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Dissertation Defense

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My Contributions

- Seven major steps for modeling thermal system by means of electrical analogy are identified,
- TEG was demonstrated to function as a heat-removal pump and was modeled by LTspice simulator,
- Two separate electrical circuits were achieved as novel ways to model complex heat-transfer systems,
- The real-world performance of the LTC3105 converter was thoroughly investigated,
- A novel RC analogy to estimate the cold-side temp. variations of a TEG when an impulse-like electromagnetic wave is applied on the absorbing side of the system,
- Another novel similarity, comparable to an N-type doped semiconductor material's carrier density dependence with temperature, was discovered and proposed, and
- A cheaper and reliable method for energy delivery to remote residential areas is proposed.

List of Publications

Journals

- Modeling, Simulation, and Implementation of a Solar Thermoelectric Energy-Harvesting System; *will be submitted for publication after defense*
- A System Dynamics Model for Energy Planning in Niger; *International Journal of Energy and Power Engineering. Vol.3. No.6, 2014.*
- Buffering PV Output during Cloud Transient with Energy Storage; *ISBN 978-3-65946223-8 Academic Publishing.*

Conferences

- "LTspice Model of a Solar Thermoelectric Generation System," submitted to the *IEEE 8th University of Clemson Power System Conference 2016.*
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Designing, Building, and Testing a Solar Thermoelectric Generation, STEG, for Energy Delivery to Remote Residential Areas in Developing Regions

CONTENTS

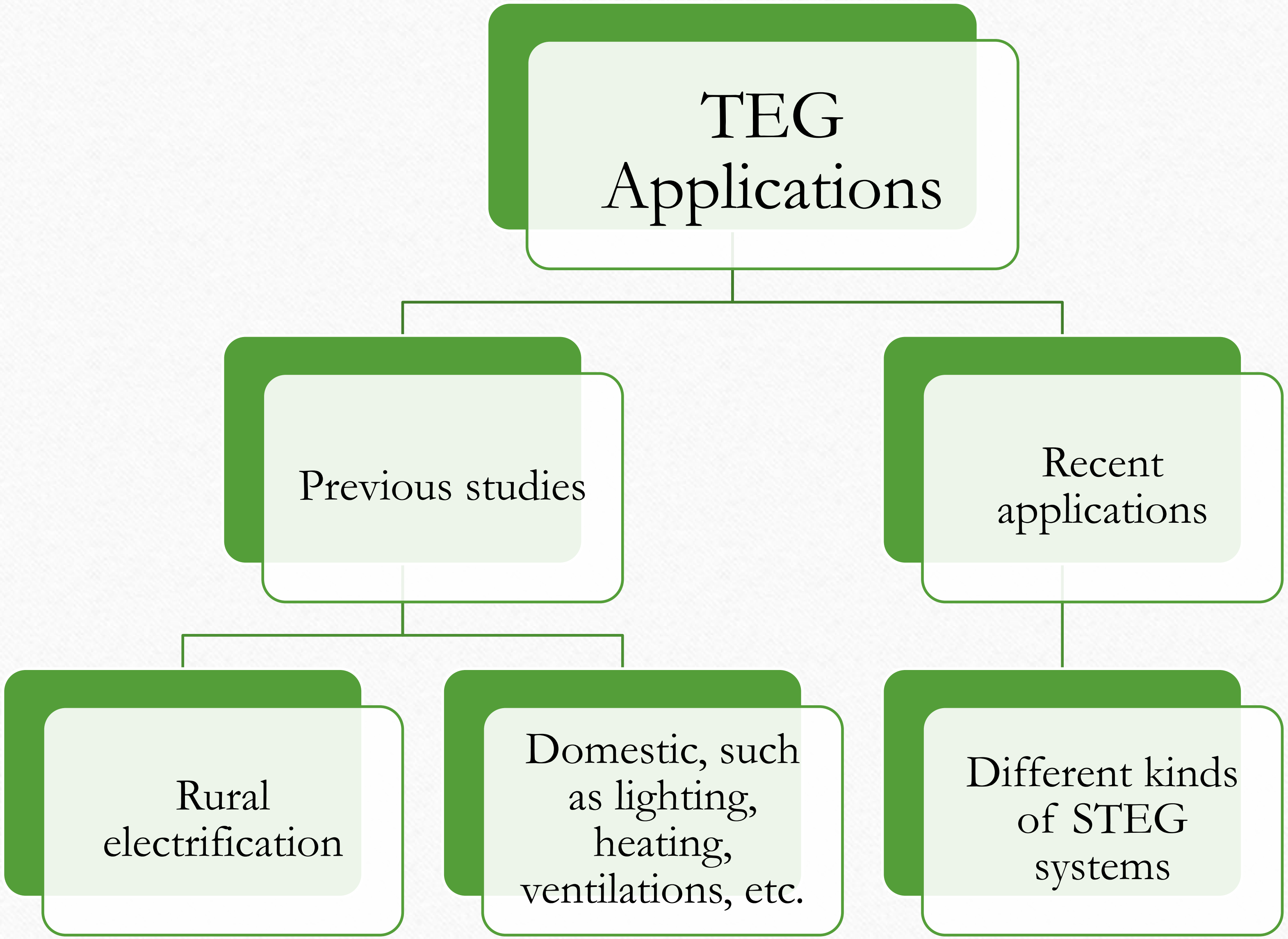
- Literature survey, and Research background
- Summary of the Previous Work (Indoor)
- Real-world STEG, LTspice Modeling, Results, and Discussion,
- Future Work, Conclusion, and Q & A

State-of-the-art

- TEGs have been proposed for woodstoves
- Body heat powered watches
- Car seat cooling/heating for passenger comfort

(Toyota, GM, Nissan, Ford, and Range Rover)

- Industrial waste heat recovery to power ancillary devices
- Vehicular waste heat recovery to enhance fuel economy
- Harvesting micropower for low power applications, such as wireless, mobile sensors, and bio-sensors


TEG Applications
Previous studies
Recent applications
Rural electrification
Domestic, such as lighting, heating, ventilations, etc.
Different kinds of STEG systems

Thermal-to-Electrical Equivalence

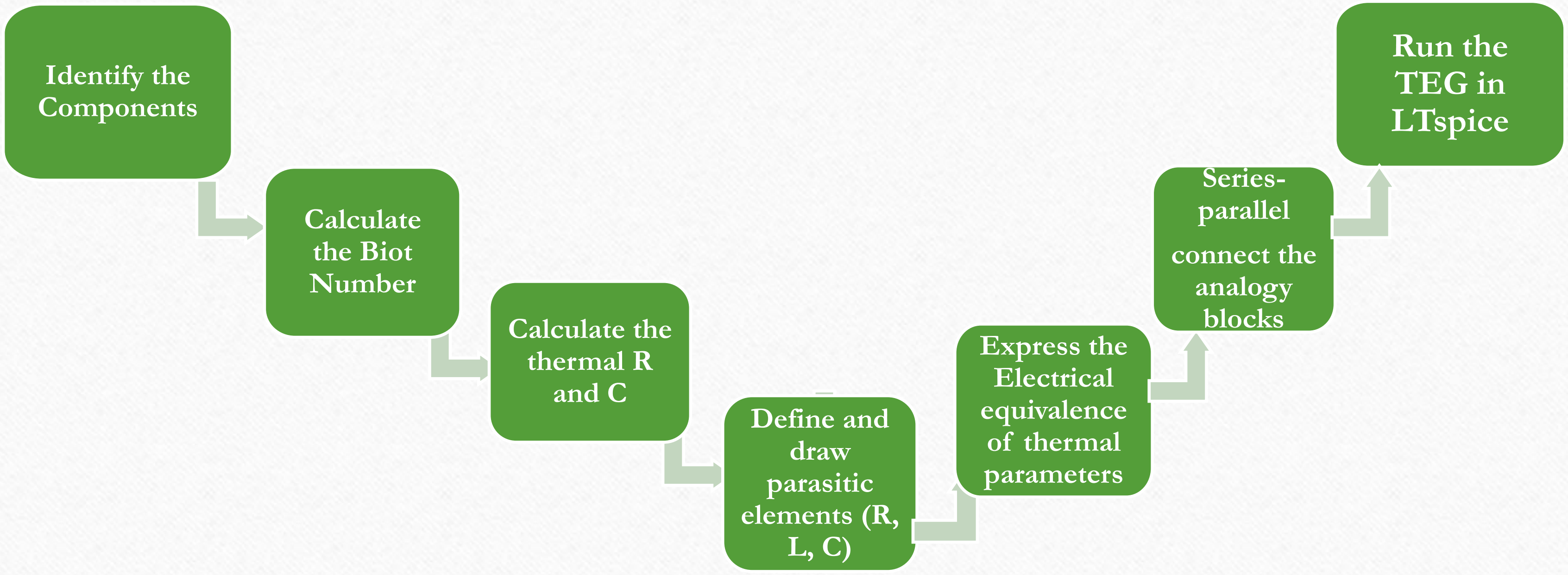
Thermal

- °C/Watt
- Joules/°C
- Watt
- °C
- Ambient Temperature

Electrical

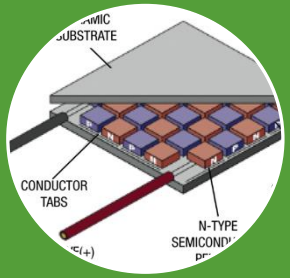
- Ohm (Resistor)
- Farad (Capacitor)
- Ampere (Current Source)
- Volt (Voltage Source)
- Ground (0V)

