ENTROPY PRODUCTION: INTEGRATING RENEWABLE ENERGY SOURCES INTO SUSTAINABLE ENERGY SOLUTIONS

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ABSTRACT

An investigation of the transient entropy property term, entropy storage, for a solar thermal and desalination device was performed. It was illustrated that entropy production rates provide a means of comparing alternative energy solutions and a measure of their sustainability. To satisfy these objectives one needs accurate calculation of entropy production rates. It was confirmed that neglecting the energy storage terms is a valid approximation for the first law analysis, but not for the second law analysis where entropy storage terms are significant. For a generalized solar thermal system neglecting the entropy storage terms introduced a maximum difference in the entropy production rate of 7.4% and a difference of 7.3% in the daily average. Similar differences for the solar desalination process were observed. In the solar desalination process the second law performance is greater than that for the reverse osmosis process, the chief competitor, when the entropy storage are correctly included in the analysis. The results demonstrate that for variable energy sources such as renewable energy systems, the second law analysis provides a measure of the sustainability of competing system and that the entropy storage terms should be included in the analysis.

INTRODUCTION

Entropy production analysis has been promoted as being an important tool for identifying where major losses in a system occur, as a design tool to identify system improvements and as a measure of sustainability. The process with the lower entropy production rate is the more sustainable one because it converts one form of energy into another useful form more efficiently. However, use of this second law based tool is not widespread at a practical level because of its complexity and subtleties. There are numerous examples of reporting entropy production rates as part of energy analysis of a system performance in the literature[1-7], but there are few instances where decisions to implement design modifications are based on reducing entropy production rates [8,9]. In these reported investigations, the developments of the entropy production analysis of a particular device or process are the key outcomes of the investigation. However, in most cases issues related to heat flows and the associated entropy flows are not described. The system boundaries are not defined to allow the total entropy production of the delivered product to be identified. For example, [5] provide a complete and thorough second law analysis of a reverse osmosis desalination plant starting with the power input to the pumps. They do not include the entropy production associated with the production of this power that would allow a direct comparison with competing renewable energy desalination technologies. This inconsistency in system definition prevents a direct comparison of the entropy production with other competing technologies and of its use as a measure of sustainability.

The examples discussed in this presentation are intended to highlight cases involving renewable energy sources, specifically solar energy, where including entropy production into the analysis leads to a better understanding and potential improvements of the system. They also illustrate the fundamental information misconceptions by practitioners that are limiting the accurate and productive use of the second law, especially as a means of integrating energy system solutions and addressing sustainability concerns. These examples include formulating the entropy production analysis for renewable energy systems, their integration with traditional systems and comparing them to nonrenewable or fuel driven resources.

The transient entropy term is one feature of the entropy production analysis that is neglected in most of the previous reported studies. Renewable energy sources are variable in nature and systems involving them usually include an energy storage device such as thermal storage device or batteries as well as energy stored in the energy collection device itself. Neglecting the transient entropy term leads to erroneous predictions of entropy production during the startup and time immediately after the renewable energy source has ended when the stored energy in the system continues to produce useful output. For example, Modaresifar [8,9] demonstrates that fresh water is produced in a solar desalination device after sunset due to the stored thermal energy in the device.

The quasi-steady state analysis, which is commonly used in solar thermal energy simulations, especially in the first law analysis, may not be accurate in the second law analysis. Using daily simulations to avoid these transient effects [9] may not lead to an accurate prediction of the entropy production in these systems and its use as a measure of the sustainability. Additionally, one has also lost the opportunity to fully understand the device process and to possibly improve it when using the daily integrated results.

A generalized system with the same physical characteristics as that of a solar thermal collector will be used to investigate the effects of the transient entropy property changes and energy storage on its performance. The system

will be simplified and the incident solar radiation will be represented by a parabolic function so that a closed form solution can be developed to investigate the second law characteristics. A quasi-steady state and transient solution will be obtained to measure of the accuracy of the quasisteady state solution. The subtleties of describing the heat flows associated with this type of analysis are discussed during this development. The results of this demonstration will be extended to a more complex problem involving a solution, salt and water that is involved in the solar desalination process. This demonstration emphasizes the use of entropy production rates as a measure of the sustainability of competing systems.

DEVELOPMENT:.

