Thermoelectric Generators (TEGs) and Thermoelectric Coolers (TECs) Modeling and Optimal Operation Points Investigation

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ABSTRACT

Sustainable energy is gradually becoming the norm today due to greenhouse warming effects; as a result, the quests for different renewable energy sources such as photovoltaic cells as well as energy efficient electrical appliances are becoming popular. Therefore, this article explores the alternative energy case for thermoelectricity with focus on the steady-state mathematics, mixed modelings and simulations of multiple TEGs and TECs modules to study their performance dynamics and to establish their optimal operation points using Matlab and Simulink. The research substantiates that the output current from TEGs or input current to TECs, initially respectively increases the output power of TEGs and the cooling power of TECs, until the current reaches a certain maximum optimal point, after which any further increase in the current, decreases the TEGs' and or TECs' respective output and cooling powers as well as efficiencies, due to Ohmic heating and or entropy change caused by the increasing current. The research main contributions are elaborate easy to understand TEGs/TECs theoretical formulations as well as static and dynamic simulated models in Matlab/Simulink, that can be used initially to dynamically investigate an infinite quantity of TEG and TEC modules connections, be it in series and or in parallel. This is to assist system designers grasp TEGs and TECs theoretical operations better and their limits, when designing energy efficient waste heat recovery (using TEGs)/cooling (using TECs) systems for industrial, residential, commercial and vehicular applications.

1. Introduction

According to [1], energy security and green economy are becoming paramount today; as a result, the demands for renewable and alternative energy sources such as solar, wind, hydro energy, bio-fuels and fuel cells, as well as energy efficient loads, are on the rise in an effort to ensure energy sustainability and carbon free environment. In this regards, we investigated thermoelectricity as a potential alternative energy for sustainable energy source and loads – that is, as a clean DC power source for low energy lighting/applications and as well to provide clean cooling/heating in various human habitats. Thermoelectricity as reviewed in [2], practically focuses on the Seebeck and Peltier effects. Seebeck effect is basically converting heat to DC electricity and the device that does this is a thermoelectric

generator (TEG). The reversed phenomenon is a Peltier effect – which is basically the production of cold from DC electricity and if the direction of current flow changes (swap voltage polarity), heat is also produced and the device that does this is called a thermoelectric cooler (TEC). Therefore, by efficiently applying thermoelectricity prudently, a clean alternative energy source for DC low power applications using TEGs and or energy efficient loads in the forms of heat pumps, air conditioners, refrigerators etc using TECs; can be passably implemented to help sustain some human habitats basic energy consumption such as lighting, cooling and heating; as well as reduce environmental pollution.

As already examined in [2], thermoelectricity lends itself to various applications with focus on how TEGs and TECs can be used respectively as a power source and as a load. Furthermore, studied in [3], is a re-configurable TEG DC-DC converter for maximum TEG energy harvesting in a battery-powered wireless sensors network (WSN). Described in [4], is the analysis and design of a thermoelectric energy harvester (TEH) prototype for

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powering up outdoor sensors and devices. Solar energy was harvested using different TEG arrays in [5] and a theoretical analysis of implementing a re-configurable TEG was researched in [6]. Electronic cooling was investigated in [7] and the findings revealed that the TEC cooling capacity could be increased by increasing its cold side junction temperature and decreasing its temperature difference. A multi-stage TEC module in cascade was examined in [8]; whereas in [9], an extensive mathematical analyses were articulated for TEG and TEC design and materials. A TEG model was developed in [10] for maximum power point tracking but lacks the detailed underlining maths and the parallel TEG combinations was limited to just 2. A comprehensive TEG and TEC models with the detailed maths supporting the TEG and TEC models, were presented respectively in [11] and [12]. In [13], a modeling of TEG using Modelica is asserted but deficient in the comprehensive maths, especially considering modeling infinite multiple TEGs and as well TECs modules — which were not articulated. A parametric ANSYS study of TEG and TEC was presented in [14]; however, the detailed maths and especially for the case for infinite TEG and TEC modules use/ connection, was inadequate. In addition, for large scale TEGs and TECs applications, the following studies were examined. In [15], 600 TEGs with a temperature difference of $\sim 120^\circ\text{C}$, were applied to harvest and generate up to 1 kW of DC power from geothermal heat. It was further indicated a 2 kW power could be achieved with a higher temperature difference and also the TEG cost is much lower to generate equivalent amount of power than using photovoltaic. However, the study lacks the theoretical details to substantiate it. TEG harvesting of waste thermal energy from household heat sources such as a generator exhaust pipe and a kerosene stove, were performed in [16] and various parameters measurements were made but without detailing the maths to calculate these parameters. Light and heat from the Sun are the most common forms of energy abundant on Earth; as a result, [17] reviewed the possibility of integrating photovoltaic and TEG in a hybrid photovoltaic-TEG system and further examined the efficiency improvement. A 128 TEGs system was assembled in [18] to generate $\sim 684\text{ W}$ of power from radiation heat transfer at a temperature difference of $\sim 125\text{ K}$ and with a corresponding power density of 845 W/m^2 . Their results further justified that with a greater practical temperature difference of 200 K , the respective generated power and power density of their TEGs system could attain 1.23 kW and 1.51 kW/m^2 . Their TEGs system open circuit voltage, its output power, its power density and its conversion efficiency were investigated in details at different temperature differences; however, the underlining maths was not elaborated. A grid-tied 20 W TEG experimental model using 24 modules in series with the heat harvested from a waste incinerator, was experimented in a lab and the preliminary and analytical models of the electric output power as a function of specific temperatures, were investigated in [19]. A micro combined cold, heat and power system for a small household with a TEC as the cooler and achieving a cooling power of 26.8 W , was presented in [20]. In [21], a 3D printable TEG device architecture with a high thermocouple density of 190 per cm^2 by using a thin substrate as an electrical insulation between the thermoelectric elements, resulted in a high-power output of $47.8\text{ }\mu\text{W/cm}^2$ from a 30 K

temperature difference. A stove-powered TEG (SPTEG) was used in [22] to generate power from waste heat released during cooking. They researched series and parallel TEGs connections and the effect of pressure to address low power output due to irregular temperature. Finally, an experimental and a numerical investigations on TECs for comparing air-to-air and air-to-water refrigeration were investigated in [23], with the findings revealing that air-to-water achieves 30-50% efficiency, compared to air-to-air cooling.