The Seven (7) TEG Modeling Steps



Properties of the TEGs

Bi_2Te_3



Al_2O_3

Material	ϱ[kg/m^3];	c [J/kg · K];	$\varkappa$[W/m · K]
Aluminum	2770	875	177
Alumina	3570	837	35.3
Bi_2Te_3	7530	544	1.5

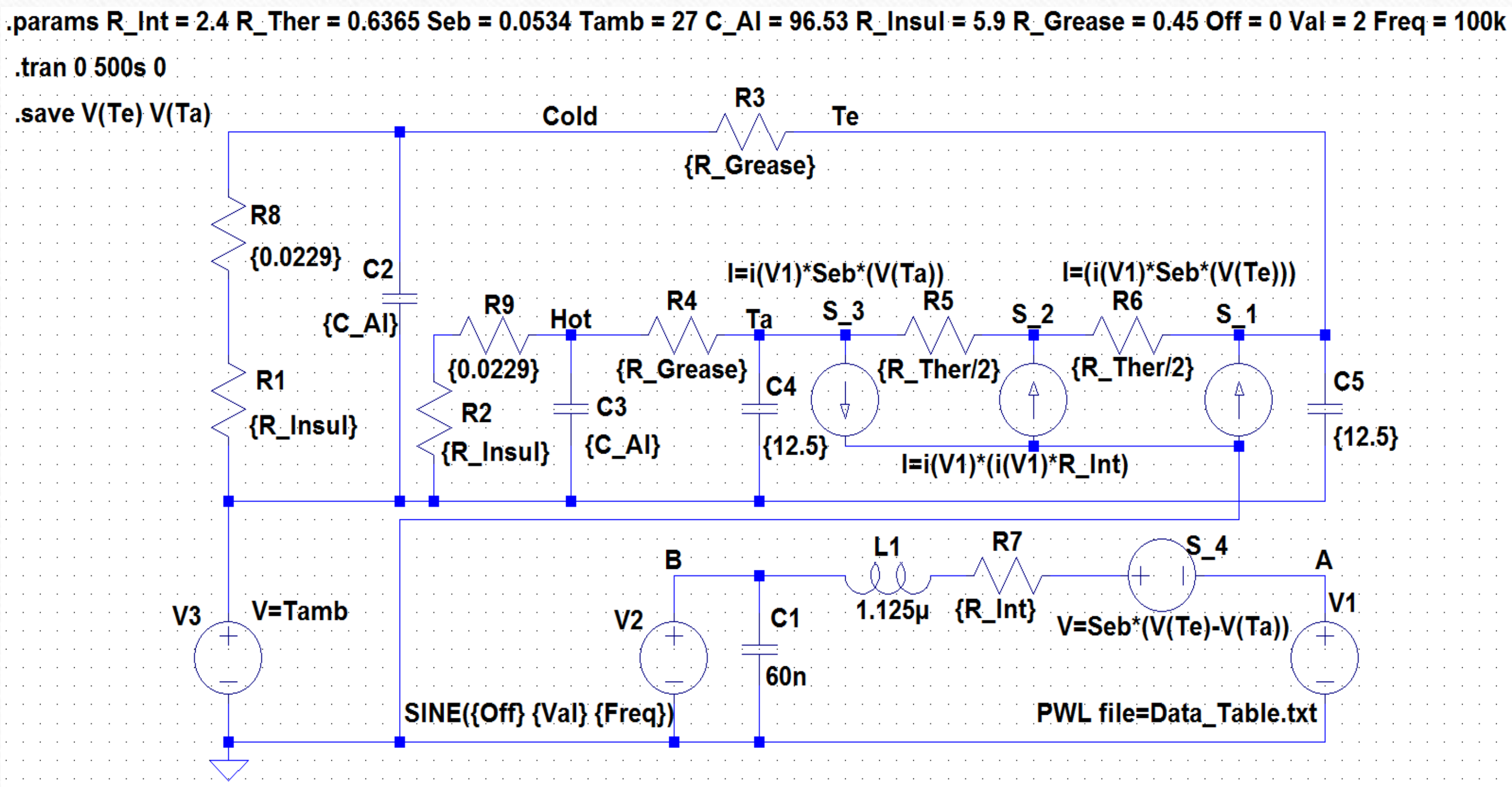
Parameters of the STEG

- Extracted from 3 sources
  - Datasheet
  - Material properties
  - Devices geometries
- Internal parasitic components
  - Inductances and Capacitances

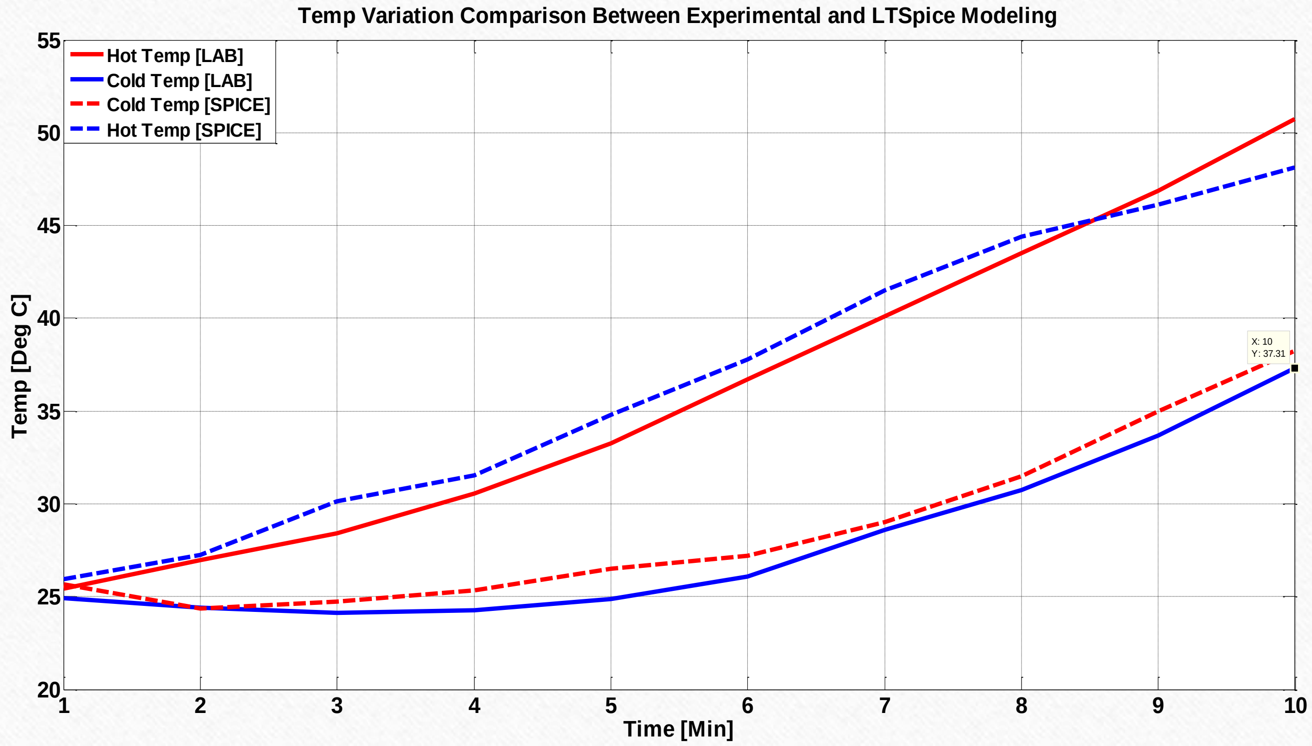
Some Computational Results of the TEG (indoor)

Mass of the ceramic plate	$2.239 \cdot 10^{-2} kg$
Molar heat capacity of the plate	$\frac{18.74 J}{K}$
Mass of the semiconductors	$2.561 \cdot 10^{-2} kg$
Molar heat capacity of the semiconductors	$\frac{4.036 J}{K}$

LTspice Model of the TEC



Comparative Results (indoor)



Error estimation:
5.47% on the hot side
2.52% on the cold side

Real-world Solar Thermoelectric Generation System (STEG)

