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Exergy analysis on solar thermal systems: A better understanding of their sustainability

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A B S T R A C T

This paper presents a review of exergy analysis of solar thermal systems. It includes both various types of solar collectors and various applications of solar thermal systems. As solar collectors are an important technology when sustainability is considered, exergy analysis, which gives a more representative performance evaluation, is a valuable method to evaluate and compare possible configurations of these systems. It should be noted that this review is based on literature published in the last two years.

1. Introduction

Thermodynamic analysis is usually done by distinguishing the systems into closed loop and open loop. Both have a boundary, and energy (E) interactions across this boundary are work (W) and heat (Q) interactions. Usually the heat transferred into the system and the work transferred out of the system, are considered positive. From the first law of thermodynamics for any process between two states 1 and 2 which are in equilibrium:

$$\int_1^2 \delta Q - \int_1^2 \delta W = E_2 - E_1 \tag{1}$$

Or performing the integrations:

$$Q_{1,2} - W_{1,2} = E_2 - E_1 \tag{2}$$

According to Eq. (2), both work and heat interactions depend on the path of the process whereas the energy change is not and its value is determined directly from the final states 1 and 2. The second law of thermodynamics applied for the same system is given by:

$$\int_1^2 \frac{\delta Q}{T} \le S_2 - S_1 \tag{3}$$

Therefore, the entropy transfer between the closed system and the environment depends on the heat transfer across the boundary (δQ) and the boundary temperature (T). The entropy transfer differentiates the heat and work transfer as two parallel forms of energy transfer and in fact as shown by Eq. (3) only energy transfer can cause entropy transfer.

Another parameter used in this type of analysis is the entropy generated given by:

$$S_{gen} = S_2 - S_1 - \int_1^2 \frac{\delta Q}{T} \ge 0 \tag{4}$$

In the open loop systems the boundary can have ports or openings through which there is mass transfer and the thermodynamic analysis takes into account the mass, energy and entropy changes. In this case the first law of thermodynamics is given by:

$$\sum_{in} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) - \sum_{out} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) + \dot{Q} - \dot{W}_{sh} = \frac{\partial E}{\partial T} \tag{5}$$

It should be noted that the work transfer is usually in the form of a rotating shaft. It can be proved that the second law of thermodynamics is given by:

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$$\sum_{in} \dot{m}s - \sum_{out} \dot{m}s + \frac{\dot{Q}}{T} \le \frac{\partial S}{\partial t} \quad (6)$$

The difference between Eq. (6) and Eq. (3) is that for closed systems the entropy transfer is associated with a mass transfer across the boundary surface. In this case the rate of entropy generation is given by:

$$\dot{S}_{gen} = \frac{\partial S}{\partial t} - \frac{\dot{Q}}{T} + \sum_{out} \dot{m}s - \sum_{in} \dot{m}s \ge 0 \quad [\mathrm{W/K}] \quad (7)$$

The availability or exergy of a system is equivalent to the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir, usually the environment. Exergy can also be viewed as the energy that is available to be used for some useful purpose. When the system and the surroundings reach equilibrium, the exergy is zero. The maximum work potential under the assumption of a constant specific heat c_p is given by:

$$\dot{W}_{\max} = \dot{m}\left[(h - T_0 s)_{in} - (h - T_0 s)_{out}\right] = \dot{m}\left[c_p(T_H - T_0) - T_0 \ln\frac{T_H}{T_0}\right] \quad (8)$$

Exergy efficiency computes the efficiency of a process taking into account the second law of thermodynamics, thus it is also called the second-law efficiency. It is a measure of the system deviation from the reversible state and is given by:

$$\eta_{II} = \frac{\dot{W}}{\dot{W}_{\max}} = 1 - \frac{\dot{W}_{lost}}{\dot{W}_{\max}} \quad (9)$$

Using Eq. (7):

$$\dot{W}_{lost} = T_0 \dot{S}_{gen} \quad (10)$$

Equation (10) is known as Gouy-Stodola theorem. Equation (9) should not be confused with the first law efficiency, which for a heat engine operating between two heat reservoirs and T_H and T_L is given by:

$$\eta_I = \frac{W}{Q_H} = \eta_{II}\left(1 - \frac{T_L}{T_H}\right) = \eta_{II}\eta_{Carnot} \quad (11)$$

