batteries is due to thermal runaway. In addition, the use of repurposed batteries for stationary applications may present a technical and regulatory hurdle.

A repurposed battery pack test bench setup has been created. This test bench setup is completed in two revisions, using different setups and charger/inverter combinations. The first setup displays the ability for the small pack, made out of a repurposed vehicle battery, to allow for manual charging/discharging to take place. The second setup works to build on this setup with the incorporation of a bi-directional charger/inverter from the solar energy industry.

6.2 Recommendations

As mentioned in Subsection 6.1, the objective of this thesis is to present the design of a vehicle battery pack with considerations for repurposing, as well as the design and lessons learned from the design/construction of a repurposed pack bench test setup. The following recommendations outline areas of focus for future work in the development of UWAFT's *Chevrolet Camaro* battery pack and a repurposed pack assembly which could be installed in industry.

New designs of the battery pack's structural frame and mounting plate should be tested, to verify strength of the geometry based on the given loading conditions. The completed optimization does not suggest exact geometry, material, or structure details, and these may need to be decided through iterations in finite element analysis and re-design. However, the structure is close to passing the given loading conditions while minimizing the overall assembly weight.

More research into the market of repurposed packs is needed. Currently, there is a large uncertainty as to the timeline for the packs coming out of service, the supply chain in order to purchase the batteries, and how vehicles may continue once the pack reaches its loss of 20% of its original capacity. Market research as the vehicles mature may provide new insight into how designers can incorporate this technology into new repurposed assemblies. With the development of a market for stationary energy storage by major automakers, proxies to the potential repurposed market may be made.

As Li-ion powered electric and hybrid vehicles begin to end service, degradation studies should be completed to verify estimates in state of health at the end of vehicle life. Current degradation estimates are largely based on the cycling of half cells in a laboratory setting, to low cycling numbers to quantify the effects of temperature, depth of discharge, or cycling rate. Studies on full pack-scale degradation on highly cycled packs should provide insight into how these packs are degrading in a vehicle and help with the assessment of packs as they are introduced in repurposed applications. The acquisition of fleet data with respect to battery performance may be needed to further this objective.

A new repurposed pack setup should be created, using the bi-directional charger/inverter and the lessons learned from revision one and revision two. The bi-directional charger/inverter is optimized for the bench test setup, and its incorporation was inhibited due to time constraints. The charger can also be scaled to larger setups, such as in a residential setting which could be used in a full scale application.

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Appendix A

Design Failure Modes and Effects Analysis

Item/Function of Part	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	DET	RPN
The charger/inverter shall convert power to charge the battery pack	Overheating	Personnel injury - Burns (10) Damage to electrical wire connections to/from charger (8) Loss of charge capability (8) Degradation of charge capability (7) Damage to charger internal electrical connections (7)	10	Loss of control input (2) Power surge (3)	3	6	180
The charger/inverter shall convert power to charge the battery pack	Short Circuit	Blown fuse (8) Damage to charger internals (7)	8	Power surge (3)	3	3	72
The charger/inverter shall convert power to charge the battery pack	Disconnect	Loss of charge capability (8) Degradation of charge capability (7) Damage to charger internals (7) Personnel injury - Shock, burns (10)	10	Wire degradation (2) Physical disconnection (2)	2	1	20
The charger/inverter shall convert power to charge the battery pack	Disconnect	Personnel Injury - Shock, burns (10) Loss of charge capability (8) Damage to charger internals (7)	10	Wire degradation (2) Physical disconnection (2)	2	1	20

