

SHORT THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY (PHD)

**Towards an Environmental Energy Recycler
Aggregator (EERA) Prototype by Harvesting
Ambient Energy Sources for Low-Powered
Internet of Things (IoT) Devices**

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1 Introduction

The global demand for green energy or renewable energy provisions have been increasingly demanding in the last decade and will continue to increase over coming days, specifically for powering up the Internet of Things (IoT). Hence, the significance and challenges posed for integrating renewable energy in almost all sectors, more importantly for low-powered devices, need to be carefully studied. Considering the small-scale Energy Harvesting (EH) users, who require building their own specific EH system for saving electricity consumption cost on their project. It is essential to have particular expertise and knowledge related to steps involved and how to aggregate and select the specific components for building own EHC. The first and foremost step before implementation of the system on physical hardware is to simulate and model the entire prototype to see the desired result. However, modelling is a necessary tool towards the implementation of the system, and unfortunately, there isn't clear and straightforward user-defined profile available for building an EH based IoT system. Regardless of better insight for energy harvesting based solutions between users, there's still a considerable demand among them towards better knowing of their own Energy Harvesting System (EHS) for getting maximum efficiency from it, in terms of cost and revenue.

This thesis aims to address the issues mentioned above and to determine a step-by-step approach towards building an EH based IoT module for powering low-powered devices or IoT applications, specifically for small-scale users. In this regard, two energy harvesting sources; Solar and Heat/Thermal energy have been under investigations regarding power generation of specific EH module and to analyse whether these sources could lead to a promising solution and to sustain the powering capacity required by IoT components. Two prototypes for complete EHC setup for both sources have been proposed, and commercially available transducers have been selected for power generation. On the other hand, commercial-off-the-shelf (COTS) power management integrated circuit (PMIC) from Linear Technology; LTC3108 is chosen for a complete power management solution. The transformation of solar and heat energy will be converted into electrical analogy, as this study is entirely based on an electrical perspective. The energy harvesting for both sources is transformed on spice equivalent circuits, where the entire system was built, modelled and simulated with LTspice simulator via solar-to-electrical and thermal-to-electrical analogy. To follow up this correlation, the parameters are extracted for both commercial products (MC-SP0.8-NF-GCS [Solar], TEC1-12722 [Thermal]) from their manufacturer's datasheet and modelled on the proposed circuitry separately. For solar power generation, the proposed EHC prototype has generated certain levels of power under various solar irradiation and temperature-dependent conditions. The range varies between 2.68 mW (minimum generated power) till 108.60 mW (maximum generated power); specifically, under various solar irradiation levels and load configurations. Whereas, for Thermal EHC prototype, there are two factors under analysis: power generation and performance analysis. In terms of power generation, there are two programmed output voltages (2.3 V, 3.3 V), and accordingly, the power has been generated. Due to the target applications which require lesser temperature gradients such as human body heat harvesting for wearables; therefore, the

temperature gradients experimented were 3.5 °C and 4.0 °C. The minimum power generated for TEC1-12722 fused as a Thermal EHC prototype went till 0.688 mW and maximum reached at 1.719 mW. The generated results for both modules are then compared with IoT power constraints and for wearable devices which typically vary between μW to mW. However, the comparative analysis is carried out between IoT elements such as different types of sensors and microcontroller units (MCU) as well as with already available complete IoT applications. Hence, the measured results produced typical power levels which could be suitable for some of the IoT components and applications. Consequently, this simulation-based analysis towards building an EH based IoT system could be used as a point of reference and provides an insight towards a fundamental step-by-step basis for developing any Solar or Thermal found IoT prototype for specific applications.

The structure of the thesis is given as the following: Chapter 2 proposes the research methodology for modelling and simulation of two energy harvesting sources; Solar and Thermal. It introduced a systematic step-by-step approach for designing an Energy Harvesting (EH) based system to power up low-powered devices in terms of visual representation to give understanding about achieving the major objectives. Chapter 3 proposes the Solar EHC Module along with mathematical modelling. Chapter 4 proposes the Thermal EHC module along with mathematical modelling. Chapter 5 characterisation and simulation results of both solar and thermal modules' power generation in terms of IoT power consumption as a comparative analysis.

I briefly describe the contents of my dissertation, mostly focusing on my contributions. For a detailed description and other related issues (Literature review, methodology, mathematical derivation, etc.), please follow the dissertation.

1.1 Research Objectives

The main objective of this research is to explore a practical solution to eliminate the need for batteries replacement to power up IoT sensors or components.

1. Finding the minimum output power required for number of Internet of Things (IoT) devices and application.
2. Reviewing the energy storing technologies in terms of IoT.
3. Analysing and reviewing the number of available Power Management ICs and their working profile in terms of compatibility with IoT features and specifically in Energy Harvesting PMICs.
4. Analysing the design consideration for building Energy Harvesting based self-powered IoT devices.
5. Reviewing the ambient energy sources and associated harvesting techniques.

6. Analysing the available energy harvesting transducers specifically Solar and Heat/Thermal in terms of harvesting techniques and their generated output power based on various parameters which affect the performance dependent on various situations such temperature and environmental impacts.
7. To establish a trial and error case study for optimal output power by simulations of commercially available Photovoltaic module and Thermal module combined with Power Management IC: For analysing the behavioural response of the system combined with EH based PMIC.
8. Comparative analysis between simulation results and already available experimental results for both prototypes after careful considerations on various environmental conditions and other parameters like cause and effect, product selection, modelling and simulation for producing the optimal output power of harvester. (*Analysed and optimal case study*)

2 Proposed Research Methodology

The modelling and simulation study has been carried out for two energy harvesting sources; Solar and Thermal. This study aims to establish a systematic step-by-step approach for designing an Energy Harvesting (EH) based system to power up low-powered devices. Mostly, dedicated tools are absent for simulating and modelling the energy harvesting system, and it is providing the hurdle for end users who would like to build their target applications and requires proper guidance in short period. Through this simulation study, two prototypes for harvesting energy systems are modelled and characterised in various parameters to analyse the behaviour of the system and most importantly, to generate the output power under various load configurations.

Before implementation of the system on physical hardware, it is highly required to build a prototype and analyse the various responses within the system, precisely the compatibility issues, power generation and power consumption, load requirement, and sustainability.

The generated power will be compared with already designed solar and thermal energy harvesting models in terms of power generation, and the output will be compared to the IoT power requirement of a specific application at the end.

The visual representation of the entire workflow is demonstrated for proper understanding of the building approach of any energy harvesting based application.

Considering the energy harvesting current users, there is not any standard and clear user-defined profile available for building an EH based IoT system. The users ranging from industrial sectors till private sectors would like to save their project-related cost for electricity consumption. Regardless of better insight of energy harvesting based solutions between users, there is still a considerable demand among them towards better knowing of their energy harvesting system for getting maximum efficiency from it, in terms of expenditure and returns. Apart from this, both solar and thermal energy sources are highly complicated as they are dependent on environmental conditions, and their selection of the transducers will directly impact the output. These stringent setups are making the modelling a necessary tool towards building and optimization of the EH system.

The comprehensive approach has been carried out for modelling and simulating the chosen energy harvesting sources. Each segment contains extensive literature and solution-based criteria in it which will be described in detail in upcoming sections.

For a general understanding of the procedure, the Figure 1 is demonstrated here, as it starts from the selection of energy harvesting sources as the basis towards the energy power generation for circuitry

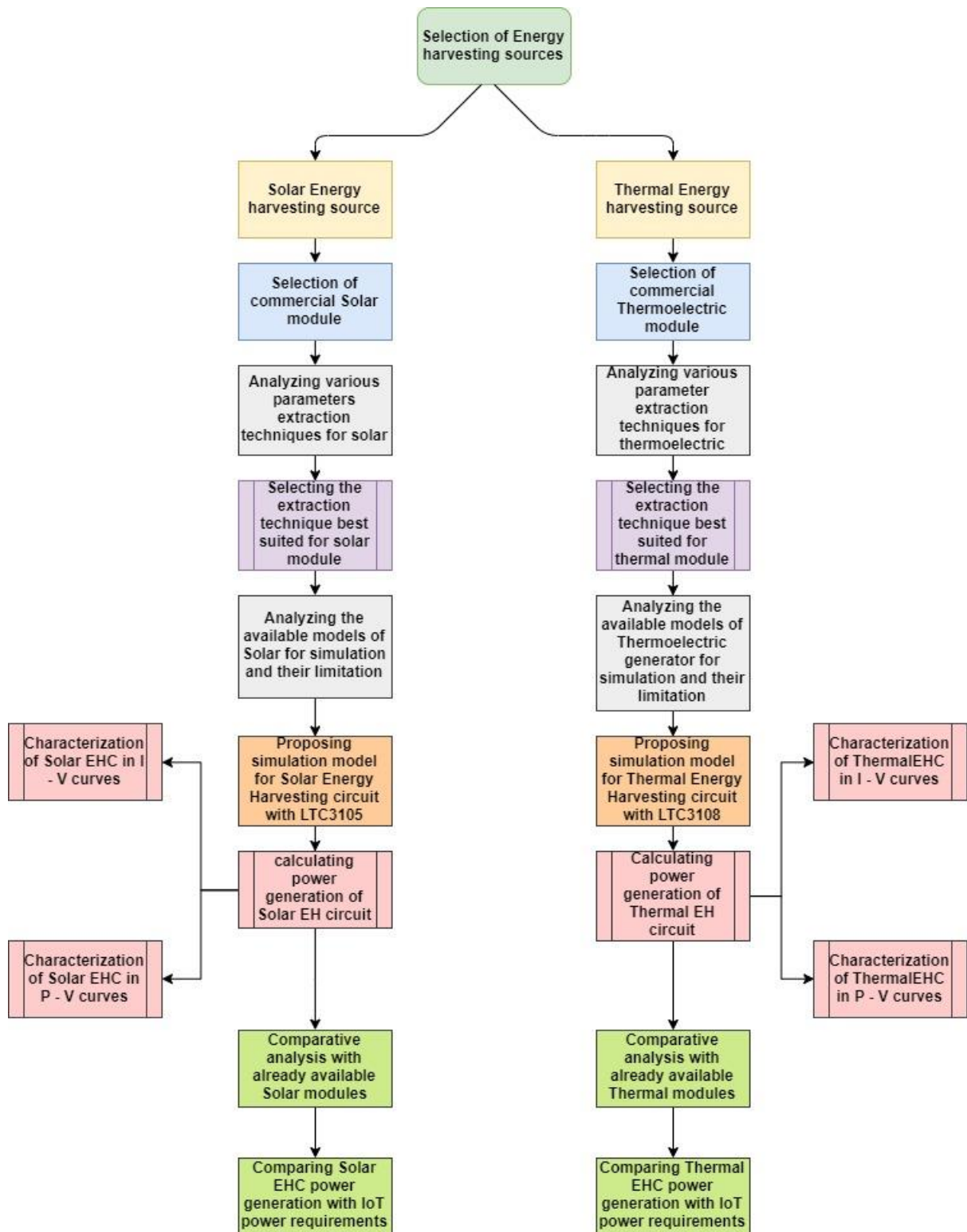


Figure 1: Systematic procedure towards building a Solar and Thermal based Energy Harvesting circuitry for low-powered devices.

Thesis I:

The comprehensive steps towards building an Energy Harvesting (EH) based Internet of Things (IoT) has been defined through extensive literature review and provided insight regarding the selection of all blocks required in that system.

