University of Southern Queensland

Faculty of Health, Engineering and Sciences

Feasibility of using Thermoelectric Generators to Improve Fuel Efficiency in Existing In-service Vehicles

Dissertation submitted by

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Abstract

Climate change is defined as the “long-term shifts in temperatures and weather patterns” (United Nations 2020). While climate change occurs naturally, this process has been significantly accelerated by human activities since the 1800s. This acceleration is largely due to the consumption of fossil fuels such as coal, oil and gas resulting in Greenhouse Gas (GHG) emissions. Globally, Australia is one of the largest contributors of GHG emissions per capita, largely due to the relatively low population density of Australia when compared to other countries.

Within Australia, the transport sector is responsible for 17.6% of total emissions with road transport making up 85% of that value. In an effort to reduce these emissions, manufacturers are required to meet higher fuel efficiency standards for all new vehicles. Unfortunately, this also means that once a vehicle is purchased by a consumer it no longer receives improvements to its fuel economy. With over 20 million vehicles concurrently registered (with this number increasing each year), the existing fleet represents a significant opportunity to reduce emissions.

This aims and objectives of this project is to identify the feasibility of using thermoelectric generators to improve fuel efficiency in existing in-service vehicles. According to the Seebeck Effect, thermoelectric generators produce a voltage differential when subjected to a temperature gradient. The main working principle behind this method of improving fuel economy is to convert a portion of the waste heat energy to electricity, then to use this electricity to supplement the vehicles electrical system. This reduces the demand on the alternator which is mechanically powered from the crankshaft, thus reducing the parasitic losses on the engine. This ultimately improves fuel economy. The main condition that such a device would need to satisfy is a cost to performance metric where the reduction in running costs is enough to offset the original investment cost within a few years.

While there have been previous attempts at utilising thermoelectric generators for this purpose, these attempts have not yet been deemed viable due to the focus on new vehicles where the electrical demand is much higher. Older vehicles often feature far less electronics with a subsequent lower electrical demand.

Research was performed in regards to the various strategies to implement TEGs while obtaining preliminary data from the test vehicle. Findings from the research and parameters from the vehicle were then used to determine a suitable TEG module that displayed the highest return per cost. Once a module was selected, a unit was designed and constructed that was largely dependent on the physically available space. The theoretical maximum output for this unit was 48 watts.

Results from testing were initially lower than expected, producing 7 watts at 3500 RPM (100 km/h) however, after analysis multiple factors were identified that contributed to these results. The two main factors responsible for this was the utilisation of static testing vs dynamic testing and underperforming TEG modules. Without expensive equipment, a static testing method was unable to adequately load the engine leading to significantly less heat output. Spare modules were later tested under known conditions and were found to be under preforming when compared to their specification datasheet. Analysing the results while accounting for this reduced performance found the module array to be 88.5% efficient with the losses attributed to minor temperature deviations between the modules and resistances in the wiring connectors.

Calculating the impact on fuel consumption while making various assumptions yielded a fuel economy improvement of 0.16% or an average saving of 1.57 L per year. If the unit were to be producing its maximum output, then these values became 1.10% and 10.82 L respectively. These values of improvement were calculated while assuming no additional weight was added to the vehicle when installing the unit. In practice the unit added 7.3 kg when replacing the original exhaust section. Re-calculating the impact on fuel economy when accounting for this change in mass yielded a 0.11 % increase in consumption or an additional 1.06 L consumed per year at 7 watts of output while, at maximum output these values became a reduction of 0.83 % or a reduction of 8.19 L per year.

If this were to be implemented on a large scale in Australia alone, there is the potential to reduce the yearly consumption by 10.82 million L with a 5% adoption rate assuming each unit achieves its maximum output. With unleaded fuel valued at approximately $2.00 per L, this represents a potential cost saving of $21,640,000 AUD per year. A cost breakdown of the device revealed the supporting components such as thermal paste, wiring, insulation etc, attributed to 42.32 % of the total cost far outweighing the modules or heatsink at 18.08 % and 26.02 % respectively (main body was 13.56%). With the total cost of the unit at $411.33, even at maximum output, it would require approximately 25 years before the savings would outweigh the original investment cost making this device unfeasible.

Given the poor performance to weight ratio as well as the poor performance to cost ratio of a completed thermoelectric generator device, this strategy of improving fuel economy is not feasible with the current level of thermoelectric generator modules.

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I further certify that the work provided is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Signed: Myles O'Keeffe

Date: 13/10/2022

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Glossary of Terms

Abbreviation	**Definition**
ICE	Internal Combustion Engine
TEG	Thermoelectric Generator
TEC	Thermoelectric Cooler
DIY	Do it Yourself
EV	Electric Vehicle
VSS	Vehicle Speed Sensor
RPM	Revolution per Minute
GHG	Greenhouse Gases
CVT	Continuously Variable Transmission
OEM	Original Equipment Manufacture
F1	Formula One
ERS	Energy Recovery System
AC	Alternating Current
DC	Direct Current
AUD	Australian Dollar

Chapter 1: Introduction

1.1 Preliminary Statement

This chapter will briefly introduce and identify the importance of reducing greenhouse gasses, the transport sectors' contribution towards this, the current mitigation strategies and the potential for further reductions.

1.2 Project Background

1.2.1 Worldwide Emissions

While Abram et al. (2016) was able to identify the first evidence of human influenced climate change starting in the 1830's during the Industrial era. Brulle (2018) reported that climate change was only officially addressed many years later in 1988 as a national issue. Since then, there have been countless studies that have supported the link between global warming and the excess Greenhouse Gases (GHG) produced by human activities, primarily the burning of fossil fuels.

Due to the irrefutable link between climate change and excess GHG emissions, 196 countries have adopted the Paris agreement in 2015 with 186 of those countries committing to reducing their emissions (UNFCCC 2021).

1.2.2 Australian Emissions

Of these 186 countries, Australia is currently one of the largest contributors of GHG per capita. As such Australia has vowed to reduce its GHG emissions by 26-28% by 2030 (based on 2005 levels of output).

The largest contributor to this statistic is the Energy refinement sector (burning fossil fuels to create electricity etc) at 33.6%. The second highest being the Stationary energy sector (burning fossil fuels for energy in non-transport applications) at 20.4%, closely followed by the Transport sector at 17.6% (Stanley et al. 2018). This report will be focusing on the Transport sector in particular.

Within the transport sector, road transport accounts for 84% of these emissions, while emissions from new vehicles have been steadily dropping in accordance with the current requirements set by the government. The overall emissions of this sector have been rising due to the average distance travelled per capita increasing at a rate that outpaces the former (Stanley et al. 2018). It can be argued that this phenomenon is exacerbated by the unique challenges associated with the local landscape, in particular Australia's relatively low population density. This results in the average distance travelled becoming much larger, these extended distances are not well suited for highly efficient public transport alternatives.

1.2.3 Current Strategies

Beginning in 1970 with the Clean Air Act (EPA 2022), vehicle manufactures were faced with enforced restrictions on new vehicle emissions. These ever-increasing restrictions have prompted manufactures to constantly innovate, develop and execute multitube strategies and techniques to produce increasingly more efficient designs. There are two main approaches to reducing the pollution produced by ICE. The first is post process the exhaust fumes from the ICE and the second is to improve the efficiency of the ICE in general so that less pollution is produced for a given amount of work. As research and development on ICE efficiency began to stagnate, manufactures began looking to other elements of their vehicles that could be optimised for better fuel economy.

Just a few of these modern strategies include: Direct Injection, Aerodynamics, Turbochargers, Variable valve timing, Cylinder deactivation, transmissions with more gears, CVT transmissions, Catalytic converters, Stop start technology, the reduction of overall weight (increased use of composites) and replacing mechanical subsystems with smarter electric versions to name a few. While it can be argued that some of these efforts have been in order to increase their products desirability to the end user, as low ongoing running costs is often used as a feature/benchmark to compare vehicles from different manufactures. This marketing objective is secondary to the task of passing regulations on order for the vehicle to be sold.

1.2.4 Electric Vehicles

An emerging alternative to ICE vehicles is electric vehicles, which are responsible for 50-70% less emissions per instance over the life of the vehicle (Stanley et al. 2018). Fortunately, EV sales are on the rise with the number of new EVs purchased in 2021 more than doubling that of 2020 however, their market share on new vehicles purchased is still only 2% (EVC 2022). This coupled with their relatively recent introduction results in EV’s only contributing to 0.2% of the fleet of the vehicles on the road today. There are a few reasons for this slower adoption rate with one of the most significant being the lack of supporting infrastructure.

As of May 2022, there are 2531 standard charging points and 470 superchargers opposed to approximately 7000 traditional service stations (Swart 2022). This statistic is improving with new charging stations opening at a steady pace however it will be some time before the level of support is on par with ICE vehicles. This is excluding that charging a drained EV can take up to 30 minutes on a supercharger and multiple hours on a standard charger. Naturally, charging times are also dependant on battery size.

1.2.5 Existing Vehicles

After taking EVs into account, there are currently north of 20 million ICE vehicles registered in Australia with this number growing steadily. Once purchased, these vehicles generally receive no further support or improvements to fuel economy from their manufacturer. Furthermore, without significant cost, time and effort there are very few ‘trusted and proven’ aftermarket products commercially available aside from modern eco tyres. Advancements in materials and construction has led to the development of economy focused tyres that feature less rolling resistance than what was fitted on the vehicle at the time of sale. This existing fleet represents a significant opportunity to reduce emissions from the transport sector if a viable product can be developed.

1.2.6 Opportunity for Emission Reduction

When observing the conversion of energy from potential chemical energy to mechanical energy in an ICE, over 60% is lost in the form of heat (Yu, Wang & Zhou 2019). It is no surprise that larger manufactures have already begun development into recycling this excess heat in the form of electricity through the use of thermoelectric generators. However, previous efforts have specifically focused on new vehicle applications that require a large amounts of power generation to offset the load placed on the alternator. It remains to be seen if the current TEGs available would already be sufficient in increasing the fuel economy of the existing fleet for a reasonable cost.

1.3 Project Context

1.3.1 Project Motivation

This capstone project was a student-suggested topic. This topic aligns with the interests of the student alongside the belief that the existing fleet of vehicles on the road today represents a large untapped area for improvements by retrofitting modern methods and components. In this project these improvements manifest as an increase to fuel economy.

1.3.2 Aims & Objectives

This project evaluates the development of energy recovery methods in vehicles, particularly the recycling of waste heat generated from the combustion cycle. This project aims to verify if the current level of technology can be successfully applied to the existing fleet. The intent is to increase fuel economy and subsequently reduce carbon emissions overall.

The individual objectives of this project are:

- The proposed device would be primarily aimed at the end consumer/owner of the vehicle as a potential aftermarket modification that will reduce the running costs for the intended vehicle. As such the device must not be cost prohibitive and should see returns on the initial investment after a reasonable period of time.
- To achieve the widest possible market, the device must be designed to be relatively universal with respect to its fitment, heat source and incorporation into the vehicles electrical system. While a universal design limits the individual potential performance obtainable, it significantly reduces the cost by eliminating the R&D that would be required to develop vehicle specific kits along with reduced manufacturing costs.
- The proposed device is intended to be used and potentially installed by the general population. As such there must be a reasonable level of safety and failsafe included in the design to ensure both the safety of the user and the reliability of the vehicle.
- The installation of the device should be reversible with relatively little effort required. This would aid marketability of the device as it relieves potential anxiety (for the owner) associated with making a permanent modification to the vehicle.

If successful the techniques and theory discussed may be applied to engines in other applications providing, they are of a sufficient size and produce enough heat flow.

1.3.3 Project Overview

Chapter 1 introduces a brief background on climate change and its contributors. It discusses the ongoing issue of the existing fleet as well as the opportunities for improvement.

Chapter 2 provides a literature review on the various aspects surrounding this project and how these aspects interact with one another. Notably the electrical system of the average vehicle, characteristics of an alternator and an overview of thermoelectric generators.

Chapter 3 outlines the methodology undertaken to complete this project, the elected strategies alongside the alternatives and the associated justification.

Chapter 4 showcases the resulting data from the static driving tests and provides an analysis on these results to form calculated estimations on the projects feasibility.

Chapter 5 contains a concise summary of the findings as well as recommendations for future research.

1.4 Project Consequential Effects & Ethical Responsibilities

1.4.1 Consequential Effects

If successful, this project could eventually lead to the reduction of fossil fuel consumption not only locally but worldwide, less fossil fuel consumption supports environmental health and by extension human and wildlife health. Even if successful, this project will not solve the global issue of burning fossil fuels for transport. Despite this fact, it is wise to seek improvements for vehicles, especially for the existing fleet that no longer receives improvements from their manufacturer.

There are indeed future safety concerns with this project, if the contents were to be reproduced without proper care and diligence, in the worst case possible, could lead to a vehicle accident with the potential for loss of human life.

1.4.2 Ethical Responsibilities

As a student of the Engineering profession, it is imperative that I uphold the Code of Ethics and Guidelines put forth by Engineers Australia now and into the future. The Code of Ethics list four main areas being, Demonstrate integrity, Practice competency, Exercise leadership and Promote sustainability.

How the nature of this project interacts with these areas is as follows:

<u>Demonstrate integrity</u>

1.2 Be honest and trustworthy

All data and results should be accurately represented and documented

Practice competently

2.2 Represent areas competence objectively

Not to falsify or misrepresent qualifications, seeking qualified individuals when needed

2.3 Act on the basis of adequate knowledge

Ensuring that modifications made to the vehicle are within the legal law and in compliance of main roads.

Promote sustainability

4.2 Practice engineering to foster the health, safety and wellbeing of the community and the environment

The main purpose of this project is the reduction of pollution via a reduction in fossil fuel consumption, a by-product of this target is economic relief on the owners of these vehicles.

4.3 Balance the needs of the present with the needs of future generations

The purpose of this project is moving towards the long-term goal of reducing emissions, this task will require an initial investment cost but the long-term benefits are substantial.

Chapter 2: Literature Review

2.1 Overview

This chapter first addresses the underling concepts related to this project as well as discussing the literature on alternate energy recovery methods in vehicles alongside previous attempts at similar devices. This section also serves to identify gaps in knowledge in previous research and developments.

2.2 Implemented Electrical Circuits in Electric Vehicles

2.2.1 Standard Electrical Layout

The modern 12-volt electrical system first saw its introduction back in the 50's, superseding the 6-volt electrical standard (Vintage Auto Garage 2021). While there have been countless innovations and improvements resulting in the modern electrical system being far more complex and intricate. The underlying principles still remain the same with these additions simply building upon the original design in a modular fashion.

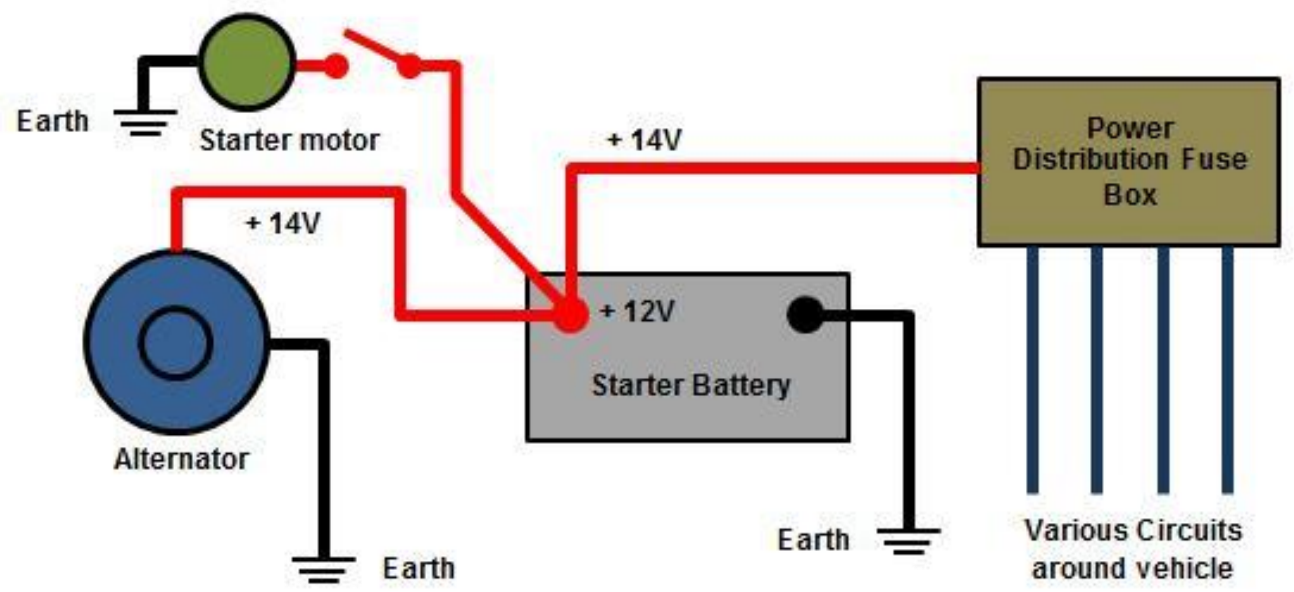


Figure 1 - Standard electrical layout of a vehicle

The basic layout consists of a 12-volt battery with its positive terminal connected to the various circuits within the vehicle. The negative terminal grounded to the body/chassis of the vehicle and in most cases the engine as well. Then most, if not all of the circuits are terminated by connecting to the body of the vehicle creating a complete circuit.

2.2.2 Operational Charging Systems

In almost all vehicle electrical systems today (ICE), the alternator is the sole component responsible for power (electricity) generation. Although the alternator pre dates the first automobile by 50 years (ELREG 2020). It was many years after the introduction of the automobile, in the 1960s that the alternator became standard equipment for most manufacturers. Since then, it has seen many developments with these improvements focused on two main areas, these being:

As vehicles developed, the electrical system of a vehicle has become more and more complex with multiple new systems such as air-conditioning, electric heating, electric brakes, electric steering, more intense lighting and multiple computer-controlled components such as engine management. With each one of these additions increasing the overall electrical demand. Early model alternators produced around 30 Amps, in comparison most modern factory alternators produce north of 100 amps with some specialised aftermarket units producing up to 500 Amps (D4S 2022).

The efficiency of most modern alternators lie in the region of 55 to 60 % with some high efficiency truck units extending up towards 70% (NACFE 2022). Unfortunately, development of this efficiency has plateaued due to multiple factors including the restrictions on available space in the engine compartment, the harsh environment including elevated heat cycles, vibration and debris, the variable input which fluctuates in proportion the engines RPM as well as the associated cost involved in refining the design any further.

While there are numerous variations of alternators including, physical size, electrical output, mounting methods etc. Every modern iteration of the alternator shares a common underlying principle when generating electricity as well as their integration into the vehicle. A brief overview is as follows:

The alternator is driven via a belt from the engines crank pulley, this turns a rotor shaft fitted with many opposing magnets (electro). This rotor spins inside a stator which consists of several coils of wire wound in a specific pattern through an iron ring. This relative motion of the magnetic fields over the conductive wires generates a voltage according the principles of Faraday’s law of induction. The electricity generated is alternating current (AC) and is rectified into direct current (DC) using either an internal or external regulator before being connected into the vehicles electrical system (Evans 2021).

Due to the first law of thermodynamics (conservation) which expresses that energy cannot be created nor destroyed, only converted from one form of energy to another. Therefore, the alternator has a parasitic effect on the engine which intern reduces the overall fuel economy of the vehicle.

2.2.3 The Battery’s Effect on Electrical Systems

Despite being able to power all of the vehicles electrical components in the system even without the engine running, the main purpose of the battery is simply to start the engine. Once the engine is started, most of the electrical load is accounted for by the alternator due to the net charging and discharge of the battery (Goeres 2017). Despite this, it is not suitable to run a vehicle solely off the alternator as this will eventually lead components failing including the alternator itself.

2.3 Alternators & Operations of Electric Vehicles

2.3.1 Existing Alternator Controls & Activations

During operation of the vehicle, the number of electrical components running and the subsequent power draw is constantly fluctuating. For example, operating the vehicle at night in the rain would require the additional use of headlights, taillights and wipers when compared to driving during the day in dry weather. It is for this reason alongside battery health and minimising losses, that the alternator only generates power as required instead of a linear output with respect to engines Revolutions Per Minute (RPM).

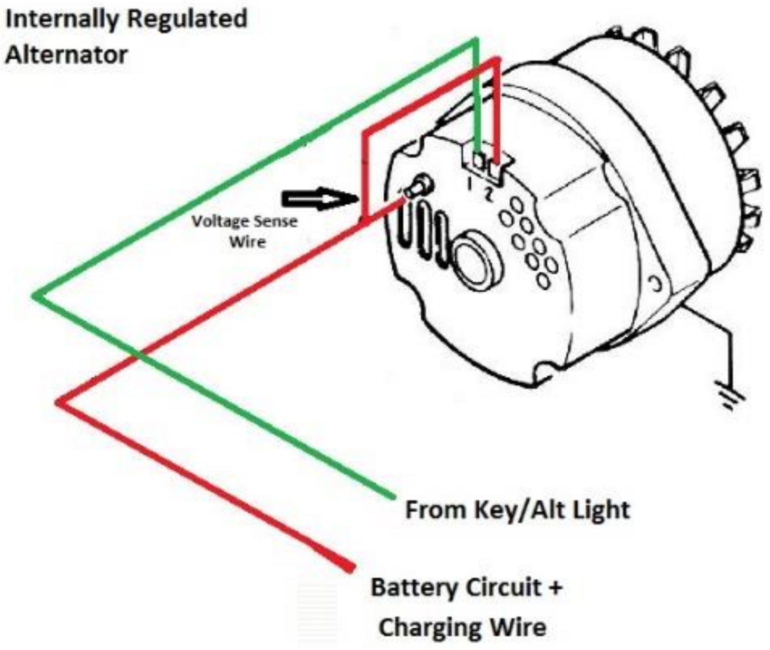


Figure 2 - Sense wire on rear of alternator

In most applications an alternator utilises a "sense wire" to monitor the current voltage of the vehicles electrical system. It uses this information to adjust the voltage and subsequent strength of the electro magnets contained on the rotor shaft inside the alternator, stronger effective magnets allow the alternator to generate more power at a given RPM.

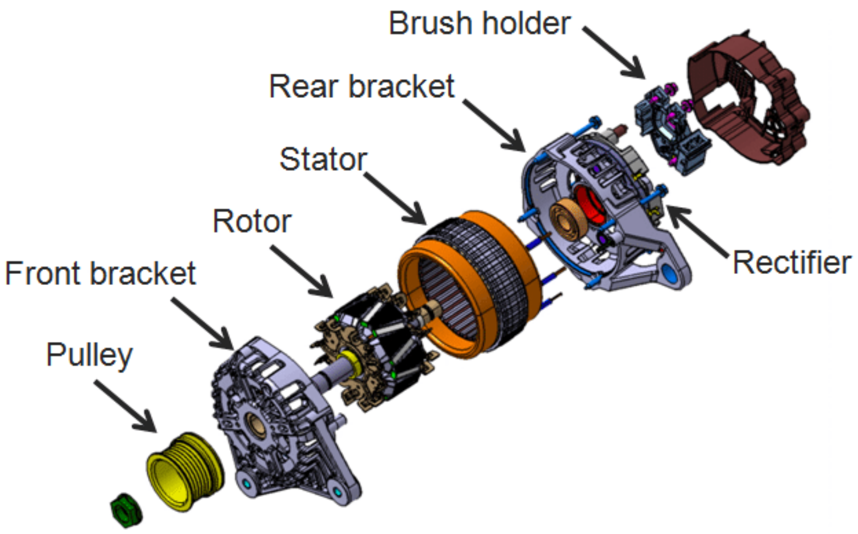


Figure 3 - Exploded view of an alternator

This ability to adjust magnet strength depending on the demand allows for greater power to be generated at low RPMs (high strength) and for less losses to drag at high RPM (weak strength). This means that the parasitic losses felt by the engine are also dependant on electrical load. In theory relieving this load via an alternative source will reduce these parasitic losses.