The input to a solar energy system is solar radiation. The first who examined the exergy of solar radiation was Petela during his doctoral studies [1]. He recently published a chapter in which he reviewed exergy analysis of thermal radiation processes and stated that the exergy factor is [2]:

$$\psi = 1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\left(\frac{T_0}{T}\right)^4 \quad (12)$$

where T and T_0 are the temperatures of the radiation reservoir and the environment, respectively. This result has been obtained independently by Landsberg [3] and Press [4]. Another recent contribution on the subject is by Beretta and Gyftopoulos [5] who proved that the interaction between two black bodies at different temperatures involved irreversibilities in both black bodies.

The exergy factor of the radiation emitted by a source of geometric factor *f* has been obtained recently [6–8]:

$$\psi = 1 - \frac{4}{3}\frac{T_0}{T} + \frac{1}{3}\frac{1}{f}\left(\frac{T_0}{T}\right)^4 \quad \left(f \ge \left(\frac{T_0}{T}\right)^3\right) \quad (13)$$

When $f < (T_0/T)^3$ work cannot be extracted from radiation energy. Equation (12) is a particular case of the more general Eq. (13) since it is valid only for hemispherical radiation sources ($f = 1$).

The purpose of this paper is to present a review of the application of exergy analysis on solar thermal systems based on literature published in the last two years. It includes works on the exergy analysis of various types of solar collectors and applications and on the process analysis for both low temperature and high temperature systems. The exergy analysis is not a substitute but merely a necessary complementary tool for the energy analysis, when the sustainability of the systems is considered, in order to evaluate their sustainability.

2. Solar collectors

Exergy analysis has been performed in literature for different types of solar collectors. Most work has been done in the field of flat-plate solar collectors. The second most popular area of research refers to combined photovoltaic and thermal (PV/T) collectors. Parabolic trough collectors have been also studied, but the number of studies published in this area is about one third of that in connection with PV/T collectors. Parabolic dish collectors have high exergetic efficiency and have been also analyzed and optimized by a number of researchers. Other types of collectors less often treated are compound parabolic collectors, evacuated tube collectors, heat pipe collectors and cavity receivers. Also, a novel collector type has been proposed and analyzed in the following sections.

2.1. Flat-plate collectors

Flat-plate collectors are widely used in applications. Despite this type of collectors have been well analyzed for a long time, there is still much interest in the general aspects of exergy analysis. Most specific studies published in 2013 and 2014 refer to air solar collectors while studies concerning hybrid (water and air) collectors are less frequent in literature. Interest exists on the influence that non-conventional working fluids, such as carbon dioxide or nanofluids, have on the collector performance.

Energy and exergy analyses of flat plate collectors have been carried out by Jafarkazemi and Ahmadifard [9] and Ge at al [10]. The exergetic efficiency of finned double-pass solar collectors has been evaluated by Fudholi et al. [11].

Several types of air collectors have been analyzed by using exergy efficiency as an indicator. A review of solar air heaters including their energetic and exergetic performance has been performed by Oztop et al. [12]. The principle of a thermoelectric solar air collector (TESAC) is simple. The incident solar radiation heats up the absorber plate; a temperature difference is created between the thermoelectric modules that generate a direct current. Only a small part of the absorbed solar radiation is converted to electricity, while the rest increases the temperature of the absorber plate.

Khasee et al. [13] performed energy and exergy analyses for a double-pass TESAC. Bayrak et al. [14] used energy and exergy analysis methods to study the performance of porous baffles inserted inside solar air heaters (SAHs). A remedy for the low thermo-physical properties of air when used as a working fluid is proposed by Benli [15]. Bouadila et al. [16,17] conducted an experimental study to evaluate the thermal performance of a new solar air heater using a packed bed of spherical capsules with a latent heat storage system. The Unglazed Transpired Solar Collector (UTC), as a suitable device for preheating the outside air, has been studied by using exergy analysis in Golneshan and Nemati [18]. This sort of collector is used mostly for preheating ventilation air as well as in heating air for crop drying. Bahrehmand and Ameri [19] proposed energy and exergy models for single and two-glass cover solar air collector systems with natural convection flow.

