DAILY THERMODYNAMIC ANALYSIS OF A SOLAR DISH-DRIVEN REHEATING ORGANIC RANKINE CYCLE

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Solar concentrating systems can play a critical role in the future for designing sustainable cities. The goal of this investigation is the energy analysis of a solar-driven power plant based on the solar dish collector, storage thermal tank and a reheating organic Rankine cycle. The present thermodynamic cycle is a more efficient choice compared to other similar designs due to the existence of a double expansion with an intermediate reheating. Also, the use of the solar dish collector enables efficient operation in medium and high temperatures. More specifically, this investigation is performed on dynamic conditions aiming to determine the unit's performance on a usual summer day. The analysis is done with a dynamic model based on mathematical formulas which are inserted into Engineering Equation Solver. The simulation results proved that a collecting area of 500 m^2 (50 modules) coupled with a storage tank of 5 m^3 volume that feeds an Organic Rankine Cycle of 50 kW_{el} nominal power leads to daily electricity production of 577 kWh_{el}. The system efficiency is found to be 12.6%, the thermodynamic cycle efficiency 20.8% and the solar field thermal efficiency 60.8%. Therefore, it is obvious that the suggested unit leads to satisfying results, and it is a promising one for the design of sustainable renewably driven units in the future.

Key words*: Solar dish collector, Concentrating Solar Power, Dynamic analysis, Daily analysis, Parametric study, Organic Rankine cycle.*

1. Introduction

The proper utilization of renewable energies is a critical way to overcome the existing energy crisis [1]. Specifically, the utilization of solar irradiation for electricity production is a promising technique, especially in the designs of Concentrating Solar Power plants (CSP) because this idea can be applied both in small and great-scale applications [2]. Among the CSP, the small-scale applications present a great interest due to the advantage of application in decentralized cases. One promising decentralized CSP idea is the use of a solar-driven organic Rankine cycle (ORC) and a significant amount of research has been conducted in the last years in this direction [3].

The simple ORC includes only the basic devices which are the expander, condenser, pump and heat recovery unit, while the improved ORC includes usually a recuperator for exploiting waste heat from the expander outlet. The application of the recuperator can improve the thermodynamic efficiency of the ORC by up to 25% [4]. Moreover, the use of regeneration is another technique for increasing the cycle thermodynamic performance [5]. Furthermore, it is interesting to state that the design of a double-stage ORC with two expansions can lead to a thermodynamic efficiency enhancement of around 10% [6].

In the literature, there are various investigations regarding the exploitation of the solar potential with different ORC configurations. Also, different solar collectors have been examined from non-concentrating technologies to concentrating technologies with significant concentration ratios. The use of flat plate collectors (non-concentrating system) for driving ORC leads usually to low-efficiency values because the flat plate collector operates in relatively low temperatures up to 100^{o}C, while higher temperatures present restricted thermal performance. In this direction, Wang et al. [7] calculated the system efficiency of this case as around 8%. In another investigation, Marion et al. [8] concluded that the use of a flat plate collector directly connected to an ORC configuration leads to a system efficiency of up to 7%. The next classification of studies regards the application of evacuated tube collectors. Manolakos et al. [9] found that the use of this collector type for driving an ORC can lead to an efficiency of around 7%. Also, Calise et al. [10] calculated the efficiency of a solar-fed ORC with evacuated flat plate collectors to be up to 10%.

The next classification of the studies regards the application of concentrating solar thermal collectors for operating in higher temperatures, the fact that enables the ORC to operate in higher temperatures and leads to a higher thermodynamic efficiency. However, the application of concentrating systems is associated with the need for using a tracking unit that increases the cost and the complexity of the unit. The use of a low-concentrating collector (compound parabolic collector) can lead to an efficiency of 11.7% according to the study of Carlini et al. [11]. Great research has been conducted in the domain of linear concentrating systems which usually need a single-axis tracking system. More promising results have been found with these systems compared to the aforementioned. Specifically, Tzivanidis et al. [12] found that the use of parabolic trough collectors can make the system efficiency around 15%. Additionally, in another study about linear Fresnel rectors, the system's efficiency was calculated at 19.7% [13]. Another interesting idea is the application of a point focal concentrating unit with a dish concentrator for driving and ORC. This technology has been found to lead to an efficiency of 21.4% according to Refiei et al. [14]. Practically, the application of a high concentrating ratio makes possible the efficient thermal performance in higher temperatures, something that makes the solar-to-heat conversion an efficient and sustainable process. However, the solar dish designs need a double-axis tracking system for concentrating properly the incident solar beam irradiation on the focal region.