Generalized Solar System

The generalized system used to investigate the effect of the transient entropy property term is shown in Figure 1 and includes the energy storage terms for the device, E_{Sr} and the working fluid, E_{Swf} . The absorbed incident solar radiation entering the system and the heat loss from the solar thermal device is shown.



Figure 1 System sketch for the generalized solar thermal device and its associated energy flows.

The energy for the system shown in Figure 1 is:

$$m_r h_i + (\tau \alpha) Q_{SOL} = E_{Sr} + E_{Swf} + Q_{LOSS} + m_r h_e \quad (1)$$

The heat loss, Q_{LOSS} , and energy storage terms for the device, E_{Sr} , and the working fluid, E_{Swf} , are related to the average temperature of the system. For the purpose of this analysis, it is assumed that the mass flow rate, m_r , is sufficiently large that the spatial variation of the temperature through the system is a linear function and equals the arithmetic average of the inlet and outlet temperatures, T_i and T_e , respectively. Introducing the equation of state and the definition of the energy storage terms and rearranging Eq. (1) yields:

$$(1/2)(m_D c_D + m_{wf} c_{wf}) \frac{dT_e}{dt} =$$

$$-(m_r c_{wf} + C_L/2)(T_e - T_i) + (\tau \alpha)Q_{SOL}$$

$$(2)$$

Where $T_i = T_{\infty}$ = ambient temperature = constant.

The generalized function for the incident solar radiation is a parabola with the maximum value at solar noon and zero value at sunrise and sunset. The function is normalized with respect to day length, $t_{\rm d}.$

$$Q_{SOL} = 4Q_{s,peak}[(t/t_d)-(t/t_d)^2]$$
 (3)

 $Q_{s,peak}$ equals the peak incident solar radiation for the day, W/m^2 , and t_d equals the day length, hours. Eq. (3) applies for time between sunrise and sunset.

The solution to Eq. (2) for the time period between sunrise and sunset when the initial condition is that the device and enclosed fluid are at the ambient temperature is:

$$T_e = T_i + C_3 \exp[-C_2 t] + b_0 + b_1 t + b_2 t^2$$
(4)

Where:

$$C_1 = \frac{(\tau \alpha)Q_{s, peak}}{(1/2)(m_D c_D + m_{wf} c_{wf})}$$
(5)

$$C_2 = \frac{(m_r c_{wf} + C_L/2)}{(1/2)(m_D c_D + m_{wf} c_{wf})}$$
(6)

$$C_3 = -b_0 = \frac{\left[\frac{4C_1}{t_d} + \frac{8C_1}{(C_2 t_d^2)}\right]}{C_2^2} \tag{7}$$

$$b_{\rm I} = \frac{[4C_1/t_d + 8C_1/(C_2 t_d^2)]}{C_2} \tag{8}$$

$$b_2 = \frac{-4C_1}{C_2 t_d^2} \tag{9}$$

At sunset, the exit temperature is above the ambient and inlet temperature even though there is no incident solar radiation. The transient response continues under this condition until the solar device cools to the ambient temperature. Modifying Eq. (2) for zero incident solar radiation and solving for the exit temperature yields the following:

$$T_{e} = T_{i} + (T_{e}(t_{d}) - T_{i}) \exp[-C_{2}(t - t_{d})]$$
(10)

Where $T_e(t_d)$ is the exit temperature calculated from Eq. (3) at time equal to the day length, sunset.

The collected useful energy rate for the device is related to the change in the enthalpy of the working fluid mass flow rate.

$$q_{use} = (m_r c_{wf})(T_e - T_i) \tag{11}$$

The Transient simulation model is described above using Eqs. (3-11) and represents a closed form solution for the behavior of the system. The quasi-steady state simulation model is based on the same system definition. However, the energy storage terms are neglected. This is equivalent to setting the first time derivative in Eq. (2) to zero. The exit

temperature based on the quasi-steady state model is determined from resulting equation.

$$T_e \Big|_{QS} = T_i + \frac{(\tau \alpha) Q_{SOL}}{(m_r c_{wf} + C_L/2)}$$
(12)

The collected useful energy rate for the quasi-steady state model is determined using Eq. (11) with the exit temperature calculated with Eq. (12).

