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Final Report

Project 3
Energy Harvesting Bluetooth Low Energy Beacon

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Information page

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Abstract

Environmentally friendly technology is designed and constructed to harvest the wasted heat of an LED driver and utilizing the harvested energy as an input power source for a Bluetooth Low Energy beacon or BLE beacon. A beacon is a device which sends radio signals to its zonal environment in a specified time interval, and the signal can be received by the nearby bluetooth enabled devices. The beacons can be used for different purposes in indoor environments; including sending advertisements to the clients of a mall, indoor's navigator, tracking the user's location and sending any other data, for instance, sensor data. The developed technology has the potential to be extended to other indoor applications that generate heat. Helvar provided the group with LL1x80-350-700 Active LED driver and its thermal picture when operating at full load. The thermoelectric generator, or TEG, is used for the energy conversion in the prototype. When a temperature difference is applied over a TEG a voltage across the device is created. Feasibility studies of the project are made using resistors that produce the same temperature as the hottest spot of the LED driver. A circuit to boost the obtained voltage out of the TEG is designed and implemented. An initial PCB is designed, constructed and tested. Thereafter, a final, more reliable PCB is with a smaller footprint is designed. At this stage, the nRF52840 Dongle, the Bluetooth Low Energy module can make the connection to the nearby smartphones through the nRF Connect application.

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Abbreviations

BLE - Bluetooth Low Energy

DC - Direct Current

KiCad - Software used for circuit design

LED - Light Emitting Diode

PCB - Printed Circuit Board

SDK - Software Development Kit

SES - Segger Embedded Studio

SMD - Surface Mounted Device

TEG - Thermoelectric Generator

THT - Through-hole Technology

1. Introduction

Bluetooth low energy beacon is a hardware transmitter to nearby electronic devices such as smartphones. It can be used for interior navigation, sending advertisements to the clients of a mall, or any particular data such as temperature to the approached receivers in its particular zone. In this project a prototype is developed to harvest the thermal energy generated by power loss of a luminaire's LED driver to power up a BLE beacon to send signals. A thermoelectric generator is used as an energy converter to convert heat flux into electrical energy. The temperature difference between the hot and cold sides of the TEG produces electrical energy due to the Seebeck effect. Developing a green environmentally friendly and battery-free technology without the restriction of battery life and maintenance are the motivations behind the project. The developed technology might be extended to other applications, which produce heat.

Report Structure

Report structure outlines briefly the chapters of the Report.

Chapter 2 Motivation and objective of the project
Chapter 3 Research, modeling, feasibility analysis of the project
Chapter 4 Mechanical design, implementation and assembly
Chapter 5 Circuit and PCB design of initial and final prototype
Chapter 6 Experiments and results
Chapter 7 Software development of BLE module
Chapter 8 Reflection of the project with respect to the project plan and changes
Chapter 9 Quality control of the project with respect to the expected output
Chapter 10 Time management assessment
Chapter 11 Risk analysis of the project
Chapter 12 Further development of the prototype
Chapter 13 Cost analysis of the prototype
Chapter 14 Discussion and conclusion of the project

2. Objective

The objective of the project is to design and implement an environmentally friendly technology to power up nRF52840 Dongle, BLE module, using the harvested thermal energy or power loss of LL1x80-350-700 Active LED driver, to send radio signal once every second to smartphones through nRF Connect application. One of the challenges of the project is to provide a solution to eliminate the life span factor related to battery life duration, as the battery life span for beacons is about 2-3 years, which brings about battery replacement and maintenance. Furthermore, the energy harvesting technology can be applied to other indoor environment applications which produce dissipated heat. The BLE module must be located in the setup in a place where it can send its signals to the receivers without obstacle that hinders the signal emission.

To fulfil the objectives, the feasibility analysis is made, an electronic circuit is designed, tested and implemented on a breadboard. In addition to the final PCB, initial PCB is designed via KiCad software and implemented and produced in the workshop. A setup with the PCB, LED driver testbed, TEGs, heat sink, and nRF52840 Dongle is designed and it will be assembled as the final prototype. Software development is needed for the BLE module to send a signal in a specified interval.

3. Feasibility Analysis

To find out whether the project is durable, we had to measure the voltage produced by a TEG on the LED driver. Helvar provided us with thermal images of the LL1x80-350-700 Active+ LED driver which showed that there are two hotspots whose temperature is about 80°C of size 4cm^2.

3.1. The LED Driver Simulation Experiments

Since there was a lack of any appropriate load for the LED driver, the hotspots of the LED driver were simulated with two 10Ω 7W resistors whose area was equal to that of one hotspot.

Before ordering the TEGs, an experiment was conducted with resistors heating a Peltier element. In this experiment, the heatsink 1 (in figure 2) was used. The output of the Peltier element was 0.5-0.8V. Unfortunately, the next time the Peltier element was tested again, it didn’t work any longer, thus three TG12-4 TEGs from Marlow Industries was ordered.

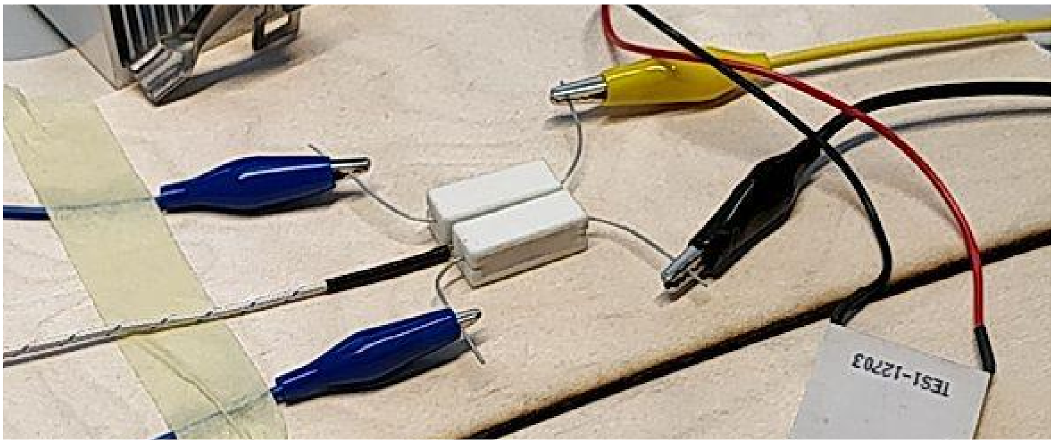
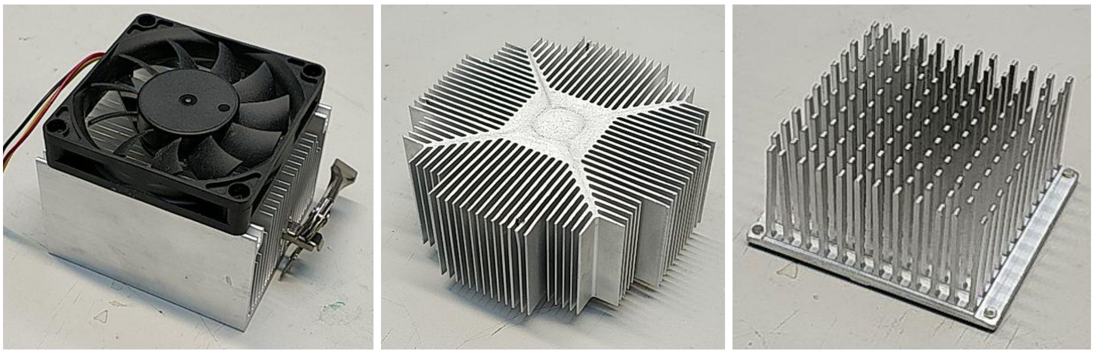


Figure 1. Resistors used to heat TEG.

3.2. Heatsink Experiments

To find out the effect of different heatsinks on the produced voltage, three tests similar to that described in 3.1. was conducted but with different heat sinks that can be seen below in figures 2, 3 and 4. The tests were carried out using a multimeter measuring the current and the voltage across a 10Ω resistor. The fan of the heatsink 1 was never used. The aim is to avoid moving parts in our design for the sake of longevity. The results can be seen in figure 5.



Figures 2, 3 and 4. Heatsink 1, 2 and 3. Note that the images are not to scale.

We also experimented with two TEGs stacked on top of each other using heatsink 1. It did not provide any additional performance, rather the cold side of both TEGs wasn't being cooled effectively. This caused a gradual temperature gradient over the elements resulting in effectively a zero temperature difference over the individual elements, thus the power output was almost zero. Note that the bumps in the red graph most likely come from inconsistent heating, i.e. the TEG heated up faster, causing a spike in the voltage.

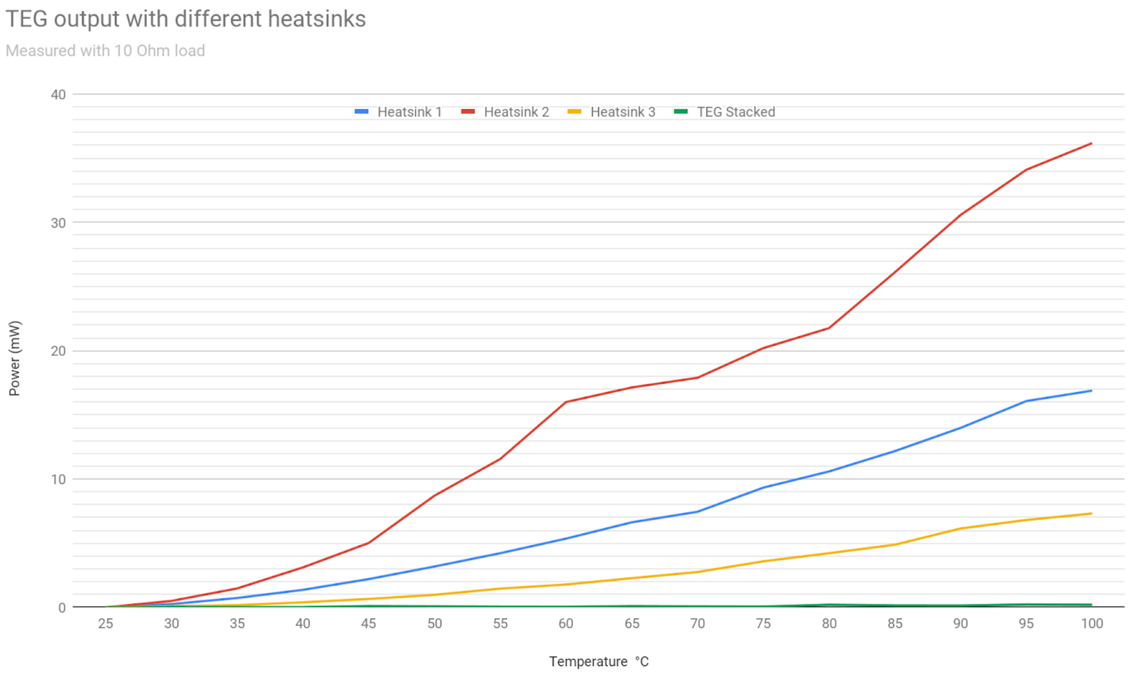


Figure 5. The results from heatsink experiments.

3.3. Converter Experiments

The purpose of the first test was to measure the voltage output of the R-78S DC-DC boost converter when a voltage similar to that one generated by the TEG i.e. 0.6V is supplied. The output was about 3.2V.

Next, the same test was done again but this time with an actual TEG heated by resistors. Now the output was 3.1-3.2V.

In the last experiments related to the converter, an oscilloscope was utilized to see how much ripple is generated by the converter. The ripple was rather small and no oscillation was to be noted despite the capacitance exceeding the recommended amount. The amount of ripple was similar to that being outputted by the TEG.

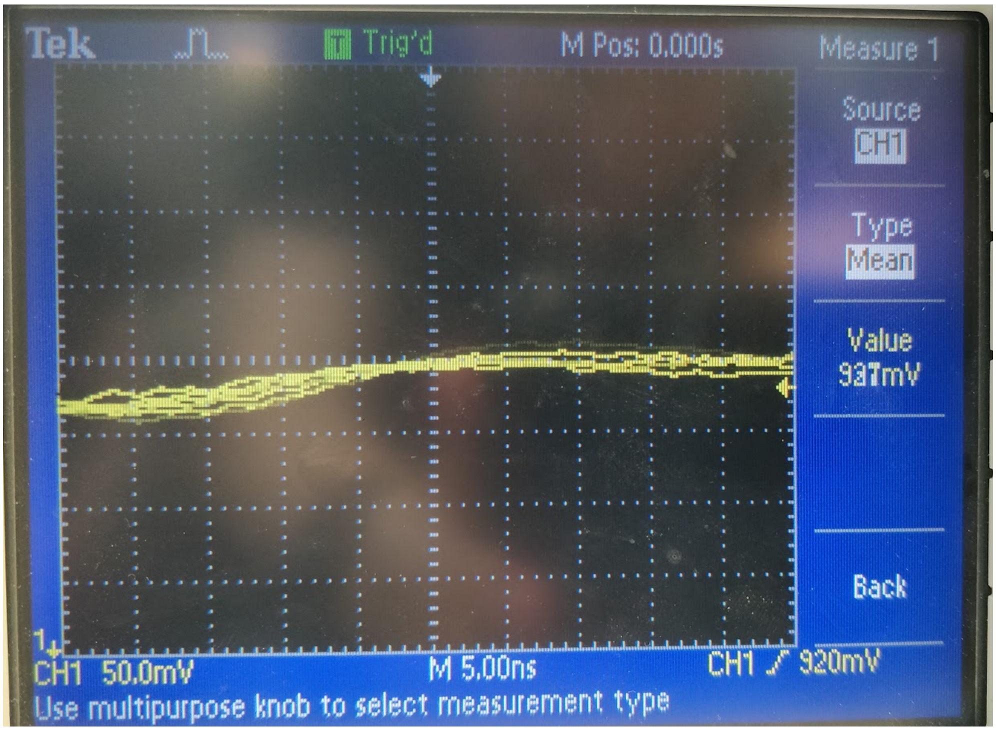


Figure 6. Demonstration of the ripple.

3.4. Capacitor Experiments

Since the input current that the nRF52840 Dongle requires changes substantially depending on whether it is sending the advertisement, capacitors of different sizes were added to provide the necessary current at those instances. The voltage was then monitored with an oscilloscope. No abnormalities were detected in the voltage.

First, the power supply was used to simulate the output of the R-78S DC-DC converter, and a 1F supercapacitor in parallel with a zener diode was used to prevent overcharging. Refer to the section on the PCB for more detail regarding the circuit. The goal was to test whether the converter could handle the capacitive load, since the capacitance of the supercapacitor exceeds the output capacitance ratings of the converter. The converter worked fine while the power was supplied so the input of the converter was short-circuited to see whether the converter can handle the capacitance. Then capacitors of sizes 0.1μF, 1μF and 10μF were added in parallel to achieve higher peak currents. The capacitive load didn‘t seem to affect the operation of the converter.

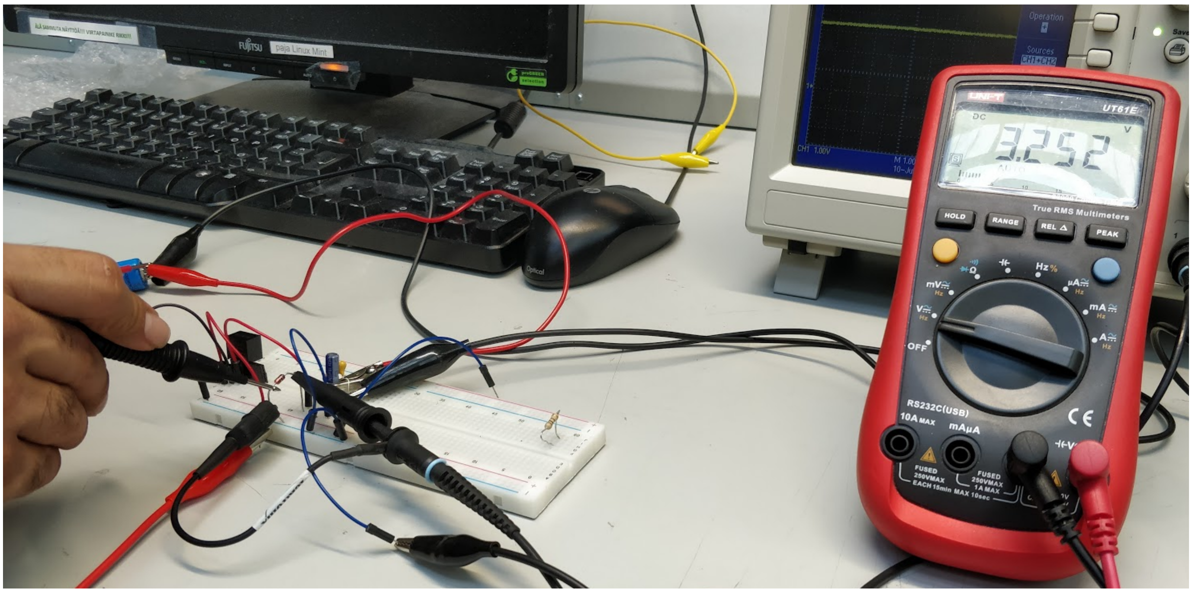


Figure 7. Capacitor experiment.

3.5. Testbed

A testbed was constructed to safely test the prototype with the driver. The mains input was covered with a wooden box to prevent fatal electrocution. The wire was strapped to the wooden board with strain relief, and the case of the driver safely grounded. Using resistors as a load proved to be problematic, since all the energy would be dissipated through heat. Thus a large LED would’ve been needed to dissipate some of the energy through light to avoid excessive heat. Figuring out a setup provided difficult, so it was put on hold. You can see the constructed LED driver setup in figure 8 below.

