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An Advanced Review of Thermodynamics of Electromagnetism

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Abstract: *We present an advanced review of thermodynamics of electromagnetic systems that has effective applications. The review highlights a previously introduced entropy approach that found plausible explanations of new discoveries in the field of electromagnetism. We started by studying the similarity and reversible interchangeability of heat, electric current and magnetic flux. Then, it is presented a fundamental energy equation that embraced the thermal, mechanical, electrical and magnetic potentials. According to the principles of entropy production, it is reviewed modified statements of the second law of thermodynamic that proved the existence of irreversibilities and entropy generation in transfer of electric and magnetic energies through substantial differences of their driving potentials similar to irreversibilities and entropy generation encountered by flow of the thermal energy. Accordingly, the Maxwell's equations of electromagnetic waves were casted into an energy frame of reference that replaces the time by entropy. Such transformation led to plausible definitions of the natures of electric charge, magnetic flux, energy quanta and the photovoltaic effect. Such definitions explained the discovered Tesla's wireless power transmission as "Electrical Radiant Energy," the MIT discovery of wireless power transmission of the magnetic flux as "Evanescent Waves." The introduced review led also to new discoveries in the field of photovoltaic cells and optical fibers, and to delete discrepancies in the SI system of units. Such approach was applied also in different citations for further applications as the failure analysis of transformers and power quality assessment.*

Keywords: *Entropy, Maxwell's Equations, Electromagnetic Waves, Electric Energy, Magnetic Flux, Photovoltaic Cells.*

1. Introduction

Most literatures that dealt with thermodynamic systems are concerned mainly by transfer of mechanical and thermal energies. Similarly; literatures which dealt with flow of electric or magnetic energies were concerned mainly by solids that have electric or magnetic properties. Both analyses are ineffective when dealing with a general thermodynamic system that may involve fluid flow while it is subjected to transfer of heat, electric, magnetic and mechanical energies. However, literature that dealt with the transfer of electric and magnetic energies were involved mainly in momentum conservation while they gave a narrow space to the energy transfer that considers the entropy as an essential thermodynamic property [1]. Such truncations paralyze explanation of different electromagnetic phenomena as the entropy flow is associated by the flow of electric and magnetic energies as it is associated by the flow of thermal energy.

Reviewing the thermodynamics of electromagnetism, it is found different ambiguities in this field which should be plausibly explained as the duality confusion, the transfer of electric energy in pace as discovered by Tesla [2], the wireless power transmission by magnetic resonance as discovered by the MIT [3]. Additionally there are found conflicts in the SI system of units between units of analogous identities in the thermal, electric and magnetic fields [4]. Similarly; the definition of the energy quanta, as postulated by Planck, has some redundancies from the dimensional point of view [5]. We haven't plausible explanation of the efficiencies of modern photovoltaic cells that exceeds the limit determined by the classical thermodynamics as derived by Shockley and Queisser [6].

Considering the flows in physical systems are driven by forces in conjugate pairs, the heat flow is driven by differences in temperature between the system and the surrounding, volume flow is by differences in pressure, electric charge flow by differences in electrical potential, the magnetic flux by difference in magnetic potential, and mass flow by differences in concentration[7]. According to literature; the flow of heat is associated mainly by production of entropy and the total rate of entropy production, $\sum S_i$, is not limited by equilibrium theory [7]. So, it should be considered also the entropy production by the flow of electric and magnetic energies, of fluxes J_i, with driving forces, or potential λ_i. According to literature, the rate of entropy production by these fluxes is given by the following equation under general equilibrium and nonequlibrium conditions [8]:

$$\dot{S}_{tot} = \sum \lambda_i J_i \quad (1)$$

Eq. (1) states blankly the flow of electric flux, which is derived by the electric potential, and the flow of magnetic flux, which is derived by magnetic potential, are associated, similar to heat flow, by entropy production "$\dot{S}$" [9].

Such entropy concept was found to provide a fertile ground for following the direction of processes, reversible or irreversible, that belongs to fluxes driven by forces. From the thermodynamics point of view, it represented a fundamental property in the fundamental equation of state that characterizes the behavior of thermodynamic systems [10]. So, it will be compared in this review the studies of the thermodynamics of electromagnetism that highlight the entropy generation associated by the flow of electric and magnetic energies and that ignores such essential property that characterize the flow of energy in general. The paper starts in section II by studying the similarity and analogy of flow of electric, magnetic, and thermal energies. In Section III, it will be reviewed an approach that emphasized the importance of entropy as a property of the system to express the electric and magnetic potentials into a fundamental equation that embraces those potentials. Section IV will be devoted to review the modifications of SI system of units to delete redundancies in the SI system of units in the electromagnetic field. Section V, will review the statements of the second law of thermodynamic that involve the entropy production by the transfer of electric and magnetic energies through differences in their driving potentials. Section 6 will track the application of an approach that casted the Maxwell's equations of electromagnetic waves into an energy frame of reference by replacing the time by entropy. Accordingly, Section VI reviews modification of Planck's quantization postulate that considers its dimensions related to the frequency of the electromagnetic waves. Section VII will review the highlighted definitions, in the presented article, of natures of the electric charge and magnetic flux that led to plausible explanations of the discovered Tesla's wireless power transmission as "Electrical Radiant Energy," and the MIT discovery of wireless power transmission of the magnetic flux as "Evanescent Waves. Section VIII will track the application of the followed entropy approach to modify the Einstein's description of the photovoltaic effect and, hence, to clarify the duality confusion. Then, it will be introduced a plausible explanation of exceeding the efficiency limit of photovoltaic cells defined by Shockley and Queisser. Section IX will be concerned by reviewing the thermodynamic potentials in the field of thermo-electromagnetic systems. In Section X we summarize this paper. It is our hope this paper will serve as a recipe for engineers interested in understanding the thermodynamics of electromagnetism on clear basis.

