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Chapter

Dynamic Extended Exergy Analysis of Photon Enhanced Thermionic Emitter Based Electricity Generation

Canberk Unal, Emin Acikkalp and David Borge-Diez

Abstract

Exergy is the very useful tool to evaluate energy systems besides energy analysis based on the first law of the thermodynamics. In contrast to energy, exergy is not conserved and always decreases. There are many types of exergy analysis involving exergoeconomic, exergoenvironmental, advanced exergy-based analyses, extended exergy analysis etc. In this study, an application of the extended exergy analysis is performed. In extended exergy analysis, not only energy related system is considered but also all materials and energy flows' exergy, non-energetic and immaterial fluxes (capital, labor and environmental impact) are turned into exergy equivalent values and utilized in the analysis, which are calculating for local econometric and social data. These methods can be applied to societies or energy based or non-energy-based system. In this study, dynamic exergy analysis and extended exergy application of electricity generation from photon enhanced thermionic emitter is conducted. According to results, some important values can be listed as; extended exergy destruction, conventional based exergy destruction, extended exergy efficiency, conventional exergy efficiency, extended sustainability ratio, conventional sustainability ratio, extended exergy-based depletion ratio and conventional exergy-based depletion ratio are 542106006 MJ, 542084601 MJ, 0.01094, 0.01094, 1.011, 1.011, 0.978 and 0.989 respectively.

Keywords: exergy analysis, extended exergy analysis, photon enhanced thermionic emitter, dynamic performance evaluation, solar energy

1. Introduction

Energy is a concept transferred from an object to another in form of work or to heat. Energy is a conserved quantity; the law of conservation of energy states that energy can be converted in form, but not created or destroyed [1]. From an economic and social perspective, energy is the most important factor that ensures progress in world living standards and country development. Together with the great developments and changes in the industrial field, the increase in the world population at the same time reveals the need for energy [2]. 87 percent of the energy produced in the world is provided by fossil fuels, 6 percent from renewable sources, and 7 percent from nuclear energy sources. "About 64.5% of the world's

electrical energy production is realized by fossil resources (38.7% coal, 18.3% natural gas, 7.5% oil)" [3]. Turkey has no significant energy resources in petroleum and natural gas reserves. In addition, it is a market country that has an important place between Europe and Asia. About 27% of current energy needs in Turkey are known to be met by domestic energy production. When the distribution of Turkey installed power in the energy sector on the basis of resources is examined, natural gas 26.5%, hydraulic energy 32%, coal 21.3%, wind energy 7.7%, solar energy 5.3%, geothermal energy 1.4%, 5.8% share belongs to other resources [4].

The total monetary size of Turkey's energy market is around 84 billion dollars. 60.1 billion dollars of this amount was imported. Renewable energy is the biggest resource that can close a deficit of approximately 24 million dollars. Solar Energy is the biggest renewable energy source. Turkey is a country rich in solar energy [5]. In terms of number of installed solar power plant in Turkey is 556 pieces. Turkey's solar energy installed capacity of 5095 MW in 2018. Turkey ranks 12th in the world in terms of installed capacity [6]. Solar energy is nowadays used in air conditioning (heating–cooling) of residences and workplaces, cooking, supplying hot water and heating swimming pools; in agricultural technology, greenhouse heating and drying of agricultural products; In industry, solar cookers, solar furnaces, cookers, salt and fresh water production from sea water, solar pumps, solar cells, solar pools, heat pipe applications; It is used in a controlled manner in transportation-communication vehicles, signaling and automation, electricity production [7].

Photon enhanced thermionic emission (PETE) combines photovoltaic and thermionic effects into a single physical process to take advantage of both the high per-quanta energy of photons, and the available thermal energy due to thermalization and absorption losses [8]. It can be described by a simple three-step process: first, photoexitation of the valence electrons into a conduction band. Second, thermalization and diffusion of the conduction electrons throughout the cathode; and finally emission of the thermalized electrons into a vacuum and collection by the anode [9]. PETE cells have an advantage in efficiency over purely thermionic cells because the presence of electrons in the conduction band from photovoltaic effects reduces the effective work function of the material, making it easier for electrons to escape into the vacuum. Similarly, PETE cells do not suffer from the problem of low efficiency at high temperatures as standard photovoltaic cells do. This is because the degradation effect is specific to the two-layer semiconductor junction design of standard photocells. Further, since a PETE cell can operate efficiently at high temperature, it can be run in conjunction with a heat engine attached to the anode [10].

Exergy is the property of the system, which is the maximum work potential cand be distracted from a system, once it reaches to equilibrium state with a reference state [11]. Unlike energy, exergy is not conserved, and it's perpetually depleted due to irreversibilities (entropy generation). Some of the exergy is destroyed due to irreversibilities at within the system, and a few of it's thrown into the surroundings from the system boundaries (loss of exergy) [12]. If the exergy losses or destruction decrease, in other words, if the exergy efficiency increases, resource consumption and loss exergy emissions within the method can decrease inversely [13].

