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Extended exergy analysis of a solar driven water production plant via reverse osmosis

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ABSTRACT

Water scarcity and contamination of available water are becoming one of the most complex problems worldwide and they compromise economic development, global sustainability, and human supply, among others. Water is required in almost all human activities and also for planet equilibrium in terms of biodiversity. In this research a new home scaled water desalination plant, using a reverse osmosis technology and driven with solar energy is analyzed via extended exergy analysis, which is one of the most accurate methods for evaluating both energy performance and sustainability. The proposed system, that is presented and analyzed, consists of a solar concentrator having 1000 concentrating rate, a Photon Enhanced Thermionic Emitter, a Dye-Sensitized Solar Cell for the electricity generation and a Reverse Osmosis Desalination Plant (RODP) for water purification using the produced electricity. This system allows water desalination in small scale plants requiring low density energy sources and can produce sustainable water for multiples uses, such as domestic use or agricultural, among others. The most important results are labor and capital exergy equivalents, 42.68 *MJ/workhour* and 12.09 *MJ/Euro*, respectively, and an exergy destruction of 389.700 *GJ* for all the system annually. The proposed technology can be extended and used in different locations and the Extended Exergy Analysis can be used as a powerful tool for both design and optimization.

1. Introduction

Due to the large increase in global population and taking into account the associated increasing resource needs, the whole capacity of the earth to provide enough resources for satisfying all the inhabitants is being compromised [1]. All the economic activities associated with human population are increasing global impact on the environment and, particularly, water scarcity and contamination of available water, are one of the most complex problems due to its implications in terms of economic development, sustainability and human supply. Water is required in almost all human activities, such as manufacturing, agriculture, for feeding animals, or for human consumption, for drinking purpose and for hygienic requirements, among others (cleaning, cooking, etc.).

Cities are becoming the main location where humans concentrate, and as buildings, transport and related activities increase, needs of energy, water and resources are also increasing. Many different scopes are presented in the literature requiring a methodology to face this growing problem. One of the most conclusive studies, published by the Brundtland Commission [2], stated in 1973 that sustainable development consists in securing water, energy and food supplies for current and future generations, while maintaining a healthy and self-sufficient environment. Different international organizations, being United Nations (UN) the main one, constantly alert and provide sustainable development goals [3] in order to tackle the current situation that is steadily getting worse. From a research point of view, various researchers have concluded that energy, water and indirectly food systems are highly interconnected and that an equilibrium is required to ensure sustainability. The inner relations are that food production requires

Abbreviations: DSCE, Dye-Sensitized Solar Cell; EEA, Extended Exergy Analysis; EE, Extended Exergy; GHG, Greenhouse Gases; HDI, Human development index; LCA, Life Cycle Analysis; MED, Multi Effect Distillation; PETE, Photon Enhanced Thermionic Emitter; RE, Renewable Energy; RODP, Reverse Osmosis Desalination Plant; TCO, Transparent Conducting Oxide; UN, United Nations.

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Nomenclature and formulae

Formulae

A	Area (m^2)
C	Concentration ratio
CC	Capital cost (€)
d	DSCE thin film thickness (m)
e	Specific exergy (kJ/kg)
E	Exergy (GJ)
E	Extended exergy
E_f	Fermi energy (eV)
E_g	Band gap energy (eV)
G	Total horizontal solar energy (kJ/m^2)
j	Current density (A/cm^2)
J	Operating current density (A/m^2)
L	Length (m)
m	Mass (kg)
$\dot{m}$	Mass flow rate(kg/s)
m^*	Ideality factor for the DSCE
M	National monetary amount of wages and salaries (€/year)
N	Number
n	Overall conduction band electron density
n_c	Effective density of states in the conduction band
neq	Equilibrium electron density
n_i	Intrinsic carrier concentration
n_v	Effective density of states in the valence band
P	Hydraulic pressure (kPa)
Q	Heat
SW	Solar energy (GJ)
W	Power (W)
T	Temperature (K)
V	Voltage (V)

Subscripts

0	Environment for reference state
a	Anode
b	Saltwater
c	Catode
C	Monetary unit / capital
D	Destruction
$DSCE$	Dye-Sensitized Solar Cell
e	Electron
E	Environmental
f	Fermi
h	Inhabitants
in	In / Input
L	Labor
net	Total
n	Overall conduction band electron density
n_c	Effective density of states in the conduction band
neq	Equilibrium electron density
n_i	Intrinsic carrier concentration
n_v	Effective density of states in the valence band
o	Primitive Society
P	Penetration water
$PETE$	Photon Enhanced Thermionic Emitter
$pump$	Pump
rad	Radiation
$RODP$	Reverse Osmosis Desalination Plant
$surv$	Consumption for human survival (MJ/person day
sc	Short Circuit
W	Osmosis membrane
w	Water
wh	Work-hours in a year
$surface$	Surface
peq	Equilibrium hole density

Superscripts

–	Average
·	Rate (s^{-1})

Constants

dn	Photon-enhanced conduction band electron density
ec	Electron charge (Coulomb)
E_f	Fermi energy (eV)
E_g	Band gap energy (eV)
H	Planck's constant (Js)
k	Boltzmann constant (J/K)
K_W	Water permeability coefficient
K_{bb}	Coefficient at which electrons recombine per volume
K_p	Coefficient at which electrons emit per volume
P_s	AM1.5 direct circumsolar spectrum
T_s	Temperature of the sun (K)

Greek letters

$h\nu$	Photon energy (J)
x	Salinity
Δ	Increment
λ	Decreasing rates of the power output because of the operating temperature of DSCE
ϕ_b	Schottky barrier height (J)
ϕ_o	Light intensity under 1 sun condition ($m^{-2}s^{-1}$)
Γ	Rate of photoexcitation
Φ	Work function (eV)
η	Mechanic efficiency (%)
π	Osmotic Pressure (kPa)
ρ	Density (kg/m^3)
φ	Extended exergy efficiency (%)
χ	Electron affinity

land, water and energy, associated with transport activities, water treatment and water supply require energy and energy production requires water and land as well, sometimes food (for example biofuels) [4] and other resources. From a whole point of view, water is needed for water irrigation as well as for human consumption, but also in almost all industrial processes and in many electrical generation systems, for cooling purpose, for example.

From the agricultural point of view, taking into account the current rate of population growth, the agricultural sector is challenged with increase in demand and, therefore, production. It is estimated that it would be required doubling food production by 2050 [5]. Recent research shows that approximately 71% of current world water withdrawals are related, directly or indirectly, to the agricultural sector [6] and its consumptions. Energy sector also consumes a high share, that accounts for around 15% of the global water withdrawals [7] and is also responsible for up to 65% of global Greenhouse Gases (GHG) emissions [8]. Taking into account this situation, energy and water usage improvements are directly linked, and therefore, strategies to secure both of them are required [9–15]. The absence of global design strategies and analysis and optimizing tools for energy-water systems, are one of the most important threatens of these resources to meet growing demand, and in this research a novel exergy approach, including Life Cycle Analysis (LCA) in its scope, is presented for a solar driven desalinization system [16,17].