2. Similarity and Exchangeability of Heat, Electric and Magnetic Fluxes

Investigating the definitions of the thermoelectric effect in literature, such definition indicates the similarity of the natures of heat and electric current and that the conversion of heat into electric current, and vice versa, can be described as a process of replacing the thermal potential of heat by an electric potential or vice versa [11]. Such conclusions can be deducted also when reviewing the discoveries of Joule, Seebeck, Peltier, and Thomson [12].According to Joule's law, the flow of an electric current into a conductor generates heat that is dissipated to surroundings indicates also the similarity of their natures [13]. The German physicist Thomas J. Seebeck discovered the thermocouple, or the Seebeck effect, which generates an electromotive force when its junctions are placed at different temperatures [14]. Accordingly, the Seebeck effect was utilized in thermoelectric generators where heat is converted into electric current which indicates the conversion process as replacing the thermal potential between the junctions of the thermocouples into electric potential or electromotive force [15]. In 1834, the French physicist Jean C. A. Peltier discovered an effect, inverse to the Seebeck effect, when he passed an electric current through a thermocouple, then the temperature of one junction increases and the temperature of the other decreases. Such effect may be considered also as a proof of the reversibility of conversion of electric current into heat by an exchange between the electric potential of the electrical current and the thermal potential of heat in both directions [16, 17].The Scottish scientist William Thomson (later Lord Kelvin) discovered in 1854 that if a temperature difference exists between any two points of a current-carrying conductor, heat is either evolved or absorbed depending upon the material [18].So, the Seebeck effect was considered as a result of the combined Peltier and Thomson effects assuring the similarity of the natures of heat and electric current and their reversible interchangeability by replacing their potentials through the discovered effects [19].

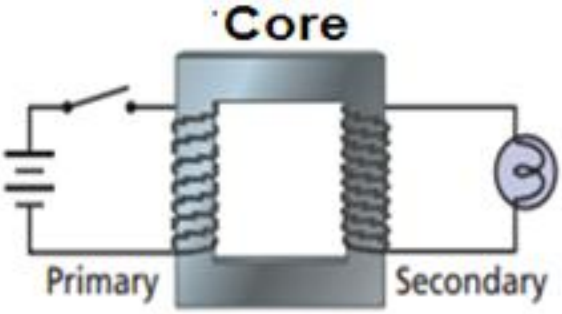

Fig1. *Faraday's experiment of magnetic induction*

Reviewing Faraday's experiment of magnetic induction, Fig. 1, the results of this experiment was interpreted as follows: the electric current in the primary coil is converted by induction into magnetic flux in the core; then the induced magnetic flux of the core is converted once more into an electric current in the secondary coil [20]. Such way of understanding showed that both fluxes, electric and magnetic, should have similar natures and that their conversion process is experienced by exchanging their potentials, electric or magnetic, firstly in the primary coil and after in the secondary coil [21].

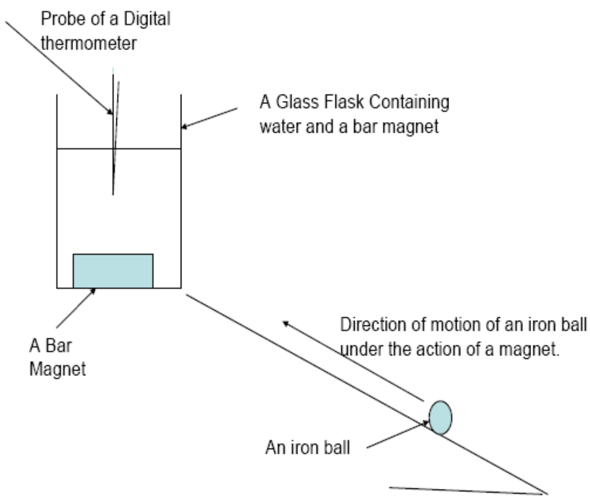

Fig2. *Measurements of substitutability of thermal and magnetic energies during attraction of iron balls by an immersed magnet.*

Reviewing the results of a simple experiment, Fig. 2, that used a permanent magnet immersed into a water basin to attract iron balls along an inclined smooth glass plane; the heat lost from the water was found equivalent to the done magnetic work in attraction of the balls along the shown plate [18, 19]. Such results proves the performed magnetic work to attract the balls is equally substituted by the heat lost from the water; or that potential of heat absorbed from water is replaced by magnetic potential into the magnet to substitute the lost magnetic energy from the magnet [22].Similarly, it was possible, in other experiments, to measure the equivalence of the heating rates, in magnetic fluids, to the applied alternating magnetic power [23]. Reviewing also the definition of the magnetocaloric effect in literature as applied in refrigeration; it is possible to deduce the same conclusion of that heat and magnetic flux have similar nature but have different and exchangeable potentials [24].Consequently, it was postulated the similarity of the natures of the magnetic flux and heat and their reversible interchangeability through exchanging their potentials [25].Finally; heat, electric charges and magnetic fluxes could be defined as forms of equivalent energies in transfer which are reversibly interchangeable by exchanging their potentials through thermoelectric effect, magnetocaloric effect, and magnetic induction [25].

According to quantum literatures, it is stated that the light, as a spectrum of thermal radiation, the electric charge and magnetic flux are quantized into discrete quantities [26]. Such common discretization phenomena were also considered as a feature of the similarity of these fluxes and that they have the same nature [26].