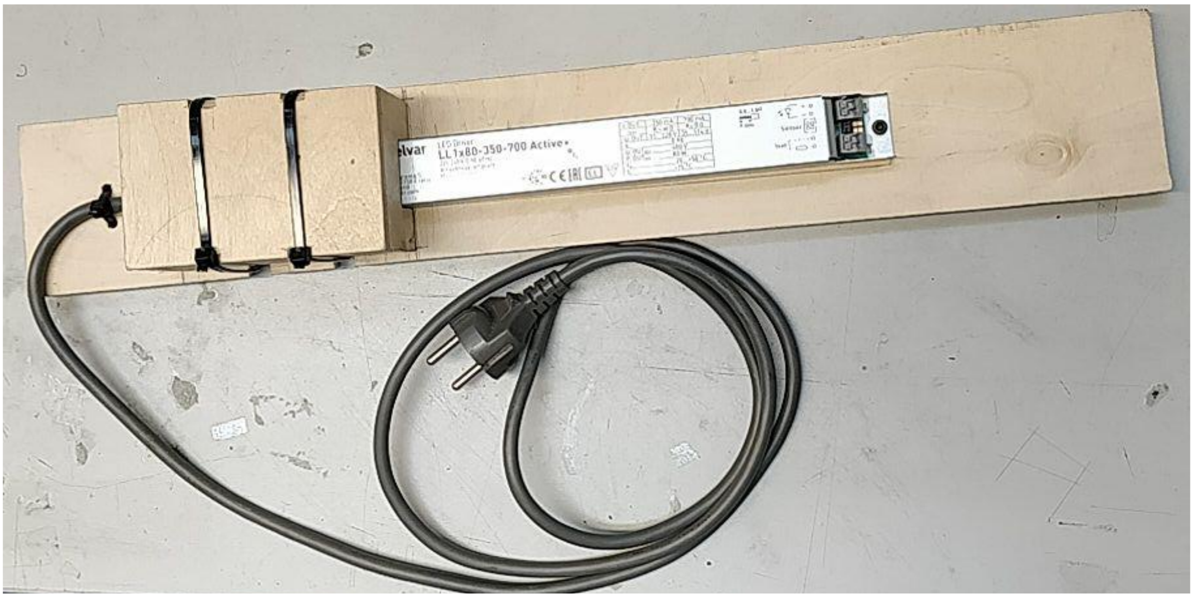


Figure 8. Our testbed which wasn't used.

After some talk with the company, they offered to make a test setup for us with a LED driver. After getting the setup from Helvar around mid-July, the same experiments were conducted as with the simple resistor setup as described in 3.1., but now with the new test bed. You can see the LED driver setup we received from Helvar in figure 9 below.

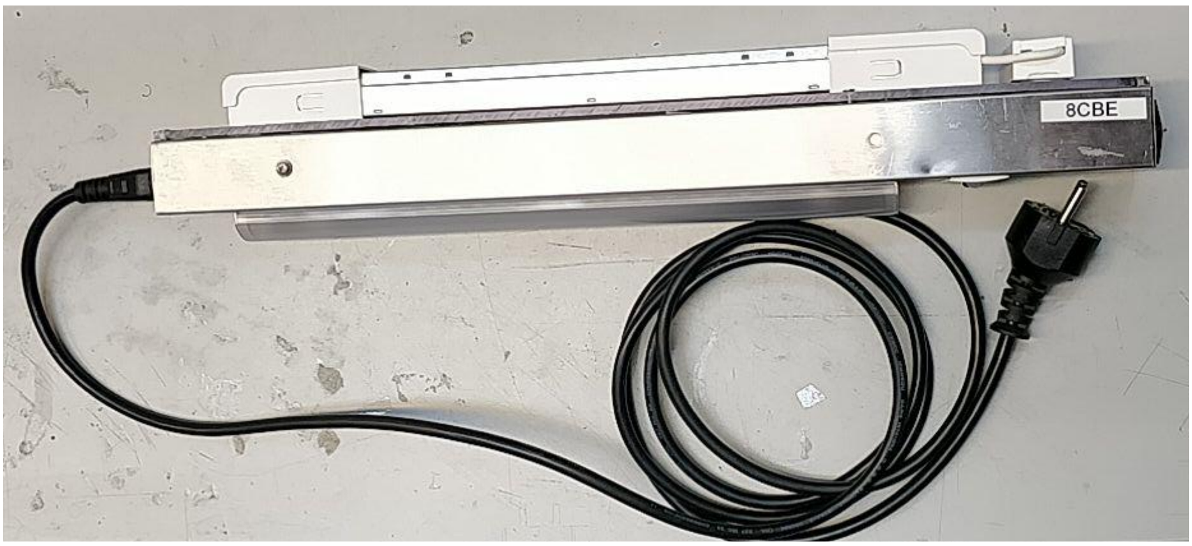


Figure 9. Testbed provided by Helvar

The tests provided lower voltage than expected from the resistor tests described in 3.1. The output of the TEG was 0.25V as opposed to the expected voltage in the 0.5-0.8V range. Using a thermal camera, the surface temperature of the driver was measured. The actual temperature of the LED driver was lower than in the thermal image provided by Helvar as seen below.

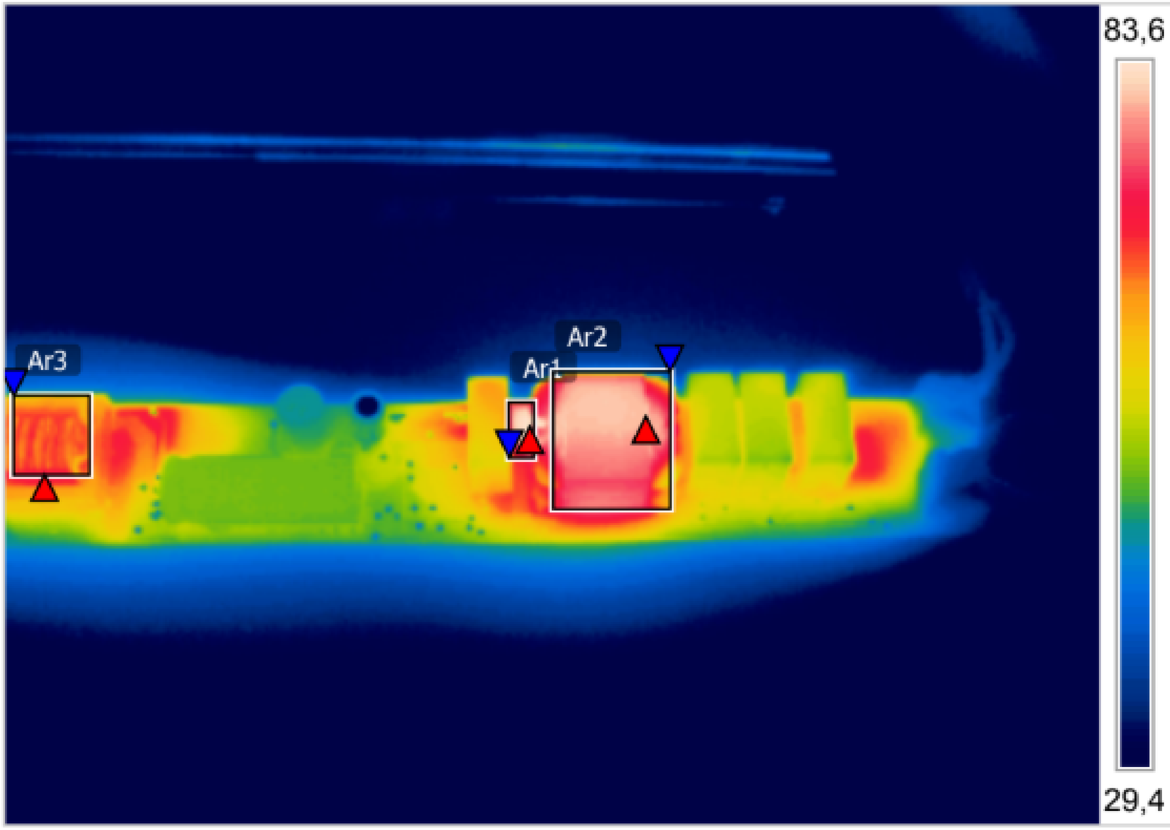


Figure 10. Thermal image from LL1x80-350-700 Active+ LED driver operating at full-load as provided by Helvar.

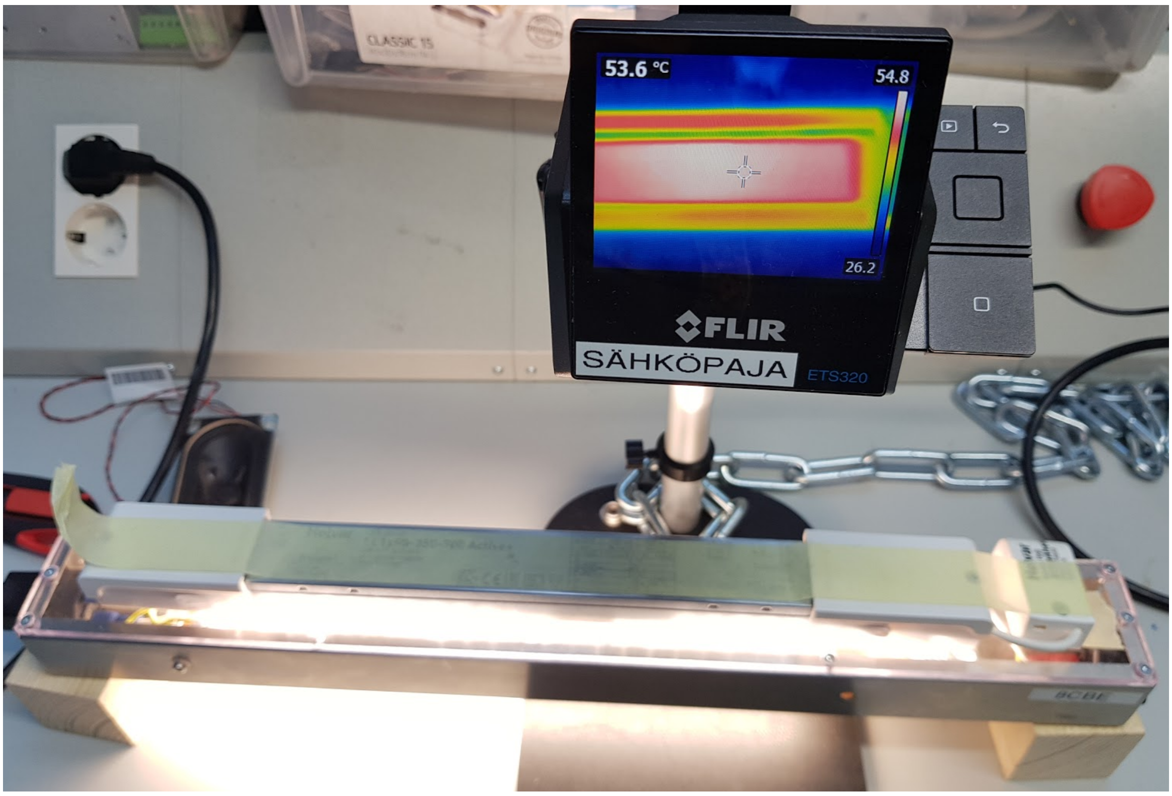


Figure 11. Thermal image of the test bed.

The temperature of the driver sits at around 50°C as seen in figure 11 above. The surface was covered with masking tape to prevent reflections from the surface allowing us to take a more accurate thermal image. The hottest spot turned out to be around 30°C lower than previously expected. This changes the design of the setup, as this decreases the produced voltage. Having lower temperature on the surface area of the LED driver, leads to lower input voltage for the boost converter. In order for the R-78S boost converter to start working, at least 0.6V input voltage is required.

There are several approaches to increase the harvested voltage. First, to implement multiple TEGs on the surface area of the LED driver and attach them in series; second, to replace the heatsink with one that is more efficient; and third, to increase the temperature of the surface area by increasing the load. Furthermore, the most reliable approach is to replace the R-78S boost converter with a new boost converter with lower input voltage. Replacing the DC-DC converter makes a complete overhaul of the PCB design necessary.

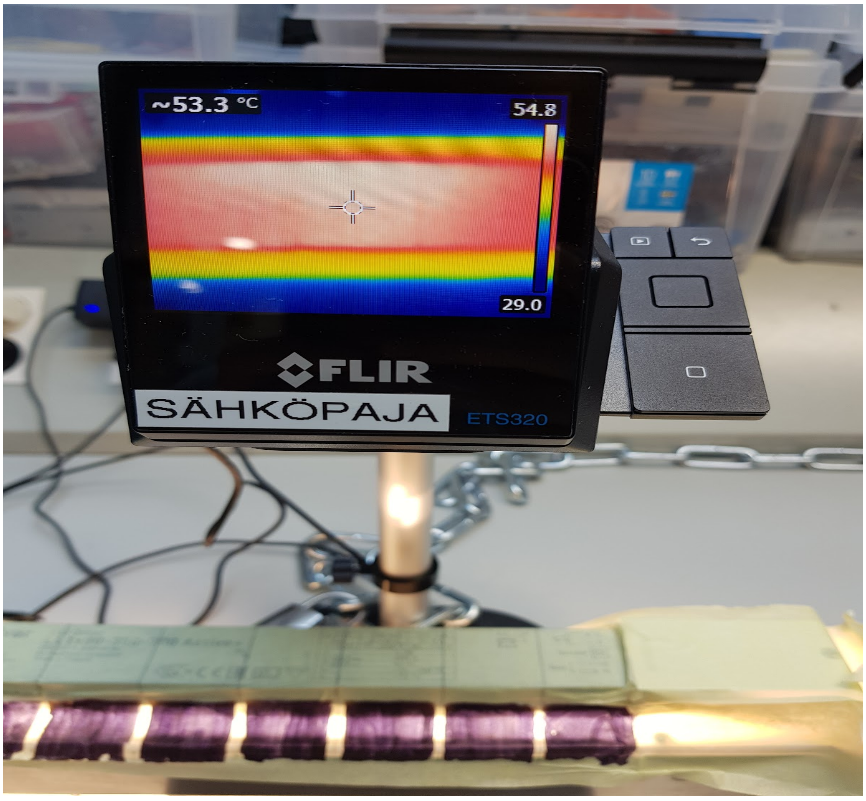


Figure 12. Temperature measurement of the LED driver at seven specified points

In order to optimise the number of TEGs, and find the hottest spots over the surface area of the LED driver, the temperature of the LED driver is measured through a thermal camera at seven points. The LED driver has enough surface area for placing seven $30\times30\ mm$ TEGs. The temperature over the galvanized steel surface area of the LED driver is almost homogenous; however, the temperature over the

LED driver is slightly increasing by approaching the areas nearby to the controlling gate of the LED driver.

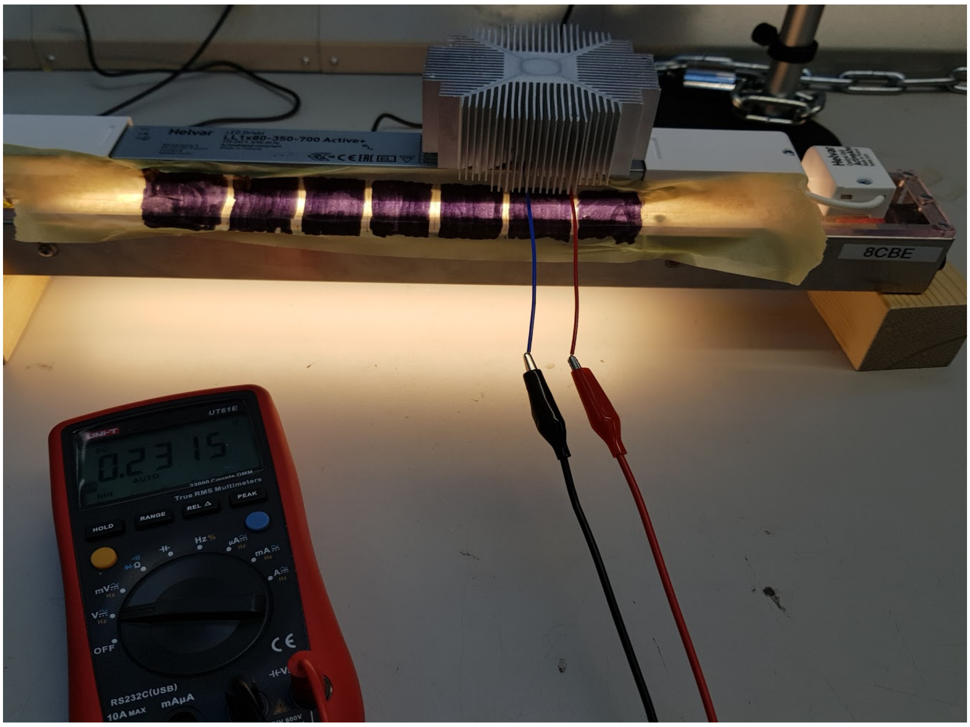


Figure 13. Voltage measurement out of one TEG on a certain spot

Figure 13 shows the voltage measurement of produced voltage out of a TEG on the predefined spots with a heat-sink and air as coolant. The voltage is measured when the setup reaches its thermal equilibrium at the seven spots to find the optimum areas for placing the TEGs.