These are just a few noted studies; however, lacking in the TEGs/TECs literature are comprehensive details on their maths, modeling and operations when connected in series and also in parallel to increase the output power (in the case of TEG) and the cooling power (in the case of TEC). This article therefore, expands on i) developing and expressing further the theoretical maths covering TEGs and TECs various parameters/modules with focus on the total internal resistance, ii) the modeling of multiple TEGs and TECs modules focusing on their electrical parameters and finally iii) their static and dynamic simulations with focus on the optimal operation points investigation as well as the interpretations thereof. The results are then validated with established published studies and concluding remarks are drawn.

2. TEGs and TECs Mathematical Analyses and Modeling

In [9], [11] and [12], the standard static mathematics defining various TEG and TEC parameters as well as their modeling are demonstrated. We developed further and present in the following sections: i) TEGs and TECs maths and ii) the implemented models (based on their maths) using Matlab/Simulink and the simulations of TEG/TEC modules, be it in series and or in parallel connections.

2.1. TEGs and TECs Steady-state Mathematical Analyses

The derivations thus far of the TEG and TEC parameters have been based-on the p-n junction thermoelement resistance at the thermocouple level and by extension at the module level as indicated in [9], [11] and [12]. However, in practice, more than one TEG and TEC modules will be needed for more power production and this will take the form of series and or parallel connections; as a result, the electrical resistance will often change. This section redefines the change in R to R_t and is articulated next.

(I) TEGs Steady-state Mathematical Analysis

The following TEG parameters mathematics are developed and presented step-wise for multiple TEGs case as follows:

- Thermoelectric (TE) device p-n junction thermocouple resistance (r)

The TE device p-n thermocouple resistance r in ohm is:

$$r = \rho L/A \quad (\Omega) \quad (1)$$

with ρ being the TEG/TEC electrical resistivity in $\Omega\cdot\text{m}$, L is the length in (m) of the TEG/TEC p-n thermocouple and the TEG/TEC p-n thermocouple area is A in metre squared (m^2).

- TE device (TEG and TEC) module resistance (R)

The resistance in (Ω) of a TEG/TEC module is computed as:

$$R = nr \quad (\Omega) \quad (2)$$

where n (which differs, could be 100, 127, 199, 255 etc) is a TEG/TEC manufacturer p-n thermocouples amount used in a TEG/TEC. The more the n , the more powerful is the TEG/TEC.

- TEG/TEC module(s) total resistance (R_t)

The total resistance R_t in (Ω) of a TEG/TEC module(s) is simply calculated as:

$$R_t = n \frac{T_s}{T_p} r = R \frac{T_s}{T_p} \quad (\Omega) \quad (3)$$

with T_p being the TEGs/TECs (TEG/TEC modules) amount connected in parallel and T_s the TEGs/TECs (TEG/TEC modules) amount connected in series. NB: all the TEGs/TECs used in (3), have to be identical model to make sure the R of each TEG/TEC is not vastly different; if not, (3) would be inaccurate.

- TEG(s) output voltage (V_o)

The TEG(s) voltage generated in volt, can be derived as:

$$V_o = nS\Delta T - IR_t \quad (V) \quad (4)$$

with S being the TE device Seebeck coefficient in V/K, $\Delta T = T_h - T_c$ the TEG(s) temperature difference in kelvin or °C and the output current of the TEG(s) is I in ampere.

- TEG(s) output current (I)

The TEG(s) generated current I in ampere is deduced as:

$$I = \frac{nS\Delta T}{R_L + R_t} \quad (A) \quad (5)$$

with R_L being the resistance of the electrical load connected to the TEG(s) output. NB: more I causes the TEG(s) more Joule heating, which negatively affects the TEGs efficiency.

- TEG(s) hot-side heat absorbed (Q_h)

TEG(s) produce DC power when their hot-side is at a high temperature T_h , during which the TEG(s) becomes hotter and the absorbed heat in watt is Q_h , given as:

$$Q_h = n[(SIT_h) + (K\Delta T)] - 0.5I^2R_t \quad (W) \quad (6)$$

with K being the TEG(s) thermal conductance in W/K.

- TEG(s) cold-side heat emitted (Q_c)

TEG(s) produce DC power when the cold-side of the TEG(s) is at a low temperature T_c releasing the heat Q_c in watt.

$$Q_c = n[(SIT_c) + (K\Delta T)] + 0.5I^2R_t \quad (W) \quad (7)$$

- TEG(s) output power (P_o)

The TEG(s) modules generated power P_o in watt, is found variously as follows:

$$P_o = Q_h - Q_c \quad (W) \quad (8)$$

$$P_o = IV_o = n[(S\Delta T)] - I^2R_t \quad (W) \quad (9)$$

- TEG(s) electrical/conversion/thermal efficiency (η)

η is the TEG(s) power output P_o divided by the TEG(s) hot-side heat absorbed Q_h . η being a performance parameter is:

$$\eta = P_o/Q_h \quad (10)$$

The conversion efficiency details is presented later.

- TEG/TEC Carnot's efficiency (η_c)

Carnot efficiency is the efficiency determined based-on the temperatures T_h and T_c .

$$\eta_c = \frac{\Delta T}{T_h} = \frac{T_h - T_c}{T_h} = 1 - \frac{T_c}{T_h} \quad (11)$$

- TEG(s) conversion efficiency expression (η_e)

Simply, η_e is the raw expression of η . That is, when equations of Q_h and P_o (respectively (6) and (8) or (9)) are both substituted in (10).

$$\eta_e = \eta_c \frac{(nR_L/R_t)}{[(1+nR_L/R_t) - 0.5\eta_c + ((1/(2Z\bar{T}))(1+nR_L/R_t)^2(1+T_c/T_h))]} \quad (12)$$

with $Z\bar{T}$ being the TE device average dimensionless merit figure. NB: Z is the TE device merit figure in per K (K^{-1}) and $\bar{T} = (T_h + T_c) / 2$, is the TE device average temperature in K.

