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Conceptual Design of Small Scale Multi-Generation Concentrated Solar Plant for a Medical Center in Egypt

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Abstract

Small scale multi-generation solar plant is designed for a medical center building in Egypt. The plant consists of solar collector field of 120 kW peak thermal capacity, thermal storage tank with 3 tons of therminol-66 oil, an organic Rankine cycle (ORC) of 4.3 kW nominal electric power production capacity, and thermally driven absorption chiller (TDC) of 35 kW cooling capacity. The present article reports on the plant layout, thermodynamic analysis, solar field design, ORC and TDC integration, thermal storage system, and control system and operation strategy. The plant is modeled and analyzed using parabolic trough (PTC) and Linear Fresnel collectors (LFR) at different operation modes in typical winter and summer days. The power output from the solar field in typical summer days results in simultaneous operation of the ORC and TDC using PTC for about 10 and 12 hr/day, respectively. The use of LFR solar collectors results in reduction in the operation hours of ORC and TDC by about 50% and 30%, respectively. Low power output of the solar collector field in winter allows for operation of the ORC unit only. Careful design and operation of the plant can increase the overall plant efficiency which improves its economic value. The effectiveness of CSP multi-generation plants is demonstrated thus promoting their wide adoption in the Mediterranean basin.

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Keywords: Multi-generation, Solar, Parabolic Trough, Linear Fresnel, Cooling, Absorption Chiller, Organic Rankine Cycle

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1. Introduction

Given the global challenges related to climate change and resource shortages, both high efficiency energy supply and intensive utilization of renewable energy sources are required, especially in the building sector. Energy consumption in the building sector accounts for over 40% of worldwide primary energy use and 24% of greenhouse gas emissions. In this regard, solar energy can play a fundamental role to replace fossil fuel plants, and to move from a carbon technology to a green technology [1, 2]. One of many ways to utilize solar energy as an energy source is developing a Concentrated Solar Power (CSP) system. CSP is a system that uses direct solar radiation

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concentrated to generate heat onto a small area for producing electricity [3, 4]. This system has been developed in several countries such as Algeria, Egypt, Greece, India, Italy, Mexico, Morocco, Spain, and America [5].

CSP technologies mainly use parabolic troughs, solar towers, dish/engine systems, and linear Fresnel reflectors. Parabolic trough and linear Fresnel are systems that use line focusing to capture solar radiation, while solar tower and dish engine system uses point focusing [6, 7]. Despite the fact that Egypt is located in the south of the Mediterranean, granting abundant amount of energy source with considerably high intensity suitable for CSP, the development of CSP has not yet initiated. The present project work aims at the development of a pilot small scale multi-generation CSP plant that serves as a prototype for installation in remote areas.

Multi-generation CSP plants set an example of high efficiency and renewable energy facility, suitable for civil buildings. They offer combined generation of electricity, cooling, heating, desalination, etc. [8-10]. Careful design and operation of these plants can increase the overall plant efficiency and thereby increasing the useful output of the plant, which improves its economic value. This paper discusses the design activities of the multi-generation concentrating solar plant that has been carried out within the framework of STS-Med ENPI project. The project aims to demonstrate the effectiveness of Concentrating Solar (CS) small scale integrated systems and promote their wide adoption in the Mediterranean basin. The plant is expected to be installed by the end of 2015 in Belbis, Egypt.

2. Site Description and Load Analysis

The plant shall be installed at SEKEM medical center near Belbis city which lies in the north of Egypt at latitude 31° and longitude 30°. The total surface area of the building is about 963 m^2. Classification of the building electric loads in kW are mainly to supply cooling during summer (63% of electric load), winter heating (50%), equipment electric loads (17%) , and water pumping for irrigating the landscape (20%). The solar plant is designed to mainly provide chilled water to cover about 35 kw$_{th}$ (about 10 TR) peak of building cooling load during summer. The extra power output from the solar field shall be used to generate electricity. In winter, the plant shall be mainly used to provide electric power of about 4.3 kW$_e$ peak. The extra power output from the solar field shall be used to produce hot water for heating purposes. A thermal energy storage system shall work in conjunction with the solar field, power block, and chiller.