Table 1: Temperature and voltage measurement

Area number	1	2	3	4	5	6	7
Temperature(°C)	51.2	51.8	52.8	52	50.5	47.7	44.8
Voltage(V)	0.19	0.21	0.22	0.22	0.19	0.18	0.12

Row one in table 1 represents the ordering number of the areas, area number one is the nearest area to the controlling gate of the LED driver, and the orders are arranged in ascending approach up to seven.

Table 1 clearly illustrates the more temperature on the hot side of the TEG leads to generate more voltage out of the TEG while the temperature on the cold side is constant. furthermore, table 1 shows the temperature is almost the same over the surface area of the LED driver, and as a result the produced voltage out of the TEG on these areas are more or less the same. It is worth mentioning that the measurements are done spot by spot.

If seven TEGs are placed in series over the LED driver at the same time, they can harvest less energy and produce less voltage than the sum of the produced voltage of the seven areas shown in the table above. This is because there is less area available for the heat-sink to exchange the heat flux produced by the luminaire to the ambient. Moreover, within table 1, the hottest spots of the LED drivers are identified which is useful for the optimum design of setup by estimation of the number of TEGs that are required and their best place on the luminaire. There is a fact, the more temperature difference over the TEGs contribute to generate more energy.

Out of curiosity we decided to test the LED driver with three TEGs and the three heatsinks we had previously used. Not the most scientific test but we didn't really have anything else to do without our actual heatsink at this point. To our dismay we only achieved a voltage around 0.5-0.6V, which wasn't enough to power up and operate our DC-DC converter. Instead of looking into a different converter, we decided to order a couple more TEGs. This later proved to be a complete waste of time and money. We didn't even use any thermal paste at this point. The test can be seen in figure 12 below.

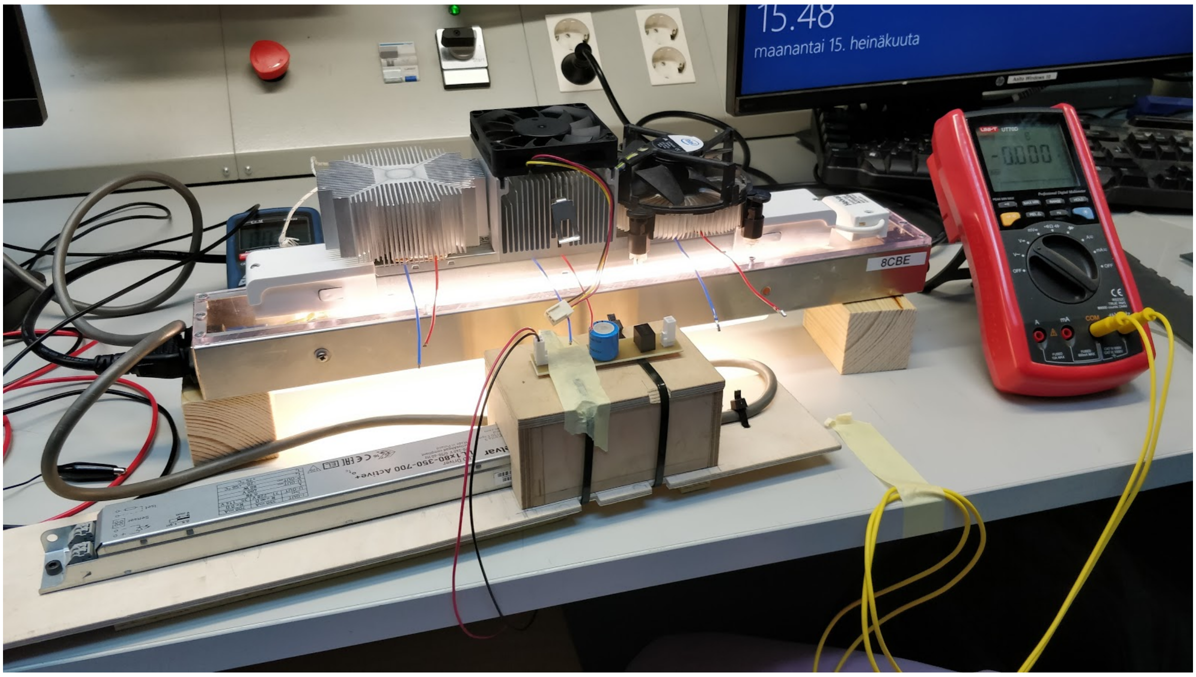


Figure 12. The LED driver configuration from Helvar with TEGs and different heatsinks on top of the TEGs.

3.6. Experiments with New Heatsink

Our order of more TEGs and a new heatsink arrives. The group expected the new heatsink to perform well enough to produce the required 0.6V with three TEGs that is required by the converter. Thus an experiment was performed to test this and it was found out that this was not the case. The new heatsink can be seen in figure 13. The dimensions of the heatsink are 200 mm x 101.6 mm x 32 mm.

Figure 13. The new heatsink.

It was decided to perform more tests where the test setup provided by Helvar is allowed to heat with time and measure the output of the TEGs connected in series. The first experiment was conducted with four TEGs without thermal paste. The experiment provided interesting results. The graph in figure 14 shows how the voltage increases rapidly, but with a decreasing rate akin to a root function. After the 30min mark the voltage starts decreasing exponentially. Eventually the system reaches an equilibrium and the voltage ceases decreasing.

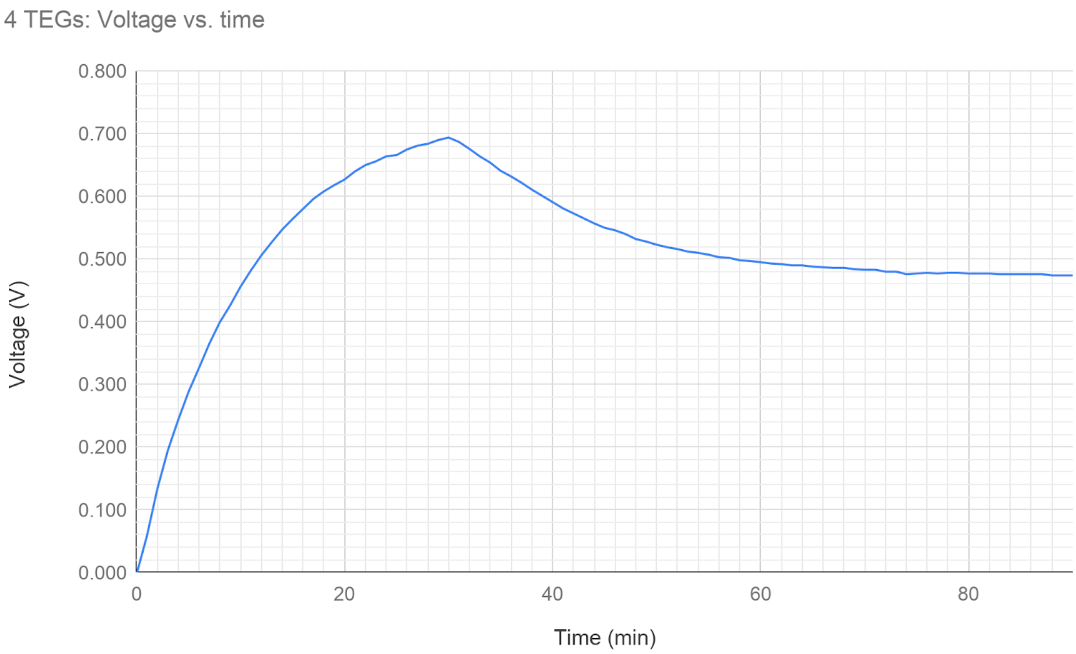


Figure 14. The voltage-time graph for four TEGs.

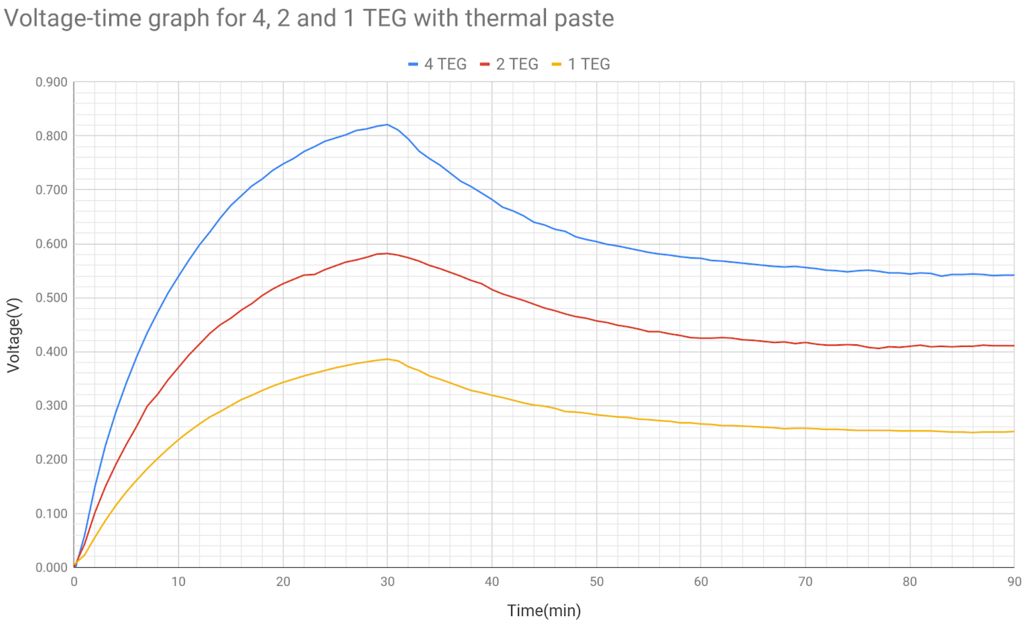


Figure 15. The voltage-time graph for 4, 2, and 1 TEGs with thermal paste applied.

Further experiments where conducted with varying amounts of TEGs. Each experiment yielded a graph with identical trends. Curiously the voltage always starts decreasing at the thirty minute mark despite the varying number of TEGs. The initial hypothesis was that perhaps with less TEGs the heatsink would reach a saturation point slower as a smaller surface area is conducting heat. Instead, this is more likely due to a characteristic of the LED driver and LEDs connected to it.

Adding TEGs doesn't increase the output voltage linearly. Instead there is a loss in the output per TEG. For example with one TEG the maximum is 0.386V whereas with four the maximum is 0.821V which is only 2.1 times the voltage an individual TEG compared to having quadruple the amount of TEGs.

Group 4 agreed to allow us to use some of their thermal paste in our experiments. The application of thermal paste did not affect the trends seen in the voltage, however it did increase the maximums and the equilibrium voltage, which was a desired outcome.

Due to the inability to sustain a voltage of over 0.6V despite using more TEGs it was decided to look at alternatives solutions. Considering that swapping the heatsink had no guarantee of providing better results, this option was ruled out. Adding more TEGs was not really realistic as it had already been shown that the voltage gain from adding more quickly decreased. The other alternative was to look for a converter with a lower input voltage requirement.

The new converter that was found requires minimum sustained voltage of 0.3, but to startup it requires 0.5V, which shouldn't be a problem as the voltage peaks and then decreases to its steady state voltage. Additional tests were done to figure out the minimum required TEGs to ensure operation. Unfortunately, even with the new converter a single TEG is not sufficient as it could only provide a maximum of 0.39V and a sustained steady state voltage of 0.25V. Instead the experiments showed that two TEGs would provide sufficient voltage with a comfortable amount of headroom with the maximum being 0.58V and a sustained voltage of 0.41V well past the 30min mark.

3.7. Controlled Temperature Experiments

To gain a better data of the valid operational range for the use of TEGs additional experiments were conducted with the resistors. This time the measurements were taken after the temperature difference was stable. Additionally a metal plate was placed in between the resistors and the TEG to mimic the actual setup. Thermal paste was also applied onto the surfaces of the TEG.

The results are shown below in figure 18. The graph shows a strong linear relationship between the temperature and voltage, which is to be expected. The trendline gives the steady state voltage given by one TEG at a certain temperature.

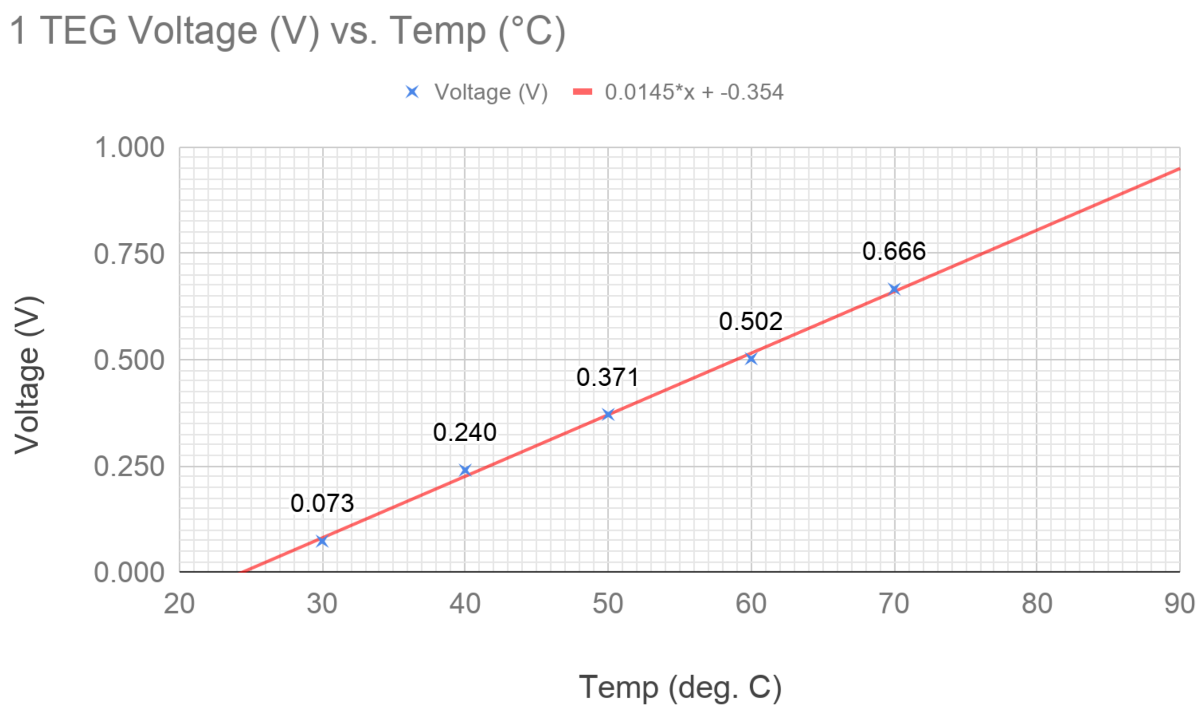
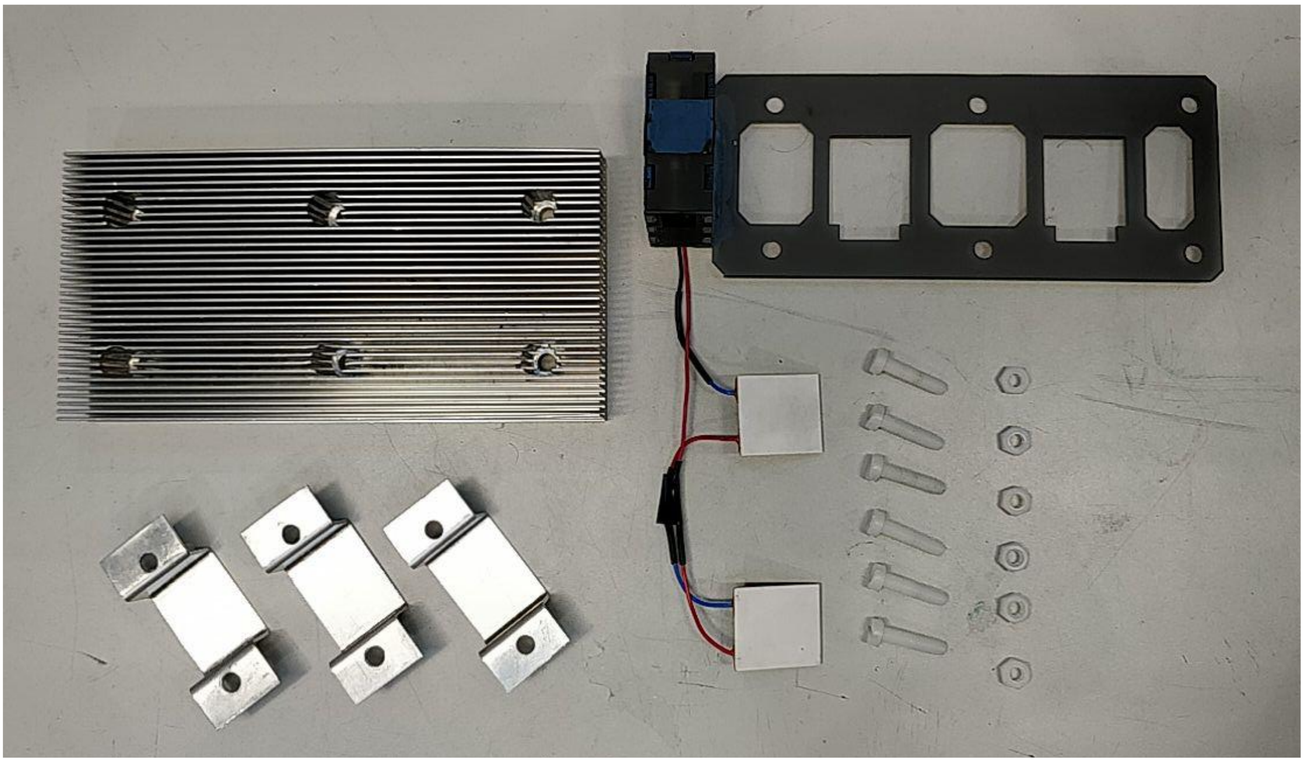


Figure 18. Voltage as a function of temperature with one TEG.

