ΠΑΝΕΠΙΣΤΗΜΙΟ
ΙΩΑΝΝΙΝΩΝ

ΤΜΗΜΑ ΠΛΗΡΟΦΟΡΙΚΗΣ & ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ

ΣΧΟΛΗ ΠΛΗΡΟΦΟΡΙΚΗΣ & ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ

ΜΕΤΑΠΤΥΧΙΑΚΗ ΕΡΓΑΣΙΑ

«ΤΡΟΦΟΔΟΤΙΚΟ ΚΟΜΒΩΝ IoT ΜΕ ΣΥΓΚΟΜΙΔΗ ΕΝΕΡΓΕΙΑΣ ΑΠΟ ΠΟΛΛΑΠΛΕΣ ΠΗΓΕΣ»

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Υπογραφή

ΕΥΧΑΡΙΣΤΙΕΣ

Κατά την διάρκεια αυτής της διπλωματικής, θα ήθελα να ευχαριστήσω την οικογένεια μου για την στήριξη τους. Επίσης τον κ. Γρηγόριο Δουμένη ως επιβλέπων καθηγητή κατά την διάρκεια της και τον κ. Φώτιο Βαρτζιώτη για την βοήθεια που προσέφερε στην ανάπτυξη των προσομοιώσεων.

ΠΕΡΙΛΗΨΗ

Η παρούσα διπλωματική αφορά στην σχεδίαση πειραματικού συστήματος τροφοδοσίας μικροϊσχύος για την ενεργειακά αυτόνομη λειτουργία ασύρματων κόμβων αισθητήρων στο διαδίκτυο των αντικειμένων (IoT). Η διπλωματική εντάσσεται στα πλαίσια ερευνητικών προγραμμάτων για την σχεδίαση και κατασκευή συστημάτων τροφοδοσίας για τις ανάγκες πρότυπων, ενεργειακά αυτόνομων ενσωματωμένων συστημάτων. Περιλαμβάνει στο πρώτο μέρος μια ανάλυση των χαρακτηριστικών της διάχυτης ενέργειας, με έμφαση στο ορατό φάσμα καθώς και στην ροή θερμότητας (thermalgradient). Στο 2^{ο} μέρος παρουσιάζεται σχεδίαση αναφοράς για την συγκομιδή ενέργειας και την τροφοδοσία εμπορικά διαθέσιμων κόμβων IoT. Τα αποτελέσματα εφαρμόζονται στην σχεδίαση και κατασκευή πρωτότυπου πολυσυλλεκτικού τροφοδοτικού, με δυνατότητα ταυτόχρονης συγκομιδής από φωτοβολταϊκό συλλέκτη, από τριβοηλεκτρικό μετατροπέα ή/και από θερμοηλεκτρικό μετατροπέα (3ο μέρος). Στη συνέχεια παρουσιάζονται οι επιδόσεις και τα αποτελέσματα των μετρήσεων των κατασκευασμένων τροφοδοτικών και προτείνεται περαιτέρω εξέλιξη της παρούσας εργασίας.

Λέξεις-κλειδιά: Τροφοδοσία ενσωματωμένων συστημάτων, IoT, Energy harvesting, Ambient energy, IoT power supply.

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MASTER OF SCIENCE

«Multi-Source energy harvesting power supplies for IoT systems»

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1 Introduction

The goal of this thesis is to present the architecture, design, and implementation of energy harvesting power supplies, capable of powering IoT devices. The first chapter presents the properties of ambient energy in different forms, including light, thermal, vibration, RF, and friction. In the second chapter we focus on the extraction of electrical energy from these micropower sources using appropriate transducers. A list of selected -commercially available-transducers and harvesters is presented for each energy source.

The third chapter presents the design of the power supply, starting from system requirements and design space exploration. Then system specifications are presented as Input/Output Voltage, Capacity of the storage element and Max Output currents. The specifications are derived from real-world IoT node examples. We proceed with the detailed design of the Power Supply and an overview of the produced PCBs.

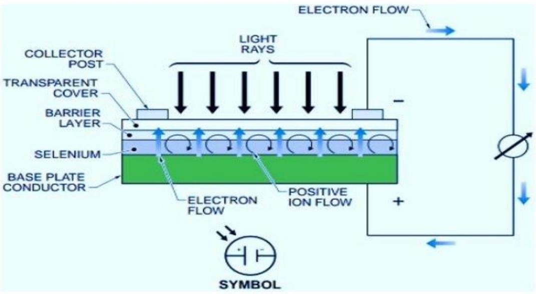
On the fourth chapter we present the construction of the power supply, as well as the performed tests to verify that the power supply's operation. Further, corner tests, as well as efficiency metrics are presented and analyzed. In the final chapter the conclusions are presented, and future work and extensions of this system are proposed. This thesis was conducted in the context of research project EFOS (GSRT, T2EDK-00350), which tackles an energy autonomous electric field mill sensor for maritime applications.

2 Ambient Micropower Sources

2.1 Sources

2.1.1 Light

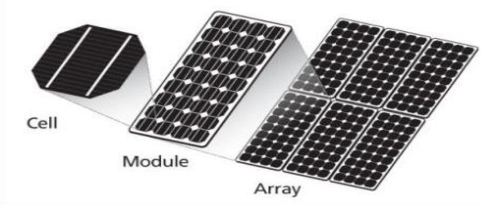
Light is the most common source for energy harvesting applications. Many applications are using light energy to feed their electronic devices. In order to produce electrical energy from a light source, a solar cell need to be used. Such cells are using the photoelectric effect to convert light irradiation directly to electricity.



Picture 1 Photovoltaic cell energy transformation cycle

Light energy is present in different levels of density. There are 2 main categories: indoor light and outdoor (solar) irradiance. Indoor light has density of about 100μW/cm^2 whereas outdoors the density can be up to 100mW/cm^2 (Parvendra Kumar, 2020).

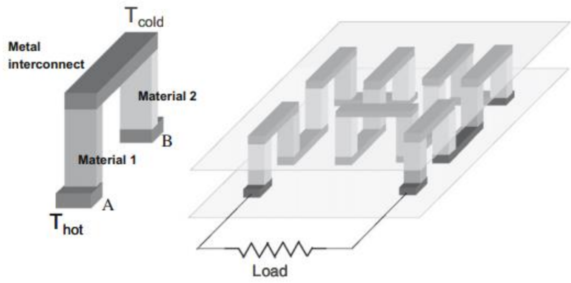
In the picture above it is shown how a selenium based Photovoltaic cell works. When the selenium atoms into the cell are illuminated, they gain energy, and electrons start to move towards the negative pole. Then there is a voltage potential onto the two poles of the cell and flow is created. To step up the voltage, multiple cells are connected in series to provide a greater voltage differential. To produce greater current multiple cells are connected in parallel to each other. Where multiple cells are connected to each other, a solar module is created with usable voltages and currents. The following picture shows what is a solar cell, how it becomes a solar module and at the end it creates an array (Alex, 2021).



Picture 2 Solar Cell to Module to Array

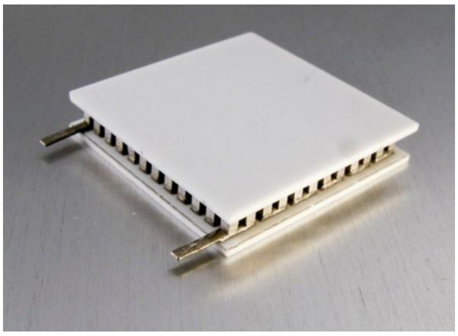
2.1.2 Thermal

Thermal energy harvesting is a different technique to collect energy from ambient recourses. Thermal energy can be extracted from different sources, that were categorized as human sources and industrial. Human energy sources can output power about 20mW/cm² but only the 30μW/cm² can be harvested. On the other hand, industrial thermal sources can output about 100mW/cm² where a range between 1-10mW/cm² can be harvested. This takes place in systems when a temperature differential is present. The thermoelectric generators are utilizing the Seebeck effect which happens when two junctions of dissimilar conductors are kept in different temperatures and an open voltage circuit is created between them. The following picture shows a thermocouple (left) and a thermopile (right) in their schematic form.



Picture 3 Schematics of a thermocouple and a Thermopile

As it is shown in the picture a thermocouple is the main element that provides the voltage differential. To make useful voltage differential multiple thermocouples are connected in series to create thermopile. A thermopile is the finalized generator that is used to harvest energy from the temperature difference. The picture below shows a thermoelectric generator in its product form (R.J.M. Vullers R. v., 2009).



Picture 4 ThermoElectric Generator TEG

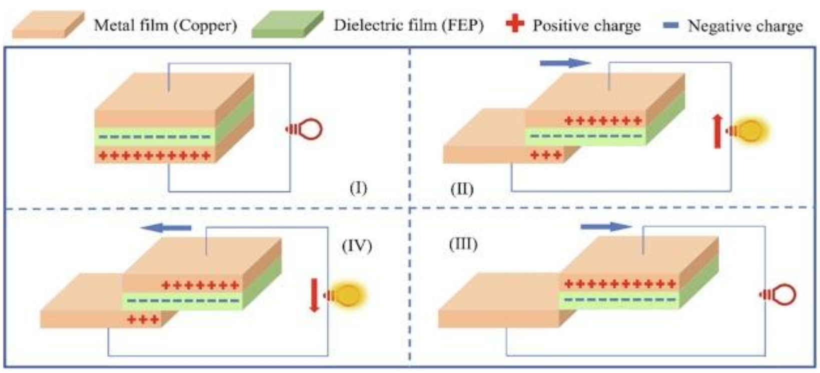
2.1.3 RF

Radio Frequency (RF) energy harvesting is a method of converting radio waves into usable electrical energy. This energy is collected from ambient sources, such as TV and radio broadcast towers, Wi-Fi, and cellular networks (unknown, 2012). The energy is then stored in a small device, such as a battery, and used to power low-power electronics, such as sensors, wearables, and Internet of Things (IoT) devices (Senhao Zhang, 2022). RF energy harvesting works by using an antenna to capture the RF signals, which are then converted into direct current (DC) voltage using a rectifier. The voltage is then stored in a storage element, such as a capacitor or battery. The stored energy can be used to power electronic devices or to recharge other batteries. One of the main advantages of RF energy harvesting is its potential to power low-power electronic devices without the need for external power sources, such as a battery or electrical outlet. This allows for the development of self-sustaining systems, such as wireless sensors, that can operate for extended periods of time without the need for battery replacements or recharging. Additionally, RF energy harvesting can be used to reduce the dependence on traditional power sources, such as fossil fuels, and to promote sustainability. There are several challenges associated with RF energy harvesting, including the limited availability of RF energy in certain environments, and the limited efficiency of the energy conversion process. The amount of energy that can be harvested from RF sources is also dependent on the distance from the source, the frequency of the RF signals, and the orientation of the antenna.

Despite these challenges, RF energy harvesting has the potential to revolutionize the way we power low-power electronic devices. This technology can provide a sustainable, low-cost, and convenient solution for powering small electronics, especially in remote or inaccessible locations. In the future, RF energy harvesting may be integrated into a wide range of devices, from wearable technology to medical sensors, and even cars and buildings. In conclusion, RF energy harvesting is a promising technology that has the potential to provide a sustainable solution for powering low-power electronic devices. Despite its limitations, the benefits of this technology make it a valuable tool for reducing dependence on traditional power sources and promoting sustainability (Husam Hamid Ibrahim, 2022).

2.1.4 Friction

Friction energy harvesting is a technology that generates electrical energy from mechanical friction. This technology is based on the triboelectric effect, which occurs when two materials come into contact and then separate, generating an electrical charge. Friction energy harvesting can be used in a variety of applications, including wearable electronics, wireless sensors, and self-powered systems. The basic principle of friction energy harvesting is the conversion of mechanical energy into electrical energy. This is achieved by using two materials with different electronegativities, which are in contact with each other. When the materials rub against each other, a charge is generated due to the transfer of electrons. The charge can then be collected and stored in a capacitor or battery for later use. One of the main advantages of friction energy harvesting is its ability to generate power from a wide range of sources, including human motion, mechanical vibrations, and wind. For example, wearable devices that are designed to harvest energy from human motion can generate power from the friction between the body and the device. Similarly, self-powered sensors that are placed on rotating machinery can generate power from the friction between the sensor and the machine. Friction energy harvesting can also be used to power wireless sensors in remote locations where traditional power sources are not available. By using the energy generated by friction, these sensors can operate for long periods of time without the need for frequent maintenance or battery replacements. However, there are also challenges associated with friction energy harvesting. One of the main challenges is the low power density that can be achieved compared to other energy harvesting technologies. Additionally, the materials used in friction energy harvesting must be carefully chosen to ensure that they are compatible with the environment in which they will be used. For example, if the materials are exposed to moisture or other contaminants, their performance may be compromised. Despite these challenges, friction energy harvesting has shown great potential as a technology for generating electrical power from mechanical sources. As research in this field continues, it is likely that new materials and designs will be developed that will further enhance the performance and reliability of friction energy harvesting systems (Syed Nasimul Alam, 2023).



Picture 5 Triboelectric

2.1.5 Vibration

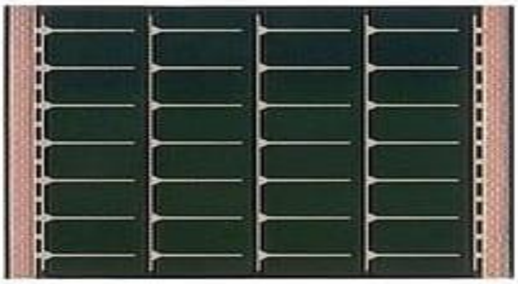
Vibration energy harvesting is the process of converting mechanical energy from vibrations into usable electrical energy. This technology has gained attention in recent years due to its potential for powering small electronic devices without the need for external power sources or batteries. There are different types of vibration energy harvesting technologies, including piezoelectric, electromagnetic, and electrostatic harvesters. Piezoelectric harvesters convert mechanical stress or strain into electrical energy, while electromagnetic harvesters use the principle of electromagnetic induction to generate electrical power. Electrostatic harvesters, on the other hand, utilize the Coulomb force to generate electrical energy (Andrew Muscat, 2022). Vibration energy harvesters can be used in a variety of applications, such as wireless sensors, healthcare devices, and wearable electronics. In addition, they can be used to power devices in remote or hard-to-reach locations, such as sensors in bridges, buildings, and industrial equipment. One of the main challenges in vibration energy harvesting is the low energy density of the harvested power. This means that the amount of power generated from a single harvester is typically low, and multiple harvesters may need to be used in parallel to achieve the required power output. In addition, the efficiency of energy conversion from mechanical energy to electrical energy is limited, and it can be affected by factors such as the frequency, amplitude, and damping of the vibrations (Priyanka Singla, 2022).

To improve the performance of vibration energy harvesters, various techniques have been developed, such as using resonant structures, optimizing the design of the harvester, and incorporating multiple energy harvesting mechanisms. In addition, advanced materials and fabrication methods have been utilized to improve the sensitivity and robustness of the harvesters. In summary, vibration energy harvesting is a promising technology for powering small electronic devices using mechanical energy from vibrations. While there are still challenges to be addressed, research continues to address these issues (Tanju Yildirim, 2017).

2.2 Analyzing micropower sources

2.2.1 Photovoltaic

To make a simple but effective power supply, one energy source is the use of photovoltaic or solar cells. In short, PVs are one of the most common techniques to harvest energy from the environment. Many studies and research have been done on a self-powered PV application. Some very known examples are PV self-powered wearable devices, PV self-powered household systems, PV self-powered environmental monitoring devices or in our case a PV self-powered power supply for IoT devices. The principle that is behind power generation is the photoelectric effect. This is an effect that when a surface is illuminated from a light source, current starts flowing through the circuit. It is not the main point of this thesis to fully examine how a photovoltaic cell works, we need to have a basic knowledge on how it performs. The portability design of PV applications makes them easy to install in places with no or limited power. As the technologies of PVs continue to improve the harvester's efficiency is increasing. Which means that smaller cells are needed to power up an electronic IoT device. With the need for more IoT devices to work autonomously, sometimes multiple solar cells are used to withstand the energy demand.



Picture 6 PV cell (flexible)

As is known most PV cells are hard non-flexible panels. Using that kind of panels, it is needed to compromise in shape of the final product. On the other hand, there are also PV cells, that are created from flexible materials. Using this type of technology, cells can be implemented almost everywhere despite the shape of the enclosure. The application we propose to create uses commercially available solar cells. Such cells are used so that we would be able to test and create a prototype of the power supply. On the following chart we present the cells that have been chosen to be tested and be part of the prototype. It must be considered that one of the main criteria is the pricing of the cells. It is preferred not to use expensive components, in order to keep the whole prototype and design affordable.

Table 1 Commercial Photovoltaic cells

name	characteristics	manufacturer
SM531K10L	5.5V 205mA	ANYSOLAR Ltd
SM401K08TF	5.5V 157mA	ANYSOLAR Ltd

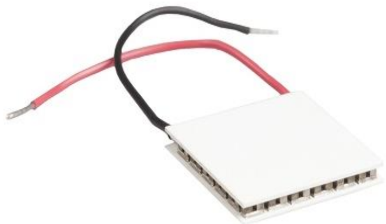
These Solar Cells have been chosen to be used for the application due to their Voltage output and their ability to be proof against bad weather conditions. The SM401K08TF and the SM531K10L were also used to create a spice model later for the design.

Picture 7 SM531K10L PV

2.2.2 Thermoelectric

Another energy source used in energy harvesting applications are Thermoelectric Generators. ThermoElectric Generator in short called TEGs, and this is how will be called. TEGs utilize the thermal flow to generate electric energy. This technology has gained significant attention in recent years due to its potential for power generation in various applications. TEGs are the devices that convert heat energy into electrical energy by exploiting the Seebeck effect. (R.J.M. Vullers R. v., 2009)

The following picture shows a commercial TEG element that can been used in applications.



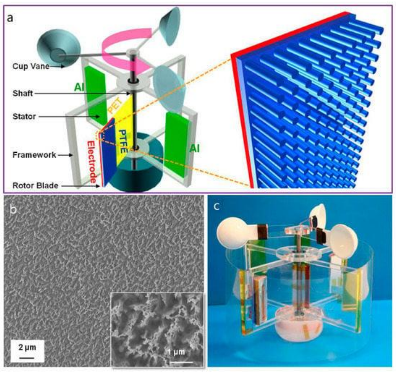
Picture 8 European Thermodynamics TEG module

Thermal energy harvesting has been used in outdoor applications. In asphalt pavement surfaces the radiated heat could be used to harvest energy. Research have made prototype devices to use the wasted heat to produce energy for a IoT WSN system. (Gabriel Filios, 2019)

2.2.3 Triboelectric

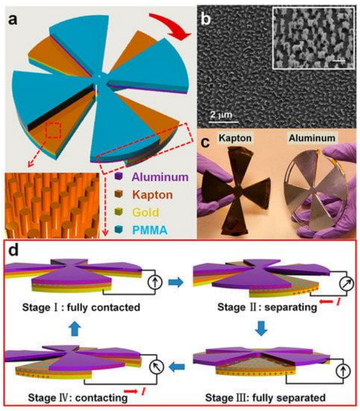
Triboelectric is a type of energy harvesting that can be used when two surfaces utilize the triboelectric phenomenon. The triboelectric phenomenon has been created by transforming mechanical energy into electrical. Triboelectric generators are the devices that make this energy transformation possible. Recently TENGs have gained attention due to their low manufacturing cost, high efficiency, and wide availability of materials. To this date TENGs can be used in a variety of applications such as: energy harvesters, sensors, or a combination of both. Recent research shows interest in TENGs that can produce energy from rotational motion. These kinds of generators are called R-TENGs, and they can perform in different environments such as air-turbines, vehicles etc.

As for energy harvesting applications R-TENGs need to be assembled in a way that they can produce energy to harvest. Different kinds of mechanical devices have been constructed to make use of this technology. One of the first designs was implemented by using radial flaps. That design used rotational force to move the rotor. The rotor had flexible film electrodes and every time it was contacting the stator an electric charge occurred.



Picture 9 rotating flaps R-TENGs

Many researchers have developed mechanical structures that differ on how the triboelectric surfaces were contacting each other. Another interesting rotating assembly was the Radially Segmented Disk, where the surfaces rotate on each other. (Apostolos Segkos, 2023)



Picture 10 segmented disk R-TENGs

3 Power Supply Design

3.1 System Requirements

To develop an energy harvesting Power Supply Unit (PSU), first we must set some key requirements. This thesis was conducted and funded by the research project EFOS, which tackles an Electric Field Mill Sensor for ships. The requirements were set in the project. The following table shows some of the system and hardware requirements as set by the project:

- Modularity and scalability (interchangeable inputs of various types and numbers).
- Small (Stamp size).
- High end-to-end Efficiency.
- Vin PV: up to 25V.
- Vin TEG: -1V to 1V.
- Vin TB: up to 20V AC.
- Vstore: 5V (Capacitor Temporal Storage).
- Vbat: 3.2V to 4.2V (Multichemistry Battery Storage).
- Vout:3.3V, 5V, 24V.

In terms of architecture, one of the main challenges is the requirement for modularity and scalability. Further, we wanted the energy harvesting modules to work independently from each other, so if one is not charging or fails it will not act on the others. Also, it is preferred to pick up the harvested energy from the storage capacitors when they are full and let them charge to the maximum point.

Monolithic solutions of existing commercial energy/power management units will be used as the main system components. The modules to be analyzed are commercially available and already used in IoT applications, industrial applications, stand-alone systems, wearable devices, and other special purpose uses. Due to the design of the physical structure more than one energy harvesting subsystems are required. This is necessary due to the shape of the structure, where photovoltaic collectors will be placed around the perimeter of a conical structure with no fixed orientation with respect to the sun.

As a result, the different illumination of the collectors will result in a mismatch of the maximum possible power that the system can harvest. Ideally, the management system should have more than one input for power collectors. Unfortunately, investigations into commercially available products have not been successful for such a multi-source system. For this reason, the solution is to combine multiple management systems.