3. Technological Alternatives for Basic Plant Components

The main difficulty encountered in the design phase of the plant is related to the selection of appropriate technology of basic plant components. The selection is influenced by the thermodynamic performance of plant components, availability of commercial products, and potential for local manufacturing in Egypt.

3.1. Solar field

The emphasis in the present project is on the development of concentrating solar collectors. Among the CSP technologies, the plants with parabolic trough collectors (PTC) using oil as heat transfer fluid (HTF) are found to be more attractive commercially. Also the linear Fresnel reflector (LFR) has been reported as cheaper design due to the use of flat mirrors and structural advantages, though with a lower optical efficiency [11]. Both options have been investigated in the present project work. The comparison between the two types of collectors also considers the development of local manufacturing potential of LFR in Egypt.

The solar field has been designed for one day at summer to produce 120 kW$_{th}$ at the design conditions of DNI 900 W/m^2 and ambient temperature of 30 □C. This criteria result in an approximate collector net surface area (NSCA) of 208 m^2 using parabolic trough collectors and 296 m^2 using LFR collectors. The increase in collector area using LFR is due to its lower thermal efficiency as compared to PTC. The performance of the solar field is determined for typical summer and winter days in order to evaluate the overall collector field efficiency and its impact and plant output. Referring to the TDC and ORC technical characteristics at nominal conditions, the required heat input for TDC is 50 kW at hot oil supply temperature of 88 □C and for ORC is 53 kW for hot oil supply temperature of 125 □C. The above preliminary selection of NSCA for LFR corresponds to a solar multiple value of about 1.2.

3.2. Solar Power Technologies

Small scale power modules suitable for solar driven applications include micro steam and gas turbines, sterling engines, and Organic Rankine Cycle (ORC). The operation of steam turbines requires a high temperature steam generation which may pose operation and maintenance problems for small and micro scale multi-generation plants. The ORC process is well-suited for low grade heat source due to the lower boiling temperature and pressure of the working fluid compared to water. The electrical efficiency of the ORC process (electric output versus thermal input) is in general between 6 to 20 %, depending on the heat source and heat sink temperature [12]. ORC processes have good part load behavior. The vapor pressure in the ORC unit is considerably lower than that used in steam turbines and therefore does not require the use of expensive high-pressure technology, with good controllability and low operating and maintenance cost [13]. Compared to a Stirling engine, the investment costs for ORC are far less [12]. In the present project, the adoption of low temperature ORC offers the advantages of low cost solar field and convenience in switching between different plant operations modes. Commercial units of ORC with electric power starting from 3 kW are available.

3.3. Thermally driven chillers (TDC)

The process of cooling using thermally driven chiller is driven by heat and not by mechanical or electric power like in conventional compression cycles. Lithium bromide-water units are more suitable for solar applications since their operating (generator) temperature is lower and thus more readily obtainable with low-cost solar collectors [14 - 17]. Commercial typical chilling capacities are in the range of several hundred kW. Mainly, they are fired with waste heat, district heat or heat from co-generation. The required heat source temperature is usually above 85°C and typical COP values are between 0.69 and 0.8. Recently, a number of chiller products in the small capacity range have entered the market. In general, these are designed to operate with low driving temperatures. The lowest chiller capacity available is now 4.5 kW. Double-effect absorption chillers with two generators require driving temperatures higher than 140°C, but show COP higher than 1.0. The smallest available chiller of this type shows a capacity of approximately 170 kW. With respect to the high driving temperatures of double-effect absorption chillers, solar thermal heat from concentrating collector or wickless heat pipes collectors and climates with high fractions of direct irradiation are essential.

