AIUE Proceedings of the Energy and Human Habitat Conference 2020

A Comprehensive Thermoelectric Generator (TEG) Modelling

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Abstract:

Confronted with the ongoing electricity and energy crises in South Africa and Africa in general, this article articulates a comprehensive modelling of Thermo-Electric Generator (TEG), in an effort to devise an innovative renewable energy source that can be applied in conjunction with a heat source, to serve as an efficient hybrid power source, whereby generated heat can be converted to power, thereby increasing the total power production. The novel findings brought about is a simulated TEG model in MatLab / Simulink that can be configured with respect to an electrical load, to determine TEGs optimal parameters for an increase in output power (P_o) generation and also the TEG thermal / electrical / conversion efficiency (η).

Keywords:

Alternative Energy, Renewable Energy, TEC/TEG, Thermoelectricity and Waste Heat

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I. INTRODUCTION

According to [1], energy and electricity crises are progressively serious problems in South Africa and by extension Africa. Various alternative electrical energy sources are being explored with keen focus on renewable energy sources which include but unlimited to solar, wind energy, hydro energy, fuel cell, ocean energy, geothermal energy, bio-energy and waste heat [2][3]. Waste heat can be divided into three grades i) high grade heat >650°C, ii) medium grade heat between 277°C and 650°C and iii) low grade heat <277°C – which accounts for 66% of waste heat as stated in [4]. Low grade waste heat is thus, reasonably available and can therefore be harvested from various heat sources such as human habitats, industrial processes, appliances/devices and vehicles to name a few. In light of this, this paper focuses on the harnessing and conversion of low grade heat to electrical power based on thermoelectricity using thermo-electric generator (TEG). Thermoelectricity as examined extensively in [5][6], is basically a Seebeck-Peltier reversible triple display of the same thermo-electrical process, in which heat is converted to power using TEG or by using Thermo-Electric Coolers (TEC), power is converted to heat and or cold depending on the supply voltage polarity (i.e. the current direction).

Numerous scholarly publications have been done on thermoelectricity; however, most failed to extensively convey the mathematics governing the physics models. The goal of this manuscript is to logically express the mathematics that represent various thermoelectricity key parameters with focus on TEG and how they're applied to comprehensively model TEG(s) using MatLab/Simulink. The rationale is to ascertain a realistic TEG model, which can be used to understand, develop, simulate and design a practical TEG system that is efficient and innovative. Proceeding the introduction is the TEG mathematical analysis, followed by the TEG modelling after which the results are analysed and finally concluding remarks are drawn preceded by the research scientific contributions.

II. TEG MATHEMATICAL ANALYSIS

There are several technical parameters that enable a thermoelectric (TE) device to generate electricity when subjected to a heat source. The general thermoelectricity parameters are highlighted with emphasis on the crucial parameters that determine the performance of TEGs. The mathematics is detailed in [7]–[9], from which developed and presented next are what is applicable to the research.

i. Thermo-electric conductivities

The Wiedemann-Franz law relates the thermal and electrical conductivities as:

$$k_E = \sigma L_o T \qquad \text{(W/mK)} \qquad (1)$$

where k_E is the thermal conductivity electrons charge carrier contribution (W/mK), σ is the electrical conductivity (Siemens/m), L_o is a constant known as the Lorenz number ($2.44\text{x}10^{-8}$ WΩK^{-2}) and T is the absolute temperature in Kelvin (273.15K) or (0°Celsius).

This study has been supported by CPUT, HySA Systems UWC and TU-Sofia.