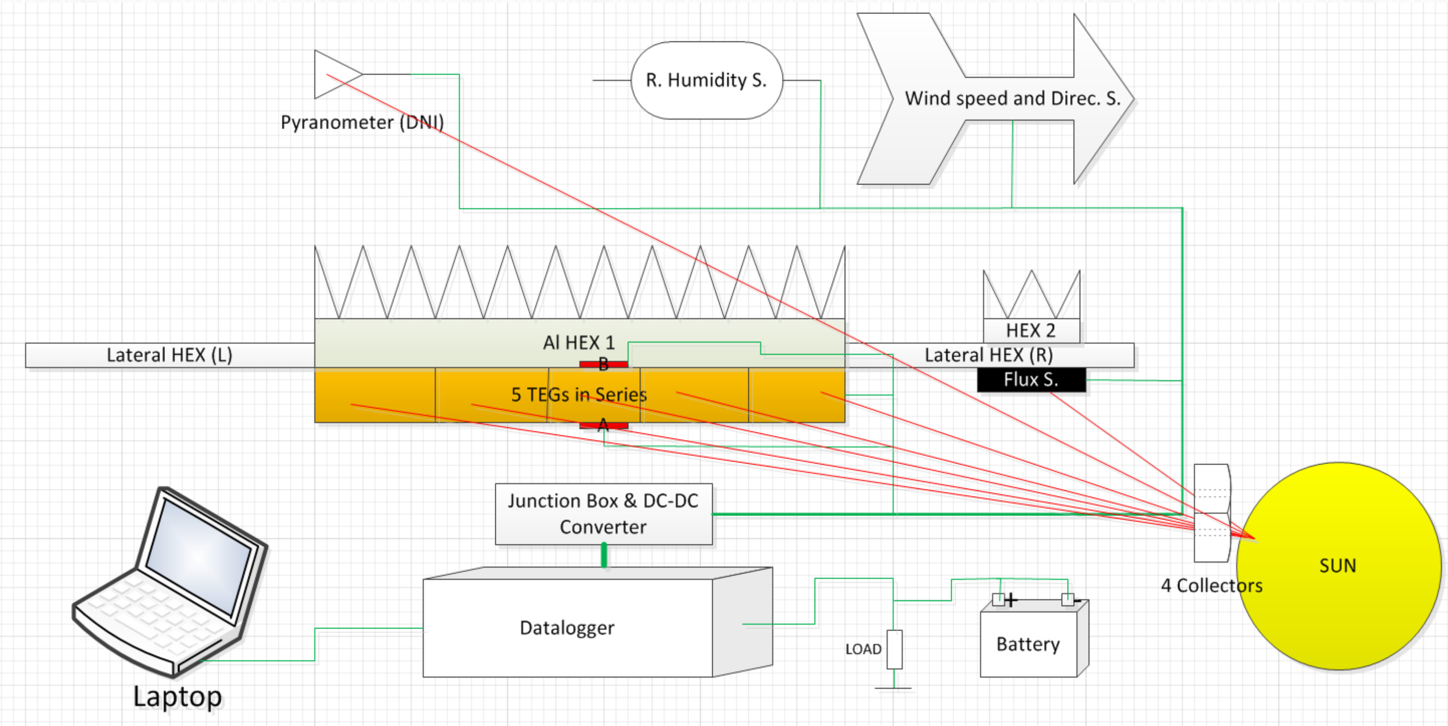
U
- Solar Tracker
- 5 TEGs
- Pyrheliometer

N
- Solar flux sensor
- Two Aluminum Heat exchangers
- Two thermocouples (K)

L
- Data-logger
- DC-DC converter
- K2 Battery

V
- Wind speed sensor
- Wind direction sensor
- Relative humidity sensor

Schematic Overview of the STEG

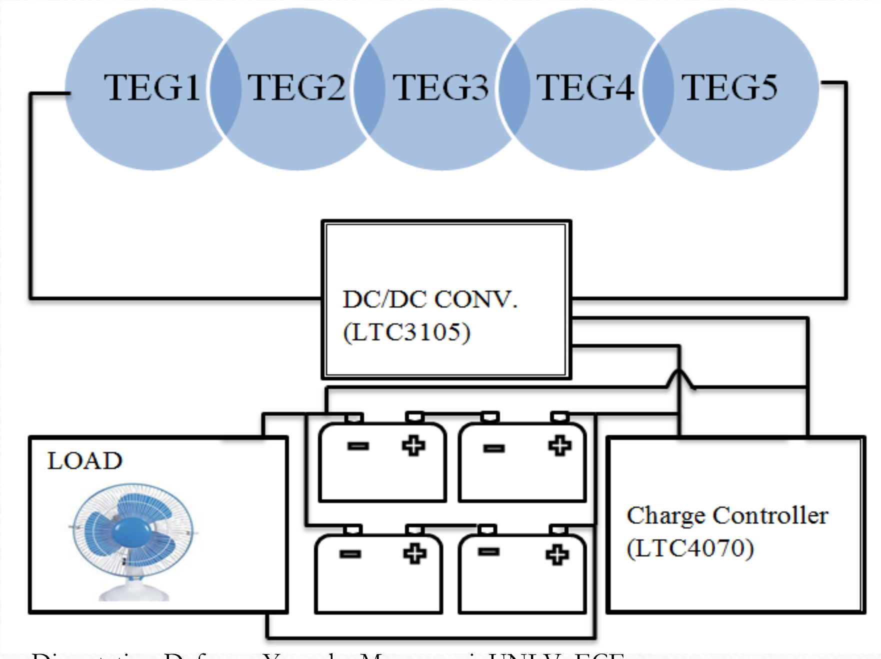


Dimensions of the Physical Components

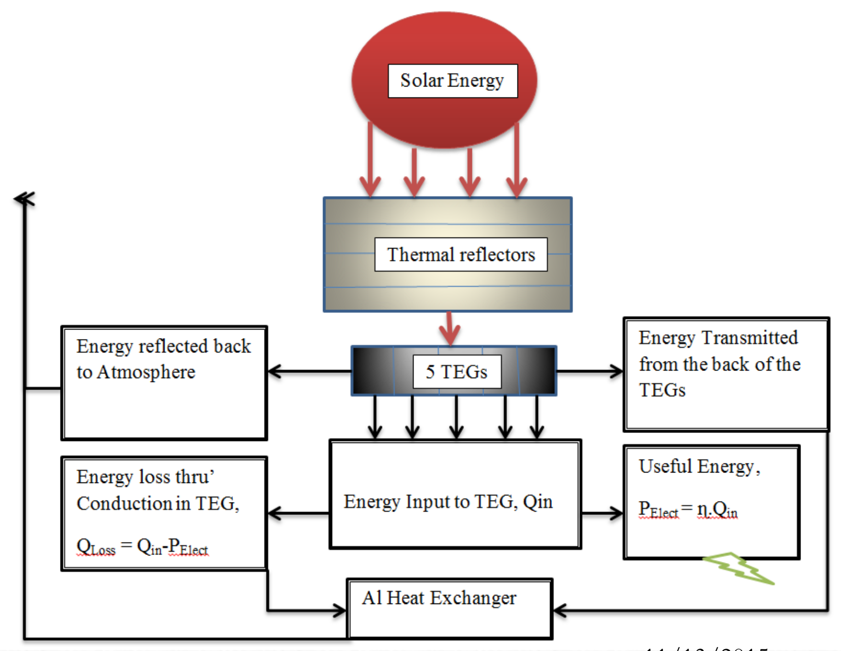
№	Components	Length(cm)	Height (cm)	Width (cm)	Thickness (cm)
1	Heat exchanger 1	50.165	7.112	7.62	0.985
2	Lateral Al plate (R)	30.48	0.635	10.16	
3	Lateral Al plate (L)	30.48	0.635	10.16	
4	PUR Insulation foam	40.132 (l)	1.905 (h)	31.115 (W)	
5	Insulation foam (hole 1)	16.764 (l_1)	1.905	5.715 (W_1)	
6	Insulation foam (hole 2)	16.764 (l_2)	1.905	5.715 (W_2)	
7	TEG	5.6	0.445	5.6	