In many regions, it is required to propose alternative methods for providing water resource, and sustainable desalinization, using Renewable Energy (RE), is one of the most important technologies that could produce enough water to match demand without compromising environment [18–20].

Most of the techniques to provide water from non-conventional sources require high energy consumption, as shown in Table 1 [21].

Despite in Table 1 Reverse Osmosis is presented as a high energy demand process, the proposed research proposes a novel approach because it proposes a cheaper technology, in comparison with existent that requires low energy density, does not use heat power sources and is suitable for small scale plants.

In the present research, a novel desalinization plant, using solar energy as source, is analyzed from the economic, environmental and whole life cycle points of view. The system consists of a solar concentrator having 1000 concentrating rate, a photon enhanced thermionic emitter and dye-sensitized solar cell for the electricity generation and a reverse osmatic desalination plant for water purification using the produced electricity. Despite thermal and mechanical vapor compression systems are the traditional systems and optimal for large plants, they are not optimal for small desalination plants using only renewable energy and at small scale plants, as presented in this research.

The most important novelties and aspects this paper deals with can be summarized as follows:

- Analyzes the increasing water demand and water scarcity and proposes a novel system, using renewable energy, to produce drinkable water that could be used for drinking or agricultural uses, among others.
- Proposes the use of Extended Exergy Analysis as tool to optimize both energy and economic performances of the system.
- Uses a case study in Turkey to validate the model and studies the most important aspects from both design and operation points of view

1.1. Exergy analysis and extended exergy analysis

Conventional exergy analysis is a one-dimensional methodology, that only focuses on studying the use of energy in a system, but this method can be extended to perform a LCA. In this extended approach, the method evaluates all energy flows for the whole extraction to final use process. As a whole cycle analysis, it also takes into account the final disposal of the product. LCA tools and methods are used to evaluate the entire supply, demand chains of a product or process, and also are a powerful tool to evaluate the environmental impact.

Combing exergy analysis into conventional LCA methodology is not a novel approach and has been discussed and suggested in different researches since the late 1990s [34]. All the research previously done allows to conclude that including exergy analysis in LCA conventional methodology is a good methodology to evaluate the global impact and efficiency of the processes, and that has many benefits. Ayres et al. [34] identified the main benefits because they concluded that using exergy as the calculation unit, it was possible to compute the consumption and wasting of nature's utility capital for the whole life of one product. This method is the best one to evaluate the whole physical life of a product and makes possible to compare environmental impacts of different processes or products, and, therefore, proposing strategies to improve the whole efficiency and resource use. As remarked by different authors, such as [34], exergy counting is not an appropriate tool of measuring environmental damage assessment because it lacks some important aspects, such as a measure of toxicity, but its global potential makes it one of the best possible available alternatives. Cornelissen and Hirs [35] also proved that exergetic content of the considered waste stream could not be considered as an exact indicator for the potential of environmental damage.

Different methods that combine the methodology of exergy analysis and LCA have been introduced and performed in the literature. All the methods are based on the same principle, but they differ in the way of performing the analysis. In this present research, a solar system for water desalinization plant, the Extended Exergy Analysis (EEA) is used as the best alternative to evaluate the whole process impact, efficiency and its improvement potential. The selected EEA methodology includes an extended exergy balance of all the materials, energy carriers, immaterial factors and non-energetic aspects (that can be considered externalities) and, therefore, provides a good measure of all the resources that are used in the plant or process and evaluates the exergy in each of them, that can be defined as the resources that are irreversibly consumed in the life cycle for the complete material or immaterial commodity. Using this method allows to evaluate and monitor the global problem of resource depletion and environment damage [36]. This global analysis can be defined as an application of the exergy concept to a wider approach, because it is used to measure different fluxes and magnitudes [37]. Extended Exergy (EE) is a concept that can be defined as a thermodynamic quantity that evaluates and quantifies the total amount of equivalent primary exergy that is available in a commodity. If only EE is employed as the selected measuring tool of a resource consumption, it is useful to propose improvements that would lead to lower exergy use and destruction. If the improvements are implemented, the whole degree of sustainability of the process will increase. This method also has limitations and assumptions are required to make possible comparing heterogeneous resource quantities and also comparison of different socio-economic scenarios but referring them to a common base extended exergy is possible and ensures exact and useful results. Taking into account this aspect, EEA provides more insight than other exergy-based methods in the literature [37–39]. Turkey has been used as a model to perform exergy analysis for solar radiation [46] but there are not previous approaches including a combined EEA of a desalination plant, using solar energy and an osmosis system. Exergy analysis can be used for many different systems, including polygeneration systems [47], allowing a deep improvement of these systems. Desalination plants using other technologies, such as gas turbines, can also be studied using exergy analysis [48].

Table 1
Characteristics of most common desalination technologies [21].

Technology	Power Consumption	Brine Production	Inner Area Use	Investment Cost/m^3	Operational Costs
SHAMS-Titanium MED desalination	Low	Yes	No	High	Moderate
AD and MED + AD TEchnology	Low	Yes	No	High	Moderate
TNO Netherlands (N.Kuipers et. al)???PLEASE CHECK	Low	Yes	No	High	Moderate
Dutch Pyramic/Seawater seawater Greenhouse	Low	Yes	Yes	High	Moderate
Aqua.abib Water Solutions	Low	No	Yes	High	Moderate
Multistage Flash	High	Yes	No	Moderate	Low
Multi Effect Distillation (MED)	High	Yes	No	Moderate	Low
Thermal Vapor Compression MED	High	Yes	No	Low	Low
Mechanical Vapor Compression	High	Yes	No	Low	Low
Reverse Osmosis	High	Yes	No	Moderate	Moderate

1.2. Exergy analysis to increase energy efficiency and water availability

As presented in Section 1.1, exergy analysis is one of the most common methods used to evaluate the energy performance in complex systems, when energy quality is evaluated. This analysis of systems or processes evaluates resource consumption, also known as exergy depleting and reveals if it is possible to design more efficient systems in terms of resource use efficiency. Therefore, this method is quite useful to evaluate the real efficiency of a project and a key component to ensure sustainable development [22–28]. The traditional methodology to analyze and describe the resources potential and its availability [29,30], efficiency of the consumption and maximum potential has been exergy analysis [31] because it quantifies exergy, named as available energy or maximum work generation limit of the resource and its exergy-based evaluation accounts for the utility potential of the resource, the resource depletion, and the whole loss of potential in the course of material and energy transformations. For analysis of natural resources, for example in this study solar radiation, exergy of natural resources is regarded as a measure of the resource quality.

This approach is quite useful because exergy can be widely used as a quantity or measure to quantify all types of resources and their utility potential. Moreover, if applied to transformation processes, it could be used to map the resource consumption and propose better technologies, that would lead to an increase in exergy efficiency [32]. When it is combined with energy analysis, exergy analysis is extensively reported in the literature as the most effective way to study the ways of utilization from primary resources, taking into account both quantity and quality [28]. Exergy depletion, a phenomenon that takes place in all kind of processes, is one of the most powerful tools to measure resource use. If the definition is extended, exergy-based analyses can be used to analyze a whole society and describe the use of resources in terms of exergy, and this tool enables to perform a complex, comprehensive and deeper insight from the sustainability point of view, allowing researchers to identify areas where large improvements are required and, moreover, evaluate the improvement potential of any system. It allows selecting the most efficient technologies [33] and is useful to determine the priority of the areas where improvement is possible and required.