Item/Function of Part	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	DET	RPN
The charger shall convert power to charge the battery pack	Degradation	Loss of charge capability (8) Degradation of charge capability (7)	8	Incorrect control input (3) Physical damage (3)	3	4	96
The charger shall convert power to charge the battery pack	Ground Fault	Personnel Injury - Shock, burns (10) Loss of charge capability (8) Damage to charger internals (7)	10	Wire degradation (2) Physical disconnection (2) Power surge (3)	3	3	90
The charger shall convert power to charge the battery pack	Faulty	Loss of charge capability (8) Degradation of charge capability (7) Damage to charger internals (7)	8	Loss of control input (2) Power surge (3) Wire degradation (2) Physical disconnection (2) Incorrect control input (3) Physical damage (3)	3	2	48
The battery pack shall store and deliver energy	Overheating	Damage to module cells (7) Loss of charge capability (8) Degradation of charge capability (7) Thermal Runaway (10)	10	Charger/inverter not a peak operation (3) Loss of control input (3) Wire degradation (2)	3	6	180

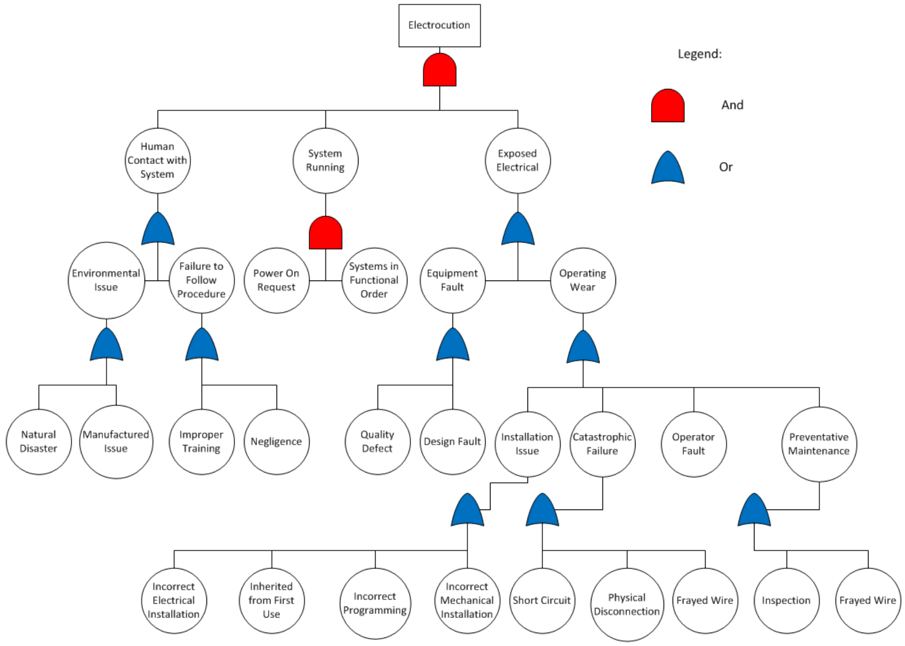
Item/Function of Part	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	DET	RPN
The battery pack shall store and deliver energy	Short Circuit	Damage to module cells (7) Loss of charge capability (8) Degradation of charge capability (7) Personnel injury - Shock, burns (10)	10	Physical damage (3)	3	3	90
The battery pack shall store and deliver energy	Corrosion	Loss of charge capability (8) Degradation of charge capability (7) Electric arc on terminal (4) Personnel injury - Shock, burns (10)	10	Physical damage to case (3)	3	3	90
The battery pack shall store and deliver energy	Over	Loss of cycling ability (8) Degradation of cycling ability (7) Module overheating (7)	8	Incorrect control input (3) Physical damage (3)	3	6	144
The battery pack shall store and deliver energy	Degradation	Loss of charge capability (8) Degradation of charge capability (7)	8	Age (3)	3	3	72
The battery pack shall store and deliver energy	Damage	Thermal runaway (10) Damage to module cells (7) Personnel injury - Shock, burns (10)	10	Physical damage (3)	3	1	30
The controller shall direct pack components	Power Loss	Module overcharge/discharge (7) Loss of charge capability (8) Component overheating (7) Component short circuit (8)	8	Wire degradation (2) Physical disconnection (2) Power surge (3)	3	1	24
The controller shall direct pack components	Programming	Module overcharge/discharge (7) Loss of charge capability (8) Component overheating (7) Component short circuit (8)	8	Human error (3)	3	6	144

