# ANALIZA I OCENA SOLARNIH ENERGETSKIH SISTEMA BUDUĆNOSTI

# A KEY REVIEW ON EXERGETIC ANALYSIS AND ASSESSMENT OF SOLAR ENERGY SYSTEMS FOR A SUSTAINABLE FUTURE

**J. Skerlić[1], M. Bojić[1], D. Nikolić[1], J. Radulović[1], D.Cvetković[1]**

***[1]Faculty of Engineering at Kragujevac, University of Kragujevac, Sestre Janjic 6, 34000***

***Kragujevac, Serbia***

E mail: autor for coresponding  jskerlic@kg.ac.rs

*Energetski resursi i njihova upotreba povezani su sa održivim razvojem. U postizanju održivog razvoja, važnu ulogu igra povećanje energetske efikasnosti procesa u kojima se koriste održivi izvori energije. Upotreba obnovljive energije nudi širok izbor izuzetnih prednosti. Takođe postoji veza između eksergije i održivog razvoja. Eksergetska analiza se uveliko koristi u projektovanju, simulaciji i proceni karakteristika sistema za solarnu energiju. Solarna energija je čista, ima je u izobilju i lako je dostupna obnovljiva energija. U ovom radu je data eksergetska analiza sistema za solarnu energije (primene solarnih kolektora, kao što su sistemi za grejanje pomoću solarne energije, fotonaponski sistemi). Detaljna energetska i eksergetska analiza obavlja se kako bi se izračunali toplotni i električni parametri tipičnog solarnog kolektora. Poboljšani električni model se koristi kako bi se izvršila procena električnih parametara kolektora. Pored toga, izvedena je modifikovana jednačina za eksergetsku efikasnost kolektora u pogledu projektnih i klimatskih parametara. U tom pogledu su dati opšti odnosi između energije, eksergije i entropije. Ovo vrlo korisno znanje je takođe neophodno za utvrđivanje energetske efikasnosti i/ili mogućnosti očuvanja energije, kao i za formulisanje pravih strategija države za upravljanje energijom i eksergijom.*

***Ključne reči**: analiza; efikasnost; eksergija; obnovljiva energija; solarna, održivost*

*Energy resources and their utilization relate to sustainable development. In attaining sustainable development, increasing the energy efficiencies of processes utilizing sustainable energy resources plays an important role. The utilization of renewable energy offers a wide range of exceptional benefits. There is also a link between exergy and sustainable development. Exergy analysis has been widely used in the design, simulation and performance evaluation of solar energy systems. Solar energy is clean, abundant and easily available renewable energy. This paper reviews exergetic analysis of solar energy systems (solar collector applications such as solar water heating systems, photovoltaics). A detailed energy and exergy analysis is carried out to calculate the thermal and electrical parameters, typical solar collector. An improved electrical model is used to estimate the electrical parameters of a collector. Further, a modified equation for the exergy efficiency of a collector is derived in terms of design and climatic parameters. In this regard, general relations between energy, exergy, and entropy are given.This very useful knowledge is also needed for identifying energy efficiency and/or energy conservation opportunities, as well as for dictating the right energy and exergy management strategies of a country.*

***Key words**: analysis; efficiency; exergy; renewable energy; solar; sustainability*

## 1. INTRODUCTION

Long-term potential actions for sustainable development are needed if we want to achieve solution to environmental problems that we face today. In comparison to conventional energy sources, renewable energy sources are inexhaustible and offer many environmental benefits At the moment conventional sources meet most of the energy demand, however the role of renewable energy resources and their current advances have to take more relevance in order to contribute to energy supply and support the energy conservation (or efficiency) strategy by establishing energy management systems. Numerous benefits including a decrease in external energy dependence; a boost to local and regional component manufacturing industries; decrease in impact of electricity production and transformation; promotion of regional engineering and consultancy services specializing in the utilization of renewable energy; increase in the level of services for the rural population, etc. are offered by use of renewable energy, Dincer [1] reported the linkages between energy and exergy, exergy and the environment, energy and sustainable development, and energy policy making and exergy in detail. With the aim to highlight the importance of the exergy and its essential utilization in numerous ways he provided the following key points: (a) it is a primary tool in best addressing the impact of energy resource utilization on the environment. (b) It is an effective method using the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of energy systems. (c) It is a suitable technique for furthering the goal of more efficient energy–resource use, for it enables the locations, types, and true magnitudes of wastes and losses to be determined. (d) It is an efficient technique revealing whether or not and by how much it is possible to design more efficient energy systems by reducing the inefficiencies in existing systems. (e) It is a key component in obtaining a sustainable development. Although it does not make the world 'ready' for the future generations, sustainable development establishes a basis on which the future world can be built. It may be said that a sustainable energy system is a cost-efficient, reliable, and environmentally friendly energy system that effectively utilizes local resources and networks. As opposed to a conventional energy system, it is not 'slow and inert' but it is flexible in terms of new techno-economic and political solutions. An exergy analysis (or second law analysis) has proven to be a powerful tool in the simulation thermodynamic analyses of energy systems. Exergy analysis method is used to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. It can, therefore, indicate the possibilities of thermodynamic improvement of the process under consideration, but only an economic analysis can decide the expediency of a possible improvement. The concepts of exergy, available energy, and availability are essentially similar. Exergy is also a measure of the maximum useful work that can be done by a system interacting with an environment which is at a constant pressure and temperature. Many authors dealt with renewable energy resources in terms of exergetic aspects. They also compared renewable and non-renewable energy sources. Their conclusion is that some of the systems seem to have high efficiencies, and in some cases they are greater than the efficiency of systems using non- renewable energy sources [1].