Picture 11 mechanical structure of EFOS

3.2 Considerations

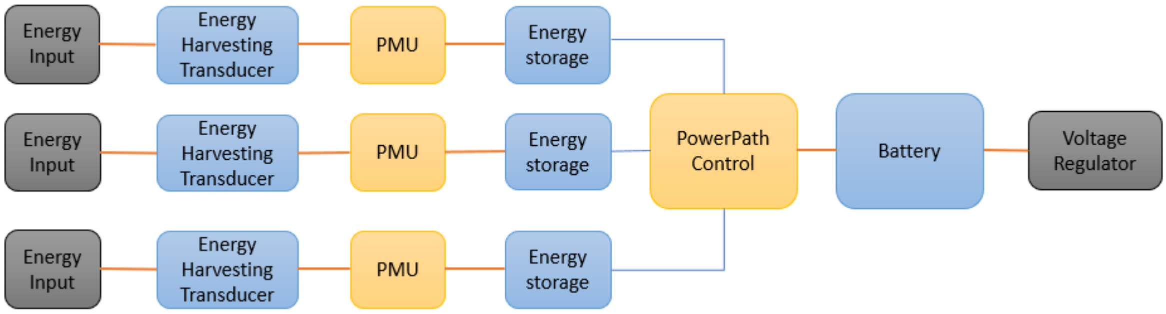
Before diving into the design and the proposed architectures for the Power Supply Unit, a general description of an energy harvesting power supply is required. An energy harvesting power supply utilizes ambient energy and stores it in a charging element for later use. Sources have already been discussed in a previous chapter. Many alternatives are presented, due to different sources, so we can “cut” the chip in sections to understand it properly. The following diagram and proposal are for a single source energy harvesting unit.

The first block of the system is the input, this part differentiates depending on the source. Second in the diagram below is the Energy Harvesting Transducer. Either a rectifier is used for AC sources or a DC-DC converter for DC sources. The DC-DC converter can be Boost, Buck-Boost, or Buck, depending on the specified part. In some applications the Maximum Power Point implementation is found here. This implementation is used to keep the harvester at its peak power point.
Third block is the Power Management logic, and it is used to transfer energy to the storage element. The storage element has its own control logic, so that it is not destroying the storage element from overcharge. This is critical because some chips can utilize batteries as charging elements instead of capacitors or supercapacitors.
Fourth in the row is energy storage. Here we can have elements such as: capacitors, supercapacitors, or rechargeable batteries.
And the fifth element is the voltage regulator, many chips have a power output already built

in. meaning that they can provide a specific voltage output to be used for a microcontroller. The following picture has a diagram that describes the general logic behind a chip. After that the DC-DC topologies are explained as well.

Picture 12 energy harvesting Block diagram

On the other hand, our consideration is to design a multi-input, multi-source energy harvesting unit. The main block diagram consists of many similarities with the single source. That is made up of many single source harvesting units. As for the energy harvesting blocks, the energy input can vary depending on the application. Then the energy harvesting will take care of extracting the ambient energy and store it in a temporary energy storage. The main difference is the PowerPath block that will monitor and collect the energy. This block is the main consideration that we will focus on and analyze. Different architectures will be presented to propose and develop a prototype design. Then an additional block that is implemented is the battery charging and monitoring. Finally, the last block of the voltage regulators will draw energy directly from the battery to convert and use.

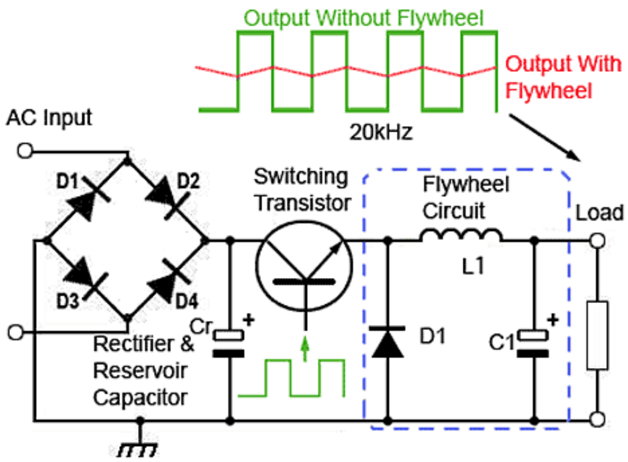


Picture 13 multi-input block diagram

One of the main blocks of an energy harvesting chip is the DC-DC converters they have. A general description of DC-DC converters is as follows.

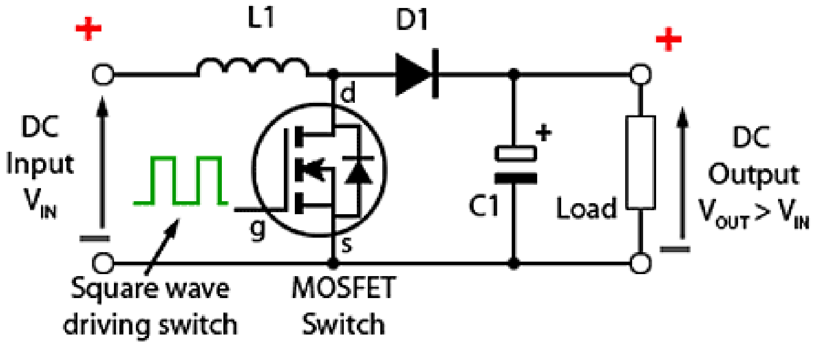
The most used types of dc-dc converters are the Buck, Boost and Buck-Boost. Generally, a dc-dc converter is used to convert voltage to another level. Different converter types are used in different applications depending on the needs. They are based on electronic components and a driving circuit to open or close the switching element. Also, these types of converters utilize high frequency switching that has many advantages to produce the required output.

A Buck converter is used in applications where the output voltage needs to be lower than the input voltage. It can also operate with AC input by using a Full Wave Bridge Rectifier. The switching transistor between the input and output of the Buck Converter continually switches on and off at high frequency. To maintain a continuous output, the circuit uses the energy stored in the inductor L, during the on periods of the switching transistor, to continue supplying the load during the off periods. The circuit operation depends on what is sometimes also called a Flywheel Circuit. This is because the circuit acts rather like a mechanical flywheel that, given regularly spaced pulses of energy, keeps spinning smoothly (outputting energy) at a steady rate. (Coates, Module 3.1 Buck Converters, 2020)



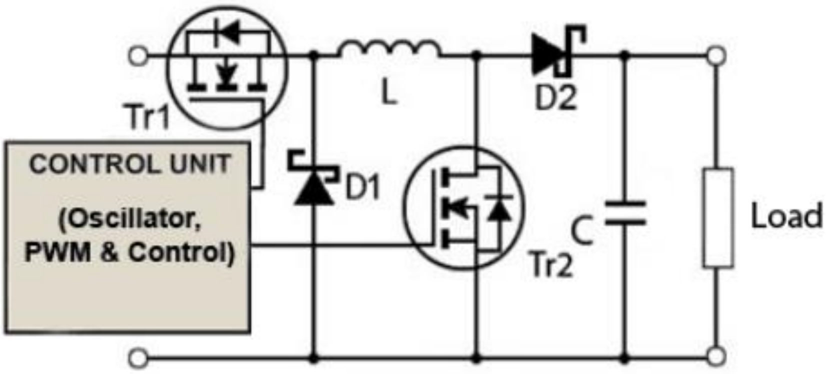
Picture 14 Buck converter

A Boost converter is used in applications where the output voltage needs to be equal or higher than the input voltage. During the operation cycle of the Boost converter, when the mosfet is in High state the current flows through the inductor and charges it. The inductor stores energy in its magnetic field. When the mosfet is in Low state then the inductor discharges to the output capacitor and the load through a forward diode. Again, when the mosfet is in High state the inductor charges again, and the cycle continues by stepping up the voltage. (Coates, Module 3.2 Boost Converters, 2020)



Picture 15 Boost Converter

A Buck-Boost converter is a combination of the two types of converters in one circuit. It is used in applications where the input voltage can vary. Applications such as battery-operated systems need that type of converter to provide the appropriate output voltage. In cases when the battery is full a Buck topology is used to regulate the output voltage, but when the battery discharges the voltage drops beyond the output level, the converter automatically changes its operation mode to a boost topology. It is an added benefit to a Buck-Boost converter that can produce the required output despite the input changes. (Coates, Module 3.3 Buck-Boost Converters, 2020)



Picture 16 Buck-Boost Converter

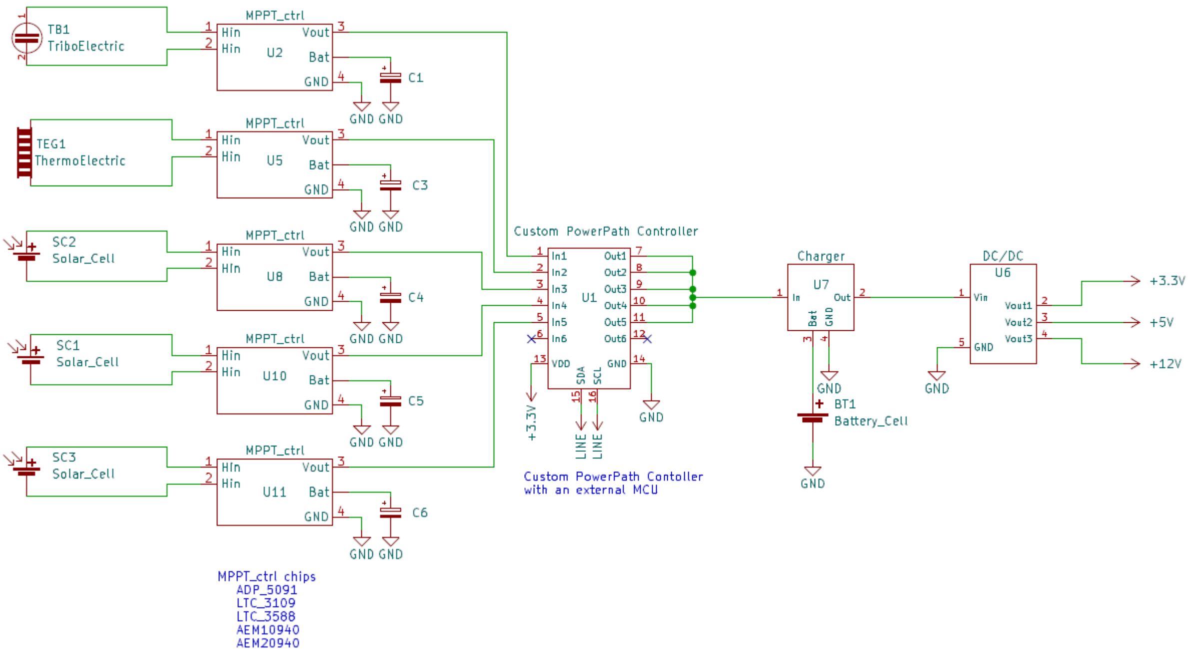
3.3 Design Space Exploration

The proposed architectures that will be considered to create the power supply are presented here. In the first stage there will be the energy collectors from the environment that will store their energy in capacitor elements. In the second stage there will be a controller which will make the transfer of energy from each harvester to a common storage element. In the third stage there is the battery charger which must be capable of accepting multiple types of batteries. The third stage is positioned to protect the battery element. With proper and controlled charging, its life expectancy is likely to be increased. It is also planned to use a chip capable of controlling the temperature of the battery so that it does not overcharge beyond limits. In the fourth stage are the voltage converters that use the energy of the battery to deliver the desired voltage at their output.

The proposed architecture(s) of this multi-source PSU must observe the following "directives":

- Every source will have its own harvesting circuit.
- Each harvest module will have its own temporary storage capacitor.
- Harvest module Vout voltage at 5V.
- Small form factor.
- Modularity.
- Use one (single) charger, capable of charging multi-chemistry batteries.
- 3.3V (and more) regulated outputs

We consider three alternative architectures for the PSU, with varying features, complexity and drawbacks. the first case, the architecture proposes the use of multiple energy harvesters each equipped with a local capacitor as interim storage. The focus is on the second stage, it was proposed to develop a mechanism to monitor the capacitors in each module and when they are full to transfer the available energy to the charger. This implementation can have the ability to prioritize the energy transfer and a robust algorithm inside the Custom PowerPath controller to make decisions on which module is ready to deliver energy. The next stages (charger, voltage controllers) are conventional.

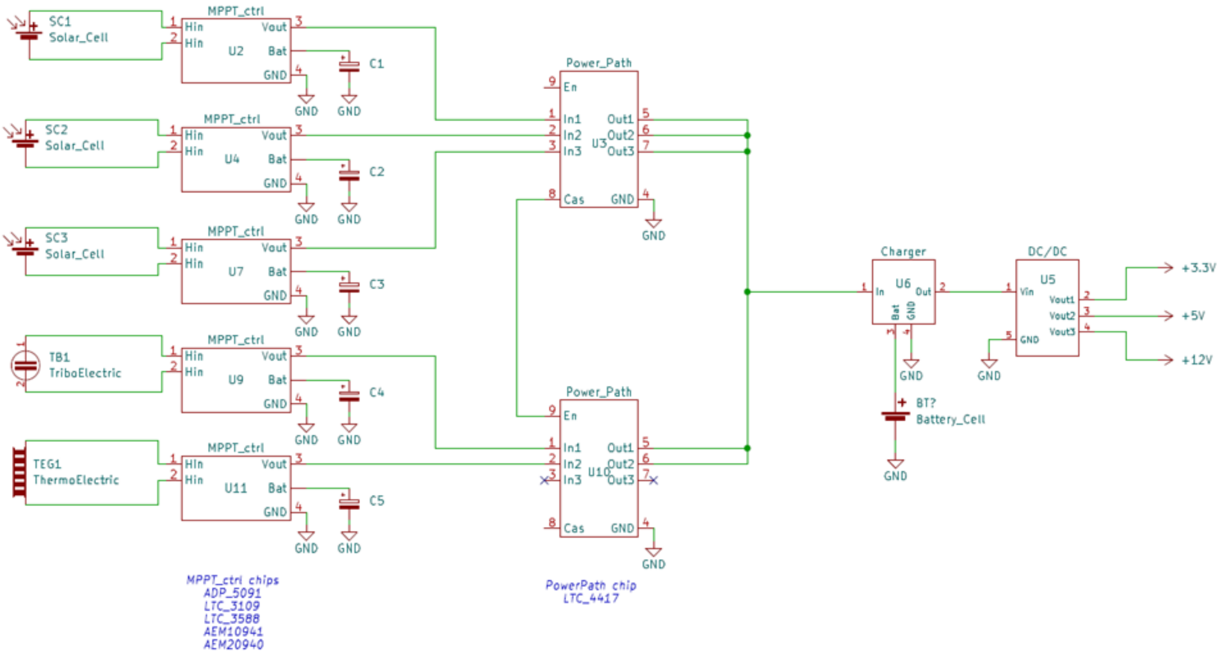


Picture 17 Expandable Active Power Path Control architecture design

This architecture was not promoted for implementation, due to its high complexity and many additional components needed to implement it. Also, the consumption factor was also accounted in because such a design needs a microcontroller or an FPGA board to implement the control strategy of the PowerPath.

The implication of this architecture on the algorithmic complexity of the control is not severe, but there are significant limitations, such need for a-priori knowledge of the number of active inputs.

In the second case, the proposed architecture (again) utilizes multiple energy harvesters that store the available energy in a local capacitor. However, in the second stage a commercially available PowerPath chip is utilized. By design, each PowerPath can handle up to three input modules, with a cascade option to allow multiple chips to handle more inputs. As in the previous case, the charger and voltage controllers are conventional.



Picture 18 Centralized Architecture Design

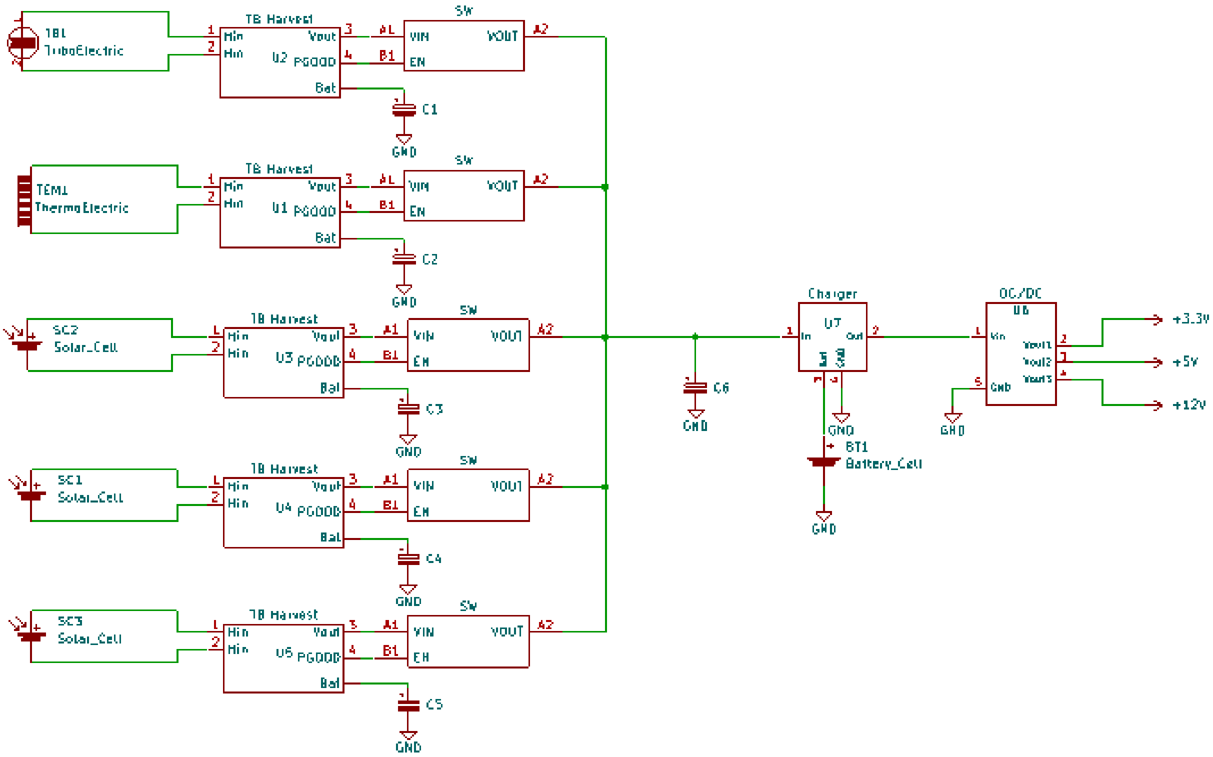
Thus a drawback of the architecture is that scalability is constrained by the number of PowerPath ICs in the design: the maximum number of input modules cannot exceed 3*N, where N the number of PowerPath chips in the design. The implementation cost is rather high because these PowerPath chips are expensive (and difficult to procure).

The benefits of the proposed architecture are: (i) pure commercial-of-the-self (COTS) implementation and (ii) integrated control strategy (the powerpath ICs have a prioritization algorithm already built in, but they need external components to operate). This architecture was rejected due to scalability and cost issues.

In the third architecture option, again each source has its own harvesting module. However, the active PowerPath implementation has been removed and substituted by a simple “switch” at the output of each harvest module. The switch has reverse polarity protection and is controlled locally by the harvesting module. Then the outputs of the switches are “bridged” towards the input of the charger, employing also a second temporal storage element (capacitor). This enables a “distributed” control scheme of the power path.

The approach has the minor drawback that all harvesting modules must have the same nominal output voltage. This implementation even though adds an additional active component on each module, it is more cost effective than the others because such switches are common and low cost electronic components.

A great benefit to this design is that scalability and flexibility is achieved with proper PCB design with no practical restrictions. The cascading has been simplified to the point that is no need for any central control circuit. An addition to the design is using switches with reverse current blocking functionality. The switches’ reverse polarity protection reduces leakage and protects the inactive modules. So, if a source is active, it will charge itself and transfer to the central storage, but it will not affect another module that will be inactive.

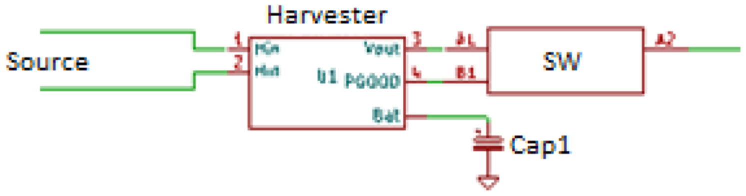


Picture 19 Distributed Power path Control Architecture Design

In detail every module will be independent from the others and will harvest energy from its input source. For the PV a Maximum Power Point capability is mandatory to the module. MPP is a feature on the chip itself, so it is critical to select the appropriate hardware that has this function. This will enable maximum power gain from the PV source.
In TEM applications a unipolarity implementation will be considered. That is required to be able to harvest energy even if the polarity switches itself. For TEMs that happens when the thermal flow is reversed.

In TB applications an appropriate harvester must be chosen so it can harvest from AC sources. All these Harvesting selections must have a common output voltage. This is the major drawback of this design. Then a common storage element which is a central capacitor will charge from all these sources. This element charges up and provides the input for the battery charger.

Inside the module the main architecture will follow the following diagram. The module itself consists of the main harvester chip, a Load switch, and the store capacitor.



Picture 20 Module Architecture

3.4 Energy Harvesting

An energy harvester ICs in a glance is a system that utilizes an input from energy generators like PVs, TEGs, or Piezo. That system can receive a small amount of energy and store it in a capacitor or a battery. The system also has all the functions that are needed in order to accomplish the best harvesting process. A main key factor for our implementation is the usage of MPP. MPP stands for Maximum Power Point and it's the peak voltage and current value when the power that we are receiving is the Maximum value that we can get. The following table includes some of the preferred energy harvester modules. All these ICs have the same goal, to harvest energy from a system that has input a PV or TEG.

Many chips from different manufacturers have been searched to implement and design the power supply unit. Many of them are presented on the table below.

