UTILIZATION OF CSP SYSTEM FOR TRI-GENERATION OF ELECTRICITY, DISTILLED WATER, AND COOLING/HEATING IN THE SOUTHERN PART OF JORDAN

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ABSTRACT

To increase the total output of CSP systems and to improve its financial feasibility a tri-generation solar system is built and tested in the southern part of Jordan. With only one solar matrix the heat generated was used to generate electricity, distilled water, and cooling in summer or heating in winter. The system is comprised of a parabolic trough solar matrix installed on the Roof of 6000 m^2 building with total aperture area of 240 m^2. The trough matrix heated thermal oil up to 260 C which is used to generate superheated steam at 13.7 bar, and 210C. The generated steam powers a 20 HP steam engine which drives a 15KWe DC generator. The steam exiting the engine at 120 C is then utilized to evaporate brackish water as it is condensed to complete the power cycle. The distillation process is then completed to generate distilled water at a peak rate of 150 liters/hr. The heat reject from the distillation process is then stored in thermally insolated hydraulic storage tank and used to heat the space in winter or to power an innovative two-stage air cooled adsorption chiller at a capacity of 20KW of cooling at 12C chilled water output and 35 C ambient. The data in the present paper present the detailed performance of all the components of the system on certain days in June 2012. The results shows that the system is technically feasible and has produced a peak of 128 KWth of thermal power, 10 KW of electricity, 20 KW of cooling, and a total of 1040 liters of distilled water. On Jun 30th 2012 the system saved 860 KWh of electricity and 440 Kg of CO_2.

1.INTRODUCTION

Despite the many advantages of CSP systems, including their insensitivity to solar intermittency and the lower cost of thermal energy storage, the utilization of CSP to generate electricity alone has become more expensive than electricity generation from low prices Crystalline PV cells. Nonetheless, thermal power generation from CSP systems still at lower cost than PV systems. Unfortunately, to generate electricity alone at efficiency of 35% most of the thermal energy generated by CSP collector is wasted. In fact the use of wet cooling tower to condense the steam in the power cycle makes CSP system less favorable for countries short in water like Jordan. On the other hand this wasted energy can be utilized in other useful applications such as water desalination and cooling or heating. In the present work an investigation of apilot plant using micro CSP system for Tri-Generation of electricity, water distillation, and cooling heating is presented.

Recently some theoretical investigations were conducted regarding Poly-Generation with CSP. Palenzuela et.al (1) conducted a study for the Middle East and North Africa (MENA) region. A thermo dynamic evaluation of different configurations for coupling parabolic-trough (PT) solar power plants and desalination facilities in a dry location was performed. It was found that for the simulated conditions, the integration of a LT-MED unit into a PT-CSP replacing the condenser of the exhaust steam of the turbine is more efficient thermodynamically than the coupling of the CSP plant with a RO desalination plant. Furthermore, Palenzuela et.al (2) performed a simulations for different configurations of associating MED and RO desalination units with CSP. In This model the thermodynamic cycle was investigated and needed solar field size to produce 14,400 m 3/day fresh water and 50 MWe power was calculated. They found that the integration of a TVC-MED plant into a CSP plant is more competitive than both plants independently. The coupling is more efficient thermodynamically than the decoupling

requiring smaller solar field for the same power and water production.
Ghobeity et. al. (3) developed a conceptual design, system-level models, and optimization of operation for a cogeneration solar-thermal plan system level model for dynamic simulation and optimization of a plant that utilizes solar energy for combined electricity generation and water production. They used the sequential method of optimization with IPOPT and SNOPT as the local solvers, with JACOBIAN as the simulator., They concluded that the optimal operating conditions strongly depends on the FiT and the price of fresh water, hence current energy policies in Cyprus, and most of Mediterranean region, do not reflect the fact that the water produced by RES should also be considered for incentives. Moreover, the results show that for a typical steam cycle design, under current electricity and water prices (i.e., no subsidy considered for electricity or water produced by RES), extracting steam at low extraction pressures yields the highest income.