This paper reviews exergetic analysis of solar energy systems (solar collector applications such as solar water heating systems, photovoltaics). A detailed energy and exergy analysis is conducted to calculate the thermal and electrical parameters, typical solar collector. An improved electrical model is used to estimate the electrical parameters of a collector. Further, a modified equation for the exergy efficiency of a collector is derived in terms of design and climatic parameters. In this regard, general relations between energy, exergy, and entropy are given.

## 2. ENERGY AND EXERGY MODELING

Dincer et al. [4] reported that, to provide an efficient and effective use of fuels, it is essential to consider the quality and quantity of the energy used to achieve a given objective. With regard to this, the first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed, whereas the second law of thermodynamics deals with the quality of energy, i.e., it is concerned with the quality of energy to cause change, degradation of energy during a process, entropy generation and the lost opportunities to do work. To be more specific, the first law of thermodynamics is concerned only with the magnitude of energy with no regard to its quality; whereas the second law of thermodynamics asserts that energy has quality as well as quantity. By quality, it means the ability or work potential of a certain energy source having certain amount of energy to cause change, i.e., the amount of energy which can be extracted as useful work which is termed as exergy. First and second law efficiencies are often called energy and exergy efficiencies, respectively. It is expected that exergy efficiencies are usually lower than the energy efficiencies, because the irreversibilities of the process destroy some of the input exergy.

Exergy is the expression for loss of available energy due to the creation of entropy in irreversible systems or processes. The exergy loss in a system or component is determined by multiplying the absolute temperature of the surroundings by the entropy increase. Entropy is the ratio of the heat absorbed by a substance to the absolute temperature at which it was added. While energy is conserved, exergy is accumulated.

Exergy analysis provides a method to evaluate the maximum work extractable from a substance relative to a reference state (i.e., dead state). It should be noticed that exergy is always evaluated with respect to a reference environment (i.e. dead state). When a system is in equilibrium with the environment, the state of the system is called the dead state due to the fact that the exergy is zero [3].

## 3. GENERAL RELATIONS

For a general steady state, steady-flow process, the four balance equations (mass, energy, entropy and exergy) are applied to find the work and heat interactions, the rate of exergy decrease, the rate of irreversibility, the energy and exergy efficiencies [4,5–6].

### *3.1. Mass, energy, entropy and exergy balances*

The mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad (1)$$

where $\dot{m}$ is the mass flow rate, and the subscript in stands for inlet and out for outlet. The general energy balance can be expressed below as the total energy inputs equal to total energy outputs.

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \qquad (2)$$

In the absence of electricity, magnetism, surface tension and nuclear reaction, the total exergy of a system $\dot{E}_x$ can be divided into four components, namely (i) physical exergy $\dot{E}_x^{PH}$, (ii) kinetic exergy $\dot{E}_x^{KN}$, (iii) potential exergy $\dot{E}_x^{PT}$, and (iv) chemical exergy$\dot{E}_x^{CH}$ [4].

$$\dot{E}_x = \dot{E}_x^{PH} + \dot{E}_x^{KN} + \dot{E}_x^{PT} + \dot{E}_x^{CH} \qquad (3)$$