4. Mechanical Design and Construction



One of the challenges in the project was how to assemble all the pieces of the puzzle. One of the primary concerns was how the heatsink was to be attached to the driver. An important aspect to this was creating a downwards mounting force towards the driver's surface sandwiching the TEGs in between. The typical way of doing this is by having a backplate that the heatsink can be screwed or bolted onto. Luckily the testbed provided by Helvar has the LED driver mounted such that a small gap of roughly 2mm is created in between the driver and the casing for the luminaire. Hence the original idea was to find a suitable plate that could fit through the gap and bolt the heatsink onto that. In addition we decided on a midplate that would have suitable cutouts for the TEGs to be hosted in. It would keep the TEGs in place to avoid sideways movement during installation and serve as a base for the box containing the circuitry.

After a bit of discussion about the mechanical design with the company, it was clear that whatever solution we came up with would be sufficient for the prototype, our focus on the rest of the project being a more valuable use of time. Our backplate idea serves its purpose and is fine for now. As the company noted the module would be mounted during installation of the luminaire and left there, making ease of installation less of an issue. We also toyed with the idea of harvesting energy from the backside of the driver, since it would be the hotter side, but we put the idea aside for a later date. We decided to go for the simple sandwich design we had initially thought of.

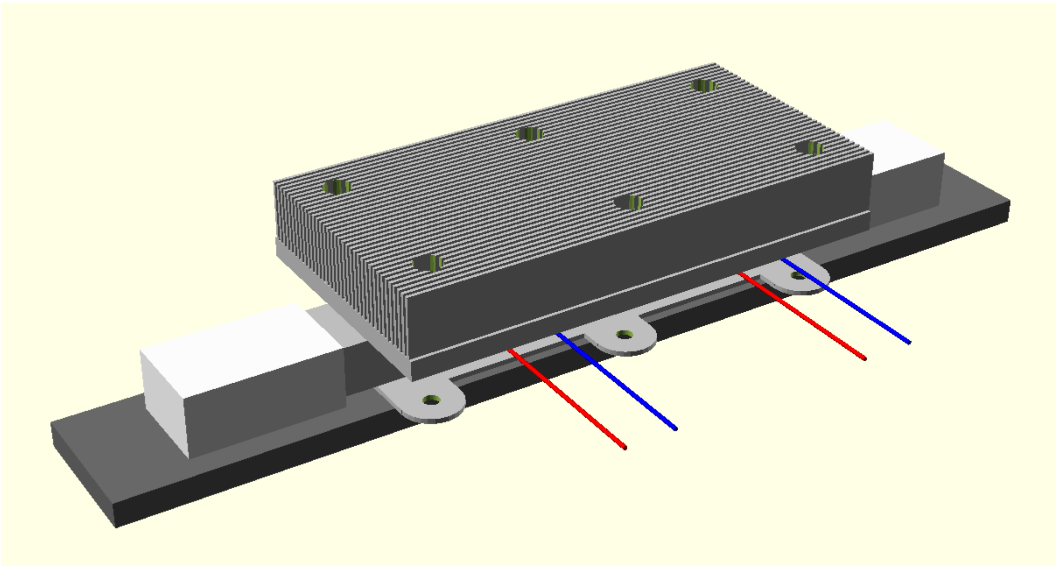


Figure 19. 3D model of initial plan for mechanical design.

We drilled 6 holes in the heatsink for M6 bolts with a 1 mm in diameter clearance. We drilled the smaller 7mm hole from the bottom and a larger hole from the top to make room for the head of the bolt. Drilling from the top proved to be a bit of a challenge since drilling the fins caused strong vibrations that prevented us from making any progress. To dampen the vibrations we inserted fitting metal plates in between the fins to keep them in place. We then managed to drill the larger diameter holes from the top using a low RPM.

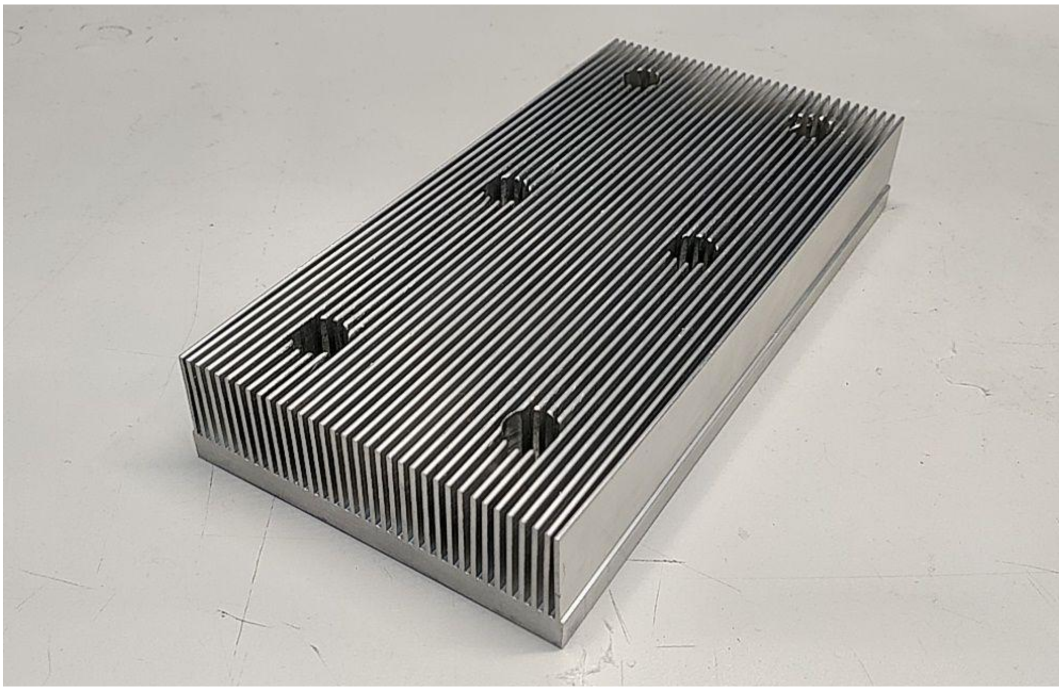


Figure 20. Heatsink with 6 drilled holes.

Out of the material we had access to at the workshop we chose to make the backplate out of a 2mm sheet of aluminium. Initially we planned to make a simple flat surface plate with holes, however we found it impossible to make enough clearance for the nuts beneath the plate due to the luminaire and the placement of the holes already drilled into the heatsink. As a solution we decided to bend three smaller backplates out of aluminium into a u-shape that goes underneath the driver and has holes for the bolts. The bending equipment we had at hand restricted us somewhat since the machine proved to be a bit clumsy. We also had to switch to a thinner 1.5mm sheet of aluminium because the thicker metal tended to snap under bending.

Figure 21. U-shaped backplate.

A midplate was cut out of PLC plastic using the workshop's laser cutter. To house the BLE beacon a box was designed to be a part of the mid plate next to the heatsink. After some tests we found that the plastic conducted heat from the driver to the heatsink surpassing the TEGs and thus reducing performance. Something not completely unexpected. As a solution we cut holes into the midplate reducing the contact area and the heat flux. This is described in more detail in chapter 6. The improvement can be seen in figure 35.

5. PCB

We decided to first make a simple prototype PCB with the tools available for use in the workshop for testing purposes. Later we would order a more complex and more compact design for the final prototype. Due to limitations at the workshop, our initial PCB design is bulkier and less reliable than the final design. After coming to the conclusion that the input voltage of the R-78S converter is too high for this application, the PCB design was updated with a new converter, TPS61201 from Texas Instruments. The PCB layouts were designed using KiCad.

5.1. Initial PCB

The goal of the initial PCB was to get something working and be able to avoid unreliable breadboard designs. Also getting a feel of using KiCad and soldering etc. was important. The actual layout wasn't important at this stage, since we weren't concerned with fitting it anywhere, so we aimed at design as simple as possible. The only restrictions being the manufacturing techniques available and the workshop.

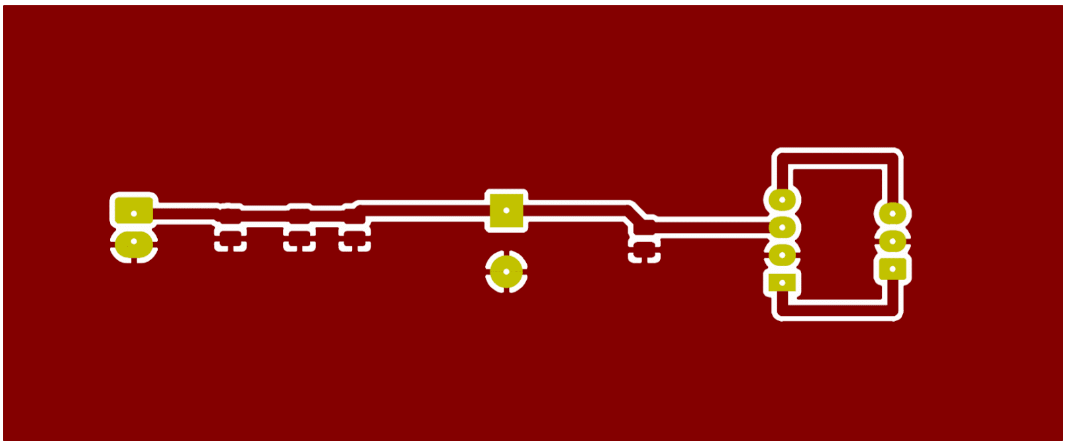


Figure 22. The print of the PCB made in the workshop.

The initial PCB prototype was manufactured using the tools in the workshop. The layout was printed in black on a plastic film. To weaken the coating on the copper side of the board, the board with the plastic film on it was treated with UV light. Since the plastic film was placed on the board, the copper coating under the black ink stayed unaffected. Then the thin film was removed by dipping the board in NaOH. To etch the board, it was given an acid bath in $Na_2S_2O_8$. The etching process took about an hour in this case. After the etching process was completed, the components were soldered onto the board. Note that the components have to be soldered onto the side with copper, which is why the SMD and the THT components are on different sides of the board.

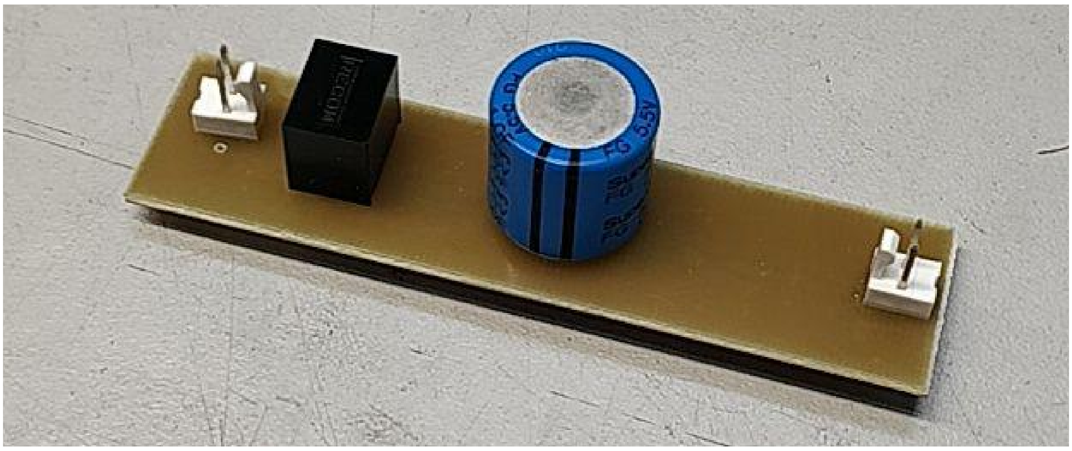
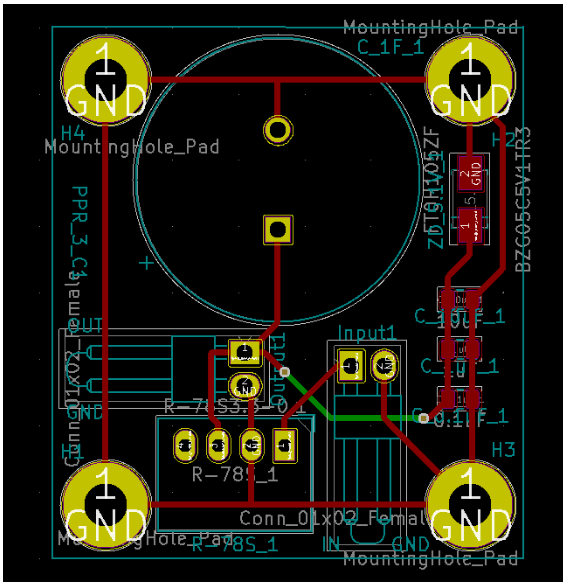


Figure 23. The bottom side of the PCB made in the workshop.

5.2. The Second Revision of PCB

We designed the second revision of PCB to be the same width as the BLE dongle we're using. We aimed to have as small a footprint as possible, and the layout aims to keep the big components, the supercapacitor and the DC-DC converter, on one side of the board to give clearance for the heatsink. The exact footprint of our supercapacitor was not found which meant we had to make a custom one. Some of the footprints like the diode and connectors could be found on Github. For reference, the PCB seen in figure 24 and 25 is roughly 36x41mm.



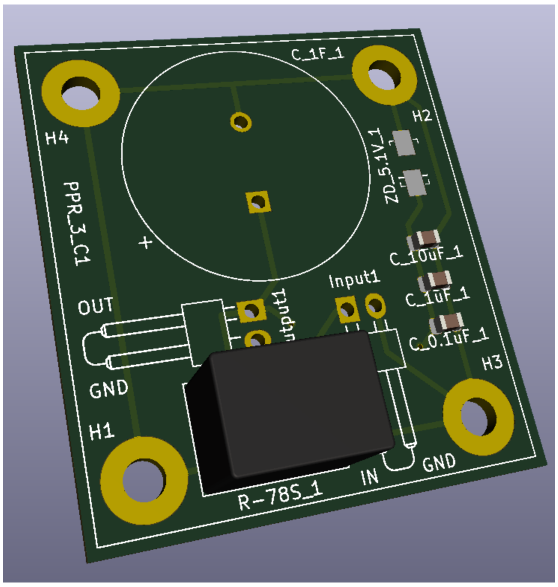


Figure 24 & 25. The layout of our second revision of PCB design and a 3D model of it.

5.3. Final PCB

Since the R-78S converter had to be replaced with a converter having a lower input voltage requirement, the PCB design had to be matched. A suitable component was soon identified from Texas Instruments. The team spent a day researching the new component, TPS61201, and the new necessary adjustments to the PCB due to the converter requiring capacitors at the input and output as well as an inductor. Suitable values had to be decided for these components.

The converter circuit schematic can be seen in figure 27. We picked out suitable components around our converter. The inductor (L_1) value was chosen using equation 3 in the datasheet [reference]. Since our value was less than the recommended minimum inductance, we chose the minimum inductance of 1.5µH. A minimum input capacitance (C_1) of 4.7µF was recommended so we chose a 10µF capacitor. For the VAUX pin a minimum of 0.1µF of capacitance was recommended for stable operation (C_3). We decided to go with two capacitors of the size mentioned. Close to the output we put a 10µF capacitor (C_2).

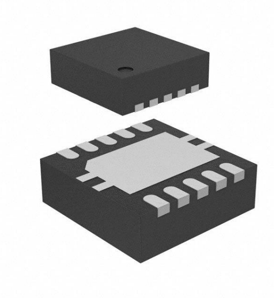


Figure 26. The TPS61201 DC-DC Converter.

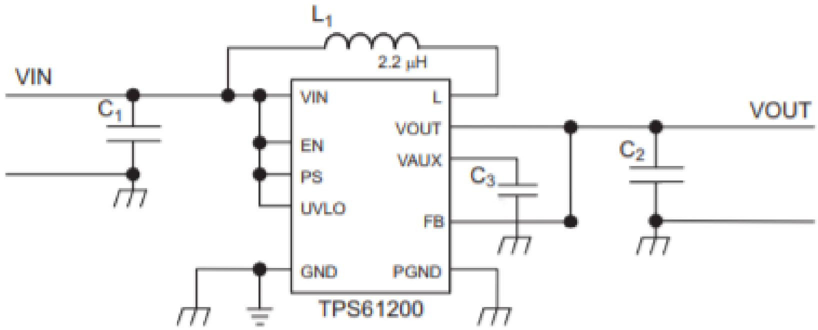
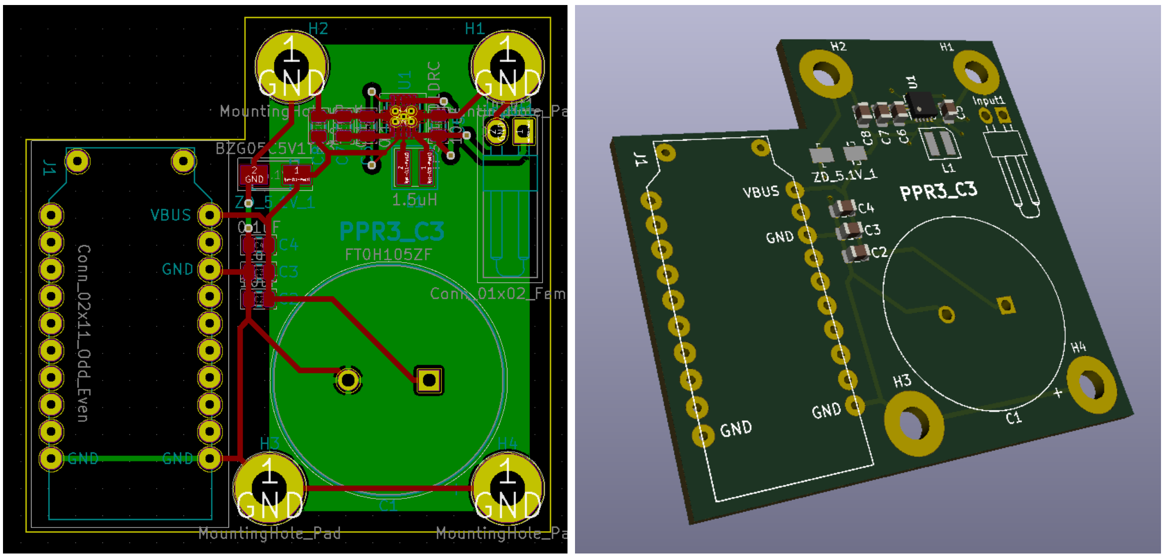


Figure 27. The TPS61201 DC-DC Converter schematic.