A techno-economic analysis of different concepts for associating MED and RO desalination units with PT-CSP plants was presented for the Mediterranean region (4). In this work the coupling of a CSP plant with a LT-MED system which replaces the conventional cooling unit of the power cycle two alternatives have been compared. The configuration where the steam of the turbine is not left to expand completely but used as the input for the LT-MED plant, is more efficient than when thermal compression is considered to use the fully exhausted steam from the LP turbine fed into a steam ejector with higher pressure steam from the HP turbine. The most optimal CSP + MED coupling which has been compared with a CSP connected with a RO unit, where no modifications are made to the power cycle and a cooling system is required.

It has been shown that this system is more thermodynamically efficient, since the additional electrical consumption of the RO does not surpass the penalization in the power production due to replacing the condenser with a MED plant. They also concluded that the results provided will help design the most appropriate configuration according to the specific demands. However, they are dependent on the seawater properties, which affect the RO process strongly, and cannot be extrapolated to other regions where the seawater conditions (salinity and temperature) are not as optimal for the use of RO desa

A combined Rankine/Kalina cycle power block is proposed for CSP plants (5). The potential advantage of the new power block is illustrated by a detailed techno-economic analysis of two 50 MW parabolic trough power plants, comparing between the standard and the novel power block. The results indicate that the proposed plant suggests a 4–11% electricity cost saving.

On the other hand, an investigation for the potential of implementing combined electric power and seawater desalination plant using concentrated solar power technologies for Wilayat Duqum in Oman (6). GIS solar radiation tools are used to select the most appropriate site for the plant location. There are basically two different options to combine concentrated solar electric power with seawater desalination. The first option is to combine a CSP plant with a thermal desalination unit, exploiting the exhaust heat of the steam cycle to drive a thermal desalination unit. The second option is to exploit only the electricity output of the CSP plant with a reverse osmosis desalination unit. According to this investigation it was found if concentrating solar power (CSP) is used for energy supply. It was found that the amount of solar radiation in the Duqum region is very promising and if CSP is used it will help providing sufficient amount of both electricity and desalinated water. Based on GIS solar radiation calculation, geographical topology, and the master development plan of the Duqum region, the most appropriate site for the CSP plant is selected proximity to the coast in an industrial area.

Price (7) conducted an overview of a computer model that is being used by scientists and developers to evaluate the tradeoff between cost, performance, and economic parameters for parabolic trough solar power plant technologies. An example is included that shows how this model has been used for a thermal storage design optimization. The annual performance calculated by the model has been validated against actual operating data from the one of the existing SEGS plants.

On the other hand, Chen et al (8) investigated a fuzzy analytic hierarchy process associated with benefits, opportunities, costs and risks to help select a suitable solar-wind power generation project. The solar-wind power generation system has a very high power-generating potential because of the complementariness between solar and wind resources. Finally, from the theoretical modeling and empirical demonstration, a fuzzy AHP with BOCR model can effectively and precisely handle such a complicated problem and lead to an outstanding result.

In reference (9) the potential of concentrating solar power plant (CSPP) technology in Jordan is assessed and the next steps for development of the first CSPP in the country are presented. It was found in this study that allowing a moderate introduction of the CSPP into the existing energy supply structure, the following two items should be implemented in the near future, and should be executed in parallel in order to achieve best results for future energy supply by RE sources: Introduction of feed-in tariffs for RE based on RE law. Erection of ground-based measurement stations for collecting long-term direct solar irradiation and meteorological data.

Zhang et al (10) explored the tradeoffs between thermal storage capacity, cost, and other system parameters in order to examine possible evolutionary pathways for thermal concentrating solar power (CSP) technologies. A representation of CSP performance that is suitable for incorporation into economic modeling tools is developed, also combined existing data in order to estimate the global solar resource characteristics needed for analysis of CSP technologies. It was found that, as the fraction of electricity supplied by CSP technologies grows, the application of thermal CSP technologies might progress from current hybrid plants, to plants with a modest amount of thermal storage, and potentially even to plants with sufficient thermal storage to provide base load generation capacity.

The parabolic trough technologies has various effect in various fields (11) in terms of both performance at design conditions and annual energy production. It was considered a reference case reflecting state-of-the-art Nevada Solar One, which showed a design efficiency and annual average efficiency of 22.4% and 15.3%, respectively, in agreement with actual performance.