Table 2 Energy harvesters

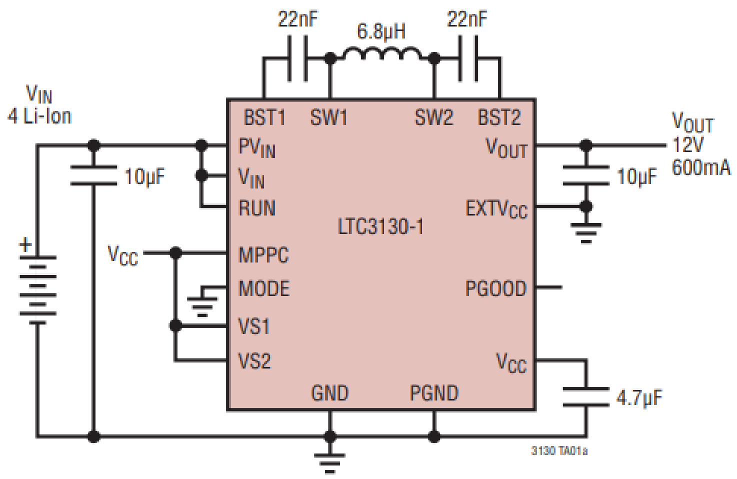
Part number	Energy source	Main characteristics
LTC3130-1	PV	600mA Buck-Boost, MPPC
LTC3109	TEG	Auto-polarity, Step-up
LTC3588-2	TB/PZ	20V AC, 100mA to load
ADP5091	PV/TEG	Single input, Dynamic MPPT
BQ25505	PV/TEG	Boost charger
AEM10941	PV	Boost, MPPT

A decision has been made to use a wide Vin range for the PV energy harvesting module. This decision was made with a view to have access to many photovoltaic cell values. It is known that commercially photovoltaic cells have many different dimensions and voltage ranges we decided to use a Vin range with maximum input of 25V, which is the highest voltage value of our design. This does not have any effect if a photovoltaic cell with less voltage is applied. Also, the decision that was made for the TEG was based in using a unipolarity chip arrangement to be able to harvest energy from TEG sources even if the thermal flow reverses. Finally for the TB/PZ harvester, an AC harvester is required and it needs to have the ability to withstand voltages up to 20V peak.

In energy harvesting there are many alternative choices that can be used, but we chose the following for our designs. These have been chosen for reasons such as availability, cost, small number of BOM (Bill of Materials) for each implementation and easy to use spice models. Having access to spice models will have an impact on the final design decisions in matter of BOM values and validation.

➢ The LTC3130-1 is a 25V 600mA Buck-Boost DC/DC converter, solar panel post charger/regulator that can be used to PV energy harvesting applications. That means the PV module will only utilize this chip at its own to harvest energy. Some key characteristics are shown below.

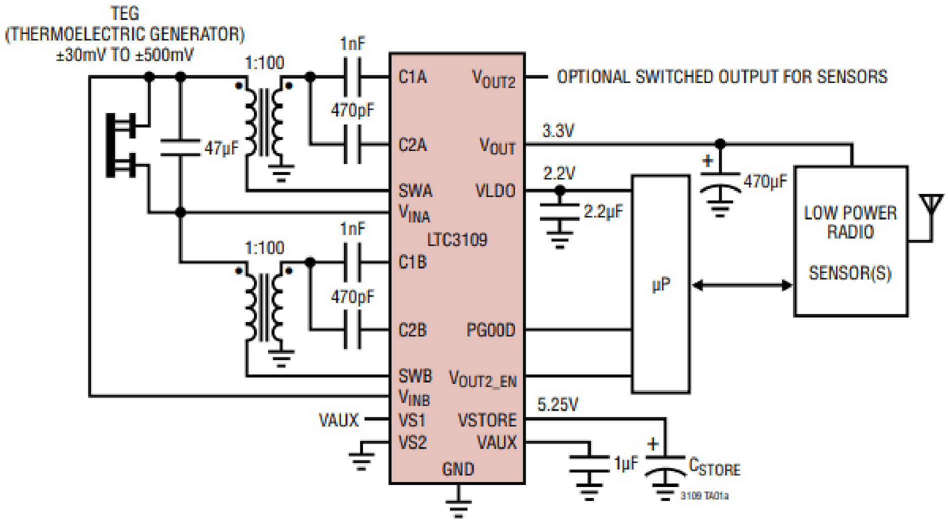
- Wide Vin range 2.4V to 25V.
- 4 Fixed Selectable Vout Voltages.
- 600mA Output in Buck mode.
- 1.6uA Quiescent current.
- Up to 95% efficiency.
- Programmable Maximum Power Point Control (MPPC).
- Power Good indicator (PGOOD).



Picture 21 Typical Application of the LTC3130-1

➢ The LTC3109 is an Auto-Polarity, Ultralow voltage step-up converter and Power manager, that can be used to harvest energy for Thermo-Electric Generators (TEG). It has a unique feature of harvesting energy from low input sources regardless of polarity. It achieves this by using 2 step-up transformers and external storage elements. Some key characteristics are shown below.

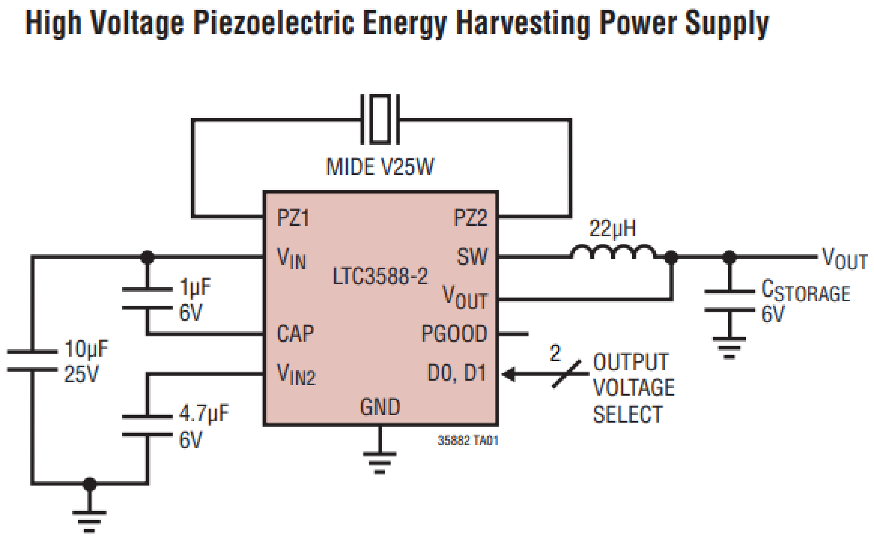
- Operates from inputs as Low as ±30mV.
- Less than ±1°C needed across the TEG.
- Proprietary Auto-Polarity Architecture.
- Complete Energy Harvesting Power Management System.
- 4 Fixed selectable Vout Voltages.
- Logic-Controlled Output.
- Power Good indicator (PGOOD).



Picture 22 Typical Application of the LTC3109.

➢ The LTC3588-2 is a Nanopower Energy Harvesting Power Supply with 14V Minimum VIN. It can be used to harvest energy from Piezo-Electric or Tribo-Electric sources. It integrates a Low loss full wave bridge rectifier, which makes implementation easier later. Some key characteristics are shown below.

- 1500nA input Quiescent Current.
- 14V to 20V Input Operating Voltage.
- Integrated Low-Loss Full-Wave Bridge Rectifier.
- Up to 100mA Output Current.
- 4 Fixed Selectable Vout Voltages.
- Power Good indication (PGOOD).

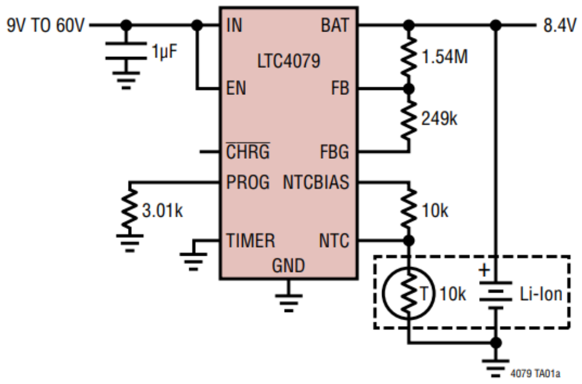


Picture 23 Typical Application of the LTC3588-2.

In conclusion these three chips are the main ingredients of the PSU, but energy harvesting is only one part of this. It is required to store the harvested energy in a battery.

The charger option was simpler due to the key requirement of multi-chemistry batteries. The chosen chip is the LTC4079 from Linear Technologies. This decision was also made for the same reasons that the energy harvesting chips were selected. This chip had everything needed for this application. Auto charging modes Constant Current (CC) to Constant Voltage (CV), temperature protection, low voltage termination and others to maintain the chosen battery in perfect condition. Some key features are shown below.

- Li-Ion/Polymer, LiFePO4, Lead-Acid or NiMH battery stacks up to 60V.
- Adjustable from 10mA to 250mA with an external resistor.
- Wide input Voltage Range 2.7V to 60V.
- Adjustable Battery Voltage 1.2V to 60V.
- Low quiescent current while charging Iin= 4uA.
- Ultralow Battery Drain Ibat <0.01uA.
- Auto Recharge.
- NTC thermistor input.
- Adjustable Safety Timer.
- Charging Status Indicator.
- Constant Voltage Feedback with 0.5% Accuracy.



Picture 24 Typical Application of the LTC4079

3.5 Electrical Characteristics and Ratings

This chapter describes the Maximum Rating of the modules that are designed to perform. In addition, the working state parameters of each module.

The absolute maximum characteristics are taken from each component datasheet. So, any stress on the modules beyond the manufacturers recommendations is prohibited and not recommended. The next bullets have the most critical absolute rating that is considered and characterizes the modules' absolute rating. Note that the 1A rating in the output can be at pulsed load for a small period. This is due to the architecture of the module and its ability to transfer up to 1A of current via the load switch.

PV module:

- Vin 2.4 to 25 V
- Iin up to 300mA
- Vout 5V
- Iout up to 1A

TEG module

- Vin -500mV to 500mV
- Iin up to 1.3mA
- Vout 5V
- Iout up to 1A

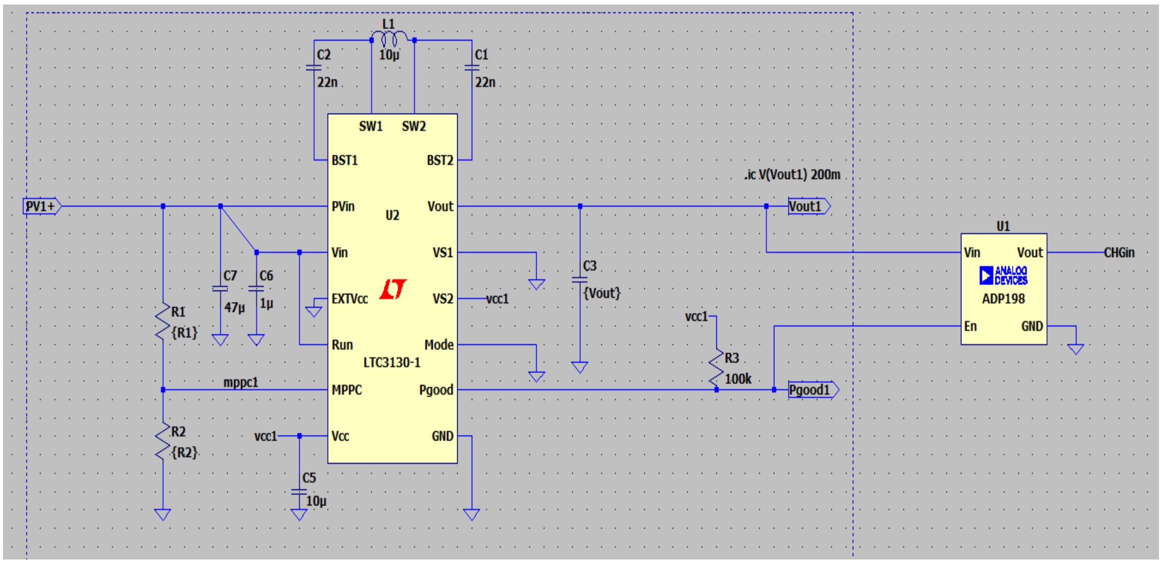
PZ module

- Vin 14 to 20V
- Iin up to 50mA
- Vout 5V
- Iout up to 1A

3.6 Simulations

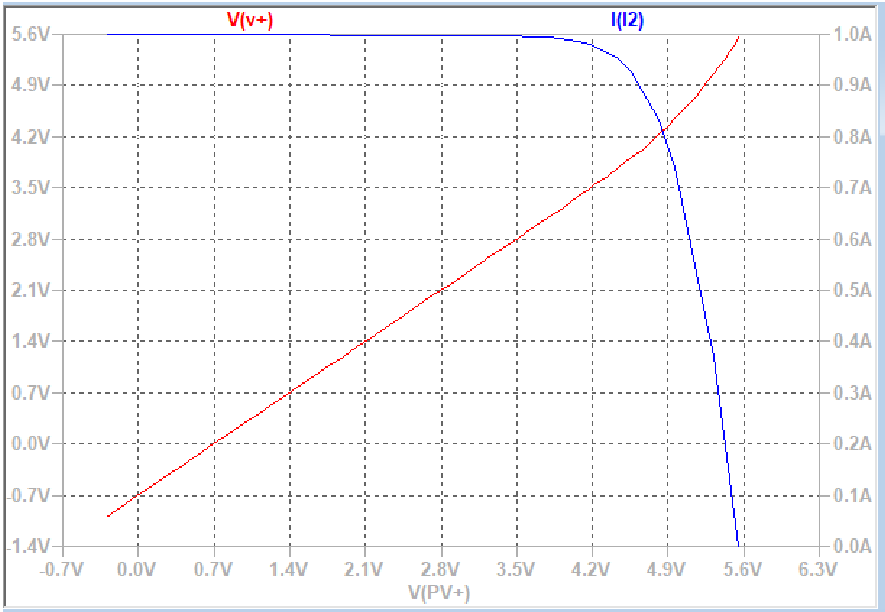
To validate a proof of concept, all the selected chips ran on spice simulation to set some of the component values and to check how they work. SPICE (Simulation Program with Integrated Circuit Emphasis) is a general-purpose circuit simulation software used in the field of electrical engineering. It allows engineers to model and simulate the behavior of electronic circuits and predict the performance of components and systems before they are physically built. It is widely used for simulation of analog circuits and power electronics and offers a user-friendly interface, a library of components, and advanced analysis capabilities. LTSpice is a popular choice for circuit designers and engineers because it is free for use, supports a wide range of simulation models, and provides accurate results.

The following picture presents the schematic of the LTC3130-1 chip. In the schematic there is the spice model LTSpice which is also provided into their libraries. Then it is surrounded by the peripheral components that are needed in order to operate. Here we can set different values on the components, so we can change the chips behavior. On the right side there is the model of a load switch that operates when PGOOD signal is HIGH. This system is used to harvest energy from PV cells. During harvesting the energy is stored at Vout. In our case there is populated an external capacitor ‘C3’. As it is shown in the schematic right below the Vout is connected to Vin of the Load switch, that happens only when the Vout Voltage is at a specified level, then an internal comparator pulls HIGH the PGOOD signal which enables the load switch, and the available energy transfer to the intermediate capacitor storage and the battery charger input.

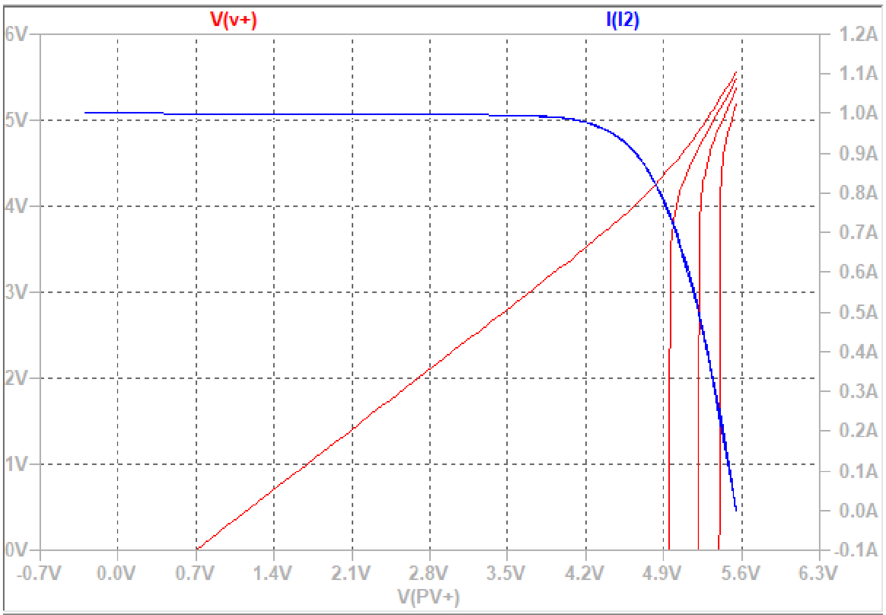


Picture 25 PV schematic in LTspice.

In need of better and more realistic results, a spice model of a PV cell has been created. That happened in order to see the MPPC, Maximum Power Point Control. The MPPC is controlling the PV’s energy to the maximum. The MPPC is set at a specific voltage using external resistors. Most of the times PVs are set to 80% of their open circuit voltage. For example, if a PV cell has an open circuit voltage of 5 volts, the MPP voltage is 4 volts. With the wide Vin of this chip a variety of PVs' can be selected, and the Maximum Power Point Voltage can be calibrated for each PV cell at the specific Maximum Power Point that the manufacturer recommends. The picture below illustrates exactly where the Maximum Power Point is achieved. It is the point where the red meets the blue line. So, if any system can operate in that region, the PV cell will provide the maximum energy it has. But that point can be altered by the illuminance. That means in different states of luminosity the MPP is either lower or higher. In the first graph it is calculated for 1000 W/m². At the second graph it is calculated for luminosities of 250, 500, 750, 1000 from right to left.

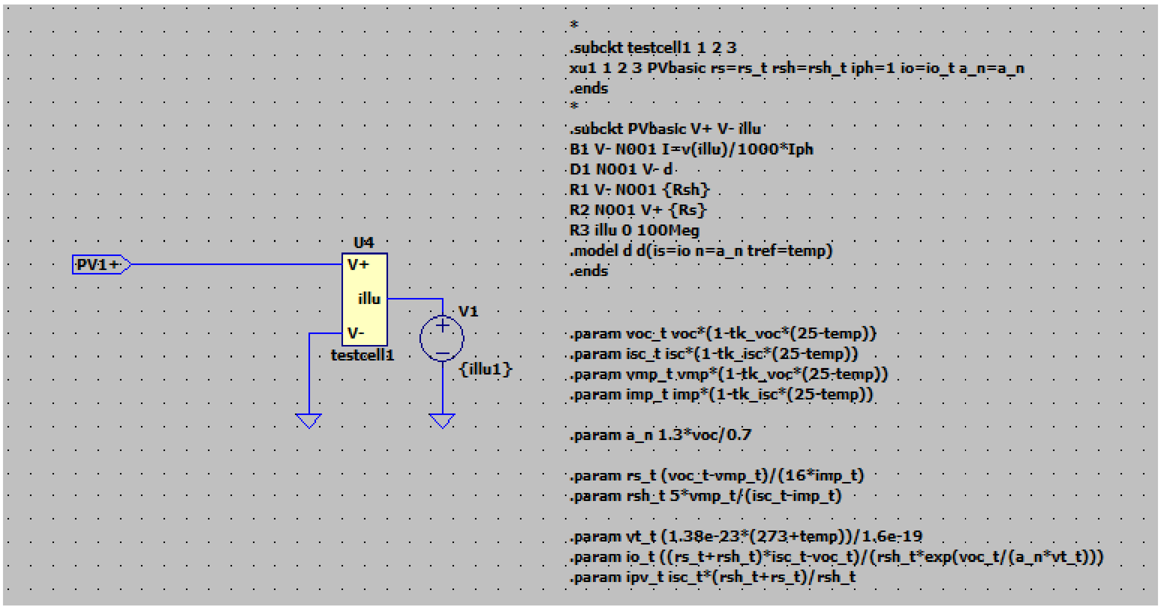


Picture 26 IV curve on LTSpice



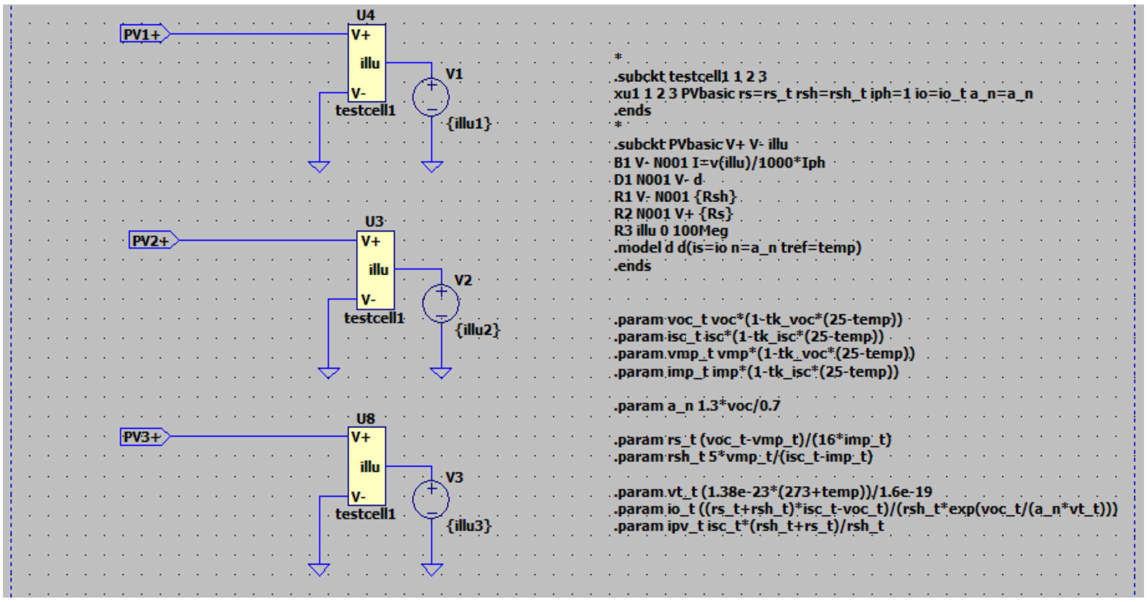
Picture 27 IV curves with different illuminance

The following picture shows the PV cell spice model that has been created to make simulations. It must be mentioned that the previous IV curves were made with this model. So, the working conditions have already been presented on the previous page. This model is made in a way that is configurable. It uses datasheet parameters to configure. With this configuration it is easy to change PV models by just reading their datasheets and using the appropriate values. A very good point of this design is the easy control of illumination. That is done by a voltage source, in this case V1 and its value is the illuminance ‘illu1’ and is measured in W/m². Meaning that if 500 Volts are applied to V1, the PV cell receives illuminance of 500 W/m². With that configuration it was easy to change the parameter to step four preset values. In this case luminance of 250, 500, 750 and 1000 W/m² were tested.