- **IoT prerequisite and power consumption threshold have been specified.**
- **Analysed and Highlighted the factors involved in the selection of EH transducers and their efficiency by specific algorithms**
- **Worked on EH based PMICs regarding power management and sustainability issues**

Related publications: [P5, P10, P16]

3 Solar Energy Harvesting Module

3.1 Selecting a Solar Energy Harvesting Module

For harvesting solar energy, it is required to have a transducer to transform solar energy into electrical energy. Here, the selection of the module and related techniques are implemented after a thorough investigation of the solar energy. In this regard, a commercial solar model MC-SP0.8-NF-GCS from Multicomp [1] has been selected to analyse the behaviour of the module over the number of parameters for characterising the Energy harvesting system's requirement. This module is prepared explicitly for energy harvesting based applications for wearables.

3.2 Parameter extraction for MC-SP0.8-NF-GCS from Multicomp

For extraction of parameters, the analytical technique has been applied, as this is easier to be used by small scale users and represents a solution to this problem, due to their simplicity and minimum data requirement (included in the datasheet) for modelling solar behaviour. The steps involved in the selection and analysis of parameters are highlighted in Figure 2.



Figure 2: Step-by-step analysis and calculation towards the selection of parameter extraction technique

3.2.1 Five Parameter identification from Datasheet

In order to calculate the parameters for equivalent solar circuit of the commercial solar module MC-SP0.8-NF-GCS, the analytical methodology has been applied and data collected from the manufacturer's datasheet only. To reduce the complexity of the calculations, the ideality factor

should be kept fixed [2]; however, $a=1.3$ for polycrystalline cell is suggested [3]. The parameters will be extracted by certain equations for finding I_{pv} , I_o , R_s , R_{sh} and a based on Lambert W formulation [4].

Equation for Calculating R_s :

$$R_s = A \left(W_{-1} (B \exp(C)) - (D + C) \right) \quad (1)$$

Where,

$$A = \frac{aV_T}{I_{mp}}$$

$$B = - \frac{V_{mp}(2I_{mp} - I_{sc})}{V_{mp}I_{sc} + V_{oc}(I_{mp} - I_{sc})}$$

$$C = - \frac{2V_{mp} - V_{oc}}{aV_T} + \frac{(V_{mp}I_{sc} - V_{oc}I_{mp})}{(V_{mp}I_{sc} + V_{oc}(I_{mp} - I_{sc}))} \quad (2)$$

$$D = \frac{V_{mp} - V_{oc}}{aV_T}$$

Equation for calculating R_{sh} :

$$R_{sh} = \frac{(V_{mp} - I_{mp}R_s)(V_{mp} - R_s(I_{sc} - I_{mp}) - aV_T)}{(V_{mp} - I_{mp}R_s)(I_{sc} - I_{mp}) - aV_T I_{mp}} \quad (3)$$

Equation for calculating I_o :

$$I_o = \frac{(R_{sh} + R_s)I_{sc} - V_{oc}}{R_{sh} \exp\left(\frac{V_{oc}}{aV_T}\right)} \quad (4)$$

Equation for calculating I_{pv} :

$$I_{pv} = \frac{R_{sh} + R_s}{R_{sh}} I_{sc} \quad (5)$$

The following procedure is applied to calculate the parameters from the manufacturer's datasheet:

- Approximating the ideality factor, “a” as 1.3 (Polycrystalline Cell)
- Calculating the Series Resistance R_s with Equation 1
- Calculating the Shunt Resistance R_{sh} with Equation 3

- Calculating the Saturation Current I_0 with Equation 4
- Calculating the Photodiode Current I_{pv} with Equation 5

The electrical characteristics of the selected model from the manufacturer's datasheet are represented in Table 1, this data will be inserted into the derived equations to calculate the equivalent circuit parameters. These parameters are considered at (STC) Standard Test Conditions as 1000 W/m^2 , incident normal radiance, Cell temperature at $25 \text{ }^\circ\text{C}$ and Air Mass AM1.5g.

Table 1: Electrical Specifications of MC-SP0.8-NF-GCS from Multicomp

Characteristics	Specifications
Maximum Power Pmax	0.8 W
Maximum Power Voltage (Vmp)	3.85 V
Maximum Power Current (Imp)	0.21 A
Open Circuit Voltage (Voc)	4.80 V
Short Circuit Current (Isc)	0.23 A
Temperature Coefficient of Isc (alpha)	0.06%/K
Temperature Coefficients of Voc (beta)	-0.36%/K
Temperature Coefficients of Pm	-0.45%/K

The required equations for finding the unknown parameters have been calculated based on the manufacturer's available datasheet of the solar cell, and for performing calculations, the MATLAB tool was used. The calculated data which will be initialised in the module are tabulated in Table 2.

Table 2: Calculated parameters of MC-SP0.8-NF-GCS from Multicomp

Parameters	Calculated Values
I_0	1.949e-30
I_{pv}	0.2303
R_s	0.3208
R_{sh}	235.142
a	1.3

3.3 Mathematical Modelling of Solar Equivalent Circuit on LTspice

After extraction of parameters, the selected solar model MC-SP0.8-NF-GCS will be modelled over LTSpice simulator to analyse the real-time behaviour of the solar module in terms of $I - V$ and $P - V$ characteristics. The actual representation of the model on LTspice is shown in Figure 3.

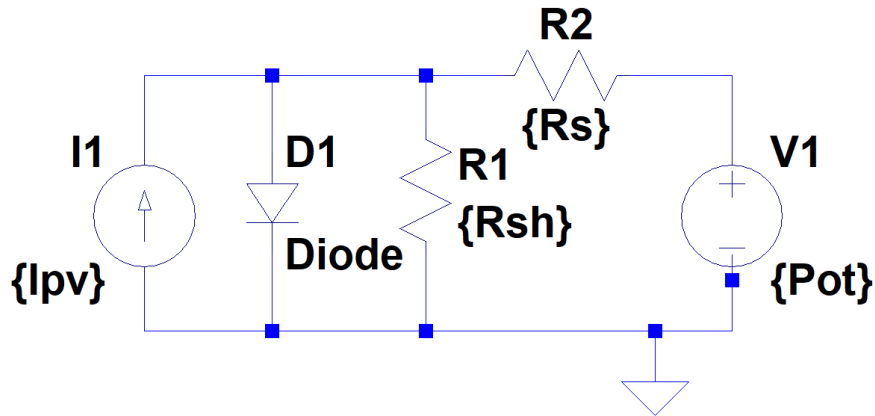


Figure 3: Solar equivalent circuit model for MC-SP0.8-NF-GCS

3.4 Proposed Solar Energy Harvesting Circuit with LTC3105

The commercial solar module MC-SP0.8-NF-GCS transformed into mathematical and electrical formulations can now be modelled with complete energy harvesting circuitry. The solar module will be combined with step-up power management IC from Linear Technology; LTC3105. Hence the complete Solar Energy Harvesting Circuit (EHC) combined with LTC3105 PMIC ready for modelling and simulation can be seen in Figure 4.

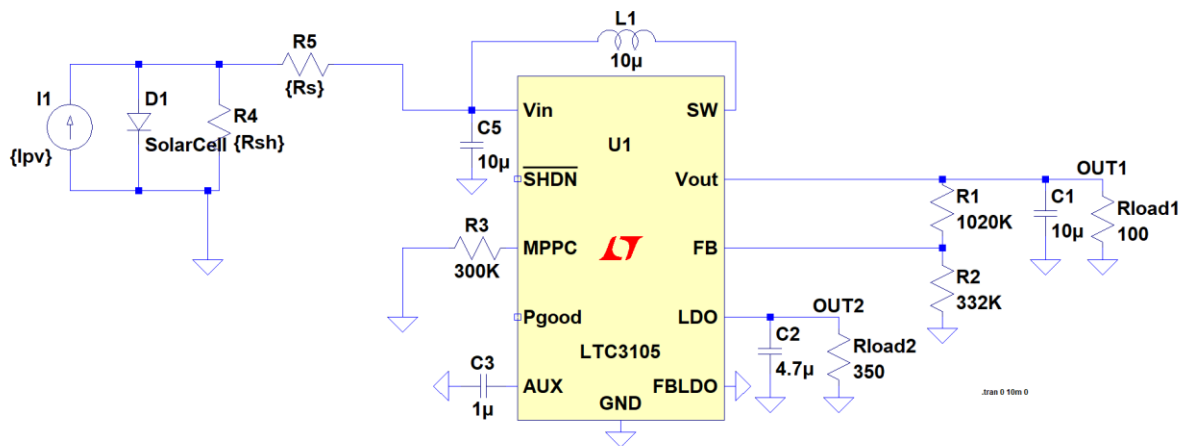


Figure 4: Solar Energy Harvesting Circuitry of MC-SP0.8-NF-GCS combined with LTC3105

Thesis II (Part a)

Transforming the commercial Solar module into an electrical SPICE model have been analysed and defined according to the manufacturer's datasheet (techniques supporting limited data revealed by manufacturer's)

- *The Solar parameter extraction techniques experimented with mathematical formulations have been analysed and presented another version with modification in ideality factor for solar module and then presented according to the accurate results produced*

Related Publications: [P1, P4, P9, P13]

4 Thermal Energy Harvesting Modelling

4.1 Selecting Thermal Energy Harvesting Module

For building a thermal-based Energy harvesting simulation setup, the first characteristic is to harvest the thermal energy. One aspect to understand here is that it is a purely electrical circuit simulation analysis; therefore, the selected commercial device will be modelled and simulated on the simulator according to the electrical perspective only. In terms of harvesting heat energy, the focus is on wearable devices from human body heat, as the basis for building this thermal-based energy harvesting module.

In this regard, a commercial thermoelectric module TEC-12722 from Thermonamic [5] has been chosen. This model is selected to analyse the behaviour of the module over the number of parameters. The module is explicitly supporting the IoT based application for wearable devices from human body heat.

4.2 Parameter extraction of TEC-12722 from Thermonamic

The associated extraction technique that will be applied in the selected model is based on the third category, which is *Extraction via the manufacturer's datasheet only*. This technique has been followed by 7-step procedure towards extraction of required data from limited manufacturer's datasheet for electrical parameters, whereas for thermal parameters, the experimental analysis has been followed. The visual representation of this significant step is highlighted in the following Figure 5.