Electrical Block Diagram and Energy Chart

Architecture of the STEG

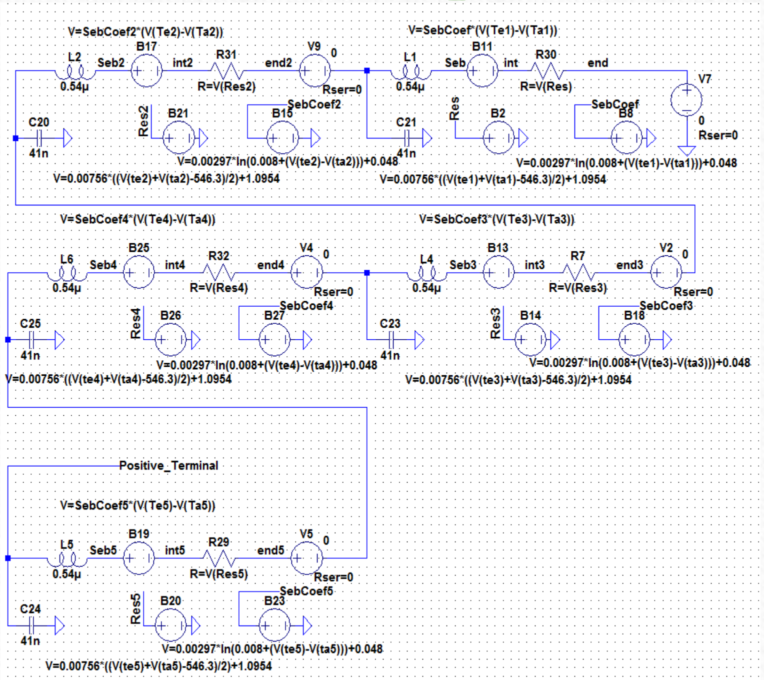


STEG Energy Flow Chart

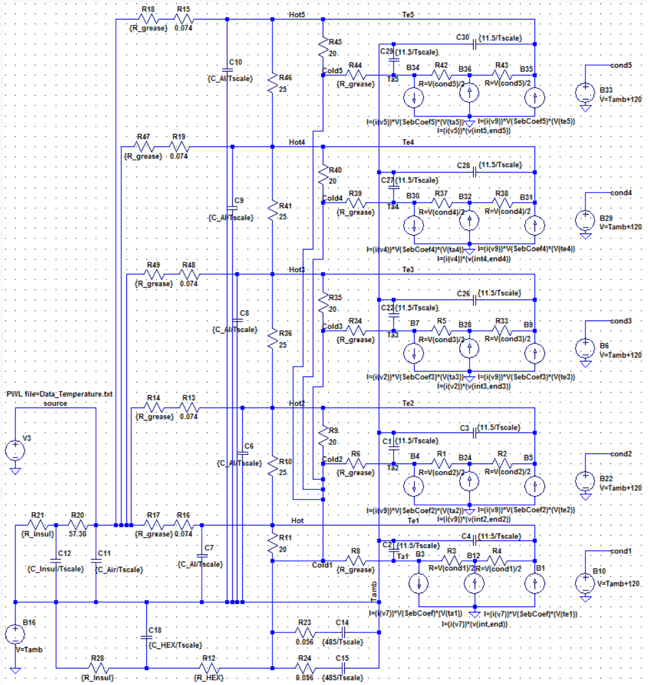


LTspice Model of the STEG

Electrical portion



Thermal portion



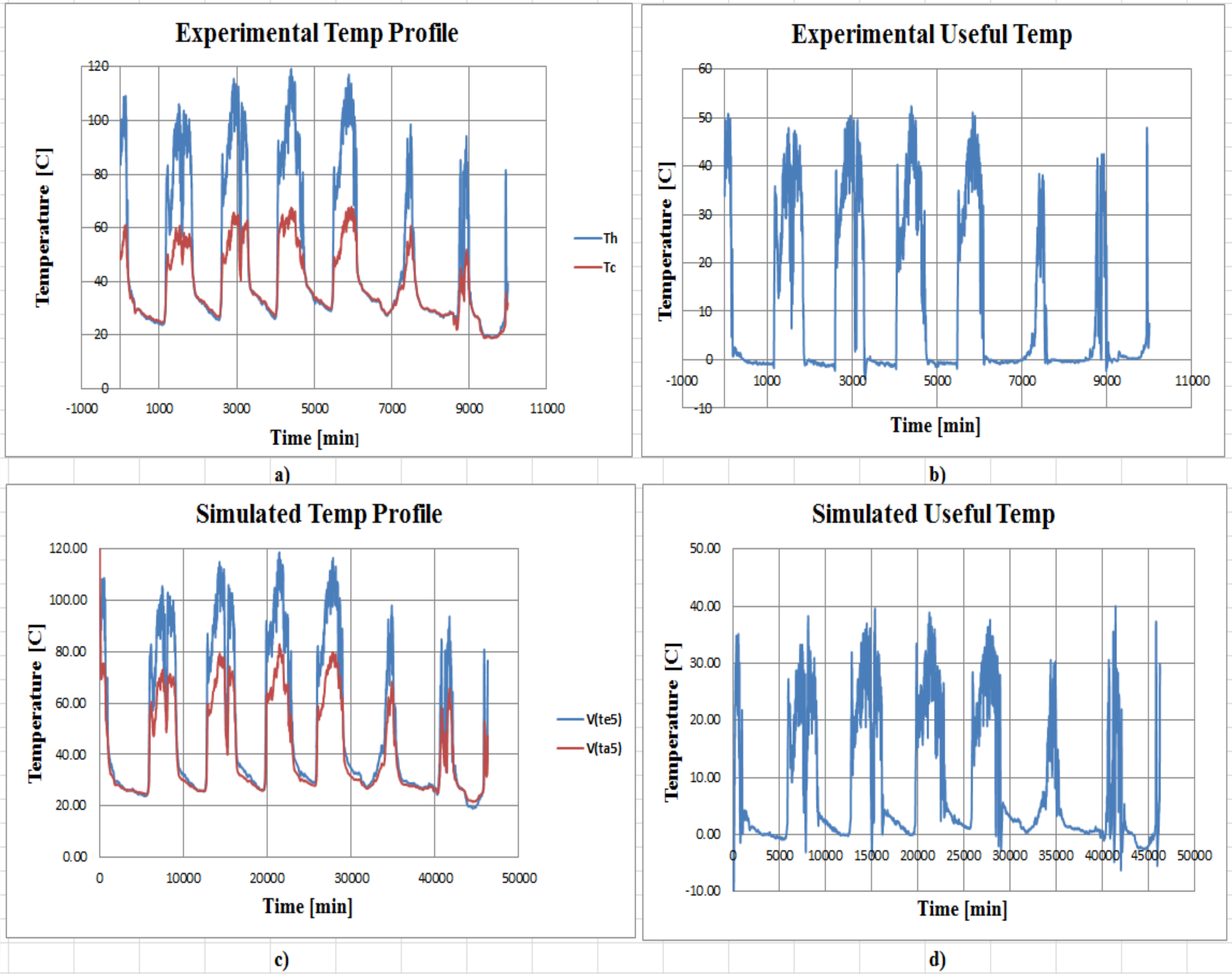
Description of the Thermal Parts

Nº	Components	Descriptions	Equation/Values
Thermal Resistances [K/W]			
1	R_m	Internal resistance of the TEG	$R_m = \frac{(\rho_n + \rho_p) \cdot N}{G}$
2	R_{Insul} , R21, and R28	Resistance of the insulation foam split into two equal parts for convenience	5.9
3	R6, R8, R14, R18, R17, R34, R39, R44, R47, R49 or R_grease	Thermal resistance of the thermal grease	0.20
4	R9, R11, R35, R40, R45	Thermal resistances between the cold and hot side due to any transient or stationary air gap	20
5	R10, R36, R41, R46	Thermal resistances between the TEGs	25
6	R20	Thermal resistance of the ambient Air	57.30
7	R23, R24	Thermal resistance of the lateral HEX, Right and Left, respectively	0.056
8	R12 or R_HEX	Thermal resistance of the HEX to the ambient	0.074
9	R13, R15, R16, R19, R48	Thermal resistance of the aluminum HEX	0.074
Thermal Capacities [J/K]			
1	C18 or C_{HEX}	Capacitance of the Aluminum HEX	2694
2	C11	Thermal capacitance of the ambient Air	148
3	C12	Thermal capacitance of the insulation foam	91
4	C14, C15	Thermal capacitance of the lateral HEX, Right and Left, respectively	485
5	C6, C7, C8, C9, C10	Thermal capacitances of the solar reflectors virtually sitting on the TEGs	25
6	C1, C2, C3, C4, C22, C26, C27, C28, C29, C30	Thermal capacitances of the TEGs split equally into two per device	11.5

Comparative Results: STC vs Real-world Test

Designations	STC	Real-Environment STEG
Hot Side Temp	300°C	0 to 125°C
Cold Side Temp	30°C	0 to 70°C
Temp Differential	270°C	0 to 58°C
Efficiency	6 %	0 to 1.30 %