3.4. Thermal Storage

Thermal energy storage systems (TES) reduce the mismatch between energy supply by the sun and energy demand [18]. TES systems can be integrated to mitigate short fluctuations in solar insolation (buffering), improve dispatchability of a plant by displacement or extension of delivery period, and improve the plant annual capacity factor. In the present work, thermocline storage tank using thermal oil has been used for thermal energy storage. This choice is dedicated by low cost, ease of maintenance, direct coupling between the solar field and chiller and power blocks without using heat exchangers.

4. Plant Layout, Sequence of Operation, and Control Strategy

A schematic layout of the CSP plant proposed in this project is shown in Figure 1. The heat transfer fluid, Therminol 66, is pumped through the solar field (LFR or PTC) where it gets heated up to the nominal temperature of 140-160°C. The fluid is then sent to the storage system. The heat transfer fluid is pumped to the ORC and TDC using separate pump for each component. A three-way thermostatic mixing valve is installed at the inlet of ORC unit evaporator and the absorption chiller generator in order to control the hot fluid supply temperature to each of them. The power unit integrated in the solar power plant is a 4-8 kWe non-recuperative Rankine cycle using HFC-245fa as working fluid. The thermally driven chiller (TDC) is single stage with 35 kW cooling capacity and 48 kW heating capacity. Technical details and design data of the plant are reported in Table 1. A preliminary evaluation of plant cost based on market survey shows that the plant cost is about 350,000 €. This cost is composed of about 140,000 € for the solar field, 60,000 € for the ORC, 30,000 € for the chiller, and 120,000 € for piping, pumps, cooling towers, control, and other auxiliary equipment. Major reductions in plant cost are expected by wide applications of multi-generation plants and mass production of small scale equipment such as the ORC and absorption chiller.

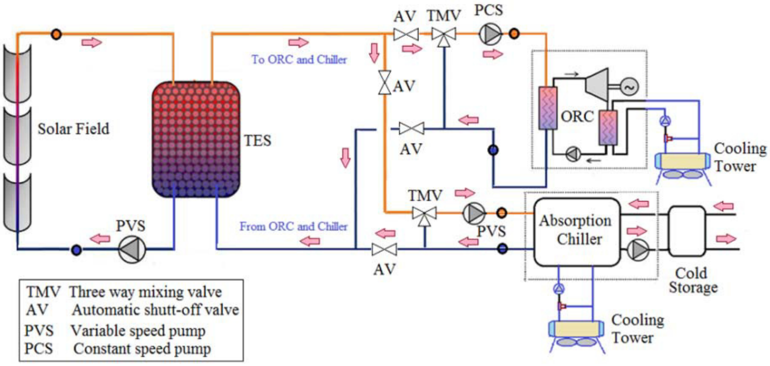

Figure 1: Schematic layout of the CSP multi-generation plant

Table 1: Technical data for the CSP plant components

Solar field			
Aperture area (m^2)	208 for PTC, 296 for LFR	Peak power (kW)	120
Heat transfer fluid	Therminol- 66	Outlet temperature (˚C)	160
Mass flow rate (kg/s)	Function of control strategy and minimum Reynolds number in collector receiver pipe		
ORC unit			
Electrical output (kW)		4-8	
Heat medium (therminol oil)	Heat input (kW)	53-95	
	Inlet temperature (ºC)	125-150	
	Outlet temperature (ºC)	115-130	
Cooling water	Heat rejection (kW)	45-85	
	Inlet temperature (ºC)	31	
	Outlet temperature (ºC)	35	
Absorption Chiller		Cooling mode	Heating mode
Capacity (kW)		35	48
Chilled/Hot Water	Inlet temperature (C)	12.5	47.4
	Outlet temperature (C)	7	55
	Flow (L/s)	1.52	
Heat Medium (therminol- 66)	Heat input (kW)	50	
	Inlet temperature (C)	88	
	Outlet temperature (C)	83	
Cooling Water	Heat rejection (kW)	85	