The present brief literature summary indicates the existence of an important scientific interest in the examination of different ideas about solar-fed ORCs. In this direction, this work combines two efficient designs together; the solar dish concentrator, and the recuperative ORC with reheating. The goal is to design and investigate a highly efficient unit that can exploit properly incident solar irradiation. Specifically, it is useful to state that the recuperating ORC with reheating is a pioneering design that has not been extensively examined and its combination with the efficient solar dish system can lead to a sustainable solution for electricity production. Moreover, the present design includes a modeling of variable expander isentropic efficiency which makes it possible to highlight the benefits of a two-stage expansion. To our knowledge, the suggested solar-driven configuration has not been examined previously and it is a new contribution to the present scientific field. The investigation is performed in dynamic operating conditions for a typical sunny day with a created homemade code in Engineering

Equation Solver [15]. Moreover, the present study includes a parametric investigation of the system's daily performance by applying different high saturation temperature levels of the ORC. The results can be exploited for estimating with accuracy the daily yield and performance of the suggested configuration, as well as for giving the basic design aspects of this idea.

2. Material and Methods

2.1. The suggested system

This analysis examines a system that includes a solar field with solar dishes, an insulated thermal tank and an advanced ORC. Figure 1 shows the studied unit and the basic energy flows are given. It is crucial to state that in this analysis, 10 modules of solar dishes are used with a total collecting area of 500 m^2, while there is an insulated thermal tank with a volume of 5000 l. Every solar dish includes a spiral absorber inside a cavity receiver and more details about the collector design can be found in Ref. [16]. The working fluid both in the collectors and in the tank is a proper thermal oil [17] which can operate up to 400^{o}C without evaporation danger.

The ORC is a cycle that has two expanders, a reheater, a recuperator, a condenser, a pump, and a heat recovery system. In this analysis, screw expanders were chosen as the most suitable devices. The working medium in the thermodynamic cycle is cyclopentane as a proper choice [18]. The superheating of the expander is chosen at 5 K, the approach temperature variation between the streams on the recuperator at 5 K, the electrical-generator efficiency at 98%, the motor efficiency at 80%, the mechanical efficiency of the shaft at 99% and the pump's isentropic efficiency at 80%. Moreover, a useful assumption regarding the condenser was made by selecting its temperature to be 5 K greater than the maximum daily environmental temperature. More information regarding the mathematical formulation of this ORC is given in Ref. [19]. Table 1 summarizes the aforementioned parameters.

Table 1. Main input parameters of the examined system

Parameter	**Values**
Superheating in the expander inlet	5 K
Recuperator pinch point	5 K
Electrical-generator efficiency	98%
Motor efficiency	80%
Mechanical efficiency of the shaft	99%
pump's isentropic efficiency	80%
Condenser temperature	5 K greater than the maximum daily environmental temperature