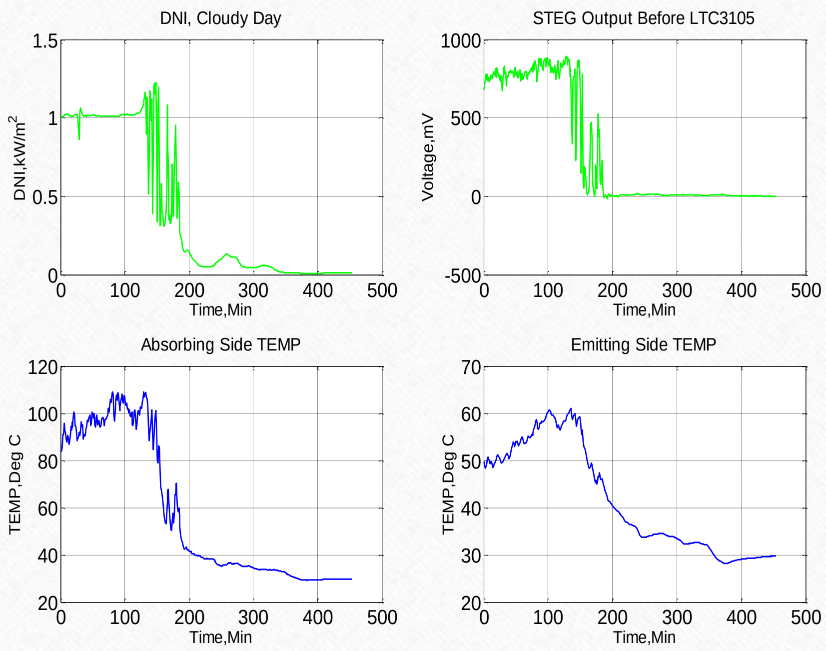
Comparative Results: Experiment vs Simulation



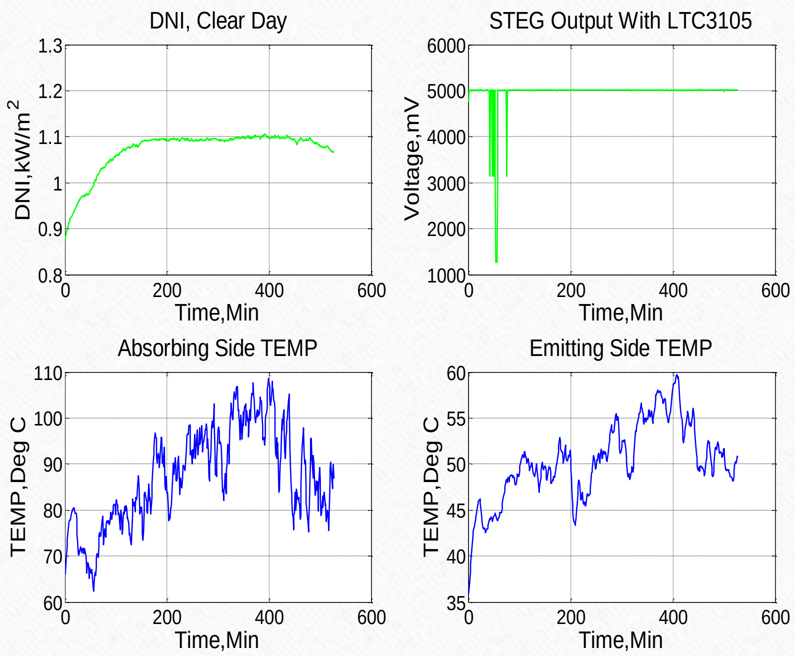
- Error rate 0-10%
- 80% from Cold side
- LTspice model is 25% less accurate
- ΔT is proportional to the DNI

Comparative Results: Cloudy day vs Clear day (Experiment)

Cloudy day

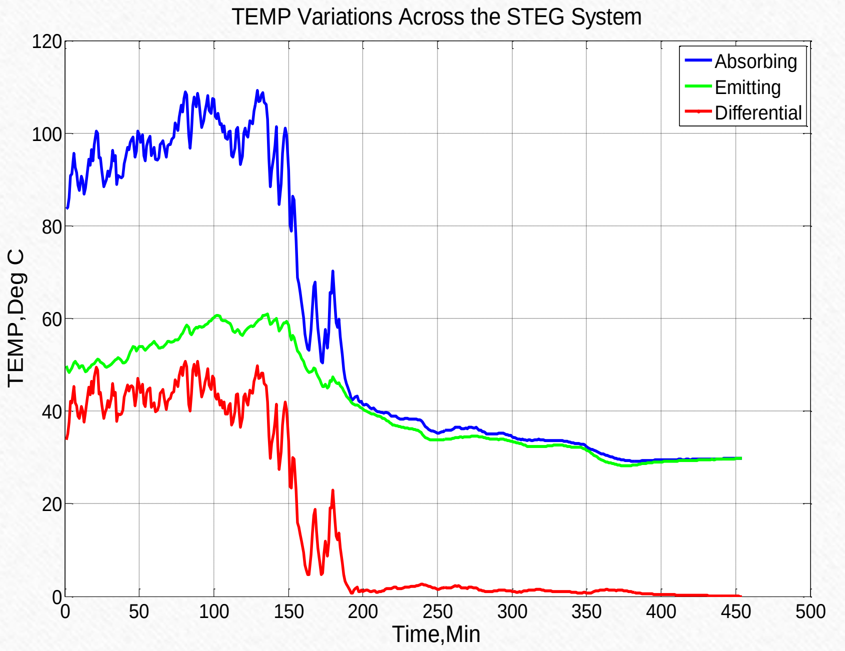


Clear day

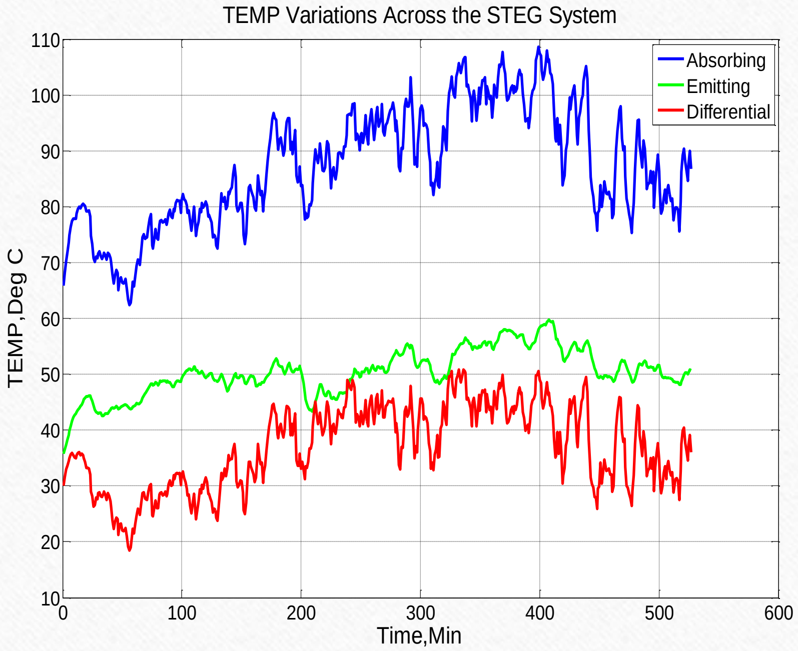


Comparative Results: Temperature Variations (Experiment)

Cloudy day

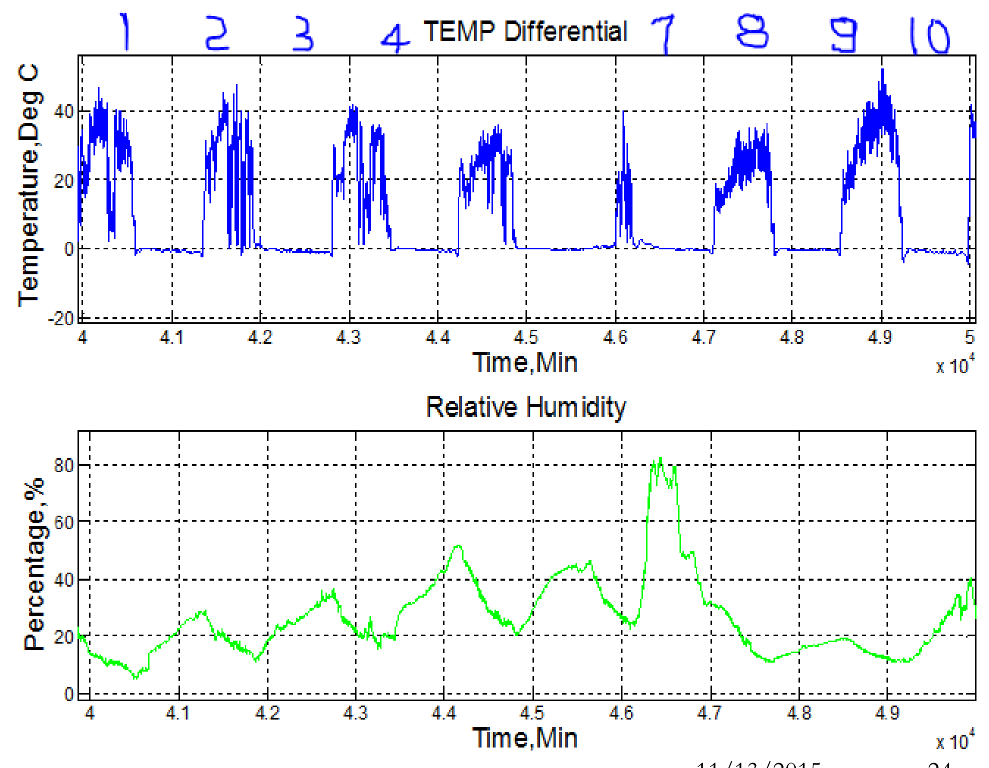


Clear day



Effects of RH on the STEG System (Experiment)