Item/Function of Part	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	DET	RPN
The controller shall direct pack components	Input Loss	Module overcharge/discharge (7) Loss of charge capability (8) Component overheating (7) Component short circuit (8)	8	Wire degradation (2) Physical disconnection (2) Power surge (3)	3	6	144
The controller shall direct pack components	Output Loss	Module overcharge/discharge (7) Loss of charge capability (8) Component overheating (7) Component short circuit (8)	8	Wire degradation (2) Physical disconnection (2) Power surge (3)	3	6	144
The controller shall direct pack components	Overheating	Personnel injury - Burns (10) Damage to electrical electrical connections to/from controller (8) Loss of charge capability (8) Degradation of charge capability (7)	10	Incorrect control input (3) Physical damage (3) Power surge (3)	3	6	180
The controller shall direct pack components	Short Circuit	Blown fuse (8) Damage to controller internals (7)	8	Power surge (3)	3	3	72
The controller shall direct pack components	Damage	Thermal runaway (10) Personnel injury - Shock, burns (10)	10	Physical damage (3)	3	1	30
The battery pack casing shall protect personnel from electrical components	Damage	Personnel injury - Shock, burns (10) Damage to component internals (7) Loss of charge capability (8)	10	Corrosion (3) Physical damage (3)	3	6	180

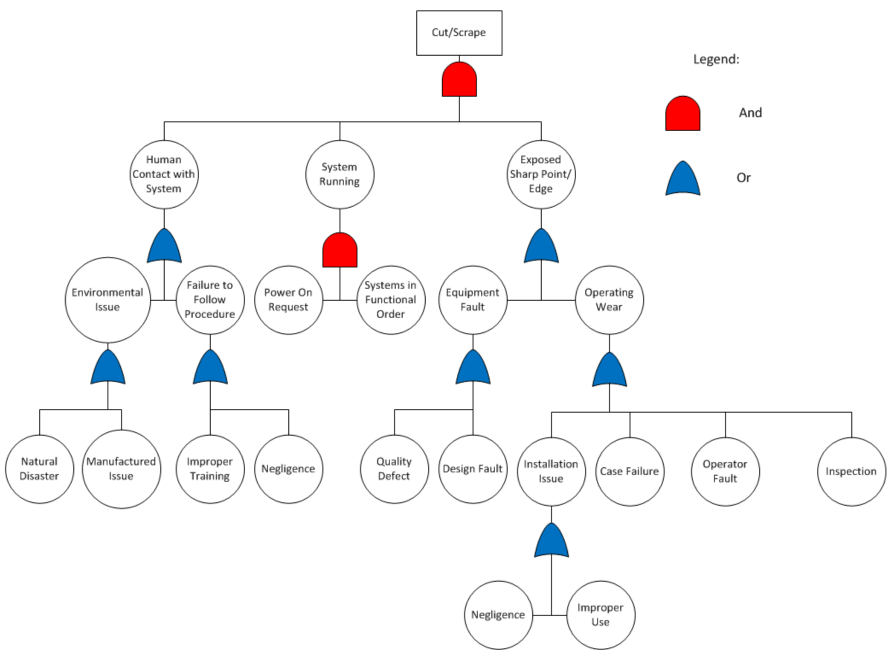
Item/Function of Part	Potential Failure Mode	Potential Effect(s) of Failure	SEV	Potential Cause(s) of Failure	OCC	DET	RPN
The battery pack casing shall protect personnel from electrical components	Degradation	Personnel injury - Shock, burns (10) Damage to component internals (7) Degradation of charge capability (7)	10	Corrosion (3) Physical damage (3)	3	2	60