The plant operation is determined by the control facilities available in the ORC and TDC as provided by the manufacturers. The present article reports only on the operation of TDC and ORC at nominal design values. For the selected ORC unit, the nominal hot fluid supply temperature is 125 ˚C with heat input of 53 kW and electric power output of 4.3 kW. For the TDC, the nominal hot fluid supply temperature is 88 ˚C with heat input of 50 kW and cooling capacity of 35 kW. As illustrated in Figure 1, different independent control variables can be operated to regulate the power plant. The speed of the solar loop pump controls the HTF mass flow rate circulating in the solar collectors and the exit temperature from the solar field. Regulation of the ORC three way mixing valve controls the HTF temperature entering into the ORC evaporator and ultimately changes the mass flow rate of oil taken from the storage tank. The thermal power input to the chiller generator is controlled by adjusting the variable pump speed at generator inlet and inlet fluid temperature by using the three way mixing valve. Analysis of plant operation and control at partial load shall be presented in future work.

5. Thermodynamic analysis

5.1. Solar field

The solar field has been designed for one day at summer to produce 120 kW_{th} at the design conditions. Two alternatives for solar field have been investigated including PTC and LFR. The calculated variables to analyze the solar field performance are the incident direct solar power on the field (G), the outlet power of the solar field (Q_c) and the thermal efficiency of the solar collector field (η_c). A simple way to calculate the efficiency is to use equation (1) below and the parameters found on the data sheet of the collector.

$$\eta_c = \eta_o K_\theta K_E - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G} \tag{1}$$

Where η_o is the maximum collector efficiency or the optical efficiency, a_1 and a_2 are loss coefficients in W/K.m^2. K_E is the end effect correction facto. K_θ is the incidence angle modifier IAM=IAML(θ_i)*IAMT(θ_t) that is function of transversal (θ_t) and incidence (θ_i) angles. For a north-south mounted collector:

$$\theta_t = atan\{sin(\gamma_s)\, tan(\theta_z)\} \tag{2}$$

$$\theta_i = atan\{cos(\gamma_s)\, tan(\theta_z)\, cos(\theta_t)\} \tag{3}$$

Where γ_s the solar azimuth is angle (0 at south and +90 at west) and θ_z is the solar zenith angle. The collector performance parameters should be determined according to standard tests such as the European standard EN12975. T_m is the mean collector fluid temperature and T_a is the temperature of the ambient air. The direct solar radiation G on the collector surface is determined through an algorithm that includes date, time and location based on ASHRAE clear-sky model with a site clearness index of 0.92 [19]. The site average ambient temperature is taken as 30 □C in summer and 20 □C in winter. The outlet field power Q_c is calculated using the following expression:

$$Q_c = \dot{m}_{sf}\, c_p \left(T_{fi} - T_{fo}\right) = \eta_c\, G\, A \tag{4}$$

Where, $\dot{m}_{sf}$ is the mass flow rate in the solar collector and c_p is the oil specific heat. The inlet temperature of the field T_{fi} is determined by the thermal storage model. The outlet temperature of the field T_{fo} is calculated using the collector efficiency curve. G is the incident direct solar radiation (DNI), and A is the total collectors' surface area.

The parabolic trough collector investigated in the present study has the following characteristics: η_o=0.747, a1=0.64, a2=0.0. The performance characteristics of LFR collector investigated in the present study are as follows: η_o=0.5, a1=0.216, a2=0. The total length of LFR collector is given by$L_{tot} = n_{mod}\, L_{mod}$. Where n_{mod} and L_{mod} are the number of modules and length of a single module. The end effect correction factor K_E is calculated using:

$$K_E = \frac{L_{tot} - d_f tan(\theta_i)}{L_{tot}} \tag{5}$$

Where d_f is the vertical receiver-mirror distance. Values of the incidence angle modifier are shown in Table 3. The geometric data for the LFR collector are: d_f=3.564 m, number of mirrors nm=18, single mirror width d1=0.31 m. Anet=Ltotd1nm. The longitudinal and transversal incidence angle modifiers for LFR and PTC are taken as function of the incidence angles θ_i and θ_t as provided by manufacturers' datasheets. For PTC, the transversal incident angle modifier is equal to one and the end effect correction factor K_E=1.