2.3.2 Other Alternate Electrical Sources

Much research has devoted into the development of these alternative sources that harness otherwise wasted energy.

2.3.2.1 Braking Energy Recovery

There are multiple variations on this style of recovery system however all of them function by redirecting the force normally required for braking to either turn a flywheel, spring or directly charge a secondary supercapacitor battery. This energy is later reused to assist in acceleration or to charge the main battery at a slower rate. This technology has almost exclusively been used in OEM hybrid and electric vehicles. There has only been one example of KERS (Kinetic Energy Recovery System) being used in an ICE powered vehicle. This was in Formula One (F1) motorsport during 2009 and 2011, although the system was able to store energy and generate power (Ozgun 2017). KERS was abandoned due to its complexity alongside the loss in cornering ability resulting from the extra weight. Due to its complexity and general reliance on at least a partially electric drivetrain, it is difficult to retrofit this technology to a standard ICE vehicle.

It is worth noting that while modern F1 has two forms of ERS (Energy Recovery System), one consisting of a generator attached to the crankshaft of the engine and another integrated into the turbocharger. The ERS in F1 is aimed towards generating extra horsepower for short bursts rather than fuel economy. The timing of these bursts are controlled by the driver and their team to assist with overtaking and defence. By limiting the use of these bursts, F1 is able to introduce more strategy and excitement for its viewership. Due to the complexity and reliance on hard braking, current F1 ERS is not suitable for general passenger vehicles.

2.3.2.2 Vibration Energy Recovery

The concept behind Vibration Energy Recovery utilises an actuator in conjunction with the compression and decompression of the vehicles suspension system. Yu, Wang & Zhou (2019) preformed simulations of this technology but found it to be very ineffective with an output over an average given distance to be half that of Braking Energy Recovery. It was also noted in this study that this technology is proportional to vehicle speed and road roughness. Due to roads becoming generally smoother for both increased safety, comfort and fuel efficiency, this technology shows signs of reduced returns.

2.3.2.3 Waste Heat Recovery

Has been researched and funded by many parties including vehicle manufactures such as BMW and Ford. This interest likely prompted by the fact “In a passenger vehicle, only 25% of the energy from the fuel combustion is used for vehicle mobility and accessories running, while 40% is wasted as exhaust gas” (Jaziri et al. 2019). There have been numerous designs of heat exchangers with all of them revolving around a standard form factor TEG module. The highest preforming in vehicle system developed for BMW and Ford produced 600 watts in 2012 however, it was noted in their report that the weight and size of the unit were a considerable downside. In theory, only a fraction of this output needs to be obtained to offset an alternator during normal operation on a basic car.

2.4 The Thermoelectric Generator

2.4.1 Background

A thermoelectric generator is a device that generates electricity when exposed to a temperature gradient across its two sides. This principle behind TEG's is known as the Seebeck effect, discovered in 1821 and states that when two jointed dissimilar metals experience a temperature gradient across the joint, a voltage differential is generated. With the power generated being proportional to the temperature gradient up until the limits of the TEG discussed later.

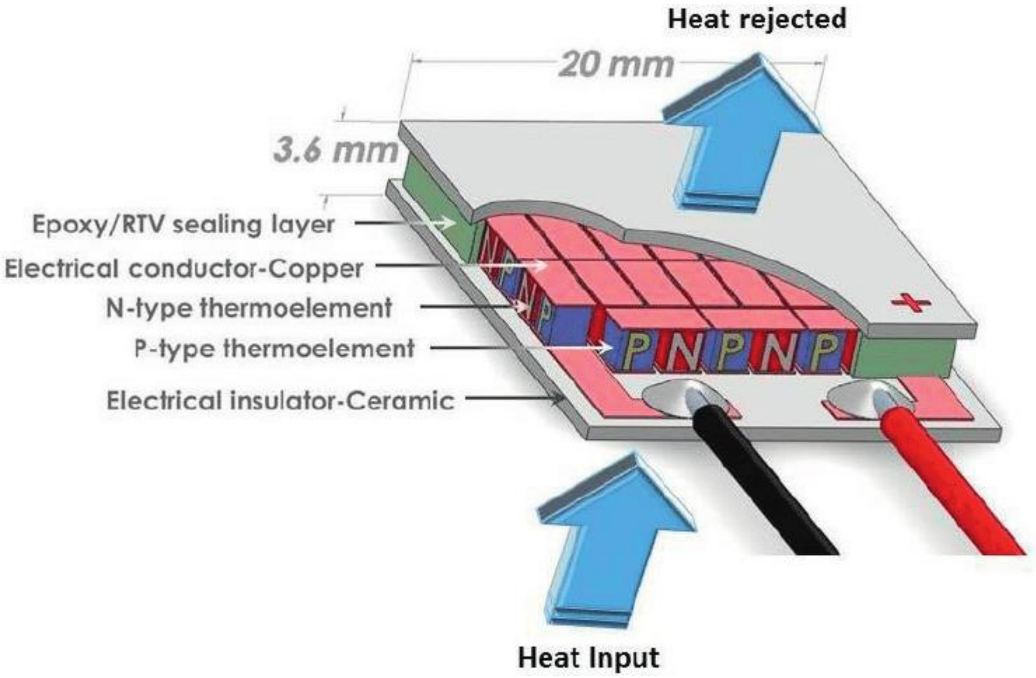


Figure 4 - Thermoelectric generator module

The electricity generated per each connection is rather small and generally unusable (with the exception of sensor applications), often in mV and mA. In order to increase this output to a more usable level, many small joints (or pairs) are connected together in a combination of both series and parallel depending on the desired output characteristics of the module. These connections are arranged in a grid format on a singular 2d plane to both promote the highest possible temperature gradient alongside a higher density power generation.

Due to the construction method mentioned above, all commercially available TEGs are in the form of a flat or rectangle panel, with some of these being multi-layered for specialised applications. There have been endeavours to construct a TEG in a curved format for pipe applications however, no ready-made examples were available for purchase at the time of writing.

Unfortunately, the energy conversion efficiency of a TEG is quite low, usually limited to 5-15%. This limitation is both a function of temperature delta and materials used for the semiconductor/conductor. As such development is constantly progressing on new, more efficient materials however. Despite their current low efficiency, TEGs are opening opportunities for power generation in situations and environments where other methods are simply not possible. These opportunities stem from TEG characteristics such as their lightweight, low profile form factor, simplicity, solid state design (no moving parts), high reliability and the fact they are maintenance free.

It is worth noting that a Thermoelectric generator is closely related to a Thermoelectric cooler. A TEC consists of a very similar construction but utilises the Peltier effect to generate a temperature gradient when a voltage is applied. Both a TEG and TEC module is capable of being used in each other's application however the efficiencies for both drop significantly.

2.4.2 Existing Thermoelectric Generator Circuits

Like batteries TEGs are often used as part of a larger array of modules in order to increase the maximum available power output, parallel to increase current and series to increase voltage. However, due to the construction of a TEG featuring numerous internal connections, TEGs have a relatively large internal resistance. Furthermore, this internal resistance varies with temperature as does voltage and current. Electrically, a TEG module can be represented as a power source with an inline resistance.

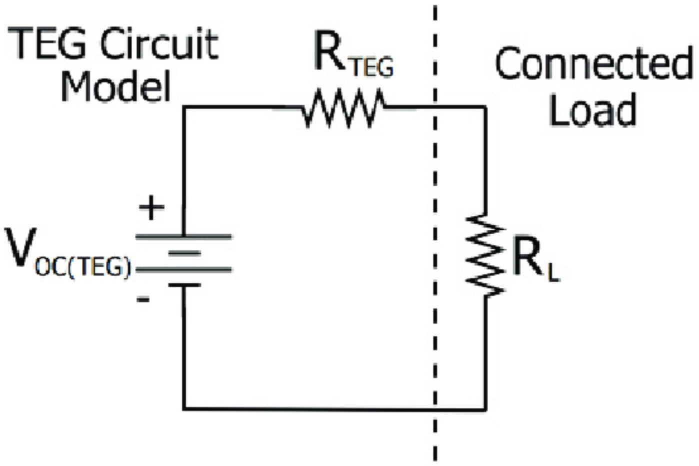


Figure 5 - Electrical representation of a TEG

These characteristics and behaviour can lead to inefficiency's when multiple modules are used with mismatched temperatures, both in series and or parallel. Montecucco, Siviter & R. Knox 2014, conducted experimental research on the effects of three temperature mismatched TEGs wired in both orientations. Given all other variables equal, they found a maximum power (in watts) drop of 9.22% in series and 12.90% in parallel. Fortunately, their findings suggest while there is a measurable difference in output, this inefficiency is relatively minor.

As specified on all TEG specification sheets as well as demonstrated in the previously mentioned, the maximum output of a singular module is dependent on the impedance of the load. It has been widely established that the maximum power output is achieved when the load resistance is equal to the internal resistance. In practice this results in an ideal load voltage that is half of the open circuit voltage.

2.4.3 Current Integration Methods

Once an output is achieved, it is essential to control and regulate this output when attempting to charge a battery. Current studies all refence the use of MPPT controllers however it is still worth addressing all possible types. Currently there are three main styles of chargers that are used to achieve this, these are PWM, MPPT and MVPT.

2.4.3.1 Pulse Width Modulation (PWM)

Is the most basic style of charging algorithm and functions similar to a switch in between the source and the load. For battery chargers it alternates between a closed circuit (charging the battery) and an open circuit when the voltage is read. It uses this voltage to adjust the pulse width (duty cycle) in order to reach a specified target. Due to the relatively simple nature of the design, PWM chargers are very affordable but, significantly less efficient then MPPT.

2.4.3.2 Maximum Power Point Tracking (MPPT)

Widely accepted as the preferred method to control/regulate solar panels, due to its exceptionally high efficiency. The MPPT algorithm monitors the state of charge of the battery while constantly adjusting the voltage and current to extract as much power as possible out of the panels. The MPPT algorithm is up to 30% more efficient then the PWM algorithm and due to the increased complexity, MPPT units are significantly more expensive than their PWM counterpart.

2.4.3.3 Maximum Voltage Point Tracking (MVPT)

Newest style of control algorithm developed in 2019, this method monitors each panel/source individually and maximizes the output of each panel separately. There are very few controllers currently available on the market that utilise this algorithm with the ones that are available featuring poorly documented specifications alongside a cost similar or exceeding MPPT style controllers.

2.5 Measuring Fuel Consumptions

In order measure and quantify the effects of any fuel saving device, it is essential to accurately monitor the fuel consumed over a defined distance to calculate fuel economy.

Almost all automobiles feature at least one sensor within the fuel system, with this sensor developing into a few different types over time but, all still serving the same end purpose. This base level sensor is dedicated to obtaining data that is interpreted into displaying the current amount of fuel in reserve. This data while not technically essential, it serves as a major convenience for the driver in order to easily plan daily operation of the vehicle while avoiding becoming stranded. These fuel level sensors and by extension fuel level gauges (electric) became standard equipment in 1925.

Many vehicles feature additional fuel related sensors, these are most often fuel pressure sensors in vehicles fitted with EFI (majority of vehicles after 1990), these pressure sensors communicate with the vehicles ECU to distribute the correct amount of fuel for each combustion cycle. Less common is fuel flow sensors, vehicles fitted with these use this information in conjunction with the odometer (measures the distance travelled) to display a real-time readout of the current fuel economy or similar functions such as expected range remaining by combining this data with the reserve fuel sensor mentioned above. It is worth noting that it is also possible to represent the current fuel economy by utilising the vehicles MAF alongside a digital VVS since the fuel to air ratio is proportional to the fuel ratio.

Unfortunately, relying on the standard OEM sensors is generally unsuitable for this project, while some cars are capable of digitally displaying the average fuel economy since the last refill, this feature is relatively rare. There are aftermarket options available that can obtain this data however, these systems are designed for larger companies to monitor their fleet and thus are quite costly.

2.6 Summation of the Literature Review

The established literature discusses in depth, multiple aspects related to the electrical system of an automobile and its implications on fuel efficiency. Whilst there has been research conducted, both theoretically and experimentally, this has shown to provide a reduction in the electrical systems parasitic effect.

All previous lines of inquiry have been in relation to new automobiles which have a much higher electrical demand in comparison to older vehicles. Furthermore, information on the size, cost, weight and test conditions of these completed units are scarce therefore creates a knowledge gap.

Due to this project utilising a static testing method as opposed to dynamic testing. The effect on fuel economy will be a calculated value rather than a measured value. A measured value would be preferred however this method would require far more time investment to obtain consistent results.

Chapter 3: Methodology

3.1 Introduction

This chapter outlines and discusses the methodology used for this project. This includes the overall approach process, limitations, resources, risk assessment, ethics and consequences, the design/selection of individual elements, fluid dynamics, FEA optimisation, electrical integration as well as the various experiments and methods utilised to minimise variables.

3.2 Methodology Approach

The flow chart below outlines the overall approach that was taken to complete this project. This process allowed for sequential problem solving, minimising the need to revisit prior aspects for alterations.

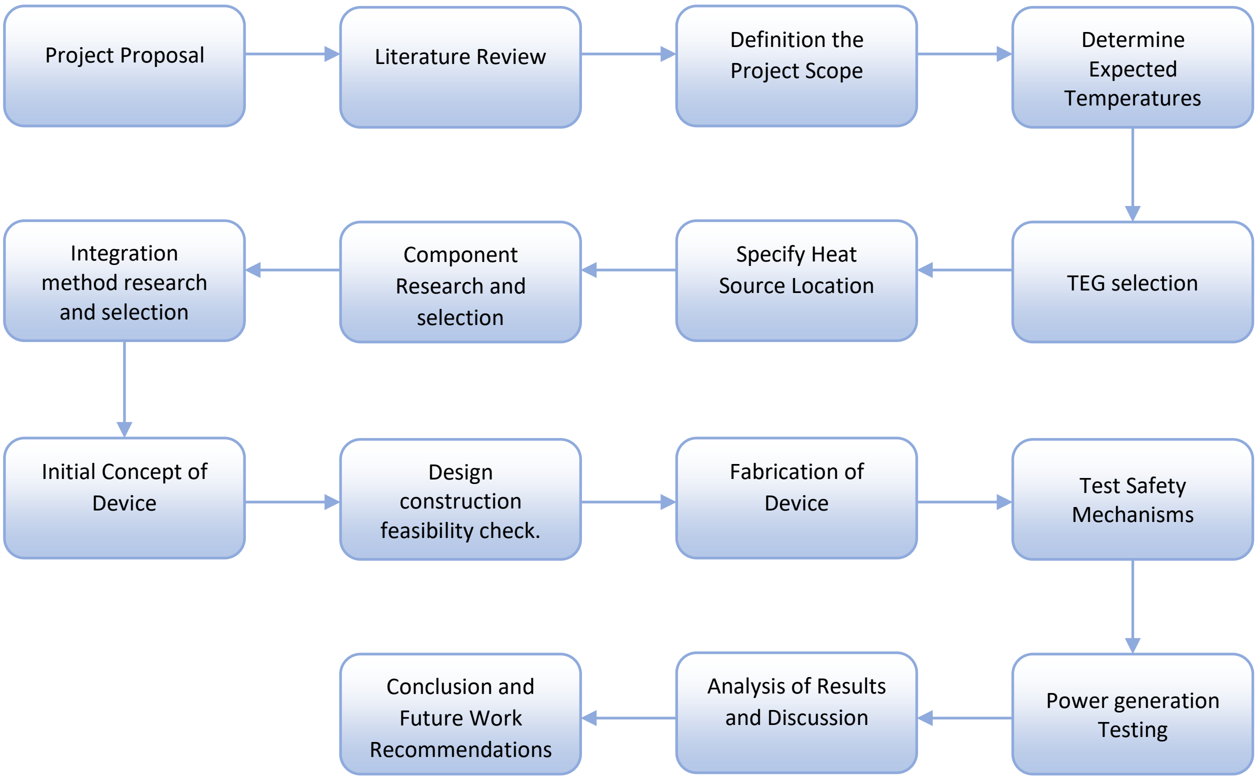


Figure 6 - Flow chart of Project Approach

3.3 Resource Planning

3.3.1 Selected Vehicle

Due to the limitations of being a sole undergraduate student undertaking this project, the vehicles available to me are relatively limited without significant investment. Of the vehicles available, the most appropriate was a 1991 Toyota Corolla hatch.

Figure 7 - 1991 Toyota Corolla hatch

There are three main reasons that supported this selection:

- The vehicle is powered by a smaller four-cylinder engine (4AGE – 1.6L). Smaller engines present a greater percentage potential for power recovery (mechanical). As mentioned earlier, the static losses incurred from the alternator are primarily based on the electrical power draw and RPM. On a smaller output engine, this represents a greater percentage.
- The vehicle is semi-modern. The vehicle features common electrical draws such as EFI which makes the electrical draw similar to the average vehicle in service.
- The relatively older age of the vehicle results in a simpler electrical system which should allow for easier integration.

3.3.2 Tools & Equipment

Almost all of the required tools and equipment were already available prior to the commencement of this project, including the two workspaces that used in the construction and fitting of the device. The tools used were general metal working tools most notably a grinder for cutting the sheet metal, a mig welder for assembling the unit and a table saw for cutting down the premade heatsink. The equipment used to simulate the relative airspeed of a moving vehicle was a battery-operated leaf blower.

The items that did require sourcing were two pieces of equipment used for measurement. These were multiple K type probe accessories for a multimeter and an infrared temperature gun. The probes were purchased from Jaycar and required for measuring multiple areas including: the surface temperature of the exhaust, the temperature of the exhaust flow and the temperatures of both the hotplate and coldplate of the finished device. The infrared thermometer gun was purchased from total tools and enabled quick and safe temperature checking of various areas.

3.3.3 Materials & Components

The project incorporated materials and components from multiple sources, a brief breakdown of these sources are as follows:

- Main body steel, offcut sheet material from the professional workshop
- Aluminium hotplate, local metal supplier
- Heatsink, metal supplier in Sydney
- TEG modules, online retailer AliExpress
- Electronics, various online retailers as well as local suppliers such as Jaycar and Outback Batteries Toowoomba.

3.3.4 Skills & Technique

The skills required to effectively complete this project are:

- Fabrication skills
- Electrical skills
- Mechanical skills

NOTE: *Refer to the Risk Management Plan in the Appendix, Section 7.4*

3.4 Methodology Limitations

As this project is being conducted by an undergrad student, naturally there are some limitations to the scope of this dissertation, these are:

- Knowledge and Resources – A student generally lacks the knowledge that an expert in this field has obtained over the many years, sometimes decades of experience they have accumulated. A professional in the industry will likely have access to much more application specific tools and high precision measurement devices.
- Time – The time period allocated to this project is limited to less than one year, an officially supported study or development team from a larger company may have multiple years to devote to the task at hand.
- Cost – While there was some financial assistance available from USQ at the beginning of the project, this project is almost solely funded by the student themselves. It us unrealistic to expect an individual to possess a similar amount of investment money when compared to a global manufacturer such as Toyota or Volkswagen.

3.5 Design of Elements Methodology

This chapter discusses the multiple design areas required for the development and construction of this energy recovery device. It addresses the possible alternatives as well as the upsides/downsides of each, finally selecting the most optimal solution for the given circumstances.

3.5.1 Starting Parameters

3.5.1.1 Factory Fuel Economy

This vehicle was fitted with a 1.6L 4AGE engine from factory with an advertised economy of 7.4 litres per 100 km. Unfortunately, it was not stated how this value was achieved, whether it was highway or city driving, lab environment testing or real-world testing. As the tests are static and the affects on fuel economy will be based off theoretical calculations, the value of 7.4 litres per 100 km will be used for both the 60 km/h and 100 km/h tests. This assumed value will not affect the percentage reduction in fuel consumption.

If experimental fuel consumption testing were being conducted then it would be imperative to measure the average fuel economy over multiple tests to identify the unmodified fuel economy instead of relying on the manufacturer’s specifications.

3.5.1.2 Factory Power Draw

In order to establish a desired level of power generation, it was necessary to first determine the amount of power the alternator was generating under normal operating circumstances. Using a clamp meter, it was determined that there was a load 3 amps under idling conditions. This measurement was taken from the negative terminal of the battery since the entire circuit passed through this singular cable. Using the Power formula P=VI, the alternator was generating 44 watts at idle.

While researching the effects of removing an alternator from a vehicles electrical circuit. Detailed power draw information was found for a 1991-1995 Honda Civic. When comparing the two vehicles and the driveline used in each it was found that they feature very similar characteristics thus it was deemed reasonable to assume that the electrical power draw would also be similar. This resource suggested the power draw at 100 km/h would be around 135 watts, this value was used going forwards as it was the conservative option.

3.5.2 The Selected TEG Location

The exhaust system in a standard vehicle while simple in appearance, actually preforms many important functions in order for the vehicle to function and behave correctly. These include:

- **Routing** – Exhaust gas is toxic, for this reason it must be routed away from the occupants of the vehicle. From factory almost all exhausts are routed under the vehicle towards the rear with the exhaust introducing the exhaust gas to the atmosphere past the last opening of the cabin.
- **Heat** – Exhaust gases from the combustion process are often in excess of a couple hundred degrees Celsius. This high temperature if left uncontrolled will damage or destroy many of the components in the engine bay. It is not uncommon for the combustion event to still be ignited when entering the exhaust manifold, this coupled with the elevated temperatures would also serve as a significant fire hazard if not contained in the exhaust.
- **Sound & vibrations** – The process of igniting pressurised gasses in an enclosed airspace (combustion) generates a significant amount of sound (sound/pressure waves) as a by-product. This sound level if left alone is far too high and uncomfortable for both the passengers and the general public. In some cases, this noise level is high enough to cause long term hearing damage if sustained for moderate periods of time. As such one of the duties of the exhaust system is to reduce this noise significantly to comfortable levels. There are multiple different strategies that are often employed simultaneously to achieve this task, some of these include mufflers/silencers, resonators, header design, materials and sizing to name a few.
- **Pollution reduction** – All modern automobiles require a catalytic converter by law to reduce the harmful carbon emissions of the combustion cycle. This device is located inline in the exhaust, usually as close as reasonably possible to the collector, this is due to the catalytic converter requiring an elevated temperature to function correctly.
- **Scavenging** – In naturally aspirated applications, the tuning of the exhaust can have a significant effect on performance, this effect is known as savaging and is based off timing the pressure waves in the exhaust to coincide with the opening of the valves inside the head. The timing is adjusted by selecting the correct length and diameter of the primary tubes, when done correctly this process helps to evacuate all of the burnt exhaust gasses in the chamber as well as pull in more fresh fuel mixture leading to a more efficient combustion.

- **Sensors** – Almost all modern automobiles have at least one sensor in the exhaust system. This sensor is most often an oxygen sensor, an oxygen sensor detects the oxygen content in the exhaust and relays this information back to the ECU. The ECU uses this data to detect a lean or rich combustion state and make real time adjustments to the fuelling to bring the air fuel ratio back into target range. This is to maximise efficiency as well as promote long engine life.

After inspection and consideration, the most logical location to place the power generating unit is directly after the catalytic converter, there are a number of reasons for this, they are as follows:

- **Temperature -** Due to the chemical reaction occurring inside the catalytic converter it is often the hottest or second hottest section of a standard exhaust system (excluding turbos fitted to some vehicles). Directly after the catalytic converter it is often the second hottest available section with the hottest section being the start of the exhaust where the exhaust manifold meets the head of the engine. This manifold location mentioned is not suitable due a couple of reasons
- **Vehicle Specific Design -** An PGD in this location would require a vehicle specific design instead of a universal one due to many vehicles having a unique engine bay layout.
- **Little Airflow -** TEGs operate more efficiently with larger temperature gradients, this gradient is usually achieved with air cooling. The engine bay where section one is located normally contains quite warm ambient air with little airflow.
- **Limited Space** – Some vehicles may not have clearance space or will have complex geometry that make retrofitting flat TEG modules difficult.
- **Catalytic Converter Performance** – Catalytic converters which are responsible for reducing harmful emissions only function correctly once a minimum temperature is reached. Thus, it would be unwise to remove heat upstream of the catalytic converter as this could extend the time required to reach operating temperature increasing emissions upon start-up. Although unlikely, if enough heat were to be removed at the manifold, then the catalytic converter would cease to function outright.