Extended Exergetic Accounting (EEA), provides a route to formally convert immaterial and non-energetic commodities into exergetic equivalents [14, 15]. According to EEA, material, energy carriers and externalities (capital, labour, and environmental remediation) represent resource expenses and are expressed in exergy as a unified metric. EEA has incorporated some elements of preexisting theories such as: cumulative exergy analysis, thermoeconomics and life cycle analysis, etc. and combines them into a consistent and expanded formulation (Extended Exergy) [16]. There are fundamental similarities between EEA and exergy methods. Like thermoeconomics, EEA results in a system of cost equations in which though

inhomogeneous quantities like labour, material and energy flux, capital are all homogeneously expressed in primary exergy equivalents. Like Cumulative Exergy Consumption, EEA computes the cumulative primary exergy "embodied" in a product over its entire production process. Like Exergy Life Cycle Assessment, EEA computations cover the entire life cycle of the considered system [17].

2. System description

Electricity generation by means of Solar source is dived into two part as: directly, which photovoltaic panels is used, and using concentrated solar collectors to obtain heat energy as heat input in a heat engine. A photon enhanced thermionic includes these two principles. Its emitter is made of a semiconductor as cathode and there is a vacuum gap between anodes. Considered system is illustrated in the **Figure 1** where a solar concentrator having 1000 concentration rate. Operation principal of the PETE can be expressed in next sentences. Solar energy passes into concentrator and illuminate the cathode heated up. This energy causes to excite electrons and electron population increase at conduction band. They have bigger energy than electron affinity and emitted into vacuum. Released electrons are collected by the anode and this is resulted in currency. The higher cathode temperature causes the more electron emittance and increase the efficiency of the process and this is the reason that its electricity efficiency is higher than the conventional photovoltaics (PV) panels. Another advantage of it is that it can be heated up via waste heat from an engine, turbine, and industrial heat to generate electricity when sun is no exist in the nighttime. In this paper GaAs is selected as cathode material since it is very promising candidate.
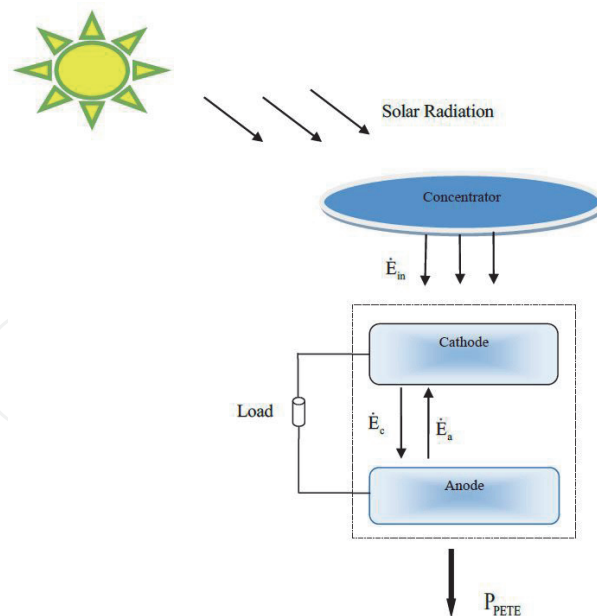
Figure 1.
Schematic of the system.

3. Methodology

Mathematical description and explanations of physical meaning of the exergy, extended exergy accounting and photon enhanced thermionic emitter are described. Daily dynamic and annual analyses are performed by TRNSYS and

Simulink and analyses are conducted. Izmir, which is the third biggest city in Turkey and has great monetary flow, is chosen.

3.1 Exergy analysis

Exergy is one of the most useful method used for evaluating the performance of various thermodynamic systems because exergy destruction is a measure of the losses in the system. Losses in the system is called as irreversibilities that is resulted from the entropy generation. These losses are main reason of inefficiencies and excessive depletion of the fuel source. In other words, exergy is the measure of how quality energy resource is used, and it is not conserved like energy and always decrease. Because of these, exergy analysis should be utilized in optimization and design studies of energy conversion devices. Exergy analysis provided to determine place and amount of the irreversibilities, and it must be decreased to save energy, money and emission by obtaining more efficient systems. Conventional exergy analysis involves three variables, $\dot{E}_F, \dot{E}_P, \dot{E}_D$, which represent the fuel exergy rate, the product exergy, and the exergy destruction rate, respectively. Exergy is not conserved, in contrast to energy.

The exergy destruction rate can be calculated as follows.

$$\dot{E}_D = \dot{E}_F - \dot{E}_P \tag{1}$$

The exergetic efficiency is

$$\varphi = \frac{\dot{E}_P}{\dot{E}_F} \quad \text{or} \quad \varphi = 1 - \frac{\dot{E}_D}{\dot{E}_F} \tag{2}$$

3.2 Extended exergy analysis

Exergy analysis is very important tool to describe losses resulted from the irreversibilities, which cause inefficiencies, as it is mentioned above. However, exergy analysis is mostly used as a sustainability indicator, it does not include material or resource depletion, human factor, effect of capital and environmental remediation. In extended exergy accounting, not only not only energy flows are included but also exergy equivalent of the materials, resources, the environmental remediation costs and labor and capital needed by in a process. *EE* can be expressed as follows:

$$E_{in} + E_L + E_C + E_E = EE \ (MJ) \tag{3}$$

E_C indicates the total monetary cost of the equipment, expressed in terms of its equivalent exergetic content, E_L indicates the sum of the labor contribution expressed in terms of its equivalent exergetic input, and E_E is exergy consumption of environmental remediation for removing pollutant emissions. The difference of extended exergy accounting to other exergy analysis approaches is the inclusion of labor, capital, and environmental impact as exergy units. 'The value of 'ee_L' is calculated as.