5.2. Thermal Storage

The energy balance of the storage tank is written as:

$$M * c_P * \frac{dT_{st}}{dt} = \dot{m}_{sf} * c_P * \left(T_{fi} - T_{fo}\right) + \dot{m}_l * c_p * (T_{lo} - T_{li}) \tag{6}$$

Where, $\dot{m}_l$ is the mass flow rate extracted from the storage tank to the load including the chiller and ORC. T_{lo} and T_{li} are the oil return and supply temperatures to the load blocks. Equation (6) can be written as:

$$M * c_P * \frac{dT_{st}}{dt} = Q_c - (Q_{HEX-ORC} + Q_{HEX-TDC}) \quad (7)$$

The storage capacity of oil storage tank depends on the mass of oil in the tank and the temperature difference. In the present design, the tank is considered as fully charged when its temperature is uniform at T_{max} 160 C. The number of storage hours for the tank can be calculated using:

$$Storage\ hours = \frac{M_{st} c_p (T_{max} - T_{min})}{Q_{HEX-ORC} + Q_{HEX-TDC}} \quad (8)$$

As due different modes of operation of the plant, different minimum temperatures are required at nominal working conditions of the TDC and ORC. The minimum value of hot oil inlet temperature to the ORC is 125 C with heat input of $Q_{HEX-ORC}$ = 53 kW and to the TDC is 88 C with heat input of $Q_{HEX-TDC}$ = 50 kW. The storage oil mass of 3 tons used in the present project corresponds to 0.83 working hours of ORC unit, or 1.8 hours of TDC, or 0.83 hours for ORC followed by 0.92 hours of TDC. This design conditions shall be investigated by analysis of the plant operation in typical summer and winter days.

5.3. ORC Unit

Detailed thermodynamic model for the ORC includes heat and mass transfer models for the unit components including evaporator, turbine, pump, and condenser. In the present work the manufacturer performance data are used to estimate the heat consumption of the ORC unit and the gross electric power output. The gross electric power of the ORS unit W_{egross} is calculated using Eq. (9). Where $Q_{HEX-ORC}$ is the thermal power provided at the ORC unit evaporator from the storage tank. The value of η_{orc} is taken as 8.3% according to ORC manufacture data sheet, see Table 1.

$$W_{egross} = \eta_{orc}\, Q_{HEX-ORC} \quad (9)$$

5.4. Absorption Chiller

The cooling and heating capacity of the absorption chiller are calculated based on the manufacturer performance data. The coefficient of performance of the chiller in cooling (COP_c) and heating modes (COP_h) are given by Equations (10 and 11). Where QHEX-TDC is the thermal power provided at the TDC generator from the storage tank. Values of COP_c=0.7 and COP_h= 0.87 have been implemented in calculations according to manufacturer datasheet, see Table 1.

$$COP_c = Q_{Cooling} / Q_{HEX-TDC} \quad (10)$$

$$COP_h = Q_{heating} / Q_{HEX-TDC} \quad (11)$$

6. Results and Discussion

The plant model equations are solved using the commercial software “Engineering Equation Solver (EES)”. The climatic variables determine the solar field performance, which defines the temperature level of the thermal storage tank. The temperature level of the tank determines the performance of the ORC and TDC. Three days of summer (July 15th, 16th, 17th) and three days in winter (January 15th, 16th, 17th) are selected as representative days for plant performance analysis. The building calls for cooling in summer (chiller works in cooling mode) and heating in winter (chiller works in cooling mode). The ORC electric output is directly injected into the building local electric grid. Both the ORC and TDC are supplied by thermal power from the storage tank. The TDC and ORC are switched off when the oil temperature in the storage tank is lower than the required nominal input temperature, 88 C for the TDC and 125 C for the ORC.