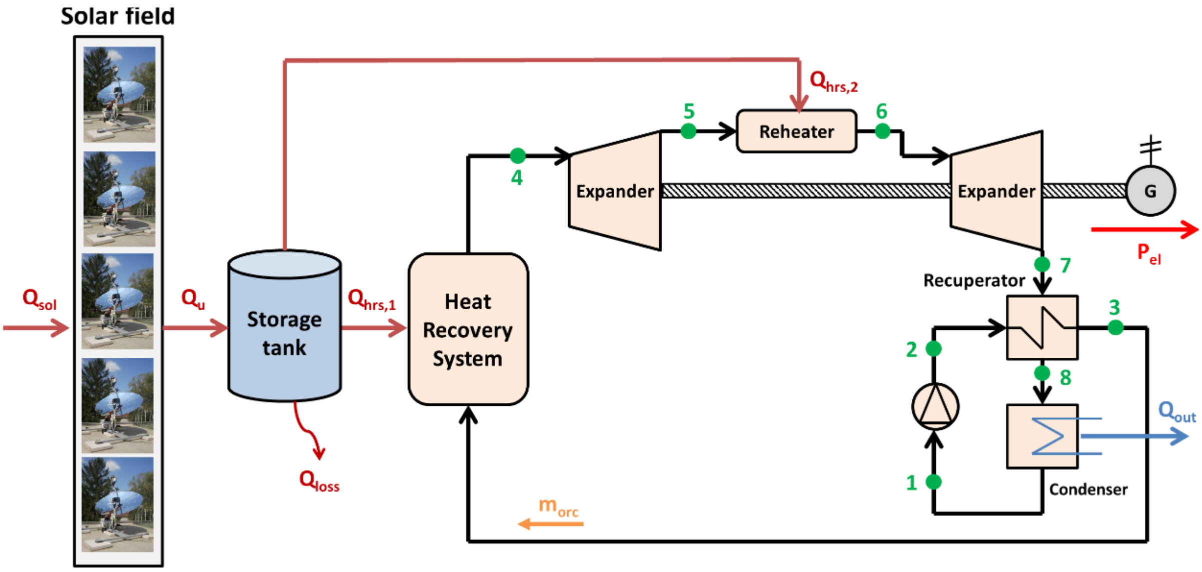

Figure 1. The examined solar dish-driven recuperative ORC with reheating

2.2. Main mathematical modeling

The solar dish thermal efficiency ($\eta_{col,\,inst}$) is estimated by applying the next formula which has been retrieved by Ref. [20]:

$$\eta_{col,inst} = 0.68199 - 0.19456 \cdot \frac{T_{f,in}-T_{am}}{G_b} - 0.00056 \cdot \frac{\left(T_{f,in}-T_{am}\right)^2}{G_b} \tag{1}$$

Additionally, the solar thermal efficiency can be written as:

$$\eta_{col,inst} = \frac{Q_u}{Q_{sol}} = \frac{m\cdot c_p\cdot\left(T_{f,out}-T_{f,in}\right)}{A_a\cdot G_b} \tag{2}$$

Where, (Q_u) is the useful thermal product from the solar system, (Q_{sol}) is the solar energy input on the field, ($T_{f,\,in}$) is the inlet temperature in the collectors, ($T_{f,\,out}$) the outlet temperature from the collectors, (T_{am}) the ambient temperature, (G_b) the direct solar beam irradiation and (A_α) the collecting aperture of all the modules.

The energy balance in the tank is described as:

$$\rho \cdot c_p \cdot V \cdot \frac{dT_{st}}{dt} = Q_u - Q_{loss} - Q_{hrs,1} - Q_{hrs,2} \tag{3}$$

Where (ρ) is the density, (c_p) the specific heat capacity, (V) the tank volume, (T_{st}) is the mean storage temperature, (Q_{loss}) the tank thermal losses, ($Q_{hrs,1}$) the heat input in the heat recovery system and ($Q_{hrs,2}$) the heat input for the reheating. In this analysis, the tank is modeled with 5 mixing zones where every zone is assumed to have a uniform temperature. The number of zones has been selected after a proper sensitivity analysis.

The screw expander isentropic efficiency is modeled below for both expanders [21]:

$$\eta_{is,exp} = c \cdot \left[0.9403305 + 0.0293295 \cdot ln(V_{out}) - 0.026698 \cdot V_r\right] \tag{4}$$

$$c = \begin{cases} 1 - 0.264 \cdot \ln(V_r), & for\ V_r > 7 \\ 1, & for\ V_r \le 7 \end{cases} \tag{5}$$

Where ($\eta_{is,\,exp}$) is the expander isentropic efficiency, (V_r) is the volumetric ratio and (V_{out}) is the specific volume in the outlet. Also, it is useful to add that the reheating is performed for a medium pressure which is the geometrical mean of the maximum and minimum cycle pressures.

The daily electricity yield (E_{el}) is calculated as:

$$E_{el} = \int_{day} P_{el,net}\, dt \tag{6}$$

Where ($P_{el, net}$) is the net electricity of the system by taking into account the pump consumption and (t) is the time variable.