$$ee_L = \frac{365 N_h e_{surv} HDI}{HDI_o N_{wh}} \ (MJ/wh) \tag{4}$$

ee$_L$' means the specific exergetic equivalent of the labor. 'E_{surv}' refers to the minimum exergy consumption for a person's survival. 'N_h' is the value of

population. 'N_{wh}' refers to the number of working hours per year. f is the consumption correction factor for modern living standards.

$$f = \frac{HDI}{HDI_0} \tag{5}$$

'HDI' is the human development index published by the United Nations every year. 'HDI_0' is the human development index of a pre-industrial society. E_L' is the total exergy equivalent of Labor and represents contribution of the human work on the process. 'E_L' is found by multiplying the specified exergetic equivalent of labor by the number of working hours per year.

$$E_L = ee_L N_{wh} \; (MJ) \tag{6}$$

'ee_C' is the specific exergetic equivalent of the capital. The value of 'ee_C' is calculated as.

$$ee_C = \frac{365 e_{surv} N_h HDI}{HDI_o S} \; (MJ) \tag{7}$$

'S' indicates the amount of the national monetary wage as the average wage and the total energy equivalent of the currency.

The value of 'E_C' is the amount of monetary flow in the process and it is calculated as:

$$E_C = ee_C \sum CC \; (MJ) \tag{8}$$

where, 'C' is the capital cost. The first thing in calculations is to collect data involving population of the country, numbers of the workers in the country, average annual wage, human development index, capital circulation of the country. Second thing is to calculate number of consumed materials, releasing CO_2, total exergy input, exergy for the survival, exergy equivalents of the specific labor and capital are done. Using previous values, total exergy of the equivalent labor and capital, cumulative exergy consumption, product exergy (or equivalent) and exergy destruction, environmental remediation can be obtained. In this paper, only the operations calculations of the considered system are researched. Therefore, cumulative exergy and environmental remediation are excluded, which is no emission realizing in operation conditions.

3.3 Analysis of the PETE

Photon powered thermionic emission (PETE) is a new concept of solar power generation. It combines different quantum and thermal mechanisms directly in a physical process. It is possible to overcome both the disadvantages faced by conventional thermal systems and the natural loss of photovoltaic cells.

Unlike traditional photovoltaic cells, the PETE has higher efficiency at high temperatures, which gives an opportunity usage as bottom cycle in hybrid applications for efficiency increasing.

It sees the cathode as a clumped system with average properties and no spatial variation, so it can be called a zero-dimensional model. The cathode absorbs all band gap radiation. The anode is metallic and has good reflectivity and the void charge in the gap between the electrodes is ignored.

The output power current is given by;

$$P_p = (j_c - j_a)V \tag{9}$$

'J_c' is the density of the emission current from the cathode surface and 'J_a' is the density of the emission current from the anode surface. 'V' is the cathode electron emitting area.

The emission current density of the cathode is proportional to the Electron concentration 'n'. The emission current density of the cathode can be expressed as:

$$j_c = en\sqrt{\frac{kT_c}{2\pi m_e}}e^{-\chi/kT_c} \; (A/cm^2) \tag{10}$$

Where 'n' is the conduction band electrons concentration. 'm_e' is the electron effective mass. 'χ' is the electron affinity. 'T_C' is the anode temperature. 'k' is Boltzmann's constant.

The reverse emission current density from the anode follows the standard thermionic emission formulation:

$$j_a = A_o T_a^2 e^{-\Phi_a/kT_a} \; (A/cm^2) \tag{11}$$

'A_0' 120 A cm^{-2} K^{-2} is the Richardson–Dushman constant. 'T_A' is the anode temperature. 'k' is Boltzmann's constant. The energy barrier for emission from the anode is equal to the anode operating function '$\emptyset_a$' for voltage above the flat band value.

$$\Phi_c = \chi + E_g - E_f \tag{12}$$

4. Results and discussion

In this paper, performance and sustainability of the photon enhanced thermionic emitter is evaluated via extended exergy analysis. This analysis is performed for annual and hourly values. In **Tables 1–3**, annual results can be seen, and hourly values are shown in **Figures 2–8**.

Annual values are arranged in tables. In this tables, some calculated values are put in order as e_{surv} is the daily exergy amount needed a person for surviving, ee_L is the specific exergy equivalent of the labor, which represents daily labor exergy per

E_{in} (MJ)	N_h -	N_w (h)	N_{wh} (wh)	S (Euro/ year)	M_2 (MEuro)	f	e_{surv} (MJ/day-person)	ee_L (MJ/ wh)	ee_K (MJ/ Euro)
588582	83900373	33810000	79115400000	11325	460916.40	14.40	10.50	42.68	12.09

Table 1.
Data used in extended exergy accounting.

EE_L (MJ)	EE_K (MJ)	E_P (MJ)	E_D (MJ)
2133.75	1551.24	353513.77	547732043

Table 2.
Results of the extended exergy accounting.