Entropy Production Rate for Generalized Solar System

The system definition for the entropy balance for the generalized solar energy system is show in Figure 2. This system is modified from that shown in Figure 1 to reflect the entropy flow associated with the heat flows. This modification also reflects a basic second law question that is not commonly mentioned when new practitioners are introduced to the second law and entropy production rate. That question is "Is the heat flow used in another process to produce a useful energy output or is it allowed to reach equilibrium with the surroundings without doing useful work?" The location of the system boundary and what devices are included in it are determined based on the answer to this question. In the present case, the heat flow input from the sun should be viewed as coming from the sun and the system boundary for this energy flow should be at the temperature of the sun. This feature is shown in Figure 2 as the dotted line extension the original system definition. Using this approach includes the irreversibility of this thermal For the entropy flow transport to the defined system. associated with the heat loss from the solar thermal device the system boundary is defined at the ambient temperature because no attempt is made to use this energy flow in another process. By defining the system in this manner one avoids the complicated integral involved in evaluating the entropy flow of a heat flow at a variable temperature and it insures that all sources of entropy production related to the process are included in the analysis.



Figure 2 System sketch for the generalized solar thermal device and its associated entropy flows. The system definition has been modified from that shown in Figure 1.

The entropy balance for this system is:

$$\dot{\sigma}_{p} = m_{r}(s_{e} - s_{i}) + \frac{dS_{D}}{dt} + \frac{dS_{wf}}{dt} + C_{L}\frac{(T_{ave} - T_{i})}{T_{ave}} - \frac{Q_{SOL}}{T_{SUN}}$$
(13)

Introducing the T-ds equation to relate the entropy change to the temperatures for an incompressible working fluid and for a constant pressure process yields:

$$\dot{\sigma}_{p} = m_{r}c_{wf} \ln \left[\frac{T_{e}}{T_{i}}\right] + \left[\frac{(m_{D}c_{D} + m_{wf}c_{wf})}{Tave}\right] \frac{dT_{ave}}{dt} + C_{L} \frac{(T_{ave} - T_{i})}{T_{ave}} - \frac{Q_{SOL}}{T_{SUN}}$$

$$(14)$$

The entropy production rate for the quasi-steady state model neglects the transient entropy property terms.

$$\dot{\sigma}_{p} = m_{r}c_{wf} \ln\left[\frac{T_{e}}{T_{i}}\right] + C_{L}\frac{(T_{ave} - T_{i})}{T_{ave}} - \frac{Q_{SOL}}{T_{SUN}}$$
(15)

The above developments were used to calculate the exit temperature, collected useful energy rate and entropy production rate for a typical day in July for the Boston, Massachusetts, USA region. The peak solar energy for the day was 918.5 w/m² and the day length was 15 hours with sunrise at 430 hours. The results are discussed later.

Solar Desalination Process Model

The system shown in Figure 3 illustrates schematically a tray design solar desalination. The system description and the model development are described in detail in [8, 9] and is not repeat here. In this tray design, a film of salty water is placed in thermal contact with absorber plate using trays mounted to its rear surface and the condensing surface is placed in a shaded region to minimize it temperature. The condensing surface is inclined at an angle of 40° in order to allow the condensed water vapor to flow down into the fresh water trough. In this solar distillation design, an absorber plate is thermally isolated from the environment using a glazing surface that is transparent to the incident solar radiation. Water trays are in contact with the rear surface of the absorber plate and are inclined to provide gravity flow through the collector. The trays have a fin efficiency of 0.97 and a combined surface area greater than the absorber plate area. In this configuration, the glazing surface is separated from condensing surface that is the common configuration of most solar distillation units.



Figure 3 schematic diagram of the solar still analyzed in this work. The incident solar radiation is absorbed on the absorber plate. The evaporated water vapor is condensed on the shaded rear surface where the freshwater is collected.

In addition to minimizing the condensing surface temperature, this configuration also avoids reducing the solar energy incident on the absorber surface due to condensation or frost formation in the winter months on the glazing surface. The brackish water inlet is to the side of the collector and feeds the water trays as shown in the rear view section of Figure 3. The volume surrounding the water trays and bounded by the condensing plate is defined as the chamber. Fresh water is condensed by maintaining the chamber above its dew point temperature and the condensing plate below it. The fresh water accumulates on the condensing plate and is collected at the outlet as shown. The heated, concentrated salty water flows out of the trays as shown.