After choosing the required components the PCB was redesigned. The new design has the BLE-dongle soldered onto pins on the PCB for better durability and a secure connection. The new design also has a cutout for the USB on the dongle to allow for updating of the software after assembly. Additionally small changes were made after the assistant meeting the next day. In figures 28 and 29 you can see the final circuit design. On the backside of the PCB we have a copper layer to aid cooling of the DC-DC converter. There is no copper layer under the BLE device to try to prevent disturbances in the radio signal. The antenna of the BLE is located in the lower left corner below the two ground pins in the figure.



Figures 28 & 29. The final KiCad circuit design.

Since the PCB is relatively small and simple, the only challenge in the soldering was the DC-DC converter as it has ten small IO pads as well as a thermal pad on the bottom with the dimension being approximately 3x3mm. It took some practice until it was successfully soldered on with a hot air gun.

6. The Final Build Experiments (PCB 2.0)

After soldering the components into the PCB, many experiments were conducted due to problems that arose. First an experiment was made with the finished build, measuring the output voltage of the two TEGs. Unfortunately, the output didn't reach 0.5V that is required for the converter to start working. The results can be seen in the figure 30 below.

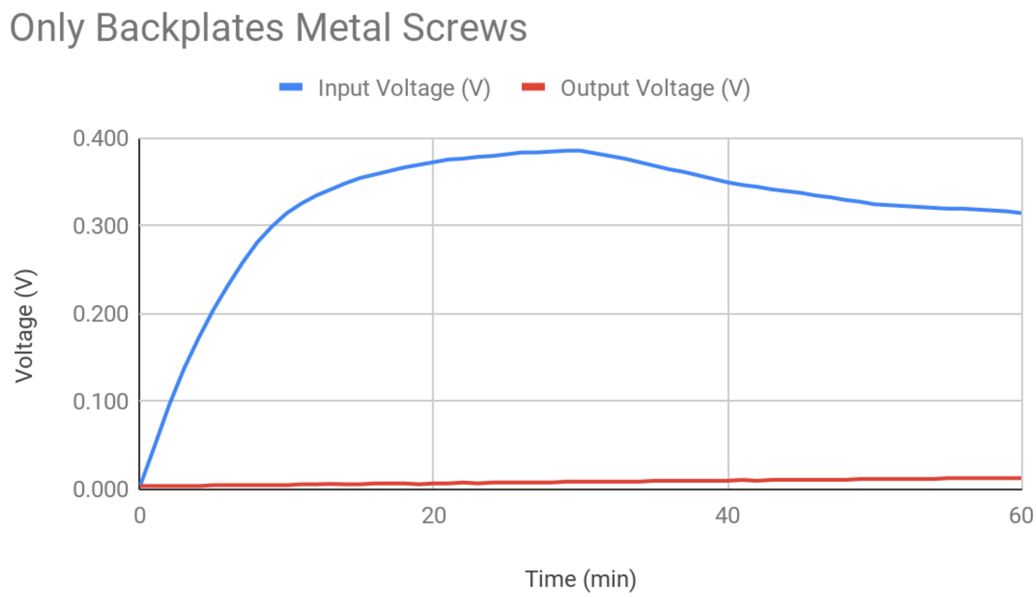


Figure 30.. The input and output voltages of the final PCB with metal screws.

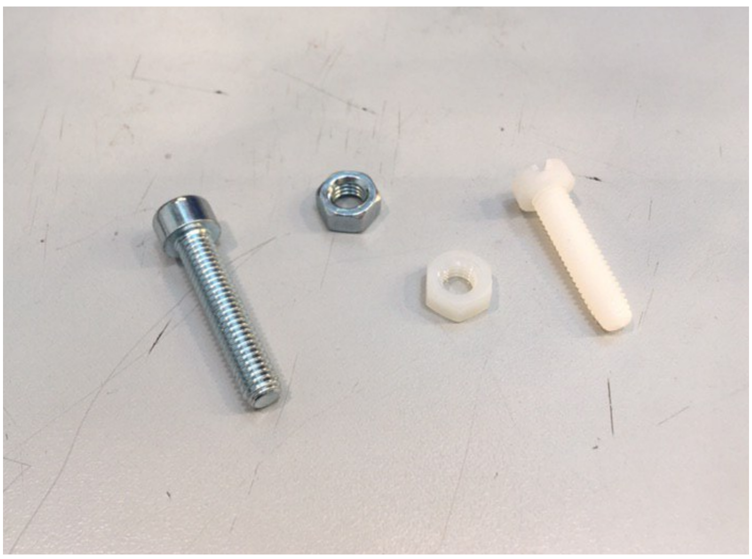


Figure 31. The nuts and bolts.

To increase the peak voltage, we decided to change the metal screws with plastic screws and redo the experiment. The voltage increased quicker but suddenly something unexpected happened; the voltage dropped abruptly from 4.3V to 2.5V. This can be seen in figure 32 below. To make sure that nothing got broken during the experiment, we chose to redo the experiment and also measure the current drawn by the PCB. During this experiment the voltage increased as earlier, but after 36 minutes, we removed the current measuring multimeter and the input voltage dropped. When we disconnected the PCB, the input voltage went back up. Then we connected the PCB again, the voltage dropped again. Clearly the PCB, most likely the converter, is causing this to happen.

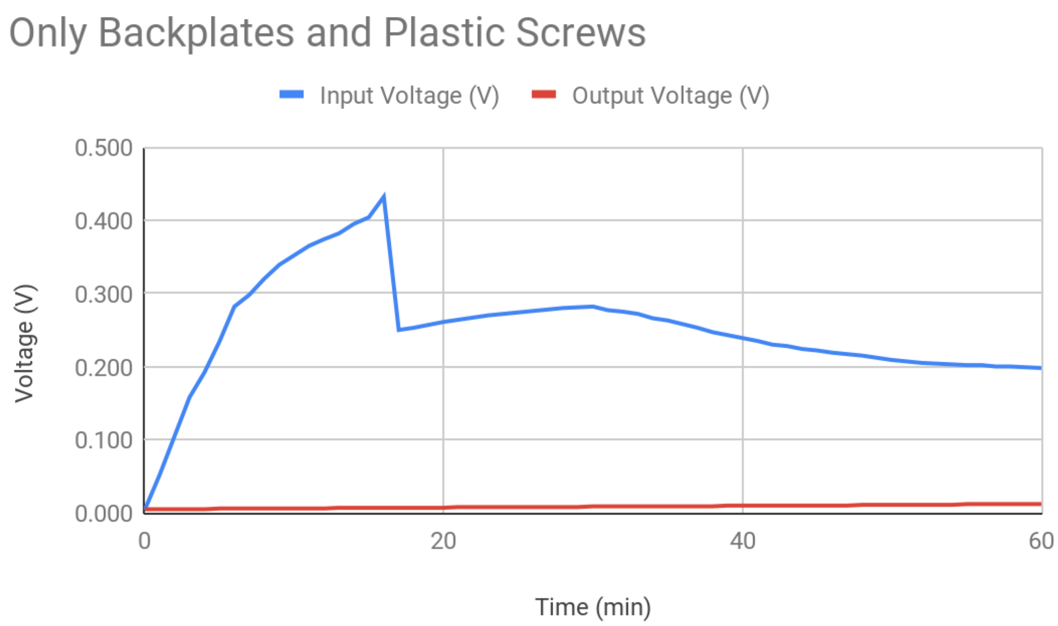


Figure 32. The input and output voltages of the final PCB when the plastic screws are used.

Since this experiment didn't quite help figuring out what was happening, we did the same experiment once more this time measuring the voltage at VAUX. The results were interesting as can be seen from the 33.

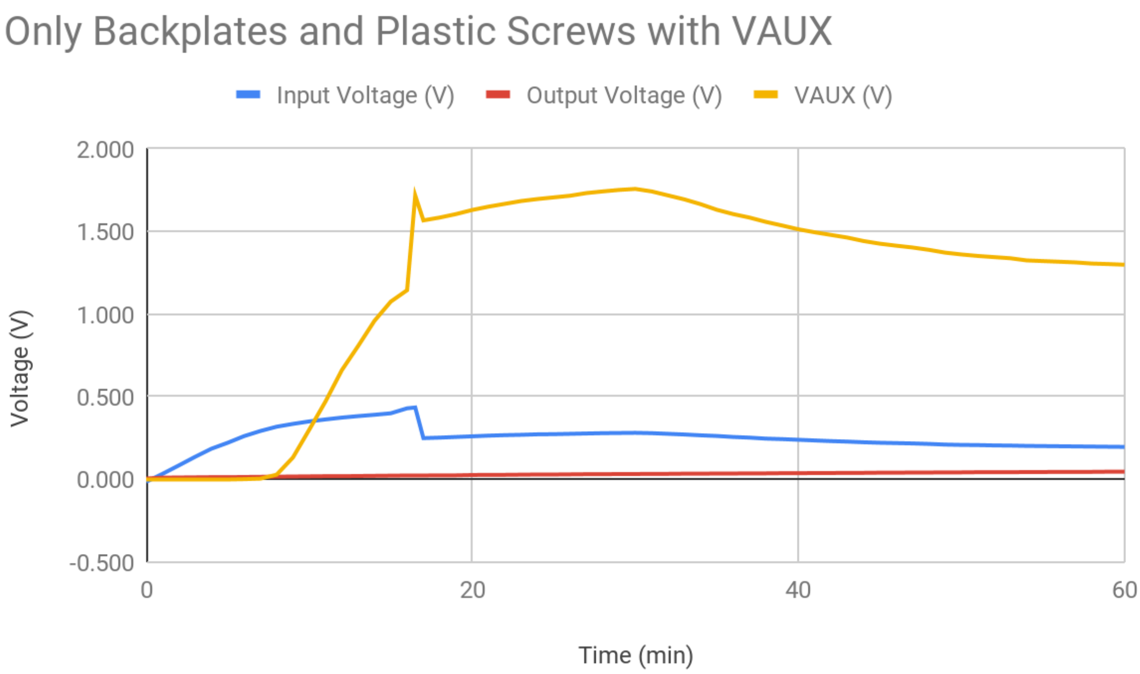


Figure 33. The input, output and VAUX voltage of the final PCB when the plastic screws are used.

At this point we were confounded and decided to go and ask an assistant. The assistant advised to remove the supercapacitor and redo the experiment. The experiment was repeated. The results can be seen below in figure 34. The experiment shows that the supercapacitor was not the problem.

Figure 34. The input, output, and VAUX voltage of the final PCB without the supercapacitor with plastic screws.

After adding the midplate to the setup, experiments showed that the midplate had increased thermal conduction from the luminaire to the heatsink. This resulted in the temperature difference decreasing and lowering the output voltage. This is shown in figure 35 below as the blue line.

To combat the loss in performance, holes were cut into the midplate to decrease the surface area of the contact between the two surfaces. The same experiment was conducted with the cut midplate. The experiment is shown below in figure 35 as the red line. The decrease in surface area increased peak voltage by 44 mV, which is a noteworthy gain.

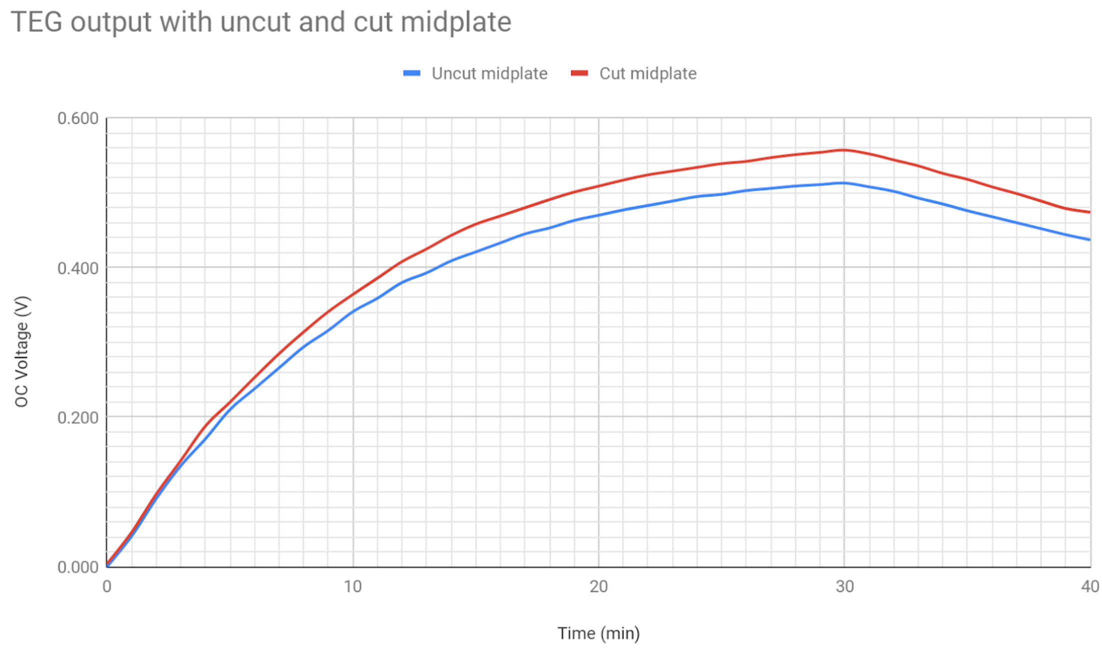


Figure 35. The output voltage of 2 TEGs with uncut and cut midplate.

Since the temperature produced by the testbed is too low for the setup to work, we created a setup simulating the luminaires of different sizes. Again we used resistors to produce the heat but this time the resistors were inside a hollow aluminum tube to simulate the luminaire. The temperature of the aluminum tube was measured with two thermometers. The setup can be seen in figure 36. To estimate the minimum temperature required for the PCB to work, we conducted an experiment supplying different input voltages to resistors.

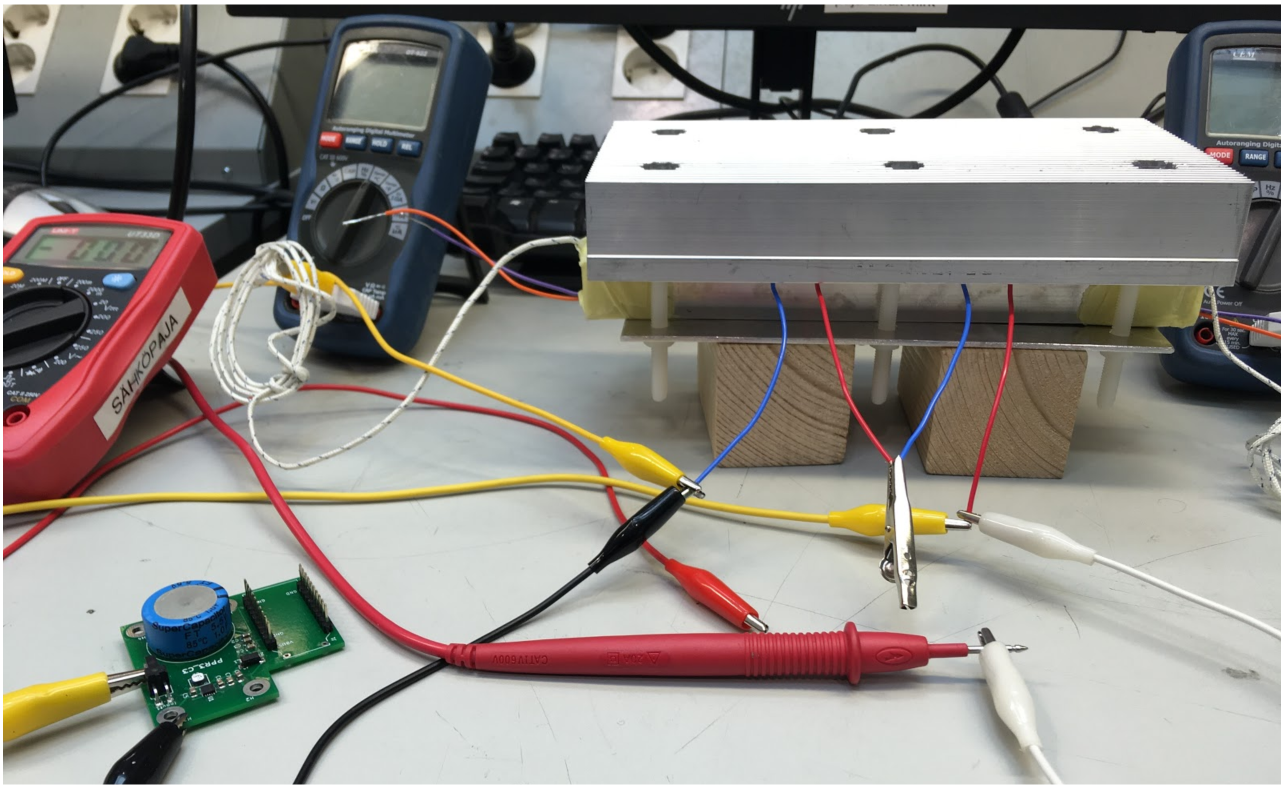


Figure 36a. The test setup used to create different temperatures.