The collector field temperature and mass flow rate control is accomplished by fixing an outlet temperature from the field and varying mass flow rate above a given minimum value. In another option, the temperature difference over the collector field (difference between outlet and inlet fluid temperatures) is fixed by varying the collector mass flow rate above a given minimum value that ensures turbulent flow in the receiver pipe.

6.1. Plant Operation in Summer

Figure 2 shows the variation of collector output power, ORC electric power output, and TDC cooling capacity with time for three days in July representative of summer operating conditions in plant location. For the summer time, the peak value of DNI is about 800 W/m^2. The power production by the field reaches a maximum of 109 kW at noon time. The power production of the field allows stable operation for the ORC for an average of 10 hrs/day and 12 hrs/day for the TDC. The efficiency of the solar field reached 65.7 % for almost all the day time except near to sunrise and sunset times as shown in Figure 3. The energy conversion overall efficiency for the TDC and ORC, $\eta_{overall}$ is the ratio of the sum electric power output of ORC and cooling capacity of TDC to the total thermal power input to ORC and TDC, reaches values of about 70% in the first and last hours of the day when the TDC is only working and remains constant at 38% for the middle of the day. Figure 4 shows that the collector field output temperature attains a high value of 171 °C. The mass flow rate in the collector field changes with time in order to keep a constant temperature difference of 20 °C between the inlet and outlet temperature of the field. The effect of changing the control of collector field to maintain a constant outlet temperature of 160 °C is also investigated. The difference in the number of operating hours of ORC and TDC as well as the collector efficiency is very small in comparison with the results shown in Figure 2.

6.2. Plant Operation in Winter

In contrast, for the winter time the peak DNI is about 600 W/m^2 and as a direct consequence, simultaneous operation of the ORC and TDC in the heating mode and nominal design conditions is found to be not feasible. Since the priority of the building in winter season is for electricity generation, the plant is modeled by switching-off the TDC and feeding all collector power to the ORC. Figure 5 shows the variation of collector output power and ORC electric power output with time for three days in January representative of winter conditions in plant location. The disturbance in storage tank temperature and consequent interruption in ORC operation in the middle of the day result from the decrease in DNI values at these times which is characteristic of solar radiation data in winter at the plant location. Also, as compared to summer season, the collector efficiency decreases to values between 31% and 48.5%. This is attributed as due to incidence angle modifier effect and low values of DNI. A part from these periods of disturbance, the ORC unit operates in stable conditions for about 8.5 hr/day.

6.3. Plant Operation Using LFR Collectors

The plant operation in summer has been analyzed using an LFR collector of the same peak power output at the design point as the TPC collector as explained in sections 3.1 and 5.1. Figure 6 shows that the peak output power of the collector field is about 116 kW at noon time. However, the rate of decrease of collector output power with time is higher as compared to PTC collector field. This is attributed due to the reduction in the efficiency of LFR collector due to the effect incidence angle modifiers. This decrease results in 4.5 and 8 working hours of the ORC and TDC, respectively as compared to 10 and 12 hr using PTC. Analysis of plant performance in winter using LFR collectors is shown in Figure 7. The ORC is only connected to the storage tank and the TDC is switched-off. It can be observed that the operation of ORC is largely interrupted with an effective operation hours of 3 hr corresponding to a reduction of about 60% as compared to PTC collector.