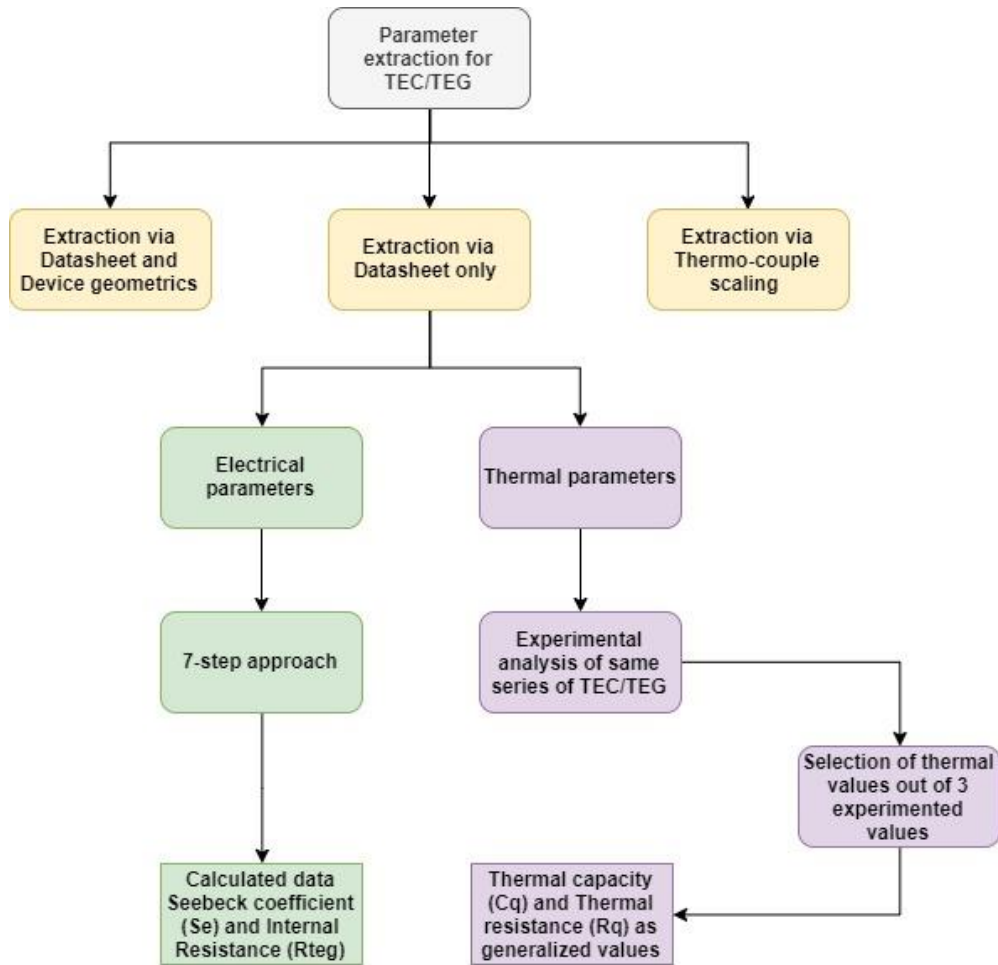


Figure 5: Comprehensive approach towards thermal module parameter extraction

The following Table 3, consisting of Performance characteristics of the selected module TEC-12722 [5].

Table 3: Performance characteristics of TEC1-12722

Th (°C)	27	50	Dry air: Temperature of Hot side
DTmax (°C)	70	79	Temperature difference of hot and cold side of the module when cooling capacity is zero at cold side
Umax (V)	16	17.2	Voltage applied to the module at DTmax
I _{max} (A)	18.5	18.5	DC current through the module at DTmax
Q _{Cmax} (W)	185.3	202.5	Cooling capacity at cold side of the module at DT = 0°C
AC resistance (Ω)	0.68	0.74	The tested module resistance under AC
Tolerance (%)	± 10		For electrical and thermal parameters

4.2.1 Extraction of Electrical Parameters through 7 steps

The parameters belong to the electrical part are Seebeck coefficient (Se), electrical resistance (R_{TEG}). The calculation for electrical parameters follows a 7-steps approach [6].

1) Reading and observing maximum output voltage (V_{Opt}) of TEC-12722 from the Figure 6.

V_{Opt} value is 16V for $T_h = 27^\circ\text{C}$

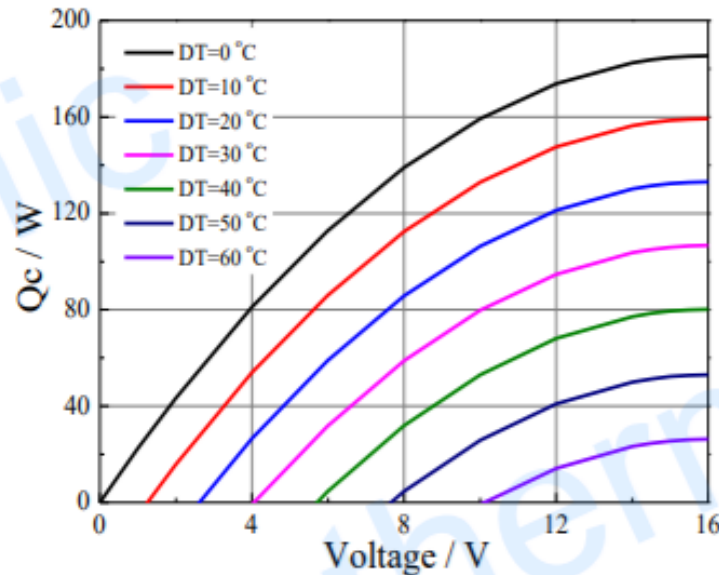


Figure 6: Performance curve at $T_h = 27^\circ\text{C}$ for TEC1-12722

2) Calculating the Seebeck Coefficient with the formula:

$$Se = \frac{V_{Opt}\{V\}}{T_h\{K\}}$$

$$Se = \frac{V_{Opt}\{V\}}{T_h\{K\}} = \frac{16}{27+273} = 53 \text{ mV/K}$$

3) Determining the maximum performance for zero temperature difference which is Q_{Cold} .

$$Q_{Cold} = 185W$$

4) Calculating electrical resistance value with:

$$R_0 = \frac{V_{Opt}^2}{2 \cdot Q_{Cold}}$$

$$R_0 = \frac{V_{Opt}^2}{2 \cdot Q_{Cold}} = \frac{16^2}{2 \cdot 185} = 0.692\Omega$$

5) Determining the maximum temperature difference between the cold and hot sides which is DT_{max} – the temperature which should secure the value for thermal performance returns to 0.

$$DT_{max} = 70^{\circ}\text{C}$$

6) Determining the Quality Factor ($X = \left\{ \frac{R_q}{R_0} \right\}$) which is the ratio between thermal resistance and electrical resistance, while using available parameters such as Seebeck Coefficient and DT_{max} from Figure 7.

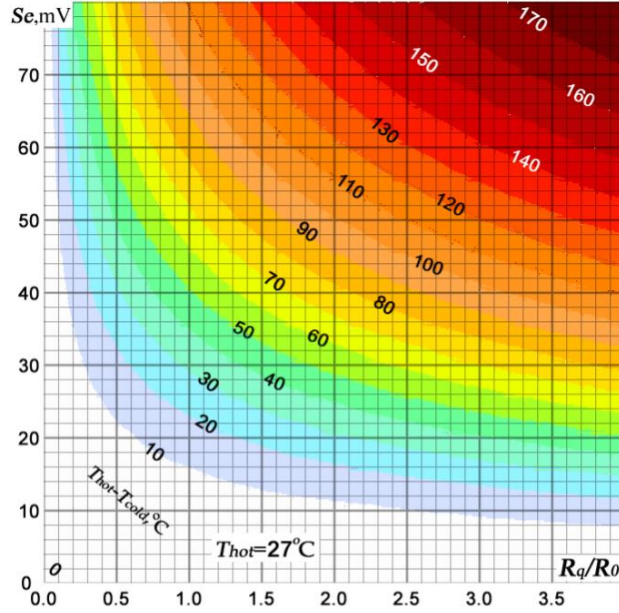


Figure 7: Relationship between Seebeck parameter and DT_{max} necessarily gathering results for thermal resistance for a wide range of variables [6]

By using Figure 7, after matching relevant values within each other, we get:

$$X = \left\{ \frac{R_q}{R_0} \right\} = 0.95$$

7) Calculating the value of thermal resistance with $R_q = R_0 \cdot X$

$$R_q = R_0 X = 0.692 \cdot 0.95 = 0.6574 \text{ K/W}$$

4.2.2 Extraction of Thermal Parameters

Out of four required parameters for the equivalent model, the remaining two belongs to the thermal domain, which is thermal resistance (R_q) and heat capacity (C_q). These values were selected as the generalised variables, which were experimented and simulated by Kubov in this work [7].

The nominal value for C_q and R_q is measured and experimented by the author in terms of 3 variations to see the impact of temperature dependence; the values were chosen as (lower, middle, higher). However, for internal thermal resistance, $R_q = (1.5, 3.0, 6.0)$, the values were changed two times higher and two times lesser from the chosen one, i.e. $R_q = 3$.

Same calculations and experiment have been considered for thermal capacity C_q in 3 different variations as $C_q = (7.5, 15, 30)$, the nominal values were changed two times higher and two times lesser than the chosen one $C_q = 15$.

Therefore, we considered the mid-range value as a general consideration for thermal resistance and heat capacity in our model.

Thus, parameters calculated for TEC1-12722 are tabulated in Table 4.

Table 4: Calculated Electrical and Thermal Parameters for TEC1-12722

Parameters		Calculated values	Units
Electrical	R_{TEG}	53	mV/K
	Se	0.692	Ω
Thermal	Cq	15	J/K
	Rq	3	K/W

4.3 Mathematical Modelling of Thermal Equivalent Circuit

In order to simulate the commercial thermal model on simulator, it is required to transform the characteristics of the selected model in terms of electrical specifications over the simulator.

The model chosen for our research requirement is Kubov's SPICE model based on Peltier-Seebeck element can be seen in Figure 8, due to its simplicity and it contains a small set of variables specifically in power generation inside the thermoelectric module. This interconvertible model of Peltier-Seebeck element converts electricity into heat and heat into electricity. The major limitation comes from manufacturer's datasheet as the data is not providing the information regarding output power generation of the TEC, which in our case is required to find out the maximum power generation of the system. However, the selection of the model is entirely based on the way parameters are extracted, which will lead to the efficiency of the selected thermoelectric module. This model is providing a straightforward approach and contains symmetric structure of the electrical scheme; it also provides transparency in the SPICE model, which could be transferred and adapted in an extended version.

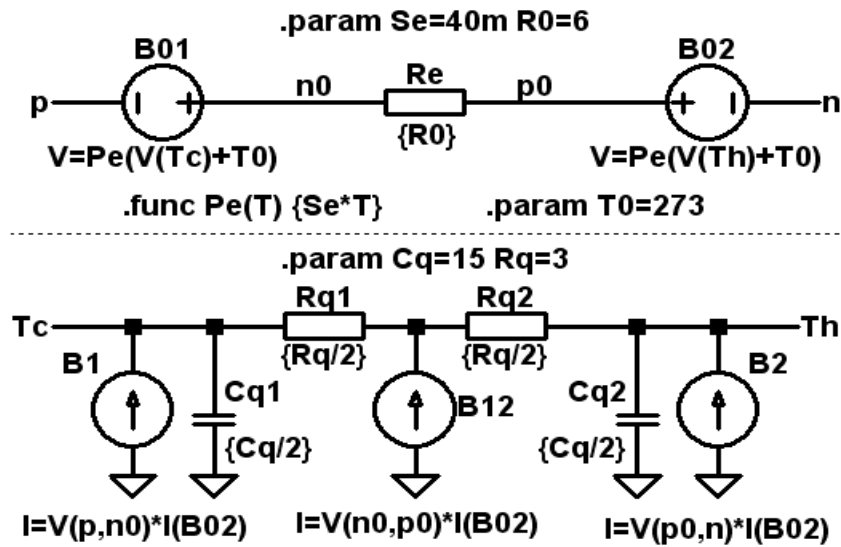


Figure 8: Kubov SPICE model for TEC/TEG [7]

4.4 Proposed Model for Thermal Energy Harvesting Circuit with LTC3108

The commercial thermoelectric module TEC1-12722 transformed into mathematical and electrical formulations can now be modelled with complete energy harvesting circuitry. The thermal module will be combined with step-up power management IC from Linear Technology; LTC3108. Hence the complete Thermal Energy Harvesting Circuit (EHC) combined with LTC3108 PMIC ready for modelling and simulation can be seen in Figure 9.