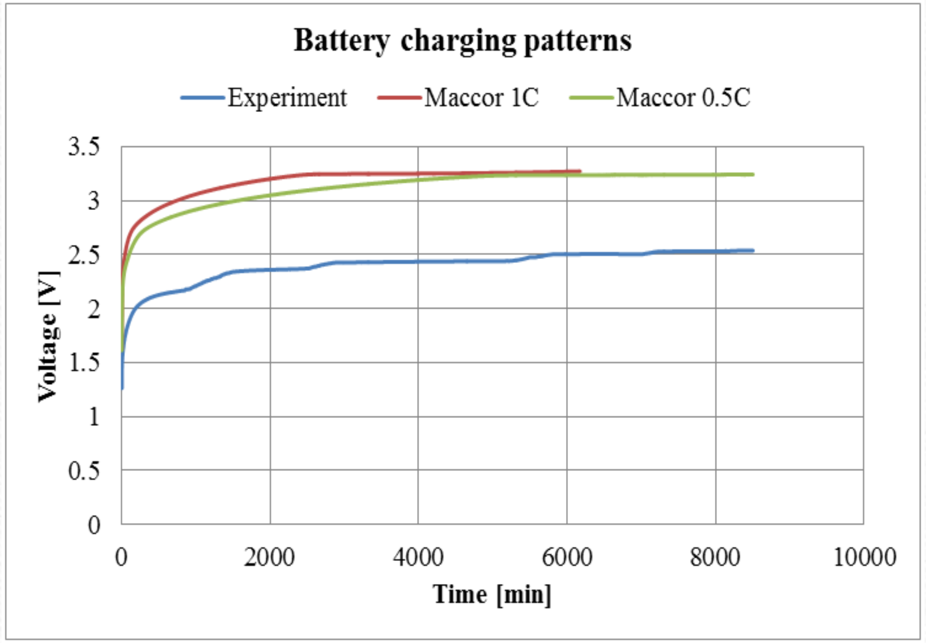
- FACT: RH higher night and lower day
- 7^{th} column: higher RH, lower ΔT
- 9^{th} column: lower RH, high ΔT



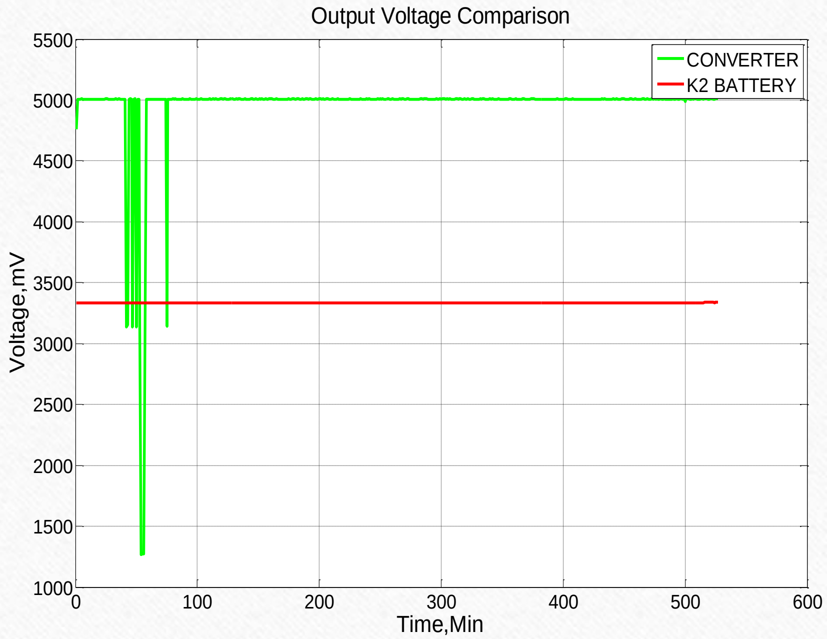
Performance of K2 Battery and LTC3105 (Sim vs Experiment)

K2 battery charging

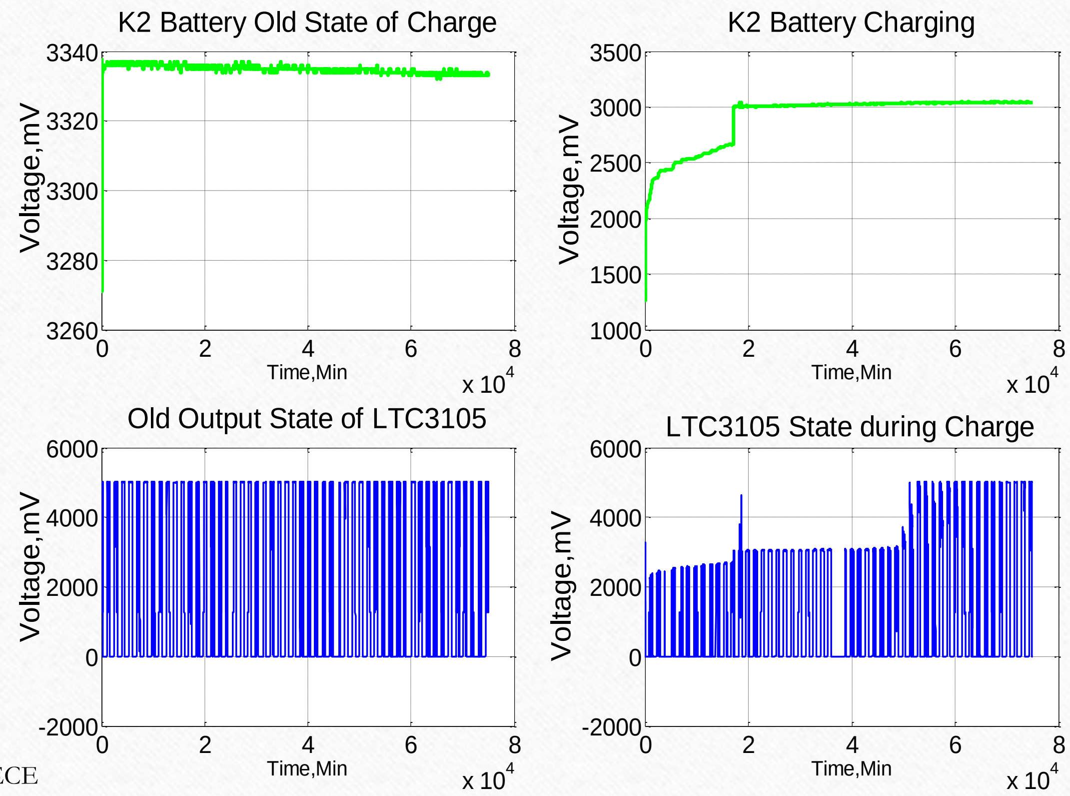
- 17 hours
- 33 hours
- 12 days



K2 battery vs LTC3105



SoC of K2 and States of the Converter (Experiment)



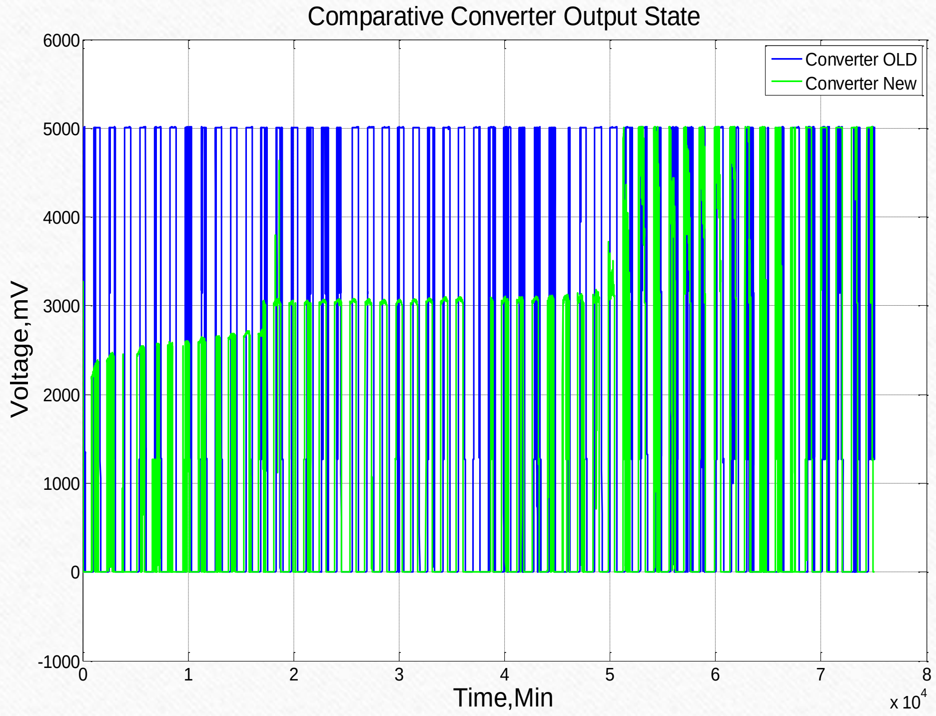
Analogy to "N-type doped semiconductor material's carrier density dependence on temperature" (Experiment)