The amount of fresh water produced is calculated using the condensation rate that is based on the condensation heat flow. The set of coupled equations based on the energy balance on the absorber plate, water in the trays, chamber and condensation plate are solved using an explicit integration procedure. The evaporation and condensing process are included in this model and require the determination of the chamber's relative humidity and partial pressure of the water vapor. The energy balance equations for the water in the trays, plate and condensing surface are recast into a temporal finite difference form and are solved over the day length in time steps of 1 sec. to allow a stable solution. The mass flow rate of the fresh water produced equals the condensation mass flow rate. The mass of freshwater produced is calculated by integrating the condensation flow over time. A Matlab program was written using these relationships to calculate the temperatures of the absorber plate, water, chamber, and glass surface as a function of the incident solar radiation and ambient air temperature [8,9].

The second law analysis of the tray design solar distillation device performed by Modaresifar [9] was an exergy analysis. Modaresifar [9] based his analysis on two system definitions that are summarized in Figure 4. Using his exergy destruction term and the defined dead state temperature allows his analysis to be restated in terms of the entropy production rate.



Figure 4 Schematic diagram of exergy balance for a solar distillation system. The dashed line boundary defines a system in which all inflows and outflows all occur at the dead state. The "product approach" system is the central block with the exergy destruction, $e_x|_D$, indicated.

The second law exergy balance for the system defined by the dashed line in Figure 4:

$$e_{x}|_{D} = \sigma_{p}T_{0} = e_{x,QSOL} - e_{x,qloss} - e_{x,qcond}$$
$$-\frac{de_{x,sys}}{dt} - (m_{w} + m_{salt})(e_{x,B} - e_{x,in})$$
(16)

 $- \overset{\cdot}{m_f} (e_{x,f} - e_{x,B})$

Where the inflow (brine) and the outflows are treated as a This approach is taken to solution of salt and water. accurately describe the irreversibility of the separation process to obtain the freshwater. The details of this development are given in [8,9] and are not repeated here. The primary focus of this work is the transient exergy term and its effect on the calculated entropy production rate. In [9] the daily average exergy destruction and second law efficient were determined and it was argued that over the course of the day the transient system exergy term would go to zero because the device returned to its original state. As will be seen in the result section this is not true, for this system and for the generalized solar thermal system. Modaresifar [9] also illustrates the difference between the dashed line system in Figure 4 and the "product approach" which neglects the exergy destroyed when the hot outflows are allowed to reach equilibrium with the dead state without attempting to use them for other purposes. The large difference between the second law efficiency of these two system is an effective argument for introducing a waste heat recovery heat exchanger. The addition of the heat exchanger does significantly improve the performance and is discussed below.

RESULTS

Generalized Solar System

The prediction of the exit temperature from the solar thermal device, the entropy production rate and the useful collected energy rates are determined for a typical day in July for the Boston. Massachusetts. USA location using the formulations described above are discussed below. The calculations were based on a parabolic description of the incident solar radiation with a peak incident solar radiation of 981.5 w/m^2 and a day length of 15 hours. A comparison of the parabolic function used in this analysis and the predicted incident solar radiation using the method of Masters [10] is given in Figure 5. The idealized parabolic function is in general agreement with the functional trend of the incident solar radiation, but yields slightly large values. These differences are acceptable for the purpose of the present



Figure 5 The comparison of the idealized parabolic function used to describe the incident absorbed solar radiation to that predicted for July 15 in the Boston, Massachusetts, USA region.

analysis in order to take advantage of the closed form solution and it is the relative comparison of simulation models that is discussed.

The idealized daily incident solar radiation model was introduced into the quasi-steady state and Transient simulation to calculate the collected useful energy rate shown in Figure 6. The first observation is that there is little difference in the collected useful energy rate between the two models which is consistent with the commonly used Frist law models. The total collected useful energy over the day for the quasi-steady state simulation is 55.6 MJ while that for the Transient simulation is 55.7 MJ, a 0.12% increase. This graph is included because the results are those commonly desired and are the basis of most economical, reduced fuel consumption and carbon emission calculations.



Figure 6 The comparison of the collected useful energy rate as a function of time of day between the quasi-steady state and transient simulations.