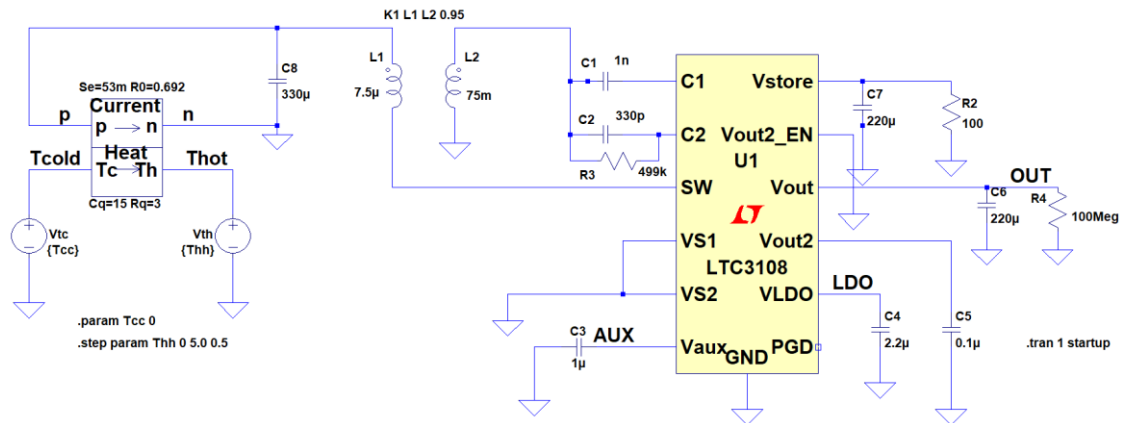


Figure 9: Thermal Energy Harvesting Circuit of TEC1-12722 with LTC3108 PMIC

Thesis II (Part b)

Transforming the commercial Heat/Thermal module into an electrical SPICE model have been analysed and defined according to the manufacturer's datasheet (techniques supporting limited data revealed by manufacturer's)

- *The Thermal parameter extraction containing both thermal and electrical aspects have been analysed and chosen along with related techniques to configure after careful analysis and simulation of parameters*

Related Publications: [P1, P4, P9, P13]

5 Simulation Results and Comparative Analysis: Results and Discussion

5.1 Characterisation of Solar Module on LTspice simulator

For analysing the performance of the module, it is essential to carry out simulation-based study for current vs voltage curves, i.e. I – V curves and power vs voltage curves, i.e. P – V curves. The simulation will be performed for analysing the system’s efficiency under various levels of solar irradiation as well as the temperature levels for both I – V and P – V curves. This is how the temperature dependence and solar irradiation impacts will be shown and analysed to see the maximum power generation under certain conditions of the solar module.

5.1.1 Impact of Solar Irradiation on I – V and P – V curves of the Module

In this segment, the plots of characteristics curve have been established by varying solar irradiation parameter and keeping temperature parameter as a constant at STC. The solar irradiance value G is being varied from 200 W/m^2 to 1000 W/m^2 and keeping the temperature variable $TEMP$ constant. Figures 10 and 11 have been demonstrating the impact of solar irradiation on I – V and P – V curves.

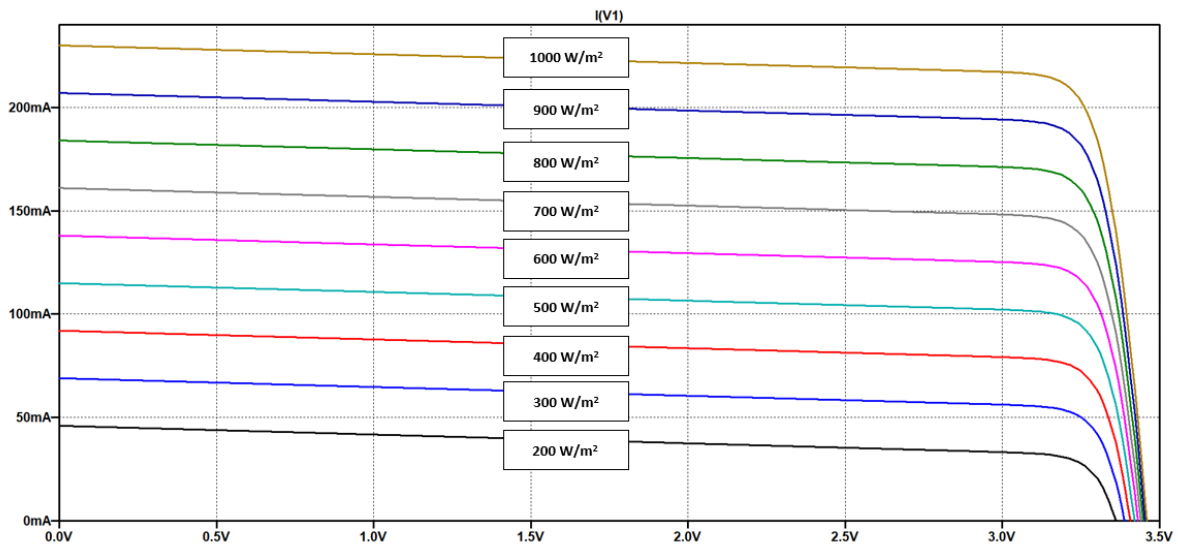


Figure 10: I – V curves of MC-SP0.8-NF-GCS for Solar irradiation levels from 200 W/m^2 to 1000 W/m^2 at 25°C

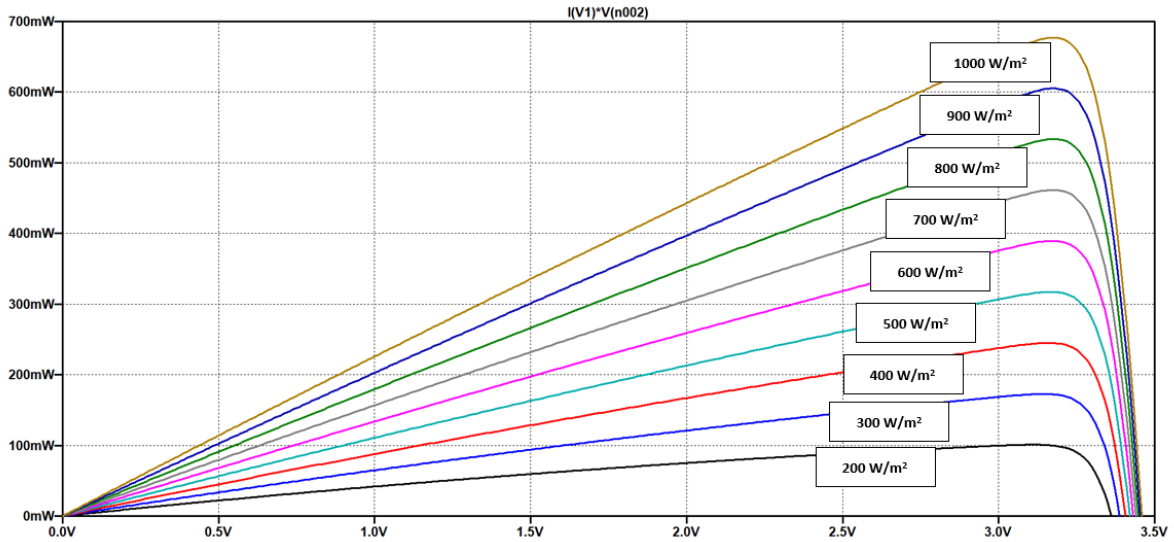


Figure 11: $P - V$ curves of MC-SP0.8-NF-GCS for Solar irradiation levels from 200 W/m^2 to 1000 W/m^2 at 25°C

5.2 Solar Energy Harvesting Circuitry (EHC) Characterisation and Performance Curves

In this phase, the solar module combined with LTC3105 PMIC will be analysed in number of parameters to see the optimal power generation under these circumstances. The following settings have been initialised over the simulation setup, and with extensive simulation analysis, the data log have been generated for voltage, current, and power values.

As from the above-analysed characterisation of the chosen module, it has been identified that the solar irradiation or incident light profoundly influences the solar module for power generation, as cloudy or rainy weather will decrease the output power generation of the solar module due to impact of incident light which is directly proportional to the cell current, hence the cell current will decrease.

Irrespective of the STC conditions applied on the Solar EH based LTC3105 module; now we will analyse the various solar irradiation levels for analysing the behaviour of the proposed module in terms of power generation.

5.2.1 Impact of Solar Irradiation on Solar EHC module: $I - V$ curves

The generated $I - V$ curves of Solar EHC module can be seen in Figure 12. By observing these curves, we can say that the highest level of solar irradiation, i.e. 1000 W/m^2 has generated the highest level of current, i.e. 33.81 mA at R_{load} configuration of 100Ω . As soon as load starts to increase with a step size of 50Ω , the generation of current starts to decrease. As an increase in load settings will directly impact on the current of the system. However, the solar irradiation is the same throughout the initial circumstance. For solar radiation levels 1000 W/m^2 till 800 W/m^2 , the output voltage remained constant at all load conditions from 100Ω till 500Ω . Whereas, from 700 W/m^2 till 500 W/m^2 the output voltage was unable to sustain at initial load conditions, but as soon as the load starts to increase, the output voltage is also increased and came to stable output at 3.3 V . Whereas, the lowest solar irradiation levels, 300 W/m^2 and 200

W/m² were not able to sustain the output voltage till 3.3 V and went till 2.0 V for the highest given load settings.