Although exergy is extensive property, it is often convenient to work with it on a unit of mass or molar basis. The total specific exergy on a mass basis may be written as follows:

$$e_x = e_x^{PH} + e_x^{KN} + e_x^{PT} + e_x^{CH} \qquad (4)$$

$$\sum \dot{E}_{x\,in} - \sum \dot{E}_{x\,out} = \sum \dot{E}_{x\,dest} \qquad (5)$$

or

$$\sum E_{\dot{x}\,heat} - \sum E_{\dot{x}\,work} + \sum E_{\dot{x}\,mass,in} - \sum E_{\dot{x}\,mass,out} = \sum E_{\dot{x}\,dest} \qquad (6)$$

with

$$E_{\dot{x}\,heat} = \sum\left(1 - \frac{T_0}{T_k}\right)\dot{Q}_k \quad (6a)$$

$$E_{\dot{x}\,work} = \dot{W} \quad (6b)$$

$$E_{\dot{x}\,mass,in} = \sum \dot{m}_{out}\tau_{out} \quad (6c)$$

$$E_{\dot{x}\,mass,out} = \sum \dot{m}_{out}\tau_{out} \quad (6d)$$

where $\dot{Q}_k$ is the heat transfer rate through the boundary at temperature $T_k$ at location k and $\dot{W}$ is the work rate.The flow (specific) exergy is $\tau$. The rate form of the entropy balance can be expressed as

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \quad (7)$$

### *3.2. Exergy efficiency*

Exergy efficiency is very useful to define efficiencies based on exergy (sometimes called Second Law efficiencies). Whereas there is no standard set of definitions in the literature, two different approaches are generally used—one is called 1 ''brute-force'', while the other is called ''functional.''

A ''brute-force'' exergy efficiency for any system is defined as the ratio of the sum of all output exergy terms to the sum of all input exergy terms. A ''functional'' exergy efficiency for any system is defined as the ratio of the exergy associated with the desired energy output to the exergy associated with the energy expended to achieve the desired output.

Exergy efficiency is defined as the ratio of total exergy output to total exergy input, i.e.

$$\varepsilon = \frac{\dot{E}_{x\,output}}{\dot{E}_{x\,input}} \quad (8)$$

where ''output or out'' stands for ''net output'' or ''product'' or ''desired value'' or ''benefit'', and ''input or in'' stands for ''given'' or ''used'' or ''fuel''.

### *3.3. Some thermodynamic parameters*

Thermodynamics analysis of *renewable energy resources* may also be performed using the following parameters.[7[a]]

Fuel depletion ratio:

$$\delta_i = \frac{\dot{I}_i}{\dot{F}_T} \quad (9)$$

Relative irreversibility:

$$\chi_i = \frac{\dot{I}_i}{\dot{I}_T} \quad (10)$$

Productivity lack:

$$\xi_i = \frac{\dot{I}_i}{\dot{P}_T} \quad (11)$$

Exergetic factor:

$$f_i = \frac{\dot{F}_i}{\dot{F}_T} \quad (12)$$

## 4. EXERGETIC ANALYSIS AND EVALUATION OF SOLAR ENERGY SYSTEMS

Calculation of the exergy of radiation is very crucial in evaluating the performance of solar energy systems using exergy analysis method, However, its calculation is a problem of unquestionable interest, since exergy represents the maximum quantity of work that can be produced in some given environment (usually the terrestrial environment, considered as an infinite heat source or sink). During the past 20 years many papers including various approaches to this calculation have been published, as reported in [7,8,9] and cited by Petela[7,10]. Then, the maximum efficiency ratio (or exergy-to energy ratio for radiation) for determining an exergy of thermal emission at temperature T, is defined as follows:

$$\boldsymbol{\tau_{srad,max}} = \mathbf{1} + \frac{\mathbf{1}}{\mathbf{3}}\left(\frac{\boldsymbol{T_0}}{\boldsymbol{T}}\right)^{\mathbf{4}} - \frac{\mathbf{4}}{\mathbf{3}}\frac{\boldsymbol{T_0}}{\boldsymbol{T}} \quad (13)$$

where $T$ was taken to equal the solar radiation temperature *($T_S$)* with 6000 K in exergetic evaluation of a solar cylindrical-parabolic cooker and a solar parabolic-cooker by Petela [10] and Ozturk [11], respectively. Eq. (13) was also derived by Szargut [12] who presented a simple scheme of a reversible prime mover (different from that of Petela) transforming the energy of radiation into mechanical or electrical work and took into account that the solar radiation had a composition similar to that of a black body.