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ii. Seebeck Coefficient (*S*)

In honour of the TEG discoverer Thomas Seebeck, *S* defines the ratio between the electromotive force (V_{emf}) and the TEG temperature difference (ΔT) expressed as:

$$S = \frac{V_{emf}}{\Delta T} = \frac{V_{emf}}{T_h - T_c} \qquad \text{(V/K)} \qquad (2)$$

where T_h and T_c are respectively the TE device hot and cold sides temperature in Kelvin.

iii. Thermoelectricity Figure of Merits (*Z* and *z*)

The TE device and material figure of merits are respectively denoted as (*Z*) and (*z*) and expressed as:

$$Z = z = \frac{S^2\sigma}{k} = \frac{S^2}{\rho k} \qquad (\mathrm{K}^{-1}) \qquad (3)$$

where $S^2\sigma$ is the TEG electrical power factor and k is the TEG thermal conductivity (W/mK) and ρ is the TEG electrical resistivity ($\rho = \sigma^{-1}$) in Ω m.

iv. TE Dimensionless Figure of Merits (*ZT* and *zT*)

The TE device and material dimensionless figure of merits are respectively denoted as (*ZT*) and (*zT*) and expressed as:

$$ZT = zT = \frac{S^2\sigma T}{k} = \frac{S^2}{L_0} = \frac{S^2 T}{\rho k} \qquad (4)$$

v. TE Average Dimensionless Figure of Merits ($Z\overline{T}$, $z\overline{T}$)

The TE device and material average dimensionless figure of merits are respectively denoted as ($Z\overline{T}$) and ($z\overline{T}$) and expressed as:

$$Z\overline{T} = z\overline{T} = \frac{S^2\sigma\overline{T}}{k} = \frac{S^2\overline{T}}{\rho k} \qquad (5)$$

where the average temperature $\overline{T} = 0.5\,(T_h + T_c)$ in K.

vi. TE Device P-N Thermocouple Unit Resistance (*r*)

The TEG internal p-n junction thermocouples combined ($r = r_p + r_n$) resistance (*r*) in Ohms is calculated using:

$$r = \frac{\rho L}{A} \qquad (\Omega) \qquad (6)$$

where L is the TEG p-n junction thermocouple combined length in meter (m) and A is the TEG p-n junction thermocouple combined area ($A = A_p + A_n$) in m^2.

vii. TE Device P-N Thermocouple Resistivity (ρ)

TEG internal p-n junction thermocouple combined electrical resistivity (ρ) in Ohms meter (Ωm) is given by:

$$\rho = \frac{rA}{L} \qquad (\Omega\mathrm{m}) \qquad (7)$$

viii. TE Device P-N Thermocouple Conductance (*K*)

TEG internal p-n junction thermocouple combined thermal conductance (*K*) in (W/K) is computed as:

$$K = \frac{kA}{L} = \frac{k\rho}{r} = \frac{S^2}{Zr} \qquad \text{(W/K)} \qquad (8)$$

NB: take special note of the difference between the various notations of K, *K* and *k* where used in this article.

ix. TEG Module Unit Resistance (*R*)

TEG module resistance (*R*) in (Ω) is deduced as:

$$R = nr \qquad (\Omega) \qquad (9)$$

where n (which varies) is the total quantity of p-n thermocouples used during the TEG manufacturing.

x. TEG Temperature Difference (ΔT)

TEG ΔT is the temperature difference between the TEG hot and cold sides temperature, calculated as:

$$\Delta T = T_h - T_c \qquad \text{(°C) or (K)} \qquad (10)$$

where T_h and T_c are respectively the TEG hot and cold sides temperature in °C or K.

xi. TEG Module Output Voltage (V_o)

A TEG module generated voltage in Volt is given as:

$$V_o = n[S\,(T_h - T_c)] - IR \qquad \text{(V)} \qquad (11)$$

where I is the output current from the TEG.

xii. TEG Module Output Current (*I*)

A TEG module output current in Amps is defined as:

$$I = \frac{nS\Delta T}{R + R_L} \qquad \text{(A)} \qquad (12)$$

where R_L is the load resistance connected to the TEG. The flow of I causes the internal Joule or Ohmic heating.

xiii. Heat Absorbed on TEG Module Hot-side (Q_h)

For TEG to generate power, TEG hot-side must be at a temperature T_h to create a constant heat flux (Q_h) in W.