All these advantages and the optimization potential can be

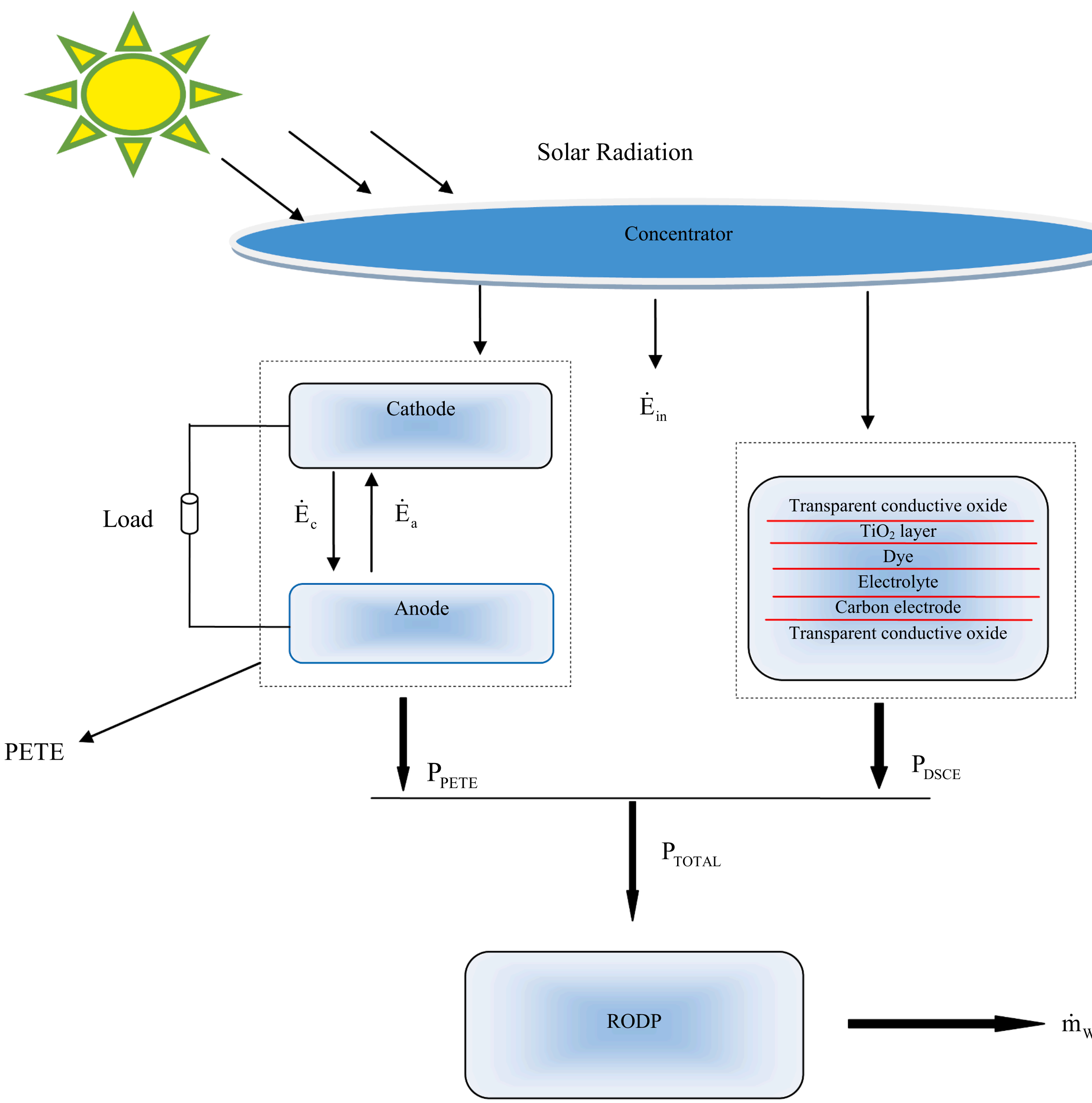

Fig. 1a. Schematic of the desalinization system.

extensively used for water systems optimization, including water desalination, distribution systems and water treatment plants, among others. In this research exergy evaluation is used as a way to design and optimize desalination plants using reverse osmosis and solar energy, and the results show its potential and benefits in terms of both design and energy optimization. Moreover, the EEA can be used to analyze and improve the whole water consumption cycle from the economic and technical points of view, and there are extensive research using EA for combined thermal systems, such as concentration solar plants, tower plants or systems for the combined production of energy, water or hydrogen [49–53]. Moreover, some multiobjective optimization tools are presented in recent literature using the thermoeconomic analysis as the core analysis tool, showing its potential for advanced analysis but also for optimization purposes [47,48].

2. System description

The presented and analyzed system, as shown in Fig. 1a and Fig. 1b, consists of a solar concentrator having 1000 concentrating rate, a Photon Enhanced Thermionic Emitter (PETE) and a Dye-Sensitized Solar Cell (DSCE) for the electricity generation and a Reverse Osmosis Desalination Plant (RODP) for water purification using the produced electricity.

A PETE has the same basic with the conventional thermionic converter, and its only difference is that the p-type semiconductor is replaced with the metallic cathode to increase the electron affinity from the surface. When illuminated with concentrated solar energy, heat is absorbed by the cathode and photons having higher energy from the bandgap create electron hole pairs. High energy level electron numbers increase at the conduction band, which cause to increase of conduction band Femi level. Electrons are emitted from the cathode to vacuum, whose energy is bigger than work function of the cathode. Since excess energy of the photon leads to increasing the temperature at the cathode and efficiency of the system is raised. Electrons emitted to the vacuum reach the anode. However, some electrons have not energy to reach anode and turn back to the cathode.

However, dye-sensitized solar cell operates in terms of photovoltaic process instead of the thermionic one. As sunlight irradiates on the DSCE, the dye molecules undergo a photoexcitation process because of high energy level photons. The excited electrons are injected into the titanium dioxide (TiO_2) conduction band and then diffuse through a semiconductor film to the Transparent Conducting Oxide (TCO). Finally, the electrons flow through an external circuit to the counter electrode. At this electrode, a redox couple exists that provides regeneration of the dye molecules to transfer positive charge to counter electrode.

The last part of the considered system is the reverse osmosis desalination plant. The RODP operates by using semi-permanent membranes for water purification. It can be used in a very wide range from biological to chemical species or from industrial processes or portable ones. In addition, its power consumption is dramatically lower than other desalination methods.

Calculations are conducted for the Izmir province in Turkey, which is one of the sunny cities of Turkey. In addition, it is the third biggest city in Turkey located on the Aegean Sea cost. The surface are of solar panels is 100 m^2 and the capacity of the RODP is 150 t/year and the cost of the water per kg is 0.030544 Euro/kg.

3. Methodology

In this section, the methodology used for the assessment of the system is described. Analyses applied and the performance criteria of the PETE, DSCE and RODP are defined in detail. Calculations are performed as daily and annually. Dynamic analysis is utilized from the TRNSYS and Simulink software.