On a daily basis, the collector thermal efficiency (η_{col}), the cycle's thermodynamic efficiency (η_{orc}) and the system's efficiency (η_{sys}) are calculated as:

$$\eta_{col} = \frac{\int_{day} Q_u \, dt}{\int_{day} Q_{sol} \, dt} \quad (7)$$

$$\eta_{orc} = \frac{\int_{day} P_{el,net} \, dt}{\int_{day} (Q_{hrs,1} + Q_{hrs,2}) \, dt} \quad (8)$$

$$\eta_{sys} = \frac{\int_{day} P_{el,net} \, dt}{\int_{day} Q_{sol} \, dt} \quad (9)$$

2.3. Simulation strategy

The present analysis is performed on dynamic conditions by investigating one typical summer day in Athens, Greece and the respective meteorological data have been extracted by Ref. [22]. Figure 2 exhibits the solar direct beam irradiation and the environmental temperature distributions during the studied day of June. The total model, thermodynamic and dynamic, was created in the Engineering Equation Solver [15]. The dynamic character of the present work is mainly described by i) the variable environmental conditions and ii) the differential energy balance equation in the tank. The thermal capacity of the solar dish collector is neglected in the present work because the energy storage is performed in the tank where the proper differential equations are solved.

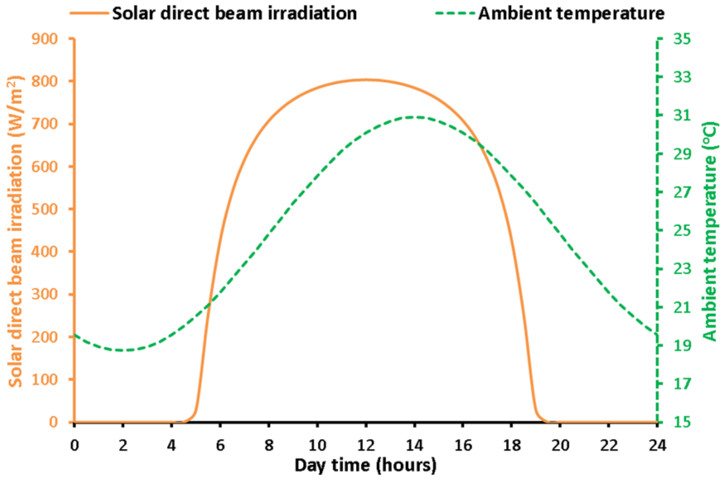

Figure 2. Climate conditions of the studied June day

The nominal ORC capacity was chosen at 50 kW_{el} after performing a preliminary sizing analysis. Moreover, the present analysis is studied parametrically for different values of the saturation temperature in the heat recovery system (T_{sat}) in the range of 120°C to 220°C. The proper control has been designed in order to operate the ORC only when there is warm enough thermal oil in the storage tank for performing a suitable simulation. Also, the minimum temperature difference in the heat recovery system was set at 5 K which is a typical value. The thermodynamic modeling of the ORC was simulated with a developed thermodynamic model written in Engineering Equation Solver [15]. This tool gives the possibility for solving numerous non-linear equations together and it includes libraries for the thermodynamic properties of the working fluids. More information concerning the mathematical modeling of this ORC can be found in Ref. [19]. Also, the previous section includes the basic equations that describe the modeling of the solar thermal field and of the storage tank.

3. Results

3.1. Daily performance

The first stage in this simulation analysis is the presentation of the daily analysis of the unit for a typical case with a saturation temperature of 185°C which leads to high system performance. It is valuable to state that for this case, the low pressure of the cycle is 0.639 bar and the high pressure is 21.1 bar for this case. Figure 3 illustrates the inlet and outlet temperature levels of the solar field and the mean storage temperature for the operation during sunny hours, from 5:00 up to 19:00. It is clear that the fluid temperature level is maximized around 15:00 which is a bit later than the solar-noon. Also, the outlet temperature is greater than the inlet temperature, while the mean storage tank temperature has an intermediate value. It is also interesting to comment that the inlet and outlet temperatures have no smooth profiles in the morning and in the afternoon due to the on/off operation and this behavior is dependent on the control system. This work has used a strict control system and thus there are some cases with open/close behavior. More specifically, the control system uses the storage tank temperature as the key parameter for deciding the operation of the system and this is the critical control parameter.