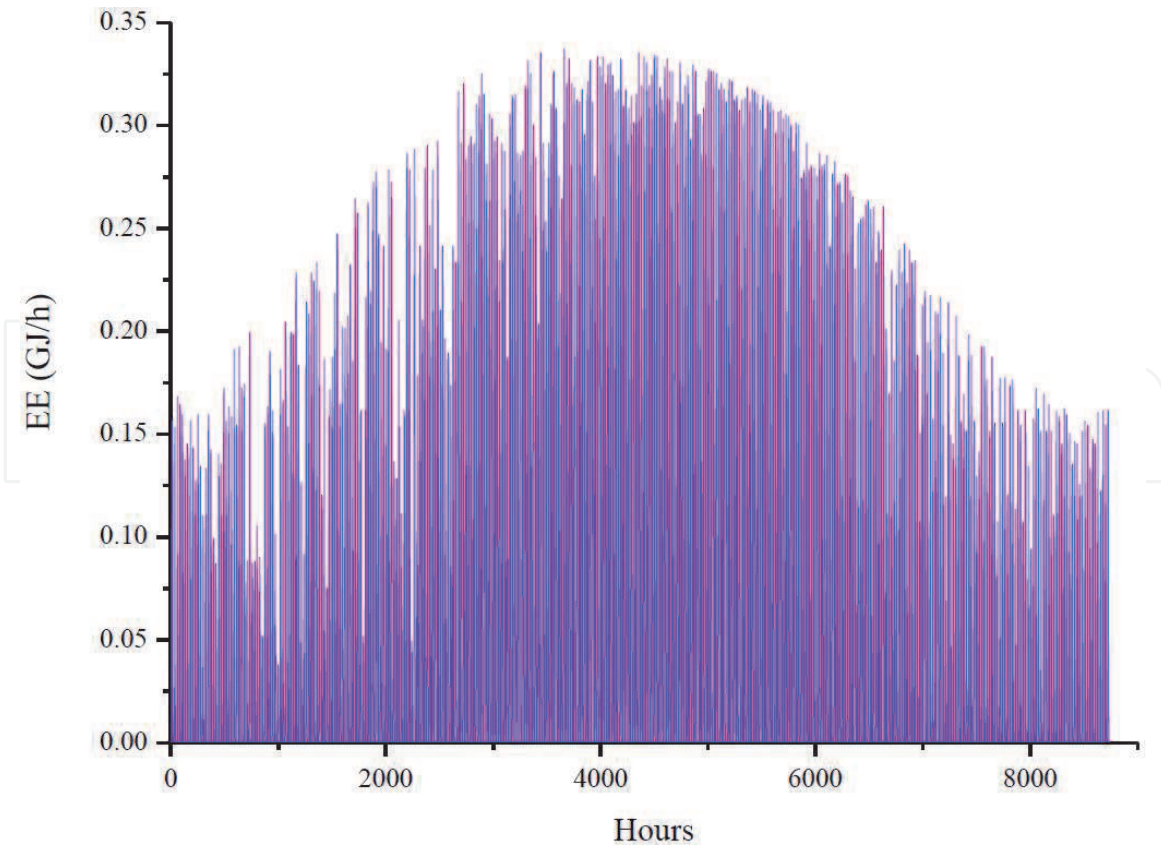| φ	SI	y
0.597	2.481	0.252

Table 3.
Extended exergy evaluation indices.