- Ionization region is *Initialization region*

- Extrinsic region is *Constant-but-Consistent region*

$$V_{LTC3105} = 3.0V = V_{K2} \qquad (60)$$

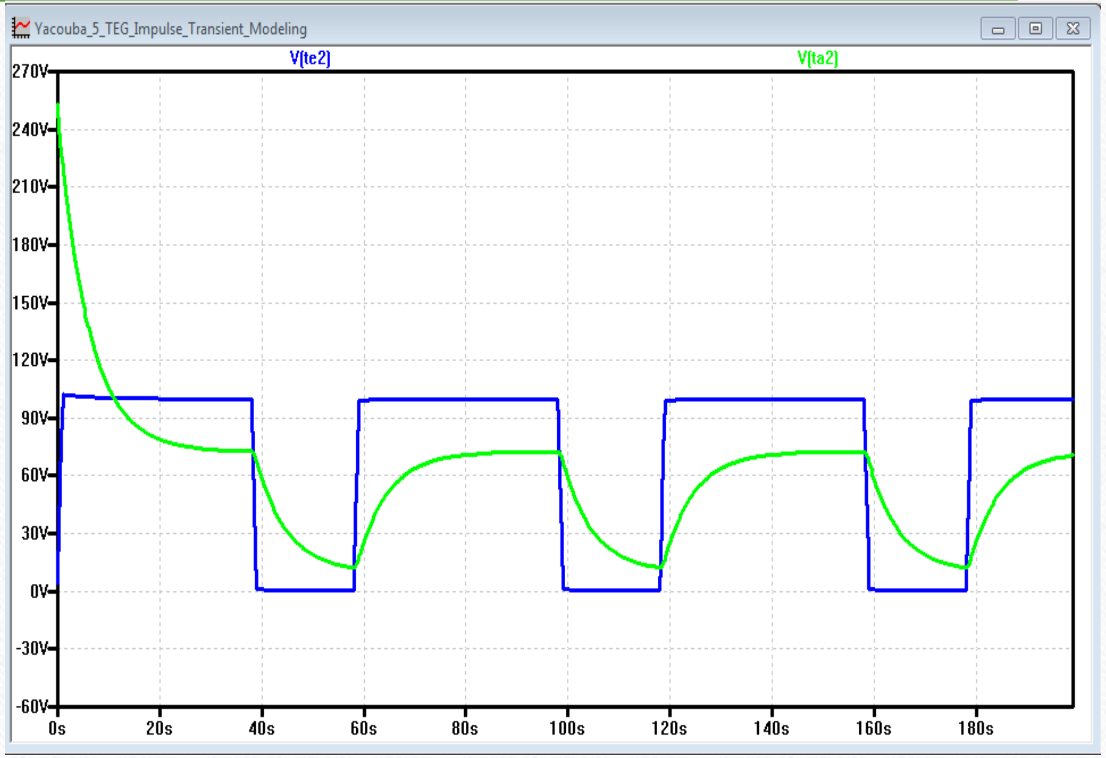
- Intrinsic-like region is a *Normal-Operation region*



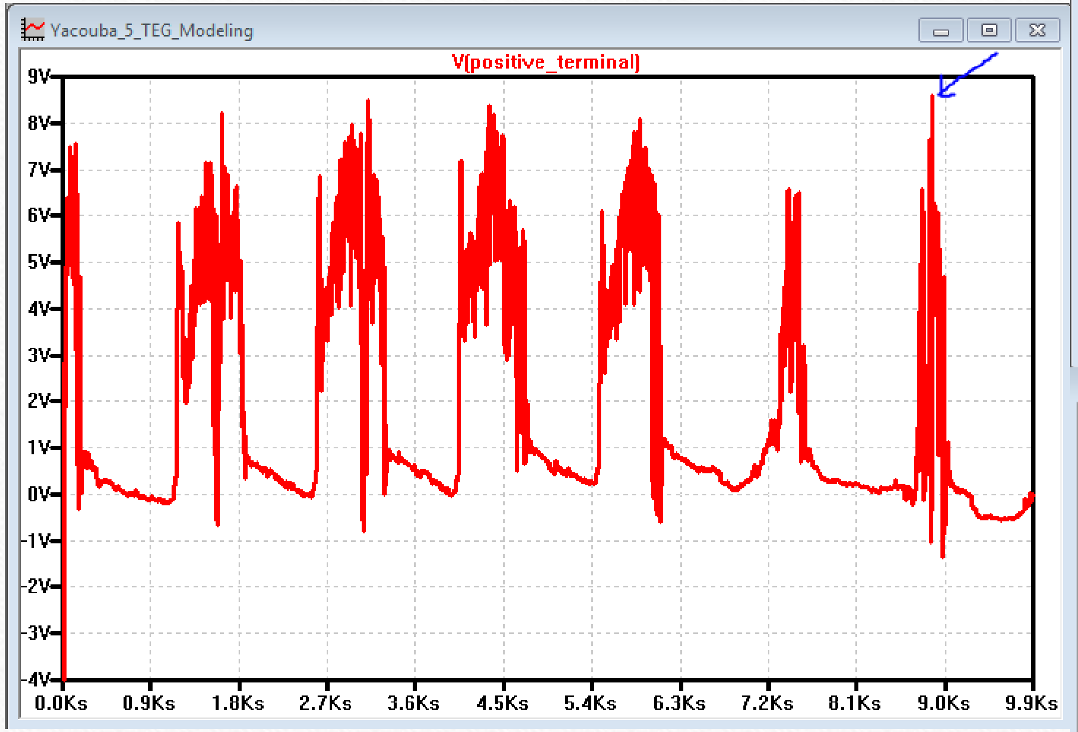
RC Analogy (Simulation)

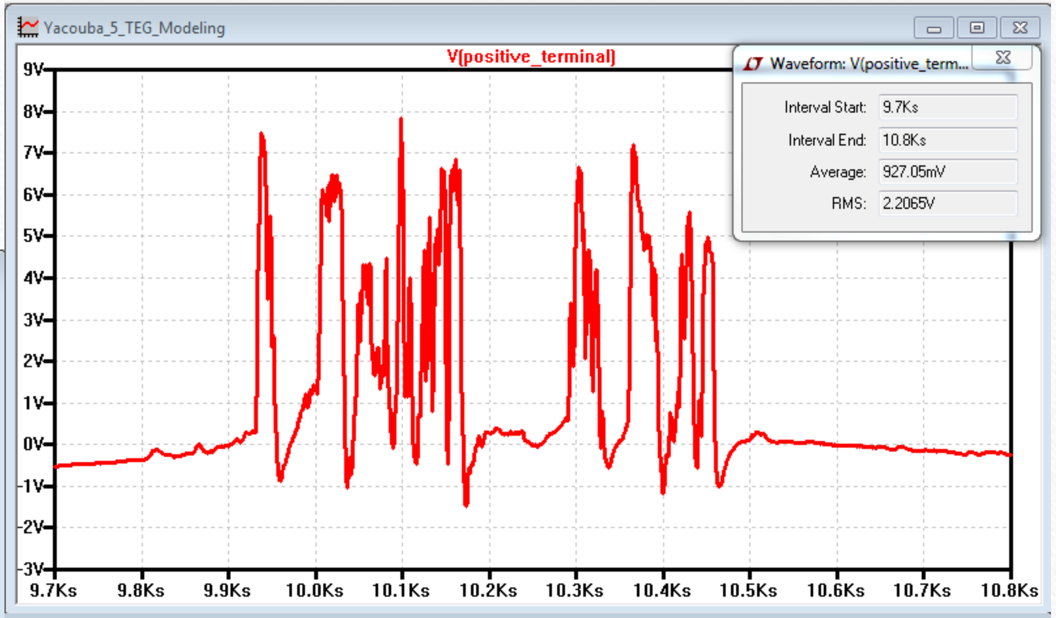
- Square-wave light was organized in a lookup table to simulate the *DNI*
- Internal parasitic *C* and *R* were used
- Rise time from 20% to 60%
- $t_r = t_{0.6} - t_{0.2} = 0.92 \cdot RC - 0.22 \cdot RC = 0.7 \cdot RC$ (65)
- t_r found is the same as t_d found in conventional *RC* analysis