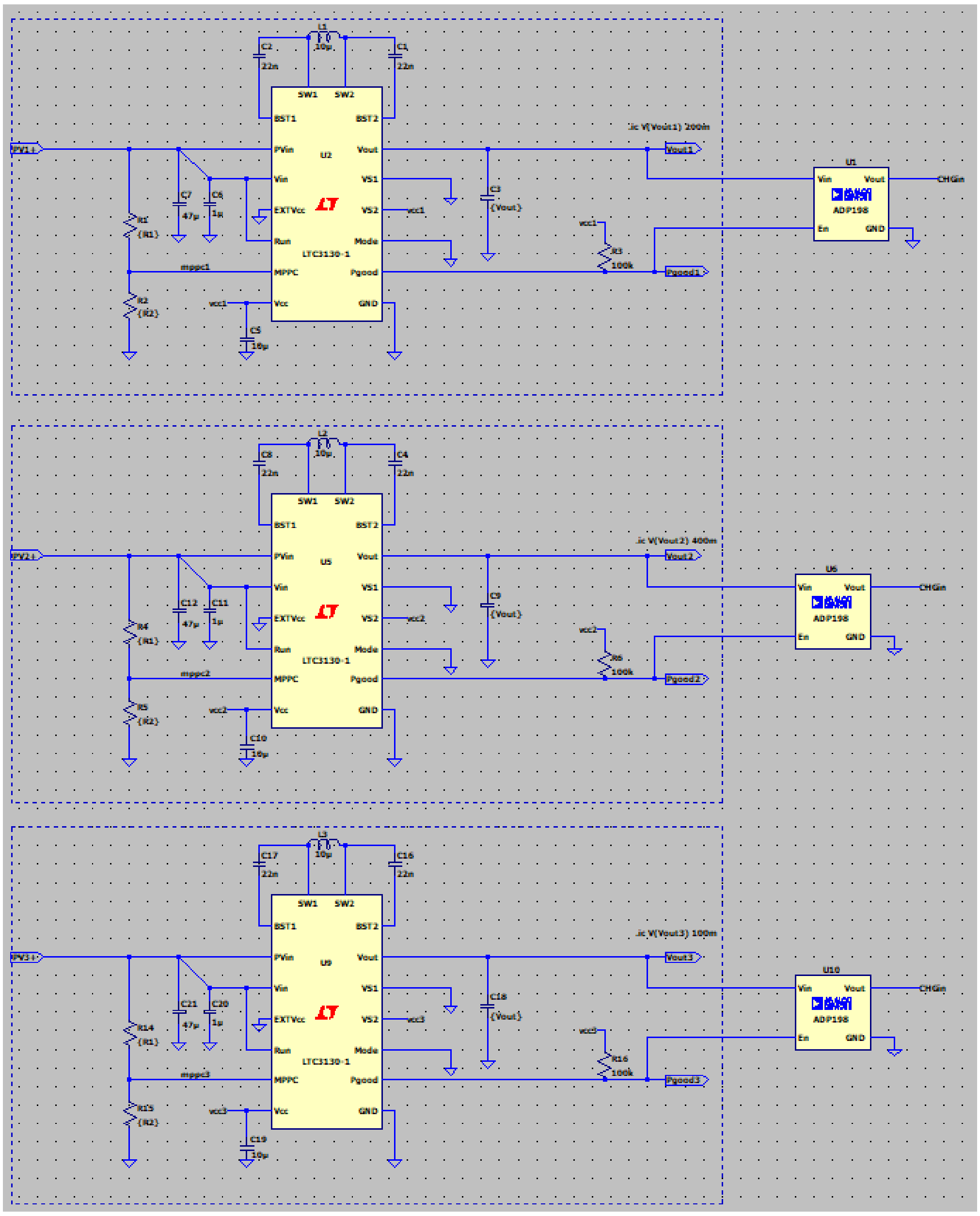
Picture 28 PV SPICE model

But in our application, we need three PVs and three harvesters. It is easy enough to duplicate the designs and make a full version of what we need to build. That is what the next 2 pictures show. The first one has three PV cells configured with the ability to differ the luminance values. As shown, it is not needed to write the parameters repeatedly. Just paste a new module and wire it appropriately.



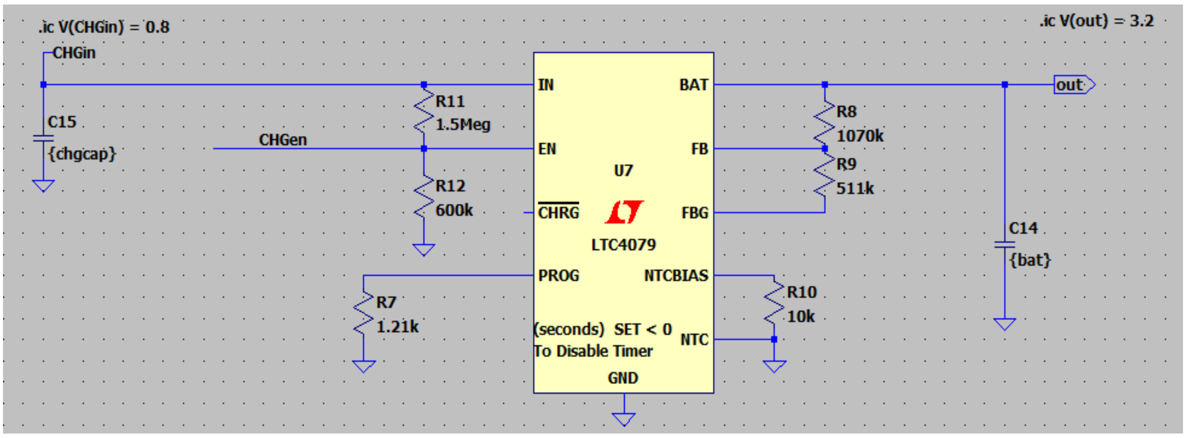
Picture 29 three PV cells

Then in the next picture are shown the three circuits of the PV harvesting modules. These are independent of each other and each of them is connected to its own PV cell. The only common connection of these circuits is the output of the load switch. By making them independent, each of them is working for itself and has no effect on the others whether it is working or not. Also, when it is fully charged, automatically transfers the stored energy to the battery charger.



Picture 30 Three harvesting circuits

Last in this chain is the battery charger. The battery charger is connected to the Vout of each load switch. The input capacitor of this charger in this application can be of critical value due to the rapid energy transfer from the harvesting circuits. It is needed to charge and to provide energy to the chip when it is needed. This charger can charge multichemistry batteries such as: Li-Ion, Li-Fe, Li-Fe-Po4 and others. But the lack of a Lithium battery spice model caused the use of a capacitor as a battery element. This capacitor is made with an internal condition voltage, to try simulating the battery. It was also necessary because the charger chip has internal protection and does not work if the battery level is zero volts.



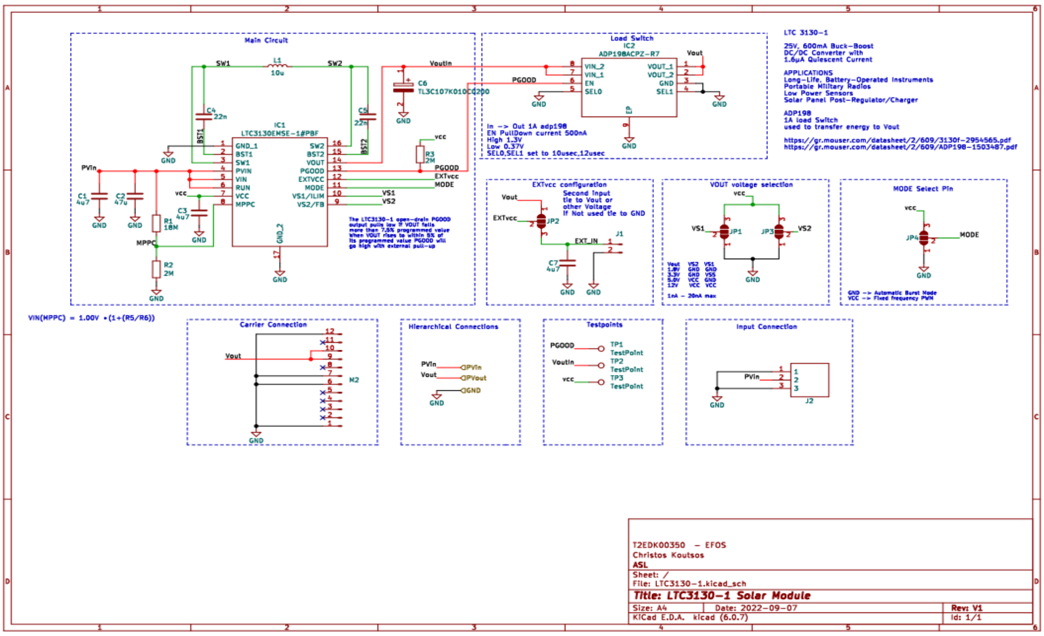
Picture 31 Battery charger

4 Design Validation

4.1 Schematic

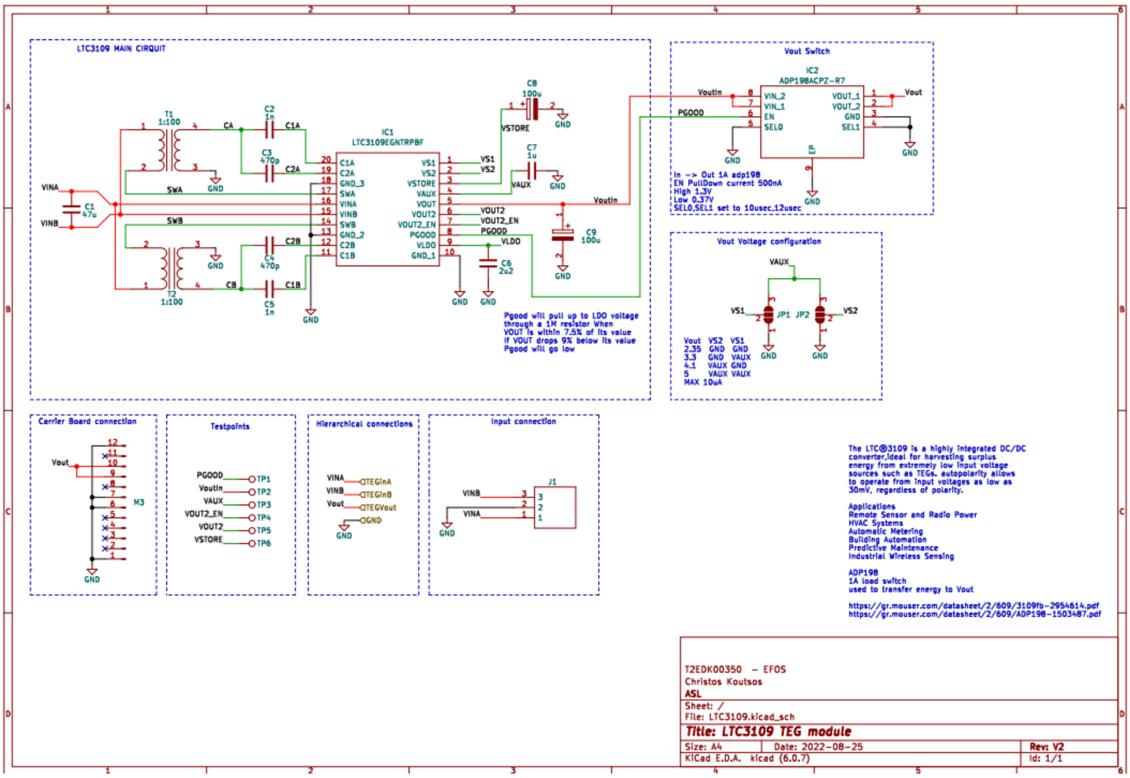
Design of the prototype boards made by using KiCad software. KiCad is a free and open-source software suite used for electronic design automation (EDA) and printed circuit board (PCB) layout. It is a powerful and versatile tool that allows designers to create professional-quality schematics and PCB layouts for a wide range of electronic projects. KiCad offers a comprehensive suite of tools for schematic capture, PCB layout, and 3D visualization. It includes a hierarchical schematic editor that supports multiple sheets, and a powerful netlist generator that allows for easy tracking and verification of connections between components. The PCB layout editor is also highly customizable, allowing users to define their own rules for routing, placement, and design constraints. One of the key advantages of KiCad is its open-source nature, which means that it is constantly being developed and improved by a global community of developers and users. This ensures that KiCad remains up-to-date with the latest technologies and trends in the electronics industry, while also making it more accessible and affordable for hobbyists, students, and small businesses. KiCad also supports a wide range of file formats, making it easy to collaborate with other software and tools. It can import and export schematic and layout files in a variety of formats, including Eagle, Altium, and LTSpice, among others. This flexibility means that designers can easily integrate KiCad into their existing workflows, without having to worry about compatibility issues.

The first step was to create the schematics for each of the chips. The schematics have been created with the guidance of the datasheet. Spice models have been tested to make the calculation of the appropriate values easier. For example, the schematic of the PV board is shown in the picture below.

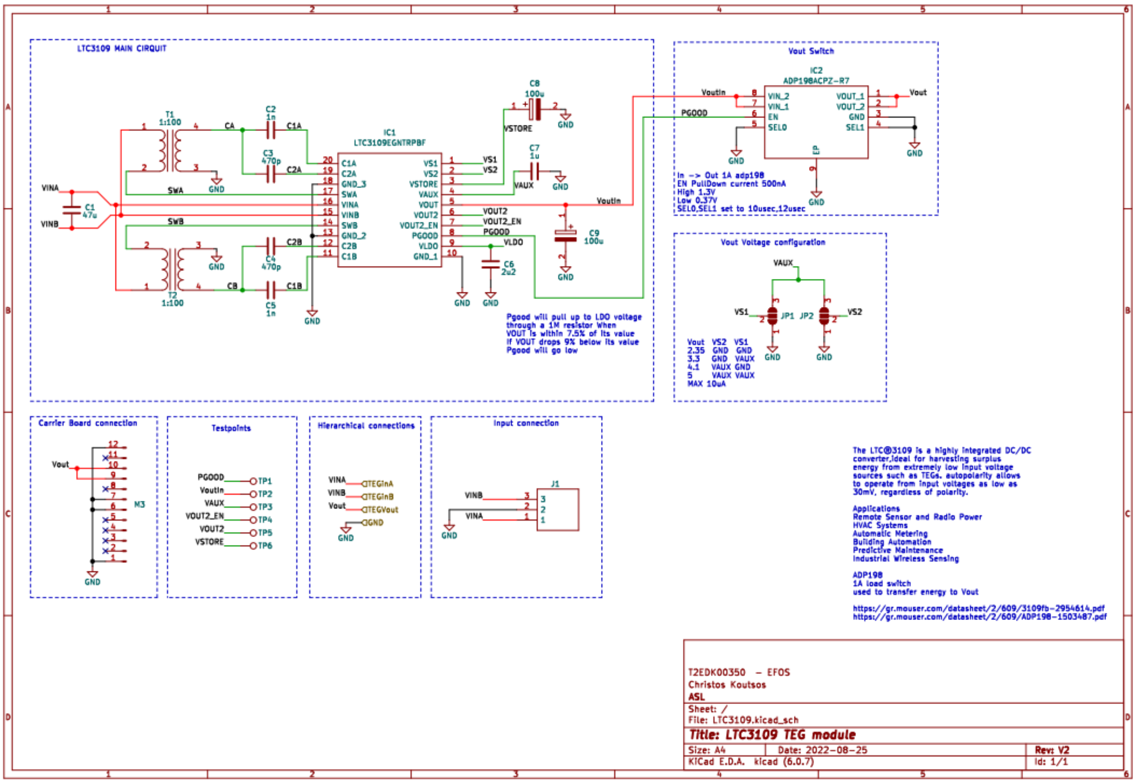


Picture 32 Schematic of the PV using LTC3130-1 chip

The same procedure was followed and for the other board and chips using the same logic and the main connections. As it is depicted, the box with the “Carrier Connection” represents the footprint that was created at first. There was no need to make a specific schematic symbol because it was easy to assign a connectors’ symbol with our custom footprint. Maybe in future work, it can be constructed to have its own specific symbol. The next pictures show the schematic diagrams of TEG using the LTC3109 and Piezo using the LTC3588-2. All these schematics use the same input connector type and utilize the same pins for energy connections.

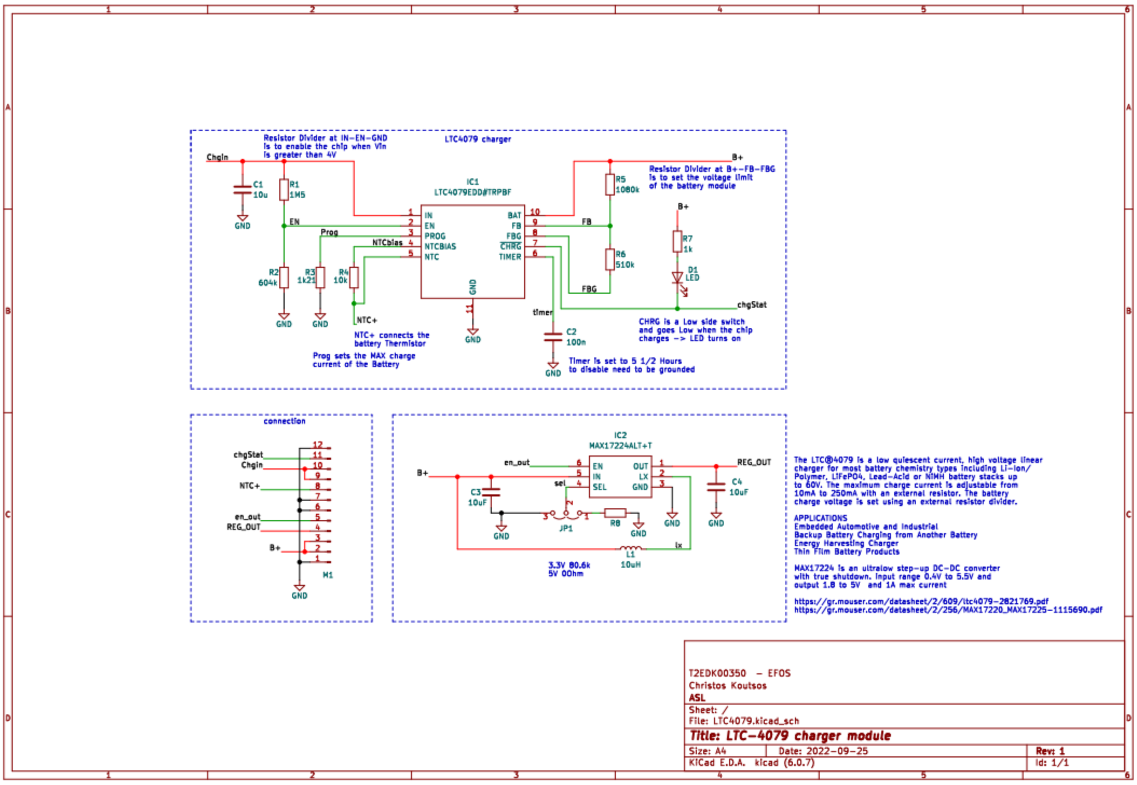


Picture 33 TEG schematic using LTC3109.



Picture 34 PZ schematic with LTC3588-2.

The last schematic design is from the charger. Again, for this design has been usedthe same footprint as before. But on this board, it has been wired differently. On the other boards the input was on a separate connector and the output utilizes 2 pins of the PCB board. Because this is the charger, it needs to connect on these two pins to input the energy available and charge the battery. Also, it needs to have: an output to connect the battery, a signal for the NTC thermistor that goes on the battery body, a status indicator pin, the control of the Regulated output and the Regulated output itself (REG_OUT).



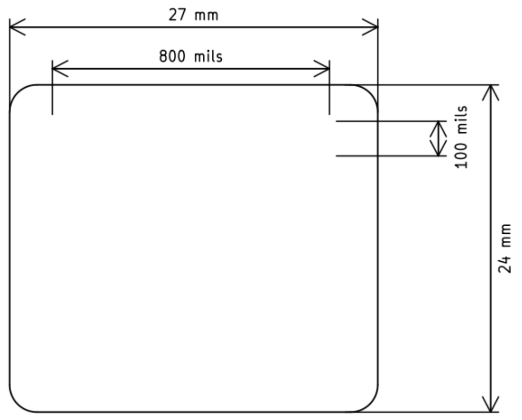
Picture 35 Multichemistry Charger LTC4079

The most important part of the work is done the next step was to select the appropriate components. Electronic component sizing is crucial to ensure that components can handle the electrical stresses and operate reliably. This involves selecting components with appropriate physical dimensions, power ratings, and tolerances to meet the requirements of a circuit. After this very important step the design part begins. Knowing the limited space needed to work to and the use of two-layer PCB, careful positioning and routing is critical, especially for the high noise tracks.

