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Annual performance simulation of a solar cogeneration plant with sensible heat storage to provide electricity demand for a small community: A transient model

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ABSTRACT

In this paper, a solar-driven power system as a means of meeting electricity demand in a small community has been investigated in terms of its transient performance on an annual basis. Using a sensible heat storage unit, the heat collected by evacuated flat plate collectors (EFP) can be stored and used at other times to feed an organic Rankine cycle (ORC). The storage unit is analysed using a one-dimensional temperature distribution model including heat loss to the ambient. The stored heat in the unit makes it possible to produce electricity at night. In order to meet the electricity demand in all seasons, evaporation temperature is controlled by the present model via adjusting the water mass flow rate of the heat source. Solar ORC using EFP collectors is a promising technology but dynamic simulation on its annual performance has not been conducted yet. Investigation of the daily performance with consideration of transient behaviour of the components is the main aim of the study. The system performance is evaluated for different seasonal weather conditions. An 8-kW expander output is desired for the peak period which is in the evening for a small community, when sufficient solar irradiance is available. The system also operates in combined heat and power mode during the winter period to supply heat for space heating purpose. Results show that 23296.8 kWh electricity is produced considering the demand pattern during the year and 19344.7 kWh heat can be used for heating for the selected four months.

Keywords:
Solar ORC; Cogeneration; Heat storage; Annual transient simulation.

INTRODUCTION

Nowadays electricity has become the most demanded energy source for household consumers because it has practical conversion ability to other needs in a dwelling. It is not only used for everyday home appliances but is also required for heating, cooling, ventilating systems and in some countries, it is also used for purification of drinking water. However, this electricity demand differs from country to country, month to month and is not same during the day. The results of a study about UK households given in Fig. 1 [1], reveals that electricity demand peaks in December and the lowest demand is noted in May. However, peak demand occurs between 6 -7 pm for all months. Fig.1 gives the results for the UK, though the trend is quite similar for all European countries [2]. It should be noted that this trend may differ according to geographical locations which receive higher solar irradiance with higher ambient temperatures; the demand will be affected because of air conditioning needs. In Cyprus, for example, winter demand is similar to that of the UK but summer demand is generally flatter with high overnight and day time consumption by the air conditioners [3].

To meet the electricity demand, production using sustainable sources is encouraged by governments and societies. However, there is the need for significantly more development in this field in order to fully satisfy the demand. Photovoltaics have been preferred for years and have an important percentage in future electricity production systems, but generation is intermitted by environmental factors. Moreover, peak demand occurs when there is no, or significantly less residual solar irradiance and residents still demand electricity at night-

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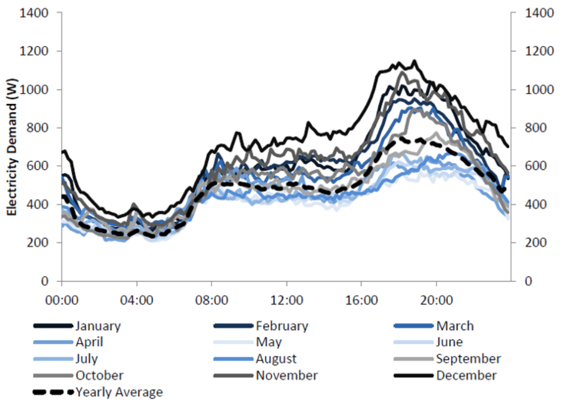

Figure 1. Monthly average electricity demand from the household in UK [1]

time. Therefore, solar ORC systems coupled with heat storage units offer an appropriate sustainable solution to this demand problem.

Since parabolic through collectors (PTC) offer high temperature output, they have been commonly preferred for Solar ORC systems. Chacartegui et al. [4] analyzed an ORC system coupled with a thermal storage unit. They conducted an off-design analysis and observed that the investment cost of direct thermal energy storage systems is lower than indirect storage systems. Li et al. [5] designed and investigated a solar thermal electricity system with water as the heat transfer and storage fluid in thermodynamic and economic considerations. They reported that the direct steam generation system offers both thermodynamic and economic advantages compared to thermal oil used systems. Although PTCs are preferred in solar power plants, these kinds of systems are not easily implemented for domestic use. They require a sun tracking system to use direct beam radiations to concentrate on the receiver. In contrast, evacuated collectors are quite good candidates for heat and power production as they do not need direct beam radiations and have promising performance under low ambient temperature and radiation conditions in regard to standard flat plate collectors. Freeman et al. [3] used evacuated flat plate collectors and studied a domestic-scale solar combined heat and power system with a thermal storage unit for matching end-user demands. They suggested that using PCM as a heat storage gives a better output for a smaller equivalent storage volume than water. Finally, Kutlu et al. [6] prepared an off-design modelling of a solar ORC system with considering to match user demand during the day. For a given typical day's conditions, they showed that power output can be adjusted by controlling the flow rate of the circulation water and it is possible to meet electricity demand even at night.