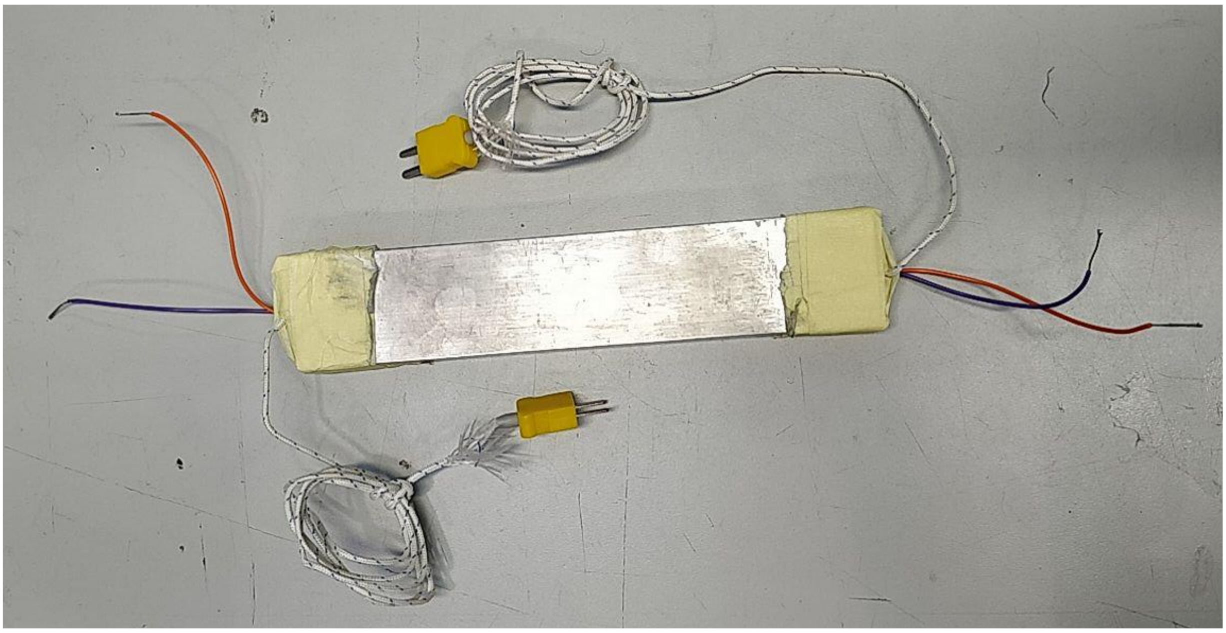


Figure 36b. Device made to simulate the LED-driver.

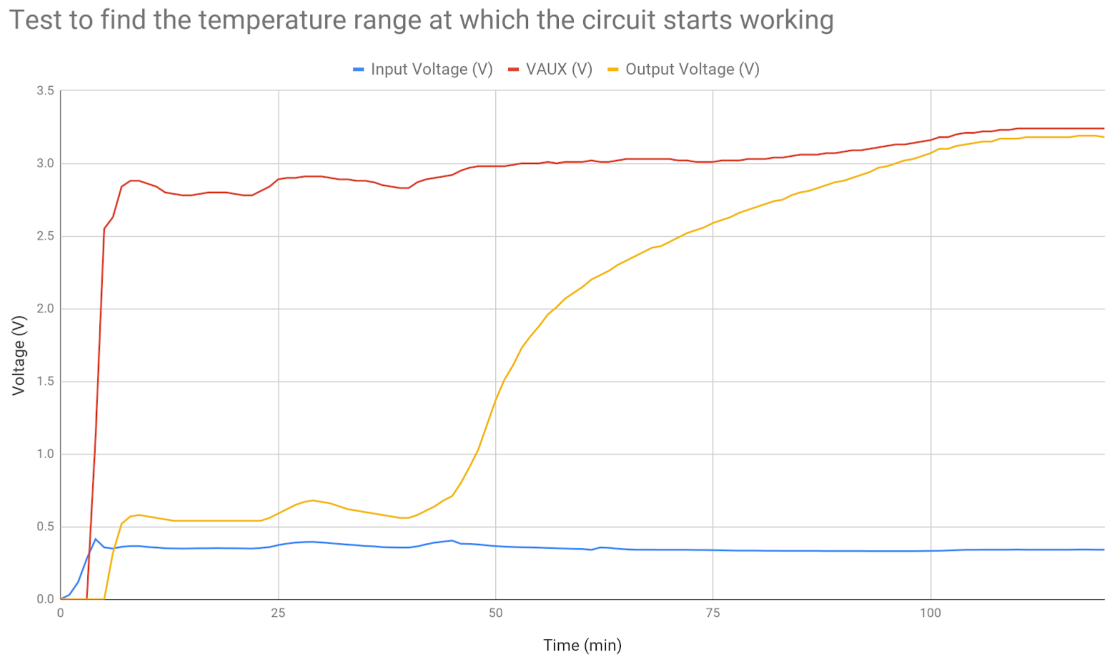


Figure 37. Results from the test with different input voltages.

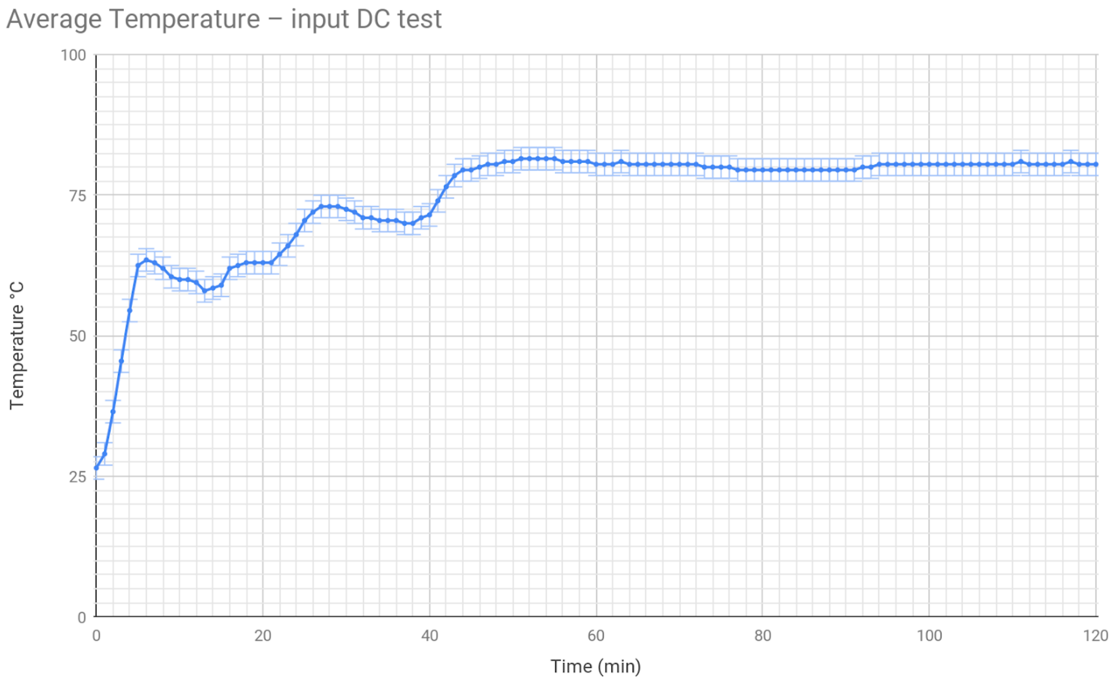


Figure 38. Temperature during the test with different supply voltages.

Now we knew the range at which the PCB should start working. To find the lower temperature limit, we conducted several more experiments using five different supply voltages. The results can be seen below in figures 39 - 43 below. The figures are organized in increasing order based on the supply voltage.

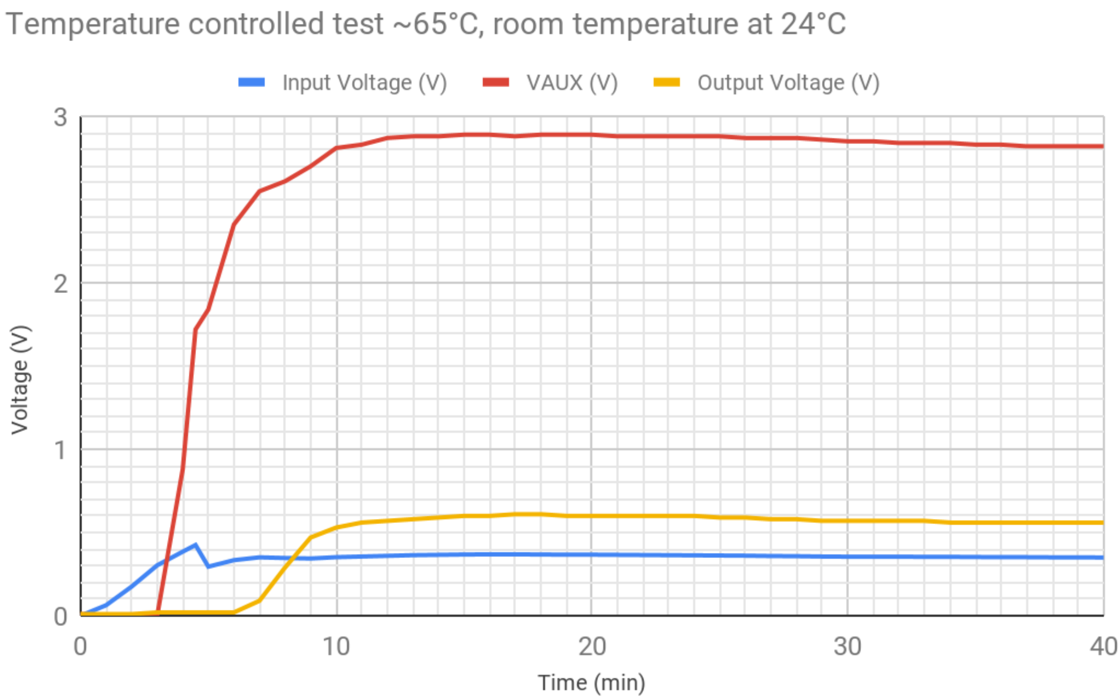


Figure 39a. Results when the input voltage was 11.5V.

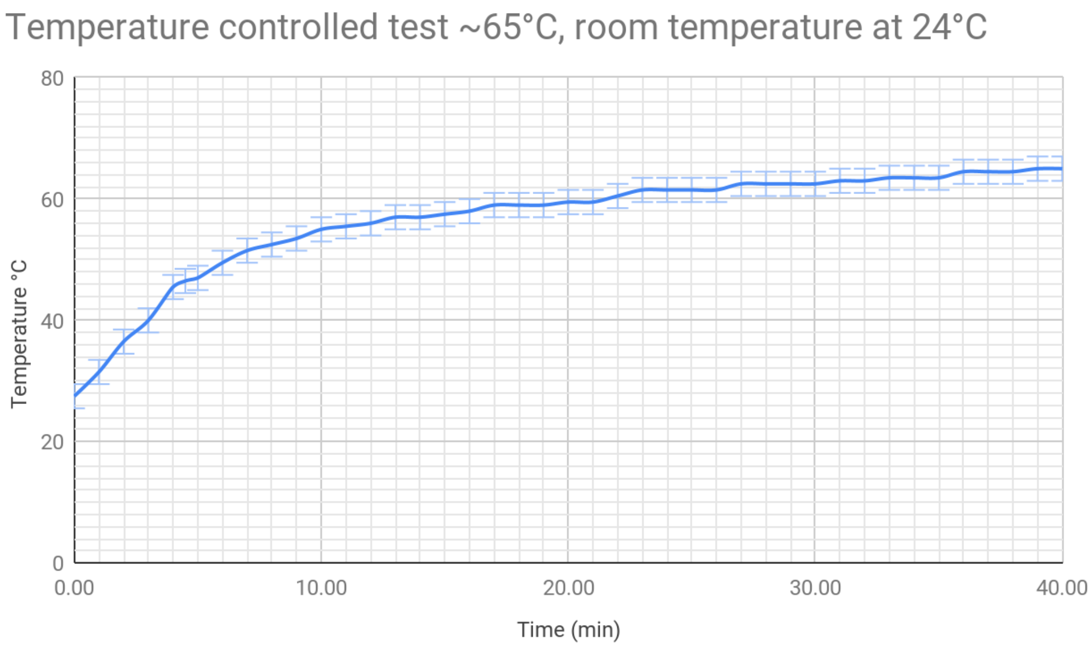


Figure 39b. Temperature during the test with the input voltage of 11.5V.

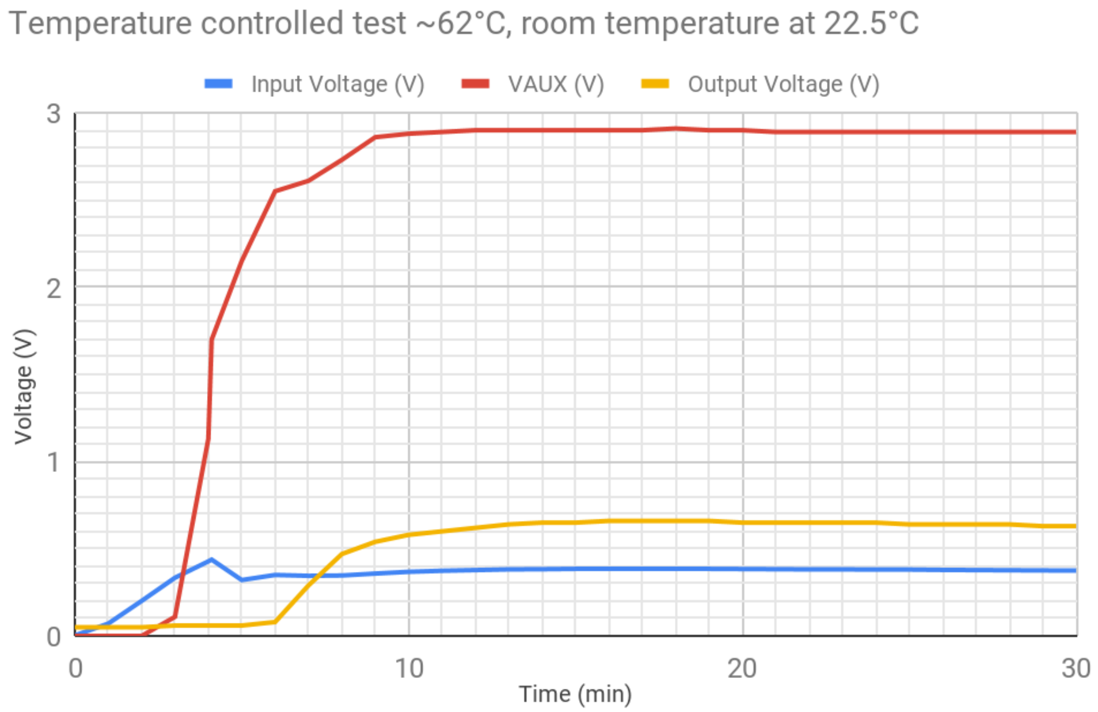


Figure 40a.. Results when the input voltage was 12.0V.

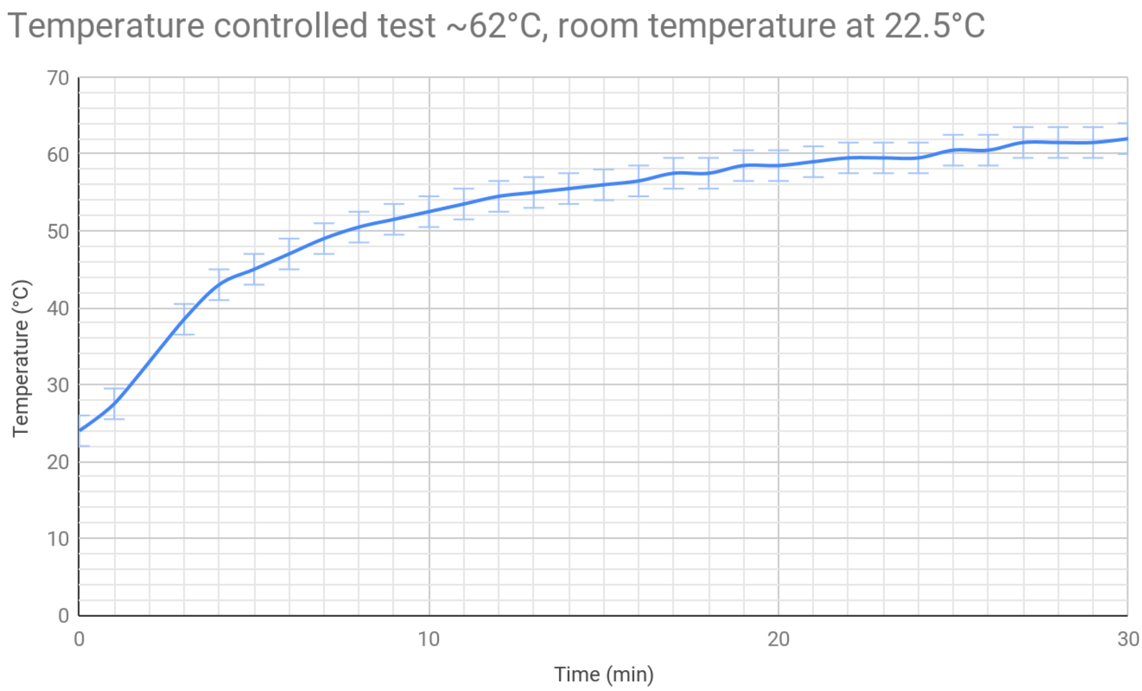


Figure 40b. Temperature during the test with the input voltage of 12V.