- TEG(s) maximum conversion efficiency (η_m)

η_m is the efficiency of the TEG(s) at $R_t/R_L = \sqrt{1 + Z\bar{T}}$. The η_m expression as a function of TEG temperatures and Z is:

$$\eta_m = \eta_c \left(\frac{(\sqrt{1+Z\bar{T}}) - 1}{(\sqrt{1+Z\bar{T}} + (T_c/T_h))} \right) \quad (13)$$

- TEGs maximum power conversion efficiency (η_{mp})

As a function of temperatures and Z , η_{mp} is the efficiency of the TEG at its maximum output power P_o – that is, at $R_t = R_L$.

$$\eta_{mp} = \eta_c/[2 - 0.5\eta_c + (2/Z\bar{T})(1+T_c/T_h)] \quad (14)$$

- TEG(s) maximum power output ($P_{o_{max}}$)

The TEG(s) maximum transfer of power theoretically happens at $R_t = R_L$. NB: in practice, $R_t = R_L$ is hardly ever the case.

$$P_{o_{max}} = (nS\Delta T)^2(R_L/R_t)/R(1+(R_L/R_t))^2 \quad (W) \quad (15)$$

- TEG(s) maximum voltage output ($V_{o_{max}}$)

TEG(s) $V_{o_{max}}$ happens at open circuit, that is when R_L is not connected or R_L is infinity (extremely large), $I = 0A$.

$$V_{o_{max}} = nS(T_h - T_c) = nS\Delta T \quad (V) \quad (16)$$

- TEG(s) maximum current output (I_{max})

TEG(s) I_{max} happens at short circuit – meaning, when the load R_L is 0Ω . NB: R_t will therefore ideally be the sole resistance.

$$I_{max} = nS\Delta T/R_t = nS(T_h - T_c)/R_t \quad (A) \quad (17)$$

- TEG(s) generated current normalized (I_n)

I_n is the normalized current of the TEG(s) in the range $0 \leq I_n \leq 1$. At the TEG(s) maximum transfer of power ($R_t = R_L$), $I_n =$

0.5. Simply, I_n is the TEG(s) generated current divided by the TEG(s) maximum current output. It is calculated as:

$$I_n = \frac{I}{I_{Max}} = \frac{R_t}{R_t + R_L} \quad (18)$$

- TEG(s) generated voltage normalized (V_n)

V_n is the normalized voltage of the TEG(s) ranging from $0 \leq V_n \leq 1$. At the TEG(s) maximum transfer of power (i.e. $R_L = R_t$), $V_n = 1/2$. V_n is the TEG(s) voltage generated divided by the TEG(s) maximum (ideal) voltage generated. It is given as:

$$V_n = \frac{V_o}{V_{Omax}} = \frac{R_L}{R_L + R_t} \quad (19)$$

- TEG(s) output power normalized (P_n)

P_n is the normalised TEG(s) power bounded between $0 \leq P_n \leq 1$. $P_n = 1$ at the TEG(s) maximum transfer of power ($R_L = R_t$). P_n is the TEG(s) power generated divided by the TEG(s) maximum output power. It is expressed as:

$$P_n = \frac{P_o}{P_{Omax}} = \frac{4(R_L/R_t)}{[(R_L/R_t) + 1]^2} \quad (20)$$

- TEG(s) conversion efficiency normalized (η_n)

η_n is the conversion efficiency of the TEG(s) in the region $0 \leq \eta_n \leq 1$. η_n depends on R_t/R_L , T_c/T_h and $Z\bar{T}$. η_n is the conversion efficiency of the TEG(s) divided by the maximum conversion efficiency of the TEG(s), deduced as:

$$\eta_n = \eta/\eta_m \quad (21)$$

- TEG(s) effective Seebeck coefficient (S_e)

S_e measured in volt/kelvin, is expressed as:

$$S_e = 4P_{Omax}/(nI_{max}\Delta T) \quad (\text{V/K}) \quad (22)$$

- TEG(s) effective electrical resistivity (ρ_e)

ρ_e measured in ohm metre, is found using:

$$\rho_e = 4[(A/L)P_{Omax}]/nI_{max}^2 \quad (\Omega.m) \quad (23)$$

- TEG(s) effective figure of merit (Z_e)

Z_e measured in per kelvin, is computed as:

$$Z_e = [(2/\bar{T})(1 + (T_c/T_h))]/[\eta_c((1/\eta_{mp}) + 0.5) - 2] \quad (\text{K}^{-1}) \quad (24)$$

- TEG(s)/TEC(s) effective thermal conductivity (k_e)

k_e measured in watt per metre kelvin, is expressed as:

$$k_e = S_e^2/(\rho_e Z_e) \quad (\text{W/mK}) \quad (25)$$

TEGs/TECs effective parameters enable researchers to factor in TEGs/TECs system losses using maximum parameters to bridge the theoretical and measured specifications differences [9].

- TEG(s) Heat Flux Density (HFD)

HFD is the amount of heat absorbed per TEGs hot-side surface area ($TEGsa$) in watt per centimetre square.

$$HFD = Q_h/TEGsa \quad (\text{W/cm}^2) \quad (26)$$

This concludes the TEG(s) modules static mathematical analysis.

(II) TECs Steady-State Mathematical Analysis

The following TEC parameters mathematics are examined and developed step-wise for multiple TECs case as follows:

- TEC(s) voltage input (V_{in})

The TEC(s) applied voltage in volt, is expressed as:

$$V_{in} = n[S(T_h - T_c)] + I_{in}R_t \quad (\text{V}) \quad (27)$$

where I_{in} is the TECs input current from the power supply.