Assari et al. [20] performed the energy and exergy analysis of an air–water combined solar collector (sometimes called dual purpose solar collector). Said et al. [21] analyzed a flat-plate solar collector operating with single wall carbon nanotubes (SWCNTs) based nanofluid as an absorbing medium. Sarkar [22] analyzed the energetic and exergetic performance of flat-plate solar collectors using supercritical CO_2 as working fluid.

The most important advantage of heat pipes, as heat transfer components, is their high rate of heat transfer at minor temperature differences. Kargarsharifabad et al. [23] performed energy and exergy analysis of flat plate solar collectors in combination with heat pipes.

2.2. Hybrid PV/T systems

Hybrid photovoltaic/thermal collectors (PV/T) consist of photovoltaic modules cooled by a suitable fluid. They simultaneously convert solar radiation into both electric and thermal energy. The heat transfer between the PV cells and the cooling fluid allows lowering the PV cells temperature and improving their efficiency. Also, low-grade heat is generated and made available for specific applications. Therefore, PV/T modules are characterized by an overall efficiency of converting solar energy into electric and thermal energy.

Ooshaksaraei et al. [24] used first and second laws of thermodynamics to examine the steady-state and transient performance of a single-path air-based bifacial PV/T panel. Marletta and Evola [25] performed a second law analysis of a water-cooled PV/T module. The authors correctly observed that the main drawback of this technology is that in the case of PV cells the electricity production potential increases at low temperatures, whereas the thermal energy usability is higher at high temperatures. The authors stress out the importance of the definition of the operational conditions that maximize the total exergy harvested by the system.

Dupeyrat et al. [26] reported experimental results regarding the energetic and exergetic performance of a flat plate PV/T collector. Buker et al. [27] studied the energy and exergy efficiencies of a polyethylene heat exchanger loop underneath PV modules. The system is designed to act as a roof element that properly blends into the surroundings and becomes a heat resource for solar assisted heating and cooling technologies.

Al-Shamani et al. [28] present an overview of the research, performance, and development of PV/T collector systems. Covered and uncovered water PV/T collector types are described and analytical and numerical models for their and simulation as well as experimental works focusing on their operation are discussed. Exergy analysis shows that uncovered PV/T collectors produce the largest total (electrical plus thermal) exergy.

Zhang et al. [29] study the dynamic performance of a novel solar photovoltaic/loop-heat-pipe (PV/LHP) heat pump system for potential use in space heating or hot water generation. The authors performed theoretical simulations for estimating the energy and exergy efficiencies and experimental verification.

Gholampour and Ameri [30] studied from the energetic and exergetic viewpoint the effect of some parameters, such as the packing factor, the fin number and the fin height as well as environmental and dimensional parameters on the performance of the PV/T system with natural air flow. Sobhnamayan et al. [31] analyzed the energy and exergy efficiency of a PV/T water collector.

Kamthania and Tiwari [32] presented an overview on the development and application aspects of the PV/T collector systems for the last 30 yr. The review covers a detailed description and thermal models of hybrid photovoltaic thermal systems, using air as the working fluid. Numerical model analysis and qualitative evaluation of thermal and electrical output in terms of the overall thermal energy and exergy for various silicon and non-silicon based modules have been carried out. Wu et al. [33] presented a review of methodologies for calculating heat and exergy losses of conventional PV/T systems. Kasaeian et al. [34] estimated the overall performance of air PV/T collectors based on energy and exergy analysis. Both unglazed and glazed air PV/T, were considered.

2.3. Parabolic trough collectors

Ceylan and Ergun [35] designed and analyzed experimentally a new temperature-controlled parabolic trough collector (TCPTC). A detailed analysis was performed by calculating energy and exergy efficiencies. Yadav et al. [36] developed a theoretical model to perform energy and exergy analysis of linear parabolic trough collector used to concentrate solar radiation on a monocrystalline silicon based photovoltaic module.

Hou et al. [37] investigated theoretically a parabolic trough solar collector. The energy and exergy efficiencies have been also calculated. Padilla et al. [38] presented an exergy analysis to study the effects of operational and environmental parameters on the performance of parabolic trough collectors. Al-Sulaiman [39] presented a detailed exergy analysis of selected thermal power systems driven by parabolic trough solar collectors. The power is produced using either a steam Rankine cycle (SRC) or a combined cycle, in which the SRC is the topping cycle and the Organic Rankine Cycle (ORC) is the bottoming cycle. Seven refrigerants for the ORC were examined.