In this application a PCB for each design is made. That means in total there are four designs, one for each chip. A design feature was built to make it easy to use on a breadboard and to be able to stack one on another. To be able to do this a common custom footprint was created to accommodate these features. The Main dimensions were carefully considered to be as small as possible. It needs to be and have a similar outline and sizing to the photo of a non-Priority stamp. Of course, it was resized to fit our needs. The footprint that was created has the following dimensions and features:

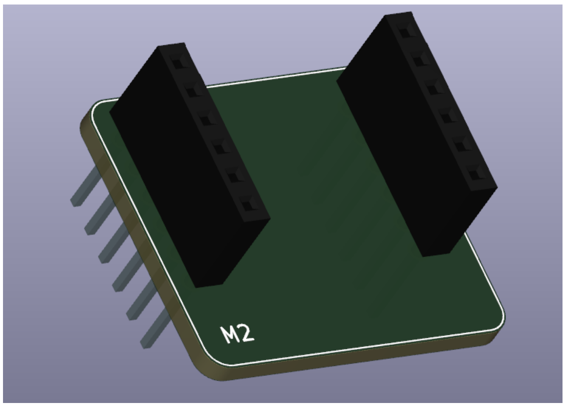
By using imperial measurements for the grid, it enables the ability to mount on a breadboard.

Dimension X: 27mm.
Dimension Y: 24mm.
Holes pitch: 100mils or 2.54mm
Holes grid: 800mils or 20.32mm



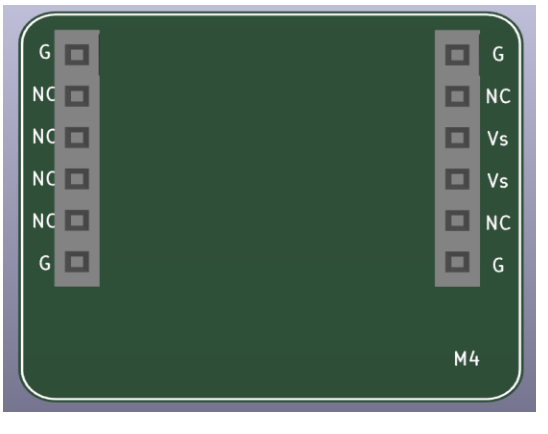
Picture 36 Footprint of the PCBs (only Dimensions, holes are not present here)

The following 3D model shows the empty footprint that was created and uses 2 rows of 6 pins that count 12 pins in total for the connections.



Picture 37 3D model of the custom footprint

The board has six common connections. This is why all the harvesting modules can be stacked together. In the following picture is illustrated a top view with the connections of the harvesting modules. In each corner of the pins a ground has been connected and on the right side from a top viewing angle there are two pin connections which are the output marked as “Vs”.



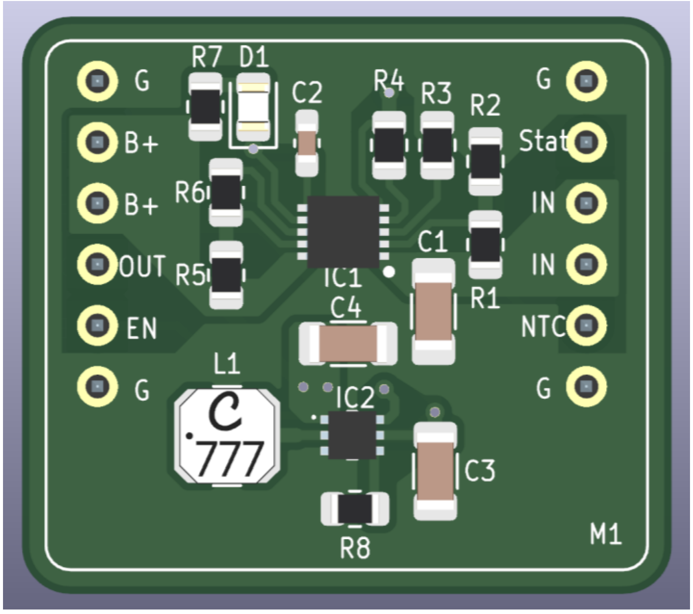
Picture 38 Top View Board

Table 3 Module Pinout

NAME	PIN	TYPE
GND	1	Ground
NC	2	Not Connected
NC	3	Not Connected
NC	4	Not Connected
NC	5	Not Connected
GND	6	Ground
GND	7	Ground
NC	8	Not Connected
VS	9	Vout
VS	10	Vout
NC	11	Not Connected
GND	12	Ground

All these pins use the standard 2.54mm or 100mils pitch connectors. Due to their size most manufacturers provide a Max current of 2.5 to 3 Amps.

Another design feature of this board is the NC pins that are not used for the harvesters. They have a different role in the whole design. Because the design is modular and can also provide a Battery charger solution, the NC pins of the harvesters can be used for other connections. The picture below is the charger module. As shown the NC pins have been occupied for other connections that the battery charger needs to utilize.

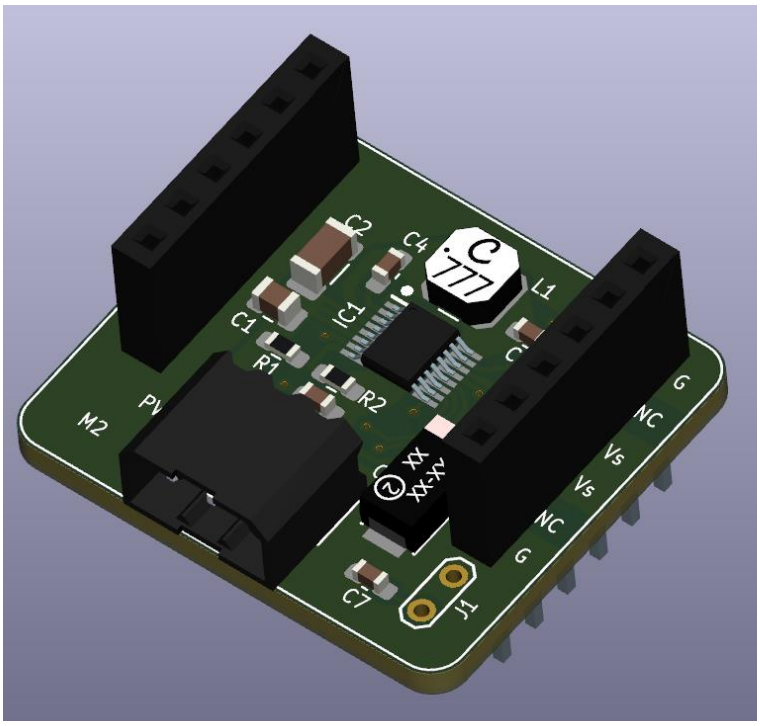


Picture 39 Charger Top View

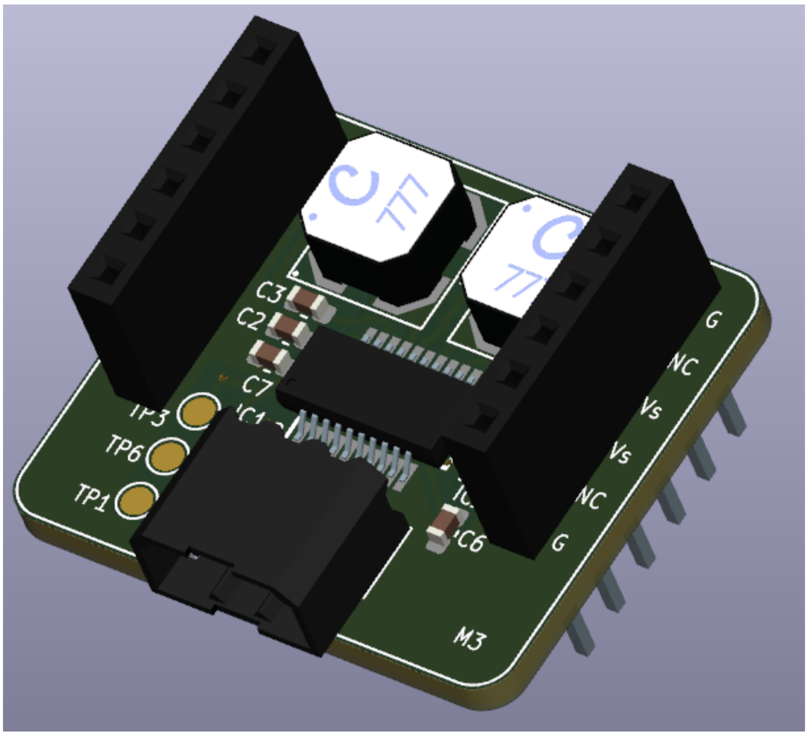
With the main board outline ready, it was time to start routing each of the PCBs. Every PCB had its own requirements and configurations. The only common element that they are sharing is the board outline and the storage capacitor.

After the completion of this work in the following pictures are the 3D models of each PCB.

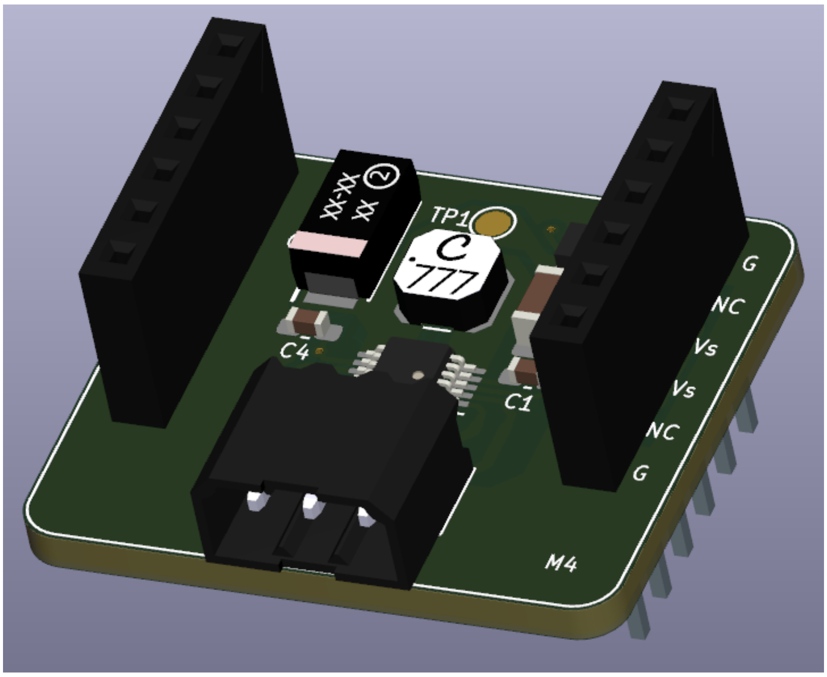
In the following pictures we can see the 3d models of each PCB after the competition of this task.



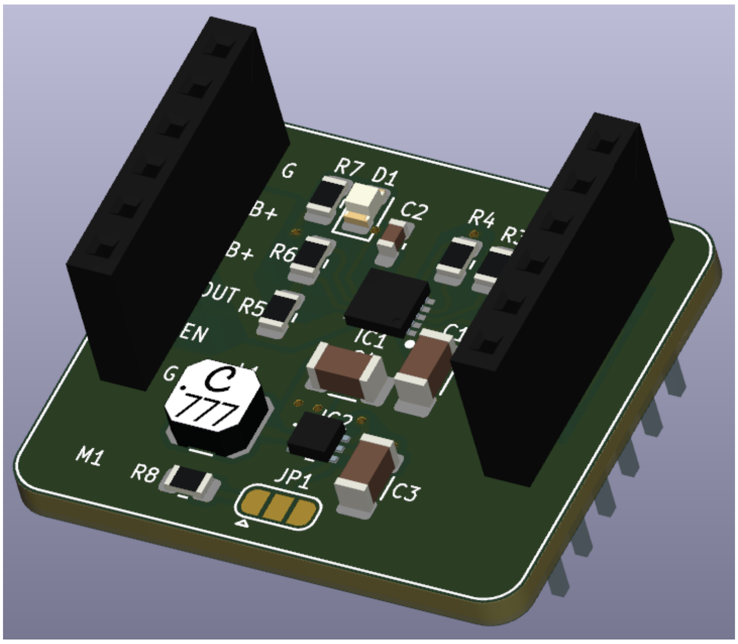
Picture 40 PV energy harvesting module



Picture 41 TEM harvesting module



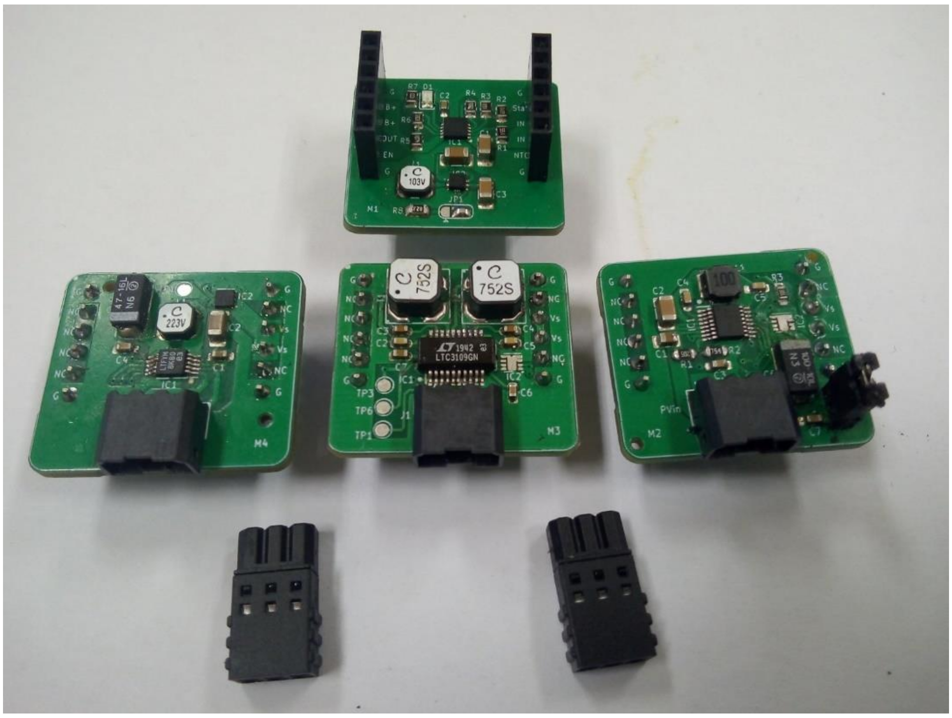
Picture 42 TB harvesting module



Picture 43 Battery charging module

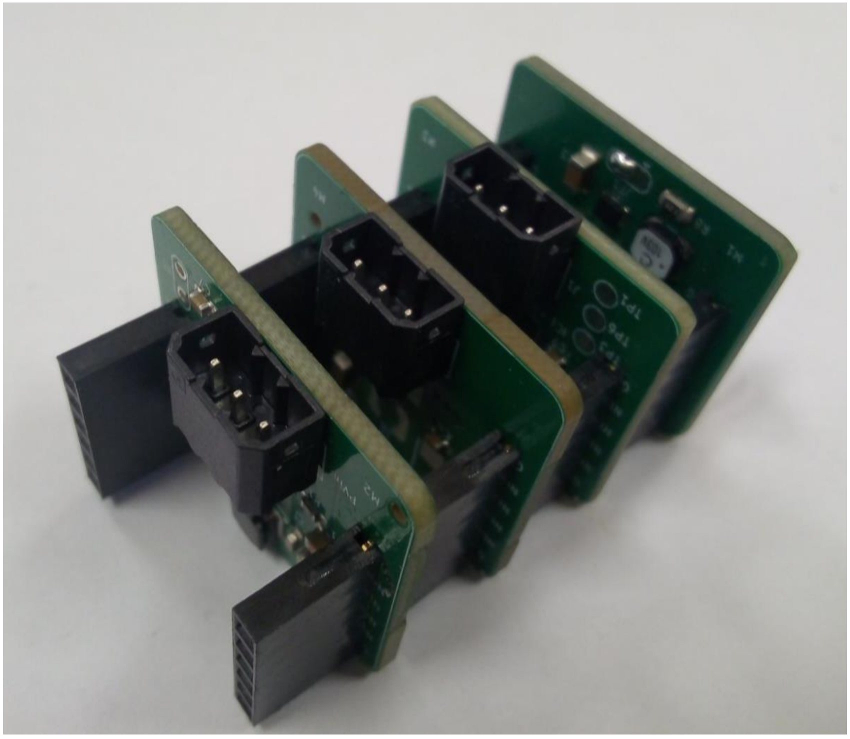
4.2 PCB Design

The prototypes as we can see are completely made and fully assembled, after that it is needed to test their capabilities and efficiencies. Also, a major factor is how they are going to work when two or more are connected in parallel. In the picture below the top PCB is the battery charger with an integrated DC-DC converter at 5Volts, the charger module has the code name “M1”. From left to right there is the Tribo module also characterized as “M4”, the Thermoelectric module in the middle as “M3”, and on the right the Photovoltaic module as “M2”.



Picture 44 Prototype assembled boards.

On this version the PCBs have been assembled with every component needed but the connectors are single sided, to make it easier to test the boards. On the following picture another set of PCBs are assembled, but the connectors are two sided, so the modules can be stacked. As they are designed it does not matter which module is on top and which is on the bottom, but it is needed to assemble them properly. For example, the Vs which is the Vout voltage of each module is on the right-hand side when the big black connector faces down. All the input connectors must face the same way. Also, when stacked all the modules are aligned to each other.

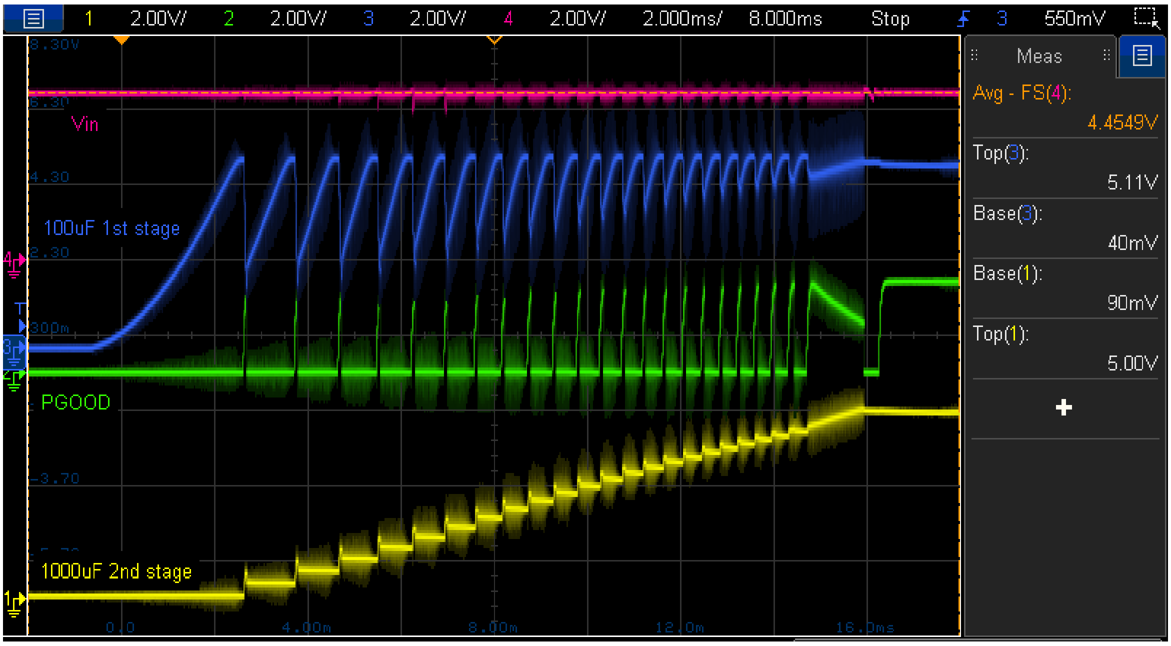


Picture 45 Stacked modules

4.3 Design Validation

Due to their design, they were mounted on the breadboards and tests began to characterize their working state. Most of the tests were done with photovoltaic module which was the main energy source for this application. The other two modules, thermoelectric and piezoelectric have been subjected to the main tests to ensure that they work the way they were supposed to. Also, the charger and the 5V DC-DC converter module have been characterized to calculate the overall efficiency.

The PV harvester system is the so-called PV module. It consists of the LTC3130-1 chip and the ADP198 load switch. This combination within its architecture allows the internal tantalum capacitor, which is the 1st stage, to charge independently without charging back from the external storage capacitor which is the 2nd stage. The load switch is controlled by the LTC3130-1's PGOOD signal. PGOOD is intended to go HIGH when the 1st stage voltage on the Vout branch reaches a level of 92.5% of the programmed voltage. If the Vout voltage drops more than 7.5% of the programmed voltage then PGOOD will become LOW, and the switch will close. In the picture is the startup procedure of the PV module with controlled input and values of 4.5V and 400mA.



Picture 46 Start-up PV module oscilloscope

- In the blue line is the 100μF 1st stage capacitor.
- In the yellow line is the 2nd stage capacitor of 1000μF capacity.
- In the green line is the PGOOD signal that controls the load switch.
- In the purple line is the system input voltage of 4.5V and maximum current of 400mA.

We observe that whenever the 1st stage capacitor reaches the programmed voltage of 5V then energy is transferred to the 2nd stage capacitor. Every time the PGOOD signal becomes HIGH it makes instantaneous energy transfer and the dip in the blue line appears. We see that the 2nd stage capacitor gradually charges until they both reach the threshold where the PGOOD becomes and remains HIGH. In this case we know from the datasheet that it is 92.5% of the programmed voltage, which is 92.5% of 5Volts. Once the 2nd stage capacitor also reaches this threshold then the two capacitors are paralleled. So, the total capacitance is the sum of these capacitors. The only thing that separates these stages is the load switch which at 5V has an RDSon resistance of about 80mΩ for loads up to 1A.

Efficiency was calculated with a simple way of measuring the input voltage and amperage and then calculate the input power. On the output side there was a load at the preset voltage of the module, in this case 5Volts. The voltage at the 2nd stage capacitor is monitored because step loads are placed here. Voltage and load current are used to calculate load power, now having the calculated values of Pin and Pload it was as simple enough to divide them and calculate the percentage. The following picture shows a graph of the calculated efficiency in blue. The orange is the 2nd stage capacitor voltage, on the X axis there are the load steps, on the left Y it is the efficiency and on the right Y is the voltage.