3.5.3 Parameters Identified at its Location

Once a suitable location had been found, the next step was to establish the starting parameters as well as the physical limitations, the starting parameters include the surface temperature of the pipe, the flow rate of the gases and the exhaust gas temperature. It is important to note that these parameters will exhibit non-linear behaviour due to three variables. These variables are:

- **RPM & Load -** the engines RPM is directly related to the number of combustion cycles for a given time period and is generally (depending on throttle position) associated with a larger combustion cycle (more fuel & air). Thus the higher the RPM, the more heat is pumped into the exhaust system. The engine load is how much work is required from the engine, this metric can also be viewed as how much resistance has been placed on the engine, higher loads require the combustion of more fuel to overcome the resistance. The combustion of more fuel results in more mechanical output with the by-product of increased heat.
- **Ambient temperature & flow -** this will affect the cooling rate of the exhaust however, it should be noted that this temperature range is relatively narrow when compared to the temperature delta between the temperature of the exhaust and the ambient air. The flow however is directly linked to the velocity of the vehicle in motion.
- **Previous driving behaviour -** since the exhaust pipe is made from a mild steel or aluminized steel (aluminized coating for corrosion resistance), the exhaust has a significant thermal capacity. This thermal capacity acts like a buffer or capacitor in practice, thus change in the surface temperature is more consistent and gradual then the exhaust gasses flowing through it.

3.5.3.1 Starting Parameters

To begin selecting appropriate components, it was necessary to first identify the expected temperature ranges at the selected location.

Metric	**Scenario**	**Speed** $\pm 5km/h$	**RPM** $\pm 100\ rev/min$	**Temperature**
Average Surface Temperature	Normal city driving	60	2500	180
Highway Surface Temperature	Normal highway driving	100	3500	160
Max Surface Temperature	Hard Driving /Racetrack	100+	>7500	N/A
City Flow	Normal City Driving	60	2500	320
Highway Flow	Normal highway driving	100	3500	500
Max Flow temperature	Hard Driving/ Racetrack	100+	>7500	N/A

Table 1 - Starting Parameters

Although it is not advised it is reasonable that an end user may partake in hard driving, track use or improper use of the vehicle it was not feasible to obtain this data in a safe manner therefore these values were not obtained.

Originally the flowrate of different scenarios was also intended to be measured however, the measurements exceeded the upper limits of the available anemometer. The original intention was to use these values to calculate temperature gradient along the length of the unit. Fortunately, due to multiple factors such as the relatively short length, high exhaust velocity and the high thermal conductivity the temperature gradient was a relatively minor factor within the scope of this project.

3.5.3.2 Physical Limitations

The proposed device is intended to be used on pre-existing vehicles with minimal modification, this requirement requires the unit to fit within the available space at the install location. In the case of the test vehicle corolla, these physical limits are as follows:

Description	**Maximum Limit** mm/in
Length	900
Radius (Radially from centreline)	90
Exhaust Diameter (OD)	57 / 2.25’

Table 2 - Physical Limitations

Due to the curved geometry of the factory bodywork on the test vehicle, the available width and height were instead measured as a radius from the original exhaust centreline that was centrally located in the cavity.

3.6 Base Material Selection

3.6.1 Background

The body of the unit consists of two separate materials in order to optimise heat transfer where needed while minimising cost where heat transfer is not a desired characteristic. The main body of the unit preformed the same duties as the original section of exhaust pipe, given this role, Grade 350 mild steel was used for its construction as it was both similar to the original material and was readily available at the workshop for no cost.

The secondary part of the body is the hotplate. The design task of the hotplate is to transfer heat energy from the exhaust flow through to the TEG modules while maintaining dimensional stability under various loads. In order to select a suitable material for this component it is necessary to undertake a material selection process, especially since the performance of the unit is linked to this component.

3.6.2 Performance Criteria

The design task of the hotplate is to transfer heat energy from the exhaust flow through to the TEG modules. To perform this role effectively, the material must exhibit the following properties:

- **High thermal conductivity -** promotes the transfer of heat to the modules and simultaneously spreads the heat along the plate reducing hotspots.
- **Light weight -** as this component will be used in a mobile application, a reduction in weight when possible is ideal.
- **High strength/rigidity -** the plate will be used in an application where there is support in one direction at the outer edges with a load that is applied alone the central unsupported region.
- **Low cost -** the purpose of the completed unit is to reduce the running costs of a vehicle at a reasonable investment cost.

3.6.3 Material Selection Criteria's

There are a number of selection methods, all with certain benefits and drawbacks, for this reason there is no optimal method and a method must be chosen dependant on the scenario. The main selection methods include:

- Accept or Reject
- Merit Rating
- Weighted Merit Rating
- Property Parameter
- Weighted Property Parameter

For many of these processes it is possible to apply a weighted factor on desired characteristics, initially this seems ideal since almost all applications have characteristics that are more desired than others. Unfortunately, in practice it is difficult to select and apply these weighted factor values without becoming biased to a particular result, as such weighted metrics will be avoided in this project. To find a suitable material for the hotplate, a two-stage process consisting of a merit rating and a relative absolute property parameter selection process was be used.

3.6.4 Analysis of Selected Material Criteria

The merit rating selection process was chosen to quickly narrow the list of potential materials based of a broad selection criteria of desired material characteristics. For each material the desired material characteristics were given a rating from one to five with five being the highest. The scale of one to five was used as the characteristics being graded were broad without any measurable values. The five materials with the highest average score where then kept while the lower scoring materials were removed.

The Relative Absolute Property Parameter selection process was chosen to filter the five remaining materials as it removed any unintentional bias and instead compared the materials relative to each other based off their measurable properties.

3.6.5 Selection of Materials for the Base

With the numerous variations of materials in existence and the scope of this project, it is not feasible to compare every material to find the most optimal. Therefore, a reasonable selection of the more common materials were compared to find not necessarily the best material in existence but a suitable material for the project. Given the performance criteria listed in 3.7.2, it is natural to assume an alloy as a suitable material therefore, in order to not exclude possibilities based off prior bias, a selection of other common materials were included in the initial selection process. The materials compared were:

Abbreviation	Material
M1	Alloy 3003
M2	Alloy 5005
M3	Alloy 5052-H32
M4	Alloy 5083 H16
M5	Alloy 6061-T6
M6	Alloy 7075-T6
M7	304 Stainless Steel
M8	350 Mild Steel
M9	Copper C11000
M10	Brass C26000

Table 3 - Defining material list

The five highest scoring materials were then compared to one another using a relative absolute property parameter selection process. This process can be found in 4.

3.7 Thermoelectric Generator Methodology

After some research it was found that there are many calculations related to the design of a TEG and its theoretical maximum output based off a number of variables such as the materials used. However, since the scope of this project is to utilise more affordable off the shelf components. It is more logical to identify the expected temperature ranges and the minimum desired power output and select a TEG based of these parameters and a cost per performance rating. A cold side of 30 degrees Celsius was used for these comparisons.

After some investigation it was found that TEG's are not produced in an ascending order but instead all have unique output characteristics with various working temperature ranges. Thus, selecting the most appropriate TEG required an individual comparison of most the TEG's available.

Further research showed that the main limiting factor of a TEG module the solder used to make the internal connections. Therefore only TEG modules that could withstand the expected 180 degrees Celsius with some additional headroom were originally considered. However, it quickly became apparent that modules that could withstand a hot side of 180˚ were cost prohibitive with a minimum Cost/Watt of approximately $5.00/Watt. Re-evaluating TEGs with a lower max temperature found the TEG model - SP1848-27145 to be the most optimal. This TEG boasted a performance rating of <$2.00/Watt and a max temperature of 150˚.

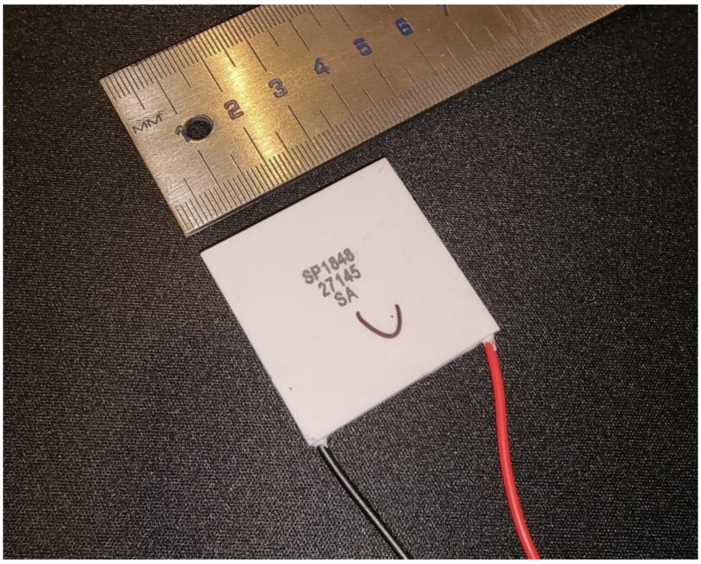


Figure 8 - TEG Module SP1848-27145

The large disparity in terms of cost/watt between certain modules is primarily due to bulk manufacturing and an abundance of supply. The TEG chosen was by far the most common module available when comparing the options currently available. There were numerous third-party sellers, all with competitive pricing.

This lower hot side threshold requires a suitable design so that this temperature is not exceeded, damaging the module. The possible methods that could be utilised to achieve this will be covered in the next chapter.

3.7.1 Manufacturers Specifications of Chosen TEG Module

The TEG Specification datasheet listed the output in terms of open voltage and current at certain temperatures. For ease of interpretation, the output characteristics of the module has been represented in terms power (watts).

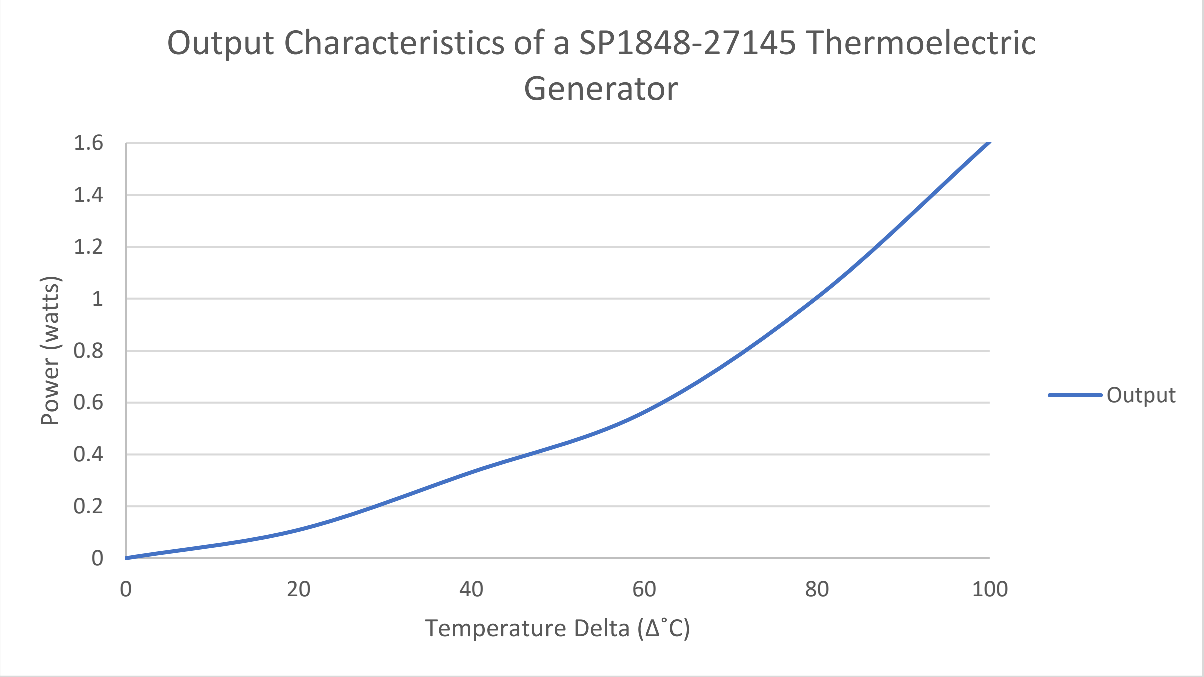


Figure 9 - TEG output characteristics

3.7.1.1 Number of TEGs and wiring

Given the specs of SP1848-27145 TEG, a single module is not sufficient to generate adequate power, thus an array of these modules must be formed to increase the energy harvested.

For this project 32 modules were used, these were wired such that there were two banks connected in parallel with each bank consisting of 16 modules wired in series. Assuming zero losses this combination should result in an output of 76.8 volts and 1.338 amps, when a temperature delta of 100 degrees Celsius is experienced across the modules. Using the power formula P = V*I and a perfect buck converter, this translates to an output of 7.136 amps at 14.4 volts.

While this output exceeds the average draw of the electrical system, it does not account for losses in both the TEG array and the charger/controller.

3.7.1.2 Increasing the Temperature Gradient

As stated, earlier in this report and numerous times throughout the resource materials. The performance of a TEG module is directly linked to the temperature gradient through the TEG. Thus, not only is it important to heat one side reasonably close to its limits it is also imperative to cool the other. Generally, speaking there are two main methods in which to achieve this those being Air cooling and Water cooling. Both methods ultimately utilise convection to transfer heat to the surrounding ambient air however water cooling includes an extra process stage that is capable of bypassing certain restrictions most often related to space by utilising water to transport the heat to another area with less restrictions. This most often results in water cooling preforming better but with considerable extra complexity and cost.

Considering the scope of this project, air cooling was deemed to be more appropriate due to its simplicity and installation location. More specifically an extruded type heatsink will be sourced for both for its cost effectiveness and robustness. This type of heatsink often features high rigidity and will also be used to provide adequate clamping pressure on the modules.

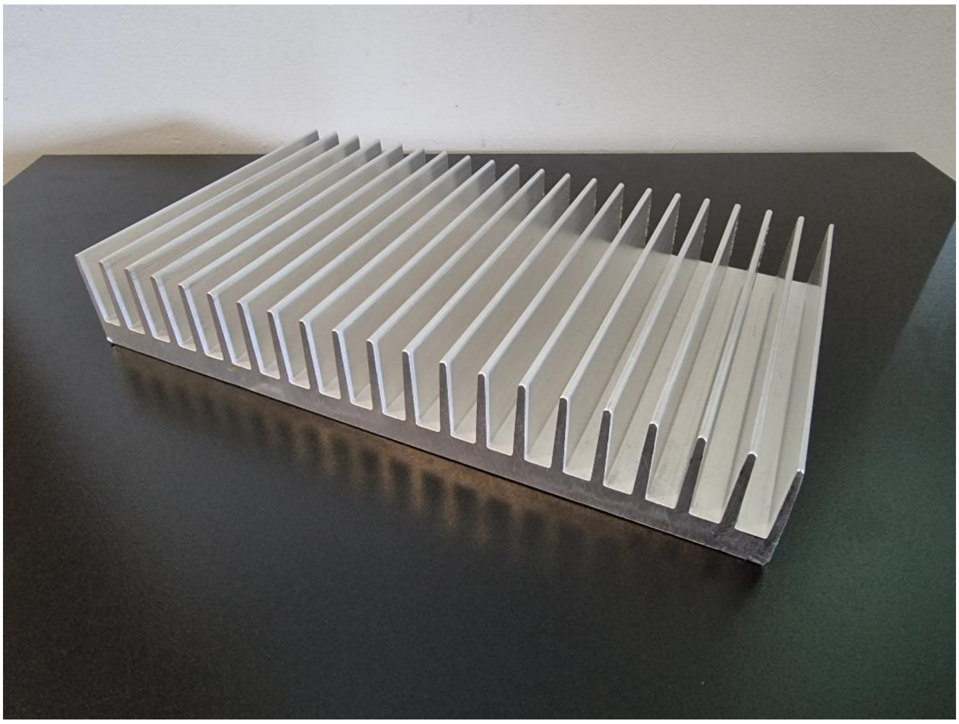


Figure 10 – The extruded type heatsink used in the project

3.7.2 Temperature Regulation of TEG Module

The specification of the chosen TEG has a maximum temperature range of 150 degrees Celsius and thus this limitation must be accounted for to avoid damaging the modules. There are multiple methods that could be used to control the maximum temperature. Some of these methods and limitations are as follows

1. Place the unit later in the exhaust system so that the average temperature experienced is within range. This method is simple but would negatively affect output while also extending the warm up period. Not only does this method limit efficiency but, this method is still not immune to overheating should abnormal conditions arise (hot day, heat soak, excessive driving etc).
2. Bypass pipe with temperature-controlled valve. This method requires an additional pipe/duct that bypasses the entire unit with a diverter valve at the intake of the unit. Should the temperature of the modules approach their maximum limit, this valve would begin to open and redirect heat away from the modules as required. This strategy allows the unit to operate close to maximum efficiency at all times with the major downside being the extra room required for the bypass pipe as well as the control mechanism for the diverter valve.
3. A ‘y piece’ fitted up stream that utilises the Venturi Effect to draw in ambient air, mixing and cooling the exhaust gases flowing through the unit. This method would require a temperature-controlled butterfly valve to control the mix ratio and subsequent temperature. This this method would also enable the unit to operate close to the maximum temperature at all times and requires less physical space. The two major downsides of this strategy are that the noise output will like increase when the valve is open and that drawing in ambient air into the exhaust falls into a legal grey area since despite being and intake could be interpreted as an exhaust leak.
4. Injecting water upstream. Injecting water into the exhaust, utilising vaporization would reduce the exhaust temperature. Like other methods (2) and (3), this would require a control algorithm to maintain a controlled temperature. The two major drawbacks of this method would be the consumption of water alongside the degradation of the exhaust from corrosion namely rust.

The ideal method of temperature regulation is method (2), Bypass pipe. This method is containable to a singular unit, sealed and offers variable temperature control allowing for maximum output. The control algorithm of the diverter valve would require PID tuning for optimal performance and safety but could also be completed with basic on/off control. For the purposes of this project, a more basic control algorithm will be used with a single stage threshold.

As mentioned earlier in section 2.4.2, it desirable that each module experiences similar surface temperature. Given that heat is flowing in one direction there are three factors that will promote the cooling of the surface temperature along the length. These factors and their remedies are as follows;

- The first factor is the natural convection cooling created by the ambient air and the forced convection when the vehicle is in motion. This can be minimised by isolating the external surfaces of the unit with the exception of the module contact areas. This could be achieved with a creative application of exhaust wrap which is an off the shelf product made for insulating exhaust manifolds.

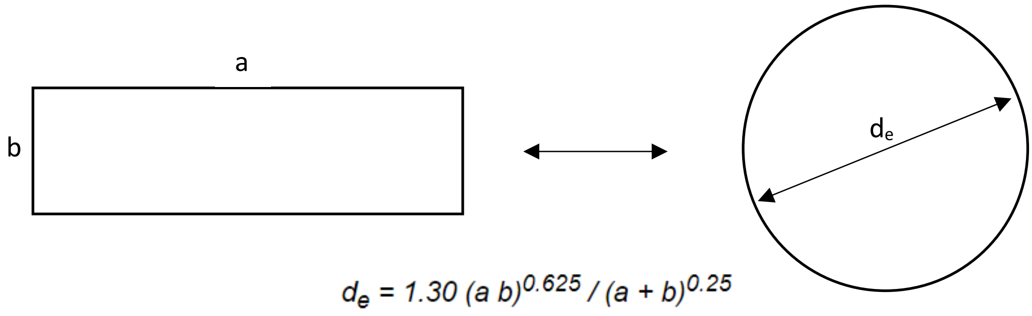
- The second factor is the cooling effect caused by the modules as they remove heat. This could be offset by utilising internal fins that gradually get larger along the length. This will gradually increase the surface area which effectively increases the heat transfer coefficient along the length of the unit. The optimal gradient of these internal fins is difficult to calculate by hand due to the number of variables and geometry. A FEA software would be needed to calculate this optimal angle.
- The third factor is the cooling effect of the exhaust system following the unit. The tail section of the exhaust acts an inefficient heatsink that will draw heat out of the unit via conduction heat transfer. This effect can be reduced to an extent by using an insulating gasket material such as fibreglass plate.

Therefore, it is reasonable to assume that the TEG modules may experience slightly different surface temperatures however given the length of the unit, velocity of the exhaust, and the materials used, the gradient should be relatively minor.

3.8 Fluid Dynamics

As the purpose of the device is to transfer heat to the TEG modules which require a flat surface, it stands to reason that the replacement section of the exhaust will feature a rectangular profile. The sizing of this duct must not be too small as to restrict flow as restricting the flow would lower the efficiency of the engine. The duct must also not to be too large as that will discourage heat transfer from the reduction in turbulence, as such a balance must be found.

The most straight forward solution to this issue is to simply match the flow rate of the exhaust already on the vehicle. The original inside diameter is 54mm which translates to a cross sectional area of 2290.22mm^2. The proposed duct features four TEG modules side by side which results in a minimum internal width of approximately 160mm, to allow adequate room for wiring down the centre, a width (a) of 170mm was selected. Using the formula listed below and a height (b) of 18.59mm results in an equivalent diameter (d_e) of 54.00mm. For ease of manufacturing a height of 20mm was used.



$$d_e = 1.30\,(a\,b)^{0.625} / (a + b)^{0.25}$$

Figure 11 - Equivalent diameter of a duct & equation (Huebscher)

3.9 Final Design of the Heat Recovery Unit Methodology

Taking the previous design choices and limitations into consideration, a design consisting of two rectangular ducts stacked on top of one another was chosen. Both the rectangular ducts need to independently flow as much as the original 54mm diameter pipe. In practice the top duct serves as a bypass passage that is normally closed whilst the bottom duct contains the hotplate and is responsible for transmitting heat to the TEG modules. Originally, to assist with heat transfer, the bottom duct was to contain additional internal fins to increase surface area (not pictured). However, during construction there was significant warping so this design aspect was abandoned due to the limited time available. Between the upper and lower ducts there is an air gap that will be used to secure the heatsink using stainless hose clamps. This style of fastening was particularly useful as it was both simple and limited unwanted heat transfer considerably.

The inlet of the unit utilised a diverter flap to direct the exhaust flow. This flap is operated by a vacuum type actuator mounted on the outside of the unit. The vacuum actuator is plumbed into the intake manifold and uses a solenoid valve for control, with the default (unpowered) state redirecting the exhaust away from the TEGs as a failsafe should the control mechanism fail. The TEGs are 'sandwiched' between the bottom of the unit and an extruded type heatsink. The TEG modules are arranged four wide and eight deep, they are wired in two parallel banks of 15 modules wired in series.

The following Figures 13 and 14, the 3D model is designed to be a simplification of the design concept.