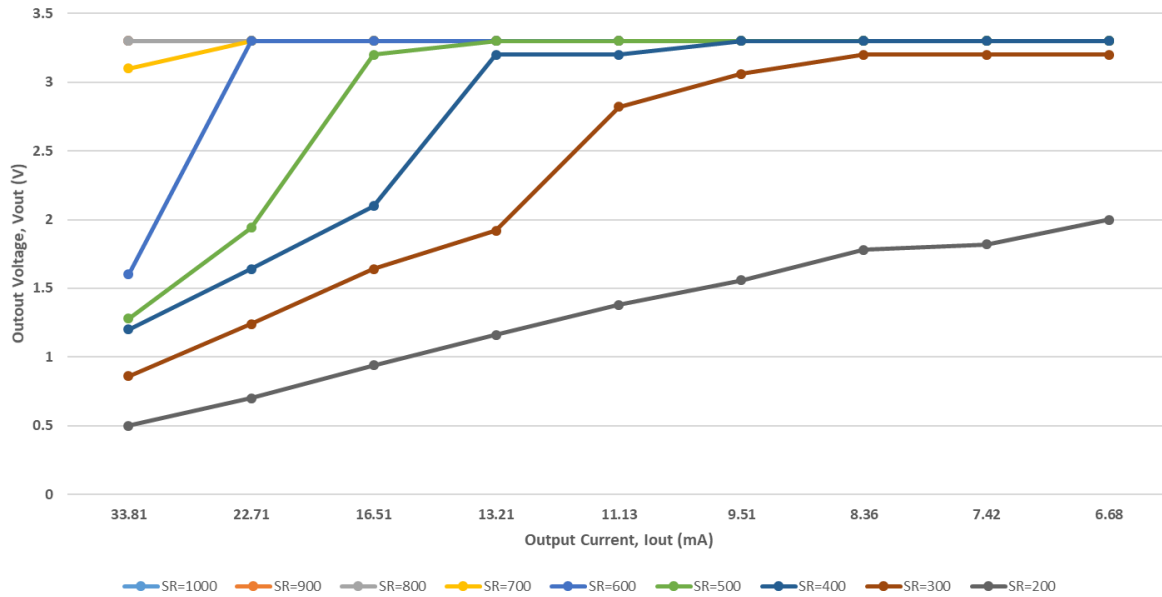


Figure 12: Solar EHC Output Voltage – Output Current curves at 3.3 V considering various levels of Solar irradiation under different load configurations

5.2.2 Impact of Solar Irradiation on Solar EHC module: P – V curves

The generated power curves are demonstrated in Figure 13; from this, we can analyse the response of the EHC module for generating maximal output power. By observing the initial curve, we can see that the at maximum solar irradiation level, i.e. 1000 W/m² the maximum output power after following the MPPT algorithm is established at 108.60 mW under constant temperature 25°C and Rload at minimum level i.e. 100Ω. This power starts to decrease with increase in the Rload values by reaching till 22.28 mW at Rload of 500 Ω. The similar situation is followed by the next solar irradiation levels (900, 800, 700) W/m² with a slight difference as a decreased value in output power. However, the exciting phase starts from Solar irradiation 600 W/m² where at the initial load setup, the generated power recorded is 28.6 mW which is due to unstable voltage initiation at this particular solar irradiation phase, which however starts to stabilise after next load settings. The lowest possible generation of power is recorded at Solar irradiation of 200 W/m², Rload = 500; which is 8.31 mW from the EHC module.

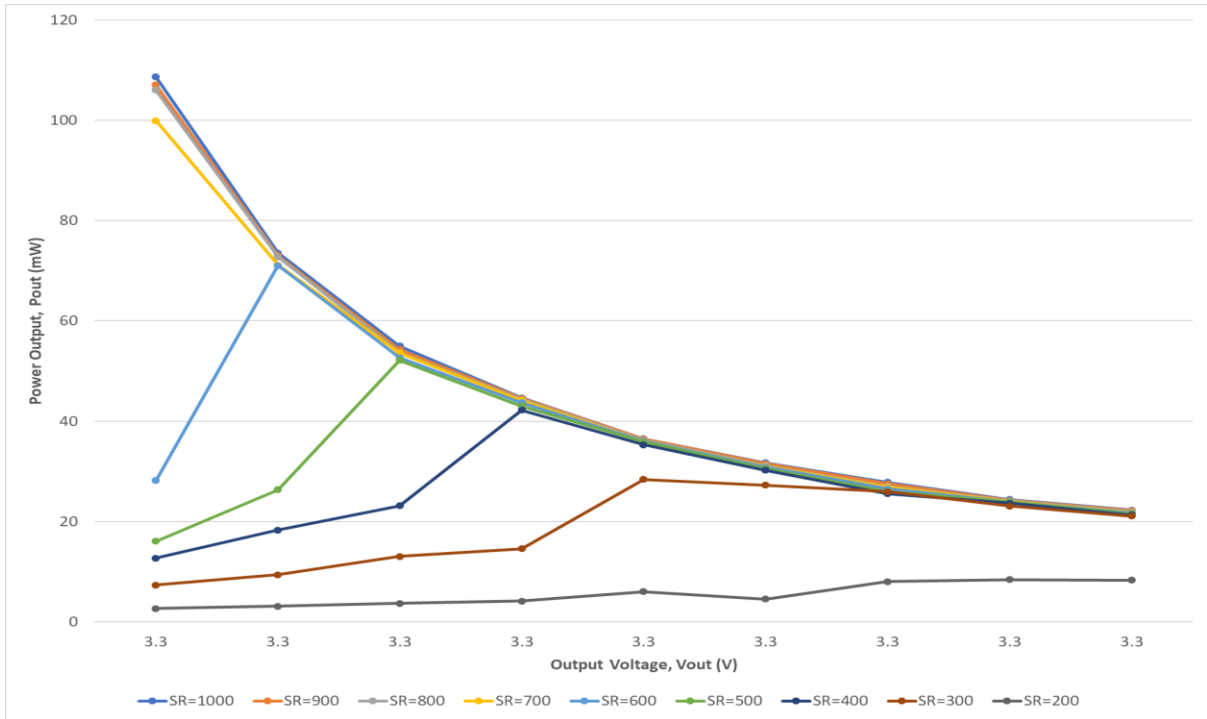


Figure 13: Solar EHC Output Power – Output Voltage curves at 3.3 V considering various levels of Solar irradiation under different load configurations

5.3 Maximum and Minimum Power Generation for Solar EHC Module

For more accessible analysis only minimum and maximum power generation values have been considered in the following Table 5, which will be compared with IoT power requirements at the end of this chapter under comparative analysis for power generation and power consumption.

Table 5: Power generation of Solar EHC module at a minimum and maximum level

Solar EHC Power Generation (Pout)		
Solar irradiation W/m ²	Pmax under minimum load mW	Pmin at maximum load mW
1000	108.60	22.28
900	107	22.21
800	106.01	21.97
700	99.89	21.85
600	28.16	21.73
500	16.09	21.56
400	12.74	21.32
300	7.37	21.08
200	2.68	8.31

Thesis III

The Solar Energy Harvesting Circuitry (EHC) along with commercial-off-the-shelf (COTS) PMIC; LTC3105 have been proposed for supporting IoT applications.

- *The entire EHC setup has been experimented with several environmental conditions; Solar irradiation and Temperature dependence, as well as three different load setups, have been set up.*
- *The sustainability of PMIC has been analysed after extensive simulation by a varying number of parameters, more specifically under various load configurations, for maximum power generation, power management and accuracy of the system.*
- *This prototype can be reused and reprogrammed by other researchers and engineers according to their prerequisite of the EH based IoT system.*

Related Publications: [P4, P5, P9, P12]

5.4 Thermal Energy Harvesting Modelling and Simulation Setup

Before proceeding towards the characterisation of TEG in terms of power generation, the first setting is to examine the open circuit testing for chosen thermal module for building the base towards further performance analysis. The main perspective taken under consideration for output voltage setting is that at what temperature range and at what load configuration the PMIC can sustain the output based on two fixed V_{out} settings; 2.3 V, 3.3 V.

The Thermal EHC module performance curves will be examined as:

- (a) Analysing characteristics curves at $V_{out} = 2.3$ V
- (b) Analysing characteristics curves at $V_{out} = 3.3$ V

5.4.1 Thermal EHC Module Characterisation and Performance Curves

For analysis of thermal EHC module, the following settings will be initialized in the simulation environment: For simulating temperature difference or heat energy on EHC module the temperature experienced by TEC on both cold and hot sides is incorporated with two voltage supplies specified as V_{tc} (cold side) and V_{th} (hot side) linked with subcircuit of the module. Where V_{tc} is held at 0 °C and V_{th} is swepted in linear step from 0 °C till 5 °C with the step size of 0.5 °C. The values for R_{LOAD} are tested and then selected based on the capability of the PMIC to sustain the load on two different V_{OUT} settings; 2.3 V, 3.3 V. There are three variations in the chosen range which are initialised as, smaller range [50 – 900; increment of 50], middle-

range [1000 – 9000; increment of 1000], and the larger range [100 K – 500 K; increment of 100 K]. The next sections are dedicated for separate settings and observations related to open circuit testing and analysing characteristic curves at two fixed output voltages.

5.4.2 TEG Modelling in LTspice: Open circuit testing

In order to analyse the accuracy of the TEG module, it is mandatory to simulate the open circuit testing before evaluating the further performance criterion, as shown in Figure 14.

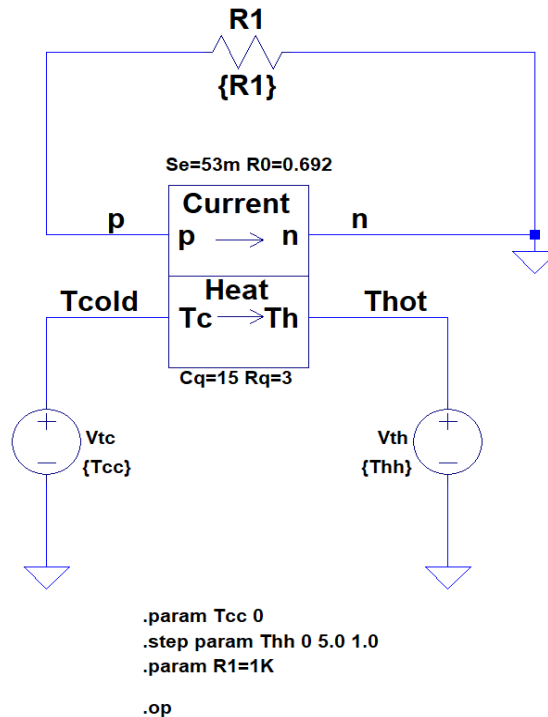


Figure 14: TEC1-12722 Open circuit test setup

The generated open circuit curve over temperature gradients can be seen in Figure 15, where open circuit voltage is varied linearly with the increase in the temperature gradients ($\Delta T = (T_H - T_C \text{ (}^\circ\text{C)})$).

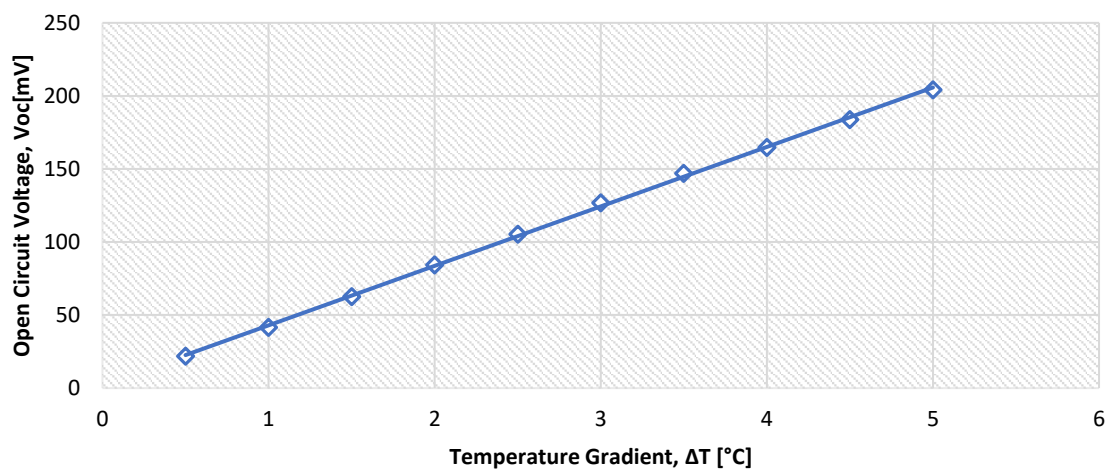


Figure 15: Open circuit testing V_{oc} vs Temperature gradients

5.4.3 Setup1: Setting V_{OUT} at 2.3 V for Thermal EHC Module

The calculated thermal and electrical parameters of TEC1-12722 mentioned in Table 4 have been initialised in the thermal EHC prototype; the output voltage will be programmed to remain at 2.3 V by setting the VS1 and VS2 pins to ground (GND) on the LTC3108 PMIC.