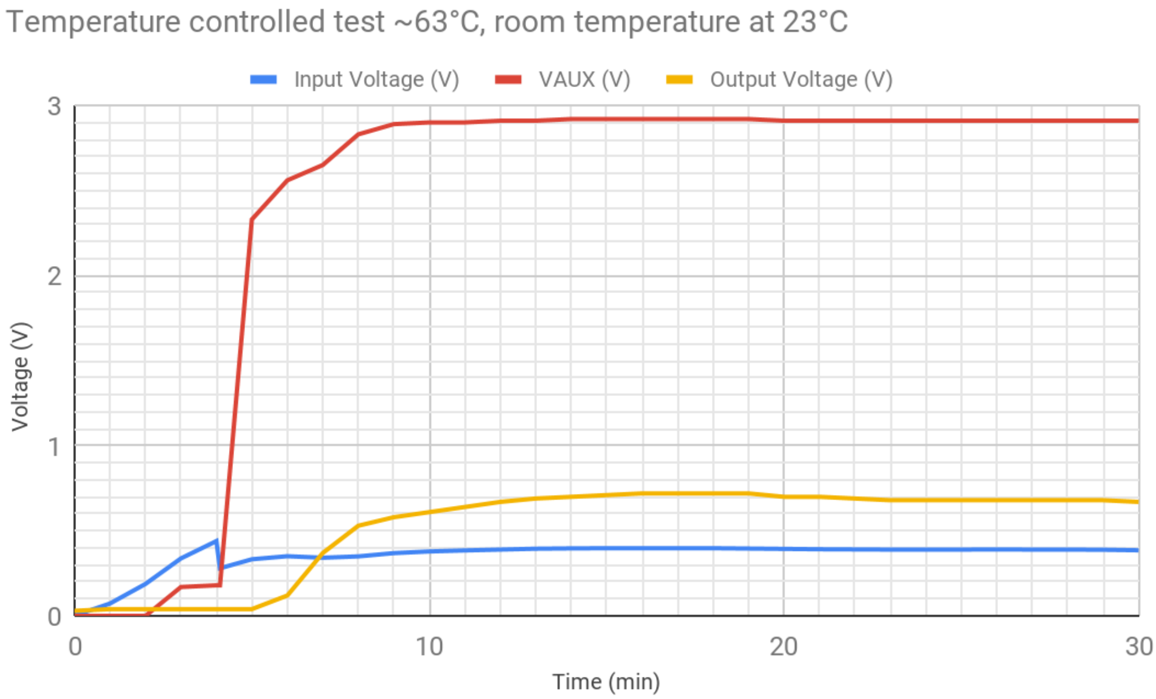


Figure 41a. Results when the input voltage was 12.2V.

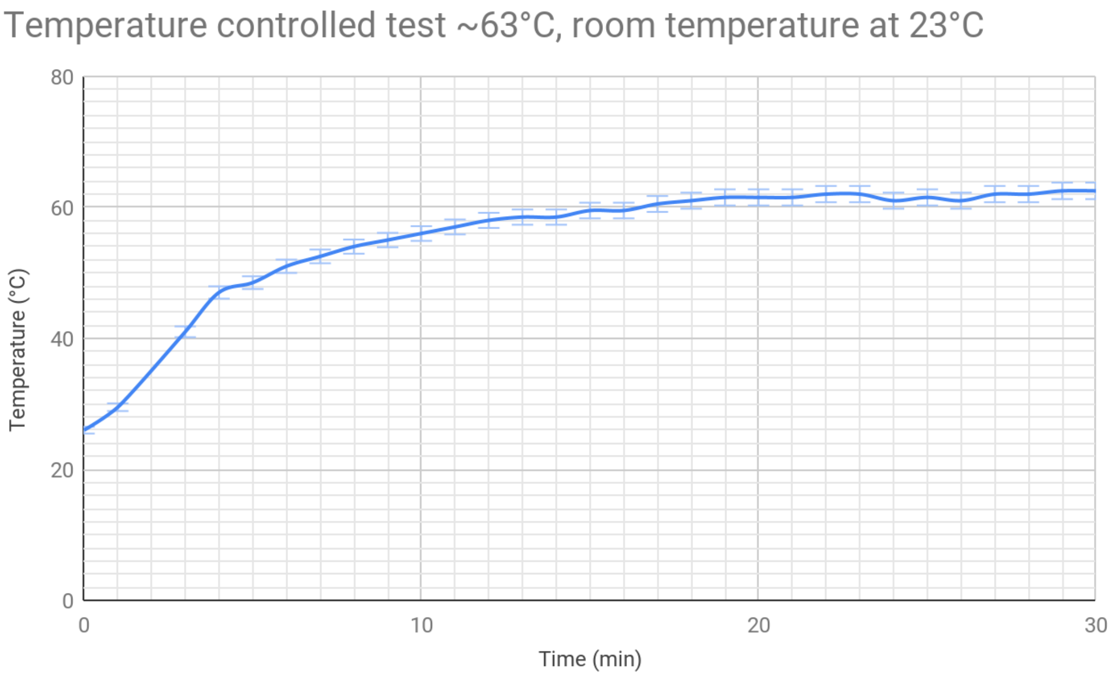


Figure 41b. Temperature during the test with the input voltage of 12.2V.

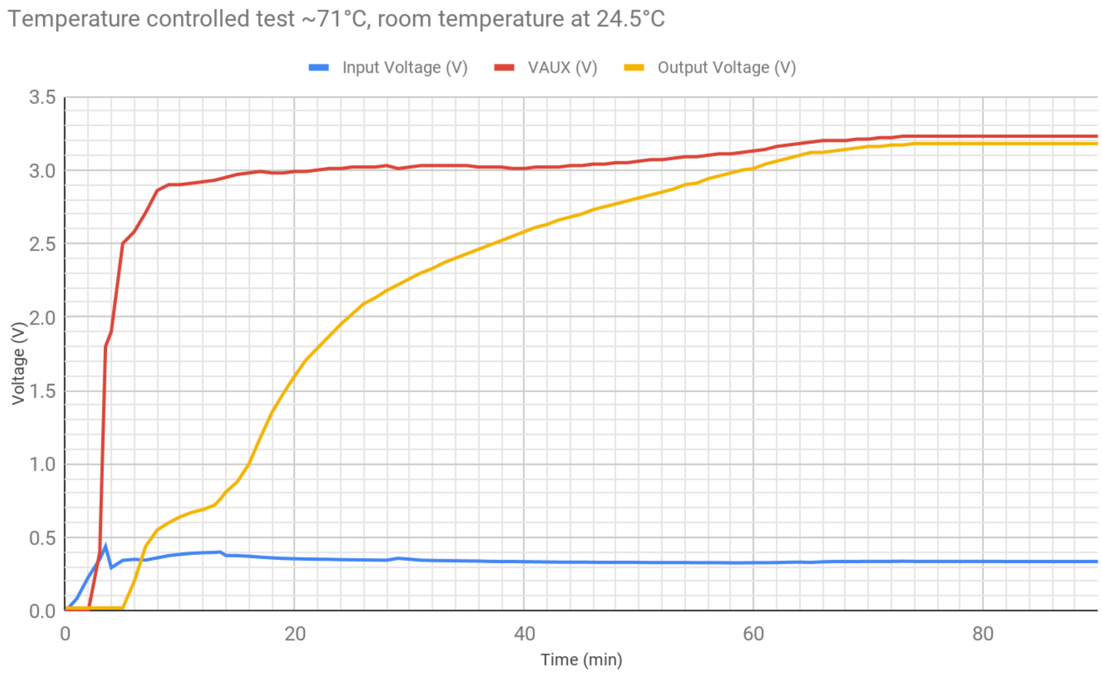


Figure 42a. Results when the input voltage was 12.4V.

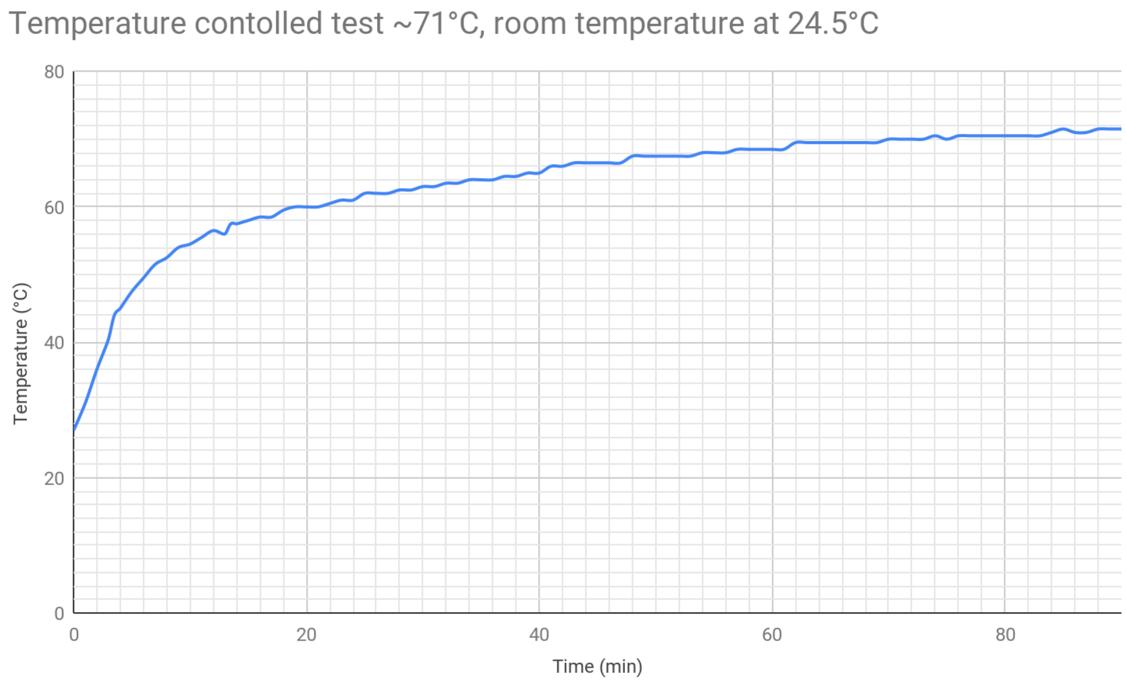


Figure 42b. Temperature during the test with the input voltage of 12.4V.

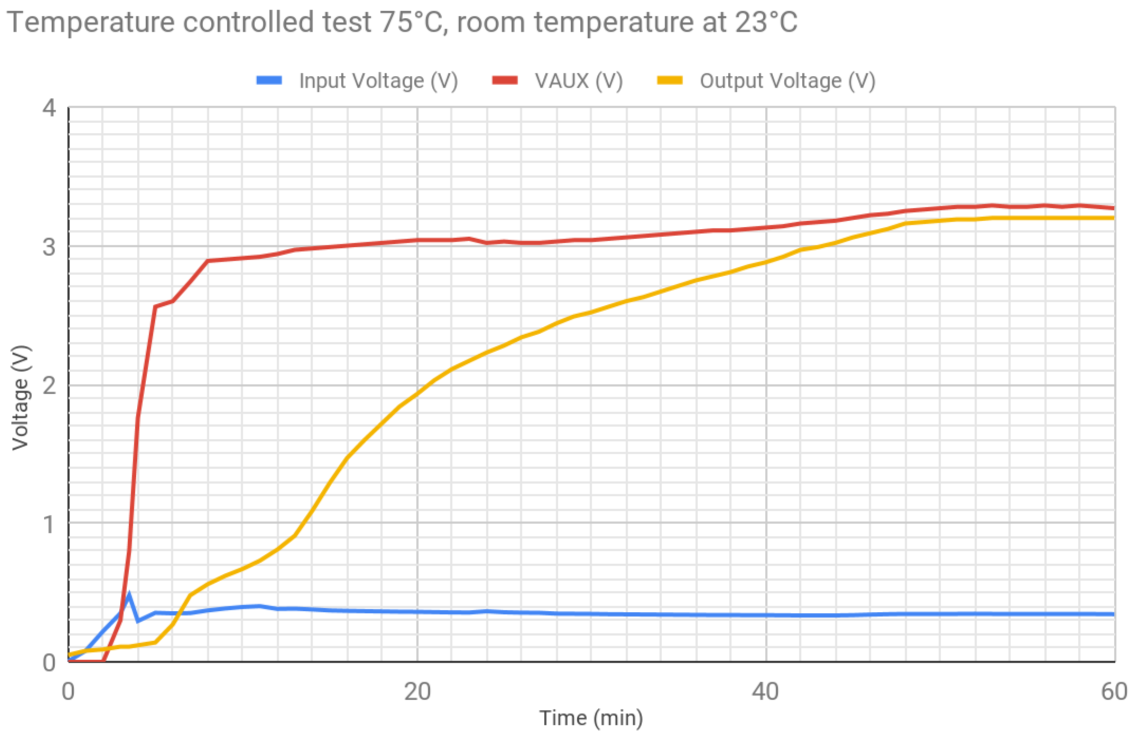


Figure 43a. Results when the input voltage was 12.5V.

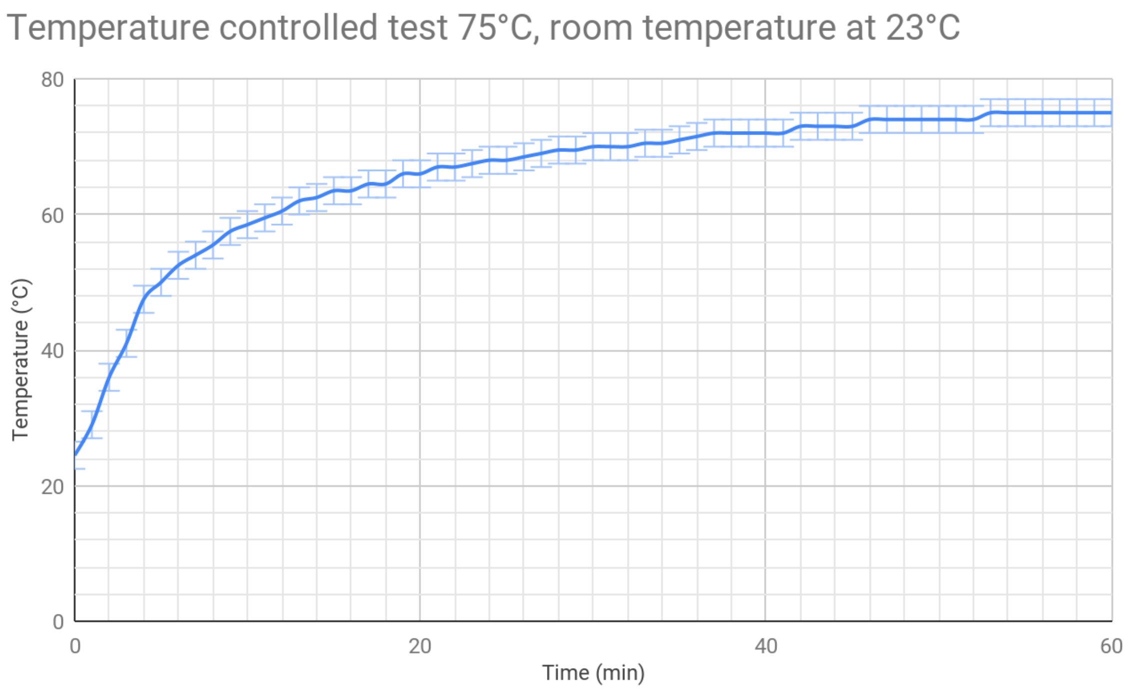


Figure 43b. Temperature during the test with the input voltage of 12.5V.

7. Software

Before work on the software began, a nRF52840 Dongle was ordered. When it was delivered, the precompiled examples from the nRF5 SDK were tested. Unfortunately, an accident including static electricity occurred and the dongle stopped working, so we couldn't continue our software development process for a couple of weeks due to problems with ordering additional units.