The fluid exit temperature for the quasi-steady state and transient simulations are compared in Figure 7. As expected there is little difference between the models and the



Figure 7 The comparison of the fluid exit temperature from the solar thermal collector as a function of time of day between the quasi-steady state and transient simulations.

commonly used approximation of neglecting the device's energy storage term is supported. One can discern a slight difference where the quasi-steady state simulation predicts a slightly higher exit temperature during the time before solar noon (12 hrs) and a slightly lower exit temperature for the time between solar noon and sunset. However, these differences are not significant and are well within the uncertainty of the simulation accuracy.

In Figures 8 and 9 details of the fluid exit temperature near solar noon and at sunset are illustrated. In Figure 8 the slight difference from the quasi-steady state simulation predicting a higher value than that of the transient simulation before solar noon and then reversing the trend is more easily observed. The more significant difference between the two simulations occurs at sunset where the transient model predicts an exponential type temperature response to the ambient temperature while the quasi-steady state model abruptly reaches the ambient temperature at sunset (Figure 9). The increased fluid exit temperature predicted by the transient model is a result of converting the energy stored in the device to useful energy collected. A similar energy conversion



Figure 8 The comparison of the fluid exit temperature from the solar thermal collector as a function of time of day between the quasi-steady state and transient simulations near the time of solar noon.



Figure 9 The comparison of the fluid exit temperature from the solar thermal collector as a function of time of day between the quasi-steady state and transient simulations near the time of sunset.

is not included in the quasi-steady state model. Again, the differences between these first law simulations are not significant and the results are consistent with the common approach used in the field.

In Figure 10 the entropy production rate as a function of the time of day are compared for the two simulations. These results are significantly different and illustrate that the quasisteady state simulation predicts a larger entropy production rate than that for the transient model by a maximum of 7.4%. The integrated daily entropy production for the quasi-steady state simulation is 0.20 MJ while that for the transient simulation is 0.18 MJ, a 7.3% decrease. These results suggest that if one is comparing entropy production rates between two competing solar thermal designs or solar radiation collection devices (solar thermal vs photovoltaics) one should include the transient entropy property term. In the present comparison, Figure 10, the shown difference suggests that the commonly used approximation to neglect the energy storage term that is justifiable for the first law analysis is not justifiable for the second law analysis. The inherent transient nature of renewable energy sources suggests that daily analysis and simulation of its second law performance should use the transient model.



Figure 10 The comparison of the entropy production rate as a function of time day between the quasi-steady state and Transient simulations.

The reason for this difference has to do with the entropy flow out of the system with the heat loss term. In the actual device and the transient simulation model the heat loss term is lower during a larger part of the day because part of the incident solar radiation is converted into internal energy of the device and is later converted to useful collected energy in the working fluid. This energy conversion path is ignored in the quasi-steady state results. The second law analysis should be used to compare different devices or systems for sustainability in order to determine the best use of the energy resource. The change in the system definition between the first and second law analysis described in the development section serves two purposes. First, it reflects that the heat loss term is not converted into a useful energy output and, second, it simplifies the heat transfer analysis. The heat flow into the system at the high temperature of the sun incorporates its high energy quality and simplifies the analysis. The need to define the ultimate use of an energy outflow from the system, especially a heat flow, is an inherent feature of the system redefinition procedure is a subtlety that needs to be discussed when practitioners are first introduced to these second law concepts. It is also important to use this procedure when energy systems are discussed for their sustainability or for means to improve their performance.

Solar Desalination Process

The impact of assuming a quasi-steady state approximation for the second law for a solar desalination device is investigated in this section. As discussed in the Development section the production of freshwater is usually modeled using a transient first law analysis because of the nonlinear relationships between the temperature of the device and the evaporation and condensation rates. However, as mention previously most of the reported second law analyses of the solar desalination process use an effective parameter approach and not the salt and water solution, a brine solution, approach reported for the reverse osmosis or MFS processes [5,11,12,13]. Modaresifar [9] follows the brine solution approach to describe properly the irreversibility associated with separating the salt from the water. However, [9] does not include the transient entropy property term in the analysis and uses a daily average to describe the irreversibility and exergy destruction because the system returns to its initial condition over the course of the day and the integrated transient entropy production term is assumed to be zero. As seen from the previous section, this is not necessarily true since there is a difference in the daily entropy production between the quasi-steady state and transient simulations. The need for an accurate second law analysis in Modaresifar's [9] investigation was to determine design improvements and to compare the sustainability as measured by the second law of the solar and reverse osmosis desalination processes.