3.1. Extended exergy analysis

Contrast to conventional exergy analysis, extended exergy analysis

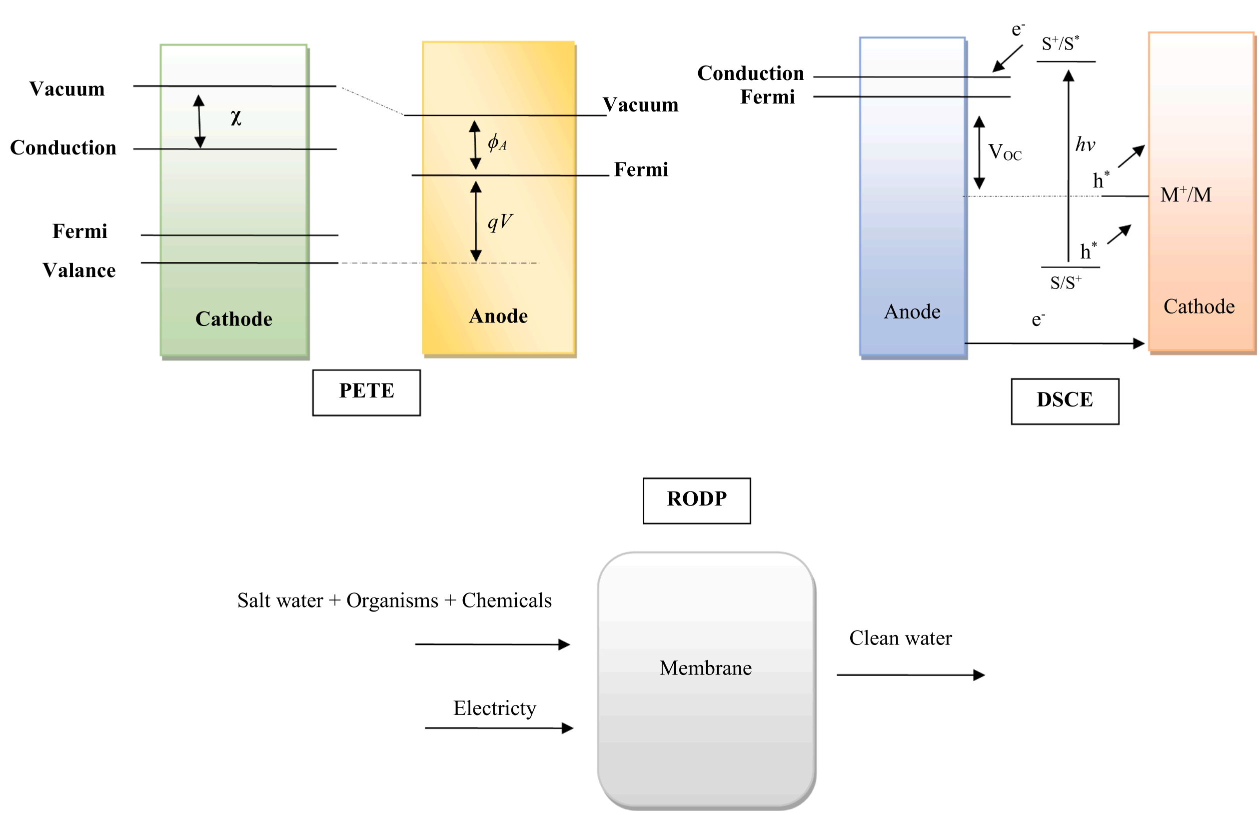

Fig. 1b. Operation principles of components (sensitizer (S), mediator (M)).

not only includes energy conversion systems and energy related parameters, but also exergy equivalent of the materials, labor, capital needed by in a process or product and exergetic equivalent of the environmental remediation costs.

The proposed methodology of the extended exergy is shown in Fig. 2.

The first stage 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. After that, calculations of the consumed materials, releasing CO_2 of the considered system, total exergy input to the system, exergy for the survival, exergy equivalents of the specific labor and capital are carried out. The second calculation process includes total exergy of the equivalent labor and capital, cumulative exergy consumption, product exergy (or equivalent) and exergy destruction, environmental remediation. Finally, extended exergy is determined as a sum of the equivalent exergy of the labor and capital, environmental remediations and cumulative exergy. Some indices can be defined like extended exergy efficiency. In this paper, only the operations calculations of the considered system are researched. Therefore, cumulative exergy and environmental remediation are excluded, as shown in the following equation [37,38]:

$$E_{in} + E_L + E_C + E_E = EE \tag{1}$$

where E_{in}, E_L, E_C and E_E are the solar energy input, exergy equivalent of the labor, capital, and environmental remediation cost respectively as *GJ*. Input energy can be written as given below:

$$E_{in} = GA_{surface}\left(1 - \frac{4T_o}{3T_s} + \frac{T_o^{\,4}}{3T_s^{\,4}}\right).t \tag{2}$$

where G is the total horizontal solar energy to the surface (kJ/m^2), $A_{surface}$ is the surface area (m^2), T_o and T_s are the environmental temperature and temperature of the sun as *(K)* and t (s/year). Specific exergetic equivalent for labor, ee_L, is defined as given in Eq. (3), and is measured in *GJ/day*:

$$ee_L = \frac{365 N_h e_{surv} HDI}{HDI_o N_{wh}} \tag{3}$$

where N_h is the population of country, *HDI* is the human development index, HDI_o is the human development index of a primitive society, e_{surv} (*MJ/person day*) refers to the exergy consumption for human survival and N_{wh} (*h*) the cumulative number of work-hours in a year. Total exergy equivalent labor (E_L) is given in GJ by

$$E_L = ee_L N_{wh} \tag{4}$$

Specific exergy equivalent of the monetary unit *(GJ/day)* is calculated from

$$ee_C = \frac{365 e_{surv} N_h HDI}{HDI_o S} \tag{5}$$

where S denotes the national monetary amount of wages and salaries as *€/year* while total exergy equivalent of the monetary unit, $\dot{E}_C$, *(GJ)* is determined using

$$E_C = ee_C \sum CC \tag{6}$$

where *CC* is the capital cost (€).