3. A Fundamental Equation of Thermodynamics which Empraces Electric and Magnetic Potentials

Studying a thermodynamic system which is subjected to flow or transfer of heat, electric current and magnetic flux while it is performing a mechanical work; the energy conservation principle, or the first law of thermodynamics, is expressed as follows [27]:

$$dU = \delta Q_{th} + \delta Q_{el} + \delta Q_{mag} - P\,dV \tag{2}$$

According to references in electrodynamics, Eq. (1) is stated also as follows [28]:

$$dU = T\,dS + E\,dÞ + H\,dM - P\,dV \tag{3}$$

In Eq. (2); T, E, and H are the thermal, electric, magnetic potentials of heat, electric current and magnetic flux respectively, S is the entropy, Þ is the electric polarization, M is the magnetization, P is the pressure, and V is the volume.

Comparing the energy equations (1) and (2); the following equalities can be concluded [28]:

$$\delta Q_{th} = T\,dS \tag{4}$$

$$\delta Q_{el} = E\,dÞ \tag{5}$$

$$Q_{mag} = H\,dM \tag{6}$$

Eq. (3) relates the flow of heat to the change in entropy “S” as a thermodynamic property that depends on the state of the system. Such dependence can be expressed by a fundamental equation of state of the system that depends on extensive coordinates formed of the internal energy U and the volume V [27].

$$S = S(U, V) \tag{7}$$

The term “dS” in Eq. (3) expresses the entropy production associated by the flow of heat driven by temperature difference. According to Eq. (1) it should be expected similar entropy production associated by the flow of electric and magnetic fluxes which are driven by electric and magnetic potentials[7]. Accordingly; it is expected the increase of such property due to the flow of electric flux by the difference of electric potential and due to the flow of magnetic flux by the difference in magnetic potentials. According to the discussed similarity and reversible interchangeability of heat, electric charge and magnetic flux as forms of diffusion fluxes which are tied by similar constitutive relations [29], it is expected analogical equations that relate the electric and magnetic fluxes to the entropy changes similar to Eq. (3) for the heat flux as follows [30]:

$$\delta Q_{el} = E\,dS \tag{8}$$

$$Q_{mag} = H\,dS \tag{9}$$

Comparing Eq. (8) to Eq. (5); we find the change of polarization $dÞ$ of an electric system is replaced by entropy production dS associated by the flow of electric charges. The following equation which is a corollary of Onsager relations and phenomenological equations expresses the dependence of entropy, as a property of the system, and the polarization [31]:

$$S = \frac{1}{2}\beta\,Þ^2 + S_0 \tag{9}$$

Where β represent a temperature-independent phenomenological coefficient and S_0 is the entropy of the system at a reference state of zero polarization. Similar dependence of the entropy on polarization is found as consequences of some Maxwell relations [32].

Comparing Eq. (9) to Eq. (6); we find the change of magnetization of a magnetic system dM is replaced by entropy production dS associated by the flow of magnetic flux. Korazhavy followed a magnetic model that depends on classical and quantum mechanics to find the following dependence of entropy, as a property of the system, on magnetization [33]:

$$S = k_B \ln(M + 1) \tag{10}$$

"k_B" denotes the Boltzmann constant. According to Eqs. (9) and (10), the entropy, as a property of electromagnetic systems, depends on the polarization "Þ" and the magnetization "M" as extensive properties of such electromagnetic systems. So, the fundamental equation of state of electromagnetic systems should include the polarization and magnetization as follows [34]:

$$S = S(U, V, \text{Þ}, \mathrm{M}) \tag{11}$$

Substituting Eqs. (8) and (9) into Eq.(2), a fundamental energy equation that embraces the flow of heat, electric charge and magnetic flux was stated as follows [28]:

$$dU = T\, dS + E\, d\mathrm{S} + H\, dS - P\, dV \tag{12}$$

Eq. (8) and Eq. (11) express the flows of electric and magnetic energies as a potential force times a differential of the corresponding increase entropy of the system and their integrals can be expressed in property diagrams between the entropy and the electric or magnetic potentials of the system. The differential of entropy is an exact differential as the entropy is a point function or a property of the system. Accordingly, Eq. (12) can be considered as a fundamental equation as it involves only properties of the system [28].

However, traditional literature of electromagnetism stated the energy equation that embraces the transfer of electric and magnetic energies as follows [35]:

$$dU = T\, dS + E\, \delta D + H\, \delta B - P\, dV \tag{13}$$

"D" is the displacement current and "B" is the magnetic flux. However, the differentials $\delta D$and δB, in Eq. (13) express differentials of energy in transfer which are not differentials of properties of the considered thermodynamic system. Accordingly, both differentials are non-exact differentials and their integrals $\int E\ \delta D \& \int H\ \delta B$ cannot be represented in a property diagram. Additionally, the displacement current "D" has the dimensions of energy flow rate and the product of its multiplication by the electric potential "E", i.e. the term "$E\ \delta D$", hasn't the dimensions of energy as the other terms of Eq. (13). Similarly, the magnetic flux "B" has the dimensions of energy. Accordingly, the term "$H\ \delta B$" hasn't the dimensions of energy as the other terms in Eq. (13). On the other hand, the differential dS in the terms of thermal, electric and magnetic energies in Eq. (12) is an exact differential as it is a differential of a property and the integrals "$\int T\ dS$", "$\int E\ dS$" and "$\int H\ dS$" represent the flows of thermal, electric and magnetic energies that can be represented into property diagrams [28]. So, Eq. (12) can be considered as a fundamental energy equation as all of its terms are properties of the system and all its differentials are exact ones while Eq. (13) cannot be considered as fundamental equation as the differentials of the displacement current "D" and the magnetic flux "B" are non-exact [34].

4. Analysis of Units and Dimensions in Eletromagnetism

The electric potential "E" is measured in Volt. Similarly, the thermal potential is measured by thermocouples in Volt [35].During their experimental work to compare the performance of some common thermocouples; Kumar and others recorded variations of the generated EMF, in volts, from an Aluminum-Iron thermocouple by the influence of the magnetic potential similar to its influence by the temperature difference [36]. According to such results and to the proved similarity and reversible interchangeability of thermal, electric and magnetic energies, it is possible to state the volt as a common unit for the measurement of the electric, thermal and magnetic potentials [37].