$$Q_h = n\,[(SIT_h) + (K\Delta T)] - 0.5I^2R \qquad \text{(W)} \qquad (13)$$

xiv. Heat Emitted on TEG Module Cold-side (Q_c)

For TEG to generate power, TEG cold-side must be at a lower temperature T_c to dissipate the heat Q_c in Watts.

$$Q_c = n\,[(SIT_c) + (K\Delta T)] + 0.5I^2R \qquad \text{(W)} \qquad (14)$$

xv. TEG Module Generated Power (P_o)

TEG output power is the difference between Q_h and Q_c.

$$P_o = Q_h - Q_c \qquad \text{(W)} \qquad (15)$$

or

$$P_o = IV_o = n\,[(SI\Delta T)] - I^2R \qquad \text{(W)} \qquad (16)$$

xvi. TEG Carnot Efficiency (η_c)

Efficiency determine based-on the TEG temperatures.

$$\eta_c = \frac{\Delta T}{T_h} = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h} \qquad (17)$$

xvii. TEG Thermal /Electrical /Conversion Efficiency (η)

This is the ratio of TEG output power and heat absorbed on TEG hot-side. It's a performance parameter.

$$\eta = P_o / Q_h \qquad (18)$$

xviii. TEG Conversion Efficiency Expression (η_e)

This efficiency is the same as η. It is simply the raw expression when P_o and Q_h equations are used in (18).

$$\eta_e = \eta_c \frac{(nR_L/R)}{[(1+nR_L/R) - 0.5\eta_c + ((1/(2Z\bar{T}))(1+nR_L/R)^2(1+T_c/T_h))]} \qquad (19)$$

xix. TEG Maximum Conversion Efficiency (η_m)

This is TEG's efficiency when $R / R_L = \sqrt{1 + Z\bar{\bar{T}}}$ and the expression for η_m is:

$$\eta_m = \eta_c \left[\frac{(\sqrt{1+Z\bar{\bar{T}}}) - 1)}{(\sqrt{1+Z\bar{\bar{T}}} + (T_c / T_h))}\right] \qquad (20)$$

xx. TEG Maximum Power Conversion Efficiency (η_{mp})

This is TEG's efficiency at maximum P_o (i.e. $R = R_L$).

$$\eta_{mp} = \eta_c / (2 - 0.5\eta_c + (2/Z\bar{T})\,(1 + T_c/T_h)) \qquad (21)$$

The efficiency parameters define the TEG effectiveness.

xxi. TEG Maximum Output Power (Po_{max})

Maximum power transfer occurs when TEG's $R = R_L$.

$$Po_{max} = (nS\Delta T)^2/4R \qquad \text{(W)} \qquad (22)$$

xxii. TEG Maximum Output Voltage (Vo_{max})

TEG maximum output voltage occurs at open circuit – i.e. when R_L = infinity or unconnected, I = 0A.

$$Vo_{max} = nS(T_h - T_c) = nS\Delta T \qquad \text{(V)} \qquad (23)$$

xxiii. TEG Maximum Output Current (I_{max})

TEG maximum current occurs at short circuit – that is, when $R_L = 0\Omega$. This means R is the only resistance.

$$I_{max} = nS(T_h - T_c) / R_t = nS\Delta T / R \qquad \text{(A)} \qquad (24)$$

The maximum parameters define the TEG useful limits.

xxiv. TEG Normalized Output Current (I_n)

This is TEG output current between $0 \leq I_n \leq 1$. At maximum power transfer ($R = R_L$), $I_n = 0.5$. I_n is TEG output current divided by the maximum current TEG can generate, expressed as:

$$I_n = \frac{I}{I_{max}} = \frac{R}{R + R_L} \qquad (25)$$

xxv. TEG Normalized Output Voltage (V_n)

This is TEG output voltage between $0 \leq V_n \leq 1$. At maximum power transfer ($R = R_L$), $V_n = 0.5$. V_n is TEG output voltage divided by the maximum voltage TEG can generate, expressed as:

$$V_n = \frac{V_O}{Vo_{max}} = \frac{R_L}{R_L + R} \qquad (26)$$

xxvi. TEG Normalized Output Power (P_n)