Appendix B

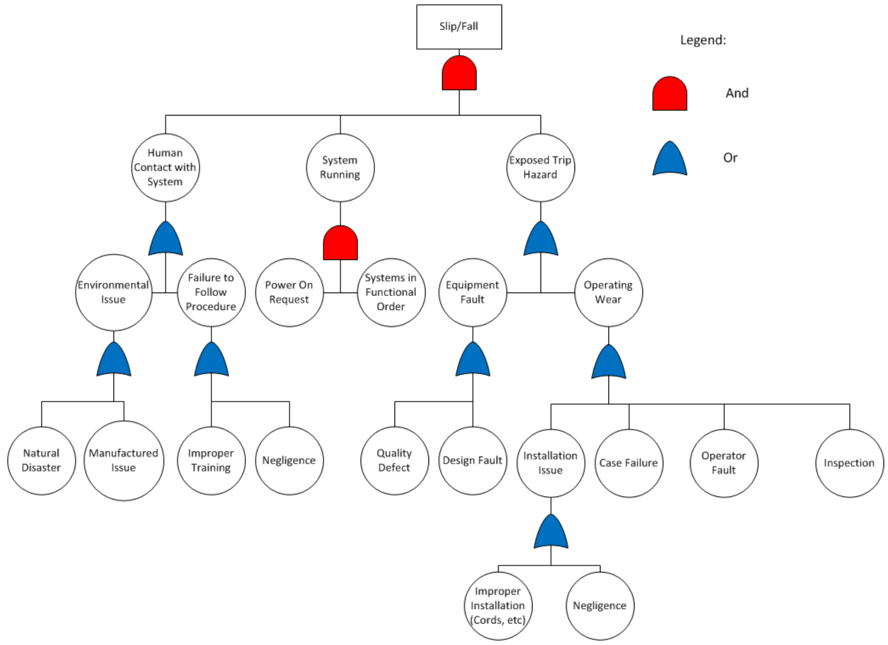
Fault Tree Analysis



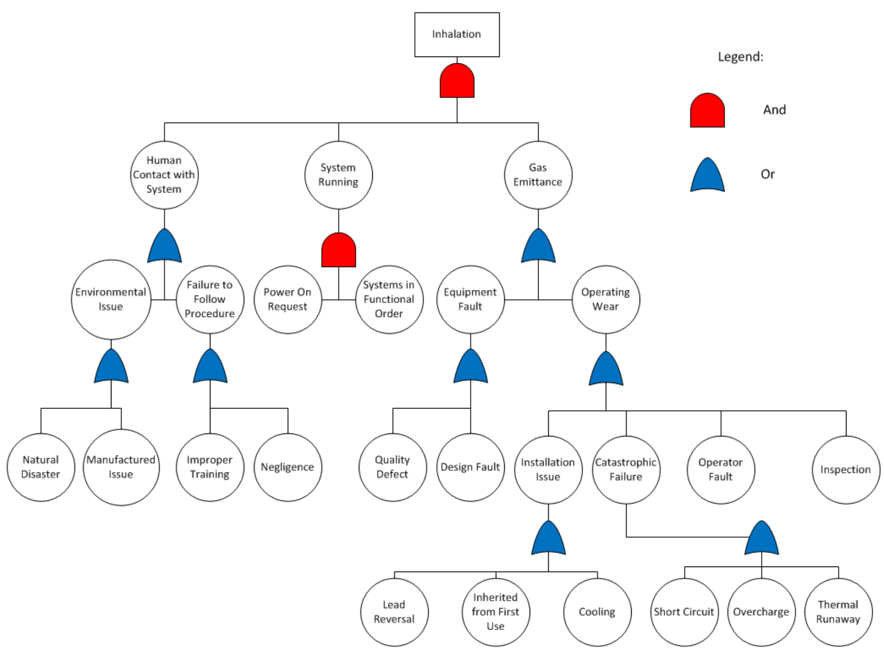
Electrocution Fault Tree Analysis



Cut/Scrape Fault Tree Analysis



Slip/Fall Fault Tree Analysis



Inhalation Fault Tree Analysis