A work focused on innovation in CSP technologies over the last decade was recently presented by Barlev et al. (12). A multitude of advancements has been developed during this period, as the topic of concentrated solar power is becoming more mainstream. Improvements have been made in reflector and collector design and materials, heat absorption and transport, power production and thermal storage. Many applications that can be integrated with CSP regimes to conserve (and sometimes produce) electricity have been suggested and implemented, keeping in mind the environmental benefits granted by limited fossil fuel usage.

For a more generic fashion reference (13) presents a study carried out to make an overview of the parabolic-trough collectors that have been built and marketed during the past century. It also presents a survey of systems which could incorporate this type of concentrating solar system to supply thermal energy up to 400 C, especially steam power cycles for electricity generation, including examples of each application.

Most of the previously mentioned investigations were based on theoretical modeling of the Poly-Generation system based on the real life performance of an existing solar power plant. Up to the authors knowledge, there is no single CSP power plant that generate electricity, water distillation, and cooling/heating as a poly-generation CSP system. As such, the system investigated in this paper is considered as the first of its type the world in totality and uniqueness.

2. SYSTEM DESCRIPTION AND SET UP

To investigate the feasibility both technical and economical of a micro CSP utilization for Tri-Generation a research grant was provided by the Jordanian Scientific Research Fund to build and test a pilot at the roof of the Faculty of Engineering at Mu'tah University in the Southern Part of Jordan at 1000 m above sea level. The building is of 6000 m2 total area. The basic sketch of the system design is demonstrated in Fig. 1. A solar Matrix of 40 micro parabolic troughs each with 6 m^2 aperture area was mounted on the roof to heat thermal oil to temperatures around 250 C. The oil is then used to generate a super-heated steam via (HE1) at 210 C and 13.7 bar that powers a 20 HP steam engine at point (1) in Fig. 1. The steam outlet from the engine is around 120 C [Point (2)] which is sufficient to evaporate waste or brackish water while it condenses in (HE2) to complete the power cycle as demonstrated in Fig. 1 in points (3) and (4). The water vapor coming out from the brackish water at point (5) in Fig. 1 is flown into a heat exchanger (HE3) to be condensed and exit as distilled water for many uses. The heat rejected from the condensation process in in (HE3) is then stored in the form of hot water in a thermal storage tank at temperatures between 60-95C. This hot water is then used to heat the space in winter while in summer it is used to power an innovative air cooled two stage adsorption chiller patented by the author of this paper (References 14 and 15). This chiller system composes of two units each with 12 KW cooling capacity providing more than 20 KW of cooling at nominal conditions. Part of the Parabolic Trough system is shown in Fig. 2. The power plant including the steam engine, steam generator and water distiller are partially shown in Fig. 3. The fan coil units of the chiller for dry cooling is shown in Fig. 4. The system is engineered and constructed by Rayer Ltd. (www.rayer.co.uk) by choosing the most suitable components from all over the globe. The system is commissioned in March 2012 and the date is being analyzed since.

3. MEASUREMENTS AND ANALYSIS

This project has measurements to be taken over the year to study the outcome and feasibility of this system on annual bases. However, in this paper a detailed analysis for a single summer day (June 30^{th}, 2012) is presented awaiting the results and analysis of the entire year.

The measured DNI data are demonstrated for this day. The Global Horizontal Irradiance (GHI) is plotted on Fig. 5 along with the Direct Normal Irradiance (DNI) and the Diffuse Horizontal Irradiance (DHI). As it can be seen the maximum DNI reached a value of 898 W/m2 at 11:20 local time (nearly solar noon) while the GHI reached a value of 1042 W/m2. The total solar insolation at that day was 8.6 KWh, while the total energy from Direct beam was 9.5 KWh. This is a very high solar intensity as can be seen. The data in Fig. 5 is taken every 10 minutes automatically. The solar parabolic trough matrix was switched on starting 7:00 AM that day and data were taken starting 7:30 every 30 minutes manually. It should be mentioned that due to some defaults in the tracking system the tracking of the solar beam was adjusted manually every 2-3 hours to ensure perfect concentration of the solar beam on the heat transfer pipe. The thermal oil temperature output from the solar matrix was between 235 C- 260 C. By measuring temperature difference between the thermal oil input to the solar matrix and output from it the thermal power outcome from the solar matrix as absorbed by the heat transfer fluid is calculated and demonstrated in Fig. 6. As it can be seen the thermal power output reached 125 KWth. It should be noted, however, that such number is based on a flow rate of 16 GPM which is the nominal flow rate of the pump since the flow meter was also faulty.