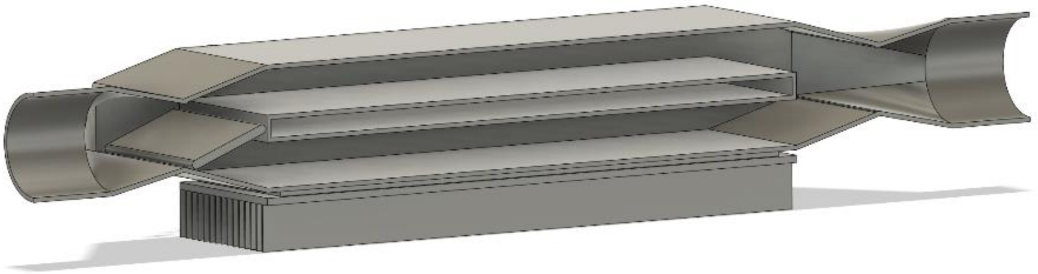


Figure 12 - Cross section concept device, Showing bypass Passage

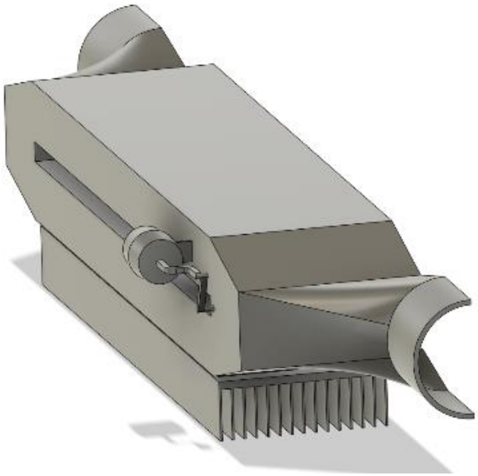


Figure 13 - Concept of device, showing the vacuum actuator that controls the valve

The following photo showcases multiple components on the unit:

- 30 TEG modules wired in two parallel banks of 15
- Pink silicone mat that protects the wiring from any potential shorts while acting a mild thermal barrier.
- The pink silicone mat also acts as a retainer for the modules due to its one-piece construction
- The vacuum actuator in the top right-hand corner of the photo responsible for directing exhaust gas
- Electrical thermostat switch located on the centreline near the actuator where the modules are separated
- Blue thermal paste that was used to promote thermal transfer between the modules and the heatsink (also located underneath modules)

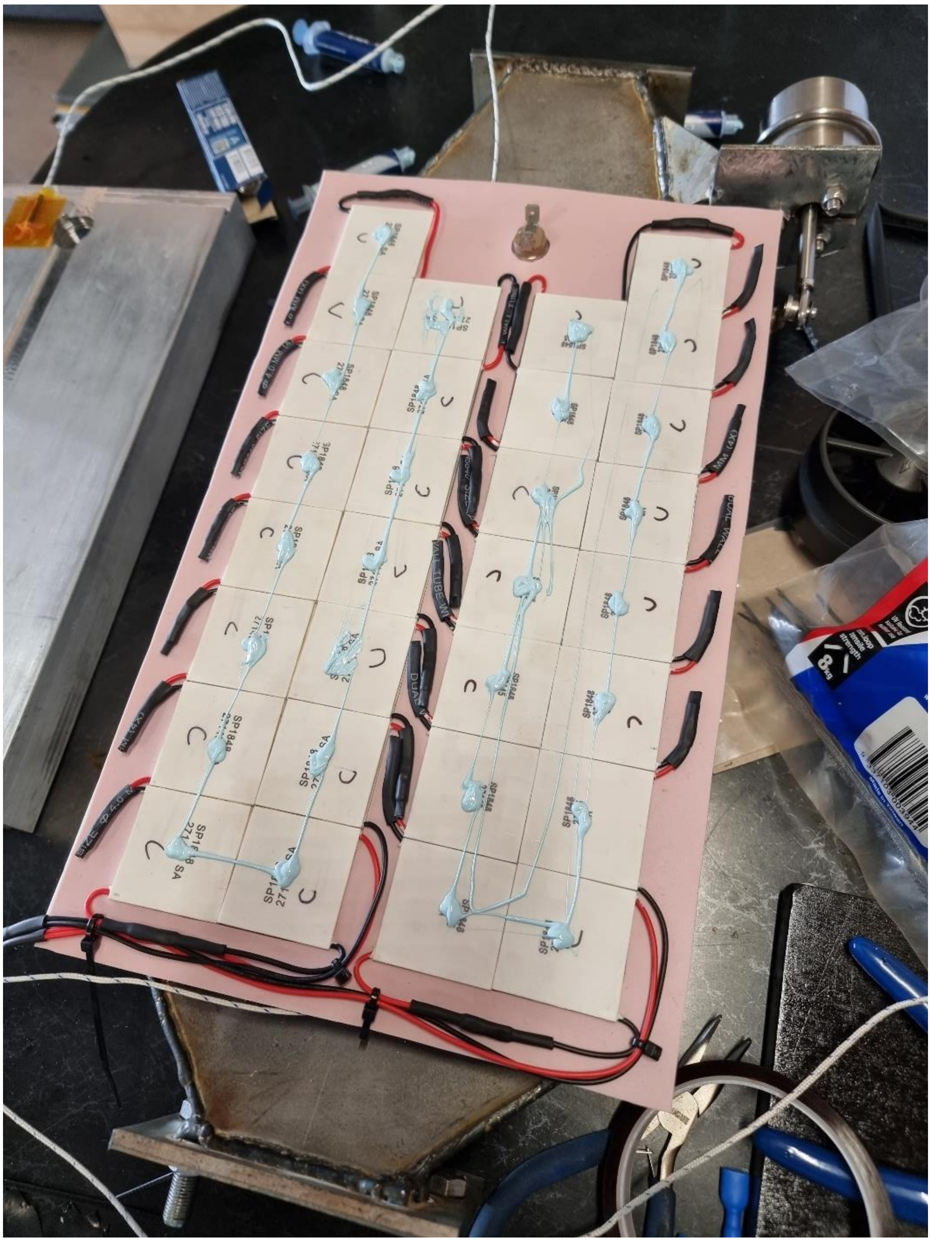


Figure 14 - TEG array

The following profile images display the finished unit, the hose clamps can be seen clamping the heatsink to the body, sandwiching the TEG modules to the hotplate.

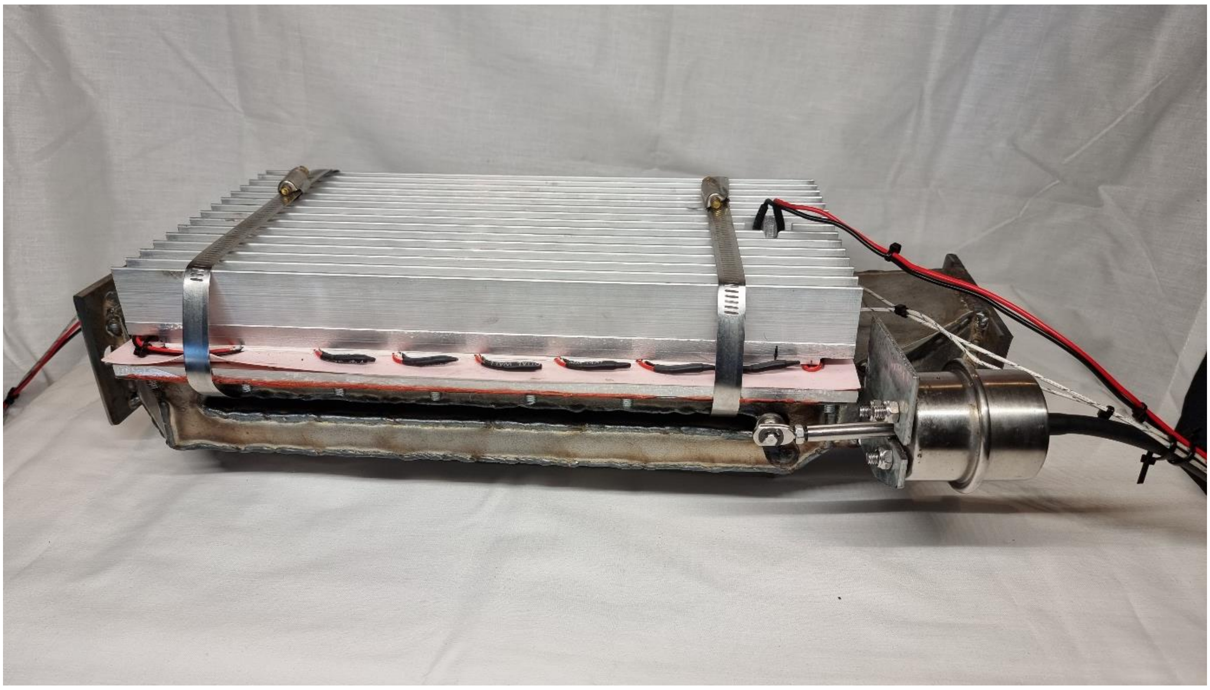


Figure 15 - Completed unit (upside down)

Figure 16 - Completed unit fitted to vehicle

3.10 Electrical Integration Methodology

After considerable research and consideration, it was decided that a SmartSolar Charge Controller MPPT 75/10 would be a suitable charger/regulator for this project. There were multiple considerations that support this selection:

Figure 17 - Smart solar charge controller MPPT 75/10

- **Solar Charger** – As mentioned earlier, solar chargers are designed to control, regulate and maximize the power generated from an input that has variable voltage and current. These characteristics of a solar panel are very similar to TEG modules.
- **Capacity** – The SmartSolar 75/10 has a maximum input voltage of 75 volts and a maximum output of 10 Amps. This makes it more than adequate to control and regulate the power expected from the TEG modules with ample headroom. The SmartSolar also boasts a peak efficiency of 98%.
- **Price** – Initially a cheaper, budget friendly option was intended to be sourced in order to keep in line with one of the original objectives of this project. However, when pursuing this direction of more budget conscious options, multiple issues were encountered such as lack of documentation, misleading specifications, supply and quality/reliability issues. During this process it was found that a MPPT controller could be built from scratch using an Arduino as a foundation for significantly less money. This strategy while low cost is highly time and skill intensive, thus was deemed outside the scope of this project. If the project were to be successful in increasing fuel economy, only then would it be wise to pursue a more affordable purpose-built unit. Using previously documented DIY solutions as a guide, a purpose built MPPT controller could be made for approximately $30.00.

- **Features** – The SmartSolar MPPT 75/10 has multiple features beyond other basic controller units that make it an ideal candidate for this project:
    - Designed with vehicle installation compatibility in mind
        - The unit is rather robust and highly resistant to the stresses that come with a vehicle deployment such as vibration, reviews for this unit suggest very high reliability.
    - Programmable battery charge algorithm
        - This allows for the charge voltage to be adjusted should voltage drop occur in the wiring, this feature will also help trouble shooting if there is an issue encountered when operating the unit in tandem with the alternator.
    - Bluetooth monitoring/programming
        - This unit features a companion app for both android and iOS, this app will greatly assist with accurate data recording and behaviour monitoring.

3.11 Testing Methodology

3.11.1 Background

In order to accurately quantify any improvements to fuel economy, it would be ideal to conduct experimental testing by physically measuring the fuel consumed under certain conditions. Unfortunately, this process has more associated risks and requires considerably more time to achieve consistent results due to increased variables. For these reasons, static testing was chosen to evaluate the theoretical effects on fuel consumption.

The testing phase will consist of three separate tests, these three tests will represent the most common scenarios in which an average vehicle is used. These tests will consist of idling, city driving and highway driving, preforming tests simulating these conditions will allow for trends and behaviours to be identified.

3.11.2 Condition Controlling/Minimisation Methods of Variables

During testing phase of this project, it is ideal to limit as many variables as possible in order to maximise the accuracy of the results obtained. More accurate and consistent data will assist the analysis process making trends more defined. Many variables will either affect fuel economy directly or place additional loads on the electrical system, indirectly reducing fuel economy. Fortunately, static testing eliminates most of the variables present with experimental (real-world) testing, the remaining variables can be effectively minimised and their strategy are as follows:

- **Driving behaviour** – This is the most substantial variable that static testing helps to eliminate. Excluding actively seeking to consume fuel, poor driving behaviour can negatively affect fuel economy up to 30%. In terms of fuel economy, poor driving behaviour specifically relates to excessive acceleration, excessive breaking and changing gear too late in the RPM range. Static testing allows for a set RPM to be maintained without being influenced by traffic.
- **Reduction of accessory use** – All vehicle accessories such as radio, air-conditioning, heater etc require power to function therefore, they all place additional load on the electrical system. These accessories will not be used during the duration of the tests to keep the load on the electrical system consistent.

Chapter 4: Results & Discussion

4.1 Outline

This chapter contains the results from the material selection process and the results from the three static tests. It examines and discusses the data recorded, uses these findings to first calculate the potential effect on fuel consumption then explores the feasibility of the project.

4.2 Material Selection Assessment

4.2.1 Optimal Hotplate Material

The first stage of material selection utilises a merit rating selection process that shows the results:

Material	Heat Resistance	Material Availability	Ease of Manufacturing	Ergonomic	Average Score
M1	4	5	3	4	0.8
M2	4	5	4	4	0.85
M3	4	3	4	4	0.75
M4	4	5	4	4	0.85
M5	5	3	4	4	0.8
M6	5	4	3	4	0.8
M7	4	5	4	2	0.75
M8	3	5	5	2	0.75
M9	1	3	1	2	0.35
M10	2	2	2	3	0.45

Table 4 - Merit rating system

The five lowest scoring materials were removed, with the remaining five progressing to the second stage selection process. The Relative Absolute Property Parameter selection process yielded the following results:

Material	*Thermal Conductivity W/mk*	*Relative Score*	*Fracture Toughness*	*Relative Score*	*Strength to weight ratio*	*Relative Score*	*Fatigue Strength MPa*	*Relative Score*
M1	190	0.9452	22.77	0.5295	68.13	0.3806	70	0.4403
M2	201	1	28.50	0.6628	43.33	0.2421	74	0.4654
M4	117	0.5821	43.00	1	80.82	0.4515	159	1
M5	167	0.8308	21.92	0.5098	102.22	0.5711	117	0.7358
M6	130	0.6468	20.31	0.4723	179	1	159	1

Material	*Stiffness of material*	*Relative Score*	*Cost per Tonne (AUD)*	*Relative Score*	*Rating without Cost*	*Ranking*	*Rating with Cost*	*Ranking*
M1	1.53	0.9871	2500	0.3066	0.6565	5	0.6171	5
M2	1.51	0.9742	2700	0.3735	0.6688	4	0.6197	4
M4	1.55	1	3600	0.1646	0.8067	2	0.6997	1
M5	1.54	0.9936	3576	0.1701	0.7282	3	0.6352	3
M6	1.48	0.9548	4309	0	0.8148	1	0.6780	2

Table 5 - Relative absolute property parameter

4.2.2 Material Selection Analysis

The Relative Absolute Property Parameter selection process in Section (4.2.1) identified that if cost were to be excluded then M6 Alloy 7075 T6 is the ideal material for the hotplate. As cost must be considered as per the original objectives of the project, M4 Alloy 6083 H16 becomes the optimal material.

Alloy 6083 H16 may not have the highest thermal conductivity however, as the task of the hotplate requires multiple other characteristics including strength, rigidity and cost. Alloy 6083 H16 becomes the ideal material.

4.3 Experimental Results

4.3.1 Summary of Results

To test the power generated under varying conditions, three static tests were conducted on the vehicle. For ease of reference these will be referred to as:

Type	Definition	RPM $\pm 100\ rev/min$	Velocity $\pm 5km$
Test 1	Idle	900	N/A
Test 2	City	2500	60
Test 3	Highway	3500	100

Table 6 - Testing criteria

These three tests were selected in order to identify trends and behaviours in common scenarios for the average vehicle.

4.3.1.1 Test 1 - Idling from Cold

Test 1 was started from a cold start up and included the vehicles automatic choke for approximately 2 minutes and 50 seconds (automatic elevated engine speed of 2000 RPM during initial warmup).

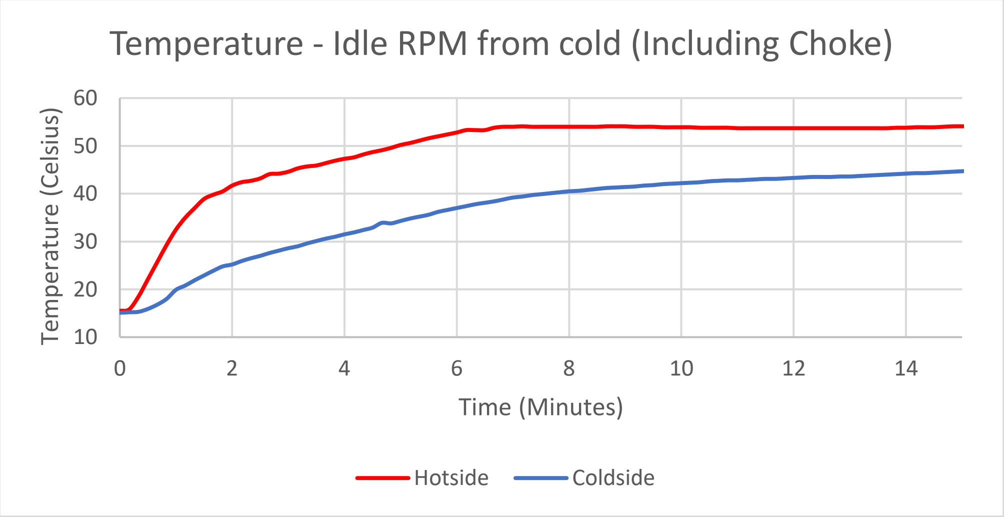


Figure 18 - Temperature Test 1

The test was conducted in open air with the only airflow being attributed to the wind. This test demonstrated that without consistent airflow, the heatsink was quickly saturated with heat becoming unable to maintain a significant temperature gradient. At idle RPM and no airspeed, the temperature of the hot side stabilised around 54 degrees Celsius with heatsink slowly rising in temperature to match.

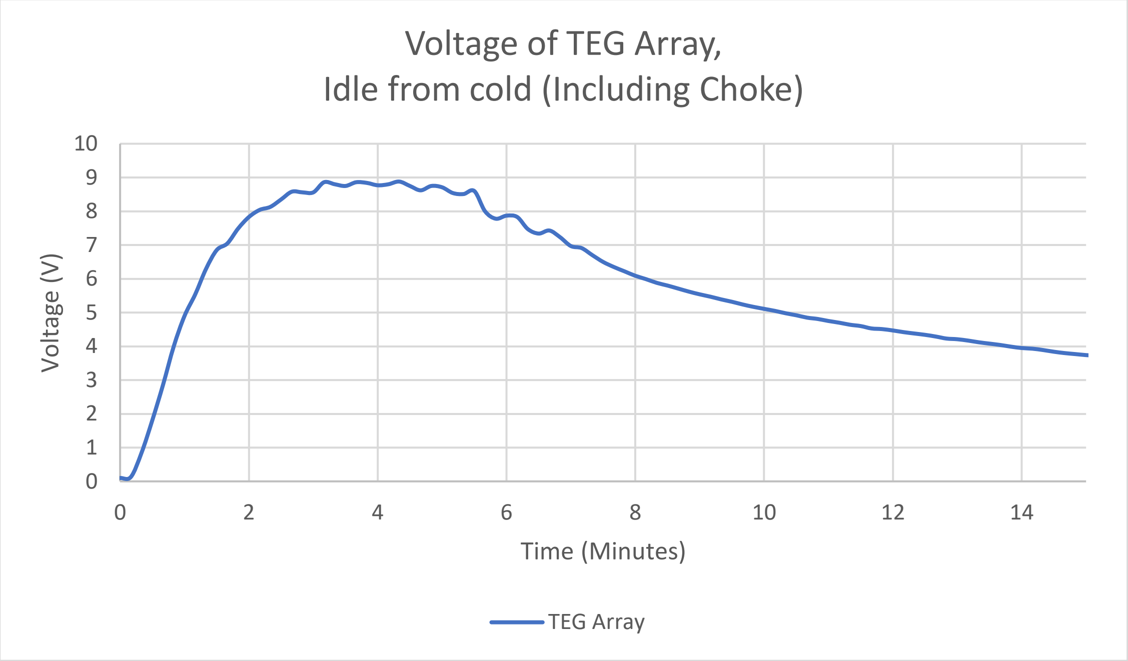


Figure 19 - Voltage Test 1

Figure 19 demonstrates how initially the voltage begins to rise due to the hotplate rising in temperature but starts to fall as the temperature of the heatsink and hotplate begin to equalise.

There is no power graph for Test 1 as the Victron smart solar controller requires an input voltage at least five volts above the connected battery to begin charging. Given this requirement, the TEG array did not produce enough voltage to reach the minimum threshold for the solar controller.

4.3.1.2 Test 2 - City speed 60km/h (2500 RPM)

Test 2 was started from a cold start up, the RPM was immediately raised to 2500 RPM which is the engine speed for maintain 60 km/h in fourth gear, a common speed when driving around a town/city.

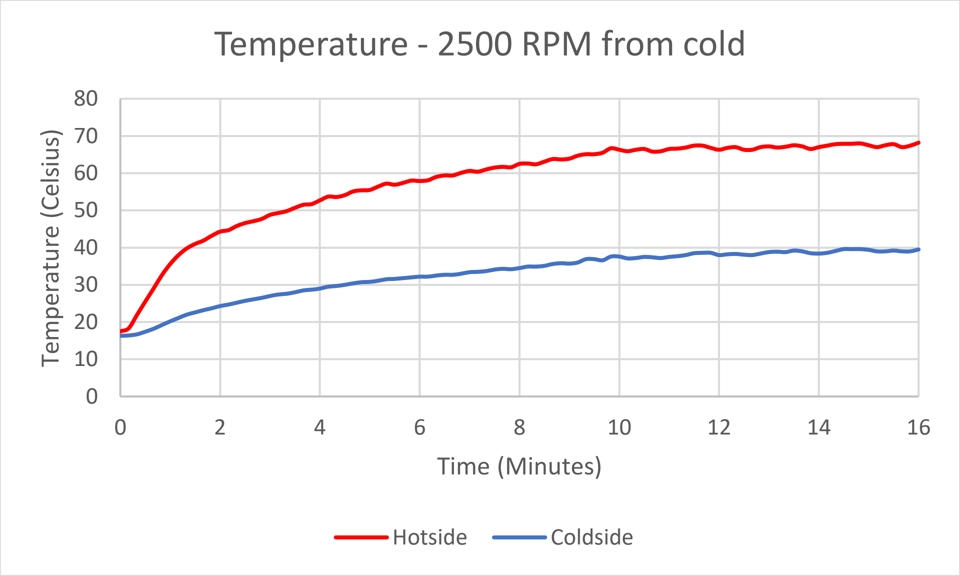


Figure 20 - Temperature Test 2

This test was limited to a 15 minute duration as the blower used to simulate airspeed relied on rechargeable batteries. During the test there were two batteries available for the blower with them having a capacity to last 16 to 18 minutes combined.

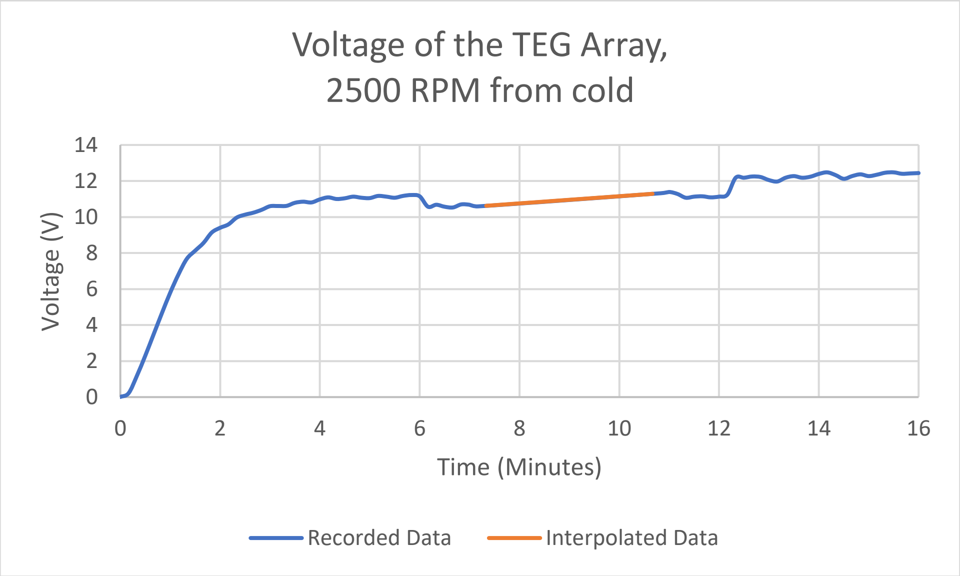


Figure 21 - Voltage Test 2

During this test the device used to record the Voltage (handset with the VictronConnect application open) went into standby mode at 7 minutes and 20 seconds and was restarted at 10 minutes and 50 seconds. Fortunately, during this time, the Voltage only rose by 0.73 volts. For the purposes of the graph, the missing data has been substituted with calculated datapoints using interpolation.