As we see the module is very efficient and reaches more than 90% for loads from 60mA and on, but that is only if the photovoltaic cell can apply such high input power. The test that was performed here had a current limit of 400mA. The following picture shows the results of this experiment. To calculate the efficiency the Vcap voltage should be at 5V.

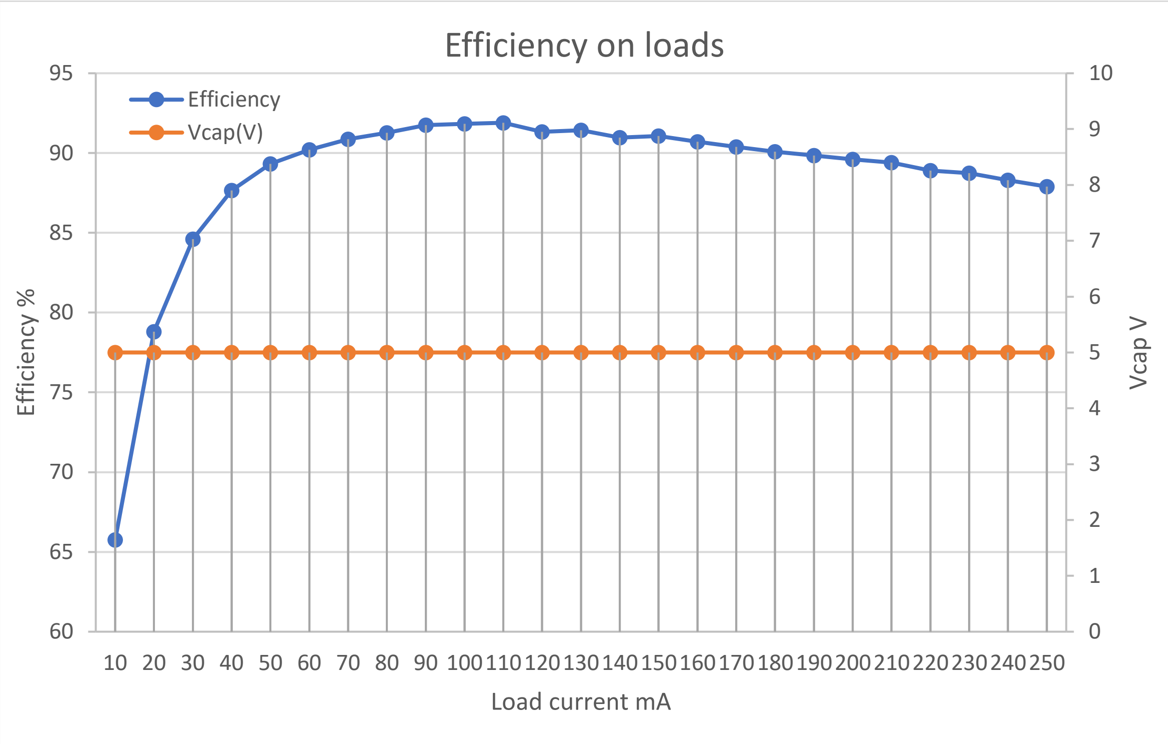


Figure 1 PV module efficiency graph

Table 4 efficiency at different current input and loads

Pin (mW)	Pload (mW)	Efficiency in %
76	50	66
127	100	79
177	150	85
228	200	88
280	250	89
333	300	90
385	350	91
438	400	91
491	450	92
545	500	92
599	550	92
657	600	91
711	650	91
770	700	91

824	750	91
882	800	91
941	850	90
999	900	90
1058	950	90
1116	1000	90
1175	1050	89
1238	1100	89
1296	1150	89
1359	1200	88
1422	1250	88

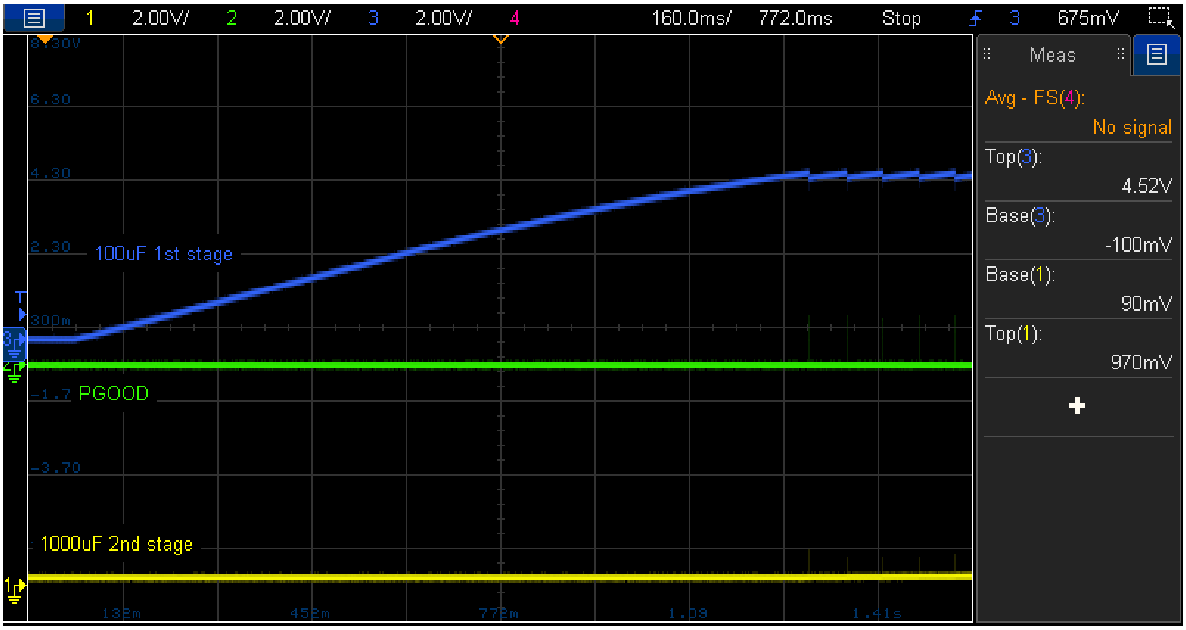
The previous table shows the efficiency of the module. The input was 4.5V DC and the module was programmed to use MPPC at a fixed voltage of 4.3V DC. Note that the loads were in 10mA steps for 1 second, in pulsed sweep mode. The table has values in mW for both Pin and Pload.

The thermoelectric harvester system is the so-called TEG module. It consists of the LTC3109 chip and the ADP198 load switch. The system has the same architecture as the PV-module because we adopted the idea that the system should be ready to provide energy only when it has already collected it from the harvester. In the same way the PGOOD signal triggers the load switch to transfer energy to the 2^{nd} stage capacitor. The values of which PGOOD is triggered, as HIGH it must have reached 92.5% of the programmed voltage and to be LOW it must be out of the programmed voltage by 9%. In our case this voltage is 5Volts. The TEG module is built for small ΔT and small input sources as it can operate from 50mV to 500mV input voltage.

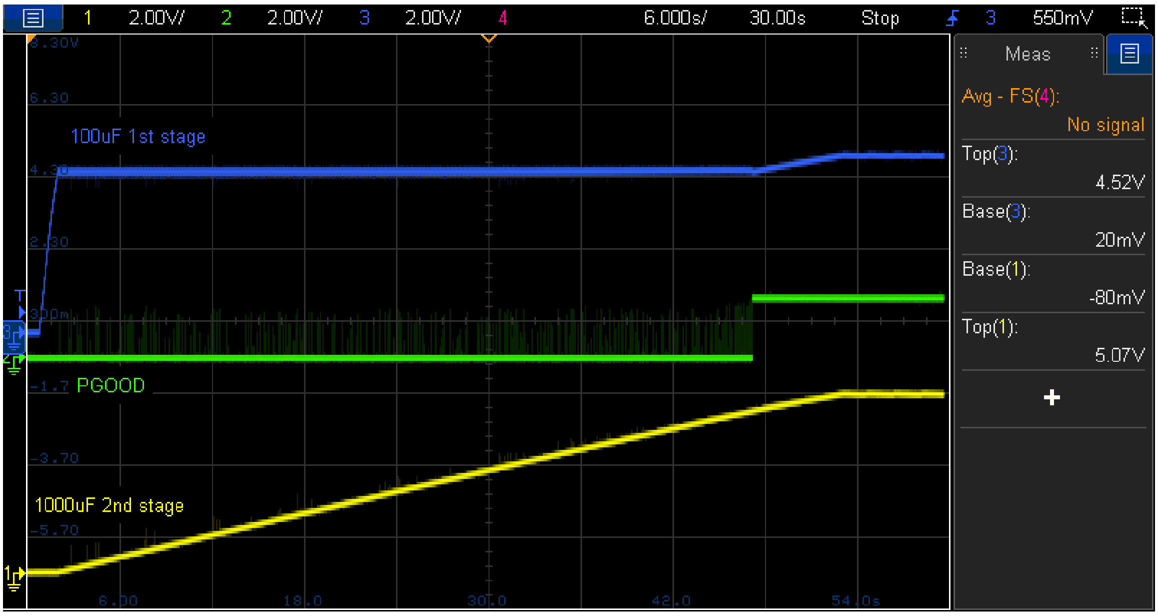
The SMU with Source Current mode was used as input. It was set to control the input current with a maximum voltage limit of 300mV. A resistor was placed on the 2^{nd} stage capacitor at a time for a proportional consumption load. For each resistor placed the current was increased to achieve an equalization of the external capacitor voltage at 5V.

The input that was used on the screen captures had values of 30mA and 130mV. Also, both 1^{st} and 2^{nd} stage capacitors were fully discharged and there was no load on the output.

- In the blue line is the 1^{st} stage capacitor of 47μF capacitance.
- In the yellow line is the 2^{nd} stage capacitor of 1mF capacitance.
- In the green line is the PGOOD signal that controls the load switch.



Picture 47 Startup TEM module.



Picture 48 TEM operation.

As we observed in the previous module, whenever the 1st stage capacitor reaches the programmed voltage of 5V energy is transferred to the 2nd stage capacitor. Every time the 1st stage capacitor dips that is when the PGOOD goes HIGH and does instantaneous energy transfer. We see that the 2nd stage capacitor gradually charges until they both reach the threshold, where PGOOD becomes and remains HIGH. In this case we know from the datasheet that it is 92.5% of the programmed voltage, which is 92.5% of 5Volts. Once the 2nd stage capacitor also reaches this threshold then the two capacitors are paralleled. The only thing that separates these two stages is the load switch which at 5V has an RDSon resistance of about 80mΩ for loads up to 1A. In this system we notice that charging takes longer.

The table below has the results of the measurements,

- The blue line represents the performance of the system.
- The orange represents the voltage of the external capacitor.

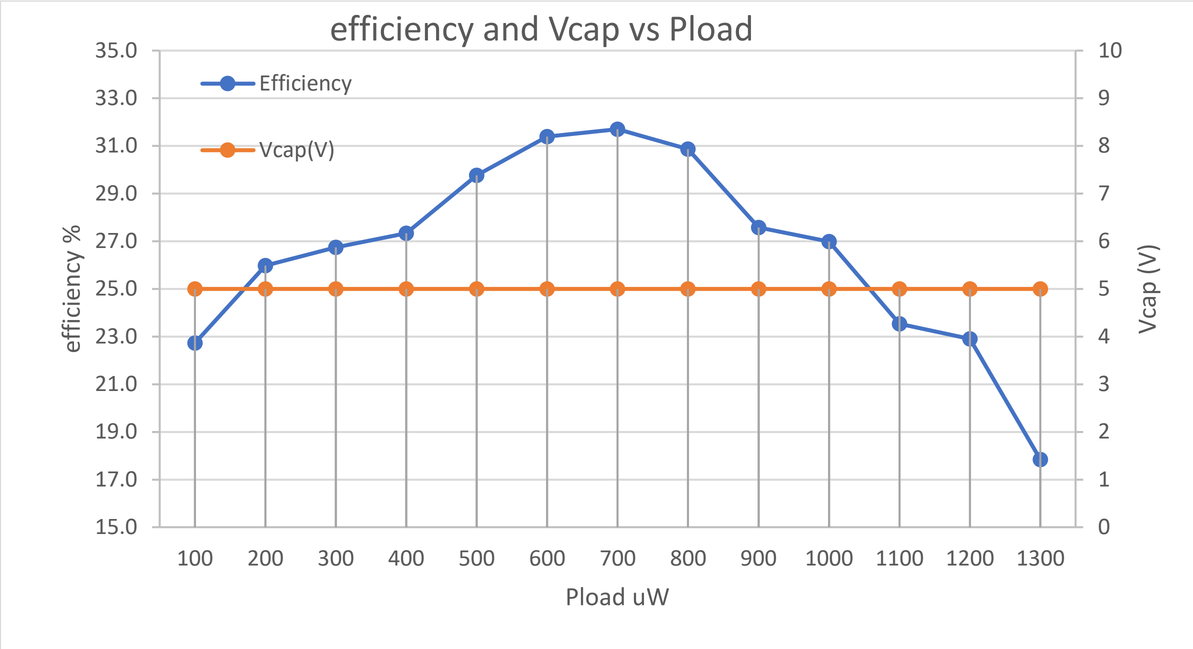


Figure 2 TEM module efficiency

In the image above, which is the rendering of the TEG module the axes have the following formatting:

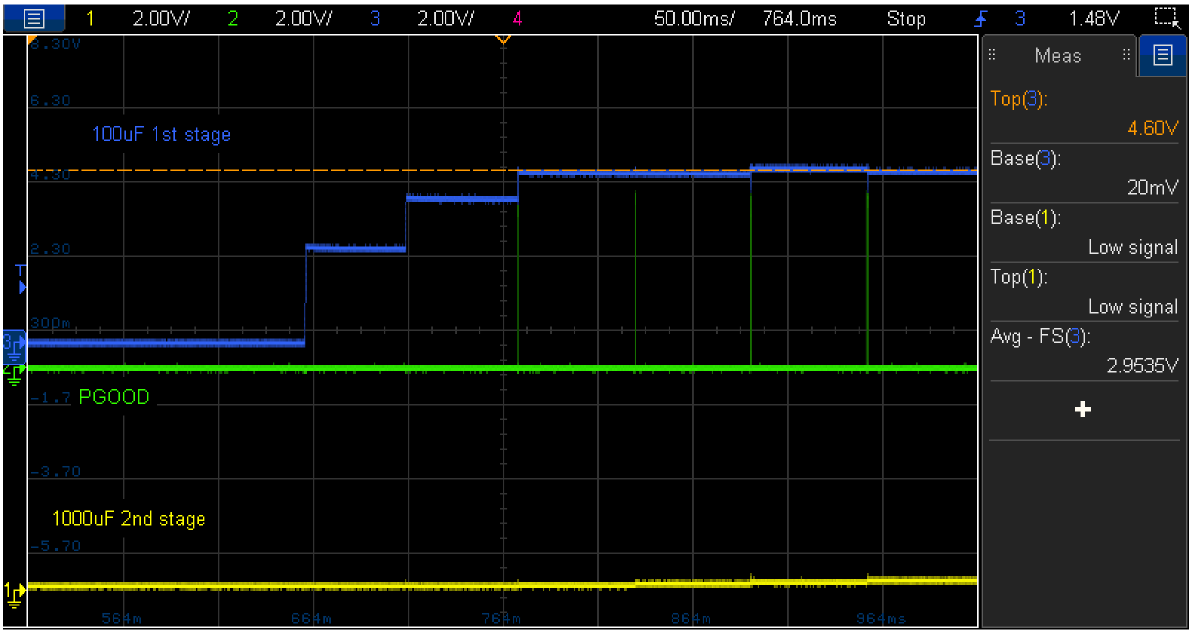
- left Y is the efficiency in percentage %
- right Y is voltage in Volt.
- horizontal X is load power in μW.

The piezoelectric harvester system is the so-called PZ module. It consists of the LTC3588-2 chip and the ADP198 load switch. The system has the same architecture as the PV-module. In the same way the PGOOD signal triggers the load switch to transfer energy to the 2nd stage capacitor. The values from which the PGOOD is triggered as High, must be more than 92% of the programmed voltage and to be LOW it must be less than 92% of the programmed voltage. In our case this voltage is 5Volts. This chip has been chosen because it offers the 5V output over the LTC3588-1 version. Of course, this also results in the need for an input greater than 14V AC to 20V AC. As a module it has been built to harvest energy from triboelectric or piezoelectric elements.

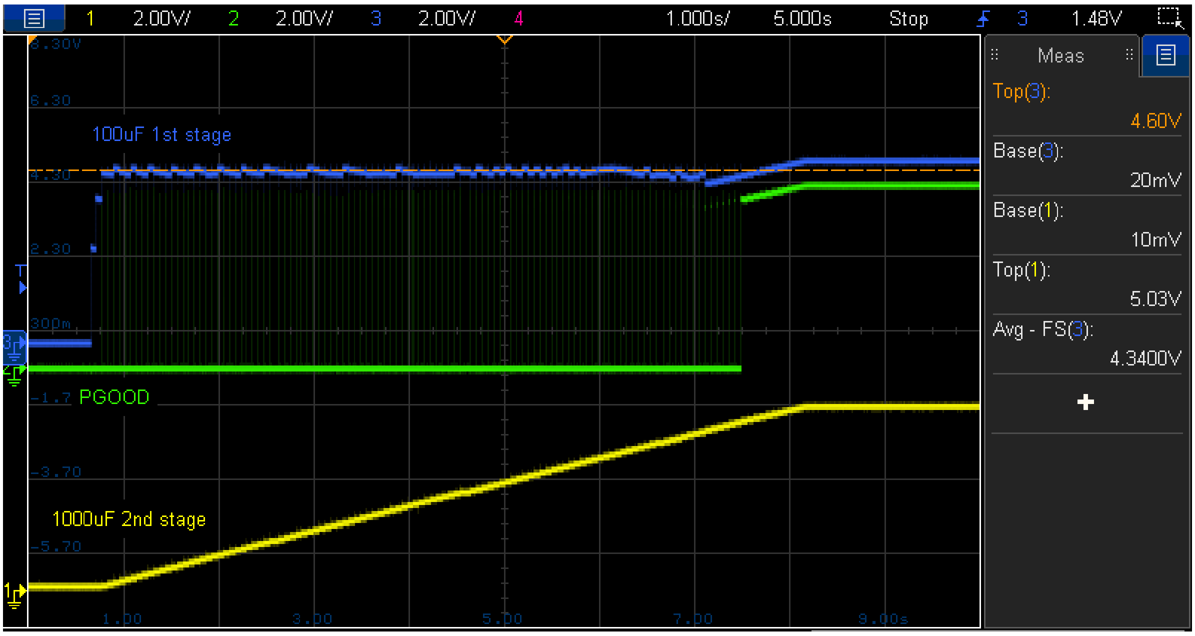
The SMU was programmed as a power supply for the operation of the module. As this module operates in AC inputs, a square wave pulse signal was applied. For this signal the peak voltages were from -18V to +18V. The pulse had a duration of 10ms for each edge. The maximum current used for the oscilloscope images was in the range of 300μA.

The image below shows the process of starting the system once it receives power and running it until both 1st and 2nd stage capacitors are charged.

- In the blue line is the 1st stage capacitor of 47µF capacitance.
- In the yellow line is the 2nd stage capacitor of 1mF capacity.
- In the green line is the PGOOD signal that controls the load switch.



Picture 49 startup Piezo



Picture 50 working state piezo.

We observe that during the charging of the 2nd stage capacitor the PGOOD signal ranges between HIGH and LOW for short periods of time, until the 2nd stage capacitor is charged. Also, this function keeps the 1st stage capacitor in a steady state. As shown in the picture above the 1st stage and the 2nd stage capacitor were connected via the load switch. When the 2nd stage was charged fully there was no need for any more pulsing and the PGOOD signal remained HIGH. Tests were made to estimate the overall efficiency of the whole module. In these tests the input signal had the following characteristics:

- Square wave
- 36V Pk-Pk
- 20ms period
- 50% duty cycle
- Max Input Current 55mA

During the test a load was applied to the output. The load was applied after the 2nd stage capacitor had reached the preset value. Then the load was applied and stepped at 10mA increments. Yet again the efficiency was calculated in the same way as in the other modules. The following picture shows the efficiency graph and the Voltage drop of the Vout capacitor as the load increases.

- left Y is the performance in percentage %
- right Y is voltage in Volt.
- horizontal X is load current in mA.
- Blue is the efficiency percentage.
- Orange is the Vout voltage.