- TEC(s) input current (I_{in})

The TECs input current in ampere is derived as:

$$I_{in} = \frac{nS\Delta T}{R_s - R_t} \quad (\text{A}) \quad (28)$$

where R_s is the internal source electrical resistance of the power supply connected to the TECs.

- TEC(s) cold-side heat absorbed (Q_c)

TECs create cold when their cold-side is at a low temperature T_c to absorb heat and supply a steady cooling power Q_c in W.

$$Q_c = n[(SI_{in}T_c) - (K\Delta T)] - 0.5I_{in}^2R_t \quad (\text{W}) \quad (29)$$

- TEC(s) hot-side heat emitted (Q_h)

TECs produce cold when their hot-side is at a high temperature T_h emitting the heat Q_h in watt.

$$Q_h = n[(SI_{in}T_h) - (K\Delta T)] + 0.5I_{in}^2R_t \quad (\text{W}) \quad (30)$$

- TEC(s) power input (P_{in})

The applied power P_{in} in watt required to power the TECs, is calculated variously as follows:

$$P_{in} = Q_h - Q_c = n[(SI_{in}\Delta T)] + I_{in}^2R_t \quad (\text{W}) \quad (31)$$

$$P_{in} = I_{in}V_{in} \quad (\text{W}) \quad (32)$$

- TEC(s) coefficient of performance (CoP)

This is TECs cooling power Q_c divided by its input power P_{in} .

$$CoP = Q_c/P_{in} \quad (33)$$

- TEC(s) CoP Expression (CoP_e)

CoP_e is the raw expression of CoP when the equations of Q_c and P_{in} (respectively (29) and (31) or (32)) are put in (33).

$$CoP_e = \frac{[(SI_{in}T_c) - (K\Delta T)] - (0.5I_{in}^2R_t/n)}{[(SI_{in}\Delta T) + (I_{in}^2R_t/n)]} \quad (34)$$

- TEC(s) current to yield CoP (I_{cop})

I_{cop} is the TECs input current in (A) needed to attain CoP .

$$I_{cop} = \frac{nS\Delta T}{R_t[(\sqrt{1+ZT})-1]} \quad (A) \quad (35)$$

- TECs maximum CoP (CoP_{max})

CoP_{max} is the TECs maximum CoP that can be achieved.

$$CoP_{max} = \frac{[T_c/\Delta T][(\sqrt{1+ZT}) - \frac{T_h}{T_c}]}{((\sqrt{1+ZT})+1)} \quad (36)$$

- TEC(s) maximum cooling power current ($I_{cp_{max}}$)

$I_{cp_{max}}$ is TECs current in ampere needed to realise max Q_c .

$$I_{cp_{max}} = nST_o/R_t \quad (A) \quad (37)$$

- TEC(s) I_{cop} maximum cooling power ($Q_{cp_{max}}$)

$Q_{cp_{max}}$ in (W), is TECs maximum Q_c attained based-on I_{cop} .

$$Q_{cp_{max}} = n[(SI_{cop}T_c) - (K\Delta T)] - 0.5I_{cop}^2R_t \quad (W) \quad (38)$$

- TEC(s) maximum temperature difference (ΔT_{max})

TEC(s) ΔT_{max} in (K), occurs at maximum I_{in} and at $Q_c = 0W$.

$$\Delta T_{max} = \left(T_h + \frac{1}{Z}\right) - \sqrt{\left(T_h + \frac{1}{Z}\right)^2 - T_h^2} \quad (K) \quad (39)$$

- TEC(s) maximum input current (I_{max})

I_{max} is TEC(s) maximum input current in (A) at $Q_c = 0W$.

$$I_{max} = nS(T_h - \Delta T_{max})/R_t \quad (A) \quad (40)$$

- TEC(s) maximum input voltage ($V_{in_{max}}$)

$V_{in_{max}}$ is the maximum V_{in} in volt, that produces maximum ΔT_{max} when $I_{in} = I_{max}$, $R_t=0$, $T_c = 0$, $Q_c = 0$ and T_h is maximum.

$$V_{in_{max}} = nST_h \quad (V) \quad (41)$$

- TEC(s) maximum cooling power ($Q_{c_{max}}$)

$Q_{c_{max}}$ is the maximum absorbable heat or cooling power in watt, at $I_{in} = I_{max}$ and $\Delta T = 0^\circ C$.

$$Q_{c_{max}} = (nS)^2(T_h^2 - \Delta T_{max}^2)/2R_t \quad (W) \quad (42)$$

- TEC(s) input current normalized (I_{in_n})

TEC(s) I_{in_n} is I_{cop} divided by I_{max} .

$$I_{in_n} = I_{cop}/I_{max} \quad (43)$$

- TEC(s) input voltage normalized (V_{in_n})

TEC(s) V_{in_n} is V_{in} divided by $V_{in_{max}}$.

$$V_{in_n} = V_{in}/V_{in_{max}} \quad (44)$$

- TEC(s) cooling power normalized (Q_{c_n})

TEC(s) Q_{c_n} is Q_c divided by $Q_{c_{max}}$.

$$Q_{c_n} = Q_c/Q_{c_{max}} \quad (45)$$

- TEC(s) CoP normalized (CoP_n)

TEC(s) CoP_n is CoP divided by CoP_{max} .

$$CoP_n = CoP/CoP_{max} \quad (46)$$

- TEC(s) normalized temperature difference (ΔT_n)

TECs ΔT_n , is ΔT divided by ΔT_{max} and it is expressed as:

$$\Delta T_n = \Delta T/\Delta T_{max} \quad (47)$$

Normalized parameters give dimensionless parameters.