Solar ORC using EFP collectors is a promising technology but dynamic simulation on its annual performance has not been conducted yet. According to the literature review, previous studies have used average monthly weather data to analyse the annual performance of systems in general. However, in this study, real daily weather data have been used and simulations have been conducted according to a transient model and considering hourly electricity demand. This study also focuses on controlling the ORC operations related to weather conditions and output requirements such as supporting heat during the winter months.

SYSTEM DESCRIPTION AND METHODOLOGY

The proposed system as given in Fig. 2 consists of three subsystems. The first one is solar field. TVP SOLAR HT-Power EFP collectors are used for heating water which comes from the bottom of the tank, which is then discharged into the top of the water tank. The second subsystem is a sensible thermal storage unit. A water tank is used as a heat storage unit to provide heat for the ORC. Moreover, it facilitates operation of the ORC when solar radiation

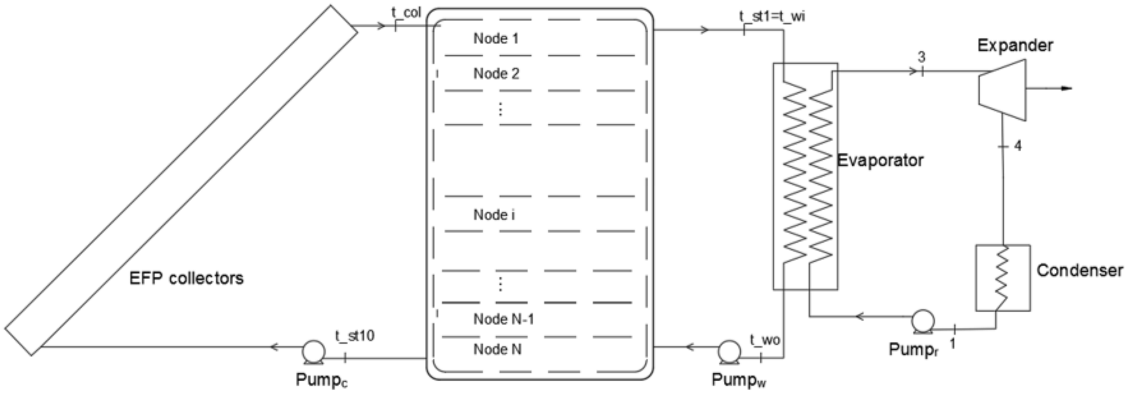

Figure 2. Schematic of the Solar ORC system

is insufficient or unavailable. The last subsystem is the ORC unit. There are four main components in the ORC namely pump, evaporator, expander and condenser.

Regarding mathematical models, the equations for the collectors were adapted from reference [7] and [8]. Thermal efficiency of the collector is given in Eq. (1):

$$\eta_{col} = \eta_0 - c_1 \frac{\overline{T} - T_{am}}{G} - c_2 \frac{\left(\overline{T} - T_{am}\right)^2}{G} \tag{1}$$

Parameters are taken as $\eta_0 = 0.76$, $c_1 = 0.399$, $c_2 = 0.0067.$, Absorbed heat by the collector increases the water temperature, the related equation is given in Eq.(2):

$$\dot{Q}_{col} = \eta_{col}.A_{col}.G = \dot{m}_{cw}.c_{pcw}.\left(T_{col} - T_{st10}\right) \tag{2}$$

$\dot{Q}_{col}$ is absorbed heat rate by the collectors, A_{col} is total collector area, G is solar irradiance, T_{col} and T_{st10} are collector outlet and collector inlet temperatures, respectively.