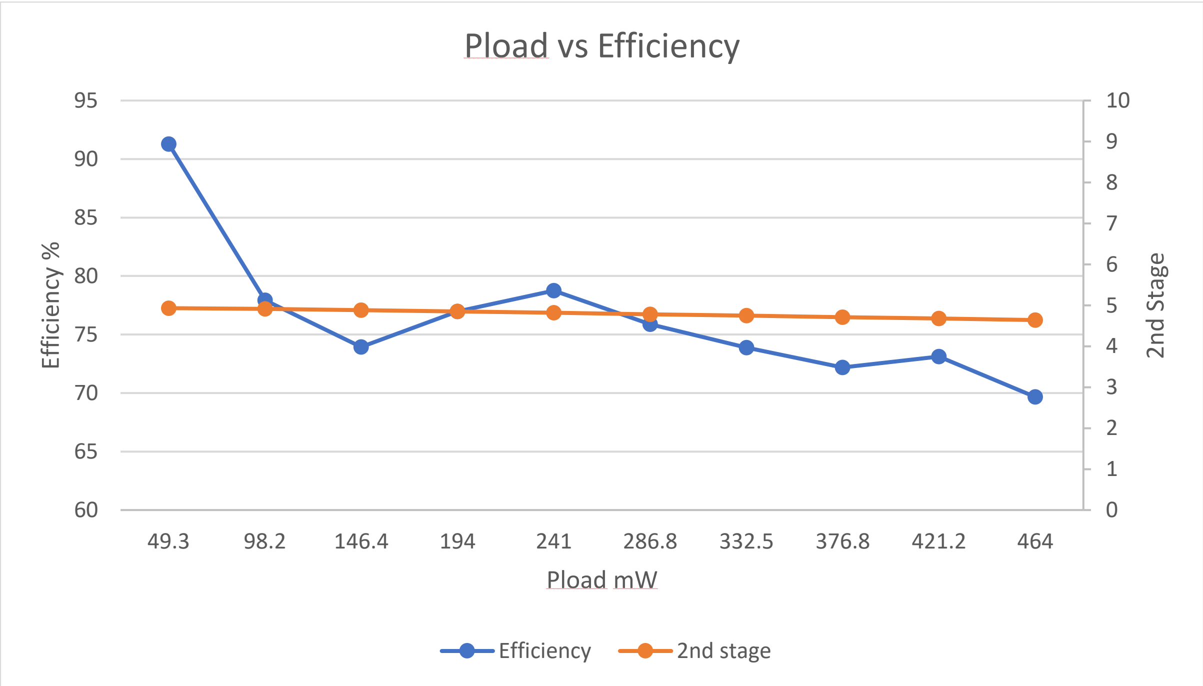


Figure 3 TB module efficiency

The battery charger subsystem uses the LTC4079 chip, which is a multichemistry battery charger. It operates in two modes, firstly in Constant Current (CC) and secondly in Constant Voltage (CV). It starts to charge at CC and changes to CV when the battery terminal voltage is approached. An additional feature is the battery temperature monitor by using an external NTC thermistor. Also, an indicator is implemented whether the battery is in charge mode or not. To characterize and measure its performance it was placed at a 5V input with a maximum current of 300mA. The maximum battery charging current was programmed at 250mA. The SMU was connected to the battery terminal to simulate the battery element. The SMU was programmed to gradually increase the voltage, so that the charger could understand that the battery was charging. The current that the charger provided was drawn from the SMU. As a result, the values of the charging current were recorded for different voltages. The SMU's voltage is critical because it indicates in which mode the charger operates. In addition, that has an impact on the input. Less input power is required as the battery charges. The efficiency of this module is calculated by dividing the charge power and input power. Charge power was dictated by the SMU voltage and the charge current in each value. As for the input it was the power that drawn from the power supply.

The figure below shows the performance of the charger in relation to the charging voltage. The measurements were made with the charger set up for a Li-Fe-Po4 type battery whose terminal charging voltage is 3.6V, the axes of the following diagram are as follows:

- blue is the charging current curve.
- orange is the efficiency curve.
- in the vertical Y1 the charging current curve in mA.
- in the vertical Y2 the efficiency curve in %.
- in the horizontal X are the voltage values in Volts.

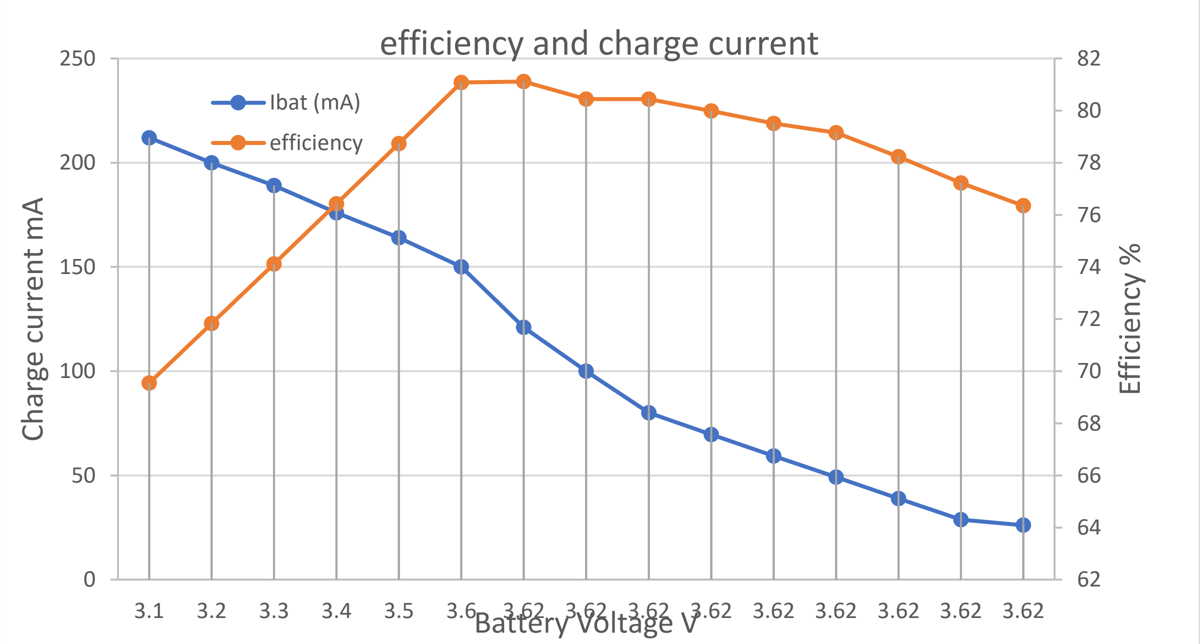


Figure 4 Charger Efficiency

Finally, the last measurement is to calculate the overall system efficiency. To do that calculation we made a concession that the PV module will be used as the main energy supply to the system. We mention that this calculation is a Peak efficiency of the whole system. Values in these calculations are the average values of each system. The calculation is made by multiplying each Average efficiency Value. The Average values are calculated from the tests that have been made previously. The formula below is used to calculate the Overall System Peak efficiency.

Overall Efficiency (%) = PV $_{Efficiency}$ Avg (%) * Charger $_{Efficiency}$ Avg (%) * 5V output $_{Efficiency}$ Avg (%)

Table 5 Peak Efficiency

Subsystem	Efficiency Avg %
PV module	90
charger	80
5V output	90
Overall system	64

As shown into the table the overall efficiency is an Average of 64%. Considering all the conversions between modules at different voltage states and charging a battery, where a chemical element is used. We observe that the overall efficiency value is at an acceptable level.

5 Conclusion & Future work

5.1 Conclusions

In conclusion, this thesis was made to harvest energy from multiple sources, different designs were proposed and the most suitable was constructed. A key factor was to keep a small outline of each sub-component. Spice simulations were helpful to monitor transient phenomena if they occur. Available and low-cost components were into our scope. An easy and configurable design is easier to troubleshoot and configure it accordingly. By making each harvesting module fully independent we can use as many as required depending on the application. Interchangeability between modules is a major key factor to this design. At last a charger module was also constructed at the same package to provide a generic solution of our design.

5.2 Future work

Future work will be a carrier board where these modules can be populated on. The carrier board will have pinouts for the harvesting modules to be populated. In addition, this board will have the battery charger and the DC-DC converters for different output voltage levels. Also, on this board the battery holder will be populated. On this board pinouts for the microcontrollers will be populated for the appropriate microcontroller and RF communication module.

6 Bibliography

Alex, R. (2021, 04 09). *Light as an Electrical Energy Source*. Ανάκτηση από EEPower: https://eepower.com/technical-articles/light-as-an-electrical-energy-source/#

Andrew Muscat, S. B. (2022, 07 25). *Electromagnetic Vibrational Energy Harvesters: A Review*. Ανάκτηση από PubMed Central: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9331882/

Apostolos Segkos, C. T. (2023). Rotating Triboelectric Nanogenerators for Energy Harvesting and Their Applications. *nanoenergy advances*, 170-219.

Coates, E. (2020). *Module 3.1 Buck Converters*. Ανάκτηση από Learn about electronics power supplies: https://learnabout-electronics.org/PSU/psu31.php

Coates, E. (2020). *Module 3.2 Boost Converters*. Ανάκτηση από Learnabout electronics Power Supplies: https://learnabout-electronics.org/PSU/psu32.php

Coates, E. (2020). *Module 3.3 Buck-Boost Converters*. Ανάκτηση από Learnabout electronics Power Supplies: https://learnabout-electronics.org/PSU/psu33.php

Gabriel Filios, I. K. (2019). An Encapsulated Energy Harvesting Platform for On-road Low Power Sensing Systems.

Husam Hamid Ibrahim, M. J.-B. (2022, 05 30). *Radio Frequency Energy Harvesting Technologies: A Comprehensive Review on Designing, Methodologies, and Potential Applications.* Ανάκτηση από PMC-PubMed Central: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9185291/

Parvendra Kumar, A. T. (2020, 10). *ENERGY HARVESTING USING PIEZO-ELECTRIC MATERIALS FOR WIRELESS SENSORS* . Ανάκτηση από ResearchGate: https://www.researchgate.net/publication/344464932_ENERGY_HARVESTING_USING_PIEZO-ELECTRIC_MATERIALS_FOR_WIRELESS_SENSORS_1

Priyanka Singla, S. R. (2022, 03 19). *A survey and experimental analysis of checkpointing techniques for energy*. Ανάκτηση από Science Direct: https://www.sciencedirect.com/science/article/pii/S1383762122000534

R.J.M. Vullers, R. v. (2009). Micropower energy harvesting. *Solid State Electronics*, 684-693.

R.J.M. Vullers, R. v. (2009, 04 25). *MicroPower Energy Harvesting (Solid State Electronic).* Ανάκτηση από Science Direct: https://www.sciencedirect.com/science/article/pii/S0038110109000720

RF energy harvesting system basics-Radio Frequency harvesting. (2012). Ανάκτηση από Home of RF and Wireless Vendors and Resources: https://www.rfwireless-world.com/Articles/RF-energy-harvesting-system-basics.html

Senhao Zhang, J. Z. (2022, 02 17). *Standalone stretchable RF systems based on asymmetric 3D microstrip antennas with on-body wireless communication and energy harvesting.* Ανάκτηση από Science Direct: https://www.sciencedirect.com/science/article/pii/S2211285522001525

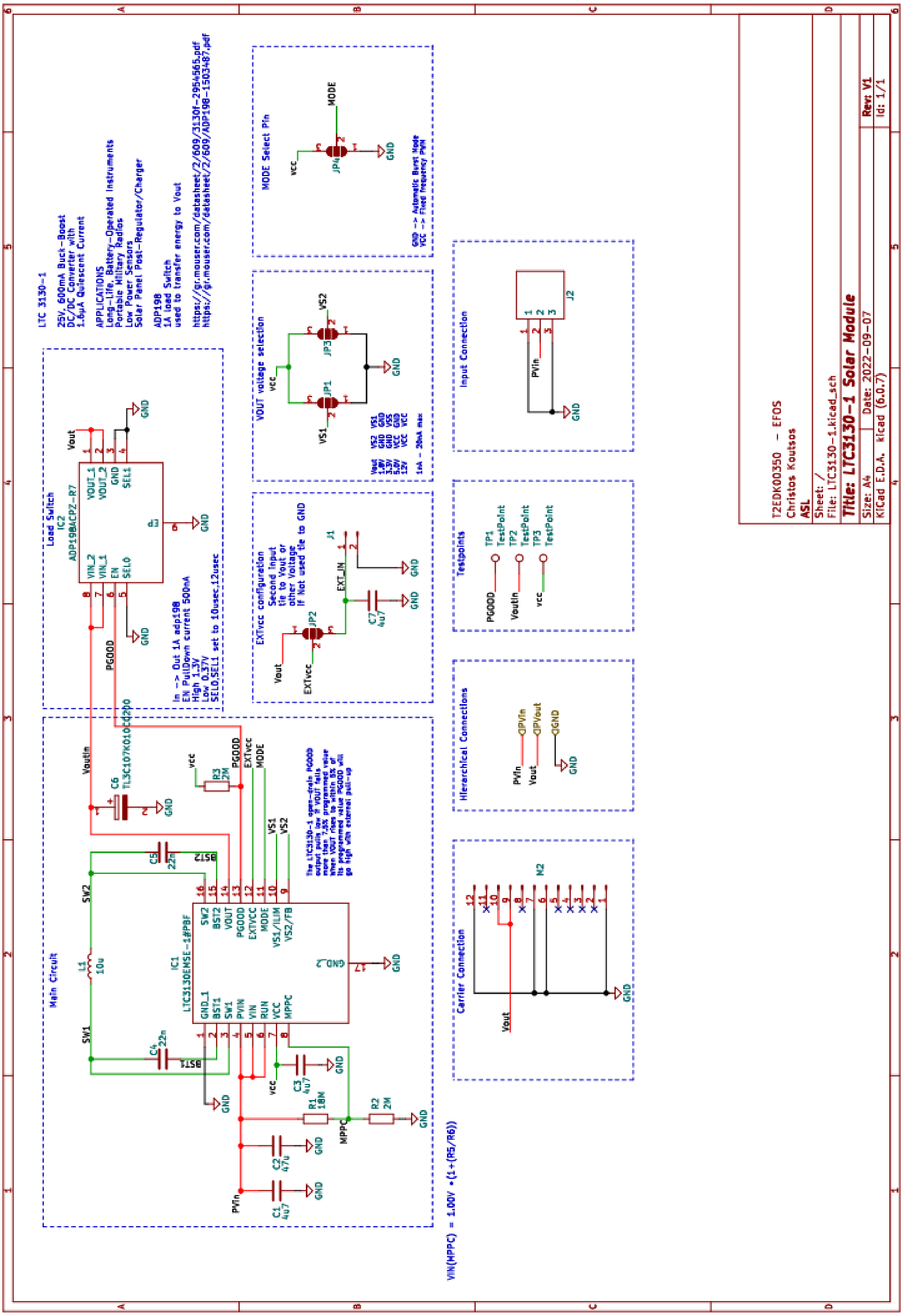
Syed Nasimul Alam, A. G. (2023, 04 20). *An introduction to triboelectric nanogenerators.* Ανάκτηση από Science Direct: https://www.sciencedirect.com/science/article/pii/S2352507X23000434#fig5

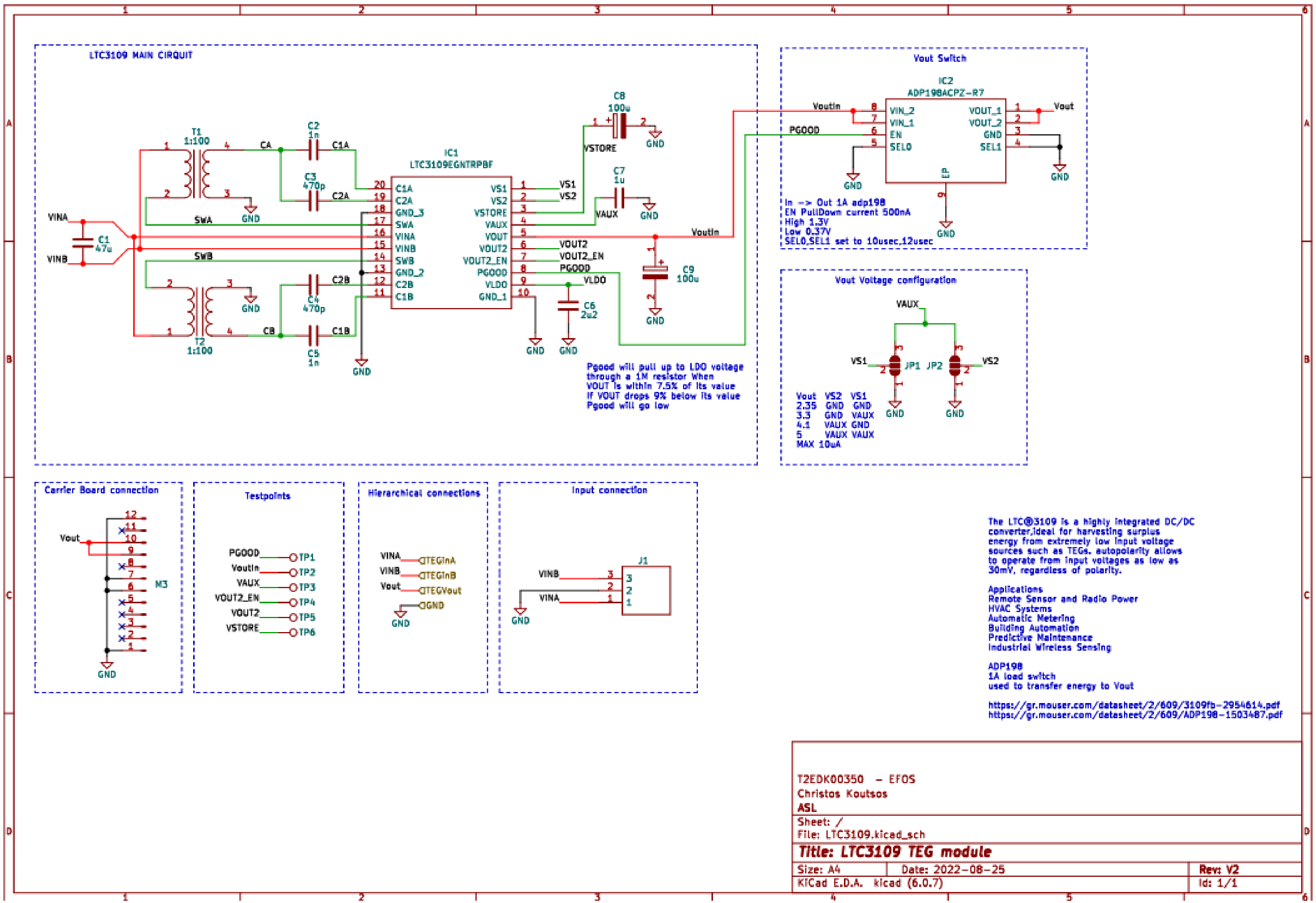
Tanju Yildirim, M. H. (2017). *A review on performance enhancement techniques for ambient vibration.* Ανάκτηση από University of Wollongong-Research Online: https://ro.uow.edu.au/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1238&context=eispapers1

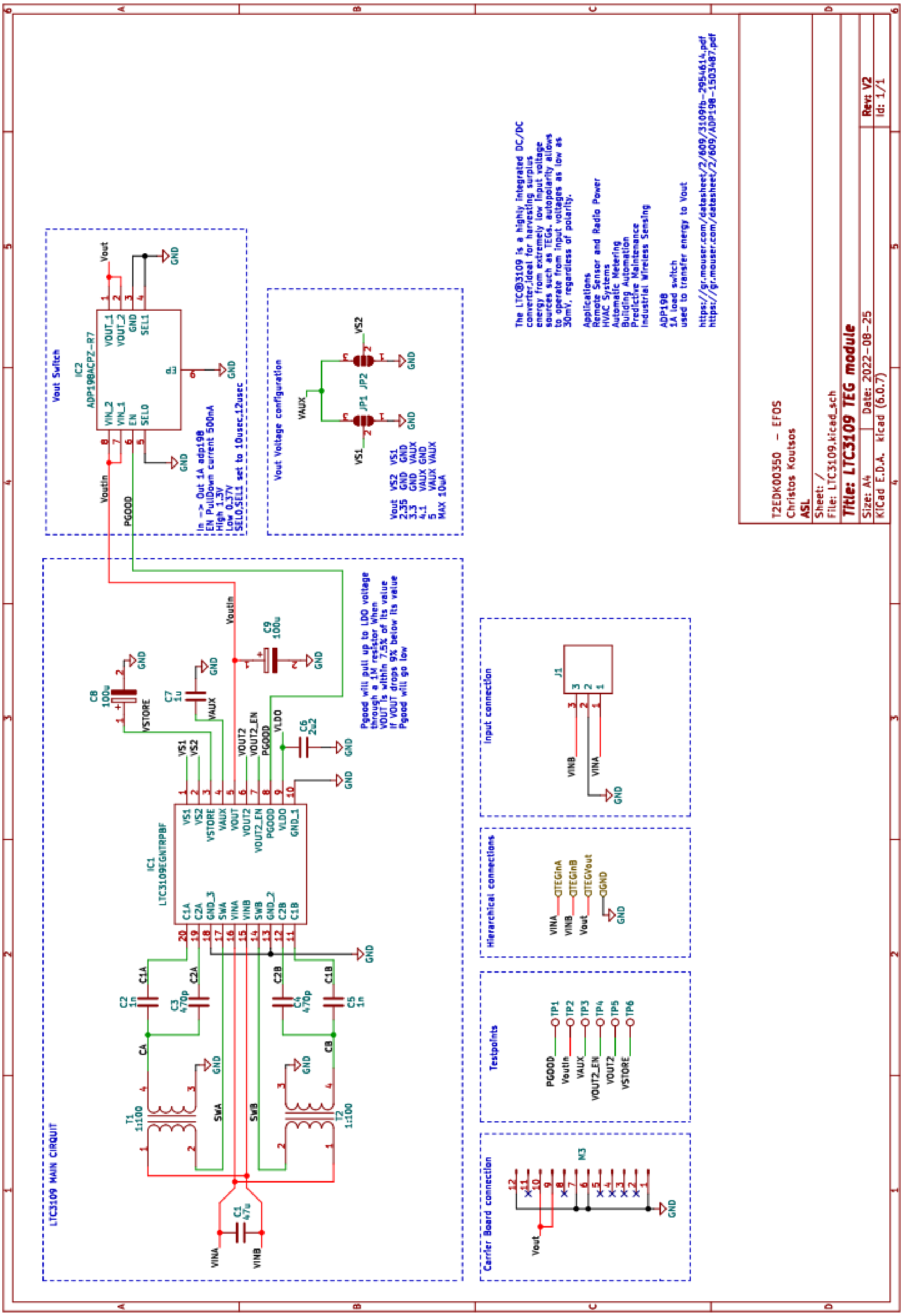
unknown. (2012). *RF energy harvesting system basics-Radio Frequency harvesting.* Ανάκτηση από Home of RF and Wireless Vendors and Resources: https://www.rfwireless-world.com/Articles/RF-energy-harvesting-system-basics.html