The thermal oil then generates steam via the non-burring oil steam generator at temperature of 210-220 C and pressure between 12-13.7 bar. That steam powers the steam engine and the mechanical output of this engine is measured and plotted also in Fig. 6. Both the RPM and torque on the shaft of the steam engine is measured and the peak Mechanical power (which should be very near to the electrical power) reached 10 KW as shown in Fig. 6. The total electricity generation was 136 KWh for the total operation time on that day.

As explained in the experimental set-up section, the steam coming out from the steam engine is then condensed to complete the power plant cycle. This steam condenses and a special heat exchanger where the heat rejected from it is used to evaporate waste water. The vapor coming out from this process is then condensed to produce distilled water as another outcome. The heat rejected from the distillation process is used to power the adsorption chiller prescribed earlier. By the end of the day the total water distilled was 1040 liters.

Consequently, the heat rejected from the distillation project is stored in a tank to power a novel air-cooled two stage adsorption chiller. A detailed temperature variation with time in one of the chillers demonstrating the inlet and outlet temperatures for the chilled water, hot water, and cooling water is shown in Fig. 7. The data shown in Fig. 7 was taken on Jun 5^{th} 2012 for one hour around solar not with zero load from one of the two 12KW ADC2 Chillers. As shown the chilled water temperature reached to 3 C, the cooling temperature from the fan coil around 30 C, and the hot water temperature varied between 70-85 C. The total cooling load from the two chillers on Jun 30^{th} 2012 is shown in Fig. 8 at the same conditions described for figures 5-7 where the capacity reached 20 KW peak. The total cooling supplied was 229 KWh for the total operation time on that day.

In conclusion it is clear that the utilization of CSP for Tri-generation is feasible both technically and financially. The total electricity consumption needed to generate the entire three outcomes of the Tri-Generation system would be 650 KWh for water distillation by evaporation and condensation, 136 KWh for electricity generation, 76 KWh for cooling assuming the COP of refrigeration machine is 3. As such, on Jun 30^{th} 2012 the Tri-Gen System saved 860 KWh of electricity and 440 Kg CO_2. The data for one year is being taken and a full feasibility of this system will be presented in a coming work. For comparison purpose a 240 m^2 PV system with 17% efficiency at 8.6 KWh/m^2/day solar insolation would provide no more than 351 KWh of electricity and save 180 Kg of CO_2.