The transient heat storage unit model considers thermal stratification of the water tank. It is analyzed by using multi node tank model which refers one-dimensional temperature distribution model [9]. The cylinder volume has been divided into 10 equal nodes to obtain temperature distribution throughout tank height. Energy balance equation can be written considering the heat loss to the environment in every control volume. Eq. (3) and Eq. (5) show the energy balance equations for the first and last nodes. Eq. (4) shows internal nodes:

$$\begin{aligned} M_{st1}.c_{pw}.\frac{\partial T_{st1}}{\partial t} &= \dot{m}_{cw}.c_{pcw}.\left(T_{col} - T_{st1}\right) \\ &+ \dot{m}_{w}.c_{pw}.\left(T_{st2} - T_{st1}\right) - U_t.A_{st1}.\left(T_{st1} - T_{am}\right) \end{aligned} \tag{3}$$

$$\begin{aligned} M_{st,i}.c_{p,w}.\frac{\partial T_{st,i}}{\partial t} &= \dot{m}_{cw}.c_{p,cw}.\left(T_{st,i-1} - T_{st,i}\right) \\ &+ \dot{m}_{w}.c_{p,w}.\left(T_{st,i+1} - T_{st,i}\right) - U_t.A_{st,i}.\left(T_{st,i} - T_{am}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} M_{stN}.c_{pw}.\frac{\partial T_{stN}}{\partial t} &= \dot{m}_{cw}.c_{pcw}.\left(T_{st(N-1)} - T_{stN}\right) \\ &+ \dot{m}_{w}.c_{pw}.\left(T_{wo} - T_{stN}\right) - U_t.A_{stN}.\left(T_{stN} - T_{am}\right) \end{aligned} \tag{5}$$

$\dot{m}_{cw}$ and $\dot{m}_{w}$ are mass flow rates of collector and evaporator sides, T_{wo} is the water temperature coming from the evaporator to the tank bottom node. U_t indicates the thermal loss coefficient of the well-insulated tank.

It was decided that a scroll type expander would be used in the analysis as this is particularly well-adapted to small-scale Rankine cycle applications. An empirical model was adapted from [10]. The evaporator is the most important component of the system given that control strategies would be possible by controlling the evaporation temperature in this study. The evaporator is designed according to NTU method. Firstly, evaporator heat transfer area is determined after that the analysis is conducted for different operating conditions by using the same evaporator. To find the effectiveness for given conditions, the effectiveness-NTU method is implemented in the analysis. Related equations and detailed investigation about the effects of circulation water mass flow rate on system performance is given in Reference [6].

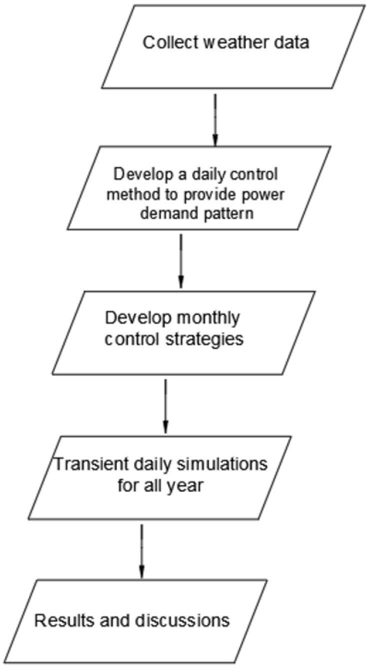

Figure 3. Procedure of the system simulation

The paper follows the order given in Fig. 3. EnergyPlus weather data is collected, as it is known that ambient temperature has an influence on condensing temperature and monthly control strategies are developed according to weather conditions. Moreover, daily control strategies are developed considering the demands. Controlled parameters are explained in Section 4. Daily simulations are conducted, results and discussions are presented in Section 5. Finally, the last section introduces the results

WEATHER DATA

The weather data in this paper relates to the climate conditions of Istanbul, Turkey. Relevant parameters such as solar irradiance and ambient temperature profiles are obtained by using the software EnergyPlus [11]. Fig. 4 and Fig. 5 show solar irradiance and environment temperature variations during the year, respectively. Istanbul is chosen for the analysis given that its irradiance profile is similar to some Mediterranean cities in summer but in winter, it is colder than in most other cities around the Mediterranean Basin. As seen in Fig. 4, solar irradiance profile is intermitted during the summer period, which contributes to testing the performance of the system