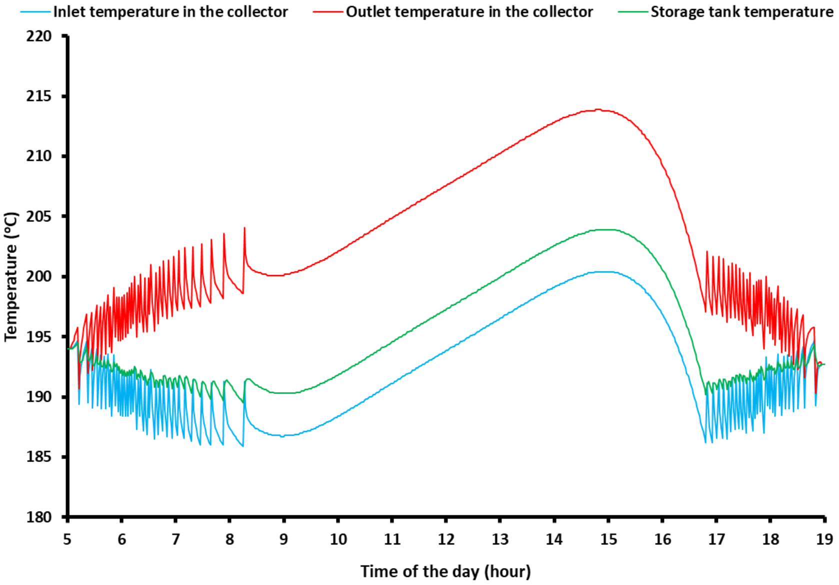

Figure 3. Temperature variations in the dynamic analysis of the system for saturation temperature (T_{sat}=185°C)

Figure 4 shows results regarding the solar field performance. Specifically, this figure gives results for the useful thermal production and for the collector efficiency during the sunny hours, from 5:00 up to 19:00. The results indicate that the useful heat production presents maximum values in the period from 10:00 up to 14:00, while from 7:00 up to 17:00, it has significant values. Also, the collector thermal efficiency has a similar behavior, but it has a more abrupt deviation at the start and at the end of the sunny hours. In other words, the thermal efficiency has an accelerated increase in the morning with useful heat production to follow at a smaller increasing rate. Furthermore, at 12:00, the useful thermal production is 242 kW and the instantaneous solar thermal efficiency is found at 62.2% which is a satisfying value.

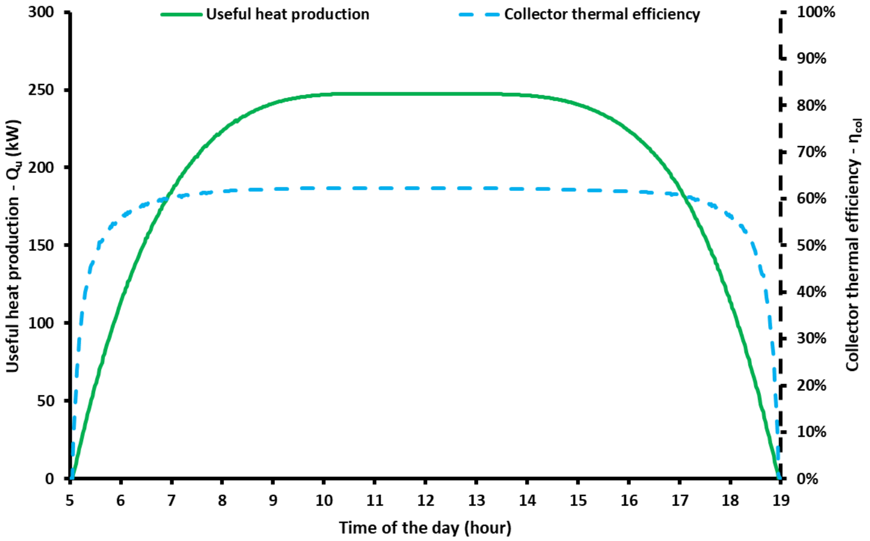

Figure 4. Solar field performance in the dynamic analysis of the system for saturation temperature (T_{sat}=185°C)

3.2. Parametric analysis

Section 3.2 regards the parametric analysis of the system's daily performance for different saturation temperature levels. This parameter is a critical one that is assumed to be a design parameter and its selection is critical to maximize the system's performance and the electricity production. Figure 5 shows the impact of the saturation temperature on solar field thermal efficiency. The rise of the saturation temperature makes the system operate at higher temperature levels and so the solar thermal collector has smaller efficiency due to the increased thermal losses. Practically, the operation of the working fluid at a higher temperature makes the receiver have a higher temperature and the result is increased convection and radiation thermal losses. It was found that the daily solar efficiency was reduced from 64.34% for T_{sat}=120°C to 59.07% for T_{sat}=220°C. The reduction of the solar field efficiency is approximately linear.