The transient effect of the First law simulation of the solar desalination devices reported are clearly illustrated in Figure 11, which is a plot of the brine temperature as a function of the time of day [9]. The functional form of the incident solar radiation for this analysis is similar to that reported in Figure 5 and one has a peak solar radiation at solar noon, 12.0 hours and zero incident solar radiation at sunset, 20.0 hours. In Figure 11 the maximum temperatures occur well after solar noon and there is an elevated temperature after sunset.



Figure 11. Comparison of the water and condensing temperatures between the pool evaporation and tray design solar desalination units. The performance for the July design days are shown. Taken from [9].

In Table 1 the results of the second law analysis for the Tray Design desalination device are summarized for the waste heat recovery and no recovery sytem configuration. The performance for the different system definitions are also summarized.

Table 1 Comparison of the Summary of second law performance measures of the Tray Design solar desalination device for the quasi-steady state and transient simulations.

Tray Design: July							
	Quasi- Steady State No Recovery	Transient No Recovery	Quasi-Steady State Recovery	Transient Recovery			
Daily Fresh water Production, kg	2.81	2.81	6.05	6.05			
Daily Entropy Production, KJ/K	88.5	87.6	86.54	83.40			
Daily Entropy Production, (Product Approach),KJ/K	83.1	79.1	NA	NA			
Second Law efficiency (Product Approach), %	6.65	11.1	NA	NA			
Second Law efficiency, %	0.63	1.63	2.79	6.33			
Mass flow rate, kg/s	0.003	0.003	0.007	0.007			
Area of Incidence, m ²	1.0	1.0	1.0	1.0			

In the second row, the simulation approach for the second law analysis is identified for the two different solar desalination processes under consideration, the waste heat recovery and no recovery designs. The first process is the no recovery process in which the hot, concentrated brine is discharged into the water source and the inlet is from the large available brine source, usually the ocean. The second process is the recovery process that includes a heat exchanger that uses the hot concentrated brine to preheat the entering cold brine. Both processes are transient simulations using the first law, but a quasi-steady state and a transient model are used to calculate the daily entropy production parameter and the results are reported in the marked separate columns.

Two system definitions are used to report the second law In the fourth row, the "product approach" efficiency. corresponds to the system defined at the exit of the solar desalination unit as shown in Figure 4 in the Development section. Using the "product approach" system definition one is neglecting the availability flow carried by the hot brine and fresh water. This is not a rigorous application of the second law because one is not asking the question "what can I do with this outflow" and one is not following the entropy and availability flows to their final equilibrium states. This is a common mistake because from a first law design perspective this system definition is perfectly adequate. It should be noted that the second law efficiency predicted for this system is greater than that reported for the correct second law definition where all outflows are tracked to their final equilibrium state as reported in the fifth row. Modaresifar, [9] used this system to identify the potential gain if the hot brine were used to preheat the entering cold brine.

The second process, the recovery process, introduces the heat exchanger and follows all the outflows to equilibrium with the surroundings. This complete system definition was used and is the reason that the "product approach" cells are left unreported, "NA".

From the table it is clear that neglecting the transient entropy property term leads to under estimating the second law performance in all cases. Modaresifar [9] uses these results to argue that the second law performance can identify the sources of entropy production and indicate means of reducing it. However, this argue is valid in this case because the same assumption, neglecting the transient entropy property term, was made in both simulation models. The more accurate estimate using the transient simulation model indicates that the performance measured by both the second law efficiency and the daily entropy production are higher than that predicted by quasi-steady state model. This difference becomes important when one wants to compare the predicted performance of a solar desalination process to competing operations such as reverse osmosis or MSF plants.

In the reverse osmosis (RO) plants reported in the literature the second law efficiencies are in the range of 4% to 4.5%. Aljundi [5] reported 4.1% for a plant in Jordan, Cerci has the 4.3% for the second law efficiency in a plant in California [6] and Y.Cengel reported 4.2% for a MSf desalination plant [7]. The second law efficiency is calculated from the exergy of products divided by the input power exergy. When one compares the calculated performance of the solar desalination process using the transient model one finds that it is higher than for these other processes.