Similar to Test 1, there is no power graph for Test 2 as the Voltage did not rise enough to cross the threshold for the solar controller to begin charging.

4.3.1.3 Test 3 - Highway speed 100km/h (3500 RPM)

Test 3 was started from a warm start up with residual heat remaining from a previous test, this resulted in the temperature data values beginning north of 30℃. During this test the RPM was immediately raised to 3500 RPM which is the engine speed to maintain 100 km/h in fifth gear, a common speed when driving on a highway.

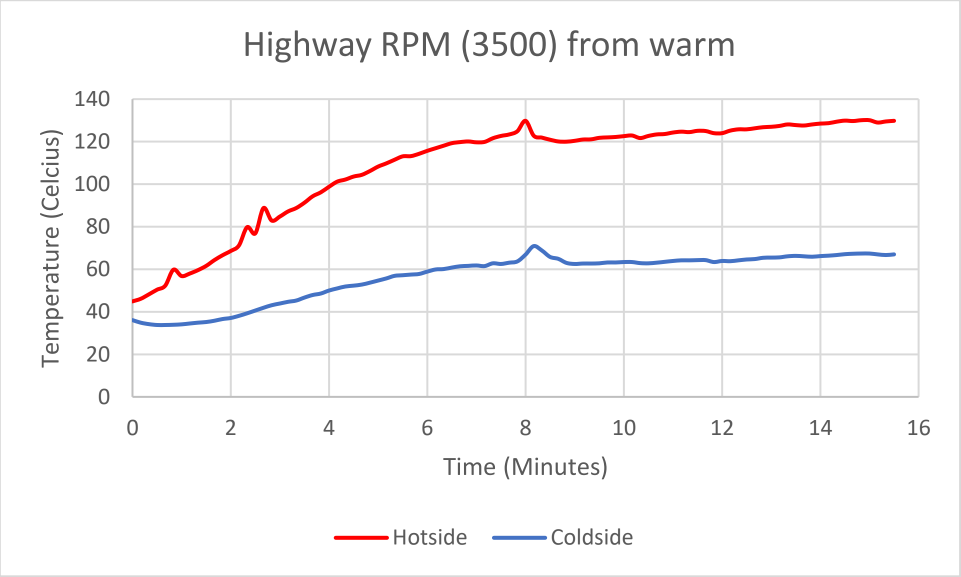


Figure 22 - Temperature Test 3

Test 3 was limited in duration due to the battery capacity of the blower, as the test was static the blower was required to simulate the airspeed that would be present if the vehicle was in motion. The spike in temperatures occurring at approximately 8 minutes is due to the first battery depleting and there being a short duration with no airflow while the battery was changed. There was no noticeable spike in Test 2 due to recruiting an assistant to be on standby with the second battery.

Applying a logarithmic trendline to the data suggests the hot side will reach a temperature of 145 degrees Celsius after 60 minutes with the cold side reaching 77 degrees Celsius. These predictions suggest a gradient of 68 degrees Celsius which is only an 8% increase over the 15-minute gradient of 63 degrees. This suggests that the majority of the heating occurs in the first few minutes of operation.

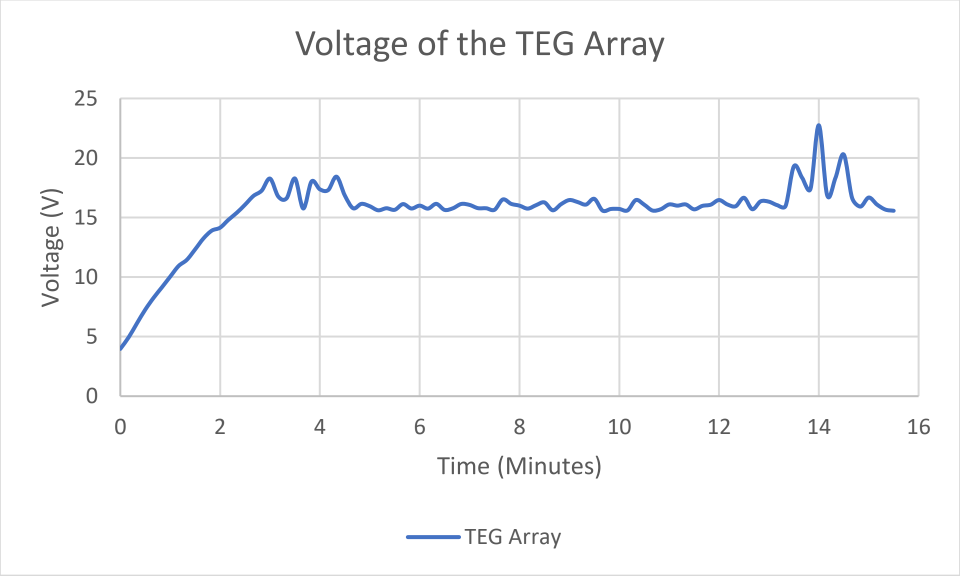


Figure 23 - Voltage Test 3

The voltage of the array begins to plateau after the three-to-four-minute mark due to two reasons, the first and more influential is that the average temperature gradient also begins to stabilise around this time. This stabilisation is due to the heat dissipation capacity equalising with the heat input.

Secondly, the voltage had crossed the threshold where the controller begins to charge the battery. This activation also meant that the controller began to constantly vary the load resistance in an attempt to maximise the power generated. This behaviour contributes to the relatively minor fluctuations seen in the voltage (and by extension current and power).

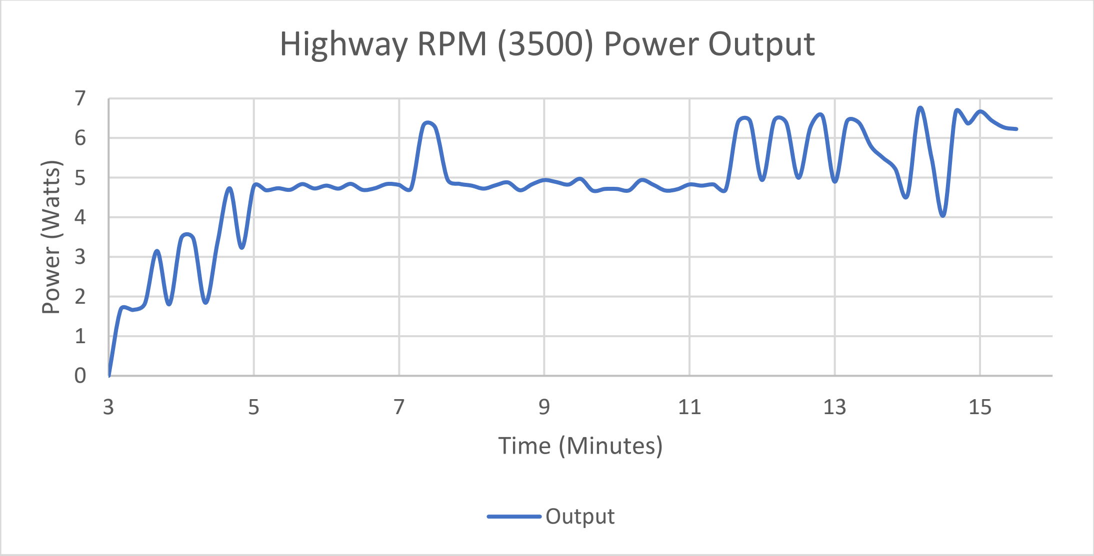


Figure 24 - Power output Test 3

With the temperature gradient beginning to stabilise around 60 degrees, the power output also stabilised between 5 and 7 watts. Note that the graph begins at the three-minute mark due there being inadequate voltage for the solar controller to start charging the battery. Lastly, the erratic output is caused by the solar controller constantly varying the resistive load in an attempt to seek optimisation of the power generated.

Using a combination of the data recorded from Test 2 and Test 3, it can be estimated that the warm up period before the unit begins to generated power is roughly 5 to 6 minutes. This estimation however is flawed due to a lack of engine load, this lack of engine load is discussed in more detail during a later Section (4.3.2.2).

4.3.2 Discovered Observations / Issues

Initially these results were less than expected however, after analysis there were various factors identified that contributed to these low output numbers.

4.3.2.1 Airspeed

The air current that would be present when a vehicle is in motion was simulated using a blower directed underneath the vehicle. The blower used was capable of generating sufficient airspeed at its outlet however the air current dissipated to 14 m/s (50.4 km/h) once it reached the heatsink (measured with an anemometer). This was not ideal as not only was this less than the theoretical speed, in practice the underbody airspeed generally increases above the relative speed of the vehicle due to the venturi effect.

4.3.2.2 Engine Load

While engine speed (RPM) at desired speeds can be simulated statically, it is difficult to place the equivalent load on the engine safely without the use of expensive equipment such as a dynamometer. In practice this meant that the engine saw much less resistance and thus required much less fuel to maintain a set engine speed. This reduction in fuel consumption led to a drop in heat produced. During testing, accessories such as air-conditioning and driving lights were turned on to help provide some load on the engine however, this imposed load is still far less that what the engine would normally experience in daily operation.

4.3.2.3 Heat Gradient

As mentioned previously in Section (3.8) the temperature gradient applied to the modules is the most significant factor affecting output with the relationship between gradient and output being exponentially related. During the test it can be seen that the temperatures were starting to stabilise with a gradient of 60 degrees when holding the engine at highway RPM. This gradient is affected by three metrics: the velocity of the air current relative to the car, the size/design of the heatsink and the material used.

- **Air -** When applying some convenient assumptions like a constant temperature over the length of the heatsink and ideal temperature distribution across the fins. Preliminary calculations suggest a gradient increase of 17 degrees should highway airspeeds be reached (when compared to the 14 m/s used during the test and not incorporating the increase due to the venturi effect). This translates to an expected power increase of approximately 62%. It should be noted that this calculation is not accounting for the temperature increase from additional engine load mentioned in the previous section. Should the temperature increase be considered, the output would further rise due to the larger overall gradient between it and the ambient air temperature.

- **Size & Design -** While a larger heatsink is capable of dissipating more heat, the overall size is largely restricted by the physically available space underneath the vehicle, this includes the ride height as a heatsink that is too tall may protrude down below the minimum road clearance required by law. In Australia the minimum road clearance allowable is 100mm (Department of Transport and Main Roads 2021). With overall size remaining a constant, an alternative design for the heatsink that features fin geometry better suited to the expected airflow would also increase the amount of heat dissipated. That said however, in this application with the size and airspeed, this would almost certainly require a custom made heatsink which would increase the cost significantly due to custom tooling and an increase in labour.
- **Material** – An objects ability to transfer heat via conduction is greatly influenced by its material's thermal conductivity. In the case of a heatsink, this characteristic is of high importance as it regulates the heat energy transferred from the surface in contact with the heat source and the fin surface where the heat energy is dissipated via convection into the surrounding air. Fortunately as the sole purpose of a heatsink is to transfer heat, materials with high thermal conductivity are almost exclusively used in prebuilt heatsinks in which this project utilised. There are materials which feature higher thermal conductivities thus a higher heat dissipation potential but these materials are specialty with various drawbacks and often require custom machining. An example of such a material is copper, copper has a very high thermal conductivity but has multiple drawbacks mainly its softness and elevated cost.
- **Insulation -** The surface area of the heatsink which both faced the hot side and in direct contact with the TEG modules measured 48,000 mm^2 while the area of overhang separated by an air gap measured 15,400 mm^2. Ideally the area not in direct contact with the modules would be completely thermally insulated however, with the modules measuring only 3.40 mm in height. This left little room for the wires, connectors, electrical insulation and thermal insulation. Given that the wires and connectors were compulsory, the electrical insulation was prioritised over the thermal. A silicone mat measuring roughly 1.10 mm thick was cut to shape and used to protect the wiring while also adding some mild thermal resistance. A secondary benefit of using silicone mat was that due to starting as a piece larger than the unit itself, it was able to be cut out as one piece resulting in it securing the modules in place during assembly. The alternative which would have been exhaust wrap (can be made of multiple materials) is both thicker and only available in strips which would require an additional strategy to keep both it and the modules them in place during assembly and in use.

4.3.2.4 Underperforming modules

Before assembly, the modules were individually tested for polarity however, they were not tested for output under known conditions. After the seemingly low output during the tests, a spare module was tested using a block of aluminium chilled to $-17\ ℃$ in a freezer overnight and a saucepan of boiling water (assumed temperature of $100\ ℃$). With no thermal paste, this test yielded an open circuit voltage of 2.46 V with an assumed temperature delta of approximately $117\ ℃$. Conducting this test again after rechilling the aluminium and using moderate amount high-grade thermal paste (Kryonaut made by thermal grizzly) yielded 3.28 Volts. The amount of thermal paste used was equivalent to what was used during construction.

Assuming a linear relationship between open circuit voltage and the temperature delta, then factoring for the experimental results listed above for a delta of $117\ ℃$, yielded the following expected output per module.

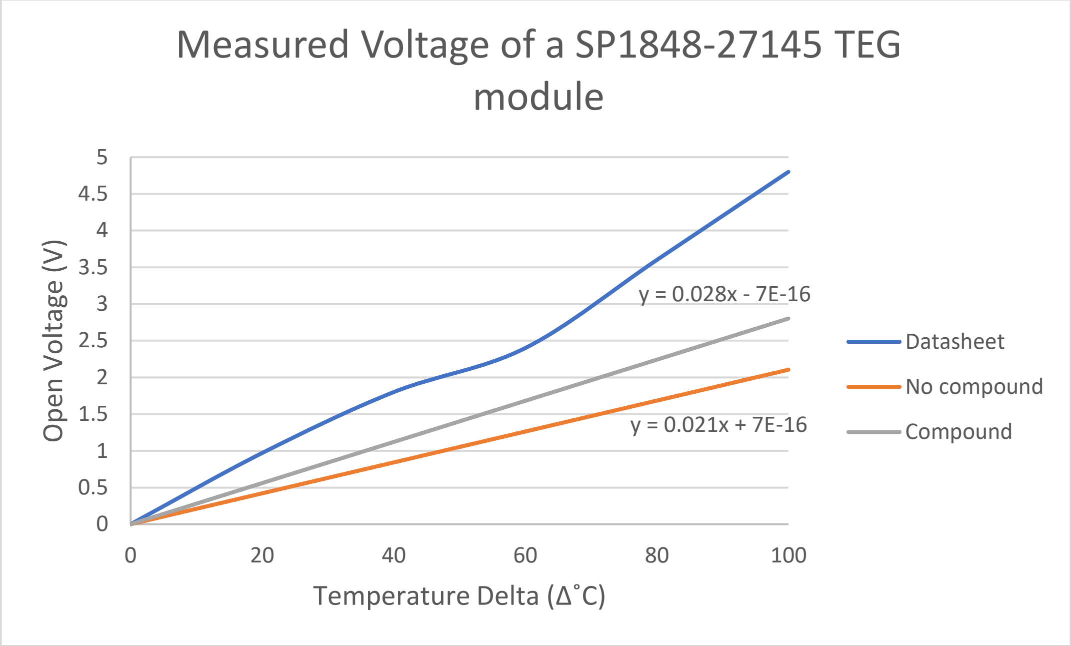


Figure 25 - Adjusted voltage of the TEG

As current produced is also linked to temperature delta and voltage, a similar process was applied to the expected current per module using the same factors calculated above.

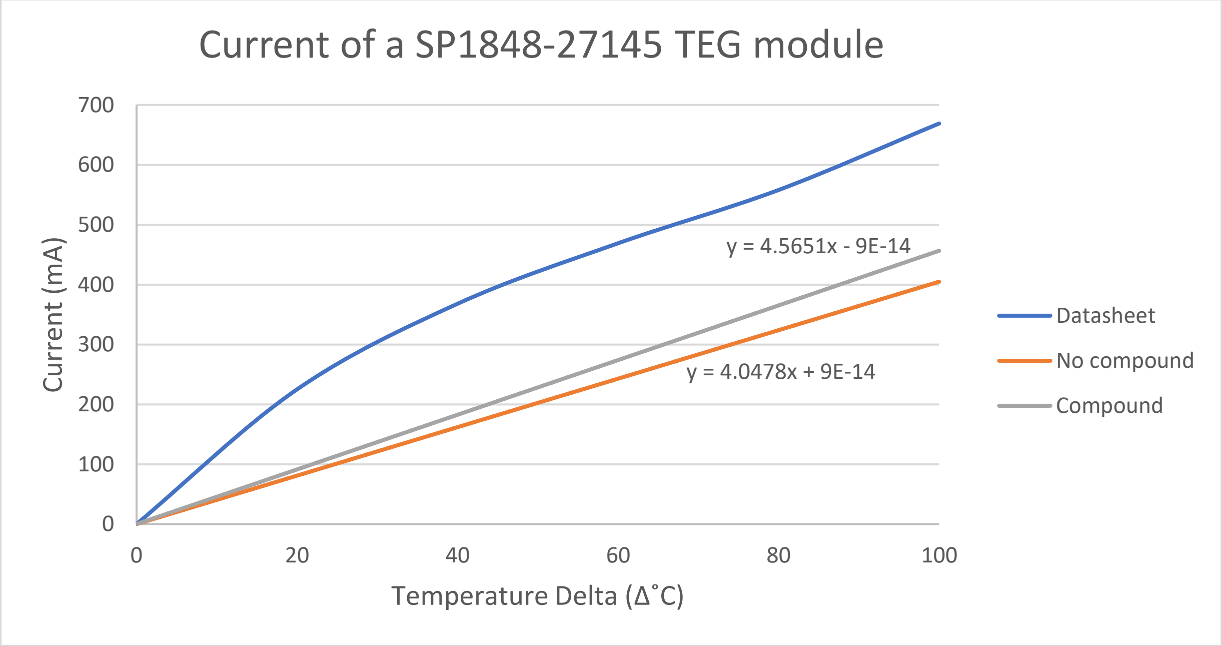


Figure 26 - Adjusted current of the TEG

Using the adjusted expected voltage and current per temperature gradient values, the expected output can be calculated.

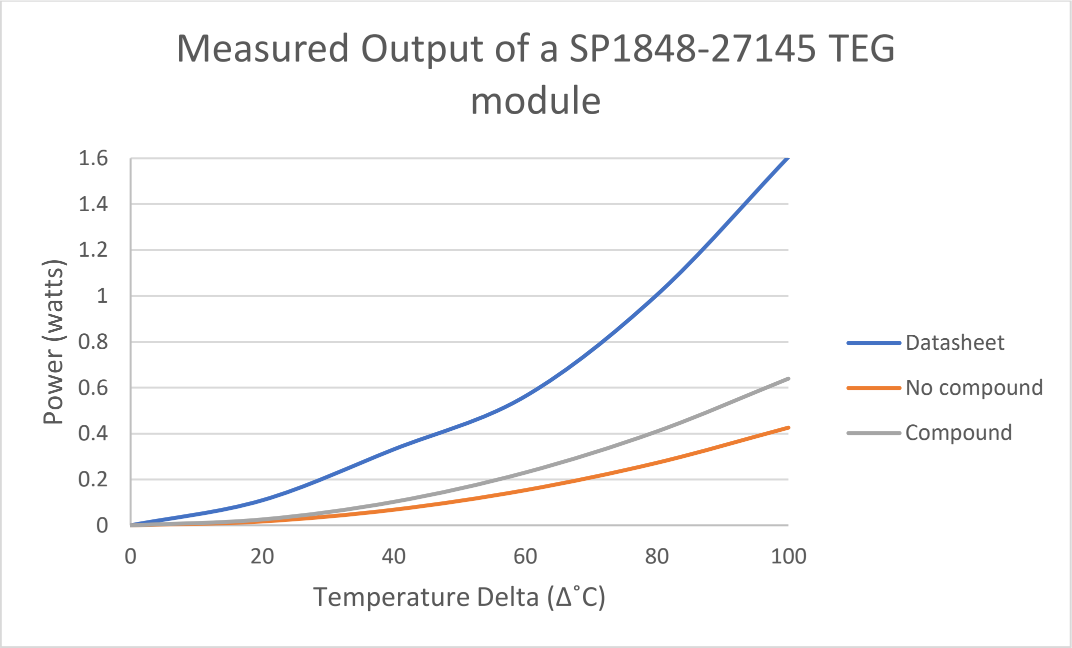


Figure 27 - Adjusted power output of the TEG

This graph demonstrates the lack of performance from the modules, at this stage it is unknown if all SP1848-27145 TEG modules preform similar to this with the specifications being incorrect or if this batch of modules suffered from poor manufacturing quality.

4.4 Theoretical Results

Using the adjusted values calculated in 4.3.2.4, the theoretical values were compared with the experimental values.

Using Data from 3500 RPM run at 15 minutes. Assuming thermal compound.

$$\Delta T = Hotplate\ (T) - Coldplate\ (T)$$
$$\Delta T = 130.1\ ℃ - 67.4\ ℃$$
$$\Delta T = 62.7\ ℃$$

Expected Voltage per module (open circuit)

$$V_{per\ module} = 0.028(\Delta T) - 7E^{-16}$$
$$V_{per\ module} = 0.028(62.7\ ℃)\ - 7E^{-16}$$
$$V_{per\ module} = 1.7556\ V$$

Expected Current per module

$$I_{per\ module} = 4.5651(\Delta T) - 9E^{-14}$$
$$I_{per\ module} = 4.5651(62.7) - 9E^{-14}$$
$$I_{per\ module} = 286.2318\ mA$$

Output for two parallel banks of 15 modules in series

$$V_{Total\ Open} = 15 * V_{per\ module}$$
$$V_{Total\ Open} = 15 * 1.7556\ V$$
$$V_{Total\ Open} = 26.334\ V$$

$$V_{Total\ Under\ load} = \frac{V_{Total\ Open}}{2}$$
$$V_{Total\ Under\ load} = \frac{26.334\ V}{2}$$
$$V_{Total\ Under\ load} = 13.167\ V$$

$$I_{Total} = 2 * I_{per\ module}$$
$$I_{Total} = 2 * 286.2318\ mA$$
$$I_{Total} = 572.4635\ mA$$

Output in Watts

$$P = V_{Total\ Under\ load}\ \times\ I_{Total}$$
$$P =\ 13.167\ V * 0.5724\ A$$
$$P \approx\ 7.5376\ Watts$$

Repeating this calculation for a no thermal paste condition

Using Data from 3500 RPM run at 15 minutes (ΔT = 62.7 ˚C)

$$P_{measured} = 6.672\ Watt$$

Expected

$$P_{no\ compound} = 5.013\ Watts$$
$$P_{compound} = 7.537\ Watts$$

It is worth noting that a different thermal paste was used during construction. Artic MX-5 thermal compound was used during construction which has a thermal conductivity of 5.0 W/mK whereas Kryonaut features a thermal conductivity of 12.5 W/mK. Artic was not used during the individual test due to all of it being used during construction. The Kryonaut was not used during construction due to its high price point.

Comparing the theoretical output against the measured experimental data.