2.4. Parabolic dish collectors

Madadi et al. [40] investigated experimentally and theoretically the energy and exergy performance of a parabolic dish collector. Investigations on the hemisphere cavity receiver of a solar dish system are reported by Liu et al. [41], including exergy analysis.

Shanmugam et al. [42] constructed and tested a low-cost parabolic dish collector with commercial thermoelectric modules made of bismuth telluride for electricity generation on its focal plane. The energy and exergy efficiencies were experimentally evaluated.

2.5. Other collector types

Nishi and Qi [43] proposed a thermal model for the optimum design of a three-dimensional Compound Parabolic Concentrator (CPC) considering the maximization of exergy delivery.

Jafarian et al. [44] proposed a novel hybrid solar chemical looping combustion (Hy-Sol-CLC); the oxygen carrier particles in a CLC system are employed to provide thermal energy storage for concentrated solar thermal energy. The exergy efficiency is reported, among other performance indicators.

Nixon et al. [45] proposed three novel solar thermal collector concepts derived from the Linear Fresnel Reflector. The authors developed a multi-criteria decision-making methodology, which include the exergy as a tool.

3. Applications and processes

There are a multitude of applications and processes under which the energy content of the solar radiation can be utilized. In many instances, the solar radiation is converted to thermal energy which is subsequently used for various purposes. These include the direct generation of space heating, hot water or even process heat (to be used, for example, for drying of various materials or desalination). In some cases, the solar collectors are coupled with phase change materials (PCMs) that store the solar thermal energy in the form of latent heat.

In other cases, the solar heat, which is usually delivered to a heat transfer fluid, can be also provided to absorption cooling systems or heat pumps, for the indirect production of cooling, especially for buildings.

Finally, several applications aim at the production of electricity as the final product through the implementation of power cycles, such as the Organic Rankine Cycle and the Kalina Cycle. The production of electricity is sometimes achieved directly, through photovoltaic systems. The generated electricity can be sold to the power grid or it can be used either for the operation of heat pumps of for other purposes, such as the electrolysis of water to produce hydrogen.

3.1. Phase change materials (PCM)

Bouadila et al. [17] tested the performance of a novel solar air heater which was combined with phase change materials in order to store latent heat. The solar radiation was converted to thermal energy and absorbed by the PCM which was in the form of spherical capsules. The melting point of the PCM was at 27 °C.

Yang et al. [46] performed numerical simulations on a solar heat storage packaged bed with PCMs. The heat is transferred to the PCM consisting of three different materials with melting temperatures at 60, 50 and 42 °C stored in capsules by flat plate solar collectors, using water as an intermediate heat transfer medium. The performance of the system was compared to one composed of a single PCM with a unique melting temperature (at 60 °C).

Utlu et al. [47] investigated and experimentally tested a hybrid wall heating (40–45 °C) system composed of flat plate solar collectors, a latent heat storage module made of paraffin, an accumulation tank used for sensible heat storage and a heat pump.

3.2. Drying

Fudholi et al. [48] performed an energetic and an exergetic analysis of a solar drying system powered by a finned double-pass solar collector for red chili. The specific energy consumption of the system was 5.26 kg/kWh for reducing the moisture content of chili from 80 to 10 % (wet basis). In another study [49], they performed an experimental analysis of a solar drying system for red seaweed from 90 to 10% of moisture (wet basis).

3.3. Heating, cooling and multigeneration

Gomri [50] investigated a hybrid Li/Br absorption cooling system utilizing heat from both an array of solar collectors and a natural gas burner. The temperature of the generator and the condenser were varied between 45–83 °C and 28–36 °C respectively, while the evaporation temperature was fixed at 5 °C.

Al-Ali et al. [51] investigated a multigenerational system capable of producing electricity, space heating, process heat, hot water and cooling. The heat input to the system was provided from geothermal and solar energy and it incorporated two ORCs and an absorption-chiller.