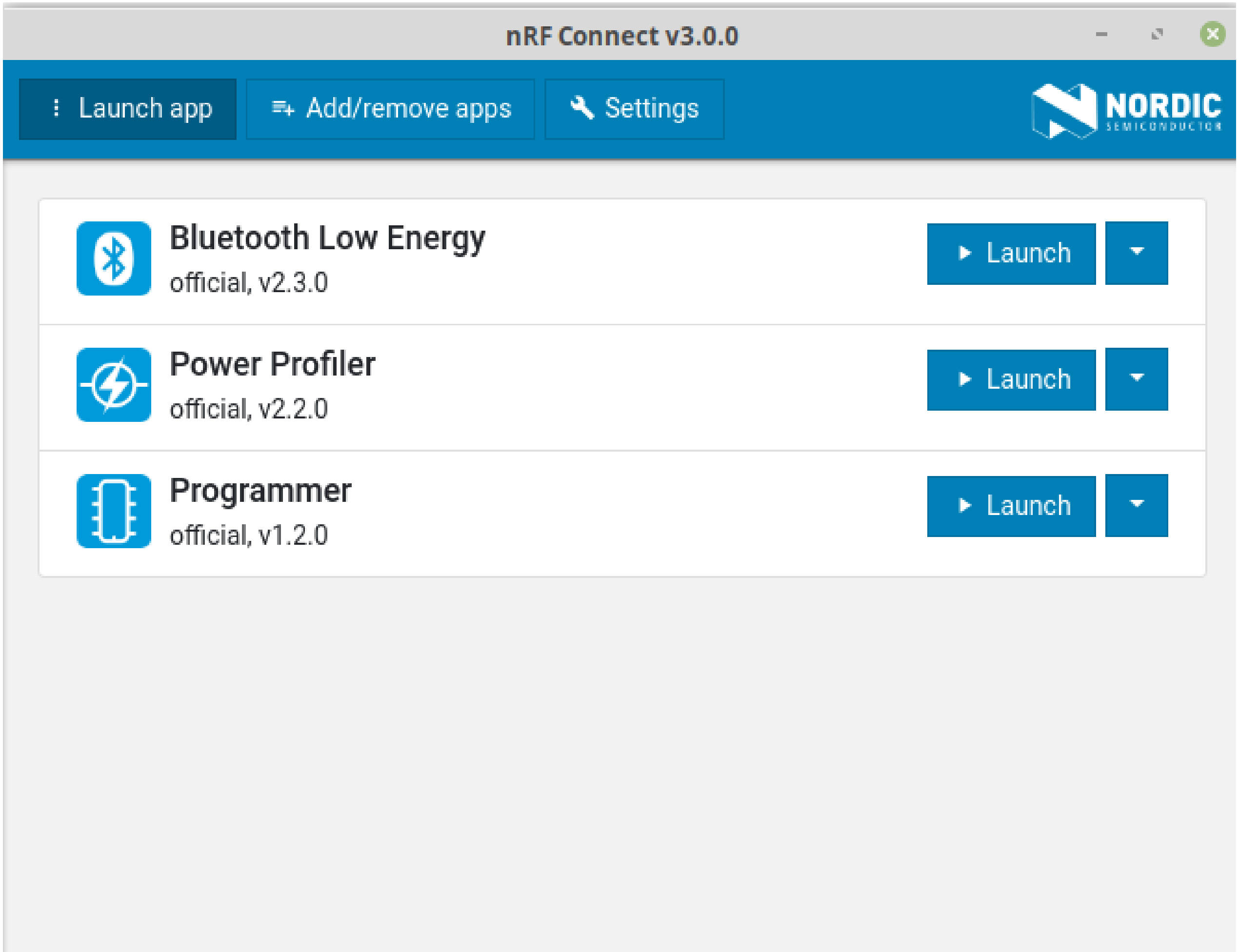


Figure 44. nRF Connect application overview.

A lot of time was spent on researching and getting a grasp of the software development kit provided by Nordic Semiconductors for their Bluetooth enabled boards. This included installing relevant software and applications like the nRF Connect, which provides a tool to flash application onto the board as well as other potentially useful applications. This tutorial provided the necessary information to install all required programs and toolchain related to the programming.

Nordic Semiconductors Devzone has a tutorial for adapting examples made for the PCA10056 board to the PCA10059 board, which is the one we have ordered for our use. This was necessary because a lot of the examples provided by the SDK are not made for the PCA10059. The necessary changes are quite minute; however it took a while to configure and learn how to use the integrated development environments. Eclipse was the first IDE that was attempted to be used, but it proved to be difficult to configure and work with the toolchains etc. Working with Eclipse and a tutorial mentioned above did teach about using IDEs and ready projects, which made it easier to start working with Segger Embedded Studio for ARM that had initially seemed too formidable and unfamiliar. It was soon discovered that importing projects was much easier as the SDK had started supporting SES projects natively since version 13.0.

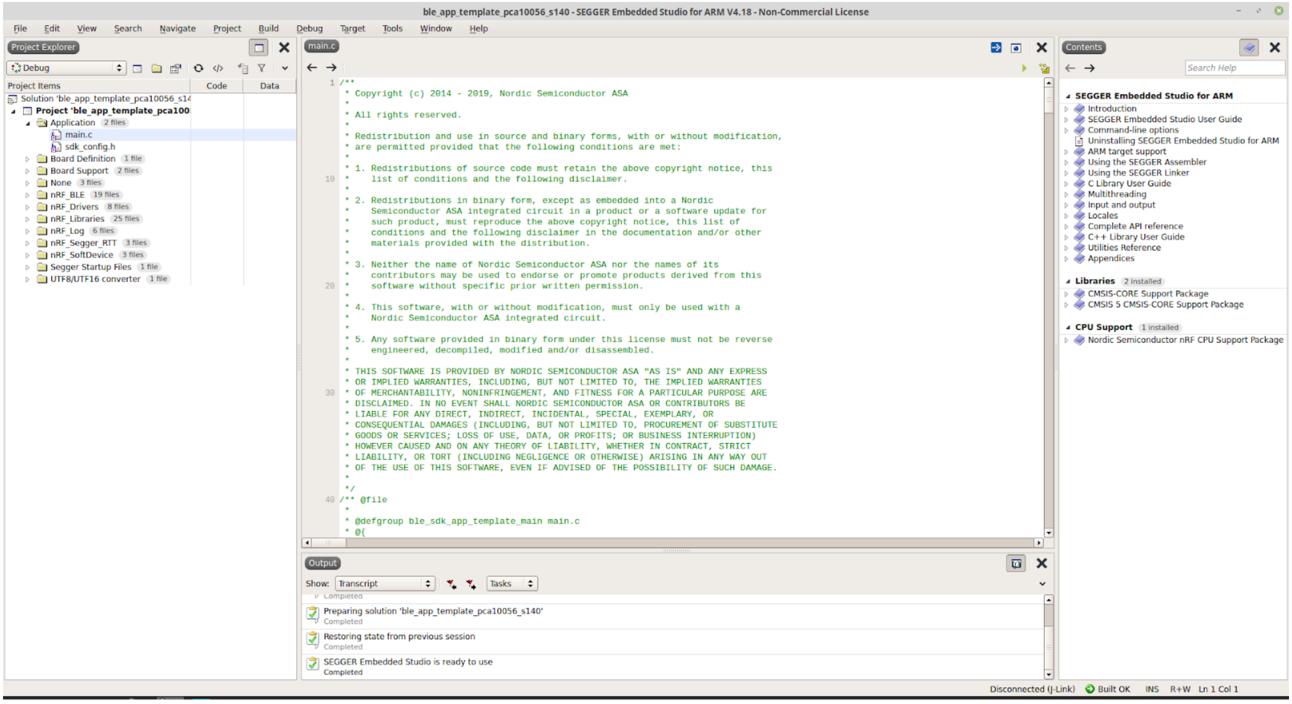


Figure 45. Segger Embedded Studio for ARM.

As a first test, the blinky example for board PCA10056 was adapted for PCA10059 as a test since it did not involve programming a softdevice. This was also an easy way to learn about the nRF Connect Programmer application that writes the data into the system memory. Next, the ble_app_eddystone example was attempted to be modified to work with our board. The process was pretty much the same. First, the preprocessor definition had to be changed to PCA10059 from PCA10056, and then the FLASH memory location had to be changed. Unlike with the blinky example, the ble_app_eddystone requires a soft device to work and thus this had to be written onto the device in addition to the application. We thought we were able to flash everything onto the board properly, but scanning for Eddystone UIDs we were not able to discern whether it had worked.

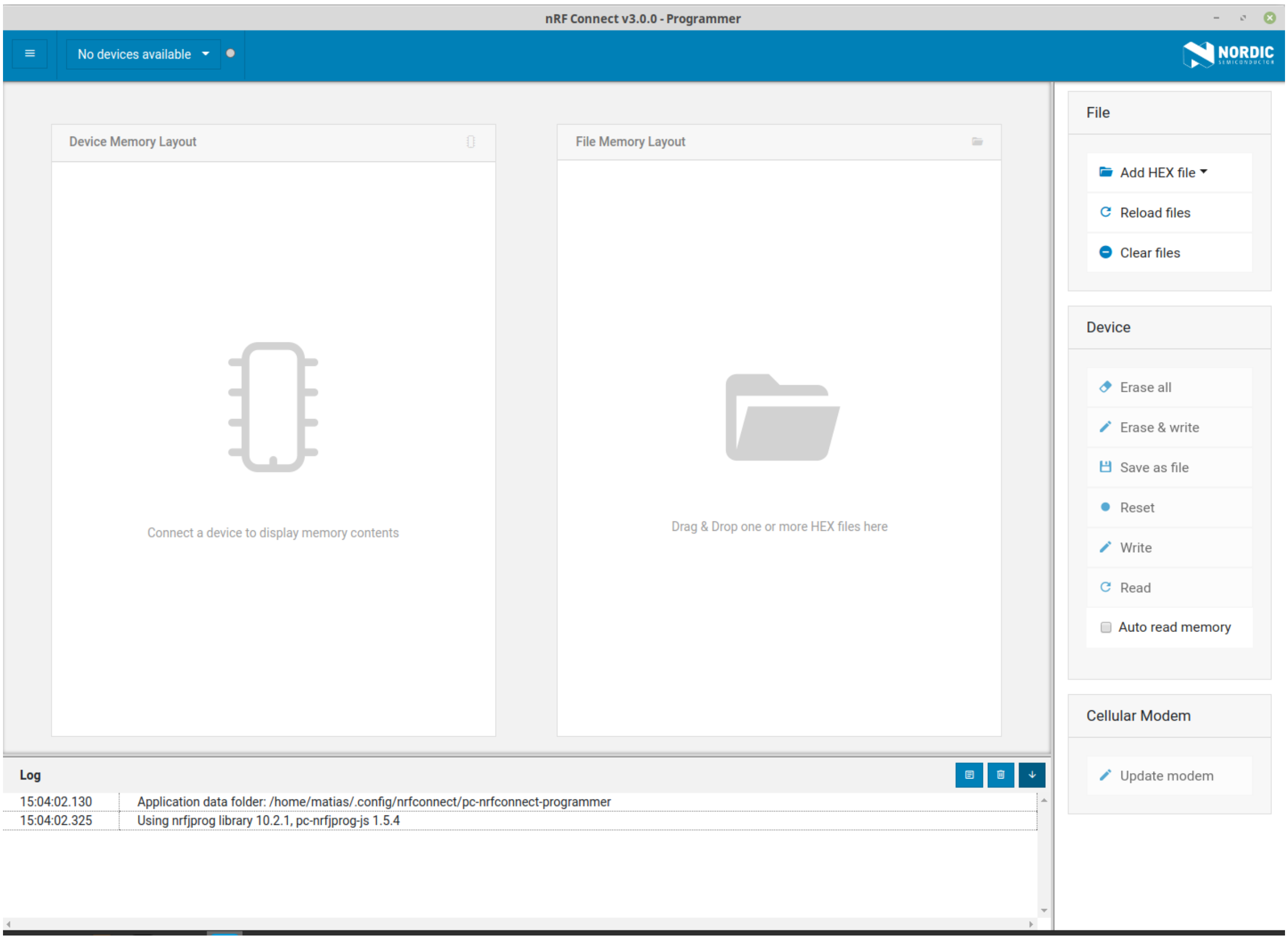


Figure 46. nRF Connect Programmer app.

Instead, a tutorial titled, “Prototyping BLE apps on the nRF5840 USB Dongle part A,” was followed. It configured the ble_app_template to work with the PCA10059 board. It was quite similar to the previous examples, except it required copying some files from different locations and editing a bit of the code to change and add a few macros. This method worked without issues and we were able to establish a connection with a phone using the nRF Beacon app for Android. This provided a suitable place to start testing whether we can power the dongle for real and then see whether modifications to code needs to be made.

During experimentation it was noticed that the BLE dongle stopped working even though it had enough voltage. This was due to the default setting of the template running the BLE beacon for only 180s. This time was increased to over 20h as to not disrupt experiments. The edited software was flashed onto a new board.

8. Reflection of the Project

A project plan is made at the starting point of the project with four phases, modeling and research, construction initial prototype, revision and design, and presentation. The project was oriented by the project plan and it was accomplished in the track of the pre-defined work packages with some changes during the project, as the actual temperature of the LED driver did not reach the expected value since the LED driver did not operate at its full-load, so this change contributed to design a new circuit and make a new feasibility analysis as there were changes in the fundamental information such as the temperature and heat flux of the LED driver. The modeling and research work package includes thermocouple research, feasibility analysis and energy device specification. The initial prototype work package includes circuit design, specifying components, assembling and initial prototyping, and software development of BLE module. Design and revision work package includes testing, measurements and experiments, mechanical and final assembly, and the final circuit design. The last work package, presentation, includes final presentation, documentation, and final report. The documentation has been done progressively during the project.

8.1. Reaching objective

The project reached the objective of powering up a BLE beacon using thermoelectric generators harvesting waste heat. However, this was achieved with a test setup and not a luminaire. This was due to the inability to change the load of the luminaire. Initially the project aimed to have the beacon operating with the luminaire temperature being 85°C. As a result of the lower load, the new design intended to work at around 50°C. This change was desirable as a wider operating range can only be a good thing in this scenario. It was also explained that the luminaires do not operate at full load due to their dimming capabilities, which made a largare operating range a necessity. The challenge of the objective increased, but otherwise remained largely the same as a result.

8.2. Timetable

Since we had to redesign the circuit to work with lower temperatures, the time required for initial prototype and revising the design was greater than estimated. This wasn’t really an issue because we had left a pretty big buffer to prevent time running out. Also less time was required to prepare everything for the final show and presentation.

The time to take for the software took slightly longer than expected. This was mostly due to the unfamiliarity of working with larger programmes, which led to trying a couple different approaches until finding one that works. The additional time was not significant compared to some of the other underestimations. The minimum necessary software was done well in advance.

A suitable heatsink should have been ordered earlier. The heatsink was a key part of the prototype and having it earlier would have allowed us to do the necessary experiments to gain an understanding of how it performs. This would have helped guide design decisions in regards to the PCB a bit earlier.

The amount of time spent on experiments especially on the latter half of the project was majorly underestimated. The sheer amount of time spent on experimentations almost certainly eclipses anything else. Part of this was due to the replacement of the converter to a more complex one.

8.3. Risk analysis

There were delays with shipments, delays in making orders, and misunderstandings. Some of these were listed in the project plan as risks while others couldn't be foreseen.

One risk that was realized was trouble with orders. Firstly we missed a deadline to make an order which put us back by a week. In addition the first BLE beacon that we ordered broke and when additional ones were ordered there were problems with US laws regarding exporting technology with certain level of security. This was impossible to foresee. Eventually we got our BLE beacons, but they took two weeks to arrive. In the grand scheme of things this did not really affect the timeline as the software part was very minor in this project.

The testbed having a lower than expected temperature was something we did not foresee. This forced us to change the design, although this was likely for the better overall. This leads to another risk that we did not foresee, which is the trouble of finding a suitable converter for this application.

8.4. Future improvement

What was accomplished during this course was a success, however the prototype that was built leaves much to improve upon. The converter is designed to operate with a higher current than that produced by the TEGs, making it less than ideal. A converter with a lower current draw and slower charging would be more suitable for us. At this point we have to admit our current skill set isn't enough to improve on this.

A better choice of components around the converter could also potentially improve performance. The high current draw significantly harms the operating range of the device. Our converter also charges an auxiliary output capacitance first before starting to charge the output. This is a function that supposedly aids stability, however it might not be necessary for our application. Again, the output capacitance on the VAUX might not be ideal either. It might be necessary to design a converter from scratch for optimised performance, although considerable time would have to spent by the team researching this option. Even then it is likely we lack the skills and knowledge to design a converter for this application.

Another big bottleneck is our heatsink which as we discovered plays a huge role in performance. The heatsink we had chosen was mostly for reference and availability, although a design fitted for smaller surfaces would most likely perform way better. As for optimizing for cost, using the entire dongle was way overkill, but for simplicity it was an obvious choice for prototyping. Using more than one TEG might not be necessary either if the circuit and heatsink was customized for our application, significantly bringing the cost down. Obviously designing a commercial product was not our goal so factors like cost were not taken into account during the course.

8.5. Approximation of Costs

Here's a list of components used in the project and the approximated costs. The components with negligible costs are included in other components.

Table 2: List of price and components

Component	**Amount**	**Unit Price (€)**	**Total Price (€)**
TG12-4 TEG	2	19.95	39.90
nRF52840-Dongle	1	9.36	9.36
Supercapacitor 1F	1	3.77	3.77
PCB	1	4.00	4.00
Heatsink	1	55.93	55.93
Other components (converter, inductor, small capacitors, Zener diode, wires, box, screws, nuts, thermal paste etc.)	1	10.00	10.00
Total		103.01	122.96

9. Discussion and Conclusions

A working technology has been developed to harvest wasted thermal energy to power up BLE beacon modules. The Bluetooth module can successfully operate using the harvested energy and map a connection with a Bluetooth enabled device. Since the surface temperature of the LED driver did not reach as high temperature as initially expected due to a lower load, we had to find another way to measure higher temperatures. We opted for using an aluminium square tube with resistors inside it to represent and mimic the behavior of the LED driver. When the input power to the tube is set for the temperature to steadily reach 70°C, TEGs are able to power the circuit to send a signal.

During the course and the project, we had to learn and use proper project planning and management skills, as well as risk and cost analysis skills. We were exposed to a plethora of new subjects, like circuit and mechanical design, in addition to PCB printing and software development.

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