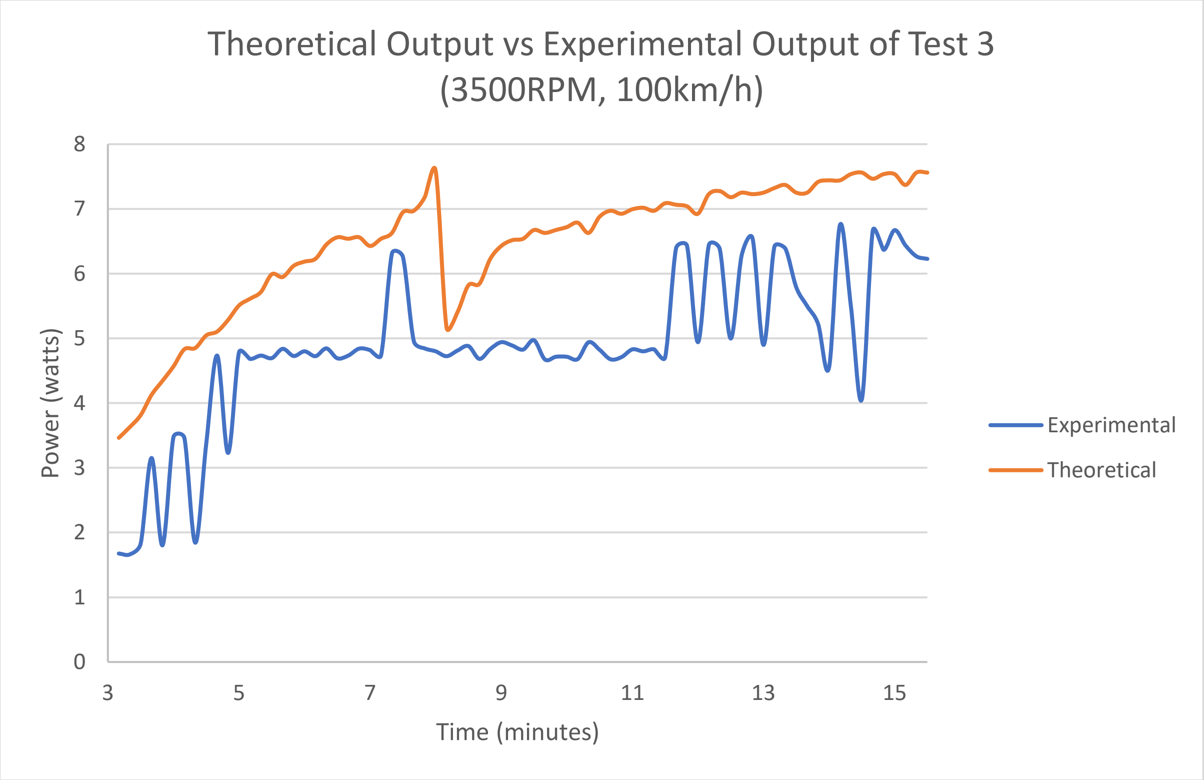


Figure 28 - Theoretical vs Experimental output of test 3

Note that the graph begins at the three-minute mark, this was due to there being an insufficient temperature gradient prior to this time, generating zero output.

4.5 Efficiency of the Array

The calculated outputs listed in the previous section 4.4 were done while assuming optimal conditions. These optimal conditions were neglecting losses incurred by modules experiencing mismatched temperature deltas and the electrical resistances in the wire and connections.

Accurately identifying the temperatures experienced by each module is not feasible within the scope of this project due to the limited physical space and monetary cost of additional temperature sensors and the matching equipment.

The resistance from the relatively short amount of wire used and crimp connectors is difficult to accurately measure due to the low resistance values but, could be estimated based off known information. The wire used to link the individual TEG modules was the pre-soldered 0.5 mm^2 (20 AWG) wire with an average resistance of 0.0333 ohms per meter. While this resistance value could be estimated to a certain degree, without the individual voltages (which are proportional to temperature delta) the formulas to predict output are not possible to complete.

Although it is not possible to compare the measured output to a more accurate theoretical output, it is possible to calculate the measured array efficiency when compared to ideal conditions.

$$\text{Using } \delta = \left|\frac{P_A - P_E}{P_E}\right| \times 100\%$$

$$P_{no\ compound\ error} = 33.1041\ \%\ (over)$$

$$P_{compound\ error} = 11.4841\ \%$$

From this calculation, the array in the device preformed at 88.52 % efficiency with the losses most likely due to a miss match in temperature deltas and slight variations physical connections of the hot and cold sides. Resistances due to the connections and wire can also reduce the output but this factor is less significant.

4.6 Impact on Fuel Economy

When estimating the impact on fuel economy, there is more than one strategy to approach this calculation. No matter which method is used, multiple assumptions must be made in order to complete the calculation. Even with these assumptions, it is difficult to incorporate all vehicles as the values required to calculate fuel economy vary substantially due to numerous factors. These factors can include, engine size, weight, vehicle size, year of manufacture, modifications, average speed, road surface, maintenance etc. For this section, estimations will be made on the potential benefits to the car used during the tests, a 1992 Corolla Hatch.

The following relationship was devised to estimate any changes to fuel consumption:

$$\frac{Original\ load\ on\ engine}{Original\ fuel\ consumption} = \frac{New\ load\ on\ engine}{New\ fuel\ consumption}$$

Power required to keep the vehicle in motion at 100km/h

The power required to keep the vehicle in motion is made up of three components: the electrical power required to run the engine, the mechanical power to overcome drag forces and the mechanical power to overcome rolling resistance.

Electrical power required to keep the vehicle running

The electrical draw to keep the vehicle running can be simplified to three main components, the ECU, the fuel pump and injectors. Utilising data previously found for another vehicle of a similar size and characteristics (Honda Civic 1992 -1995, 1.6L engine).

Power required to maintain 3500 RPM

$$P_{Elec\ Req} = 163\ Watts$$

Alternator efficiency (Mechanical to Electrical) crank

$$\begin{aligned} Alt_{eff\ Total} &= Belt_{eff} \times\ Alt_{eff} \\ Alt_{eff\ Total} &= 0.98 \times 0.3 \\ Alt_{eff\ Total} &= 0.294 \end{aligned}$$

Electrical load on Engine

$$\begin{aligned} P_{Electrical} &= {}^{P_{Elec\ Req}}\!/_{Alt_{eff\ Total}} \\ P_{Electrical} &= {}^{163\ Watts}\!/_{0.294} \\ P_{Electrical} &= 554.4218\ Watts \\ P_{Electrical} &= 0.5544\ kW \end{aligned}$$

Mechanical power required

$$P_{Mechanical} = \left(F_{Drag} + F_{Rolling}\right) \times v$$

Force due to drag

$C_D = 0.35$
$C_DA = 0.66\ m^2$
$p = 1.2\ kg/m^3$
$v = 27.7777\ m/s$

$$\begin{aligned} F_{Drag} &= {}^{1}\!/_{2}\, C_D A v^2 \\ F_{Drag} &= 0.5 \times 0.66\ m^2 \times (27.7777\ {}^{m}\!/_{s})^2 \\ F_{Drag} &= 305.5556\ N \end{aligned}$$

Force due to rolling resistance

$c = 0.02$ (asphalt)
$m = 1075\ kg$
$a_g = 9.81\ m/s^2$

$$\begin{aligned} F_{Rolling} &= cW \\ F_{Rolling} &= c \times m \times a_g \\ F_{Rolling} &= 0.02 \times 1075\ kg \times 9.81\ {}^{m}\!/_{s^2} \\ F_{Rolling} &= 210.915\ N \end{aligned}$$

Mechanical power required

$$P_{Mechanical} = \left(F_{Drag} + F_{Rolling}\right) \times v$$
$$P_{Mechanical} = (305.5556\ N + 210.915\ N) \times 27.7777\ {}^{m}/_{s}$$
$$P_{Mechanical} = 14{,}346\ Watts$$
$$P_{Mechanical} = 14.346\ kW$$

Total power required to maintain 100km/h

$$P_{Original\ Load} = P_{Mechanical} + P_{Electrical}$$
$$P_{Original\ Load} = 14.346\ kW + 0.5544\ kW$$
$$P_{Original\ Load} = 14.9008\ kW$$

New electrical load

$$P_{New\ Electrical} = \frac{\left(P_{Elec\ Req} - P_{Generated}\right)}{Alt_{eff\ Total}}$$
$$P_{New\ Electrical} = \frac{(163\ Watts - 7\ Watts)}{0.294}$$
$$P_{New\ Electrical} = 0.5306\ kW$$

New power required to maintain 100km/h

$$P_{New\ Load} = P_{Mechanical} + P_{Electrical}$$
$$P_{New\ Load} = 14.346\ kW + 0.5306\ kW$$
$$P_{New\ Load} = 14.877\ kW$$

New fuel economy at 100km/h

$$\frac{P_{Original\ Load}}{Original\ fuel\ consumption} = \frac{P_{New\ Load}}{New\ fuel\ consumption}$$
$$\frac{14.9008\ kW}{7.4\ L/100km} = \frac{14.877\ kW}{New\ fuel\ consumption}$$
$$New\ fuel\ consumption = 7.3881\ L/100km$$

Percentage reduction

$$\text{Using } \delta = \left|\frac{Fuel_{New} - Fuel_{Old}}{Fuel_{Old}}\right| * 100\%$$
$$Reduction = 0.1597\ \%$$

4.6.1 Fuel & Monetary Savings

In Australia the average vehicle travels a distance of 13,301 km per year (Budget Direct 2020). Given the factory fuel economy of 7.40 L per 100 km, this would require a minimum of 984.27 L per year. With the reduction calculated above this equates to a saving of 1.57 L per year. If a fuel cost of $2.00 per L is assumed then this reduction can be represented as a yearly saving of $3.14.

When repeating the calculation process in section 4.6 while assuming the maximum output of 48 watts was achieved, the reduction in fuel consumption calculates out to be 1.10%, 10.82 L or a saving of $21.63 per year.

From an individual user's viewpoint, this reduction in consumption is relatively minor compared to yearly vehicle running costs. If evaluated on the assumption of widespread adoption and its effect on the country's consumption of fuel then the values become more significant. Assuming a 5% adoption rate at maximum output of each unit, with over 20 million vehicles on the road (Australia) today. The reduction of fuel consumption per year is roughly 10.82 million L.

4.7 Cost

As this project was undertaken by an individual undergrad student, there was a limitation on the available funds. This limitation restricted the possible components to pre-made readily available parts as opposed to custom made parts. Custom made parts could be better optimised for the given conditions however, are generally more expensive, particularly in low production numbers. This extra cost is normally attributed to extra tooling and labour. If a similar device were to be put into production on a large scale, then the potential benefits from custom components would eventually outweigh the extra investment cost as said cost becomes shared across many units.

4.7.1 Shortages and Shipping

Throughout the duration of the project, there were shortages of components due to ongoing worldwide events. This scenario limited the available components and, in some cases, raised the cost of these components due to supply and demand.

Given the available timeframe of the project, shipping times and their associated cost also needed to be considered in order to complete the device on time. The worldwide events mentioned above also negatively impacted shipping times making them less predictable. For the purposes of this project, when possible, expedited shipping was used to mitigate this issue as much as possible. This became fortuitous as some suppliers were delayed and some orders were cancelled. As the cost of shipping was increased due to the current circumstances of the project, shipping costs were not included in the final cost breakdown for the device.

4.7.2 Cost Breakdown

The total cost of the unit built in this project (excluding shipping) was $411.33 AUD. For the purpose of analysis, the parts list has been subcategorised into four subcategories:

Category	**Cost ($)**
Heatsink	107.03
TEG modules	74.40
Body	55.80
Supporting Components (excluding solar controller)	174.10

Table 7 - Cost breakdown

As seen above, the smaller and less obvious supporting components such as thermal paste, connectors, heat shrink etc quickly combined to become the most significant portion (42.3%) of the final cost.

In a mass production scenario, the costs involved are likely to fall on a per unit basis. The main contributor to this would be the acquisition of components at bulk pricing direct from vendors/manufactures or even parts made to order to suit the specific application. Unfortunately, with the information available, it is difficult to obtain a well-informed estimate of the cost per unit in the bulk production scenario mentioned.

4.8 Weight

Any changes to the vehicles weight will naturally affect the fuel efficiency. For the earlier calculations in 4.6 the total weight was considered to be consistent in order to calculate the effect of power generation alone. The final constructed unit weighed 10.5 kg with the section of exhaust it was replacing weighing 3.2 kg, therefore a net gain of 7.3 kg.

Completing these calculations again while accounting for this extra mass yielded:

Power Generation	**Reduction in consumption** (%)	**Reduction in consumption** (L)	**Monetary Savings** ($, at $2 per L)
7	-0.1072	-1.0552	-2.11
48	1.0965	10.7934	21.59

Table 8 - Influence of weight

These results indicate that at the 7 watt power generation seen during testing, the effect of the unit would actually be a net loss as the unit costs more energy to move its mass then the unit itself provides. It is important to reiterate that these calculations are only accounting for sustained motion and not acceleration which would be more significantly influenced by a change in vehicle weight.

4.9 Viability

The original objective was to determine if a reasonably priced unit capable of reducing fuel consumption could be constructed. To be feasible the margin of fuel consumption reduction would need to be able to reimburse the original investment cost within a reasonable time frame.

When considering the effect on fuel consumption it is clear that this device is not viable. Even when negating the weight of the device, it would take 25 years at maximum output for the unit to reimburse its initial purchase cost for the average user. Furthermore, this calculation of return on investment is ignoring labour costs to build and instal, lifespan of the device, recycling of the device and the environmental impact of sourcing the individual components.

Chapter 5: Conclusions

5.1 Outline

This chapter condenses, reiterates and concludes the findings of this project. It re-establishes the original aims and objectives set forth at the beginning of the project, briefly summarises the implications of the research along with the findings and lastly provides recommendations for potential future research, ending with concluding statements.

5.2 Summarised Aims

The aim of this project was to verify if the currently available thermoelectric generator modules could recover waste heat energy in the form of electricity from a vehicles exhaust. This recycled electrical energy could then be used to assist the alternator in supplying the vehicles electrical demand. The purpose of such a device was to reduce the amount of mechanical energy converted into electricity, therefore increasing fuel economy. To be financially viable this unit would need to increase fuel economy by a significant margin in order for the initial investment cost to be reimbursed within a couple of years. Due to the variance in vehicle design, the unit would need to be somewhat universal and compact to maximise the potential supply market.

5.3 Summation of Research

5.3.1 Potential Implications

Research showed that the concept of utilising thermoelectric generators to recover waste heat from a vehicles exhaust to improve fuel economy, is not a newly formulated idea. The goal of reducing emissions alongside tightening restrictions on new vehicles emissions had prompted multiple stakeholders to develop the concept further. Exact details on its development and the attempts previously made were not openly available. This is potentially due to several of the studies being commissioned by various competing organisations.

5.3.2 Project Outcomes

A working unit was built and tested using 30 modules with a theoretical maximum output of 48 watts. The designs components was primarily based on the data collected from the test vehicle and the physical space available. In testing it produced less power than expected due to two main reasons:

- ➢ The TEG modules produced less power at temperatures specified in their specification sheets. This was found afterwards by testing a spare module under known conditions. Analysing the results with this new information and preforming calculations based on the temperatures recorded revealed an array efficiency of 88.5% suggesting that the unit was indeed functioning as intended. The slight loss in efficiency could stem from a variety of potential reasons but is most likely due to the slight temperature differences experienced by the individual modules.

- A theoretical static testing method was chosen due to increased safety, minimisation of variables and a vastly shorter testing period required to achieve consistent results. Unfortunately, this testing method was not able to simulate the equivalent engine load experienced in normal operation, or windspeeds above 50km/h. This reduced engine load generated less heat at given RPMs while the maximum airspeed of 50km/h reduced the heat dissipation capacity at higher simulated speeds. These factors combined to reduce the temperature gradient across the TEG modules (when compared to normal driving).

These two factors subsequently reduced the expected electrical output of the simulated driving tests. The 60km/h (2500 RPM) test failed to produce a large enough gradient to begin producing power while the 100km/h (3500 RPM) test generated 7 watts after a few minutes of operation. Using the data collected and convenient assumptions, calculations suggest if adequate windspeed were to be achieved the increased heat dissipation would increase output by 42%.

The theoretical reduction of fuel consumption with 7 watts of power generation was calculated to be 0.15% (at 100km/h). If the unit's maximum output were achieved (48 watts) then the calculated reduction in fuel consumption is 1.1%. These calculations were completed assuming there was no additional weight after installing the unit, in practice the complete system resulted in an additional 7.3kg to the vehicles curb weight. When factoring in this additional weight, the reduction on fuel consumption was -0.107 % (at 7 watts) and 1.096 % (at 48 watts).

Given the cost of the unit at $411.33 it would take an average of 25 years even under ideal conditions (48 watts) before the reduction in fuel consumption would offset the original cost of the unit. This extended timeframe clearly demonstrates that this design is not feasible as a method to reduce the running costs of a vehicle. Even under ideal conditions (assuming maximum output), the current cost of Thermoelectric generators and the cost and weight of their supporting components makes them ineffective at reducing the running costs of a vehicle.

5.4 Future Work & Recommendations

Upon completion of the project, the research gaps encountered and recommendations of future work are as follows:

Development of thermoelectric generator materials - Further research on the materials used to construct a TEG or more specifically, research to optimise the Seebeck effect and to identify more effective dissimilar metals. Higher preforming materials would generate more power for a given heat differential allowing for a greater power density.

An in-depth comparison between water cooling and air cooling - At a surface level it is clear that a cooling system that utilises water will be more expensive due to the added components and complexity. However, it is unknown if the increase in performance makes this style of cooling optimal, particularly when confined to the same volume of physical space (watt per cost ratio). This data would be useful for future attempts at harnessing heat using TEG modules by acting as a general guide to the trade-offs with each method. If water cooling was cost competitive, it would allow for much greater geometrical flexibility due to its ability to

Research and development of TEG controllers – During the project it was noted that there was a lack of information on TEG power management controllers. From previous research papers it was shown that a Maximum Power Point Tracking (MPPT) style management system was the currently optimal however, when looking for a dedicated TEG controller only one was able to be found. This TEG controller was expensive (considering the capacity) and contained very little information about the unit itself. For the project a MPPT solar controller was used as solar panel seem to exhibit similar output characteristics to TEG modules. It is unknown if a controller designed for TEGs specifically would be more efficient at generating power.

Alternator Deactivation – During the research phase of the project it was found that the efficiency of alternators can vary considerably depending on the electrical load. An oversimplification of this behaviour is that generally alternators are inefficient (25%) at low load conditions, the efficiency begins to rise as the load increases to a maximum of 55% at half the alternators output rating. As the load rises beyond this midway point the efficiency begins to fall again. Could a circuit be implemented that would deactivate the alternator until the demand is in a higher efficiency region and what the effects of this be to both the fuel economy and various components health.

5.5 Concluding Statements

In conclusion, this dissertation has produced the following observations and findings:

- The power output of thermoelectric modules demonstrates an approximate exponential curve with both the voltage and current displaying a linear relationship with temperature gradient.
- The current TEGs available in circulation, generally online, are not suitable for reducing the fuel consumption of vehicles in terms of its cost to performance ratio.
- Although thermoelectric modules are compact and lightweight, the supporting components required for adequate cooling, in terms of the individual module itself, are large and heavy.
- The optimal material for the hot plate in this application was aluminium grade 5083.

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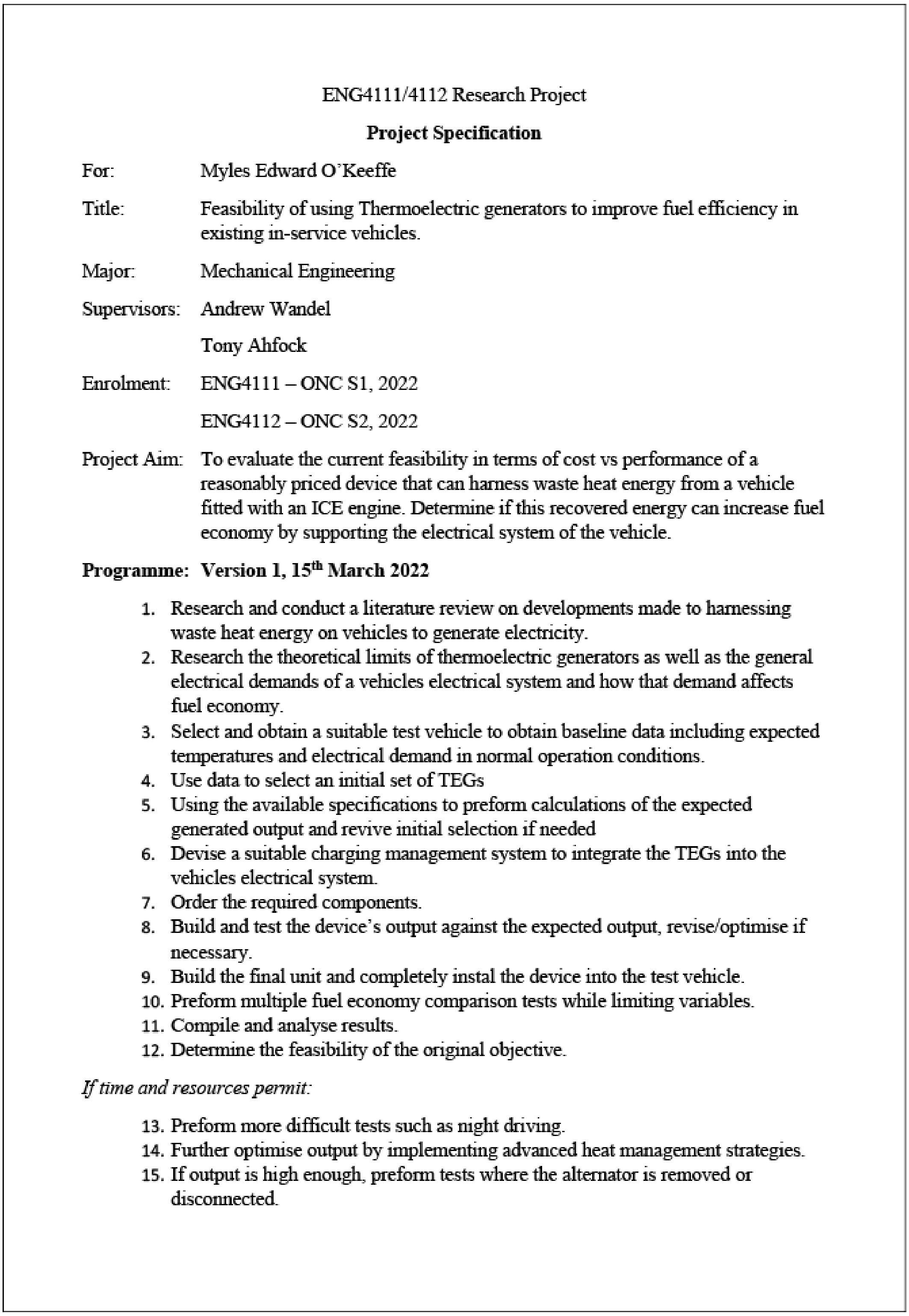
Chapter 7: Appendix

7.1 Project Specifications



ENG4111/4112 Research Project

Project Specification

For: Myles Edward O'Keeffe

Title: Feasibility of using Thermoelectric generators to improve fuel efficiency in existing in-service vehicles.

Major: Mechanical Engineering

Supervisors: Andrew Wandel
Tony Ahfock

Enrolment: ENG4111 – ONC S1, 2022
ENG4112 – ONC S2, 2022

Project Aim: To evaluate the current feasibility in terms of cost vs performance of a reasonably priced device that can harness waste heat energy from a vehicle fitted with an ICE engine. Determine if this recovered energy can increase fuel economy by supporting the electrical system of the vehicle.

Programme: Version 1, 15th March 2022

1. Research and conduct a literature review on developments made to harnessing waste heat energy on vehicles to generate electricity.
2. Research the theoretical limits of thermoelectric generators as well as the general electrical demands of a vehicles electrical system and how that demand affects fuel economy.
3. Select and obtain a suitable test vehicle to obtain baseline data including expected temperatures and electrical demand in normal operation conditions.
4. Use data to select an initial set of TEGs
5. Using the available specifications to preform calculations of the expected generated output and revive initial selection if needed
6. Devise a suitable charging management system to integrate the TEGs into the vehicles electrical system.
7. Order the required components.
8. Build and test the device's output against the expected output, revise/optimise if necessary.
9. Build the final unit and completely instal the device into the test vehicle.
10. Preform multiple fuel economy comparison tests while limiting variables.
11. Compile and analyse results.
12. Determine the feasibility of the original objective.