5.4.3.1 EHC Module I – V curves at $V_{OUT} = 2.3$

For observing the current versus voltage (I – V) curves for Thermal EHC, the temperature difference ΔT starts from 0.5°C until the output voltage comes at stable or fixed output voltage setting, while, the series of resistive load (R_{LOAD}) is implemented for measuring the values for output current (I_{OUT}) and output voltage (V_{OUT}). The generated I – V curves can be seen in Figure 16.

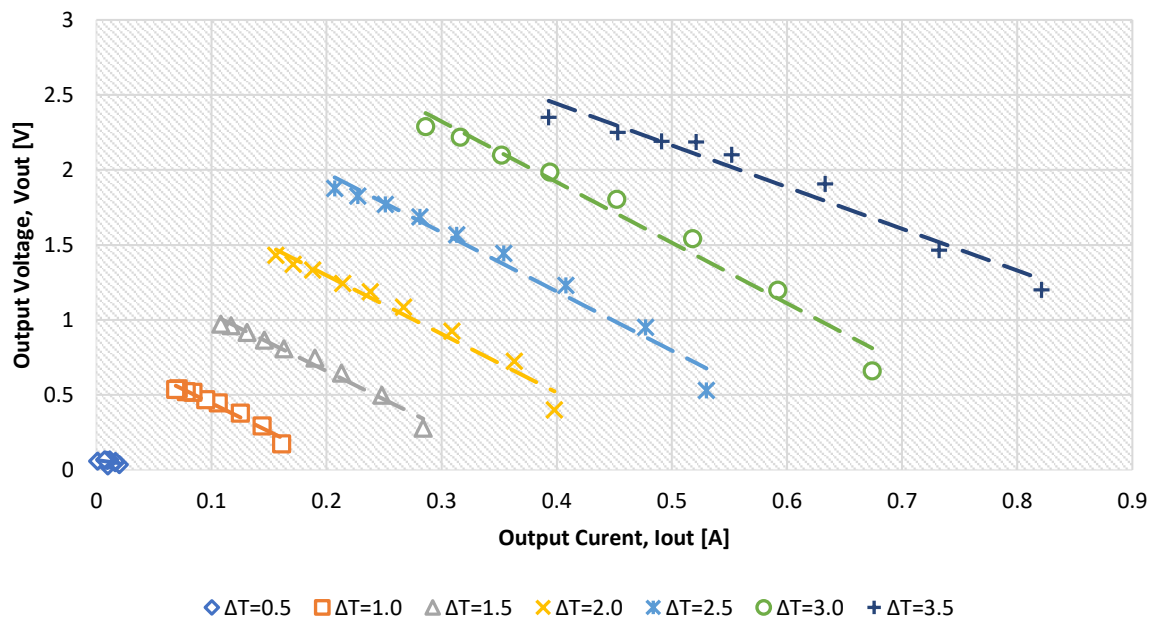


Figure 16: Thermal EHC Output Voltage – Current curve at 2.3 V

5.4.3.2 EHC Module Power curves at $V_{OUT} = 2.3$

The output power generation for Thermal EHC module will be analysed, in this regard, the open circuit testing data collected will be utilised. The direct proportional relation is established between the generated power and the temperature gradient due to already examined data collected from the voltage (V_{OUT}) versus current (I_{OUT}) curves by applying a fixed resistive load. The output power (P_{OUT}) as a function of output current (I_{OUT}) parametrized in the temperature gradients (ΔT) is demonstrated as the generated characteristic curves of Thermal EHC as shown in Figure 17.

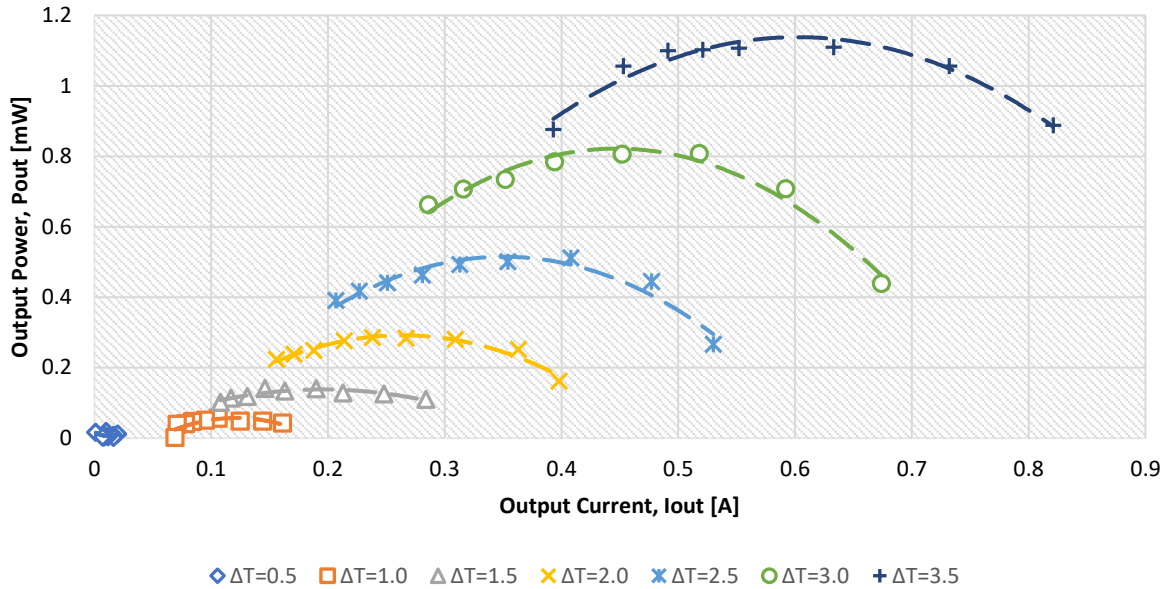


Figure 17: Thermal EHC Output Power – Output Current curve at 2.3V

By observing the curves, it is evident that the increase in temperature has significantly raised the output power generation of the module, hence following a highly quadratic nature.

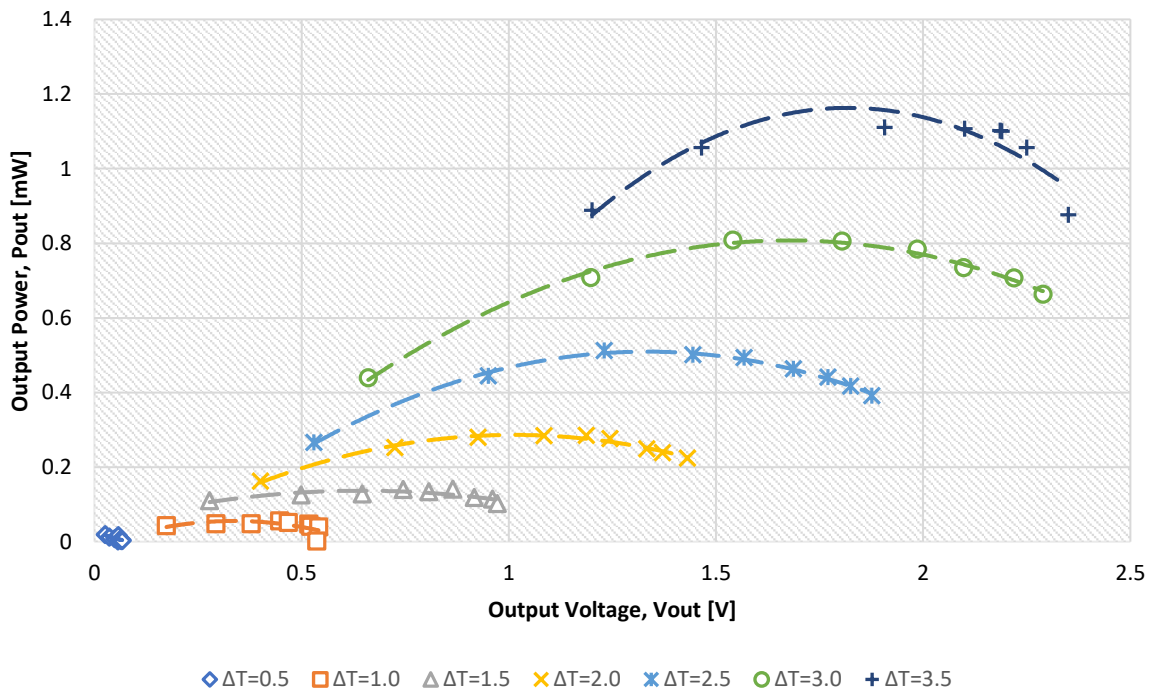


Figure 18: Thermal EHC Output Power – Output Voltage curve at 2.3 V

5.4.4 Setup 2: Setting V_{OUT} at 3.3 V for Thermal EHC Module

The already calculated parameters will be applied as in input for another setup of Thermal EHC at 3.3 V. For setting the output voltage V_{OUT} at 3.3 V, the VS1 pin will be connected with VAUX pin and VS2 with GND.

5.4.4.1 EHC Module I – V Curves at $V_{OUT} = 3.3$

The generated curves can be seen in Figure 19, which represents the existence of the linear relationship between output voltage (V_{OUT}) and output current (I_{OUT}). Other than that, this setup requires more temperature gradients to reach the stable output voltage as compared to the 2.3 V setup.

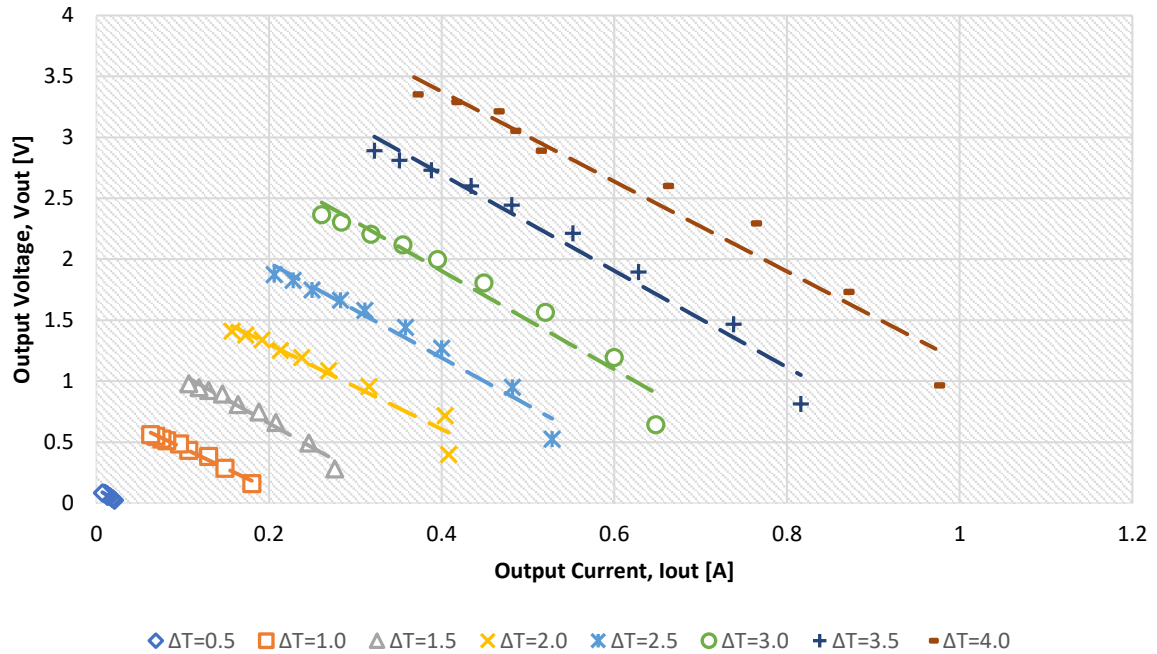


Figure 19: Thermal EHC Output Voltage – Current curve at 3.3 V

5.4.4.2 EHC Module Power Curves at $V_{OUT} = 3.3$

The results generated from I – V curves made a basis for direct proportional relation between the power supplied for a fixed load and temperature gradients. Since the power dissipation in the external load will be based on the general theory of electrical circuit analysis, i.e. $P = R_L I_{OUT}^2$. By applying this formulation, the generated power curves are obtained as the P_{OUT} as the function of I_{OUT} and V_{OUT} carrying various resistive loads. The generated curves can be seen in Figure 20, showing the maximum power generation as compared to the previous setup.