So, the entropy in Eq. (3), Eq. (8), and Eq. (11) was considered of the same unit, i.e. in Joule/volt.

Dividing both sides of Eq. (3) by the time differential "dt", it is possible to estimate the rate of heat flow in terms of the rate of entropy production as follows [28]:

$$\dot{Q}_{thermal} = T\, \dot{S} \tag{14}$$

Similarly, dividing both sides of Eq. (8) by the time differential "dt", the electric power as a rate of electric energy flow can be expressed also in terms of the rate of entropy production of the system due to the flowing electric energy as follows [28]:

$$\dot{Q}_{elec} = E\, \dot{S} \tag{15}$$

Similarly, the rate of flow magnetic energy can be expressed according to Eq. (11) as follows [28]:

$$\dot{Q}_{mag} = H\,\dot{S} \tag{16}$$

According to literature of electromagnetism, the electric power is estimated according to the following equation [30]:

$$\dot{Q}_{elec} = E\ I \tag{17}$$

"I" in Eq. (17)is defined as the electric current or as the rate of flow of electric charge. As the electric charge is a form of energy, the rate of flow of electric charge, or "I", represents actually the rate of flow of energy or the electric power and this contradicts its multiplication by the electric potential "E" in Eq. (17) to determine the electric power. Such contradiction leads to confusions in the SI system of units and was found as a source of error in the homogeneity of dimensions of Ampere's law [38].If the product of $E * I$ is the electric power, so the current "I" should be defined as the rate of flow of electric charge per unit drop in potential, i.e. W/Volt. Comparing the terms in the R.H.S of Eq. (15) and Eq. (17), it is possible to define the term "I" as the rate of flow of entropy "$\dot{S}$" that is expressed by the following equation [37]:

$$I = \dot{S} \tag{18}$$

In other words, the Ammeter measures the rate of entropy flow associated or produced by the charge flow and doesn't measure a rate of the charge flow. The rate of charge flow, or electricity flow, is explicitly the electric power. As the electric charge, similar to heat, is a form of energy, its rate of flow should be in Watt [37].

According to the proved interchangeability of electric and magnetic energies, the magnetic flux or the rate of flow magnetic energy should have also the same dimensions or units as the electric current and heat. It is defined in literature by the following Equation [35]:

$$\dot{Q}_{mag} = H\ B \tag{19}$$

When comparing Eq. (11) to Eq. (16), it can be found that the magnetic flux "B" is indicating also the rate of entropy flow associated or generated by the flow of magnetic energy [40]:

$$B = \dot{S} \tag{20}$$

Table1. *Electromagnetic Units in the SI System*

Magnetic quantity	Electric quantity
magneto-motive force Amp	electromotive force Volt
magnetic field strength Amp/m	electric field strength V/m
permeability kg m/sec^2/Amp^2	conductivity Sec^{3}Amp^2 /kg/m^3
magnetic flux m^2 kg/sec^2/Amp	current Amp
magnetic flux density kg/sec^2/Amp	current density Amp/m^2
reluctance Amp^2 / m^2 kg / sec^2	resistance m^{2}kg/sec^3/Amp^2

According to such confusion in the dimensions of electric current and magnetic flux which should be in Watt/volt, the SI system of units suffers from redundancies in assigning different units for analogous fluxes and potentials as seen in Table 1 [38]. However, followed entropy approach defined the unit of electric current "I" and the magnetic flux "B" in W/Volt and measure the thermal, electric and magnetic potentials by Volt. Accordingly, all the energy fluxes have the same unit in Joule/Volt. Table 2 shows the success of this system of units by assigning the same units for the analogous identities [37].

As the increase of entropy by heat, electric and magnetic energies has the same unit, in Joule/Volt, the total increase of a system that embraces the transfer of such energies was estimated directly as a sum of increase of entropies resulted from such flows according to the following equation [39]:

$$S_2 - S_1 = \int_1^2 [dS_{th} + dS_{elect} + dS_{mag}] \tag{21}$$

Table2. *Analogous Electromagnetic Units*

Magnetic quantity	Electric quantity
magneto-motive force Volt	electromotive force Volt
magnetic field strength Volt/m	electric field strength V/m
permeability W/m V	conductivity W/m V
magnetic flux W	current W
magnetic flux density W/m^2	current density W/m^2
reluctance V/W or Ω	resistance V/W or Ω

5. Second Law of Thermodynamics of Electromagnetic Systems

The second law of thermodynamics provides a rule that describes the direction of change in a system in the absence of external forces. It depends on natural evidence that heat flows from warm objects to cold objects, that objects fall downward in a gravity field, electric current flows from high potential to low potential, the magnetic flux emerges from magnets of high magnetic potential to iron rods of zero or less magnetic potential and solutes diffuse from regions of high concentration into regions of low concentration [41].So, the second law should be a rule which captures these facts in a remarkably concise way. Essential to the second law of thermodynamics is the idea of a reversibleflow. A flow is reversible when it is driven by an infinitesimal force, *i.e.* a difference in the force which is so close to zero that a small change in the magnitude of the force at the appropriate place can reverse the direction of the flow [42]. The total change in entropy (system plus surroundings) during a reversible heat transfer process which is defined as transferring the same heat to surrounding through infinitesimally small difference is equal to zero according to the following equality [43]:

$$\text{i.e.} \oint \frac{\delta Q_{th}}{T} = 0 \tag{22}$$

According to laws of physics, as Eq. (22) indicates the cycle integration of the differential "$\frac{\delta Q_{th}}{T}$" is zero, then such differential is a differential of property that was nominated according to the second law as entropy [43].In real processes where the temperature of the system should be higher than the temperature of surroundings; the total entropy change of the system and the surroundings exceeds the zero value as follows [44]:

$$\oint \frac{\delta Q_{th}}{T} \geq 0 \tag{23}$$

So, the second law of thermodynamics defined the entropy also as a property that measures the irreversibility of processes in thermodynamic systems. Entropy of a system is traditionally defined in terms of its statistical concept according to Ludwig Boltzmann as follows [45]:

$$S = k_B . \ln \Omega \tag{24}$$

k_B: Boltzmann's constant = 1.38. 10^{-23}, Ω is the number of arranging the microstates of a system at specified total internal energy. According to Boltzmann definition of entropy and to the concepts of the second law of thermodynamics, the entropy was proven to indicate also the arrow of time from the statistical behavior of a large number of molecules obeying the conservation of momentum and energy [46].