This is TEG output power between $0 \leq P_n \leq 1$. At maximum power transfer ($R = R_L$), $P_n = 1$. P_n is TEG output power divided by the maximum power TEG can generate, expressed as:

$$P_n = \frac{P_O}{Po_{max}} = \frac{4(R_L/R)}{[(R_L/R)+1]^2} \qquad (27)$$

xxvii. TEG Normalized Conversion Efficiency (η_n)

This is TEG conversion efficiency between $0 \leq \eta_n \leq 1$. η_n is determined by R / R_L, T_c / T_h and $Z\bar{T}$. η_n is the TEG conversion efficiency and TEG maximum conversion efficiency ratio, expressed as:

$$\eta_n = \eta / \eta_m \qquad (28)$$

xxviii. TEG Effective Seebeck Coefficient (S_e)

$$S_e = 4Po_{max} / [n\, I_{max}\Delta T] \qquad \text{(V/K)} \qquad (29)$$

xxix. TEG Effective Electrical Resistivity (ρ_e)

$$\rho_e = 4[(A/L)Po_{max}] / nI_{max}^2 \qquad (\Omega\ \text{m}) \qquad (30)$$

xxx. TEG Effective Figure of Merit (Z_e)

$$Z_e = [(2/\bar{\bar{T}})(1 + (T_c/T_h))]/[\eta_c((1/\eta_{mp}) + 0.5) - 2] \quad (\text{K}^{-1}) \qquad (31)$$

xxxi. TEG Effective Thermal Conductivity (k_e)

$$k_e = S_e^2 / \rho_e Z_e \qquad \text{(W/mK)} \qquad (32)$$

The effective parameters assist system designers bridge the gap between measured and theoretical specs, by using maximum parameters to factor in TEG system losses.

xxxii. TEG Heat Flux Density (HFD)

$$HFD = Q_h / TEG\ Surface\ Area \qquad (\text{W/m}^2) \qquad (33)$$

III. TEG(S) MODELLING

TEG has been modelled variously; however, these models lack the applicable mathematics to complement the implemented physics models and as well some of these models are rigid, basic, unclear and also lack certain parameters and features to heuristically simulate TEGs. Modelling of TEGs in [8] – [13] were examined as the bases and were developed further to realize the TEG implementations in Figs. 1 and 2 using MatLab/Simulink. What is mostly unique and advanced in Figs. 1 and 2 are the following implemented improvements and novelties:

- The mathematical analysis in Section II is included.
- Any number of TEG quantities can be simulated.
- Different TEGs configurations can be simulated.
- R_L can be changed while the simulation is running.
- Power loss due to r, R and R_L can be seen on the fly.
- Various TEGs characteristics curves are generated.
- More TEG parameters are added, tested and shown.
- The practical limitations of TEG(s) are observable.
- The user interface is clearer, better and informational.
- A better and bigger TEG(s) module can be simulated.