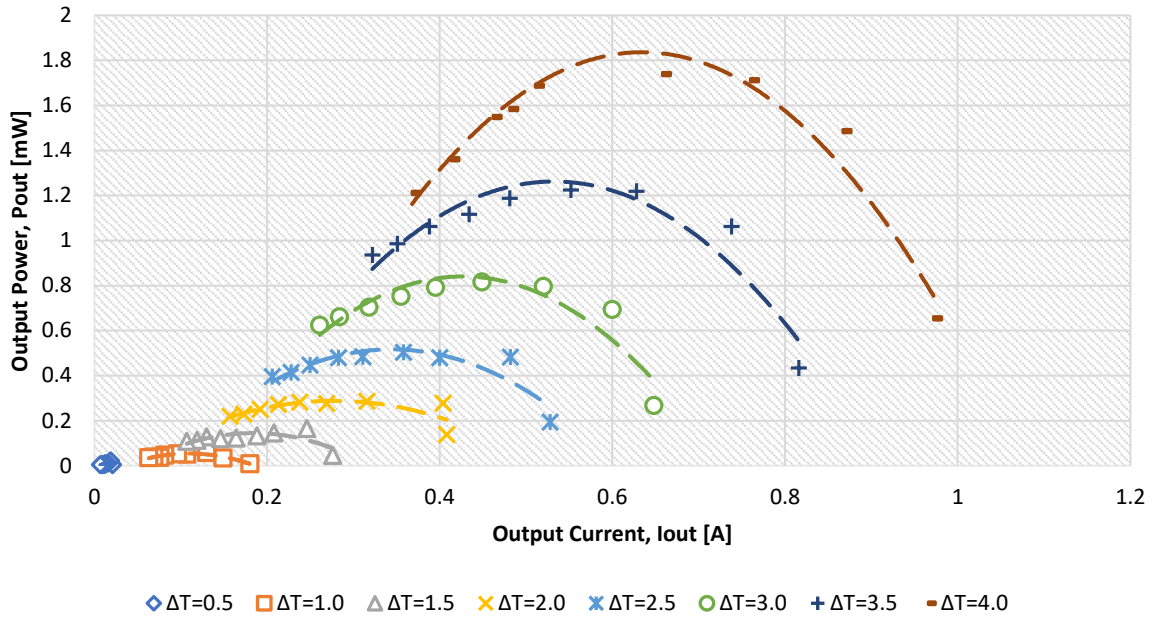


Figure 20: Thermal EHC Output Power – Current curve at 3.3 V

By carefully inspecting the generated power curves in Figure 21, it is evident that the maximal output power (P_{OUT}) is approximately half of the maximal output voltage (V_{OUT}) and this voltage is equal to the half of the open circuit output. Hence, in this regard, it has verified the formula for TEG at the maximum power transfer moment [8].

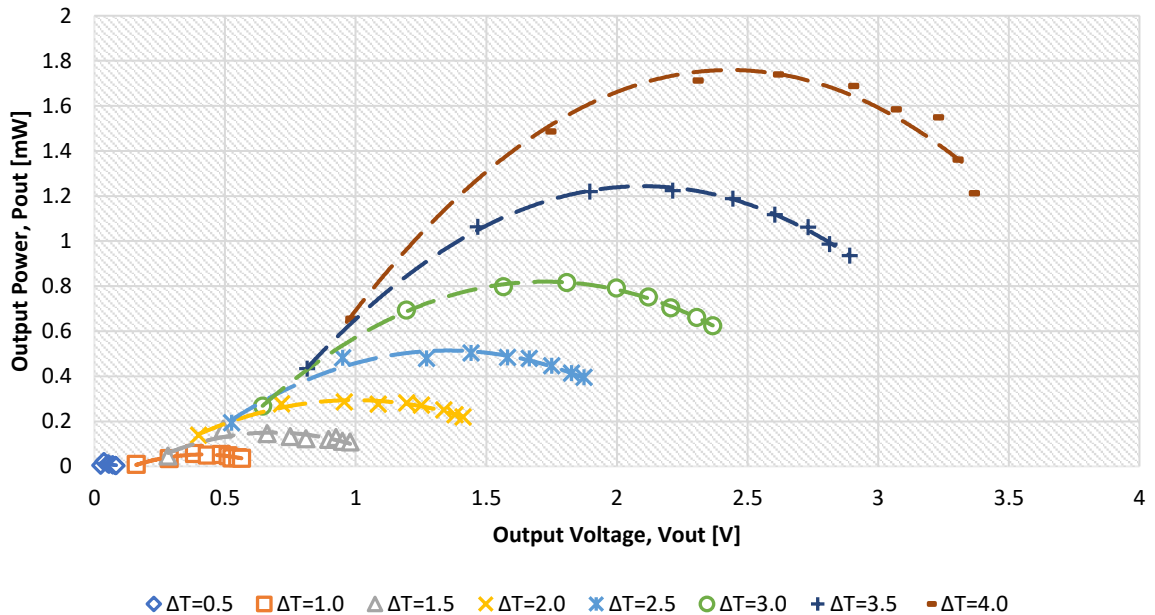


Figure 21: Thermal EHC Output Power – Voltage curve at 3.3 V

5.5 Maximum and Minimum Power Generation for Thermal EHC

For more straightforward analysis, only minimum and maximum power generation values have been considered in the following Table 6.

Table 6: Power generation of Thermal EHC module at a minimum and maximum level

Thermal EHC Power generation (P_{OUT})		
Power generation at 2.3 V_{OUT}		
Temperature ($^{\circ}C$)	P_{OUT} at R_{LOAD} Minimum (mW)	P_{OUT} at R_{LOAD} Maximum (mW)
3.5	0.688	1.098
Power generation at 3.3 V_{OUT}		
Temperature ($^{\circ}C$)	P_{OUT} at R_{LOAD} Minimum (mW)	P_{OUT} at R_{LOAD} Maximum (mW)
4.0	1.529	1.719

Thesis IV

The Thermal Energy Harvesting Circuitry (EHC) along with commercial-off-the-shelf (COTS) PMIC; LTC3108 have been proposed for supporting IoT applications.

- *The entire EHC setup has been experimented with two programmed output settings (2.3 V, 3.3 V) and temperature gradients scaled from 0.5 $^{\circ}C$ till 5.0 $^{\circ}C$ (for human body heat wearable applications), also three different variations of load setups have been experimented.*
- *The sustainability of PMIC has been analysed after extensive simulation by a varying number of parameters, more specifically under various load configurations for maximum power generation, power management and accuracy of the system.*
- *This prototype can be reused and reprogrammed by other researchers and engineers according to their prerequisite of the EH based IoT system.*

Related Publications: [P1, P5]

5.6 IoT Power Constraints

The major objective after analysis and power generation by solar and thermal modules is based on IoT power requirements. The established study of power generation will be compared with power consumption of typical IoT devices, specific components, etc., to see whether the approach for implementing energy harvesting on IoT is feasible or not. In this regard, it is mandatory to determine the basis for comparison and understanding the IoT power criteria. The average power consumption will be highlighted in three different phases given as:

- (a) Average power requirement of different sensors
- (b) Average power requirement of different Microcontroller units (MCU)s
- (c) Average power consumption of typical IoT applications

There are various types of sensors having their specific power consumption as demonstrated in Table 7 [9], and a variety of MCUs with their operating frequencies and powering requirement as shown in Table 8 [10].

Table 7: Sensor types and its powering requirements.

Sensor Type	Power Consumption
Gas sensor	500mW – 800mW
Image sensor	150mW
Pressure sensor	10mW – 15mW
Acceleration sensor	3mW
Temperature sensor	0.5mW – 5mW

Table 8: Comparison of average power consumption for MCUs.

Performance Metrics	NV-MCU	JSSC2017	ISSCC2016	VLSI2015	ISSCC2015	ISSCC2014
Architecture	Cortex-M0 32 bit	Cortex-M0 32 bit	8051 8 bit	MSP430 16 bit	MSP430 16 bit	MSP430 16 bit
Frequency [MHz]	200	30	100	25	16	20
Active power [μW/Mhz]	26.7	28.92	33	33	28.3	145
Standby power [μW]	0.7	0.009	N/A	0.7	0.32	1.2
Average power@ intermittent operation [μW]	47.14	143.3	>2900	583.2	499.8	2560

The following data presented in Table 9 for average power consumption of typical IoT application is taken from the annual report [11] presented by 4E (Energy Efficient End-use Equipment) International agency regarding Energy harvesting technologies for IoT edge devices.

Table 9: Average power consumption of several IoT applications

Product	User Link	Product Link	Battery type	Peak Power consumption (W)					Average power consumption (W)
				Initial Pairing	Network mode 1	Network mode 2	Initialize actuators, sensors	Power consumption during Rx/Tx	
Tracking device	Bluetooth Low Energy (BLE)	Bluetooth Low Energy (BLE)	1x CR2025 ½ years	0.17	0.12	0.12	0.17	0.001-0.003 (2500 ms)	n/a
Fire detector	WiFi 802.11b/g/n	-Wi-Fi 802.11b/g/n -Wireless Interconnect (IEEE 802.15.4) -Bluetooth Low Energy (BLE)	6x AA (lithium) 5 years	1.8	0.12	0.12	1.8	0.02 (10 s)	0.61
Smart Home Thermostat	WiFi 802.11b/g/n	868 MHz Band	2x AAA (alkaline)	0.46	0.06-0.1	0.06-0.1	0.25-0.4	0.003 (500 ms)	0.15
Smart Home Door/Window	WiFi 802.11b/g/n	868 MHz Band	1x AAA (alkaline)	0.15	0.1	0.1	0.17	0.003 (500 ms)	0.15
Sensor Node Thermometer	Bluetooth Low Energy (BLE)	Bluetooth Low Energy (BLE)	1x CR2025 up to 3 months	1.1 (speaker)	0.08	0.08	Not applicable	0.001 (2500 ms)	0.1

5.7 Solar and Thermal Power Generation and Comparative Analysis for IoT Power Consumptions

For solar power generation, the conditions under which analysis have been carried out are dynamic; the power levels could be intermittent due to environmental factors impacting directly to the power generation of the module. In this research, the Solar EHC prototype for commercial solar transducer MC-SP0.8-NF-GCS has generated certain levels of power generation under various environmental and temperature dependence, for the sake of easier grip on analysis the minimum and maximum power levels have been tabulated from entire collected simulation data. The range varies between 2.68 mW (minimum generated power) till 108.60 mW (maximum generated power); specifically, under various solar irradiation levels and load configurations. The above-generated data highlighted in Table 6, can be compared with the power consumption data accumulated in Tables 7 and 8, where we can loosely relate the power generation and power consumption. However, mostly the Solar EHC prototype can sustain the required power consumption criteria for IoT components as well as wearable IoT devices; in our case, considering all mentioned examples of IoT applications in Table 9. Hence this simulation also compared with experimental analysis conducted by manufacturer's have proved at a certain point that this prototype could be used as an EH based module for IoT application.