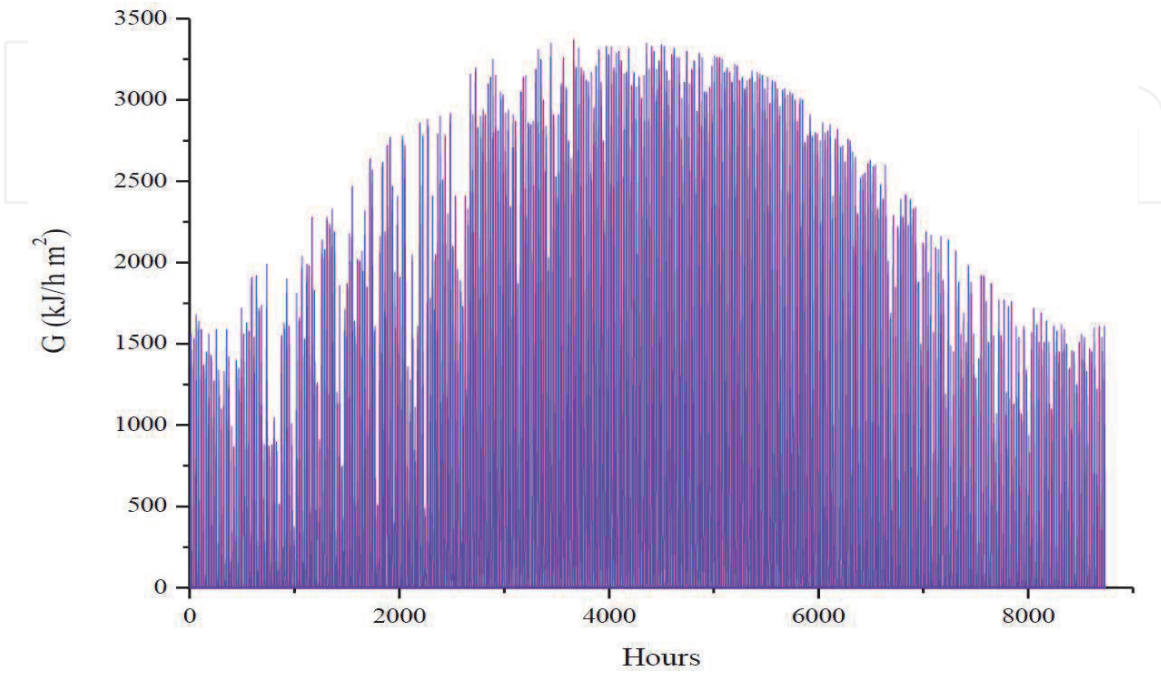
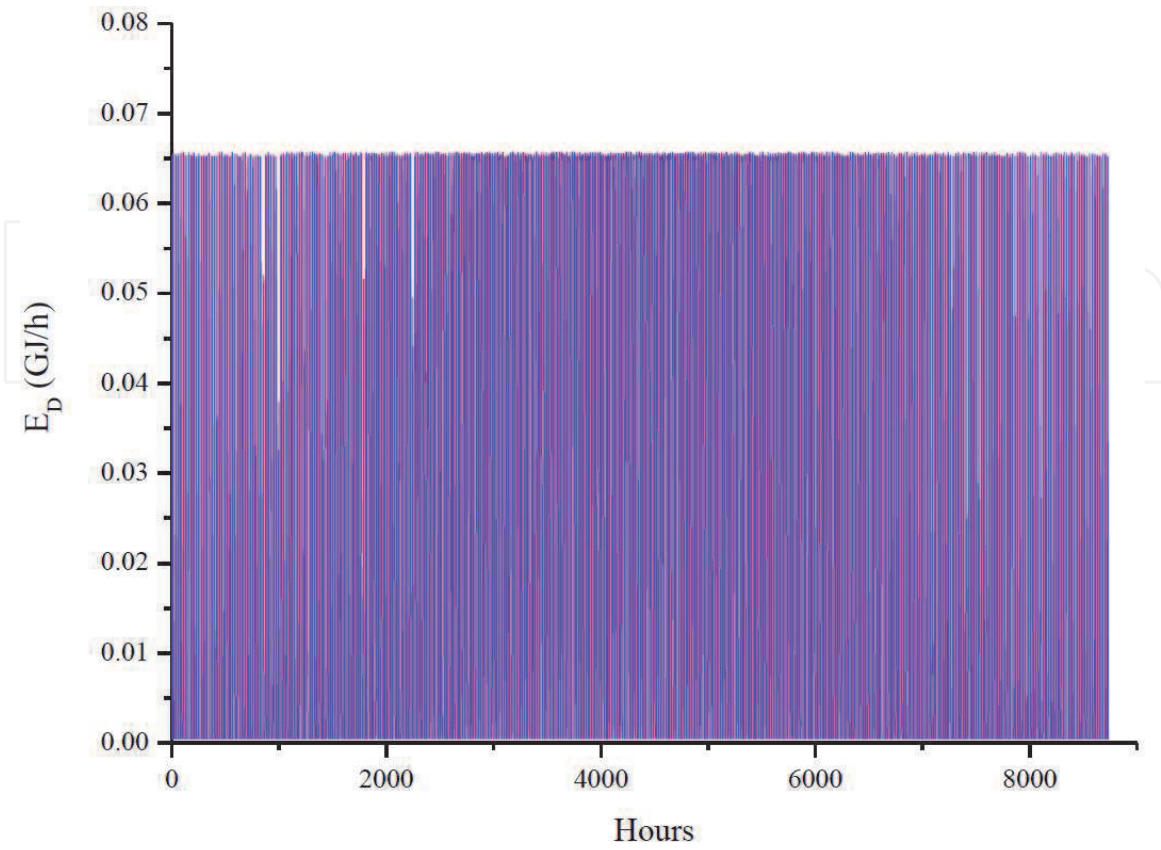**Figure 2.**
Solar irradiation.