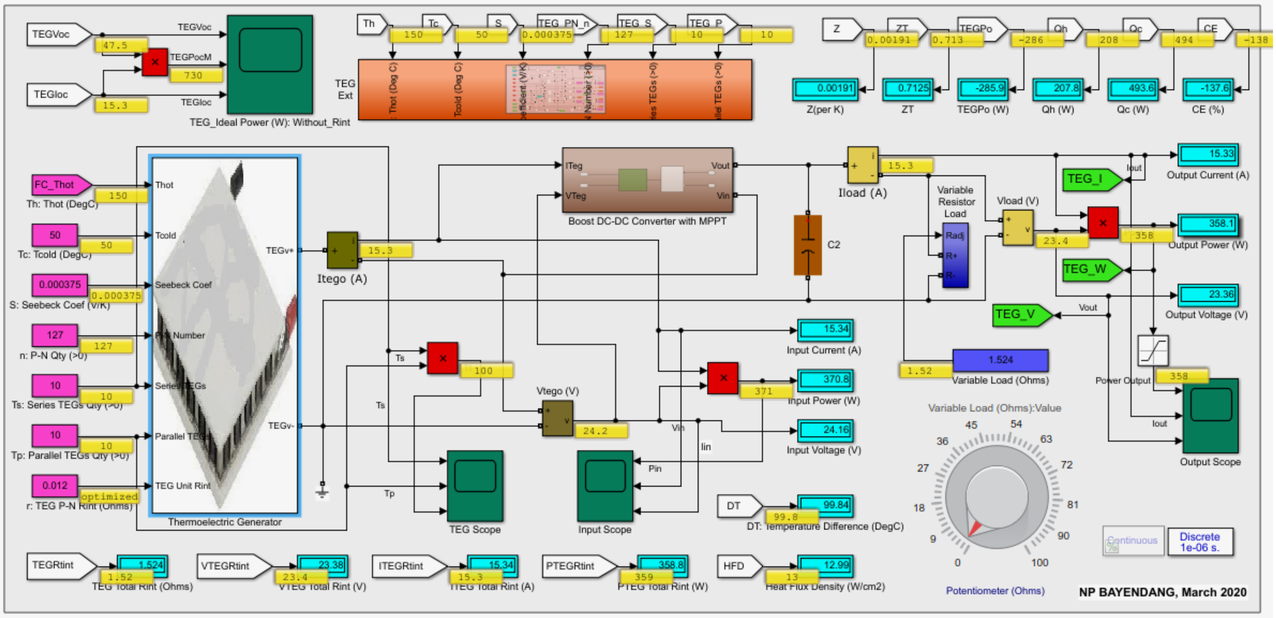

Fig. 1. TEG model developed with inclusion of Section II math

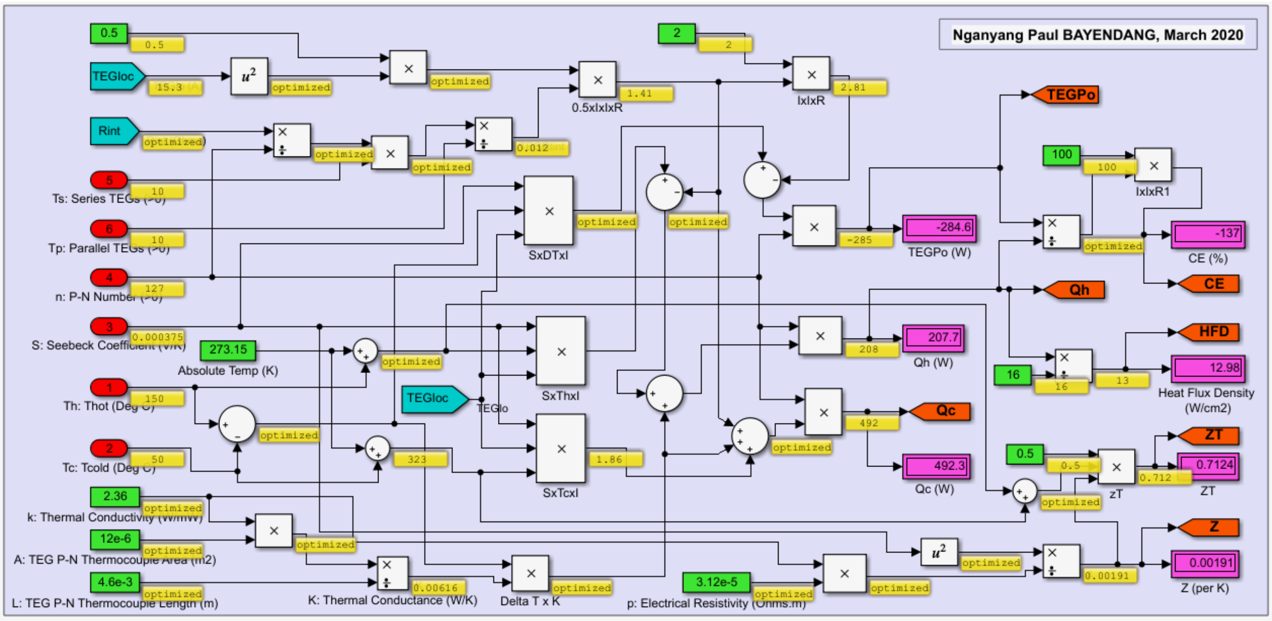

Fig. 2. TEG model novel implementation details snippet

IV. TEG(S) MODELLING RESULTS AND ANALYSES

The modelled TEG(s) was simulated using realistic datasets and specs from TEG(s) manufacturers datasheets, research articles and scholarly publications in [7] – [13]. As indicated earlier, Figs. 1 and 2 depict the user interface where a TEG input parameters of interest (e.g. Seebeck Coefficient, hot and cold side temperatures etc) can be entered, changed on the fly and the results variously displayed as well as plotted as