- TEC(s) effective Seebeck coefficient (S_e)

TECs S_e measured in VK^{-1} , is defined as:

$$S_e = 2Q_{c_{max}}/[nI_{max}(T_h + \Delta T_{max})] \quad (V/K) \quad (48)$$

- TEC(s) effective electrical resistivity (ρ_e)

TECs ρ_e measured in ohm metre, is written as:

$$\rho_e = AS_e(T_h - \Delta T_{max})/LI_{max} \quad (\Omega.m) \quad (49)$$

- TEC(s) effective figure of merit (Z_e)

TECs Z_e measured in per kelvin, is given as:

$$Z_e = 2\Delta T_{max}/(T_h - \Delta T_{max})^2 \quad (K^{-1}) \quad (50)$$

- TEC(s) midpoint current (I_{mid})

I_{mid} measured in ampere, is the mean of $I_{cp_{max}}$ and I_{cop} .

$$I_{mid} = 0.5(I_{cp_{max}} + I_{cop}) \quad (A) \quad (51)$$

- TEC(s) midpoint cooling power ($Q_{c_{mid}}$)

$Q_{c_{mid}}$ measured in watt, is expressed as:

$$Q_{c_{mid}} = n[(SI_{mid}T_c) - (K\Delta T)] - 0.5I_{mid}^2R_t \quad (W) \quad (52)$$

- TEC(s) midpoint input power (Pin_{mid})

Pin_{mid} measured in watt, is deduced as:

$$Pin_{mid} = n[(SI_{mid}\Delta T)] + I_{mid}^2R_t \quad (W) \quad (53)$$

- TEC(s) midpoint CoP (CoP_{mid})

CoP_{mid} is computed as:

$$CoP_{mid} = Q_{c_{mid}}/Pin_{mid} \quad (54)$$

Midpoint parameters ascertain safer optimal TECs design.

- TEC(s) cold flux density (CFD)

CFD is the cold amount produced (heat absorbed) per TECs cold-side surface area ($TECsa$) in W/cm^2 . It is computed as:

$$CFD = Q_c/TECsa \quad (W/cm^2) \quad (55)$$

2.2. TEGs and TECs Modelling and Simulations

Covered in Section 2.1., are the TEGs and TECs parameters of interests — which were extensively expressed mathematically with emphasis/basis on the total internal resistance R_t — which was derived and the regular TEG/TEC equations re-expressed based-on R_t to now cover TEG(s)/TEC(s). The above equations are herein further modeled in Matlab and Simulink, to institute the TEGs and TECs models that can now be utilized to simulate and investigate many connected TEGs and TECs optimal performance.

Exemplified in Figures 1a and 1b, are the TEGs static and dynamic simulated model GUIs, from which the TEGs parameters expressed in Section 2.1.I, can all be statically and dynamically configured for an infinite amount of TEGs connections and then simulated to obtain the TEG(s) optimum operation points. Figures 1c and 1d zoom-in on the TEGs internal modeling. Figure 1e expands on the TEGs R_i modeling – this must be matched to the load resistance R_L

– which can be changed before or while the simulation is running to match the TEGs R_i for maximum power transfer simulation. Figure 2 exemplifies the TECs simulator user interface. Also, multiple TECs combinations in T_s and T_p and the various parameters presented in Section 2.1.II, can be optimally simulated. Likewise, maximum power will be transferred also from the DC power supply to the TECs by matching its R_i to R_s .

Figure 1a: TEG(s) static simulator user's interface – shows the steady-state simulation with all the input parameters fixed (though can change) over-time

Figure 1b: TEG(s) dynamic simulator user's interface – shows the transient simulation with the T_p , T_c , T_s and T_p input parameters auto changing with time

Figure 1e: TEG(s) modeling and simulation – TEG(s) automatic internal source total electrical resistance R_t

Figure 2: TEC(s) simulator – simulates TECs various parameters by inputting a TEC specific data sheet parameters and calculates its theoretical outputs

3. TEGs and TECs Simulations Results

The TEGs and TECs simulations results are presented in three parts as follows, the i) TEGs parameters static simulation results ii) TECs parameters static simulation results and iii) TEGs parameters dynamic simulation results. Understanding these parameters operation is very paramount; otherwise, doing the physical design would just be a matter of taking chances and hoping for the best – which is sometimes the case, as most designers have reported very bad design results, likely from not

understanding TE devices dynamic operations and limitations. The results from investigating the TEG(s) and TEC(s) parameters optimal operation points are discussed in details in Section 4.

3.1. TEGs Parameters Static Simulation Results

Figures 3 – 6 expound the TEGs parameters simulated to determine their optimal operation points – marked in green.

Figure 3: TEG power output P_o (W) vs temperature difference ΔT ($^{\circ}\text{C}$) vs current output I (A)

Figure 4: TEG conversion efficiency η vs current output I (A)

Figure 5: TEG power output P_o (W) vs r or R or R_t (Ω) vs current output I (A)

Figure 6: TEG absorbed heat Q_h (W) vs temperature difference ΔT ($^{\circ}\text{C}$) vs output current I (A)

Figure 9: TEC input power P_m (W) vs internal resistance r or R or R_i (Ω) vs input current I_m (A)

Figure 10: TEC coefficient of performance CoP (%) vs temperature difference ΔT ($^{\circ}\text{C}$) vs input current I_m (A)

3.3. TEGs Parameters Dynamic Simulation Results

TEG modules temperatures, its series and parallel connections dynamic simulation results are depicted in Figures 11a - 11f.

Figure 11a: 36 TEGs hot (T_h) and cold (T_c) temperatures as well as temperature difference (DT) dynamics – temperature changes as simulation progresses

Figure 11b: TEGs in series (T_s), parallel (T_p) and total internal resistance (R_t) dynamics – 36 TEG modules simulated in 10 different auto reconfiguration

Figure 11c: 36 TEGs ideal output power, voltage and current dynamics; as TEGs temperatures and its 10 configurations change as simulation progresses

Figure 11d: 36 TEGs total internal resistance current, voltage and power losses dynamics; as the TEGs 10 configurations and temperatures auto change

Figure 11e: 36 TEGs output power, voltage and current dynamics as the TEGs temperatures and 10 configurations auto change as simulation progresses

Figure 11f: 36 TEGs boost converter output power, voltage and current dynamics as the TEGs temperatures and the TEGs 10 configurations auto change

4. TEGs and TECs Simulations Results Discussions

The TEGs/TECs simulations results demonstrated in Section 3, are engaged below in their following respective sub-sections.