### *4.1. Solar collector applications*

The instantaneous exergy efficiency of the solar collector can be defined as the ratio of the increased water exergy to the exergy of the solar radiation.[2]

$$\varepsilon_{scol} = \frac{\dot{E}_{x\,u}}{\dot{E}_{x\,scol}} \quad (14)$$

with

$$E_{\dot{x}u} = \dot{m}_W\left[\left(h_{w,out} - h_{w,in}\right) - T_0\left(s_{w,out} - s_{w,in}\right)\right] \quad (15a)$$

or

$$E_{\dot{x}u} = \dot{m}_W C_W\left[\left(T_{w,out} - T_{w,in}\right) - T_0\left(ln\frac{T_{w,out}}{T_{w,in}}\right)\right] \quad (15b)$$

$$E_{\dot{x}u} = \dot{Q}_u\left[1 - \frac{T}{T_{w,out} - T_{w,in}}\left(ln\frac{T_{w,out}}{T_{w,in}}\right)\right] \quad (15c)$$

and

$$E_{\dot{x}scol} = AI_T\tau_{strad,max} \quad (16c)$$

where the subscripts ‘‘in’’ and ‘‘out’’ denote the inlet and outlet of the solar collector, w water, ‘‘0‘‘ dead (reference) state, ‘‘h‘‘ heating, heat, ‘‘u‘‘ useful, ‘‘s‘‘ solar, ‘‘srad‘‘ solar radiation respectively, while $\tau_{srad,max}$ may also be calculated using Eqs. (13), (16c) given in Table 1 [7].

Table 1. Numerators (output) and denominators (input) of the limiting energy efficiency of radiation utilization by three different researchers

| *Investigators* | *Input* | *Output* | *Unified efficiency expression* |
|---|---|---|---|
| Petela [9] | Radiation energy | Useful work = radiation exergy | $1 + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 - \frac{4}{3}\frac{T_0}{T}$ |
| Spanner [13] | Radiation energy | Absolute work | $1 - \frac{4}{3}\frac{T_0}{T}$ |
| Jeter [14] | Heat | Net work of a heat engine | $1 - \frac{T_0}{T}$ |

### *4.2. Solar water heating systems*

Solar water heater is the most popular means of solar energy utilization compared with other kinds of solar energy utilization because of technological feasibility and economic attraction. Fig. 1 shows a schematic of a typical domestic-scale solar water heater, which mainly consists of a solar collector and a storage barrel [15].

Exergy efficiency of the domestic-scale solar water heater may be calculated using Eq. (8) as follows:

$$\varepsilon_{s,heater} = \frac{\dot{E}_{x\,output}}{\dot{E}_{x\,sun}} \quad (17)$$

where exergy from the storage barrel to the end-user (output exergy) may be written as follows [15], assuming the temperature distribution in the storage barrel is linear:

$$\dot{E}_{x\,output} = \dot{m}_w C_w \left(\frac{T_{top}-T_{bottom}}{2} - T_0\right) - \dot{m}_w C_w T_0 \left(ln\frac{T_{top}}{T_0} - 1\right) - \frac{T_{bottom} T_0 \dot{m}_w C_w}{T_{top}-T_{bottom}} ln\frac{T_{top}}{T_{bottom}} \tag{18}$$

and $\dot{E}_{x\,sun}$ is the exergy from sun (input exergy) and may be found using Eq. (15a).

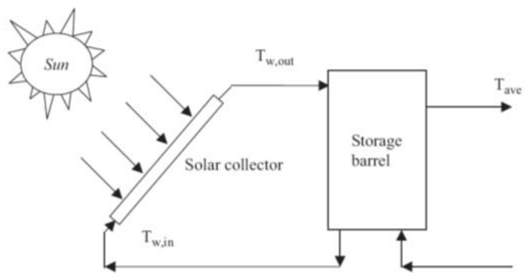


**Fig.1.** A typical domestic-scale solar water heater [15].

$$\varepsilon_{s,col} = \frac{\dot{E}_{x\,col,tank}}{\dot{E}_{x\,sun}} \tag{19}$$

where $\dot{E}_{x\,col,tank}$ is exergy from the collector to the storage barrel and may be written in a similar way given by Eq. (15b) as follows [15].

$$\dot{E}_{x\,col,tank} = \dot{m}_W C_W \left[\left(T_{w,out} - T_0\right) - T_0 \left(ln\frac{T_{w,out}}{T_0}\right)\right] \tag{20}$$

### *4.3. Photovoltaics*

Exergetic evaluation of PVs has been performed by some investigators [16,17] in hybrid (PV/thermal) systems as a part of the system. More detailed explanation of this evaluation is given in Section 4.4.

Electrical energy is not affected by ambient conditions and therefore is equivalent in work. If global irradiance is $I$, energy efficiency of the solar cell is $\eta_{scell}$, the instantaneous electrical exergy is then as follows [16].

$$E\dot{x}_e = \eta_{scell} I = \varepsilon_{scell} I \tag{21}$$

where $\varepsilon_{scell}$ is the exergetic efficiency of the solar cell.