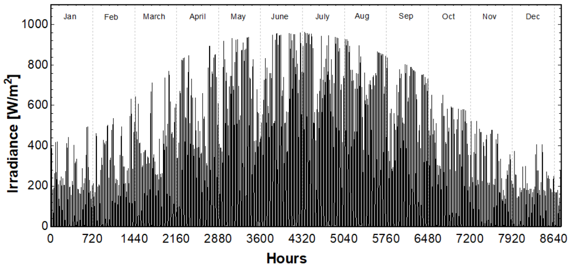

Figure 4. Solar irradiance variation during the year

under variable operating conditions. Moreover, average solar irradiance is quite low in the winter period, being around 200 W/m^2. The system is not able to produce satisfactory electricity under this irradiance values. Therefore, winter mode (CHP mode) can be activated to produce useful condensing heat for space heating purposes.

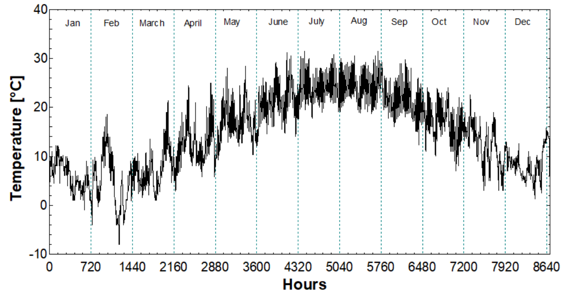

Figure 5. Ambient temperature variation during the year

CONTROL STRATEGIES

The main aim of this paper focuses on application of the control strategies. To maintain the demand profile which is given in Fig. 1, 24hrs of a day is analyzed in three different periods then heat source water circulation mass flow rate is adjusted for every period. Adjusted mass flow rates contribute to controlling the evaporating temperature, that is to say, controlling the electricity output [6]. Therefore, regarding the expander model, mass flowrate of the refrigerant R245fa is determined by the evaporating temperature. Collector mass flow rate is also adjusted according to weather conditions. In order to reach a higher temperature in the top part of the water tank, collector mass flow rates are reduced in winter months. To maintain similar operation for next days, a stop criterion must be defined. The fifth water element in the tank is chosen as stop consideration; this activates to refrigerant pump is shut off and the tank is switched to static mode until 08:00 the next day. Condensing temperature is dependent upon the ambient temperature except CHP mode.

In CHP mode, the target is to produce electricity only for collector pumps due to weak solar radiation. The condensing temperature is increased, and condensing heat can be used for space heating purposes. A summary of the monthly control strategies is given in Table 1.

SIMULATIONS

The presented system is analyzed for a small community; ten houses are selected, so the total collector area of the system is selected as 550 m^2 and water storage tank as 88 m^3. Heat exchangers are dimensioned according to NTU methods so off-design operation is considered for the whole year. Although the main aim is conducting the yearly simulation considering the transient behaviour, application of the control strategies are necessary for meeting the user electricity demand. The operation follows the given strategy; the collector pump runs, and solar energy is stored in the tank, meanwhile the ORC produ-

Table 1. Summary of the control strategies in monthly basis

Months	$\dot{m}_{col}$ (kg/s)	T_{cond}	Stop Temp.	Water flowrate (kg/s) 08:00-18:00	Water flowrate (kg/s) 18:00-24:00	Water flowrate (kg/s) 24:00-08:00
1	0.01	45	80	2	2	-
2	0.01	45	80	2	2	-
3	0.01	20	80	1	2	0.5
4	0.015	25	85	1	2	0.5
5	0.02	30	85	1	2	0.5
6	0.02	35	95	1	2	0.5
7	0.02	35	95	1	2	0.5
8	0.02	35	95	1	2	0.5
9	0.015	35	85	1	2	0.5
10	0.01	30	85	1	2	0.5
11	0.01	45	80	2	2	-
12	0.01	45	80	2	2	-