3.2. Analysis of the PETE

Equations are derived from Refs. [40,41]. Energy balance of the PETE is expressed as follows:

$$\dot{E}_{in} - P_{PETE} - \dot{E}_{rad} - \dot{Q}_H = 0 \tag{7}$$

where $\dot{E}_{in}, P_{PETE}, \dot{E}_{rad} and \dot{Q}_H$ are the solar power, power output from the PETE, the radiation power flux and, the removed heat while the power input rate $\dot{E}_{in}$ (*W*) can be calculated by

$$\dot{E}_{in} = CP_s \tag{8}$$

where C is the concentration ratio and P_s is the AM1.5 direct circumsolar spectrum and, therefore, the output power P_{PETE} (*W*) is calculated as follows:

$$P_{PETE} = (j_c - j_a)V_{PETE} \tag{9}$$

where j_c (A/cm^2) is the cathode current density, j_a (A/cm^2) is the anode current density and V_{PETE} is the voltage of the PETE. Radiation power flux $\dot{E}_{rad}$ (*W*) is determined from

$$\dot{E}_{rad} = \int_{E_g}^{\infty} \frac{(h\nu)^3 d(h\nu)}{(e^{h\nu/kT_c} - 1)} \tag{10}$$

where h (*Js*) is the Planck's constant, $h\nu$ (*J*) is the photon energy, k (*J/K*) is the Boltzmann constant and T_c (*K*) is the cathode temperature. For the system, the removed heat rate $\dot{Q}_H$ is calculated in *W* using

$$\dot{Q}_H = j_c(\Phi_a + 2kT_c) - j_a(\Phi_a + 2kT_a) \tag{11}$$

where Φ_a (*eV*) is the work function of the anode and T_a (*K*) is the anode

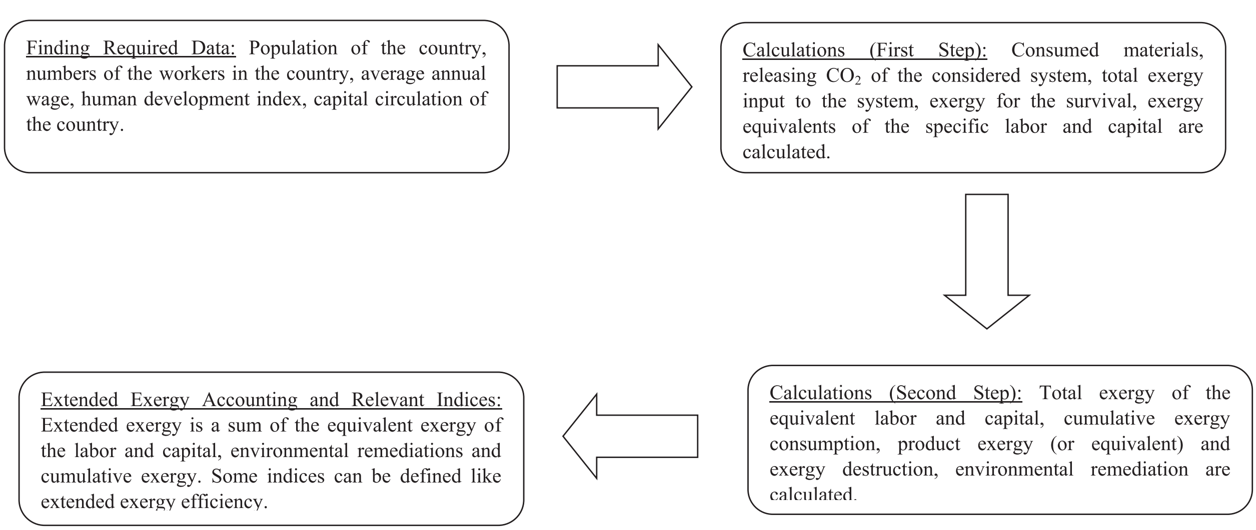

Fig. 2. Flow chart for the extended exergy accounting.

temperature. The cathode and anode current densities, j_c and j_a in A/cm^2, are computed respectively as follows:

$$j_c = en\sqrt{\frac{kT_c}{2\pi m_e}}e^{-\chi/kT_c} \quad (12)$$

$$j_a = A_o T_a^2 e^{-\Phi_a/kT_a} \quad (13)$$

where e is the electron charge (*Coulomb*), *n* is overall conduction band electron density, m_e (*kg*) is the mass of electron and χ is the electron affinity. Photon-enhanced conduction band electron density *dn* is defined as shown below:

$$dn = n - n_{eq} = \frac{[K_p + K_{bb}(n_{eq} + p_{eq})] + \sqrt{[K_p + K_{bb}(n_{eq} + p_{\partial})]^2 - 4K_{bb}[\Gamma - K_p n_{eq}]}}{2K_{bb}} \quad (14)$$

where *neq* is the equilibrium electron density, *peq* is the equilibrium hole density, *Kp* is the coefficient at which electrons emit per volume, *Kbb* is the coefficient at which electrons recombine per volume and *Γ* is the rate of photoexcitation while *neq* and *peq* are obtained from the following relations, respectively:

$$n_{eq} = n_c e^{-(E_g - E_f)/kT_c} \quad (15)$$

$$p_{eq} = n_v e^{(-E_f)/kT_c} \quad (16)$$

$$n_c = 2\left(\frac{2\pi m_n^* kT_c}{h^2}\right)^{3/2} \quad (17)$$

$$n_v = 2\left(\frac{2\pi m_p^* kT_c}{h^2}\right)^{3/2} \quad (18)$$

$$n_i = \sqrt{n_c n_v} e^{\left(-\frac{E_g q_o}{kT_c}\right)} \quad (19)$$

$$E_g = 1.17 - \frac{4.73 \times 10^{-4} T_c^2}{T_c + 636} \quad (20)$$

$$E_f = \frac{E_g}{2} + \frac{kT_c}{2}\ln\left(\frac{10^{19}}{n_i}\right) \quad (21)$$

where E_g (*eV*) is the band gap energy, E_f (*eV*) is the Fermi energy, n_c and n_v are the effective densities of states in the conduction band and valence respectively while n_i is the intrinsic carrier concentration. Using the results, the work function of the cathode (*eV*) is calculated from Eq. (22) and the overall conduction band electron and hole densities are written as shown in Eq. (23):

$$\Phi_c = \chi + E_g - E_f \quad (22)$$

$$n = dn + n_{eq},\ p = dn + p_{eq} \quad (23)$$

In this section, all equations are presented in power unit and it must be multiplied by *t* (s/year).

3.3. Analysis of the DSCE

In this section, the power output from the DSCE [42] is obtained while the shot circuit current density $J_{sc,DSCE}$ (A/m^2) is calculated from

$$J_{sc,DSCE} = \frac{e\phi_o L\alpha\left[-L\alpha\cosh\left(\frac{d}{L}\right) + \sinh\left(\frac{d}{L}\right) - L\alpha e^{(-d\alpha)}\right]}{(1 - L^2\alpha^2)\cosh\left(\frac{d}{L}\right)} \quad (24)$$

where ϕ_o ($m^{-2}s^{-1}$) is the light intensity under 1 sun condition, *d* is the thin film thickness (*m*) and *L* is the length (*m*). According to these results, the total voltage of the DSCE is obtained from

$$V_{DSCE} = \frac{kTm^*}{e}\ln\left[\frac{(J_{sc} - J_{DSCE})L\cosh\left(\frac{d}{L}\right)}{eDn_o\sinh\left(\frac{d}{L}\right)}\right] - \frac{kT}{q}\ln\left[1 + \frac{(J_{sc} - J_{DSCE})L\cosh\left(\frac{d}{L}\right)}{A_o T^2 e^{\left(-\frac{e\phi_b}{kT}\right)}}\right] \quad (25)$$

where m^* is the ideality factor, ϕ_b (*J*) is the Schottky barrier height, and *J* (A/m^2) is the operating electric current density of DSCE. Finally, the power output from the DSCE can be calculated using

$$P_{DSCE} = J_{DSCE}V_{DSCE}A_{DSCE} - \lambda(T - T_o) \quad (26)$$

where λ represents the decreasing rates of the power output because of the operating temperature of the DSCE. For converting these parameters, which are calculated as power, they are multiplied by *t* (s/year).