If time and resources permit:

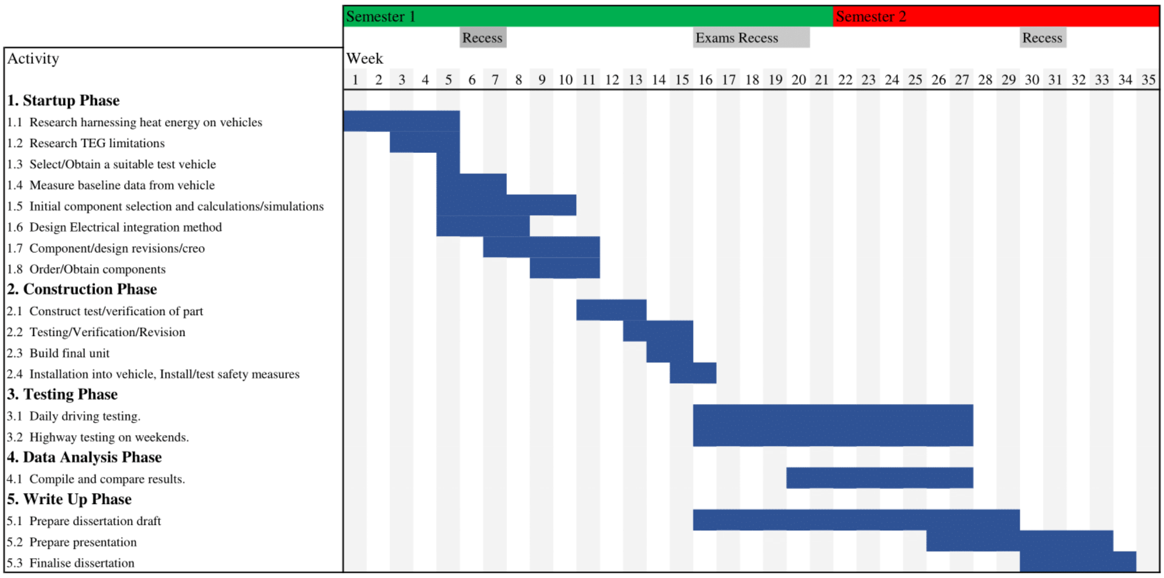
13. Preform more difficult tests such as night driving.
14. Further optimise output by implementing advanced heat management strategies.
15. If output is high enough, preform tests where the alternator is removed or disconnected.

7.2 Project Plan

ENG4111/4112 Research Project

Project Plan

The proposed schedule for this project is as follows:



It is worth noting how the tasks are skewed towards the earlier weeks. This is due to the potential time required to obtain the chosen components as well as the time required to test 'everyday driving' and obtain substantial averaged results.

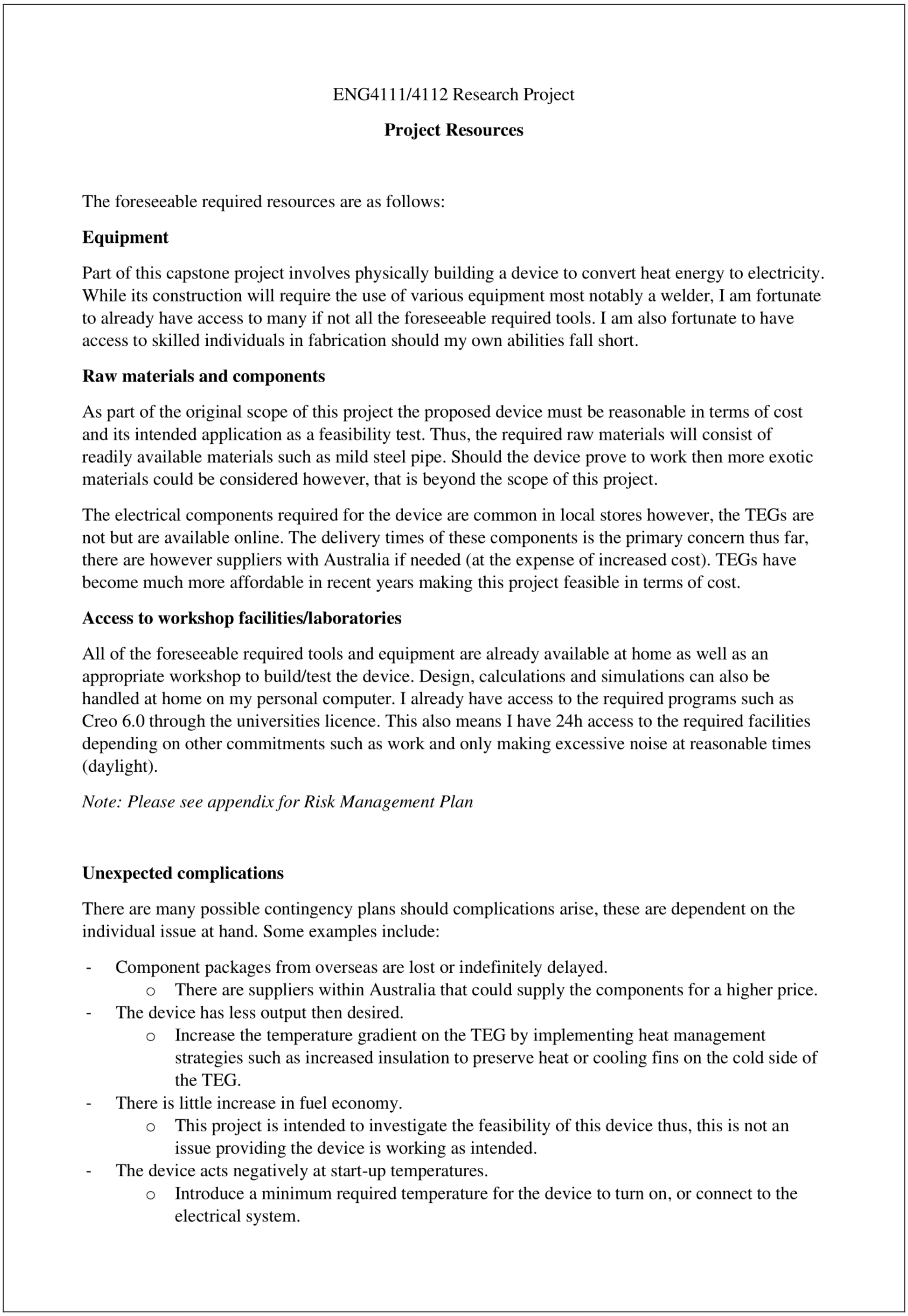
The first major phase 'Startup' is foreseen as the most intensive phase of this project as it contains the most unknowns where an overall design must be conceived and simulated. The later phases are focused on executing and testing the design conceived in phase 1.

Communication schedule

Communication will be primarily over email to provide updates or to discuss issues encountered. If a problem is encountered that is difficult to properly explain in detail through an email with photographs such as a wiring, construction or behaviour issue, then an on-campus meeting can be arranged to identify and discuss the issue as this will provide the quickest and easiest turnaround for a solution.

Given the limited time of the supervisors the frequency of updates will be limited to once a fortnight. This is to allow for a brief concentrated communication schedule should a problem arise.

7.3 Project Resources



ENG4111/4112 Research Project

Project Resources

The foreseeable required resources are as follows:

Equipment

Part of this capstone project involves physically building a device to convert heat energy to electricity. While its construction will require the use of various equipment most notably a welder, I am fortunate to already have access to many if not all the foreseeable required tools. I am also fortunate to have access to skilled individuals in fabrication should my own abilities fall short.

Raw materials and components

As part of the original scope of this project the proposed device must be reasonable in terms of cost and its intended application as a feasibility test. Thus, the required raw materials will consist of readily available materials such as mild steel pipe. Should the device prove to work then more exotic materials could be considered however, that is beyond the scope of this project.

The electrical components required for the device are common in local stores however, the TEGs are not but are available online. The delivery times of these components is the primary concern thus far, there are however suppliers with Australia if needed (at the expense of increased cost). TEGs have become much more affordable in recent years making this project feasible in terms of cost.

Access to workshop facilities/laboratories

All of the foreseeable required tools and equipment are already available at home as well as an appropriate workshop to build/test the device. Design, calculations and simulations can also be handled at home on my personal computer. I already have access to the required programs such as Creo 6.0 through the universities licence. This also means I have 24h access to the required facilities depending on other commitments such as work and only making excessive noise at reasonable times (daylight).

Note: Please see appendix for Risk Management Plan

Unexpected complications

There are many possible contingency plans should complications arise, these are dependent on the individual issue at hand. Some examples include:

- Component packages from overseas are lost or indefinitely delayed.
    - There are suppliers within Australia that could supply the components for a higher price.
- The device has less output then desired.
    - Increase the temperature gradient on the TEG by implementing heat management strategies such as increased insulation to preserve heat or cooling fins on the cold side of the TEG.
- There is little increase in fuel economy.
    - This project is intended to investigate the feasibility of this device thus, this is not an issue providing the device is working as intended.
- The device acts negatively at start-up temperatures.
    - Introduce a minimum required temperature for the device to turn on, or connect to the electrical system.

7.4 Risk Assessment

7.4.1 Hierarchy of controls

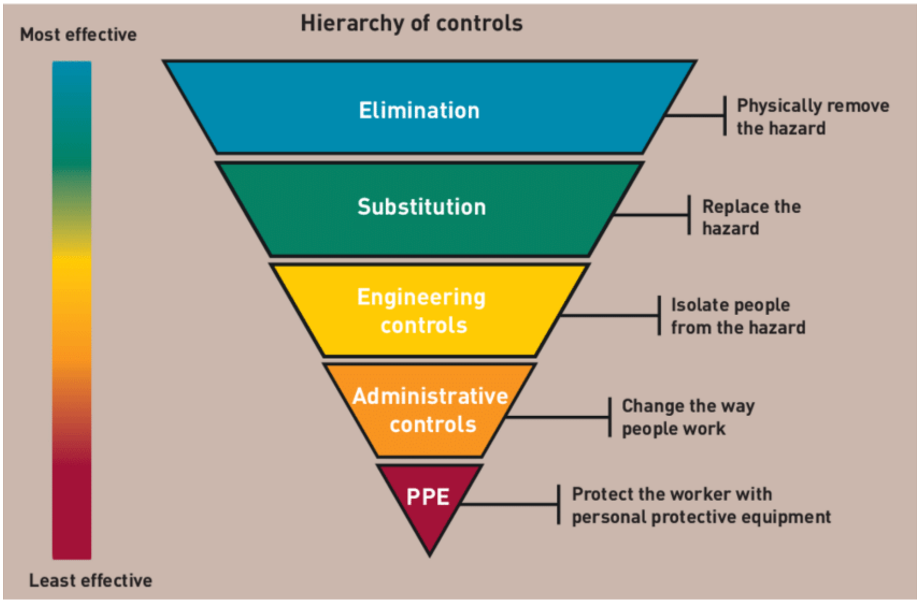
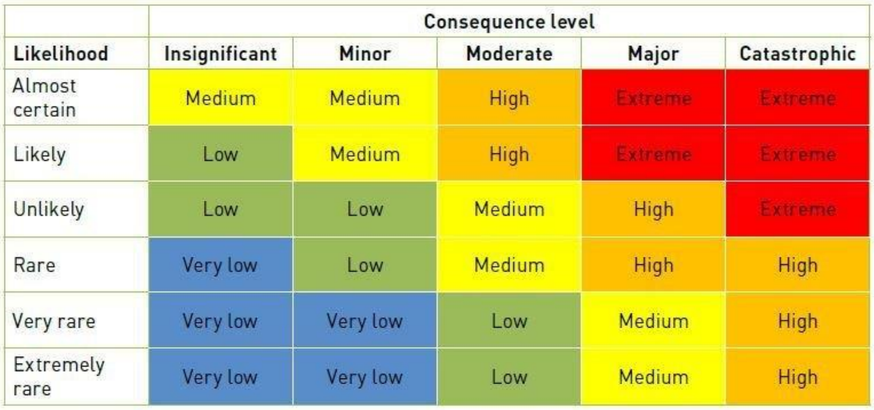


Figure 29 - Hierarchy of controls

Before conducting any engineering activity, it is imperative to first mitigate any of the potential risks and hazards involved against the Hierarchy of Controls. This process is an Industry Standard and should

7.4.2 Risk Matrix Template



	Consequence level				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost certain	Medium	Medium	High	Extreme	Extreme
Likely	Low	Medium	High	Extreme	Extreme
Unlikely	Low	Low	Medium	High	Extreme
Rare	Very low	Low	Medium	High	High
Very rare	Very low	Very low	Low	Medium	High
Extremely rare	Very low	Very low	Low	Medium	High

Figure 30 - Risk identification matrix

All Risks and Hazards were first identified and graded according the matrix above with no controls in place. Reasonable controls were then considered and utilised in order of effectiveness according to the hierarchy of control shown above. Lastly the Risks and Hazards were re-evaluated with these controls in place to determine if the rating was at a reasonable level.

The potential risks encountered during this project can categorised into two groups, these groups are defined by what the individual risk may impact. The first is personal impacts with the second category impacting materials alongside the project itself.

7.4.3 Personal Risk Assessment

Risk or Hazard	**Risk Assessment without Controls**	**Control Mitigation**	**Risk Assessment after Controls**
Temperature burns when obtaining preliminary data	Likelihood – Unlikely Impact – Moderate Rating – Medium	Correct use of equipment, non-contact/remote measuring equipment.	Likelihood – Very rare Impact – Moderate Rating – Low
Working underneath a vehicle – falling dirt and debris	Likelihood – Rare Impact – Minor Rating – Low	Pressure clean underside of vehicle, use of goggles and/or face shield.	Likelihood – Very rare Impact – Minor Rating – Very low
Working underneath vehicle – vehicle falling	Likelihood – Rare Impact – Major Rating – High	Correct use of rated jack stands, redundant supports should a jack stand fail (spare wheel under vehicle as well)	Likelihood – Very Rare Impact – Major Rating – Medium
Slipping/Tripping over in workshop	Likelihood – Rare Impact – Minor Rating – Low	Maintaining a clean and well-lit workspace.	Likelihood – Very rare Impact – Minor Rating – Very low
Hearing damage when obtaining data	Likelihood – Rare Impact – Minor Rating – Low	Hearing protection and limiting exposure.	Likelihood – Very rare Impact – Minor Rating – Very low
Cutting and Welding	Likelihood – Unlikely Impact – Moderate Rating – Medium	Outsourcing these tasks to a qualified fabricator	Likelihood – Very Rare Impact – Moderate Rating – low
Wiring (device and integration)	Likelihood – Unlikely Impact – Minor Rating – Low	Correct operating procedures and PPE	Likelihood – Very Rare Impact – Minor Rating – Very low
Minor cuts, impacts and abrasions when using hand tools	Likelihood – Unlikely Impact – Insignificant Rating – Low	Correct use of tools, clean hands or gloves to reduce slipping. Proper body position/bracing	Likelihood – Rare Impact – Insignificant Rating – Very Low
Overheating of Device	Likelihood – Unlikely Impact – Moderate	installation of warning light so operation of	Likelihood – Vary rare Impact – Moderate

	Rating – Medium	the vehicle can be ceased.	Rating – Low
Driving on public roads – accident	Likelihood – Rare Impact – Major Rating – High	Safe driving behaviour, defensive driving.	Likelihood – Very Rare Impact – Major Rating – Medium

Table 9 - Personal risk identification and controls

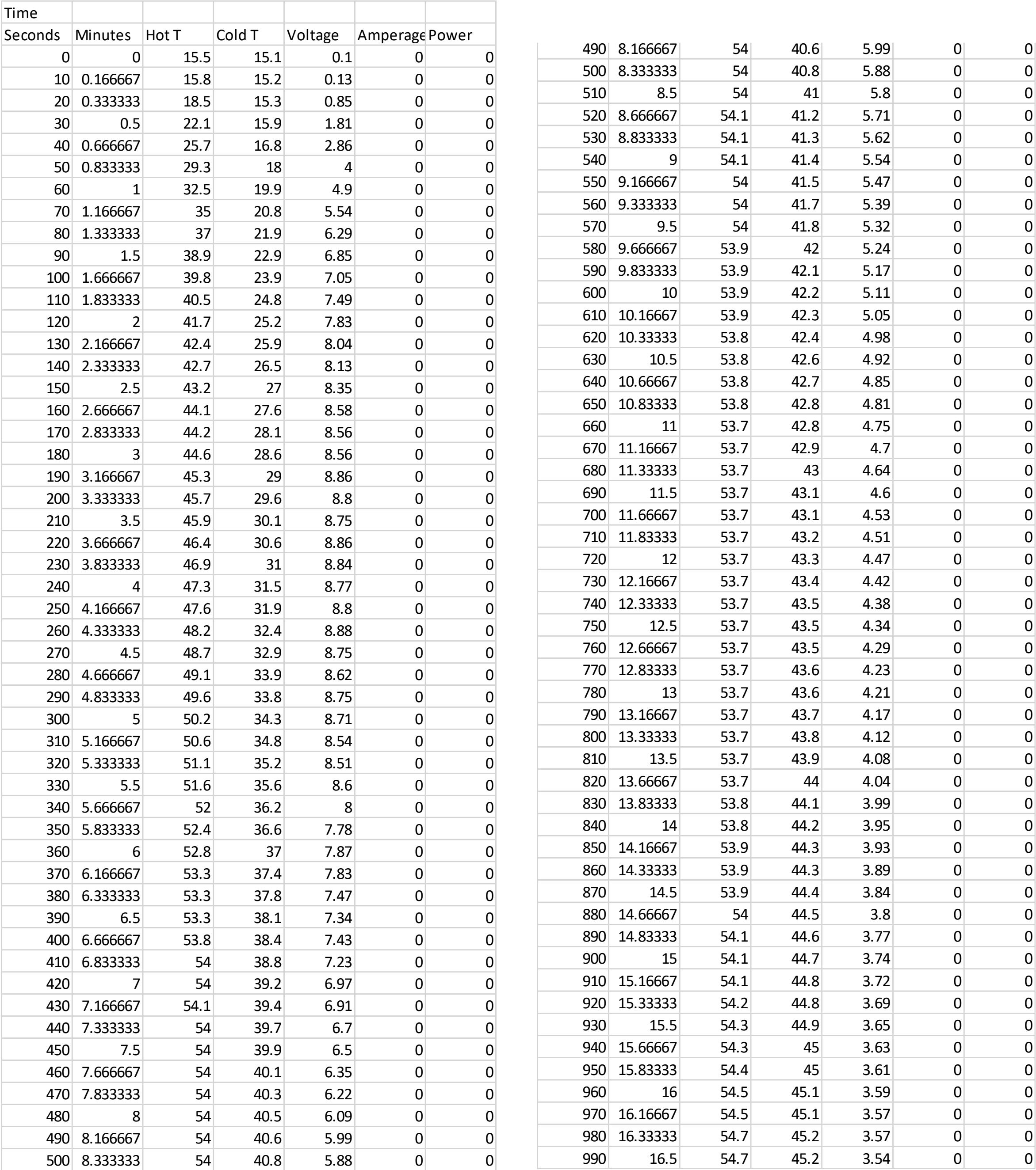
7.4.4 Project and Property Risk

Risk or Hazard	**Risk Assessment without Controls**	**Control Mitigation**	**Risk Assessment after Controls**
Report incompletion due to shipping times	Likelihood – Unlikely Impact – Moderate Rating – Medium	Careful selection of suppliers, Ordering as early as possible, Backup suppliers	Likelihood – Very rare Impact – Moderate Rating – Low
Loss of data/report through computer malfunction	Likelihood – Unlikely Impact – Moderate Rating – Medium	Cloud storage backup and local USB backup	Likelihood – Very rare Impact – Moderate Rating – Low
Personal sickness or injury (eg broken hand) resulting in time lost	Likelihood – Rare Impact – Minor Rating – Low	Maintain consistent progress throughout the duration of the project	Likelihood – Rare Impact – Minor Rating – Low
Personal struggles, life commitments, mental health, academic difficulties	Likelihood – Unlikely Impact – Moderate Rating – Medium	Regular check-ins with supervisors, seeking help and advice when needed	Likelihood – Unlikely Impact – Minor Rating – Low
Damaging tools	Likelihood – Unlikely Impact – Moderate Rating – Medium	Correct use of tools for their intended purpose.	Likelihood – Very rare Impact – Moderate Rating – Low
Fire from wire shorting on vehicle body	Likelihood – Unlikely Impact – Moderate Rating – Medium	Correctly sized wire for current draw, correctly sized fuses installed in the correct location. All wiring routed and restrained away from hazards.	Likelihood – Very rare Impact – Moderate Rating – Low

Table 10 - Project risk and property risk identification and controls

7.5 Project Data & Further Results

7.5.1 Test 1 Raw Data, Idle, 900 RPM



Time						
Seconds	Minutes	Hot T	Cold T	Voltage	Amperage	Power
0	0	15.5	15.1	0.1	0	0
10	0.166667	15.8	15.2	0.13	0	0
20	0.333333	18.5	15.3	0.85	0	0
30	0.5	22.1	15.9	1.81	0	0
40	0.666667	25.7	16.8	2.86	0	0
50	0.833333	29.3	18	4	0	0
60	1	32.5	19.9	4.9	0	0
70	1.166667	35	20.8	5.54	0	0
80	1.333333	37	21.9	6.29	0	0
90	1.5	38.9	22.9	6.85	0	0
100	1.666667	39.8	23.9	7.05	0	0
110	1.833333	40.5	24.8	7.49	0	0
120	2	41.7	25.2	7.83	0	0
130	2.166667	42.4	25.9	8.04	0	0
140	2.333333	42.7	26.5	8.13	0	0
150	2.5	43.2	27	8.35	0	0
160	2.666667	44.1	27.6	8.58	0	0
170	2.833333	44.2	28.1	8.56	0	0
180	3	44.6	28.6	8.56	0	0
190	3.166667	45.3	29	8.86	0	0
200	3.333333	45.7	29.6	8.8	0	0
210	3.5	45.9	30.1	8.75	0	0
220	3.666667	46.4	30.6	8.86	0	0
230	3.833333	46.9	31	8.84	0	0
240	4	47.3	31.5	8.77	0	0
250	4.166667	47.6	31.9	8.8	0	0
260	4.333333	48.2	32.4	8.88	0	0
270	4.5	48.7	32.9	8.75	0	0
280	4.666667	49.1	33.9	8.62	0	0
290	4.833333	49.6	33.8	8.75	0	0
300	5	50.2	34.3	8.71	0	0
310	5.166667	50.6	34.8	8.54	0	0
320	5.333333	51.1	35.2	8.51	0	0
330	5.5	51.6	35.6	8.6	0	0
340	5.666667	52	36.2	8	0	0
350	5.833333	52.4	36.6	7.78	0	0
360	6	52.8	37	7.87	0	0
370	6.166667	53.3	37.4	7.83	0	0
380	6.333333	53.3	37.8	7.47	0	0
390	6.5	53.3	38.1	7.34	0	0
400	6.666667	53.8	38.4	7.43	0	0
410	6.833333	54	38.8	7.23	0	0
420	7	54	39.2	6.97	0	0
430	7.166667	54.1	39.4	6.91	0	0
440	7.333333	54	39.7	6.7	0	0
450	7.5	54	39.9	6.5	0	0
460	7.666667	54	40.1	6.35	0	0
470	7.833333	54	40.3	6.22	0	0
480	8	54	40.5	6.09	0	0
490	8.166667	54	40.6	5.99	0	0
500	8.333333	54	40.8	5.88	0	0
490	8.166667	54	40.6	5.99	0	0
500	8.333333	54	40.8	5.88	0	0
510	8.5	54	41	5.8	0	0
520	8.666667	54.1	41.2	5.71	0	0
530	8.833333	54.1	41.3	5.62	0	0
540	9	54.1	41.4	5.54	0	0
550	9.166667	54	41.5	5.47	0	0
560	9.333333	54	41.7	5.39	0	0
570	9.5	54	41.8	5.32	0	0
580	9.666667	53.9	42	5.24	0	0
590	9.833333	53.9	42.1	5.17	0	0
600	10	53.9	42.2	5.11	0	0
610	10.16667	53.9	42.3	5.05	0	0
620	10.33333	53.8	42.4	4.98	0	0
630	10.5	53.8	42.6	4.92	0	0
640	10.66667	53.8	42.7	4.85	0	0
650	10.83333	53.8	42.8	4.81	0	0
660	11	53.7	42.8	4.75	0	0
670	11.16667	53.7	42.9	4.7	0	0
680	11.33333	53.7	43	4.64	0	0
690	11.5	53.7	43.1	4.6	0	0
700	11.66667	53.7	43.1	4.53	0	0
710	11.83333	53.7	43.2	4.51	0	0
720	12	53.7	43.3	4.47	0	0
730	12.16667	53.7	43.4	4.42	0	0
740	12.33333	53.7	43.5	4.38	0	0
750	12.5	53.7	43.5	4.34	0	0
760	12.66667	53.7	43.5	4.29	0	0
770	12.83333	53.7	43.6	4.23	0	0
780	13	53.7	43.6	4.21	0	0
790	13.16667	53.7	43.7	4.17	0	0
800	13.33333	53.7	43.8	4.12	0	0
810	13.5	53.7	43.9	4.08	0	0
820	13.66667	53.7	44	4.04	0	0
830	13.83333	53.8	44.1	3.99	0	0
840	14	53.8	44.2	3.95	0	0
850	14.16667	53.9	44.3	3.93	0	0
860	14.33333	53.9	44.3	3.89	0	0
870	14.5	53.9	44.4	3.84	0	0
880	14.66667	54	44.5	3.8	0	0
890	14.83333	54.1	44.6	3.77	0	0
900	15	54.1	44.7	3.74	0	0
910	15.16667	54.1	44.8	3.72	0	0
920	15.33333	54.2	44.8	3.69	0	0
930	15.5	54.3	44.9	3.65	0	0
940	15.66667	54.3	45	3.63	0	0
950	15.83333	54.4	45	3.61	0	0
960	16	54.5	45.1	3.59	0	0
970	16.16667	54.5	45.1	3.57	0	0
980	16.33333	54.7	45.2	3.57	0	0
990	16.5	54.7	45.2	3.54	0	0