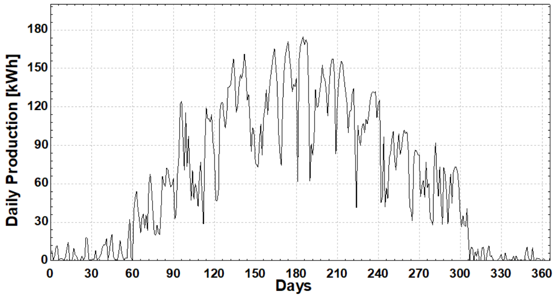

Figure 6. Daily produced electricity

ces electricity between 08:00 and 18:00. When sun sets, peak demand period starts, water flow rate is adjusted to provide higher output until 24:00. The last period is from 24:00 to 08:00. During the last period, the circulation water mass flow rate is switched to 0.5 kg/s, as generation of a high amount of electricity is not required. Simulations are conducted considering both aforementioned strategies and also every per day's irradiance profile.

Fig. 6 shows daily produced electricity as kWh. Four months (namely November, December, January and February) are adjusted for CHP mode so output is quite low. Additionally, large fluctuations are observed throughout the year regarding electricity outputs. These fluctuations occur as the solar irradiance does not follow a stable trend naturally. The control strategy allows these sharp decrements for conserving the thermal energy in the tank for following day.

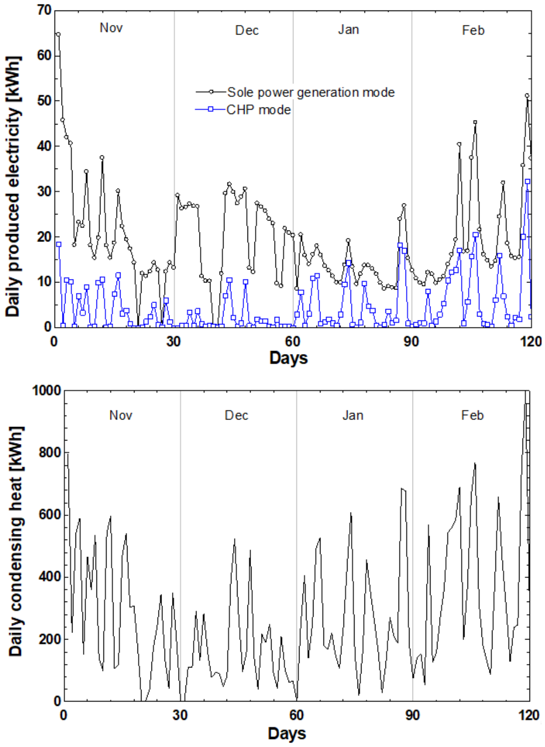

Figure 7. Comparison of outputs of the CHP and sole power generation modes and condensing heat for space heating

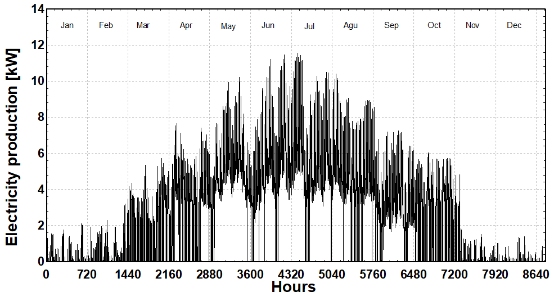

Figure 8. Hourly produced electricity

Stop criterion is activated when condition is provided thus, the ORC pump is turned off and electricity production ends for this certain day.

To understand the specifications of CHP operation, Fig 7a is given to compare CHP and sole power generation modes. It is clearly seen from the figure that electricity output is lower in CHP mode. The main reason is a higher condensing temperature which causes a lower expansion ratio in the expander. However, high condensing temperature allows the use of condensing heat for other purposes for example space heating. Fig 7b shows produced condensing heat on a daily basis. The trend is quite similar with electricity generation as heat can only be obtained while the ORC is working. CHP mode is active for four months and received useful heat is recorded as 19344.7kWh.