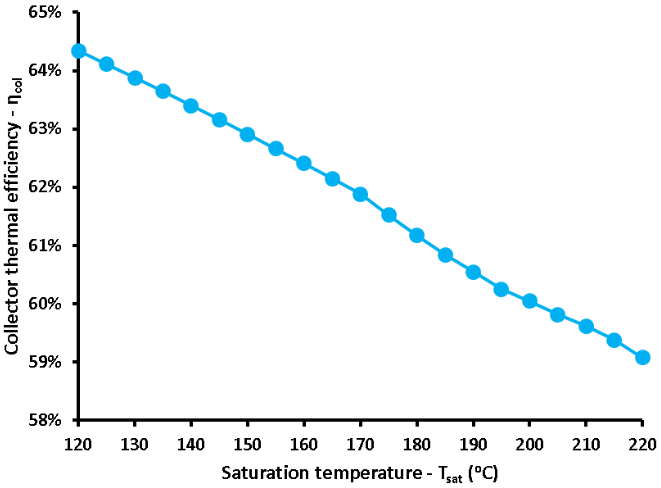

Figure 5. Variation of the daily solar collector efficiency for different saturation temperature levels

However, the increase in the operating temperature, generally, can lead to higher thermodynamic efficiency in the power cycles. In this direction, the next stage is the presentation of the saturation temperature on the ORC thermodynamic efficiency. Figure 6 illustrates this analysis, and it is clear that greater saturation temperature enhances the cycle efficiency; a reasonable result that is in accordance behavior of the ideal Carnot Cycle. However, after a limit, the reduction of the isentropic efficiency makes the thermodynamic efficiency have a reducing rate. Thus, there is maximum thermodynamic efficiency at 20.91% for $T_{sat}=195^oC$. Specifically, higher saturation temperature increases the high pressure of the organic Rankine cycle and consequently the expansion pressure ratio of the expander, something that reduces the isentropic efficiency. In other words, for the specific expansion machines, the operation in higher pressure levels (and pressure ratios) creates difficulties in the expansion process, something that reduces their performance, and the expansion process is getting far from the ideal isentropic expansion.

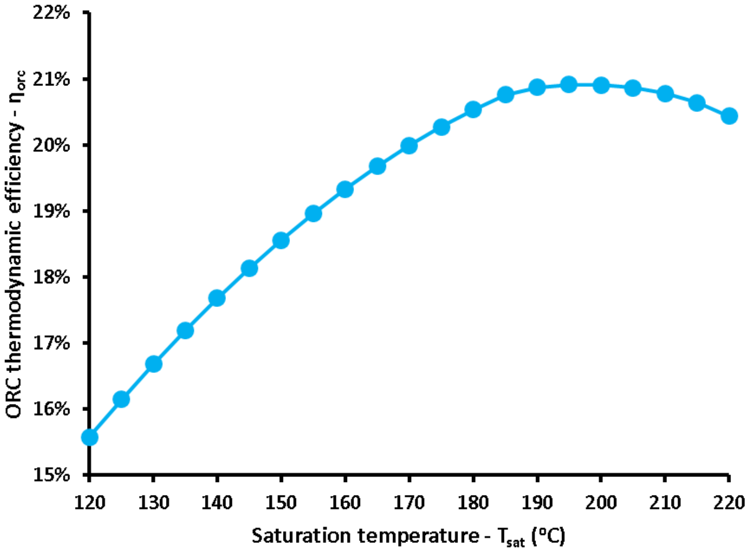

Figure 6. Variation of the daily cycle efficiency for different saturation temperature levels

Figure 7 exhibits the system efficiency which is dependent on the collector efficiency and the ORC efficiency. Practically, a greater saturation temperature increases the thermodynamic efficiency but decreases the solar field efficiency. Therefore, the system efficiency is maximized in an intermediate saturation temperature and more specifically at 185°C. In this case, the system's efficiency is 12.63%, the ORC efficiency 20.76% and the solar field efficiency 60.84%. It is valuable to state that the thermodynamic efficiency is maximized at 195°C, while the system efficiency is maximized at 185°C, a lower value due to the impact of the collectors' performance. It is also important to state that the unit has relatively high efficiency for saturation temperatures over 160°C, something that shows that the unit has to operate in medium temperatures over 160°C. This result is explained using solar concentrating technology which is able to provide significant amounts of useful thermal energy in medium and high temperatures. Also, the minimum found thermodynamic efficiency is 15.57% for $T_{sat}=120^oC$.