4. ACKNOWLEDGEMENT

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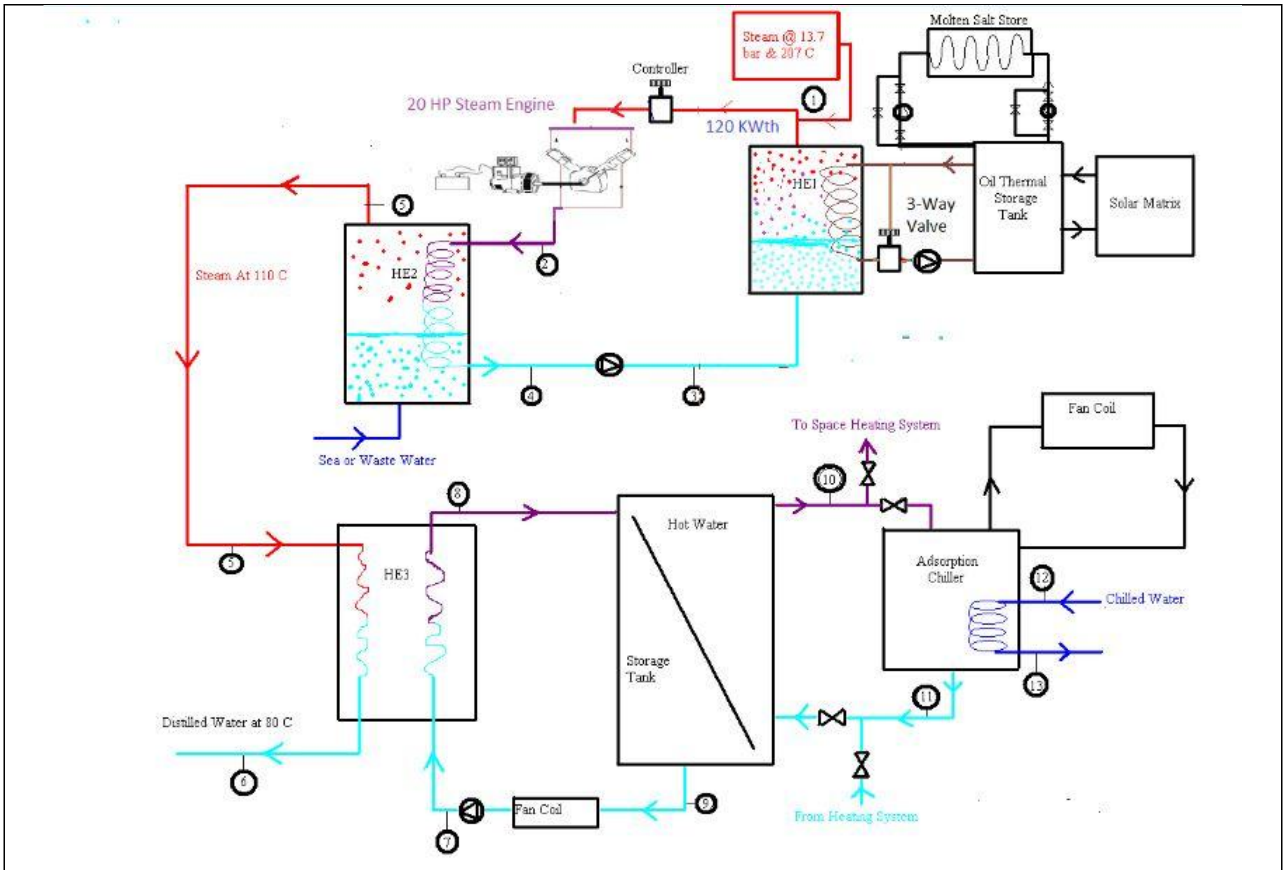

Fig. 1: Schematic diagram describing the Tri-Generation System

Fig. 2: Part of the Parabolic Trough solar collectors in the system.

Fig. 3: Power plant room

Fig. 4: Dry cooler for the Chiller

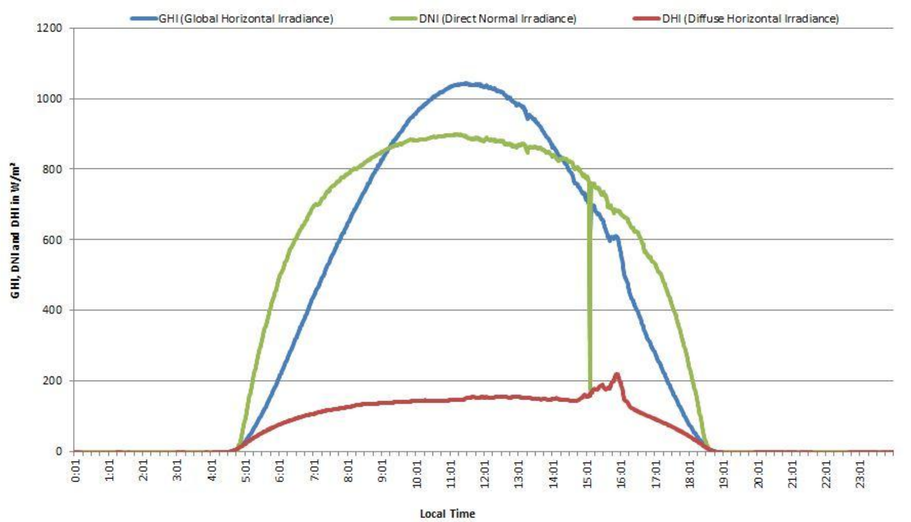

Fig. 5: Variation of DNI, GHI, and DHI with time on June 30, 2012.