One of the aims of this study is matching the electricity output with demand during the operation. Therefore, electricity yield is given in Fig. 8. The figure shows the effect

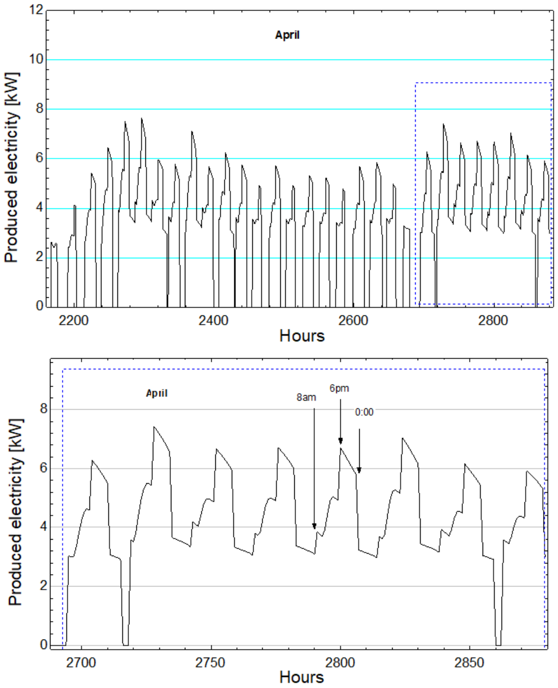

Figure 9. April hourly production

of the CHP mode on production in the winter period and as expected, higher output in summer period. In order to clearly observe the output trend and continuous production profile, there should be zoomed on a specified month. Fig. 9 presents the electricity production profile during April. Since April is a transition month, the output profile is also of a similar nature. From April, continuous (24h) production begins to form. Fig.9 shows that the 24hr production is observed for 11 days. When focusing on the last 8 days, continuous production and controlling hours can be seen clearly.

The last figure is plotted to offer an explanation of different outputs. June and September electricity generations and water tank top temperatures are compared in Fig. 10. Since these two months have the same condensing temperature, the only effecting parameter on output is the evaporating temperature which is directly related with top temperature. Thus, it is obvious that three days have almost the same output and top temperature in Fig.10.

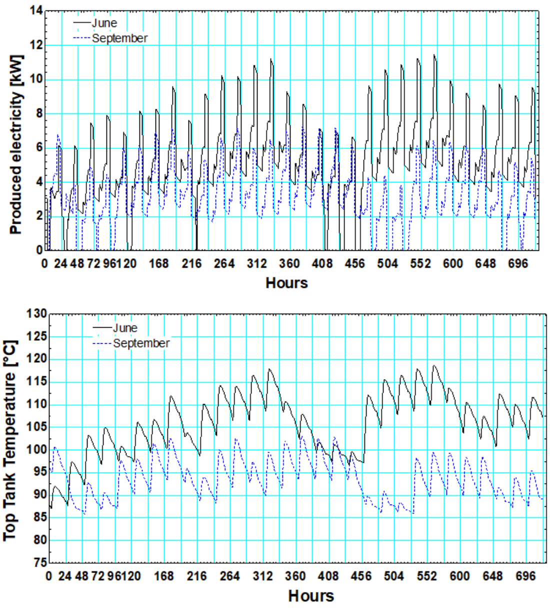

Figure 10. Comparison between June and September

Heat losses to the environment from the tank are also considered, compared and calculated as 5251 kWh during June and 4451 kWh during September. The difference is approximately 15% but produced electricity difference falls by almost 40%. This figure shows wasted heat from heat loss is a serious problem which cannot be neglected as even the ORC stops, heat loss from tank to environment never ends until to be same temperature with ambient.

CONCLUSION

In this study, a solar-driven Organic Rankine Cycle was investigated for a year with consideration given to meeting electricity demand. Components were modelled and analyzed in a transient state for the whole year. When weak solar irradiance was available in the winter period, operation was switched into CHP mode and the system produced heat and power simultaneously. Weather conditions were used as real data and performance was predicted under real conditions. The system also focused on control strategies. On the basis of the presented study, the following conclusions can be written:

- EFP collectors have been successfully implemented in the ORC system even for low irradiance periods for CHP operation.

- Although solar ORC performance totally depends on an irradiance profile, by controlling the system operation, it is possible to conserve the stored heat for next day with dispensable late-night production. However, this intermitted generation causes sharp falls in daily electricity production.

- 24hrs production needs sufficient solar irradiance. According to simulation 24hrs production occurs by April, but it depends on weather conditions.

- Electricity output depends on control strategies. Stop criteria assignment is one of the main parameters to obtain magnitude of output and production time in daily basis.

- Using 550m^2 collector area, 23296.8 kWh electricity has been produced considering the demand pattern for ten dwellings in year.

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