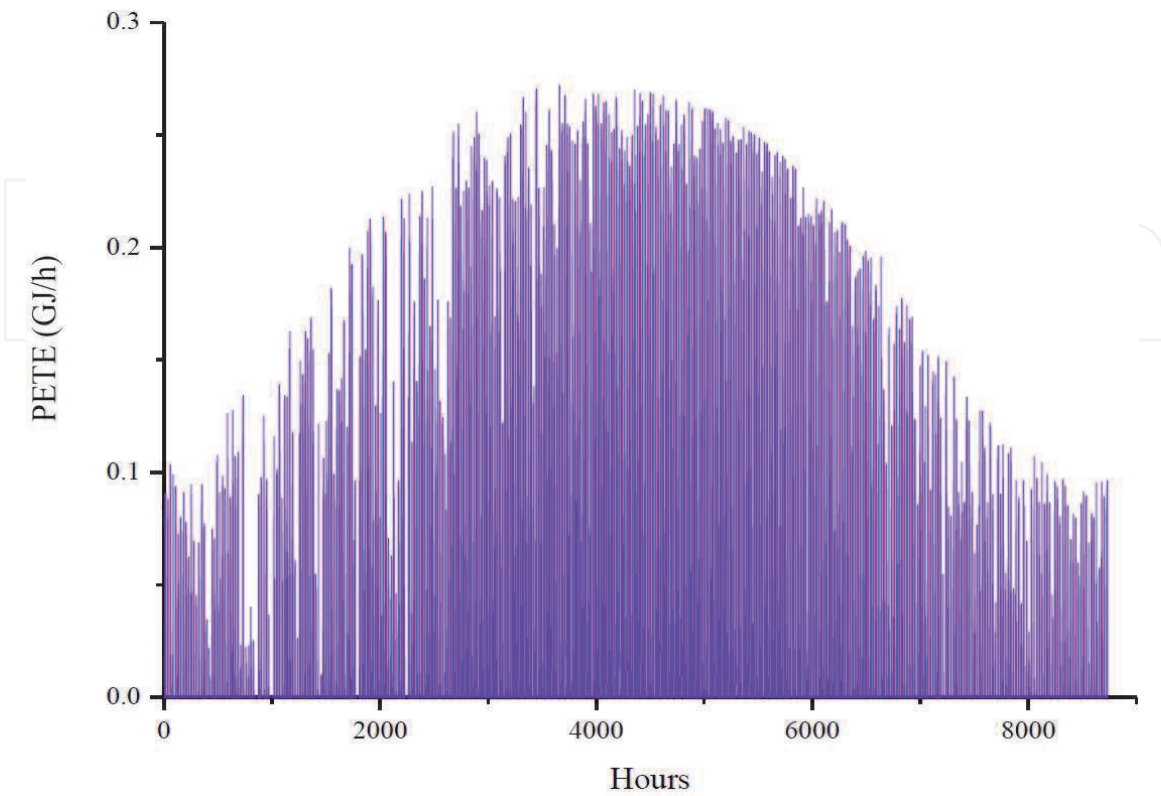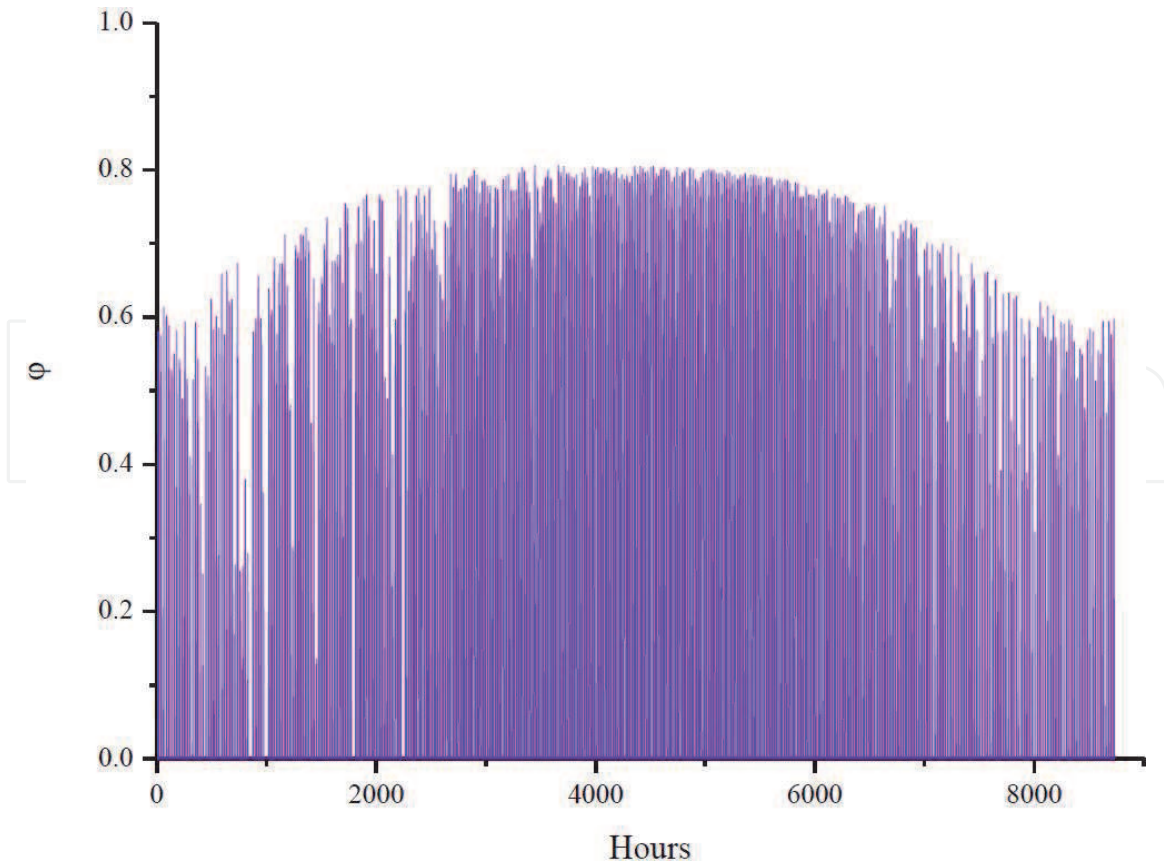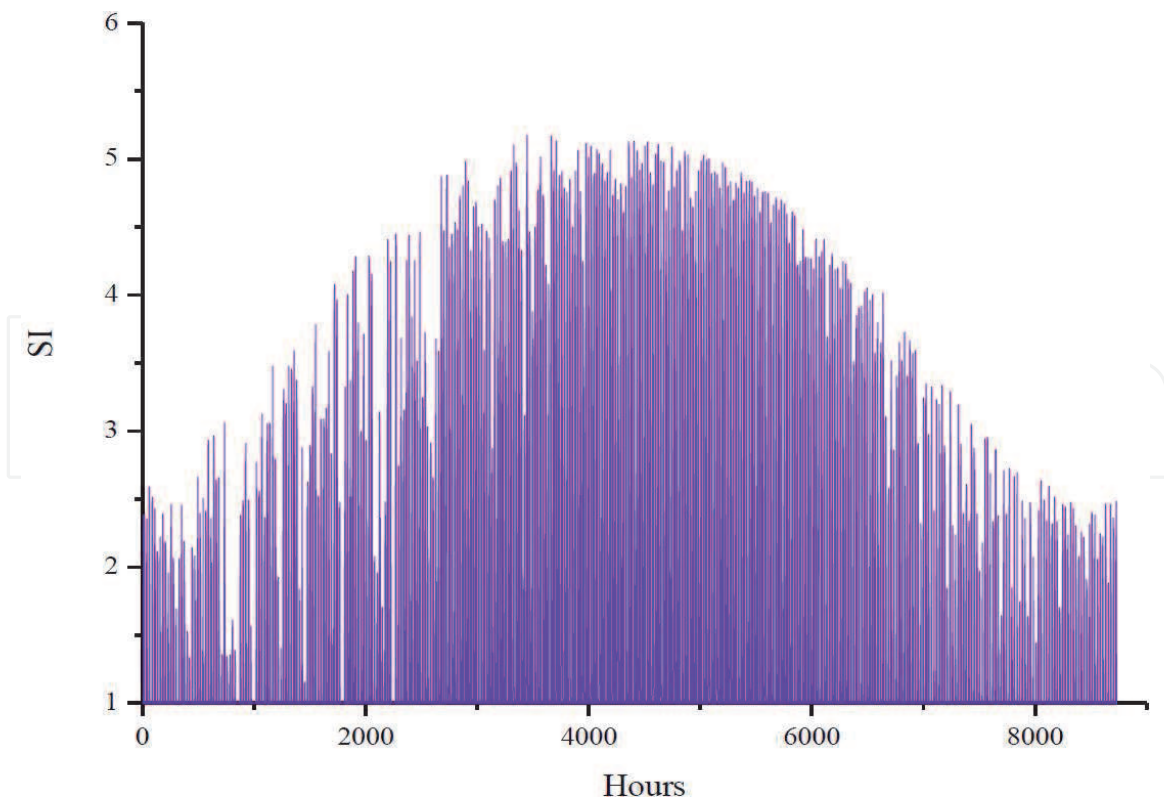