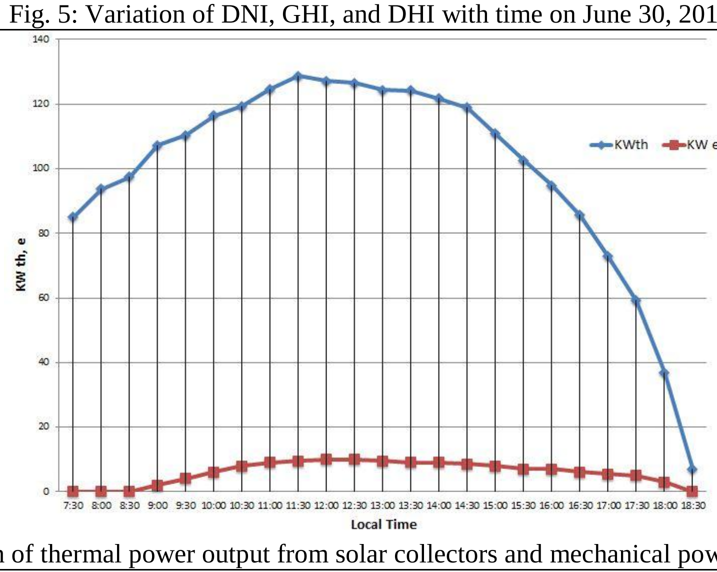

Fig. 6: Variation of thermal power output from solar collectors and mechanical power from the engine

Fig. 7: Variation of chilled water temperature, hot water temperature and cooling temperature with time on Jun 5, 2012

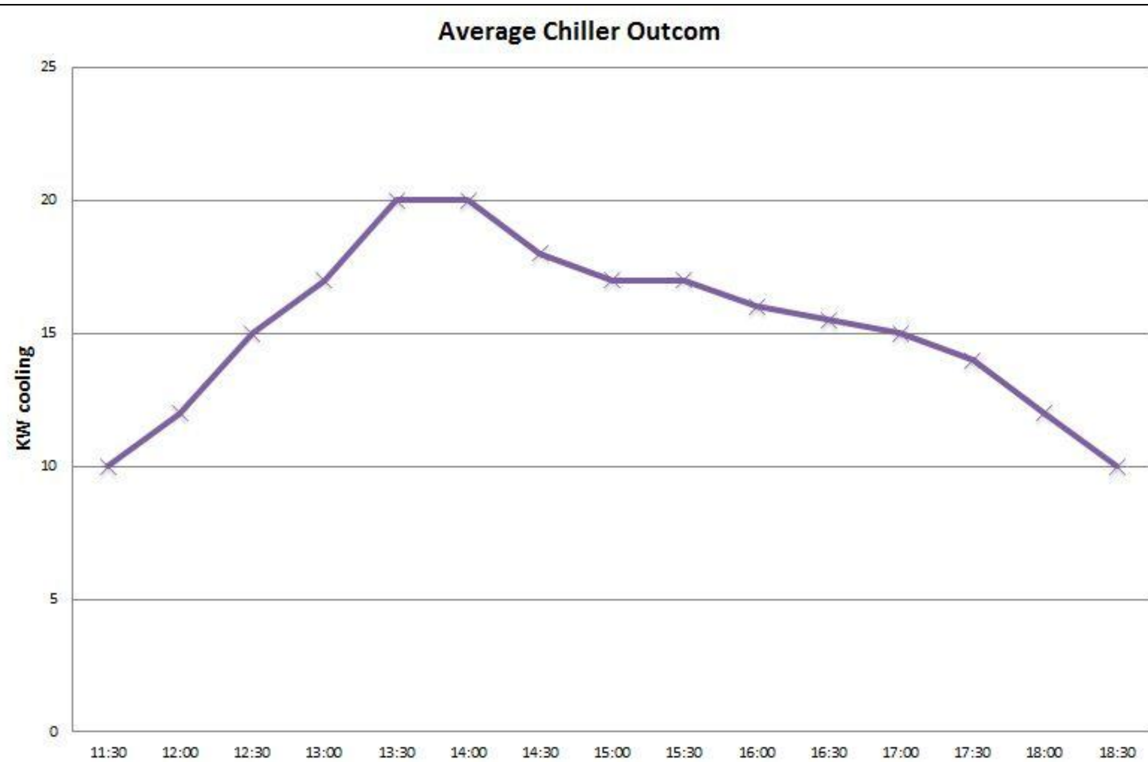

Fig. 8: Variation of mean average chiller output with time on June 30, 2012