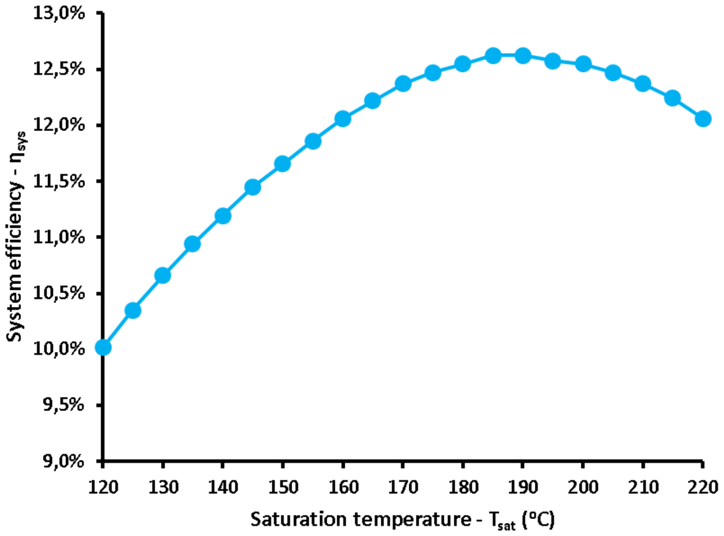

Figure 7. Variation of the daily system efficiency for different saturation temperature levels

The next stage of this investigation is the presentation of the daily electricity yield of the unit. Figure 8 illustrates the daily electrical production, and it is clear that it is maximized for saturation temperature at 185°C and more specifically it is equal to 577.3 kWh_{el} which is a significant electricity amount. Moreover, it is critical to state that the shape of the electricity yield production in Figure 8 has a similar trend to the system's efficiency curve in Figure 7, a reasonable result.

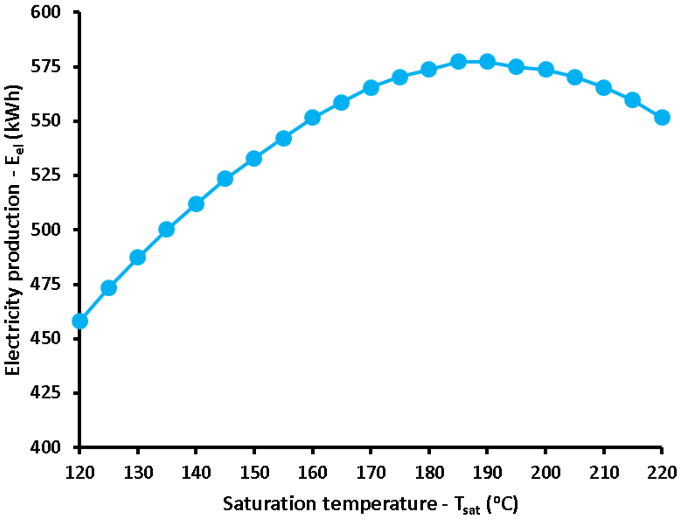

Figure 8. Variation of the daily electricity yield for different saturation temperature levels

The results of the present investigation regard the initial energy assessment of the solar-driven recuperative ORC with reheating for a typical summer day in Greece. Advanced models have been applied for the suitable modeling of the studied devices to conduct detailed work. Specifically, a lot of interest is given to the suitable investigation of the screw expanders aiming to calculate with accuracy their isentropic efficiencies. It is valuable to state that according to the present modeling, the separate expanders perform better than the use of one expander because the pressure ratio of every expander is smaller than the expansion in one device. This fact makes it possible to increase the isentropic efficiency of every expander. Moreover, the reheating leads to higher thermal efficiency, according to the thermodynamic laws, and totally, the suggested design is an efficient one. Table 2 summarizes the results of the design that maximizes the system's daily performance and also maximizes electricity production. This design is found for saturation temperature at 185°C.

Table 2. Summary of the daily results for the optimum design (T_{sat}=185°C)

Parameter	Value
Daily solar energy	4544.8 kWh
Daily useful thermal production	2765.1 kWh
Daily electricity production	573.8 kWh
Daily solar thermal efficiency	60.84%
Daily thermodynamic cycle efficiency	20.76%
Daily system efficiency	12.63%

Another interesting result is the presentation of the variation of the mean tank's temperature for the different saturation temperatures. Figure 9 shows these results for the saturation temperatures of 120°C, 160°C, 185°C and 220°C. These indicative cases were selected for covering the examined range, and also to include the optimum case of 185°C. The tank's temperature is fully dependent on the selected saturation temperature, and generally, it takes a higher value compared to the respective saturation temperature. Also, the smoothest profile during the day (sunny hours) was found for the case of 185°C, something that proves that this case leads to a continuous operation for many hours per day.