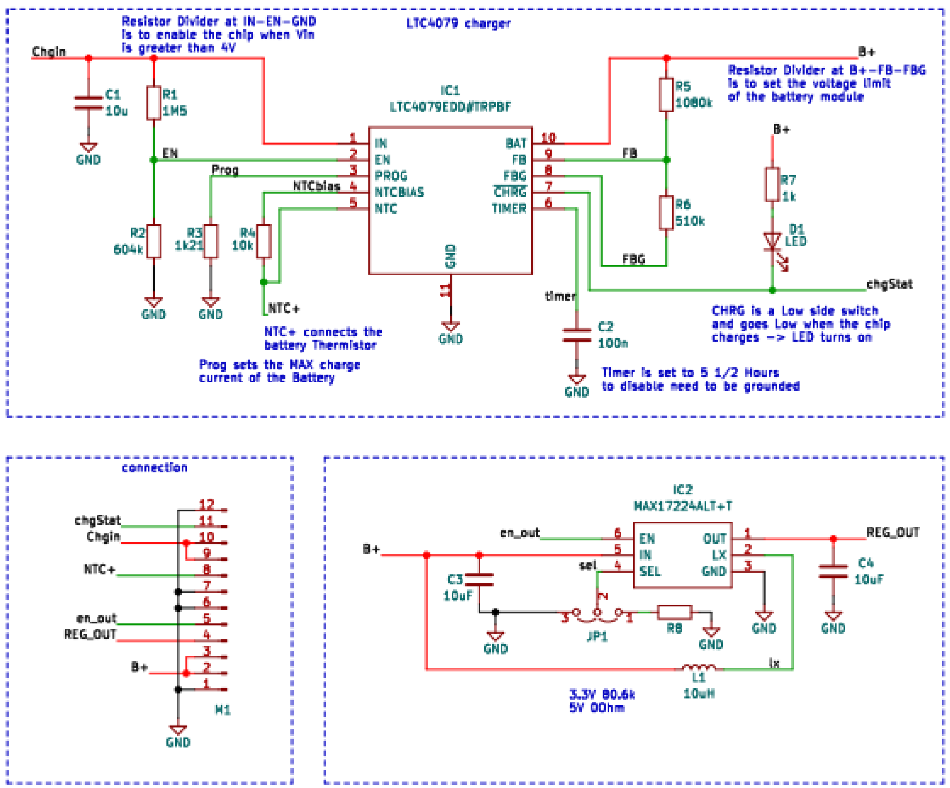
7 Appendix

7.1 Schematics




LTC3109 MAIN CIRQUIT
T1
1:100
T2
1:100
CA
CB
C1
47u
C2
1n
C3
470p
C4
470p
C5
1n
C6
2u2
C7
1u
C8
100u
C9
100u
VINA
VINB
SWA
SWB
C1A
C2A
C2B
C1B
IC1
LTC3109EGNTRPBF
C1A
C2A
GND_3
SWA
VINA
VINB
SWB
GND_2
C2B
C1B
VS1
VS2
VSTORE
VAUX
VOUT
VOUT2
VOUT2_EN
PGOOD
VLDO
GND_1
VSTORE
VAUX
Voutin
VLDO
GND
Pgood will pull up to LDO voltage
through a 1M resistor When
VOUT is within 7.5% of its value
If VOUT drops 9% below its value
Pgood will go low
Vout Switch
IC2
ADP198ACPZ-R7
VIN_2
VIN_1
EN
SEL0
VOUT_1
VOUT_2
GND
SEL1
EP
Voutin
PGOOD
Vout
In -> Out 1A adp198
EN PullDown current 500nA
High 1.3V
Low 0.37V
SEL0,SEL1 set to 10usec,12usec
Vout Voltage configuration
VAUX
VS1
JP1
JP2
VS2
Vout VS2 VS1
2.35 GND GND
3.3 GND VAUX
4.1 VAUX GND
5 VAUX VAUX
MAX 10uA
Carrier Board connection
Vout
M3
Testpoints
PGOOD TP1
Voutin TP2
VAUX TP3
VOUT2_EN TP4
VOUT2 TP5
VSTORE TP6
Hierarchical connections
VINA TEGinA
VINB TEGinB
Vout TEGVout
GND
Input connection
J1
VINB
VINA
The LTC®3109 is a highly integrated DC/DC
converter,ideal for harvesting surplus
energy from extremely low input voltage
sources such as TEGs. autopolarity allows
to operate from input voltages as low as
30mV, regardless of polarity.
Applications
Remote Sensor and Radio Power
HVAC Systems
Automatic Metering
Building Automation
Predictive Maintenance
Industrial Wireless Sensing
ADP198
1A load switch
used to transfer energy to Vout
https://gr.mouser.com/datasheet/2/609/3109fb-2954614.pdf
https://gr.mouser.com/datasheet/2/609/ADP198-1503487.pdf
T2EDK00350 - EFOS
Christos Koutsos
ASL
Sheet: /
File: LTC3109.kicad_sch
Title: LTC3109 TEG module
Size: A4
Date: 2022-08-25
Rev: V2
KiCad E.D.A. kicad (6.0.7)
Id: 1/1


LTC3109 MAIN CIRQUIT
Vout Switch
Vout Voltage configuration
Input connection
Hierarchical connections
Testpoints
Carrier Board connection
IC1
LTC3109EGNTRPBF
IC2
ADP198ACPZ-R7
In -> Out 1A adp198
EN PullDown current 500nA
High 1.3V
Low 0.37V
SEL0,SEL1 set to 10usec,12usec
Pgood will pull up to LDO voltage through a 1M resistor when VOUT is within 7.5% of its value
If VOUT drops 9% below its value Pgood will go low
The LTC®3109 is a highly integrated DC/DC converter,ideal for harvesting surplus energy from extremely low input voltage sources such as TEGs. autopolarity allows to operate from input voltages as low as 30mV, regardless of polarity.
Applications
Remote Sensor and Radio Power
HVAC Systems
Automatic Metering
Building Automation
Predictive Maintenance
Industrial Wireless Sensing
ADP198
1A load switch
used to transfer energy to Vout
https://gr.mouser.com/datasheet/2/609/3109fb-2954614.pdf
https://gr.mouser.com/datasheet/2/609/ADP198-1503487.pdf
T2EDK00350 - EFOS
Christos Koutsos
ASL
Sheet: /
File: LTC3109.kicad_sch
Title: LTC3109 TEG module
Size: A4
Date: 2022-08-25
Rev: V2
KiCad E.D.A. kicad (6.0.7)
Id: 1/1



The LTC®4079 is a low quiescent current, high voltage linear charger for most battery chemistry types including Li-Ion/Polymer, LiFePO4, Lead-Acid or NiMH battery stacks up to 60V. The maximum charge current is adjustable from 10mA to 250mA with an external resistor. The battery charge voltage is set using an external resistor divider.

APPLICATIONS
Embedded Automotive and Industrial
Backup Battery Charging from Another Battery
Energy Harvesting Charger
Thin Film Battery Products

MAX17224 is an ultralow step-up DC-DC converter with true shutdown. Input range 0.4V to 5.5V and output 1.8 to 5V and 1A max current

https://gr.mouser.com/datasheet/2/609/ltc4079-2821769.pdf
https://gr.mouser.com/datasheet/2/256/MAX17220_MAX17225-1115690.pdf

T2EDK00350 – EFOS Christos Koutsos ASL		
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Title: LTC-4079 charger module		
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LTC3130/LTC3130-1

25V, 600mA Buck-Boost DC/DC Converter with 1.6μA Quiescent Current

FEATURES

- Regulates V_{OUT} Above, Below or Equal to V_{IN}
- Wide V_{IN} Range: 2.4V to 25V, <1V to 25V (Using $EXTV_{CC}$ Input)
- V_{OUT} Range: 1V to 25V
- Adjustable Output Voltage (LTC®3130)
- Four Selectable Fixed Output Voltages (LTC3130-1)
- 1.2μA No-Load Input Current in Burst Mode® Operation (V_{IN} = 12V, V_{OUT} = 5V)
- 600mA Output Current in Buck Mode
- Pin-Selectable 850mA/450mA Current Limit (LTC3130)
- Up to 95% Efficiency
- Pin-Selectable Burst Mode Operation
- 1.2MHz Ultralow Noise PWM Frequency
- Accurate RUN Pin Threshold
- Power Good Indicator
- Programmable Maximum Power Point Control
- I_Q = 500nA in Shutdown
- Thermally-Enhanced 20-Lead 3mm × 4mm QFN and 16-Lead MSOP Packages

APPLICATIONS

- Long-Life, Battery-Operated Instruments
- Portable Military Radios
- Low Power Sensors
- Solar Panel Post-Regulator/Charger

DESCRIPTION

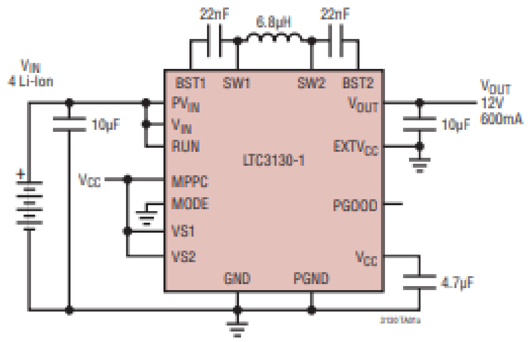
The LTC3130/LTC3130-1 are high efficiency, low noise, 600mA buck-boost converters with wide V_{IN} and V_{OUT} ranges. For high efficiency operation at light loads, Burst Mode operation can be selected, reducing the quiescent current to just 1.6μA. Converter start-up is achieved from sources as low as 7.5μW.

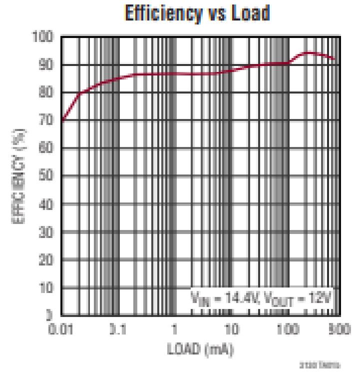
The LTC3130/LTC3130-1 employ an ultralow noise, 1.2MHz PWM architecture that minimizes solution footprint by allowing the use of tiny, low profile inductors and ceramic capacitors. Built-in loop compensation and soft-start reduces external parts count and simplifies the design. Features include an accurate RUN comparator threshold to allow predictable regulator turn-on and a maximum power point control (MPPC) capability that ensures maximum power extraction from non-ideal sources such as photovoltaic panels. The LTC3130-1 includes an internal voltage divider to provide four selectable fixed output voltages.

Additional features include a power good output, an external V_{CC} input and thermal shutdown.

The LTC3130 and LTC3130-1 are available in thermally-enhanced 20-lead 3mm × 4mm QFN and 16-lead MSOP packages.

TYPICAL APPLICATION





3130f

Auto-Polarity, Ultralow Voltage Step-Up Converter and Power Manager

FEATURES

- **Operates from Inputs as Low as ±30mV**
- **Less Than ±1°C Needed Across TEG to Harvest Energy**
- **Proprietary Auto-Polarity Architecture**
- **Complete Energy Harvesting Power Management System**
  - **Selectable V_{OUT} of 2.35V, 3.3V, 4.1V or 5V**
  - **2.2V, 5mA LDO**
  - **Logic-Controlled Output**
  - **Energy Storage Capability for Operation During Power Interruption**
- **Power Good Indicator**
- Uses Compact Step-up Transformers
- Small, 20-lead (4mm × 4mm) QFN Package or 20-Lead SSOP

APPLICATIONS

- Remote Sensor and Radio Power
- HVAC Systems
- Automatic Metering
- Building Automation
- Predictive Maintenance
- Industrial Wireless Sensing

DESCRIPTION

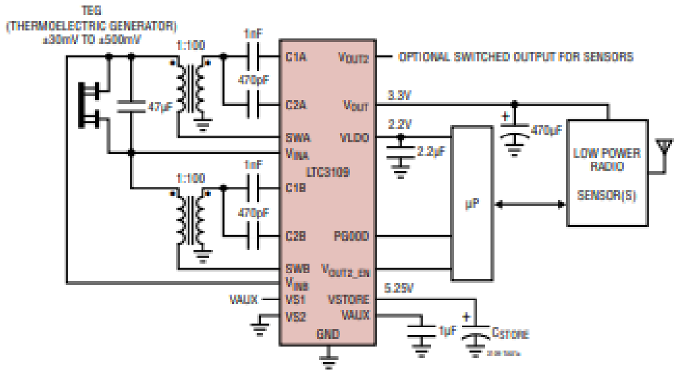
The LTC®3109 is a highly integrated DC/DC converter ideal for harvesting surplus energy from extremely low input voltage sources such as TEGs (thermoelectric generators) and thermopiles. Its unique, proprietary autopolarity topology* allows it to operate from input voltages as low as 30mV, regardless of polarity.

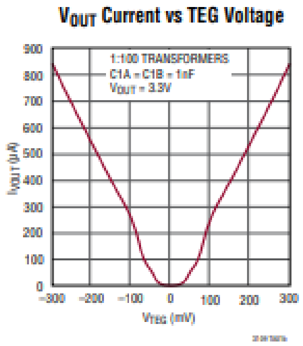
Using two compact step-up transformers and external energy storage elements, the LTC3109 provides a complete power management solution for wireless sensing and data acquisition. The 2.2V LDO can power an external microprocessor, while the main output can be programmed to one of four fixed voltages. The power good indicator signals that the main output is within regulation. A second output can be enabled by the host. A storage capacitor (or battery) can also be charged to provide power when the input voltage source is unavailable. Extremely low quiescent current and high efficiency maximizes the harvested energy available for the application.

The LTC3109 is available in a small, thermally enhanced 20-lead (4mm × 4mm) QFN package and a 20-lead SSOP package.

*Patent pending.

TYPICAL APPLICATION





LTC3588-2

Nanopower Energy Harvesting Power Supply with 14V Minimum V_{IN}

FEATURES

- **1500nA Input Quiescent Current (Output in Regulation – No Load, V_{IN} = 18V)**
- **830nA Input Quiescent Current in UVLO, V_{IN} = 12V**
- **14V to 20V Input Operating Range**
- **Integrated Low-Loss Full-Wave Bridge Rectifier**
- **16V UVLO Improves Power Utilization from High Voltage Current Limited Inputs**
- **Up to 100mA of Output Current**
- High Efficiency Integrated Hysteretic Buck DC/DC
- Selectable Output Voltages: 3.45V, 4.1V, 4.5V, 5.0V
- Input Protective Shunt – Up to 25mA Pull-Down at $V_{IN} \geq$ 20V
- Available in 10-Lead MSE and 3mm × 3mm DFN Packages

APPLICATIONS

- Piezoelectric Energy Harvesting
- Electro-Mechanical Energy Harvesting
- Low Power Battery Charging
- Wireless HVAC Sensors
- Mobile Asset Tracking
- Tire Pressure Sensors
- Battery Replacement for Industrial Sensors

DESCRIPTION

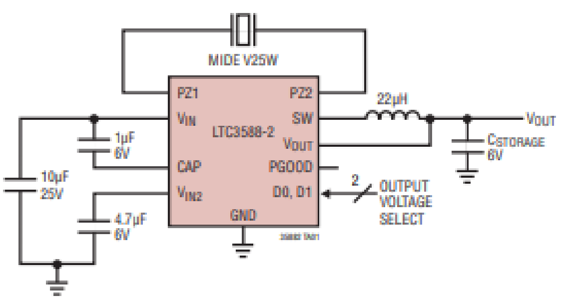
The LTC®3588-2 integrates a low-loss full-wave bridge rectifier with a high efficiency buck converter to form a complete energy harvesting solution optimized for high output impedance energy sources such as piezoelectric, solar, or magnetic transducers.

An ultralow quiescent current undervoltage lockout (UVLO) mode with a 16V rising threshold enables efficient energy extraction from sources with high open circuit voltages. This energy is transferred from the input capacitor to the output via a high efficiency synchronous buck regulator. The 16V UVLO threshold also allows for input to output current multiplication through the buck regulator. The buck features a sleep state that minimizes both input and output quiescent currents while in regulation.

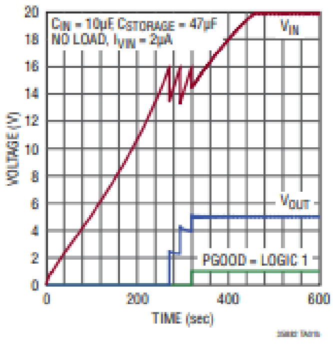
Four output voltages of 3.45V, 4.1V, 4.5V and 5.0V are pin selectable with up to 100mA of continuous output current, and suit Li-Ion and $LiFePO_4$ batteries as well as supercapacitors. An input protective shunt set at 20V provides overvoltage protection.

TYPICAL APPLICATION

High Voltage Piezoelectric Energy Harvesting Power Supply



LTC3588-2 5.0V Regulator Start-Up Profile



35882fc

60V, 250mA Linear Charger with Low Quiescent Current

FEATURES

- **Wide Input Voltage Range: 2.7V to 60V**
- **Adjustable Battery Voltage: 1.2V to 60V**
- **Adjustable Charge Current: 10mA to 250mA**
- **Low Quiescent Current While Charging: I_{IN} = 4µA**
- **Ultralow Battery Drain When Shutdown or Charged:**
  - **I_{BAT} < 0.01µA**
- **Auto Recharge**
- **Input Voltage Regulation for High Impedance Sources**
- Thermal Regulation Maximizes Output Current without Overheating
- Constant Voltage Feedback with ±0.5% Accuracy
- NTC Thermistor Input for Temperature Qualified Charging
- Adjustable Safety Timer
- Charging Status Indication
- Thermally Enhanced 10-Lead (3mm × 3mm) DFN Package
- AEC-Q100 Qualified for Automotive Applications

APPLICATIONS

- Embedded Automotive and Industrial
- Backup Battery Charging from Another Battery
- Energy Harvesting Charger
- Thin Film Battery Products

DESCRIPTION

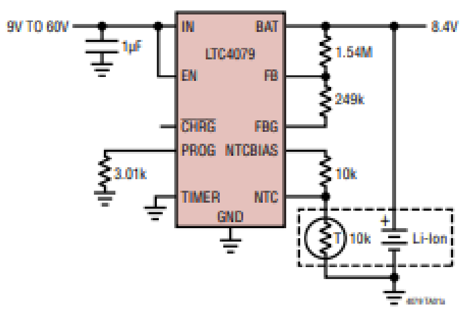
The LTC®4079 is a low quiescent current, high voltage linear charger for most battery chemistry types including Li-Ion/Polymer, $LiFePO_4$, Lead-Acid or NiMH battery stacks up to 60V. The maximum charge current is adjustable from 10mA to 250mA with an external resistor. The battery charge voltage is set using an external resistor divider.

With an integrated power device, current sensing and reverse current protection, a complete charging solution using the LTC4079 requires very few external components. Thermal regulation ensures maximum charge current up to the specified limit without the risk of overheating. Charging can be terminated by either C/10 or adjustable timer.

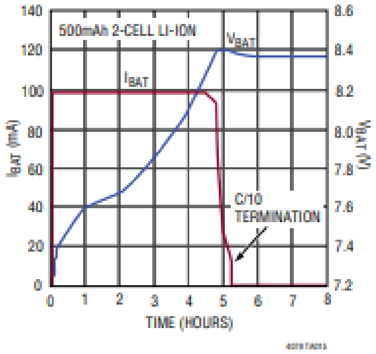
Input voltage regulation reduces charge current when the input voltage falls to an adjustable level or the battery voltage, making it well suited for energy harvesting applications. Other features include temperature qualified charging, bad battery detection, automatic recharge with sampled feedback in standby for negligible battery drain, and an open-drain $\overline{CHRG}$ status output. The device is offered in a compact, thermally enhanced 10-lead (3mm × 3mm) DFN package.

TYPICAL APPLICATION

Charging a Backup Battery



Li-Ion Battery Charge Cycle



Rev. A

Logic Controlled, 1 A, High-Side Load Switch with Reverse Current Blocking

Data Sheet **ADP198**

FEATURES

- **Low RDS_{ON} of 50 mΩ @ 3.3 V (WLCSP only)**
- **Low input voltage range: 1.65 V to 6.5 V**
- **1 A continuous operating current**
- **Built-in level shift for control logic that can be operated by 1.2 V logic**
- **Low 2.5 µA quiescent current @ V_{IN} = 2.8 V**
- **Low 1.1 µA shutdown current @ V_{IN} = 2.8 V**
- **Reverse current blocking**
- **Programmable start-up time**
- **Ultrasmall 1 mm × 1 mm, 4-ball, 0.5 mm pitch (WLCSP)**
- **Tiny 8-lead lead frame chip scale package (LFCSP) 2.0 mm × 2.0 mm × 0.55 mm, 0.5 mm pitch**

APPLICATIONS

- **Mobile phones**
- **Digital cameras and audio devices**
- **Portable and battery-powered equipment**

TYPICAL APPLICATION CIRCUITS

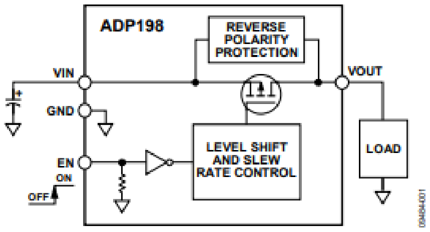


Figure 1. WLCSP

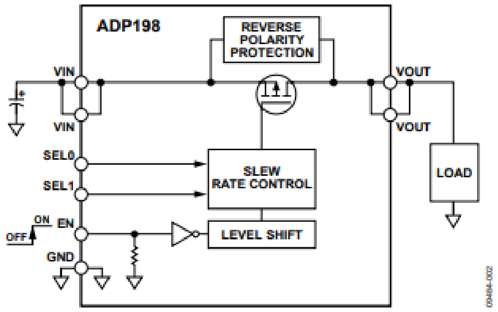


Figure 2. LFCSP

GENERAL DESCRIPTION

The ADP198 is a high-side load switch designed for operation between 1.65 V and 6.5 V that is protected against reverse current flow from output to input. A load switch provides power domain isolation, thereby helping to keep subsystems isolated and powered independently and enabling reduced power consumption. The ADP198 contains a low on-resistance P-channel MOSFET that supports more than 1 A of continuous load current. The low 2.5 µA quiescent current and ultralow shutdown current make the ADP198 ideal for battery-operated portable equipment. The built-in level shifter for enable logic makes the ADP198 compatible with modern processors and general-purpose input/output (GPIO) controllers. The LFCSP version also allows the user to program the start-up time to control the inrush current at turn on.

The ADP198 is available in an ultrasmall 1 mm × 1 mm, 4-ball, 0.5 mm pitch WLCSP. An 8-lead, 2 mm × 2 mm × 0.55 mm, 0.5 mm pitch LFCSP is also available.