Similar to the irreversible heat transfer through a substantial temperature difference, the electric energy is transferred also through a substantial electric potential and the magnetic flux is transferred also through a substantial magnetic potential. In other words, the transfer of electric current or magnetic flux may have similar irreversibilities as the transfer of heat. However, literature ignores such irreversibilities which represent similar source of irreversibilities as the irreversibility of heat transfer through substantial temperature difference. Applying the second law of thermodynamics to systems that embrace the transfer of electric current and magnetic flux; the irreversibilities of such transfer could be expressed by the following equations [25]:

$$\oint \frac{\delta Q_{el}}{E} \geq 0 \quad (25)$$

$$\oint \frac{\delta Q_{mag}}{H} \geq 0 \quad (26)$$

Eq. (25) and Eq. (26) are similar to Eq. (23) for heat transfer that expresses the natural flow of heat through a substantial temperature difference. However, transferring the electric and magnetic fluxes through infinitesimally small differences will be similarly valid to state an equivalent equation to Eq. (22) for heat [28]:

$$\oint \frac{\delta Q_{el}}{E} = 0 \quad (27)$$

$$\oint \frac{\delta Q_{mag}}{H} = 0 \quad (28)$$

As Eq. (22) was considered as a proof that defines the entropy as a property in a thermodynamics system, Eqs. (27) and (28) proves also the entropy as a property into electric or magnetic systems [28].

$$dS = \frac{\delta Q_{el}}{E} \quad (29)$$

$$dS = \frac{\delta Q_{mag}}{H} \quad (30)$$

So, we should expect a fundamental equation in a flow of energy in an electromagnetic system to be analogy to Eq. (7) of the form:

$$U = U(S_{tot}, V) \quad \text{where, } S_{tot} = S_{thermal} + S_{elect} + S_{mag} \quad (31)$$

Consequentially, the second law of thermodynamics of electromagnetic systems was found also to define the entropy as an essential coordinate of the electromagnetic systems that is associated by the transfer of electric and magnetic energies. So, the flow of electric and magnetic energies could be represented into a coordinate system formed of the entropy and the electric potential or the magnetic potential, i.e. E-s and H-s property diagrams, similar to representation of heat into a coordinate system formed of the temperature and entropy coordinates. Such representations are shown in Fig. (3), for temperature-entropy coordinates, in Fig. 4, for electric potential – entropy coordinates, and in Fig. 5 for magnetic potential – entropy diagram [28].

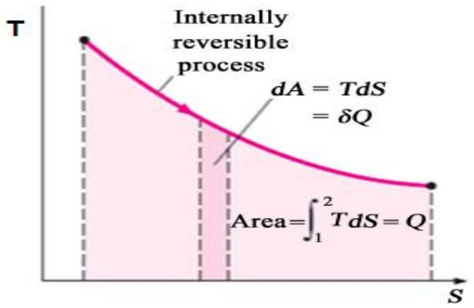

Fig3. *Graphical representation of heat transferred reversibly to a system in a T-s property diagram.*

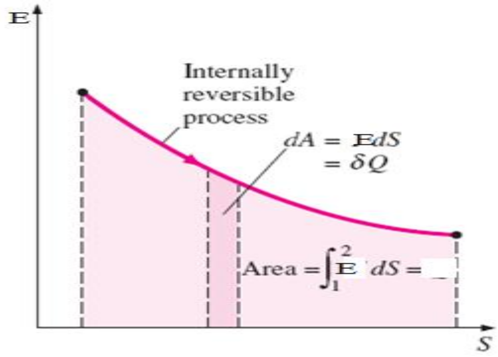

Fig4. *Graphical representation of electric energy transferred reversibly to a system in an e-s property diagram.*

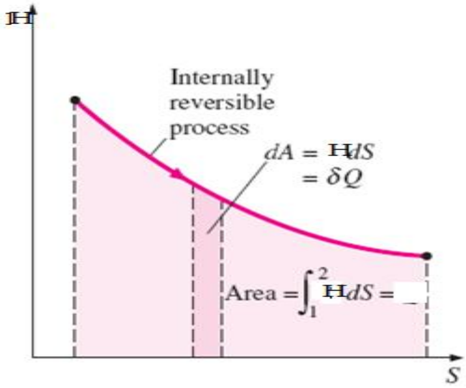

Fig5. *Graphical representation of magnetic energy transferred reversibly to a system in an h-s property diagram.*

6. Modified Maxwell's Wave Equations

The nature of flow of heat or light is identified as flow of electromagnetic waves. Maxwell had succeeded in describing the flow of electromagnetic waves by simultaneous flow of electric and magnetic energies according to the following mathematical equations [47].

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{t^2} \right) E = 0 \qquad (32)$$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{t^2} \right) H = 0 \qquad (33)$$

Where c is the speed of light in the medium, in vacuum $c = c_0$ = 299,792,458 m/s. Replacing the time in Maxwell's equation by entropy, the Maxwell's equations were casted into an energy frame of reference formed of the electric and magnetic fields, "E" and "H", andentropy "S" as follows [39].