Lopez-Villada et al. [52] evaluated and compared various solar absorption power-cooling configurations including evacuated tube collectors (ETC), parabolic trough collectors (PTC) and linear Fresnel collectors (LFC) coupled with Single-Stage Combined Absorption (SSCA) and the Goswami cycle.

Qin-Yi Li et al. [53] performed an exergetic analysis of a domestic-scale system combining a 5 kW wind turbine and an array of 11.4 m^2 copper flat-plate solar collectors as well as two heat pumps, capable of producing space heating, hot water, cooling and electricity.

Karakilcik et al. [54] analyzed exergetically and energetically a solar pond integrating conventional flat plate solar collectors in order to provide heat to the heat storage zone.

3.4. Hydrogen production

Koumi Ngoh et al. [55] carried out a techno-economic analysis of a hybrid hydrogen production system utilizing solar photovoltaic and thermal energy. The system combined parabolic trough collectors (PTC) used to generate hot pressurized steam at 320 °C, which was subsequently electrolyzed to H_2 and O_2 by electricity produced by photovoltaic panels.

Ahmadi et al. [56] proposed a novel proton exchange membrane (PEM) system for hydrogen production powered by an ORC utilizing solar and ocean thermal energy.

3.5. Electricity generation systems

Wang et al. [57] studied the off-design operation of a solar powered ORC. The solar collectors were of the compound parabolic type, while an intermediate circuit with a thermal storage tank at about 150 °C was used for regulating the operation of the system. Cau et al. [58] evaluated the annual performance of a 1 MWe solar ORC plant comparing parabolic trough with linear Fresnel solar collectors for the solar-thermal conversion.

Rovira et al. [59] evaluated different configurations for Integrated Solar Combined Cycle (ISCC) plants in which the solar heat was utilized in different heating stages of the working fluid of the heat recovery steam generator (HRSG). The heat from the collectors was provided to the plant either through an intermediate heat transfer fluid (HTF) at 390 °C or directly to the working fluid, at temperatures up to 545 °C.

Ruzzenenti et al. [60] conducted a life cycle analysis (LCA) and an exergy life cycle analysis (ELCA) for micro scale geothermal-solar ORC plants for cogeneration of power and heat.

Rao et al. [61] proposed a novel combined cycle which incorporates the use of LNG as the heat sink of the low temperature (<75 °C) solar ORC. The LNG is evaporated in the condenser of the ORC and is subsequently expanded to produce additional work. At the same time, due to the significantly low temperature of the LNG, the condensation of the working fluid of the ORC can occur at −60 °C, thus increasing the cycle efficiency.

Sun et al. [62] simulated and optimized a low temperature (~50 °C) solar-boosted Kalina cycle plant. After identifying the mass flowrate of the working fluid, the working fluid of the solar subcycle and the ammonia mass fraction as the most important operational parameters, he applied his optimization calculation based on radiation data in Kumejima Island of Japan.

3.6. Desalination

Nematollahi et al. [63] developed a model to simulate the operation of a solar-driven desalination system based on humidification-dehumidification technology. The solar collectors heat an air stream to a maximum of 65 °C, which absorbs vapor from a saline water stream. The air-vapor mixture is subsequently condensed to produced desalinated water. He validated the model with experimental data obtained from a special test-facility that they designed. The model showed good agreement with the data.

Kumar et al. [64] integrated a single slope solar still with an evacuated tube collector and operated in forced mode. The energy and exergy efficiencies have been evaluated.

4. Conclusions

In this paper a review of exergy analysis of solar thermal systems is presented based on literature published in the last two years. The review includes analysis of various types of solar collectors and solar thermal system applications and processes. Solar collectors include flat-plate collectors, hybrid photovoltaic/thermal systems, parabolic trough collectors, parabolic dish collectors and other types of solar collectors not falling in one of the above categories. Applications and processes include the use of phase change materials either in the collection or storage of thermal energy, drying, heating cooling and multigeneration, hydrogen production, hybrid systems, solar ponds, electricity generation systems and desalination.

As solar collectors are an important component when sustainability designs is considered, exergy analysis, which gives a more representative performance evaluation, is a valuable method to evaluate possible configurations of these systems. This analysis proved to be useful when considering either the solar collectors alone or the complete system to identify sources of irreversibilities.

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