This comparison is not a valid because the second law calculations in literature use the input exergy as the power input that is needed for the pumps, not at the primary energy input point. The entropy production in producing the input power is not included in the reported second law efficiency calculations for the (RO) process. The comparison between the solar and (RO) processes is not consistent because the input energy source for the (RO) process is not the primary energy input source as it is for the solar processes. Α. Rashad [14] showed that a thermal power plant has a second law efficiency of less than 50% in all conditions of loading. The performance of the primary power source must be taken into account to calculate equivalent second law parameters in order to get accurate comparison, especially when using the entropy production or second law efficiency as a measure of the sustainability of the processes.

CONCLUSION

An investigation of the transient system entropy property term, entropy storage, for a solar thermal and desalination device was performed. The objective was to illustrate the use of entropy production rates as a means of comparing alternative energy solutions and as a measure of their sustainability. The solar thermal analysis was based on a generalized system with a functionally correct form of the incident solar energy that yielded a closed form solution. To satisfy the above objectives one needs accurate calculation of entropy production rates. It was confirmed that neglecting the energy storage terms is a valid approximation for the first law analysis, but not for the second law analysis where entropy storage terms are significant for both systems investigated . For a generalized solar thermal system neglecting the entropy storage terms introduced a maximum difference in the entropy production rate of 7.4% and a difference of 7.3% in the daily average. Similar differences were observed for the solar desalination process. It was shown that by adding a waste heat recovery device the desalination system's entropy production rate decreased for the same energy input and resulted in a better performing system. In the solar desalination process the difference between including the entropy storage terms leads to a second law performance that is greater than that for the reverse osmosis process, the chief competitor. It was also demonstrated that modifying the system definition between the first and second law analysis simplifies the analysis and provides the practitioner a

framework to include all entropy production parameters associated with the process. This framework also provides design insight as to means of improving the system performance and sustainability. The results demonstrate that for variable energy sources such as renewable energy systems, the second law analysis provides a measure of the sustainability of competing system and that the entropy storage terms should be included in the analysis.

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NOMENCLATURE

b_0, b_1, b_2	Solution	parameters	defined	by	Eqs.	(7-9)	1
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C_1, C_2	Constant defined by Eqs, (5) and (6)	
C ₃	Integration Constant	Κ
c _D	Specific heat of device	J/(Kg K)
CL	Overall heat transfer factor	W/K
C _{wf}	Specific heat of working fluid	J/(Kg K)
$e_x _D$	Exergy destroyed	W
e _x , _B	Exergy of brine at outlet	J/Kg
e _{x,f}	Exergy of freshwater produced	J/Kg
e _x ,in	Exergy of brine at inlet	J/Kg
e _x , _{qcond}	Exergy carried by condensation heat flow	W
e _x , _{gloss}	Exergy carried by heat loss	W
e _x , _{OSOL}	Exergy of incident solar radiation	W
e _x , _{sys}	Exergy of device and working fluid	J/Kg
e _{x,B}	Exergy of brine at inlet	J/Kg
E _{Sr}	Energy Storage term for the device	J/s
E _{Swf}	Energy Storage term for the working fluid	J/s
h _i	Enthalpy at device inlet	J/Kg
h _e	Enthalpy at device exit	J/Kg
m _r	Mass flow rate of working fluid	Kg/s
m _D	Mass of device	Kg
$m_{\rm wf}$	Mass of working fluid in device	Kg
Q _{LOSS}	Heat loss from device	W
Q _{SOL}	Incident solar radiation on device	W
Q _{s,peak}	Peak incident solar radiation on device	W
q _{use}	Collected useful energy rate	W
se	Entropy at device exit	J/(Kg K)
si	Entropy at device inlet	J/(Kg K)
SD	Entropy of device	J/K
\mathbf{S}_{wf}	Entropy of working fluid in device	J/K
T _{ave}	Average temperature of device	Κ
Te	Exit temperature from device	Κ
Ti	Inlet temperature to device	Κ
T _{SUN}	Temperature of the sun	Κ
t _d	Daylength	hr
(τα)	Transmission-absorption coefficient for	
	solar collector	
σ_{P}	Entropy production rate	J/s

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