### *4.4. Hybrid (PV/thermal) solar collectors*

The exergy efficiency of a hybrid solar collector, that generates both electric power and heat, may be calculated as follows [17].

$$\varepsilon_{PV/Thermal} = \frac{\eta_{conver} I + E\dot{x}solar}{E\dot{x}_I} \tag{22}$$

with

$$E_{\dot{x}solar} = \frac{T_{fluid} - T_0}{T_{fluid}} \dot{Q}solar \tag{23}$$

and

$$E\dot{x}_I = 0.95 I \tag{24}$$

where $\eta_{conver}$ is the conversion efficiency, $I$ the global irradiance (W/m$^2$), $E\dot{x}solar$ the exergy of heat (W/m$^2$), $E\dot{x}_I$ the exergy of global irradiance (W/m$^2$), $E\dot{x}_{solar}$ the collected solar heat amount per unit time per panel area (W/m$^2$) and $T_{fluid}$ the supply temperature of collector fluid (K).

Fujisawa and Tani [16] defined the synthetic exergy of the PV/T collector as the total value of the electrical and thermal exergies as follows:

$$E_{\dot{x}_{PV/T}} = E_{\dot{x}_e} + E_{\dot{x}_{termal}} = (\varepsilon_e + \varepsilon_{thermal}) = \varepsilon_{PV/T} I \quad (25)$$

with

$$E\dot{x}_e = \varepsilon_e I \quad (26)$$

and

$$E_{\dot{x}_{termal}} = \dot{Q}\eta_{Carnot} = \dot{Q}\frac{T_f - T_0}{T_f} = \varepsilon_{thermal} I \quad (27)$$

Fujisawa and Tani [16] designed and constructed a PV-thermal hybrid collector on their campus. The collector consisted of a liquid heating fiat-plate solar collector with mono-Si PV cells on substrate of non-selective aluminum absorber plate, the collector area was 1.3X0.5m$^2$. From the annual experimental evaluation based on exergy, Fujisawa and Tani concluded that the PV/T collector could produce higher output density than a unit PV module or liquid heating fiat-plate solar collector. Using exergetic evaluation, the best performance of
available energy was found to be that of the coverless PV/T collector at 80.8 kWh/yr, the second to be the PV module at 72.6 kWh/yr, the third to be the single-covered PV/T collector at 71.5 kWh/yr, and the worst to be the flat-plate collector at 6.0kWh/yr.
Saitoh et al. [17] performed field measurements at a low energy house at Hokkaido University. The power generated was measured by giving the variable load for the maximum power point tracking. Two hybrid solar panels were connected in parallel, while the brine was supplied at constant temperature by a fluid supply system with a circulating pump. The volumetric flow rate per panel was fixed at 1 l/ min. The tilt angle of the panel was 30º, which gave the maximum annual global irradiance. Except for winter, the mean conversion efficiency of array and the collector efficiency were stable at 8–9% and 25–28%, respectively. The dependency on solar energy was 46.3%. Energy and exergy efficiency values of single-junction crystalline silicon PV are illustrated in Table 2 [17]. The exergy efficiencies of solar collector, PV and hybrid solar collector were found to be 4.4%, 11.2% and 13.3%, respectively. Solar collector had the lowest value. In terms of energy quality, the hybrid solar collector was very effective [17].

Table 2. Comparison of energy and exergy efficiency of solar collector, photovoltaic and hybrid collector [17]

| *Type of efficiency* | *Solar collector* | *Photovoltaic* | *Hybrid collector* |
|---|---|---|---|
| Energy efficiency (η, %) | | | |
| Heat | 46.2 | - | 32.0 |
| Power | - | 10.7 | 10.6 |
| Total | 46.2 | 10.7 | 42.6 |
| Exergy efficiency (ε, %) | | | |
| Heat | 4.4 | - | 2.1 |
| Power | - | 11.2 | 11.2 |
| Total | 4.4 | 11.2 | 13.3 |

## 5. CONCLUSION

Exergy is a way to a sustainable development. With regard to this, exergy analysis is a very useful tool that can be successfully used in the performance evaluation of *renewable energy resources* as well as all energy-related systems. The exergy efficiencies of a solar collector, a PV and a hybrid solar collector were found to be 4.4%, 11.2% and 13.3%, respectively. Solar collector had the lowest value. The hybrid solar collector was very effective in terms of energy quality, but the results have clearly indicated the necessity of the planned studies towards increasing exergy utilization efficiencies in the sector studied. This very useful knowledge is also needed for identifying energy efficiency and/or energy conservation opportunities, as well as for dictating the right energy and exergy management strategies of a country.

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