in Figs. 3, 5 – 6, which are analysed next. Fig. 4 is TEG (η , P_o) *vs* I in Mathcad – which is used to compare and validate the MatLab TEG model (P_o , η) *vs* I in Figs. 5 and 6.

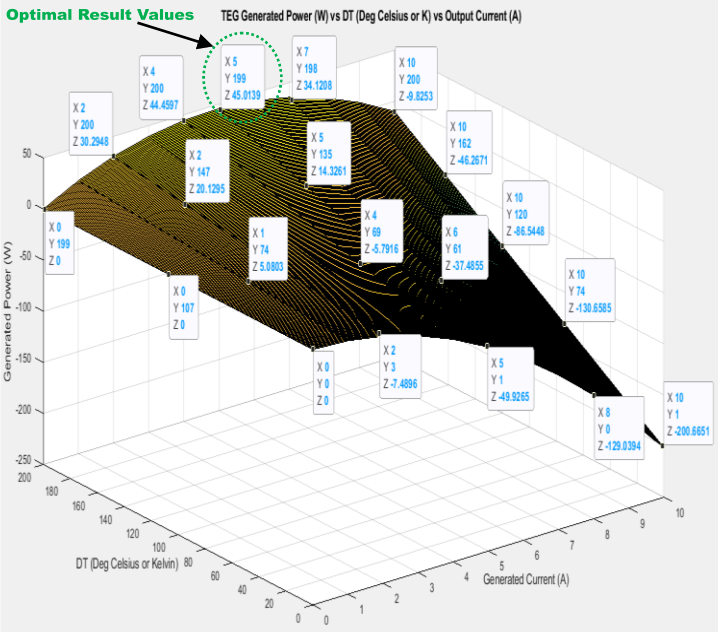

Fig. 3. TEG output power (W) vs ΔT (°C) vs output current (A)

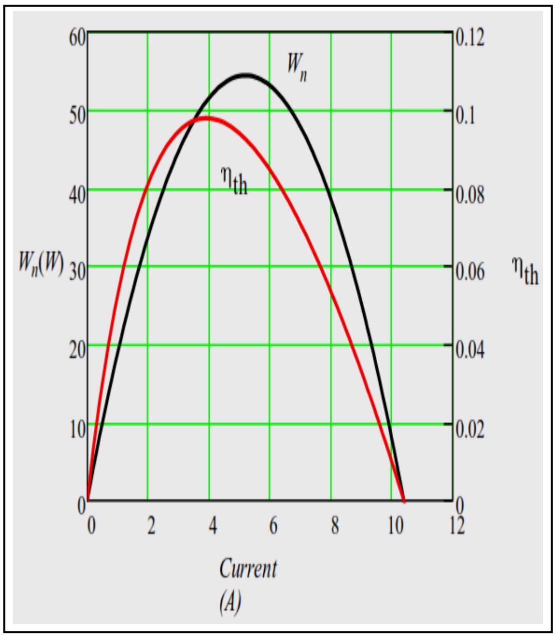

Fig. 4. Mathcad TEG (η, P_o) vs I (A) (adapted from [8])

TEG P_o is proportional to ΔT and I as shown in Fig. 3; however, I above a certain value (midpoint) as clearly evident in Fig. 5, starts to decrease P_o which is due to Joule or Ohmic heating in the TEG caused by more I. The P_o, ΔT and I optimal result is green highlighted in Fig. 3.