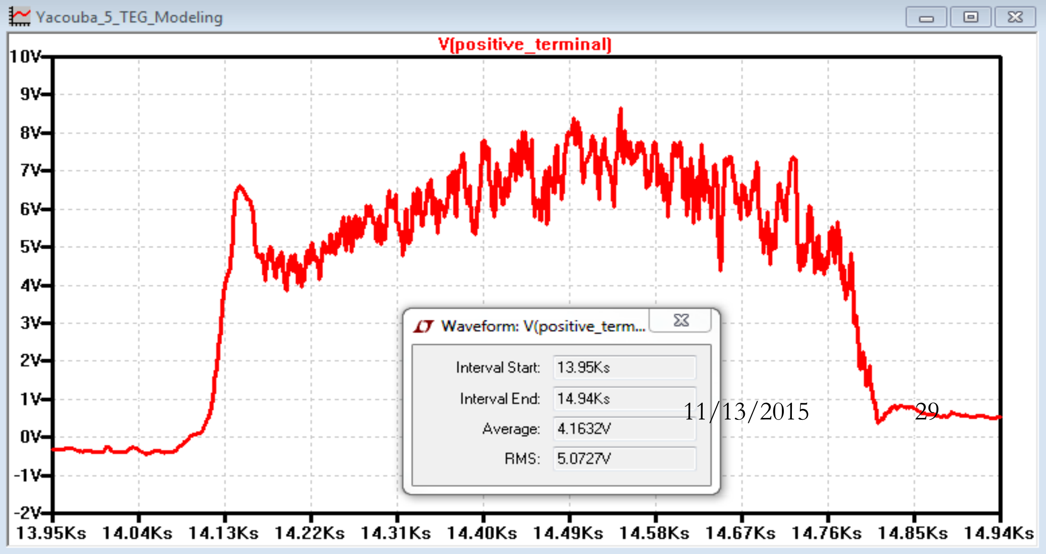
Effects of parasitic elements is shown



Comparative Results: Cloudy day vs Clear day (Simulation)







Battery Sizing

- Average daily household electricity consumption is 2kWh [82]
- Average daily sunlight hours in West Africa is 7h
- P = 0.30 kW; for t = 10 hours; E = 3kWh;
- Account for losses, DOD, effect of Temp, etc.
- Actual load = 706.25Ah; then
- **E_{GROSS} = 8.50kWh**

Battery Economic Analysis

- Battery priced by $/kWh or $/kW
- Li-ion battery packs declined by 14% from 2007 to 2014 [88].
- Current price from $250-$670
- Average price is $410/kWh [88]
- Estimated E capacity is 8.50kWh
- Battery cost is $3,485 (exorbitant !!)

ESS Application Needs (Summary)

Battery Specifications		Values
1	Estimated Energy Storage	8.50 kWh
2	Running Time	10 hours
3	Discharge Power	0.85 kW
4	Cycling Frequency	1 charge-discharge/charge/day
5	Average ambient Temp.	25^{o}C
6	Life Expectancy	1900 Cycles (5.2 years)

Battery Comparative Analysis

Lithium-ion battery

- **Estimated price is $410/kWh**
- Installation $3.6/kWh [89]
- Transportation $5/kWh
- Discharge rate is 85%
- 2.5 to 3.5 times energy-denser
- Installed capacity is 9.775kWh, 1900 cycles
- One time investment
- Total cost is **$4,092**
- Cost per kWh per cycle is **$0.25** (32)

Lead-acid battery

- **$125/kWh**
- $20/kWh
- $28/kWh
- Discharge rate is 50%
- Less energy-denser
- Installed capacity is 17kWh, (8.50kWh*2), 500 cycles
- Replaced 3 times for hot and arid climates
- Total cost is **$11,764**
- Cost per kWh per cycle **$0.72**

Lithium-ion is much more cost-effective in hot and arid climates than Lead-acid batteries.

Comparative Analysis: STEG vs PV

STEG

- Avg. daily thermal efficiency is 25%,
- Avg. thermal efficiency over 24h is 14.3%,
- Electrical efficiency is 1.30%,
- TEG lifetime less than 20 years,
- Thermal stability of TEGs is challenging,
- TEG are extraordinarily small,
- TEG operate day or night, providing heat source,
- TEG are extremely reliable and silent,
- No maintenance is required.

PV

- 2-4%, 8-12%,
- 16-20%, 29%,
- PV lifetime is around 25 years.
- PV are extremely large,
- PV operate only daytime,
- Performance is affected by hot Temp.,
- Output affected by solar variability,
- Routine maintenance is required,
- Cleaning is required (Water is an issue in arid regions).

My Contributions

- Seven major steps for modeling thermal system by means of electrical analogy are identified,
- TEG was demonstrated to function as a heat-removal pump and was modeled by LTspice simulator,
- Two separate electrical circuits were achieved as novel ways to model complex heat-transfer systems,
- The real-world performance of the LTC3105 converter was thoroughly investigated,
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- A cheaper and reliable method for energy delivery to remote residential areas is proposed.

Suggestions for Future Research

- Perform similar investigation with different types of TEGs for calibration,
- Investigate the true performance of this STEG under *light*, *normal*, and *heavy loads,*
- A thorough and systematic cost-effective analysis of the STEG system and then perform reliability and economic comparison with PV system setup for the same purpose of energy delivery to remote residential regions in developing countries,
- Investigate ways to improve the two novel electrical circuits,
- A Spice-based DC-DC converter can be designed to improve the STEG circuit,
- Performance of the STEG system mounted on a manual-solar tracker.

Conclusion

- A real-world STEG energy-harvesting system was designed, built, and simulated with Spice,
- Thermal C and R of physical parts were computed based on geometries and properties of the device,
- The system was modeled with LTspice utilizing the thermal-to-electrical analogy schemes,
- Internal parasitic L and C variations with temperatures were captured for accuracy purposes,
- Local DNI was the only input to the system,
- Energy delivery to off-grid remote and developing regions was positively demonstrated and achieved,
- ESS system (K2) was proposed and successfully tested with Maccor 4200 series and STEG,
- Simulated results and experimental data recorded on site agreed,
- Errors attributable to: 1) internal parasitic components' variation and/or 2) heterogeneity of Aluminum HEX,
- Two novel analogies were introduced,
- **Overall, the real-environment energy-harvesting system is suitable for charging battery cells from 1.2 to 6 volts.**

List of Publications

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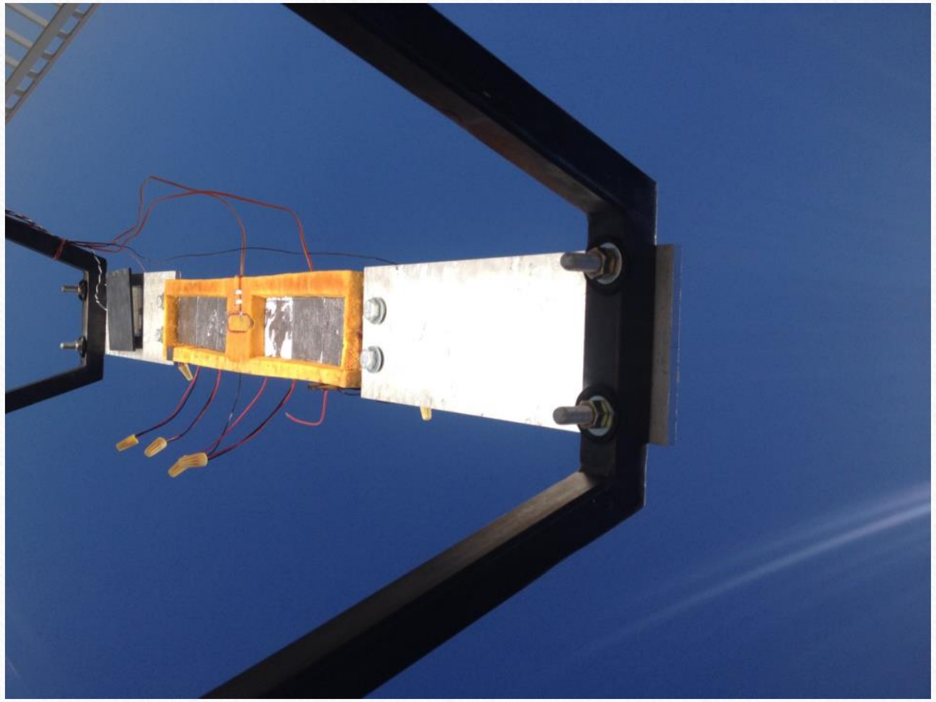
Thank you,
QUESTIONS ???



References

- A total of 103 references were consulted, please refer to the dissertation manuscript.
- Thank you,