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{s^2} \right) E = 0 \qquad (34)$$

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{s^2} \right) H = 0 \qquad (35)$$

Fig. 6 represents how such modified Maxwell's equations were represented into an energy frame of reference and the swept areas by the electromagnetic wave in the E-s and H-s planes represent the flowing electric and magnetic energies [28].However, the replacement of the time in Maxwell's equation by entropy fits also Eddington's conclusion which found the time's arrow as a property of entropy alone. In other words, it considers the entropy as a property of the system that may represent the randomness increase with time [48]:

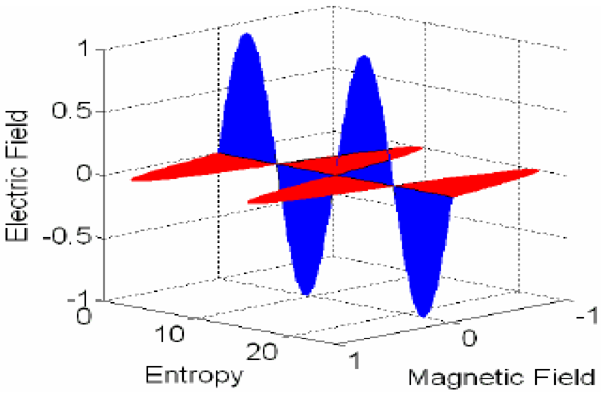

Fig6. *Flow of electromagnetic waves in an energy frame of reference that shows the electric energy flow in an e-s plane and the magnetic energy flow into an h-s plane [28]*

Denoting the imparted energy per wave-pulse, by the symbol "ℏ" in Joule/cycle, then this area is represented in Fig. 6 by the swept area per an electromagnetic cycle. This energy pulse can be estimated as the sum of the energies imparted by the electric wave and by the magnetic wave in one pulse as follows[25]:

$$Ћ = \int_0^{2\pi} E\, dS_{elect} + \int_0^{2\pi} H\, dS_{mag} \tag{36}$$

Accordingly, the energy flow per unit time in an electromagnetic wave of frequency "ν" cycle/s, or Hz, is calculated as follows:

$$\dot{W} = Ћ\,\nu \text{ Watt / wave of frequency "}\nu\text{"} \tag{37}$$

So, the term "Ћ ν" represents the rate of flow of energy imparted by an electromagnetic wave of frequency "ν" per unit time.

In his scientific work to explain the photovoltaic effect, Einstein postulated that light was made of packets of energy, or energy quanta called as "photons," where each photon carries a specific energy related to its wavelength as follows:

$$e_{photon} = h\,\nu \text{ Joule} \tag{38}$$

"h" is called Planck's constant. Planck estimated the magnitude of such quanta for a wave whose frequency is 1 Hz by the magnitude "6.62606957 × 10^{-34}" [25]. Substituting ν = 1 in Eq. (38), we get the following results:

$$e_{photon,\nu=1} = h$$

$$= 6.62606957 \times 10 - 34 \text{ Joule/cycle (or energy-pulse)} \tag{39}$$

According to Eq. (39), Planck's constant defines actually the magnitude of energy pulse, denoted previously as "Ћ". So, it is possible to state the following equality:

$$h \equiv Ћ \text{ Joule/energy-pulse} \tag{40}$$

Accordingly; the quantity "Ћν" or "hν" expresses the rate of flow of energy of an electromagnetic wave whose frequency is "ν" in Watt/wave[25].

As an example to realize the results of the introduced definition of Planck's constant, we may consider the green light at frequency "ν" = 5.76 x 10^{14} cycle/sec. Then, the rate of energy flow per wave of the green light can be estimated as follows:

$$\dot{W} = Ћ\,\nu = (6.626 \text{ x } 10^{-34} \text{ J})(5.76 \text{ x } 10^{14} \text{ s}^{-1})$$

$$= 3.82.\ 10^{-19} \text{ Watt/wave of green light} \tag{41}$$

The value of the solar constant, according to literature, is equal to 1366.1 W/m^2. Hence, we may calculate the number of waves in a bundle imparted on 1 m^2 of the earth as follows:

$$M_{per\ sq.meter} = \frac{1366.1}{3.82 \text{ x } 10^{-19}} \frac{Watt/_{m^2}}{Watt/_{wave}} = 3.6\ x\ 10^{21} \quad \text{wave /m}^2. \tag{42}$$

Similarly, it is possible to count the number of wave per glass-fiber of diameter 62.5 μ m as follows:

$$M_{per\ glass\ fiber} = \frac{\pi d^2}{4} M_{sq.meter} = 10\ x\ 10^{10} \quad \text{waves.} \tag{43}$$

Such data is consistent with previously analysis of the energy flow in optical fibers [39].

7. Analysis of the Transfer of Electric and Magnetic Energies in Space

According to the discovered Tesla's "Radiant Energy" as normal transfer of electric current in space as waves, it is possible to postulate the nature of electric charge as ionized electromagnetic waves or as electromagnetic waves that have an electric potential [49].Depending on the introduced coordinates in Maxwell's equations that involves the entropy as energy coordinate, it was possible to presume a graphical representation of the electric current as flow electromagnetic waves whose electric component has an electric potential "Δ E" as seen in Fig. 5 [25]. This graph interprets the following solution of the modified Maxwell's Eq. (34) and Eq. (35) for a wave flowing with an electric potential "+/− Δ E" as follows [49]:

$$E(r,s) = g_1(\omega s - k r) +/- \Delta E \tag{44}$$

$$H(r,s) = g_2(\omega s - k r) \tag{45}$$

The potential of the electric component of the flowing wave will be "+ ΔE" for the flow of a positive charge and "− ΔE" for a negative charge28.