3.4. Reverse osmosis desalination plant

The RODP is used for water purification, and in this type of plant, high pressure pumps are utilized to overcome the required osmotic pressure. Mass balance of the plant is calculated using two different balances, as given below:

$$\dot{m}_f = \dot{m}_P + \dot{m}_b \quad (27)$$

$$x_f\dot{m}_f = x_P\dot{m}_P + x_b\dot{m}_b \quad (28)$$

where $\dot{m}_f$, $\dot{m}_P$ and $\dot{m}_b$ are the feed water, penetration water and saltwater flow rates, measured in *kg/s* respectively while x_P, x_f and x_b are the feed salinity, penetration salinity, and saltwater salinity. The mass of water penetration through half-permeable membrane is given by [43]:

$$\dot{m}_f = (\Delta P - \Delta\pi)K_W A_W \quad (29)$$

where A_W is the osmosis membrane area (m^2) and K_W is the water permeability coefficient defined as follows [41]:

$$K_W = \frac{6.84 \times 10^{-8} \times (18.68 - (0.177 \times x_b))}{T_f} \quad (30)$$

where T_f is the feed water temperature in *K*.

Using the previous calculation, and taking into account a global power balance, the power consumed P_{net} (*kW*) is calculated using [43]

$$P_{net} = P_F + P_E \quad (31)$$

ΔP and *Δπ* are the hydraulic penetration and osmotic pressure (*kPa*), as given below, respectively [43].

$$\Delta P = \overline{P} - P_{p-RODP} \quad (32)$$

$$\Delta\pi = \overline{\pi} - \pi_p \quad (33)$$

where P_{p-RODP} and π_p the hydraulic and osmotic pressures of the penetration flow while $\overline{P}$ and $\overline{\pi}$ are the average water pressure fed and the average osmotic pressure fed on the fed side. Pressure fed at the saltwater is calculated, in *kPa* using the following relations [41]:

$$\overline{P} = 0.5(P_f + P_b) \quad (34)$$

$$\overline{\pi} = 0.5(\pi_f + \pi_b) \quad (35)$$

P_f and $P_b$are the hydraulic pressure of fed current and passed current,π_f and π_b are described as osmotic pressure of fed current and passed current. Using these parameters, the water mass flow rate $\dot{m}_W$ (*kg/s*) is calculated from [43]:

$$\dot{m}_W = \frac{W_{net}\rho_f\eta_{pump}}{\Delta P_{net}} \tag{36}$$

where $\rho_f$is the density of the water (kg/m^3) and $\eta_{pump}$is the pump mechanic efficiency.

3.5. Performance evaluation criteria

Performance criteria in this research can be defined as exergy output rates of the products, extended exergy efficiency and exergy destruction rates. Exergy outputs from the products are the power output of the PETE, the power output of the DSCE and the exergy water produced in the RODP, as written below:

$$E_{PETE} = P_{PETE}t, E_{DSCE}\mathrm{t} = P_{DSEC}, E_W = \dot{m}_W e_w \mathrm{t} \tag{37}$$

In this study, the product exergy is assumed as a sum of the power output from the PETE and DSCE and water exergy instead of the final product (water exergy). Reason for this is that subsections of the process are comprehensively investigated in the extended exergy analysis, and $e_w$is the specific exergy of the water (kJ/kg). The extended exergy efficiency is described as a ratio of the exergy output of the products to the extended exergy, as given below:

$$\varphi = \frac{E_P}{EE} \tag{38}$$

Finally, exergy destruction can be described and calculated using

$$E_D = EE - E_P \tag{39}$$

4. Results and discussion

In this section, dynamic performance results of the solar driven reverse osmosis system are presented and discussed. The results are illustrated in Figs. 3–10 while the annual results are presented in Tables 2a and 2b.

Daily exergy equivalent of the labor and capital is calculated by using the annual values and the corresponding values are 3.35 MJ/day and 78.40 MJ/day, a sum of them is equal to 81.75 MJ/day

In Tables 2a and 2b, the annual results for the exergy analysis are given. As can be seen from these tables, the efficiency is very low and the exergy destruction rate is very high. Exergy equivalents of the labor and capital, which are converted to the exergy values of labor and capital, have nearly no effect on the system. Labor and capital exergies are 3.131 GJ and 73.61 GJ while other important parameters are ee_L and $ee_{K,}$ representing specific labor and capital exergies per workhour and Euro, respectively. Labor and capital exergy equivalents are 62.73 MJ/workhour and 73.61 MJ/Euro. e_{surv} is equal to 10.50 MJ/day and this means that exergy needed for a person to survive. Exergy destruction is 27063.77 GJ for all the system annually.

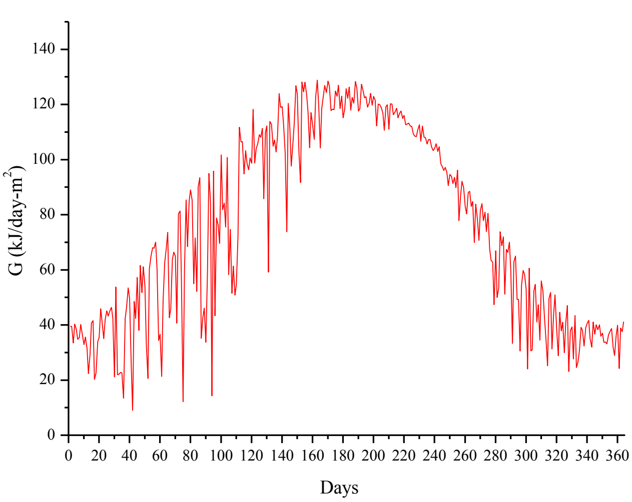

Fig. 3. Solar irradiance rate for the city of Izmir.

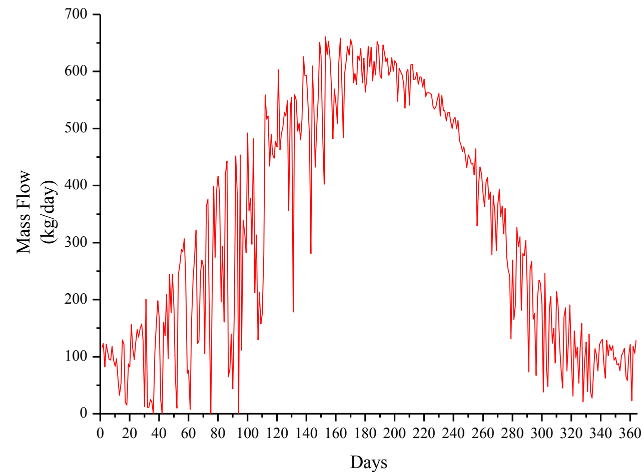

Fig. 4. Mass flow rate of the clean water produced in the system.