Figure 3.
Exergy output rate.

Figure 4.
Extended exergy rate.

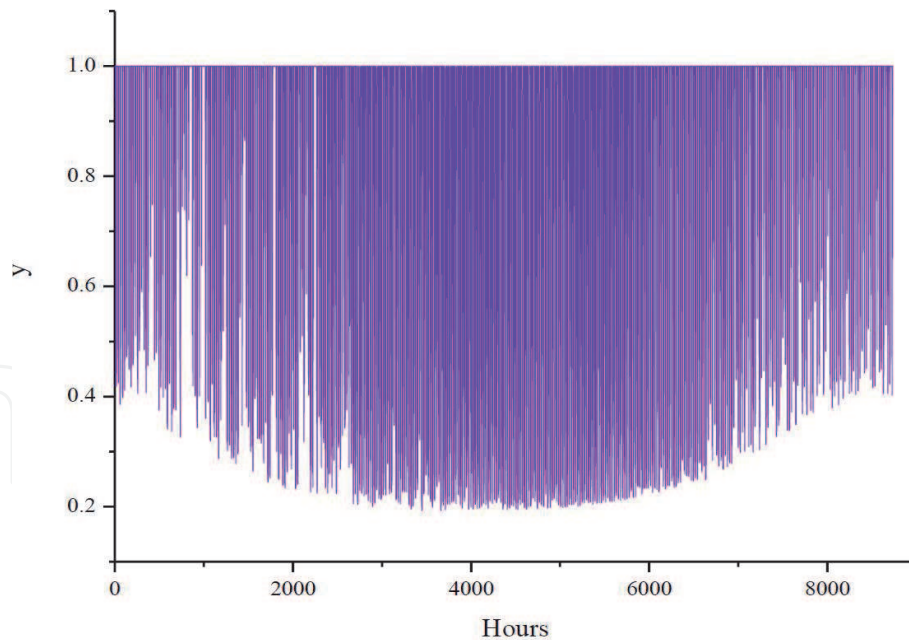**Figure 5.**
Exergy destruction rate.

Figure 6.
Extended exergy efficiency.