Table 11 - Test 1 raw data

7.5.2 Test 2 Raw Data, City Driving, 60km/h, 2500 RPM

Time Seconds	Minutes	Hot T	Cold T	Voltage	Amperage	Power
0	0	17.5	16.3	0.01	0	0
10	0.166667	18.3	16.4	0.22	0	0
20	0.333333	21.9	16.7	1.19	0	0
30	0.5	25.5	17.4	2.3	0	0
40	0.666667	29	18.2	3.48	0	0
50	0.833333	32.6	19.2	4.66	0	0
60	1	35.6	20.2	5.8	0	0
70	1.166667	38	21.1	6.82	0	0
80	1.333333	39.8	22	7.68	0	0
90	1.5	41	22.6	8.13	0	0
100	1.666667	41.9	23.2	8.56	0	0
110	1.833333	43.2	23.7	9.14	0	0
120	2	44.3	24.3	9.4	0	0
130	2.166667	44.7	24.7	9.59	0	0
140	2.333333	45.8	25.2	9.97	0	0
150	2.5	46.6	25.7	10.13	0	0
160	2.666667	47.1	26.1	10.24	0	0
170	2.833333	47.7	26.5	10.4	0	0
180	3	48.8	27	10.6	0	0
190	3.166667	49.3	27.4	10.61	0	0
200	3.333333	49.8	27.6	10.62	0	0
210	3.5	50.7	28	10.79	0	0
220	3.666667	51.5	28.5	10.85	0	0
230	3.833333	51.7	28.7	10.81	0	0
240	4	52.7	29	10.98	0	0
250	4.166667	53.7	29.5	11.09	0	0
260	4.333333	53.6	29.7	11	0	0
270	4.5	54.1	30	11.04	0	0
280	4.666667	55.1	30.4	11.13	0	0
290	4.833333	55.4	30.7	11.07	0	0
300	5	55.5	30.8	11.05	0	0
310	5.166667	56.4	31.1	11.17	0	0
320	5.333333	57.2	31.5	11.13	0	0
330	5.5	56.9	31.6	11.07	0	0
340	5.666667	57.4	31.8	11.17	0	0
350	5.833333	58	32	11.22	0	0
360	6	57.9	32.2	11.15	0	0
370	6.166667	58.1	32.2	10.57	0	0
380	6.333333	59	32.5	10.68	0	0
390	6.5	59.4	32.7	10.57	0	0
400	6.666667	59.4	32.7	10.53	0	0
410	6.833333	60.1	33	10.7	0	0
420	7	60.6	33.4	10.68	0	0
430	7.166667	60.4	33.5	10.59	0	0
440	7.333333	61	33.7	10.62318	0	0
450	7.5	61.5	34.1	10.65636	0	0
460	7.666667	61.7	34.3	10.68955	0	0
470	7.833333	61.6	34.2	10.72273	0	0
480	8	62.5	34.5	10.75591	0	0
490	8.166667	62.6	34.9	10.78909	0	0
500	8.333333	62.4	34.9	10.82227	0	0
500	8.333333	62.4	34.9	10.82227	0	0
510	8.5	63.1	35.1	10.85545	0	0
520	8.666667	63.8	35.6	10.88864	0	0
530	8.833333	63.7	35.8	10.92182	0	0
540	9	63.9	35.7	10.955	0	0
550	9.166667	64.7	36	10.98818	0	0
560	9.333333	65.1	36.9	11.02136	0	0
570	9.5	65.1	36.9	11.05455	0	0
580	9.666667	65.5	36.6	11.08773	0	0
590	9.833333	66.7	37.6	11.12091	0	0
600	10	66.3	37.6	11.15409	0	0
610	10.16667	65.9	37.1	11.18727	0	0
620	10.33333	66.3	37.2	11.22045	0	0
630	10.5	66.5	37.5	11.25364	0	0
640	10.66667	65.8	37.4	11.28682	0	0
650	10.83333	65.9	37.2	11.32	0	0
660	11	66.5	37.5	11.39	0	0
670	11.16667	66.6	37.7	11.28	0	0
680	11.33333	66.9	38	11.07	0	0
690	11.5	67.4	38.5	11.13	0	0
700	11.66667	67.4	38.6	11.15	0	0
710	11.83333	66.8	38.6	11.09	0	0
720	12	66.3	38	11.13	0	0
730	12.16667	66.8	38.2	11.24	0	0
740	12.33333	67	38.3	12.18	0	0
750	12.5	66.3	38.1	12.18	0	0
760	12.66667	66.3	38	12.25	0	0
770	12.83333	67	38.4	12.22	0	0
780	13	67.2	38.8	12.05	0	0
790	13.16667	66.9	38.9	11.97	0	0
800	13.33333	67.1	38.8	12.18	0	0
810	13.5	67.5	39.2	12.27	0	0
820	13.66667	67.2	39	12.18	0	0
830	13.83333	66.5	38.5	12.24	0	0
840	14	67	38.4	12.39	0	0
850	14.16667	67.4	38.6	12.48	0	0
860	14.33333	67.8	39.1	12.33	0	0
870	14.5	67.9	39.6	12.12	0	0
880	14.66667	67.9	39.6	12.27	0	0
890	14.83333	68	39.6	12.37	0	0
900	15	67.5	39.4	12.27	0	0
910	15.16667	67	39	12.35	0	0
920	15.33333	67.5	39	12.46	0	0
930	15.5	67.8	39.2	12.48	0	0
940	15.66667	67	39	12.4	0	0
950	15.83333	67.4	39	12.42	0	0
960	16	68.2	39.5	12.44	0	0

Table 12 - Test 2 raw data

7.5.3 Test 3 Raw Data, Highway Driving, 100km/h, 3500 RPM

Time							
Seconds	Minutes	Hot T	Cold T	Voltage	Amperage	Power	Power Cal
0	0	44.9	36.1	3.97	0	0	0
10	0.166667	46.1	34.9	4.94	0	0	0
20	0.333333	48.2	34.2	6.12	0	0	0
30	0.5	50.4	33.8	7.27	0	0	0
40	0.666667	52.3	33.8	8.26	0	0	0
50	0.833333	59.8	33.9	9.14	0	0	0
60	1	56.8	34.1	10.04	0	0	0
70	1.166667	58	34.5	10.93	0	0	0
80	1.333333	59.6	34.9	11.45	0	0	0
90	1.5	61.6	35.2	12.33	0	0	0
100	1.666667	64.3	35.8	13.25	0	0	0
110	1.833333	66.6	36.6	13.9	0	0	0
120	2	68.6	37.1	14.15	0	0	0
130	2.166667	71.2	38.1	14.81	0	0	0
140	2.333333	79.8	39.3	15.4	0	0	0
150	2.5	76.9	40.6	16.08	0	0	0
160	2.666667	88.8	41.9	16.81	0	0	0
170	2.833333	82.9	43.1	17.26	0	0	0
180	3	84.8	43.9	18.27	0	0	0
190	3.166667	87.2	44.7	16.76	0.1	1	1.676
200	3.333333	88.8	45.3	16.62	0.1	1	1.662
210	3.5	91.3	46.7	18.28	0.1	1	1.828
220	3.666667	94.3	47.9	15.76	0.2	3	3.152
230	3.833333	96.2	48.6	18.03	0.1	2	1.803
240	4	98.8	50	17.37	0.2	3	3.474
250	4.166667	101.2	51	17.31	0.2	3	3.462
260	4.333333	102.2	51.9	18.43	0.1	2	1.843
270	4.5	103.6	52.3	16.85	0.2	4	3.37
280	4.666667	104.4	52.8	15.78	0.3	4	4.734
290	4.833333	106.2	53.7	16.15	0.2	4	3.23
300	5	108.3	54.7	15.95	0.3	4	4.785
310	5.166667	109.8	55.7	15.61	0.3	4	4.683
320	5.333333	111.5	56.9	15.78	0.3	4	4.734
330	5.5	113.1	57.2	15.65	0.3	5	4.695
340	5.666667	113.2	57.5	16.13	0.3	5	4.839
350	5.833333	114.3	57.8	15.76	0.3	5	4.728
360	6	115.7	58.9	16	0.3	5	4.8
370	6.166667	116.9	59.9	15.75	0.3	5	4.725
380	6.333333	118.1	60.1	16.15	0.3	5	4.845
390	6.5	119.3	60.8	15.64	0.3	5	4.692
400	6.666667	119.8	61.4	15.78	0.3	5	4.734
410	6.833333	120.1	61.6	16.14	0.3	5	4.842
420	7	119.7	61.8	16.06	0.3	5	4.818
430	7.166667	119.9	61.5	15.79	0.3	6	4.737
440	7.333333	121.6	62.8	15.78	0.4	6	6.312
450	7.5	122.7	62.5	15.65	0.4	6	6.26
460	7.666667	123.4	63.1	16.52	0.3	6	4.956
470	7.833333	124.9	63.7	16.15	0.3	6	4.845
480	8	129.8	66.9	16	0.3	5	4.8
490	8.166667	122.8	70.9	15.75	0.3	4	4.725
500	8.333333	121.9	68.8	16.04	0.3	4	4.812
490	8.166667	122.8	70.9	15.75	0.3	4	4.725
500	8.333333	121.9	68.8	16.04	0.3	4	4.812
510	8.5	120.9	65.8	16.27	0.3	4	4.881
520	8.666667	120.1	64.9	15.61	0.3	5	4.683
530	8.833333	120	63	16.12	0.3	5	4.836
540	9	120.4	62.5	16.47	0.3	5	4.941
550	9.166667	121	62.7	16.3	0.3	5	4.89
560	9.333333	121.1	62.7	16.09	0.3	5	4.827
570	9.5	121.8	62.8	16.57	0.3	5	4.971
580	9.666667	122	63.2	15.58	0.3	5	4.674
590	9.833333	122.2	63.2	15.72	0.3	5	4.716
600	10	122.6	63.4	15.72	0.3	5	4.716
610	10.16667	122.9	63.4	15.6	0.3	5	4.68
620	10.33333	121.7	62.9	16.47	0.3	5	4.941
630	10.5	122.7	62.8	16.08	0.3	5	4.824
640	10.66667	123.4	63.1	15.59	0.3	5	4.677
650	10.83333	123.6	63.5	15.7	0.3	5	4.71
660	11	124.3	63.9	16.1	0.3	5	4.83
670	11.16667	124.7	64.2	16	0.3	5	4.8
680	11.33333	124.5	64.2	16.1	0.3	5	4.83
690	11.5	125.1	64.3	15.69	0.3	5	4.707
700	11.66667	125	64.3	15.98	0.4	6	6.392
710	11.83333	124	63.4	16.08	0.4	6	6.432
720	12	124	63.9	16.47	0.3	5	4.941
730	12.16667	125.2	63.8	16.1	0.4	6	6.44
740	12.33333	125.8	64.2	15.95	0.4	6	6.38
750	12.5	125.8	64.6	16.66	0.3	5	4.998
760	12.66667	126.3	64.8	15.7	0.4	6	6.28
770	12.83333	126.8	65.4	16.36	0.4	6	6.544
780	13	127	65.5	16.33	0.3	6	4.899
790	13.16667	127.4	65.6	16.04	0.4	6	6.416
800	13.33333	128.1	66.1	15.97	0.4	6	6.388
810	13.5	127.8	66.3	19.3	0.3	5	5.79
820	13.66667	127.6	66.1	18.33	0.3	6	5.499
830	13.83333	128.1	65.9	17.41	0.3	6	5.223
840	14	128.5	66.2	22.75	0.2	4	4.55
850	14.16667	128.7	66.4	16.88	0.4	6	6.752
860	14.33333	129.4	66.7	18.33	0.3	6	5.499
870	14.5	129.9	67.1	20.29	0.2	5	4.058
880	14.66667	129.7	67.3	16.65	0.4	6	6.66
890	14.83333	130.1	67.4	15.92	0.4	6	6.368
900	15	130.1	67.4	16.68	0.4	6	6.672
910	15.16667	129	67	16.09	0.4	6	6.436
920	15.33333	129.5	66.7	15.67	0.4	6	6.268
930	15.5	129.8	67	15.57	0.4	6	6.228

Table 13 - Test 3 raw data

7.6 Project Build Photos

Figure 31 - Bypass valve closed

Figure 32 - Bypass valve open

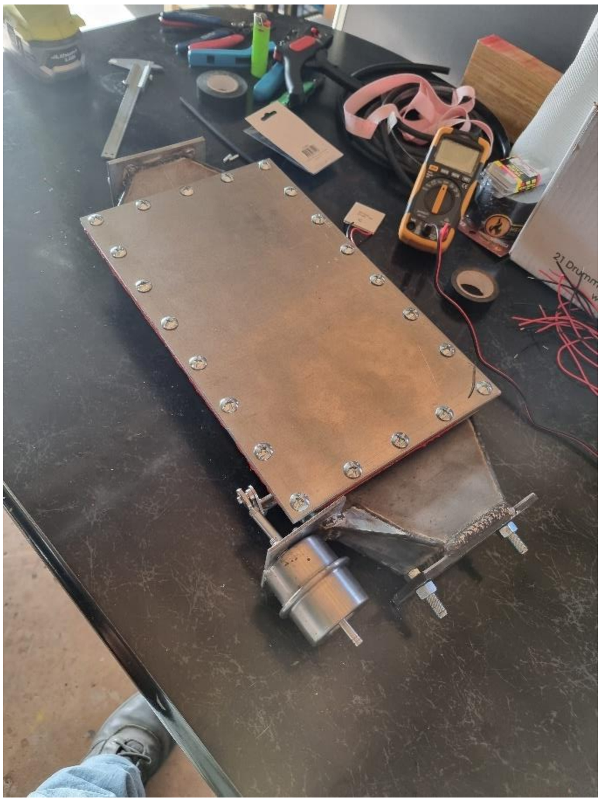


Figure 33 - Bare hotplate

Figure 34 - Hotplate with thermal paste and silicone mat

7.7 Data Acquisition Setup During Testing

Figure 35 - Data acquisition setup

7.8 Spare TEG Module Testing

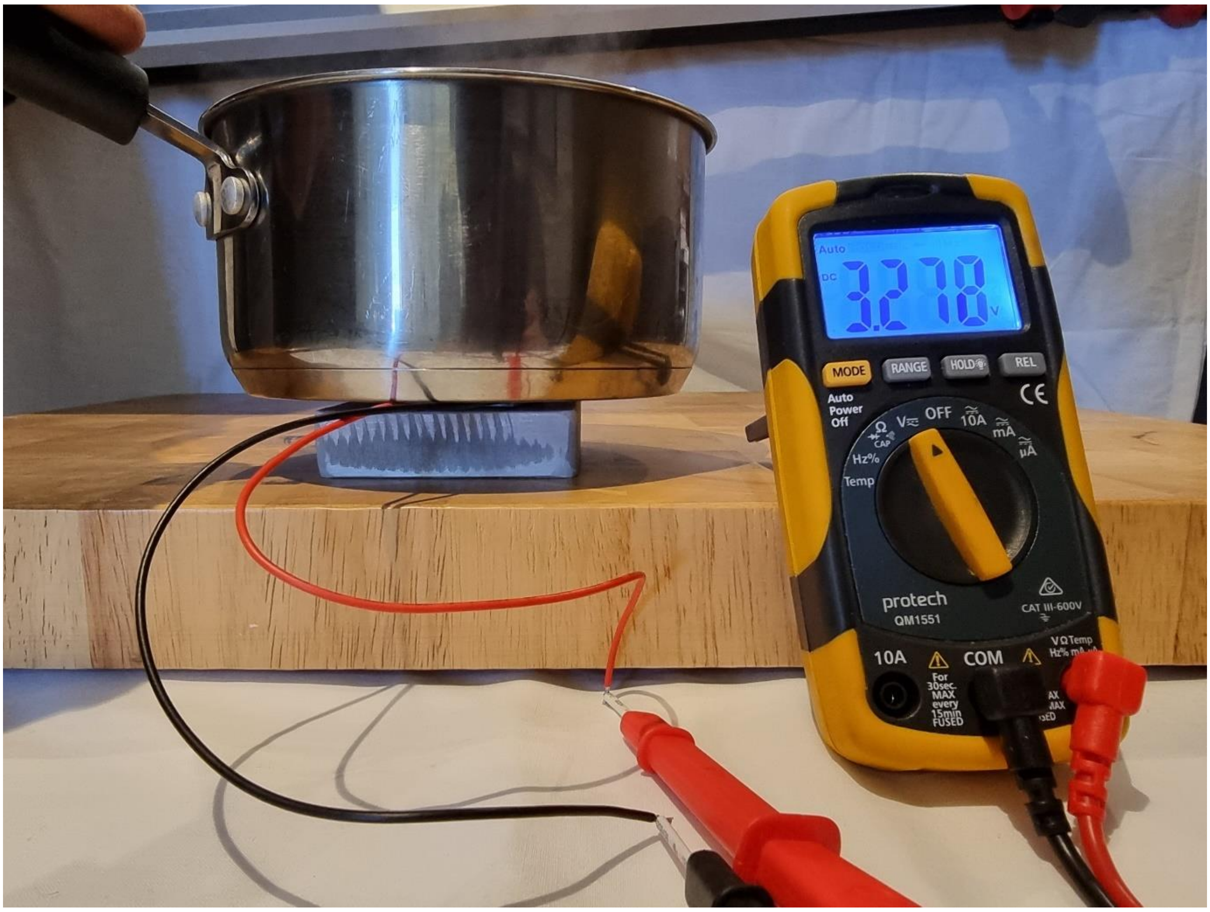
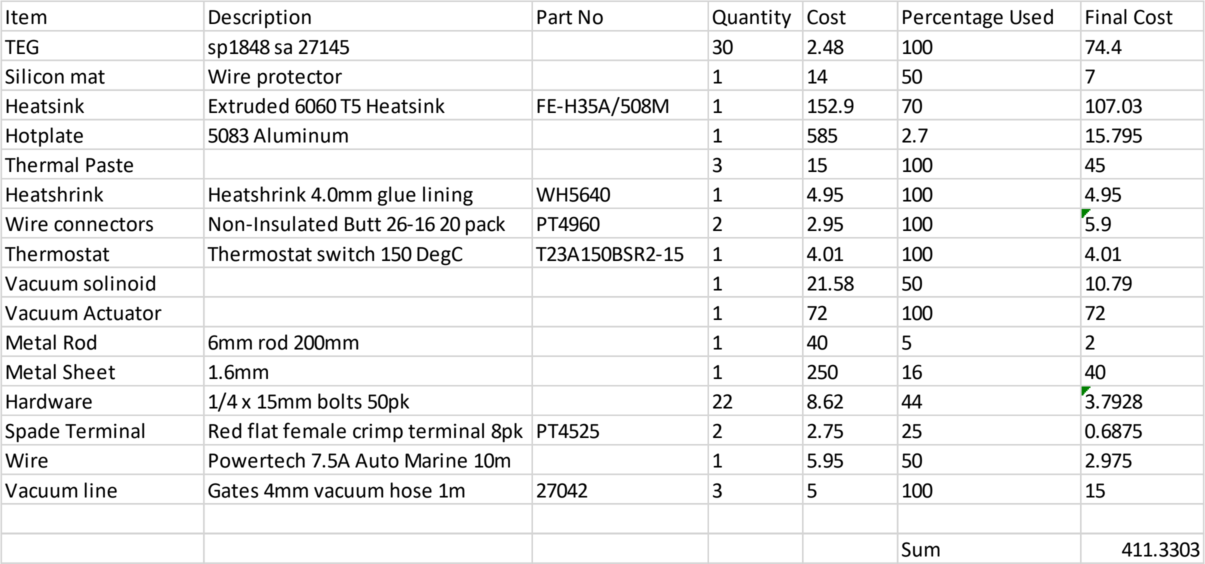


Figure 36 - Spare module testing 117 ˚C

7.9 Item Price List



Item	Description	Part No	Quantity	Cost	Percentage Used	Final Cost
TEG	sp1848 sa 27145		30	2.48	100	74.4
Silicon mat	Wire protector		1	14	50	7
Heatsink	Extruded 6060 T5 Heatsink	FE-H35A/508M	1	152.9	70	107.03
Hotplate	5083 Aluminum		1	585	2.7	15.795
Thermal Paste			3	15	100	45
Heatshrink	Heatshrink 4.0mm glue lining	WH5640	1	4.95	100	4.95
Wire connectors	Non-Insulated Butt 26-16 20 pack	PT4960	2	2.95	100	5.9
Thermostat	Thermostat switch 150 DegC	T23A150BSR2-15	1	4.01	100	4.01
Vacuum solinoid			1	21.58	50	10.79
Vacuum Actuator			1	72	100	72
Metal Rod	6mm rod 200mm		1	40	5	2
Metal Sheet	1.6mm		1	250	16	40
Hardware	1/4 x 15mm bolts 50pk		22	8.62	44	3.7928
Spade Terminal	Red flat female crimp terminal 8pk	PT4525	2	2.75	25	0.6875
Wire	Powertech 7.5A Auto Marine 10m		1	5.95	50	2.975
Vacuum line	Gates 4mm vacuum hose 1m	27042	3	5	100	15
					Sum	411.3303

Table 14 - Detailed component price list