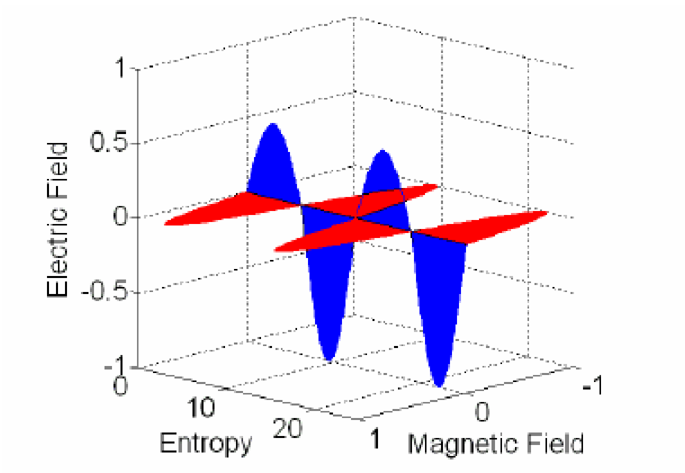

Fig7. *Flow of electric charges as e.m. Waves of negative electric potential*[52].

According to the found similarity and interchangeability of electric charge and magnetic flux by Faraday's experiment; the nature of the magnetic flux was identified also as a flow of electromagnetic waves that have a magnetic potential [22].According to such definition, it was possible to find plausible explanation of the MIT discovery of wireless power transmission of the magnetic flux, as "Evanescent waves", by the discovered magnetic resonant coupling [22].Accordingly, the previously introduced entropy approach defined the nature of magnetic flux as electromagnetic waves whose magnetic component has a magnetic potential as a plausible explanation of the MIT experiment [50]. Such definition is described mathematically by the following equations, as a solution of the modified Maxwell's equations Eq. (34) and Eq. (35), and is expressed analytically by the following equations and is represented graphically in Fig. (6) [22]:

$$E\,(r,s) \;=\; g_1\,(\omega\,s - k\,r) \tag{46}$$

$$H(r,s) \;=\; g_2\big(\omega\,s - k\,r\big) +/- \Delta\,H \tag{47}$$

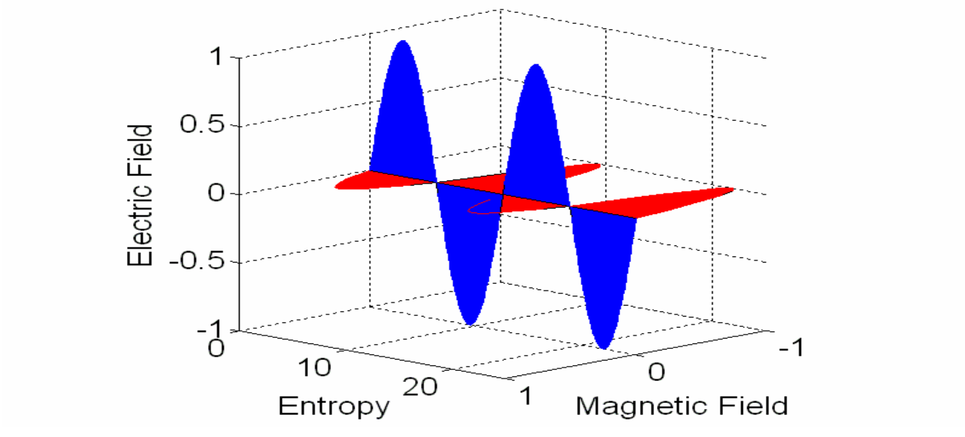

Fig8. *Graphical representation of magnetic flux [52].*

The potential of the magnetic component of the flowing electromagnetic wave defined by Eq. (41) by the term $+/-\;\Delta\,H$ which determines the strength and direction of the magnetic field associated by the flowing magnetic flux as electromagnetic waves [22].

8. Reviewing the Duality Confusion and the Photovoltaic Effect

According to the introduced definition of the electric current as a flow of electromagnetic waves, the description of the photovoltaic effect, according to Einstein, as bouncing of electrons by light is violated since, according to the considered entropy approach, the incident light or radiation has the same nature as the electric current [25].According to the reviewed entropy approach, the photovoltaic effect was concluded as replacement the thermal potential of the incident radiation by electric potential when crossing the p-n junction of photovoltaic cell by the influence of the electric potential across this junction similar to any thermoelectric effect [51].Consequentially, this explanation of the photovoltaic effect plausibly deleted the duality confusion which defined the electric current as a flow of electrons while it is actually a flow of ionized electromagnetic waves, or electromagnetic waves of an electric potential[52]. So, light shouldn't have a dual nature as waves and particles as it is not bouncing electrons but it gains electric potential when crossing the p-n junction to be converted into electric current. As the electric current is not defined as a flow of electrons, the electrons shouldn't have a dual nature to satisfy Einstein's description of the photovoltaic and we should not be confused about any duality[53].Relying on the functioning of the solar cells and the photoelectric phenomena in general, according to literature of quantum physics that postulates the photo-generation of carriers in p–n junctions and their subsequent recombination in the quasi-neutral regions, still remain obscure [54]. So, the followed entropy approach simplifies the analysis of the photovoltaic effect and finds the convincing answers for unsolved problems in the quantum physics [55].