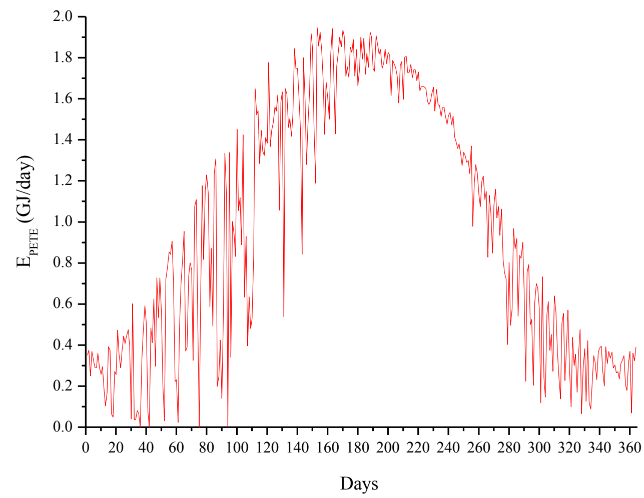

Fig. 5. Exergy output rate from the PETE.

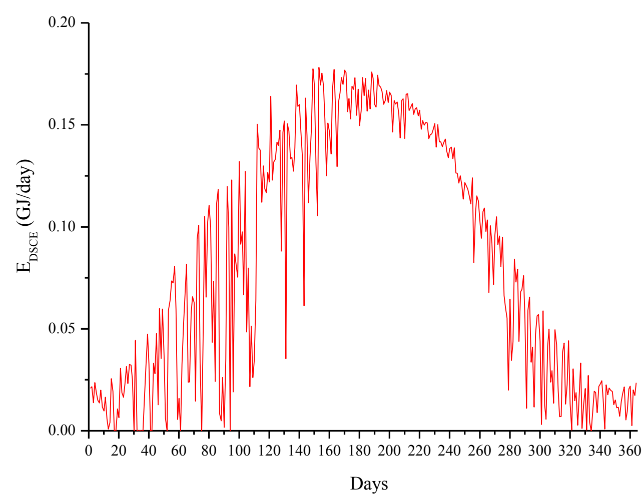

Fig. 6. Exergy output rate from the DSCE.

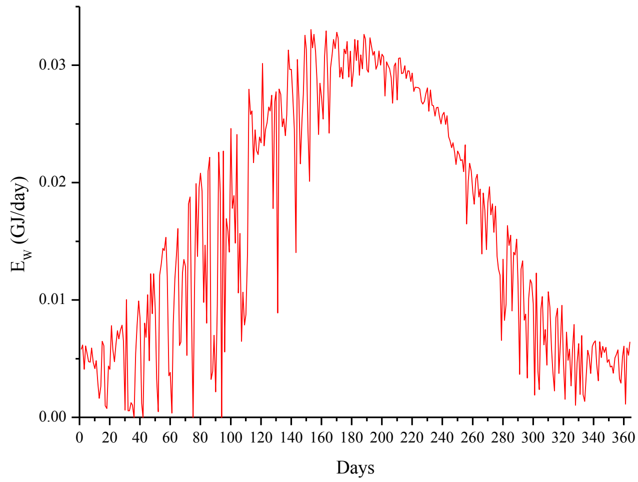

Fig. 7. Exergy rate of the produced water.

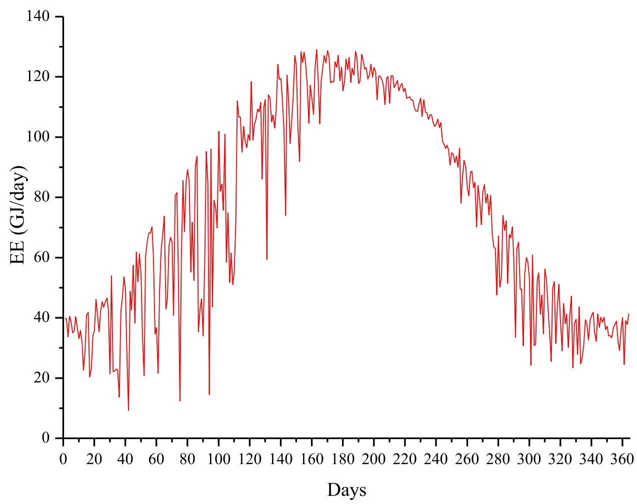

Fig. 8. Extended exergy rate of the system.

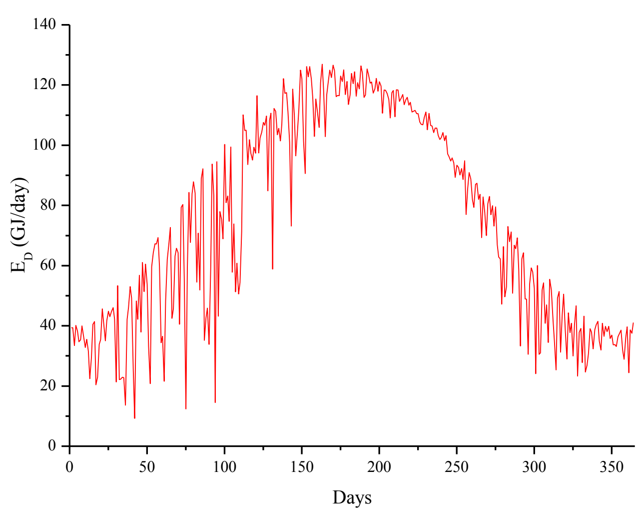

Fig. 9. Exergy destruction rate of the system.

Fig. 3 represents the solar irradiance, which is the solar energy input, of Izmir where the maximum irradiation rate is 128.9 GJ/daym^2. Results are shown in Fig. 4 where the maximum water production is 660.96 kg/day while the average production is 328.75 kg/day and the annual value is around 120 *ton/year*.

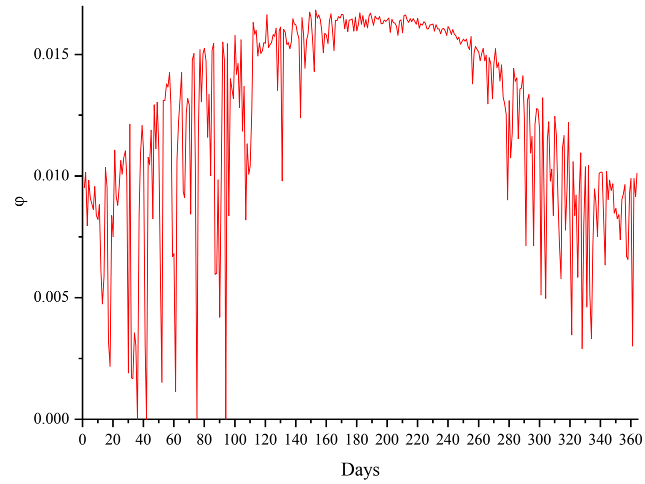

Fig. 10. Extended exergy efficiency of the system.