4.1. TEGs Parameters Static Simulation Results Discussion

Some of the crucial TEGs parameters simulated in Section 3.1. and the significance of the results are herein asserted. As exemplified in Figure 3, a TEGs generated power P_o is proportional to its temperature difference ΔT and output current I ; however, I above 5A (in this case) will decrease P_o – which is because of the TEGs internal Ohmic heating as a result of the increasing output current I . The ΔT , P_o and I optimum operation points are emphasized in green in Figure 3. In Figure 4, a TEGs conversion efficiency η is directly proportional to current output I up to ~5A max (in this case) and decreases later as highlighted in green. It should be noted that η is as well directly proportional to P_o . However, a TEG P_o is reciprocally proportional to its p-n thermocouple junction resistance r and as well to its total internal resistance R_i (more than one connected TEG modules), though pro rata to I up to ~5A (in this case) as portrayed in Figure 5. At this optimal point; R_i or R is 0Ω , I is ~5A maximum and P_o is ~105W as highlighted in green. In Figure 6, the TEGs current output I is proportional directly to the TEGs absorbed heat Q_h (at temperature T_h on the TEG hot-side) which in turn is directly dependent on the TEG ΔT . Figure 6 pictured the optimum point stressed-out in green. It should be noted that these results are not specific to a particular TEGs' connections – the results just fundamentally give a holistic theoretical understanding on what TEGs physical parameters must be taken into considerations, how they are interrelated, their associated dynamics and technical limitations and how they can be practically traded-off or optimized for optimal performance when designing TEGs power supply systems.

Figure 12: Validating our model with [9] – TEG (i) output power $P_o \approx 55W$ vs output current $I \approx 5A$ validating our Figure 3 result and (ii) conversion efficiency $\eta \approx 10\%$ vs output current $I \approx 4A$ validating our Figure 4 result.

Depicted in Figure 12, is a result of a typical TEG model simulated with Mathcad using TEG standard specifications from typical manufacturers data-sheet as presented in [9]. This was used as a benchmark to validate our TEG model simulation accuracy – which is very close, besides a few discrepancies due to minor simulation settings differences. In light of this, our implemented TEG model can be used and developed further to simulate TEGs, including infinite series and parallel connections, which are central to our research and in large scale TEGs uses.

4.2. TECs Parameters Static Simulation Results Discussion

Some of the critical TECs parameters simulated in Section 3.2. and the importance of the results are herein articulated. Figure 7 illustrates that TECs Q_c on TECs cold-side T_c , is reciprocally proportional to ΔT but proportional directly to I_{in} up to a maximum point, after which Q_c starts dropping. The reasons are due to i) Joule heating (the more I_{in} , the more the internal heating effect) and also ii) the second law of thermodynamics – simply put, heat flows from a hotter to a colder body; in this regards, the heating caused by the increasing I_{in} , increases the TECs internal temperature up to a temperature greater than that surrounding the TECs hot-side T_h ; consequently, heat now starts to flow from the TECs hot-side to its cold-side, thus making the cooling process (heat pumping) on the TECs cold-side inefficient. In Figure 7 and highlighted in red, the Q_c , ΔT and I_{in} ; display three optimal operation points depending on the TECs design constraints/ priorities. In option 1, Q_c is 115.677W with a ΔT of $1^\circ C$ and I_{in} of 6A. In option 2, Q_c is 110.668W with a ΔT of $19^\circ C$ and I_{in} of 14A. In option 3, Q_c is 105.664W with a ΔT of $4^\circ C$ and I_{in} of 16A. As evident, either ΔT and or I_{in} depending on the design constraints, can be optimized by either minimizing the TECs ΔT and or maximizing TECs I_{in} to increase Q_c within max operational limits. In Figure 8, P_{in} and I_{in} are directly proportionally, which will initially increase Q_c until a certain maximum limit, after which increasing P_{in} and I_{in} drop Q_c – contrary to ΔT which is inversely proportional to Q_c . The optimal operation point is highlighted in red. Figure 9 shows a TECs P_{in} vs I_{in} vs R . Normally R is set fixed when designed by the manufacturer but now, with R_i introduced, R can be fairly altered and if it is matched to R_s , maximum power will be transferred to the TEC(s); thereby, optimizing P_{in} and maximizing Q_c as highlighted in red. Figure 10 demonstrates how CoP akin to Q_c ; increases with decreasing ΔT and initially with increasing I up to a maximum value and then starts decreasing, as current I increases as shown variously in Figure 10. Depending on the design constraints, two optimal CoP operation points are evident as highlighted in red – in optimal operation point 1, a CoP of 3.3763 is achievable by minimizing I_{in} to 1.8644A and maximizing ΔT to $9.322^\circ C$; whereas in optimal operation point 2, a CoP of 3.3638 is attainable by maximizing I_{in} to 2.9831A and minimizing ΔT to $0^\circ C$. Finally, our TECs model is reasonably validated by comparing a specific Q_c of Figure 7 with that of Figure 13, as shown. The discrepancy is due to different TECs parameters setting. In sum, understanding the theory of TECs parameters and taking the various operational dynamics involved into considerations are very crucial in TEC(s) design/performance.

Figure 13: Validating our model with Lee, 2016 [9] – using TEC cooling power $Q_c \approx 8W$ vs input current $I \approx 1.5A$ vs $\Delta T \approx 30^\circ C$ to validate our TECs Q_c in Figure 7 result with cooling power $Q_c \approx 16W$ vs input current $I \approx 2A$ vs $\Delta T \approx 30^\circ C$.

4.3. TEGs Dynamic Simulation Results Discussion

Some of the critical TEGs dynamic simulated in Section 3.3. and the importance of the results are herein discussed. The TEGs temperatures and modules electrical connections (series, parallel, series/parallel) dynamics were simulated. In which beginning with the TEGs temperature dynamics, various arbitrary temperatures on the TEGs hot and cold sides as demonstrated in Figure 1b and Figure 11a, as well as summarized in Table 1, were simply dynamically simulated using time-series inputs. As expected, the TEGs dynamically generated power, voltage and current; increased with increasing T_h and DT but with decreasing T_c .