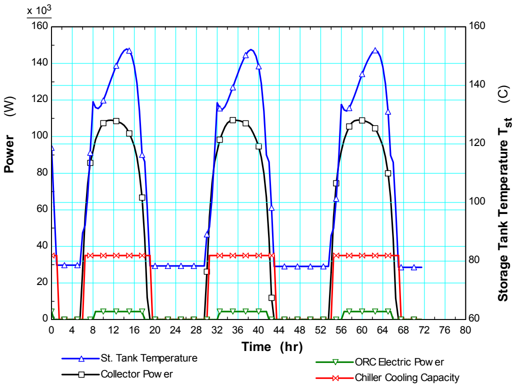

Figure 2: Variation of collector output power, ORC electric power output, and TDC cooling capacity with time for three days in July with constant 20 ^{0}C temperature difference over the PTC collector field

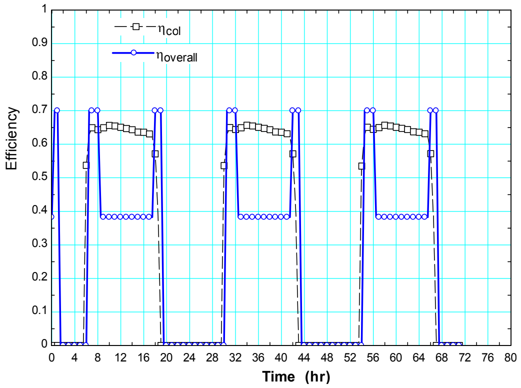

Figure 3: Variation of collector efficiency and plant overall efficiency with time for three days in July with constant 20 ^{0}C temperature difference over the PTC collector field

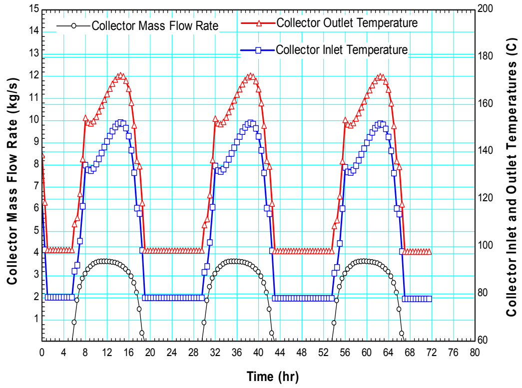

Figure 4: Variation of collector mass flow rate and inlet and outlet temperatures with time for three days in July with constant 20 □C temperature difference over the PTC collector field

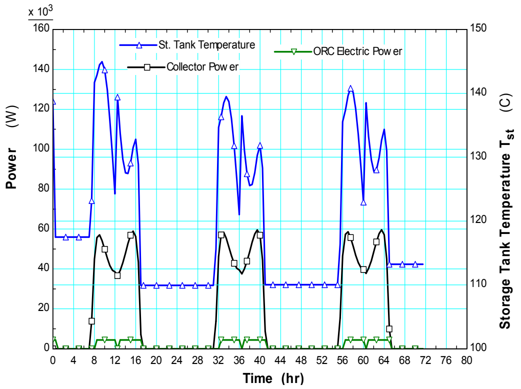

Figure 5: Variation of collector output power and ORC electric power output with time for three days in January with constant 20 □C temperature difference over the PTC collector field

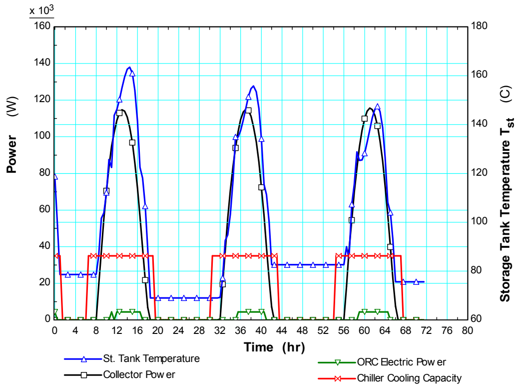

Figure 6: Variation of collector output power, ORC electric power output, and TDC cooling capacity with time for three days in July with constant 20 ^{0}C temperature difference over the LFR collector field