Figure 7.
Sustainability index.

workhour, ee_K is the specific exergy equivalent of the capital donating exergy per Euro, EE_L, EE_K, E_P, E_D, φ, SI, y, are the total equivalent exergy of the labor, total equivalent exergy of the capital, product exergy aiming output from any system,

Figure 8.
Exergy destruction ratio.

exergy destruction is depleted exergy in any system, exergy efficiency, sustainability index and exergy destruction rate respectively. According to results, corresponding values are equal to 10.50 *MJ/day person*, 42.68 *MJ/wh,* 12.09 *MJ/ Euro,* 2133.75 *MJ,* 15511.24 *MJ,* 353513.77 *MJ,* 238753 *MJ,* 0.60, 2.48 and 0.40. Examining performance indices, extended exergy efficiency which is measure of how quality energy used for product is 0.60, *SI* is the indicator how sustainable a system and equal to 2.48 and *y* is the depletion rate of the source. According to these results, system is 60% closer to the ideal one, *SI* is the 1 for the non-sustainable system and this means considered system 2.48 times sustainable. Last index shows that 0.25 of the exergy resources is depleted. Extended exergy is accounted as 592267.04 *MJ,* share of the exergy equivalent of the labor and capital can be neglected, since they are much lower than 1%. These means capital and labor has no effect on the considered system.

Figure 2 represents the solar irradiance, which is the solar energy input, of the Izmir where maximum irradiation rate is 3370 *kJ/h m^2*. Daily values of the PETE are depicted in **Figure 3**, it reaches to 272234.01 *MJ,* while its average value is 80923.38 *MJ.* Sum of the daily equivalent exergy of the labor and capital (418.82 *MJ*) is nearly 0.6% of the product exergy, which indicates these have no important effect on the product. It is indicator that capital and the labor are not important, however, technology is the most important factor.

Figure 3 is about the exergy output which means change of the electricity generation at the system. Naturally, electricity output in summer times because of the higher solar irradiation rate. As it is mentioned above total annual product exergy is 353513.77 *MJ.* When average and maximum values are researched, one can see that average is 80914.11 *MJ* and the maximum value is 272234.01 *MJ.* These values represent aimed product, and it is claimed as big as possible.

Figure 4 shows daily changes of the extended exergy and maximum value is equal to 337481.82 *MJ* and average is 135696.79 *MJ.* This is made of the sum of the equivalent exergy of the labor, capital and exergy input, which is the solar energy input to the system. However, it is mostly made of the input exergy. This means that solar exergy is the biggest part of the extended exergy accounting.

Similarly, **Figure 5** is about the change of the exergy destruction in which the maximum is 65724.17 *MJ* and average is 54773.42 *MJ*. In results, it is seen that exergy destruction rate is equal the sum daily equivalent exergy of the labor and capital when there is no production like extended exergy.

In **Figures 6–8**, daily results of the exergy efficiency, *SI* and *y* are indicated. Their maximums are 0.81, 5.17 and 1 respectively. Their expression can be done as follows. Quality of using energy source is 81%, sustainability of the system can reach to 5.17 and depletion of the energy source rises to 1, which means all the exergy is depleted. Their average values are exergy efficiency, *SI* and *y* is the 0.20, 1.62 0.80, like explained above, quality of the energy usage is only 20%, while sustainability ratio is relatively low and exergy source is 80% depleted. These results show the most important reason of this that PETE is relatively new technologies and they have not enough efficiency despite their promising and developing technologies.

According to the results, share of the exergy equivalent of the labor in the extended exergy accounting can be neglected because of its very small values. This means that effect of the labor has no important effect. Similarly, the rate of the exergy equivalent of the capital the, i.e., exergetic reflection of the monetary flow in the extended exergy accounting can be neglected too. This reason might be expressed as PETE technology is relatively cheaper than other renewable energy technologies. Another, important point is that the exergy destruction is very great and equal to nearly 30–40% of the extended exergy. This means that 30–40% of the input exergy cannot be converted to product and it is dissipated. Another important approach is to compare product exergy to exergy equivalent of the labor and capital. Therefore, one can determine how labor and capital are consumed for producing one-unit product. If these are researched, it is seen that consumed labor exergy is nearly 0.6% of the product exergy. This can be interpreted as labor has no important effect to produce electricity. It is expected results since PETE does not require any intervention to operate and only labor force is need to maintenance process. Similar investigation should make for the capital and results shows that influence of the capital on the product is the lower than the labor's one. Rate of the capital to the per unit product is calculated as 0.4%. As it is mentioned above, PETE is relatively cheaper than other renewable energy technologies and maintenance costs are not so expensive science that are relatively simple and do not have operating parts.

5. Conclusion

In this paper, solar energy usage by means of photon enhanced thermionic emitter is analyzed via extended exergy analysis, which is one of the methods for evaluating sustainability, and dynamic performance analysis is conducted. Izmir, which is the third biggest city in Turkey and has great monetary flow, is chosen as considered location. Since, it has good solar potential. Some important results and recommendations are listed as follows:

- Although system has relatively low exergy efficiency besides the high exergy destruction rate, it can be tolerable. Since, main energy source is solar power, which is renewable, and solar energy has no environmental harmful.

- Exergy equivalent of the labor has bigger than the exergetic equivalent of the capital. This difference is resulted from the higher value of the specific exergy equivalent of the labor, in other words, exergy provided by labor are valuable than capital.

- The maximum values of the indices show that it has good potential where global irradiation is high and generally, its losses are greater for the times when the solar irradiation is lower.

Finally, it is recommended that extended exergy analysis should be applied to other systems, which are energy conversion systems, because of its advantages in sustainability aspects mentioned before.

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