Daily power or the exergy output of the PETE is shown in Fig. 5 and the maximum exergy output rate of the PETE is 1.95 GJ/day, with an average value of 0.95 GJ/day. Total annual exergy output rate is 335.51 GJ/day. Comparing these values to exergy equivalent of labor and capital, their sum is 29.84 GJ/annual and 81.75 MJ/day. It can be seen that the rate of the sum of the labor and capital exergy equivalent rates to the exergy output is negligible (0.04 for the maximum value and 0.08 for the average and annual values). This means that effect of labor and capital exergy rates has just very small part to produce the product from the PETE. However, exergy efficiency is very small for the annual, average, and even maximum values of the exergy output rates of the PETE. The corresponding values are 0.013, 0.013 and 0.018, giving that exergy destruction rate or the so-called loss power of the PETE is nearly 99%.

Fig. 6 depicts the daily exergy output rates of the DSCE. One can see that the maximum and average values are equal to 0.18 GJ/day and 0.08 GJ/day for daily values and 30.22 GJ for the annual value. Similar to the results of the PETE, based on comparing the labor and capital exergy equivalent rates, one can conclude that they are more important inputs for the DSCE than the PETE. Since their share is 0.50 for the maximum values while 0.99 for the average and annual values. This means they have important effect on the product (electricity) of the DSCE. When exergy efficiency and exergy destruction rate are investigated, it can be easily seen that exergy efficiencies are nearly 0.001–0.002 and the exergy destruction is nearly equal to total exergy input.

Fig. 7 indicates the exergy rate of the produced water. According to the results, its annual, maximum, and average exergy output rates are 5.96 GJ/annual, 0.03 GJ/day, 0.02 GJ/day, respectively. These values are so much lower when compared to others, which is resulted from the low exergy values of the water. In addition, the results show that labor and capital exergy equivalent values have strong effect on the water production. Their sum is nearly 2–5 times bigger than annual, maximum and average values. Exergy efficiencies are assumed as zero and negligible. In other words, all input exergy is destructed.

Figs. 8 and 9 show the change of the extended exergy and exergy destruction results for the considered system. The extended exergy is equal to 27018.72 GJ for the annual values, 74.42 GJ/day for the average values and 126.84 GJ/day for the maximum values. According to these values, the sum of the labor and capital exergy equivalent rates has 0.1% share in the extended exergy. This means that their effect can be neglected. When exergy destruction rates are investigated, nearly more than 97% exergy input is lost. When there is no solar exergy input, exergy destruction rate is equal to the sum of the exergy equivalent labor

Table 2a
Annual results of the extended exergy analysis*.

YYear	E_{in} (GJ)	N_h (Mperson)	N_w (Mworker)	N_{wh} (Mworkhour)	Average Wage (Euro/year)	M_2 (MEuro)	f
2019	27,377	83.15	323.72	75750.48	8736	384806.71	14.40

* Values given in this table are obtained from Refs. [44,45].

Table 2b
Annual results of the extended exergy analysis (continued)*.

Year	E_L (GJ)	E_K (GJ)	E_P (GJ)	E_D (GJ)	φ	ee_L (MJ/workhour)	ee_K (MJ/Euro)	E_{surv} (MJ/day-person)
2019	3.137	73.61	389.70	27063.77	0.014	62.73	62.73	10.50

* Values given in this table are obtained from Refs. [44,45].

and capital since there is no electricity and water output under this condition.

Fig. 10 indicates a variation of the exergy efficiency. As can be seen, the average and maximum efficiencies are calculated as 0.014 and 0.019, respectively. It is concluded that exergy input is mostly lost while the exergy destruction is very high, being more than 97%. Although it is not desired to have high exergy destruction rates, solar energy is renewable energy and the system has no environmental harm effects under the operation conditions, this can be tolerable. However, the most important reason for this that the PETE and DSCE are relatively new technologies and they have not enough efficiency for now. In addition to that, they are very promising and developing technologies.

Another important reason for lower exergy efficiency is that water has very low exergy capacities and it can be solved by producing products having greater exergy potential like hydrogen. Final possibility is that the considered system is a home sized system, and it is very well known that bigger plants are much more efficient.

Exergy products obtained from components are depicted in Fig. 11. As can be seen, more than 90% of the total product was met by the PETE. This shows that the PETE is much more effective than the DSCE for the same panel area. Water exergy output is about 2% and as mentioned above, for producing higher specific exergy product, exergetic efficiency would be importantly increased.

Some results obtained from the literature were compared to those the present study. In this regard, Fellaou et al. [54] made advanced exergy analysis of a reverse osmosis desalination system. Their results indicated that a minimum exergy efficiency of 18% was obtained at the reverse osmosis unit. Kerme et. al. [55] analyzed a solar driven power, desalination, and cooling poly-generation system by utilizing energy and exergy methods. A multiple effect distillation was used in the considered system. They reported that the two main sources of exergy destruction were the solar thermal collector and desalination unit. The total exergy efficiency of the poly-generation system was 25%, with a total exergy destruction rate of 1780 kW. Koute et al. [56] evaluated solar driven cogeneration systems using supercritical CO_2 Brayton cycles and MEE-TVC desalination system. Based on their results, the second biggest entropy generation occurred in the desalination plant. According to these results, exergy efficiencies of the desalination systems were relatively low if energy source was used for producing water only, similar to the system we considered. However, if a desalination system could be utilized in a cogeneration/poly-generation system where water was not only product, exergy efficiency would be higher.

5. Conclusions

In this paper, a new home scaled water desalination plant solar energy driven is analyzed via extended exergy analysis, which is one of the methods for evaluating sustainability while the dynamic performance analysis is conducted. Izmir, which is the third biggest city in Turkey and has great monetary flow, is chosen as the considered location. Because it has good solar potential on the seaside and big tourism potential, which leads to increasing water requirement in the summertime. Some important results and recommendations, that can be considered as novel results from the study, are listed as follows:

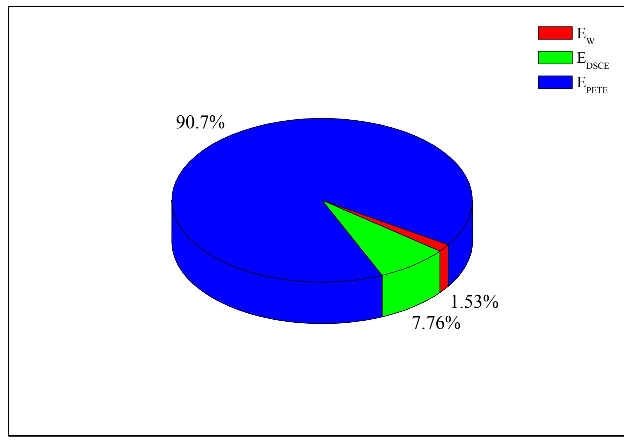

Fig. 11. Share of the product exergy for all components.

- Annual extended exergy is 27406.60 GJ, annual exergy destruction is 27376.72 GJ, annual product exergy is 389.70 GJ and exergy efficiency is 0.014.
- Although the system has a very 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.
- Instead of water production, products having much higher specific exergy content, such as hydrogen, some chemicals etc., can be produced.
- Bigger sized plants are relatively more efficient than others and these kinds of plants can be investigated in the future studies.

Finally, it is recommended that extended exergy analysis be applied to other systems because of its advantages in terms of sustainability aspects mentioned before, especially in the global situation where both water and other resources are lowering and, as proved in the presented research, the proposed methodology can be of great interest to improve the associated processes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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