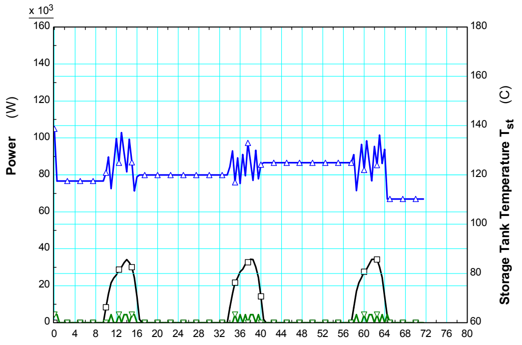

Figure 7: Variation of collector output power and ORC electric power output with time for three days in January with constant 20 ^{0}C temperature difference over the LFR collector field

6.4. Monthly Analysis of Plant Production

Analysis of plant cooling and electricity production is shown in Figure 8. Plant operation in combined electricity and cooling mode using PTC can produce about 13640 kWh of cooling and 1253 kWh of electricity per month in summer months of May, June, and July. In winter mode operation, generating electricity only, the plant produces a minimum of 923 kWh in February. Using, LFR collector field, the monthly production reduces to 9443 KWh of cooling and 791 kWh of electricity in summer months with minimum production of 264 kWh of electricity in January. The total annual production of cooling and electricity using PTC is 15233 kWh, 78696 kWh, respectively, as compared to 7605 kWh and 55611 kWh using LFR.

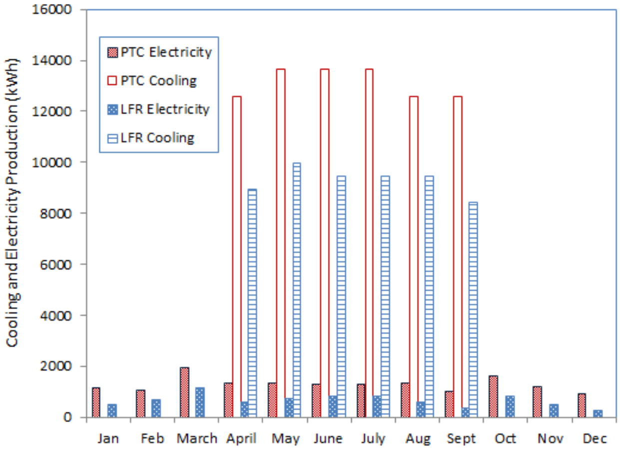

Figure 8: Monthly analysis of plant cooling and electricity production

7. Conclusion

This article reports on the conceptual design stage of small scale multi-generation solar plant for a medical center building in Egypt. Thermodynamic analysis of each component is performed and integrated in a whole plant model. Analysis of plant operation in typical days representing summer and winter seasons in plant site has been performed at nominal design conditions of plant components. The power output from the PTC solar field in summer allows for stable operation of the ORC and TDC for about 10 and 12 hours, respectively. Low power output of PTC solar collector field in winter allows for operation of ORC unit only. Stable operation of the ORC unit for about 8.5 hours/day can be achieved in winter. The results of winter simulation suggest the use of TDC with cooling mode only for summer season and recovering condenser heat of the ORC for heating purposes in winter. Collector field control that maintains a constant temperature difference over the field results in similar operation hours for the ORC and TDC as compared to maintaining a fixed collector filed outlet temperature.

The use of LFR solar collectors results in reduction in the operation hours of ORC by about 50% and TDC by about 30%. The amount of reduction in ORC working hours in winter reaches 60% as compared to PTC plant. This reduction should be compensated by an increase in the area and peak point design of LFR collectors as compared to PTC collectors. In general, the present analysis demonstrated the potential of using CSP multi-generation plants in the Mediterranean Basin. Further analysis of plant operation at partial load and off-design conditions can further improve the plant effectiveness using appropriate control system and operation strategy.

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