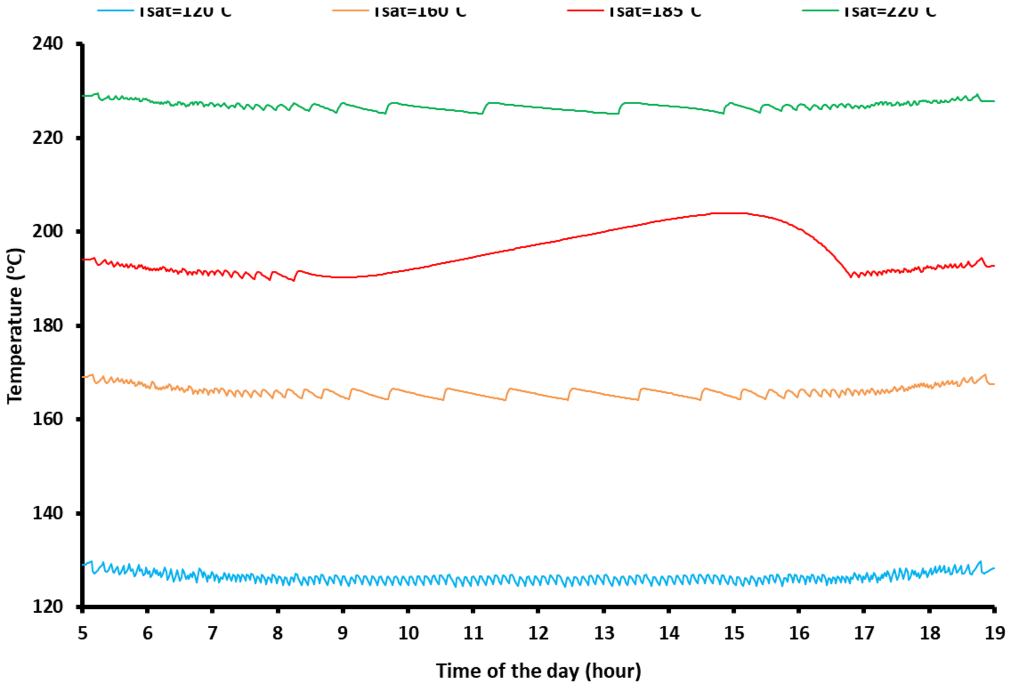

Figure 9. Daily variation of mean storage temperature for different saturation temperatures

4. Conclusions

This paper examines a novel solar-driven power production system that is based on the use of solar dish thermal collectors and a recuperation ORC with reheating. The presented results regard the dynamic performance of the unit on a usual day in the summer. The most critical conclusions of this study can be found below:

- The thermal oil temperature level is maximized inside the tank at 15:00, while the produced useful heat has maximum values in the period from 10:00 up to 14:00.

- The rise of the saturation temperature from 120°C to 220°C reduces the collector efficiency from 64.34% to 59.07% respectively, in an approximately linear way.

- The thermodynamic efficiency is maximized at 20.91% for saturation temperature equal to 195°C. The maximization of the thermodynamic efficiency in an internal value is a result of the reduction of the isentropic efficiency due to the rise of the expansion pressure ratio with the rise of the saturation temperature.

- The system efficiency has optimum performance for saturation temperature at 185°C. In this case, the system efficiency is 12.63%, the cycle thermodynamic efficiency 20.76% and the collector efficiency 60.84%. Also, for this saturation temperature level, the daily electricity production yield is maximized at 577.3 kWh_{el}.

- The selection of the saturation temperature determines the operating temperatures in the tank and more specifically the fluid temperatures in the tank are higher than the respective saturation temperature. Moreover, the selection of the saturation temperature at 185°C leads to a relatively smooth operation during the sunny hours of the day.

In the future, the suggested unit will be examined for a total year period and for different climate conditions. Also, a useful idea is to examine cogeneration and polygeneration systems that can be based on the present one for simultaneous electricity and heating, as well as for cooling or hydrogen production.

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