Akin to Fig. 5, TEG η is directly proportional to I up to 5A max, hereafter η decreases henceforth as depicted in Fig. 6 and highlighted in green. NB: Ohmic heating is proportional to current; as a result, increases the cold side temperature which reduces ΔT, P_o and subsequently η.

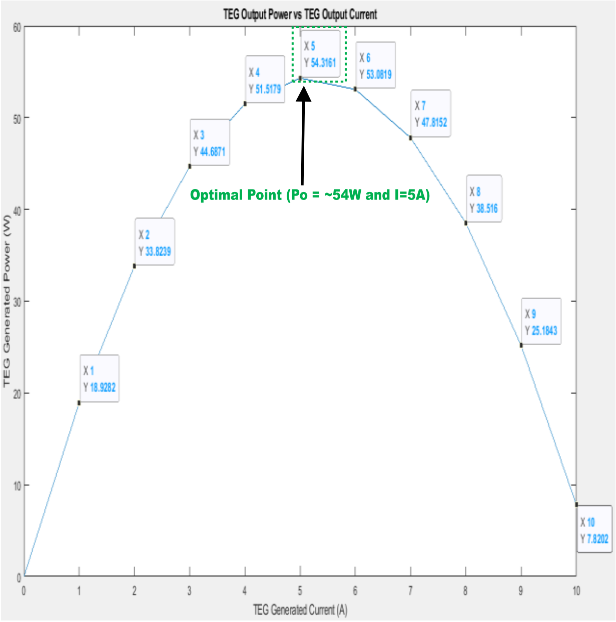

Fig. 5. TEG output power P_o (W) vs output current I (A)

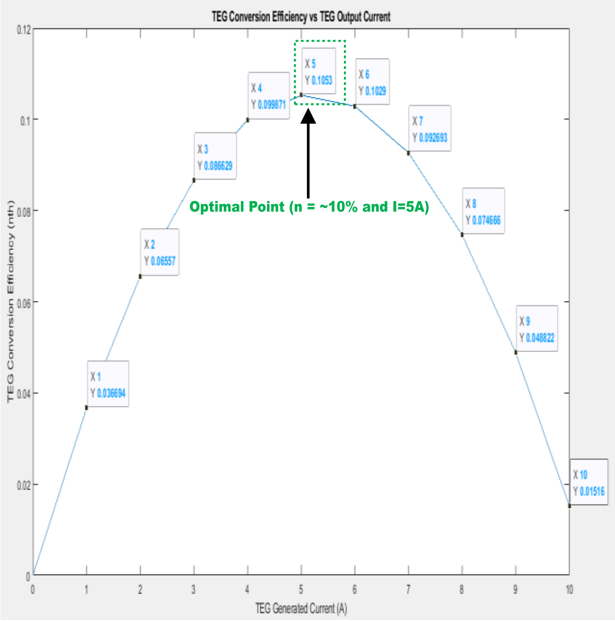

Fig. 6. TEG conversion efficiency η vs output current I (A)

V. RESEARCH SCIENTIFIC CONTRIBUTIONS

The research is herein summarised and its significance additionally to the findings established in Section III are highlighted and advanced as the scientific contributions:

- A comprehensive /extensive TEG maths is exhibited.
- A clear comprehensive TEG(s) model is instituted.
- An advanced TEG simulator is uniquely developed.
- Multiple TEGs can be simulated in various patterns.
- An efficient practical TEG(s) system can be devised.