Table 1: TEGs time-series inputs dynamic simulations results summary

Parameters	Matlab / Simulink Simulation Time									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Figure 11a										
TEG modules T_h, T_c and DT dynamic temperature inputs in $^\circ C$										
TEGs T_h	60	120	125	75	100	80	65	85	200	150
TEGs T_c	10	20	25	30	35	15	40	0	5	45
TEGs DT	50	100	100	45	65	65	25	85	195	105
Figure 11b										
36 TEG modules in 10 dynamic T_s, T_p, T_i and R_i auto configuration										
T_s	36	18	12	9	6	6	4	3	2	1
T_p	1	2	3	4	6	6	9	12	18	36
T_i	36	36	36	36	36	36	36	36	36	36
R_i (Ω)	54.86	13.72	6.09	3.42	1.52	1.52	0.67	0.38	0.16	0.04
Figure 11c										
36 TEG modules ideal (if $TEG_{R_{int}} = 0$) power, voltage and current										
$TEG_{P_{ocM}}$ (W)	129.1	479.4	423.2	70.8	108.8	108.3	7.99	73.6	196.1	12.2
$TEG_{V_{oc}}$ (V)	85.7	285.7	257.1	19.2	18.5	18.5	4.7	12.1	18.5	5
$TEG_{I_{oc}}$ (A)	1.50	5.59	3.74	0.67	5.86	5.83	1.67	6.06	10.56	2.44
Figure 11d										
36 TEG modules internal resistance power, voltage and current										
$TEG_{R_{int}}$ (Ω)	54.86	13.72	6.09	3.42	1.52	1.52	0.67	0.38	0.16	0.04
$P_{TEG_{R_{int}}}$ (W)	124.5	429	334.3	46.2	52.3	51.8	1.9	14	18.8	0.25
$V_{TEG_{R_{int}}}$ (V)	82.6	276.7	145.1	12.6	8.9	8.8	1.1	2.3	1.7	0.01
$I_{TEG_{R_{int}}}$ (A)	1.50	5.59	3.74	0.67	5.86	5.83	1.67	6.06	10.56	2.44
Figure 11e										
36 TEG modules generated (terminal) power, voltage and current										
$P_{TEG_{out}}$ (W)	4.65	50.4	88.9	24.5	56.5	56.4	6.0	59.6	177.3	11.9
$V_{TEG_{out}}$ (V)	3.09	19.0	16	6.6	9.6	9.6	3.6	9.8	16.7	4.8
$I_{TEG_{out}}$ (A)	1.50	5.59	3.74	0.67	5.86	5.83	1.67	6.06	10.56	2.44
Figure 11f										
36 TEG modules boost converter output power, voltage and current										
$P_{conv_{out}}$ (W)	3.44	54.4	82.2	22.9	51.2	51.2	5.3	53.3	167.5	11.7
$V_{conv_{out}}$ (V)	2.29	18.1	19.3	11.2	5.9	5.8	2.8	9.0	15.9	4.1
$I_{conv_{out}}$ (A)	1.50	5.37	6.34	3.8	5.7	5.8	1.8	5.9	10.4	2.7

The TEG modules quantity used and most vitally in series, parallel and mixed connection were simulated, whereby as shown in Figure 1b and Figure 11b, as well as summarized in Table 1; 36 TEGs were arbitrary chosen and then arranged in 10 different combinations to study the effects of the various arrangements and when matched to a 1.524Ω electrical load. Each arrangement gives a different R_i , consequently giving different generated powers, voltages and currents. Figure 11c depicts the TEGs ideal power, voltage and current generated – assuming the TEGs R_i or $TEG_{R_{int}}$ is trivial. Figure 11d shows the power loss, voltage drop and Ohmic current due to the presence of $TEG_{R_{int}}$. Finally, Figures 11e and 11f, show the resultant output power, voltage and current supplied to the DC-DC boost converter and from it. As apparent, more TEG modules increased the output values; however, what is more insightful is how TEGs opt to be connected and matched to a R_L – to ensure maximum power is transferred between R_i and a R_L .

5. Conclusions

Sustainable energy is becoming popular to supplement the traditional grid and for private use, as well as for green economy. In view of this, we proffer thermoelectricity as an alternative energy source (TEGs) as well as an energy efficient load (TECs) for assorted applications that require low DC power, cooling and heating. However, TEG and TEC require multiple units connected in series and or in parallel to provide decent output and cooling powers respectively. Usually, the uninformed perception would be trying to utilize more TEGs and TECs with the hope to get more output and cooling powers respectively. However, our findings asserted this is not really the case, since i) TEG and TEC are not entirely linear devices, especially with increasing current, ii) TEG and TEC temperature difference ΔT and current parameters have performance dynamics which must be operated within very strict optimal operation limits to guarantee efficiency and iii) TEGs and TECs total electrical resistance R_i changes – increases when connected in series and decreases when connected in parallel. Thus, the overall power and efficiency will be affected, especially if the source and load resistances are not matched to transfer maximum power. In essence, our research major contributions include formulas developed for various TEGs/TECs parameters with focus on the TEG and TEC modules total resistance R_i variations – when more than one TEG and or TEC modules are connected in infinite series and or in parallel combinations. Further contributions include detailed TEGs and TECs theoretical simulated models using Matlab/Simulink, whereby the TEGs and TECs models were used to easily simulate and investigate some thermoelectricity profound parameters performance dynamics, R_i losses and to validate some of their operation points with industry standard models. Assorted large scale practical applications of TEGs and TECs were examined and in light of their results, our future work will include embarking on an actual lab design, testing our implemented models using them and refining ours accordingly while taking the physical dynamics into account. Thereafter, a practical pilot 1kW implementation shall be devised for a low energy combined cooling, heating and power (CCHP) system – as an alternative energy green option for private use.