Considering the thermal EHC module, there are two factors in comparison; firstly, the power generation and power consumption, secondly, the performance analysis and selection of TEG is also an important decision which will directly influence the whole design of the system.

The power generation by Thermal EHC is demonstrated in Table 6, where the minimum and maximum power output is listed for easier understanding of the whole situation. As there were two programmed output voltages (2.3 V, 3.3 V) and accordingly the power has been generated. Due to the target applications require lesser temperature gradients such as human body heat harvesting for wearables; therefore, the temperature gradients were till 3.5°C and 4.0°C. The minimum power generated for TEC1-12722 fused as a Thermal EHC prototype went till 0.688

mW and maximum reached at 1.719 mW. By comparing the generated thermal power with required power for IoT; It is evident that TEG can generate that much power which can make the IoT device operational, considering the specific sensors in Table 7 and some of the MCUs in Table 8. Other than that, the above mentioned IoT application could be powered up by this thermal EHC prototype.

Therefore, the results obtained from the simulation authenticated the hypothesis and proposed prototypes for both solar and thermal modules that the commercially selected devices (MC-SP0.8-NF-GCS, TEC1-12722) could fulfil this demand as a power source.

Thesis V

The trial and error case study generated for efficient and maximum power output has been compared with already experimented IoT components in terms of power consumption. The comparative analysis has proved the authenticity of all steps involved in the proposed Solar and Thermal EHC for supporting IoT power demands.

Related Publications: [P1, P5, P9, P12]

List of Publications

- P1. **Syeda, Adila Afghan**; Husi, Géza
Modelling and Analysis of Energy Harvesting in Internet of Things (IoT):
Characterization of a Thermal Energy Harvesting Circuit for IoT based Applications
with LTC3108
ENERGIES 12 : 20 pp. 1-13. Paper: 3873 , 13 p. (2019)
DOI Google scholar
Journal Article/Article (Journal Article)/Scientific [30844694] [Admin approved]
- P2. Almusawi, Husam ; **Afghan, Syeda Adila** ; Géza, Husi
Designing the Mechanical Parts of a Low-Cost Hand Rehabilitation CPM Device for
Stroke Patients
In: Machado, José; Soares, Filomena; Veiga, Germano (eds.) Innovation, Engineering
and Entrepreneurship. HELIX 2018. Lecture Notes in Electrical Engineering
[s. 1.] - Nemzetközi, International : Springer International Publishing, (2019) pp. 60-
66. , 7 p.
DOI Scopus Google scholar
Chapter in Book/Conference paper (Chapter in Book)/Scientific [3382260] [Admin
approved]
- P3. Alsebai, A ; **Afghan, S**
Designing and Implementing Control panel for Diesel generator
IOP CONFERENCE SERIES: MATERIALS SCIENCE AND ENGINEERING 568
p. 012107 (2019)
DOI Egyéb URL
Journal Article/Conference paper in journal (Journal Article)/Scientific [30813395]
[Admin approved]
- P4. **Syeda, Adila Afghan** ; Husam, Almusawi ; Husi, Géza
Simulating the Electrical Characteristics of Solar Panels Based on Practical Single-
Diode Equivalent Circuit Model: Analyzing the Influence of Environmental
Parameters on Output Power
In: Machado, José; Soares, Filomena; Veiga, Germano (eds.) Innovation, Engineering
and Entrepreneurship. HELIX 2018. Lecture Notes in Electrical Engineering
[s. 1.] - Nemzetközi, International : Springer International Publishing, (2019) pp. 67-
74. , 8 p.
DOI Scopus Google scholar
Chapter in Book/Conference paper (Chapter in Book)/Scientific [3382263] [Admin
approved]
- P5. **Afghan, Syeda Adila** ; Almusawi, Husam ; Géza, Husi
Towards the self-powered Internet of Things (IoT) by energy harvesting: Trends and
technologies for green IoT
In: IEEE (eds.) 2nd International Symposium on Small-scale Intelligent
Manufacturing Systems (SIMS), 2018
New York, United States of America * : IEEE, (2018) pp. 1-6. , 6 p. DOI IEEE
Xplore WoS Scopus Google scholar
Chapter in Book/Conference paper (Chapter in Book)/Scientific [3369383] [Admin
approved]

- External citations: 13, Self citations: 0, Unhandled citations: 0, [All citations: 13](#)
- P6. Akbar, Husna ; **Afghan, Syeda Adila** ; Jokhio, Sana Hoor ; Jokhio, Imran Ali
Secure multi-level Cluster based wireless sensor network
RECENT INNOVATIONS IN MECHATRONICS 5 : Klnsz. pp. 1-7. , 7 p. (2018)
DOI Google scholar
Journal Article/Article (Journal Article)/Scientific [3384410] [Admin approved]
- P7. Almusawi, Husam AbdulKareem ; **Afghan, Syeda Adila** ; Géza, Husi
Recent trends in robotic systems for upper-limb stroke recovery: A low-cost hand and wrist rehabilitation device
In: IEEE (eds.) 2nd International Symposium on Small-scale Intelligent Manufacturing Systems (SIMS), 2018
New York, United States of America * : IEEE, (2018) pp. 1-6. , 6 p. DOI IEEE
Xplore WoS Scopus Google scholar
Chapter in Book/Conference paper (Chapter in Book)/Scientific [3369389] [Admin approved]
External citations: 2, Self citations: 0, Unhandled citations: 0, [All citations: 2](#)
- P8. Bano, Shahzadi ; **Afghan, Syeda Adila** ; Jokhio, Sana Hoor ; Talpur, Shahnawaz ; Jokhio, Imran Ali
Lightweight multi-agent framework for a cluster-based wireless sensor network
RECENT INNOVATIONS IN MECHATRONICS : Klnsz. pp. 1-7. , 7 p. (2018) DOI
Journal Article/Article (Journal Article)/Scientific [3384404] [Admin approved]
- P9. **Afghan, Syeda Adila** ; Géza, Husi
Modelling and Simulating Photovoltaic Energy Harvesting Circuit: An Analysis based on Trial and Error approximation for Optimal Output Power of a Harvester
In: IEEE (eds.) 2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC): Proceedings of the 23rd ICE/IEEE International Conference on Engineering Technology and Innovation
[s. l.], International : IEEE, (2017) pp. 504-508. , 5 p. DOI IEEE Xplore WoS Scopus
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- P10. **Afghan, Syeda Adila** ; Almusawi, Husam ; Husi, Géza
Approximating the minimum output power for energy harvesting prototype: a case study of cell phone specifications = Minimális kimeneti teljesítmény meghatározása energy harvesting prototípushoz: egy esettanulmány mobiltelefon specifikációkra In: Bitay, Enikő (eds.) A XXII. Fiatal Műszakiak Tudományos Ülésszak előadásai : Proceedings of the XXII-th International Scientific Conference of Young Engineers Kolozsvár, Romania : Óbudai Egyetem, Erdélyi Múzeum Egyesület (EME), (2017) pp. 55-58. , 4 p.
Teljes dokumentum Google scholar
Chapter in Book/Conference paper (Chapter in Book)/Scientific [3201428] [Admin approved]
- P11. Almusawi, Husam ; **Afghan, Syeda Adila** ; Husi, Géza ; Molnár, Zsolt ; Erdei, Timotei István

Reviewing the notable progress of effective techniques in the development of stroke hand rehabilitation devices = A stroke-t kapott egyének rehabilitációs eszközeiben jelentős fejlődést mutató hatékony technikák áttekintése

In: Bitay, Enikő (eds.) A XXII. Fiatal Műszakiak Tudományos Ülésszak előadásai : Proceedings of the XXII-th International Scientific Conference of Young Engineers Kolozsvár, Romania : Óbudai Egyetem, Erdélyi Múzeum Egyesület (EME), (2017) pp. 63-66. , 4 p.

Teljes dokumentum Google scholar

Chapter in Book/Conference paper (Chapter in Book)/Scientific [3201431] [Admin approved]

External citations: 0, Self citations: 3, Unhandled citations: 0, All citations: 3

- P12. **Syeda, Adila Afghan** ; Husam, Almusawi ; Husi, Geza
Simulating the electrical characteristics of a photovoltaic cell based on a single- diode equivalent circuit model
MATEC WEB OF CONFERENCES 126 p. 03002 Paper: 03002 , 6 p. (2017)
DOI Scopus Teljes dokumentum Google scholar
Journal Article/Conference paper in journal (Journal Article)/Scientific [3283182]
[Admin approved]
- P13. **Syeda, Adila Afghan** ; Husam, Almusawi ; Husi, Geza
Simulating the electrical characteristics of a photovoltaic cell based on a single- diode equivalent circuit model
ANALELE UNIVERSITATII DIN ORADEA FASCIOLA MANAGEMENT SI INGINERIE
TEHNOLOGICA / ANNALS OF THE UNIVERSITY OF ORADEA FASCICLE OF MANAGEMENT AND TECHNOLOGICAL ENGINEERING 16 (26) : 1 pp. 91-96.
, 6 p.
(2017)
Google scholar
Journal Article/Article (Journal Article)/Scientific [3235588] [Admin approved]
- P14. **Syeda, Adila Afghan** ; Husam, Almusawi ; Géza, Husi
Simulating the Eletrical Characteristics of a Photovoltaic Cell Based on a Single-Diode Equivalent Cicuit Model
In: Calin, Baban; Florin, Sandu Blaga; Gavril, Grebenisan; Alexandru-Viorel, Pele; Mircea, Teodor Pop; Alexandru, Rus; Radu, Catalin Tarca (eds.) "Imt Oradea" - 2017 : Proceedings of the Annual Seesion of Scientific Papers
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- P15. Husam, Almusawi ; **Syeda, Adila Afghan** ; Géza, Husi
Technological Advancements in Stroke Hand Rehabilitation Devices: A Review In: Adrienn, Dineva; István, Nagy (eds.) Proceedings of 4th INTERNATIONAL MECHATRONICAL STUDENT micro-CONFERENCE
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Chapter in Book/Conference paper (Chapter in Book)/Scientific [3241206] [Admin approved]

- P16. **Syeda, Adila Afghan** ; Husam, Almusawi ; Sana, Hoor Jokhio ; Géza, Husi
Estimation of minimum output power threshold for energy harvesting module: An
inspection of battery and charging parameters of cell phones
In: Adrienn, Dineva; István, Nagy (eds.) Proceedings of 4th INTERNATIONAL
MECHATRONICAL STUDENT micro-CONFERENCE
Budapest, Hungary : Óbudai Egyetem, (2016) pp. 56-71. , 16 p. Chapter in
Book/Conference paper (Chapter in Book)/Scientific [3241204] [Admin approved]
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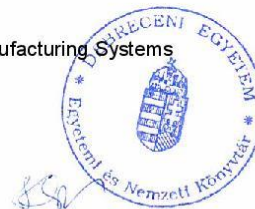
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