Similarly, the attained definition of the energy quantity "$\hbar\,\nu$" or "h ν" which represents the energy of a wave pulse or the rate of energy flow per wave may change the Einstein's definition of threshold frequency [56].In other words, the conversion of the incident radiation into electric current is mainly a function of its thermal potential and the rate of its flow that is capable of crossing the p-n junction of the photovoltaic cell [57]. The truth of this postulate is sustained by the new measurements of the high efficiency of the developed CPV solar cells that allows the electromagnetic waves of lower frequencies to be converted into electric current due to its high rates of flow as seen in Fig. 9 [58].Such efficiency of the CPV exceeds the limit determined by Shockley Queisser [59, 60],and proves the capability of conversions of waves of long wavelengths into electric current when increasing the rate of its flow. The reviewed postulate offered also plausible explanations of the processes of conversion of solar radiation into electric current when using thin films or multijunction solar cells where there are no diffusion of Boron and Sulfur atoms to create regions of holes and electrons and the main mechanism of conversion is the Seebeck effect [61].Similarly; it offers plausible explanation to the discovery of a CdTe solar cell whose open-circuit voltage exceeds the 1 Volt barriers without decreasing the flowing current as result of the high Seebeck coefficient of such materials [62].

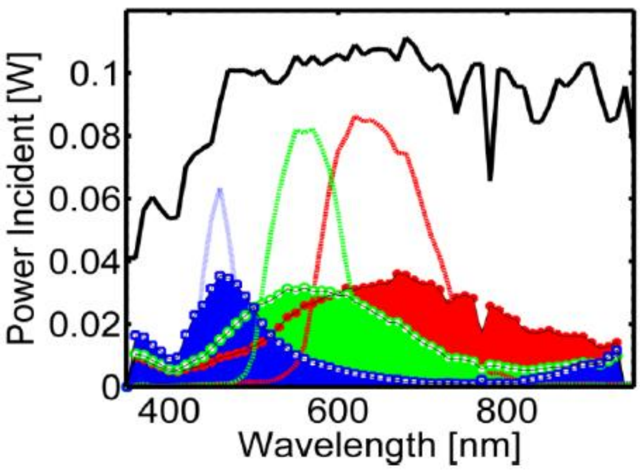

Fig9. *Simulated (dashed lines) and experimental (full area curves) power output of cpv solar cells for 3 spectral distributions [56].*

9. Thermodynamic Potentials in Electromagnetism

The following equation was stated, according to an entropy approach, as a fundamental equation of thermodynamic of electromagnetic system as all its terms express properties of the system [28].

$$dU = T\,dS + E\,dS + H\,dS - P\,dV \quad (48)$$

Trials have been made to define thermodynamic potentials in electromagnetism[63, 64]. However, without a fundamental energy equation, as Eq. (48), such trials were not successful. As the differentials "dS" in Eq. (48) belong to the same property S and the potentials "$T, E, and\ H$" have the same unit, the terms in Eq. (48) were rearranged as follows:

$$dU = (T + E + H)\, dS - P\, dV \tag{49}$$

According to Eq. (49), the internal energy is a function of the extensive properties S and V, i.e. we have:

$$U = U\,(S,V) \tag{50}$$

Accordingly, its differential can be expressed as follows:

$$dU = (\partial U/\partial S)_V\, dS + (\partial U/\partial V)_S\, dV \tag{51}$$

Comparing Eq. (49) and Eq. (51); it was possible to prove the following equalities [65]:

$$(\partial U/\partial S)_V = T + E + H \tag{52}$$

$$(\partial U/\partial V)_S = -p \tag{53}$$

According to Eq. (49) and Eq. (51); the following cases were considered[41]:

a. In case of absence of electric and magnetic fields;

$$E = H = 0\,;\ (\partial U/\partial S)_V = T,$$

$$(\partial U/\partial V)_S = -p_{mec\,h} \tag{54}$$

b. In case of absence of electric and thermal fields;

$$E = T = 0\,;\ (\partial U/\partial S)_V = H,$$

$$(\partial U/\partial V)_S = -p_{elect} \tag{55}$$

c. In case of absence of magnetic and thermal fields;

$$T = H = 0\,;\ (\partial U/\partial S)_V = E,$$

$$(\partial U/\partial V)_S = -\,p_{magnetic} \tag{56}$$

d. In case of a system influenced simultaneously by thermal and electric fields:

$$H = 0\,;\ (\partial U/\partial S)_V = T + E,$$

$$(\partial U/\partial V)_S = -(\,p_{mec\,h} + p_{elect}\,) \tag{57}$$

e. In case of a system influenced simultaneously by thermal and magnetic fields:

$$E = 0\,;\ (\partial U/\partial S)_V = T + H,$$

$$(\partial U/\partial V)_S = -(\,p_{mec\,h} + p_{magnetic}\,) \tag{58}$$

Eqs. (54), (55) and (56) define the mechanical, magnetic pressure and electric pressure as defined in literature of thermodynamics and electromagnetism [63, 64].

Equation (57) was applied to study the thermoelectric effects as Joule, Thomson Seebeck, and Peltier effects. In this case, it is possible to predict the simultaneous influence of flow of electric current and heat on the properties of the system [65]. Similarly; Eq. (58) was applied to study the effective potentials in the study of magnetocaloric effects [64].

10. Conclusions and Contributions of the Highlighted Entropy Approach in the Field of Applied Physics

According to the introduced review; the electric and magnetic energies were defined as electromagnetic waves of electric and magnetic potentials. Such conclusion paves the road to the transfer of electric and magnetic power in space without the need to a network of metallic cables as has been found in modern discoveries by Japanese scientists [66]. Similarly; the introduced entropy approach found effective selection criteria of multijunction cells based on the Seebeck coefficients of its layers [56].Such conclusion paves also the road to achieve higher efficiencies of photovoltaic cells that exceeds the Shockley and Queisser limit [56]. Additionally, the definition of electric current as flow of electromagnetic waves of electric potential paved also the road to simplified analysis of the energy flow in optical fibers by selecting radiation and electric current of the same wavelength [39]. However, different applications of the introduced entropy approach were used as a tool to power quality assessment [67] and to predict transformer and hydro-turbine failure [68, 69].

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