However, the researched TEG model and mathematics have the following limitations:

- Practical realities were not factored-in, as the model focused only on theoretical TEG at unit and module levels and not at system level where other coupling factors exist. Some of these practicalities include thermal / contact resistance heat losses when TEGs are used with heat exchangers such as heat-sinks /pipes, since TEGs require thermal management to maintain ΔT to ensure proper and reliable operations.
- The researched simulated model has to be practically tested to correlate the maths and simulated analyses.

VI. CONCLUSION

This study started by briefly introducing the ongoing electricity crisis in South Africa followed by the assorted renewable energy and power sources provisions as the innovative solutions being sought after, with keen focus on waste heat and in particular low grade waste heat which is abundantly produced in various settings and notably in domestic, commercial, industrial, vehicles and appliances. This low grade waste heat energy sources make them suitable for use with TEG – a thermoelectric device that converts heat to electricity based-on Seebeck effect. The mathematical analysis of thermoelectricity with emphasis on TEG was examined, developed and elaborately presented to determine how much power can be generated and from what optimal TEG parameters. A unique TEG model in MatLab / Simulink was developed incorporating these improvements and the advance implementation was also simulated with practical TEG specifications from different manufacturers and the generated results confirmed that, to get max output power (P_o) and η from TEGs, ΔT must be highest, which will increase I until it has no confirmatory effect on η. These outcomes were analysed in conformity with information reported in scholarly TEGs publications and datasheets. The research highlights were asserted as the scientific contributions to conclude the study. The recommendation is to practically implement the research findings to correlate the TEG mathematical and simulated analyses, whereby the TEG(s) shall be used with fuel cells to innovatively convert waste heat to power in a larger Combined Cooling Heating and Power (CCHP) system.

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AUTHORS BIOGRAPHICAL STATEMENT

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Began his electrical engineering studies at CPUT inception in 2005. He obtained his ND, BTech and MTech in 2007, 2010 and 2015 respectively and also MSc in 2015 on space engineering at FSATI / ESIEE Paris. He worked at Peralex Electronics from 2006 - 2011 as production / QA technician.

From 2012 to 2019, he has been involved in various advance research projects across five different CPUT research facilities – CPUT TTO, CPUT FSATI, CPUT AMTL, CPUT CDPES and CPUT FPRC. He started his doctorate study in 2019 at CPUT and in 2020 did 6+months mobility at TU-Sofia, Bulgaria. His DEng research focuses on renewable energy and it is titled: “Model-based Domestic and Commercial CCHP / Fuel Cell / Battery / Ultra-capacitor / Thermo-Electric Hybrid Power Energy Conversion and Energy Storage Management System: A Software-Firmware-Hardware Approach”.

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Siva is the Director for HySA systems competence centre, one of three centres under Hydrogen South Africa (HySA) national frontier programme launched in 2008. He has 20 years experience in hydrogen and fuel cells technology covering from component development up to system integration.

Siva obtained his PhD from the University of Pisa, Italy in the field of fuel cells and has worked in renowned laboratories globally, including SAIAMC since 2005. Siva is driving the development of hydrogen and fuel cell technologies at HySA Systems with a focus on the commercialization of the products emanating from the RDI, having demonstrated various prototypes in this area. He is managing ~R30M per year funding from the DSI (formerly DST) and has raised significant funding from private and government. One of his activities is to protect the intellectual property of HySA Systems in line with UWC/TTO; including patents, trade secrets, copy rights and trademarks. He has organized various conferences / workshops / seminars including a National South African Hydrogen and Fuel Cell Supply Chain Workshop with the participation of over 30 companies and SMMEs. He chaired and organised the first international conference on Hydrogen and Fuel Cells in South Africa (CARISMA2014), with participation from leading researchers and businesses globally. He has published over 150 publications including papers in peer-reviewed international journals and conference proceedings and an inventor of 12 patents and counting. He was an invited speaker at several conferences, including the Zing Hydrogen and Fuel Cells Conference (July 2013) and plenary speaker at the 2nd International Symposium on Electrochemistry (July 2012).

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