Nomenclature/Symbols

A	TEG/TEC p-n junction thermocouple area in m ²	Q_c	TEG module(s) heat emitted on its cold-side in watt
CCHP	Combined cooling, heating and power	Q_h	TEC module(s) heat emitted on its hot-side in watt
CFD	TEC(s) cold flux density in W/m	Q_h	TEG module(s) heat absorbed on its hot-side in watt
CoP	TEC(s) coefficient of performance	$Q_{cp_{max}}$	TEC(s) Icop maximum cooling power in watt
CoP_e	TEC(s) CoP expression	$Q_{C_{max}}$	TECs maximum absorbable heat in watt, when $\Delta T = 0^\circ\text{C}$
CoP_{max}	TECs maximum CoP	$Q_{C_{mid}}$	TEC(s) midpoint cooling power in watt
CoP_{mid}	TEC(s) midpoint CoP	Q_{C_n}	TEC(s) normalized cooling power is the ratio of Q_c and $Q_{C_{max}}$
CoP_n	TEC(s) normalized CoP TEC(s)	r	TE device p-n thermocouples unit resistance in ohm
ΔT	TEG(s) temperature difference ($T_h - T_c$) in $^\circ\text{C}$ or K	R	TE device (TEG and TEC) module unit resistance in ohm
ΔT_{max}	TEC(s) maximum temperature difference in $^\circ\text{C}$	R_L	TEGs electrical load resistance in Ω connected to the TEG(s)
ΔT_n	TEC(s) normalized temperature difference	R_s	Power source resistance in ohm connected to the TECs
HFD	TEG(s) heat flux density in W/m ²	R_t	TEG/TEC module(s) total resistance in ohms
I	TEGs output current in ampere through the TEG(s)	S	TE device Seebeck coefficient in V/K
I_{conv_out}	TEGs booster converter output current	Se	TEG(s)/TEC(s) effective Seebeck coefficient in V/K
I_{cop}	TEC(s) current in ampere to yield CoP	$\bar{T}$	TE device average temperature ($T_h + T_c$)/2 in K or $^\circ\text{C}$
$I_{cp_{max}}$	TEC(s) maximum cooling power current in ampere	T_c	Temperature on TEG/TEC cold-side in $^\circ\text{C}$
I_{in}	TEC module(s) input current in ampere	T_h	Temperature on TEG/TEC hot-side in $^\circ\text{C}$
I_{in_n}	TEC(s) normalized input current is the ratio of I_{cop} and I_{max}	TE	Thermoelectric
I_{Max}	TEG(s) maximum output current in ampere	TEC	Thermoelectric cooler
I_{max}	TEC(s) maximum input current in ampere when $Q_c = 0$	TECsa	TEC cold-side surface area
I_{mid}	TEC(s) midpoint current in ampere	TEG	Thermoelectric generator
I_n	TEG(s) normalized output current	TEG_{loc}	TEG ideal generated current – assuming there is no $TEG_{R_{int}}$
ITEG_{R_{int}}	TEG ohmic current – results to TEG Ohmic or Joule heating	TEG_{PocM}	TEG ideal generated power – assuming there is no $TEG_{R_{int}}$
I_{TEG_Out}	TEGs generated current (input current to the boost converter)	$TEG_{R_{int}}$	TEG internal resistance (R_i) – responsible for the power loss
K	TEC/TEG(s) thermal conductance in (W/K)	TEG_{sa}	TEG hot-side surface area
k_e	TEG(s)/TEC(s) effective thermal conductivity in W/mK	$TEGs T_c$	TEGs cold side temperature
L	TEG/TEC p-n junction thermocouple length in meter	$TEGs DT$	TEGs temperature difference
n	P-N thermocouples amount used in a TEG/TEC	$TEGs T_h$	TEGs hot side temperature
η	TEG(s) thermal/electrical/conversion efficiency	TEG_{Voc}	TEG ideal generated voltage – assuming there is no $TEG_{R_{int}}$
η_c	Carnot efficiency	TEH	Thermoelectric Energy Harvester
η_e	TEG(s) conversion efficiency expression	T_p	TEGs/TECs module quantity connected in parallel
η_n	TEG(s) conversion efficiency normalized	T_s	TEGs/TECs module quantity connected in series
η_m	TEG(s) maximum conversion efficiency	T_t	TEG/TEC modules total quantity connected
η_{mp}	TEGs max power conversion efficiency at the TEGs maximum P_o	V_{conv_out}	TEGs booster converter output voltage
ρ	TEG/TEC electrical resistivity in $\Omega.m$	V_{in}	TEC module(s) input voltage in volt
ρ_e	TEG(s)/TEC(s) effective electrical resistivity in $\Omega.m$	$V_{in_{max}}$	TEC's max V_{in} in (V) that produces max ΔT_{max} when $I_{in}=I_{max}$
P_{conv_out}	TEGs booster converter output power	V_{in_n}	TEC(s) normalized input voltage is the ratio of V_{in} and $V_{in_{max}}$
P_{in}	TEC module(s) input power in watt	V_o	TEG module(s) output voltage in volt
$P_{in_{mid}}$	TEC(s) midpoint input power in watt	$V_{o_{max}}$	TEG(s) maximum output voltage in volt
P_o	TEG(s) output power in watt – which is $Q_h - Q_c$	V_n	TEG(s) normalized output voltage
$P_{o_{max}}$	TEG(s) maximum output power in watt	V_{TEG_Out}	TEGs generated voltage (input voltage to the boost converter)
P_n	TEG(s) normalized output power	$V_{TEG_{R_{int}}}$	TEG generated voltage drop – due to TEG internal resistance
PTEG_{R_{int}}	TEG generated power loss – due to TEG internal resistance	WSN	Wireless Sensors Network
P_{TEG_Out}	TEGs generated power (input power to the boost converter)	Z	TE device figure of merit in per K
Q_c	TEC module(s) cooling power on its cold-side in (W)	Ze	TEG(s)/TEC(s) effective figure of merit in per K

ZT TE device average dimensionless figure of merit

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Data availability

Research in progress – data available upon completion.

Conflict of Interest

Authors declare no conflict of interest.

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