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Techno-Economic Analysis of a Concentrated Solar Polygeneration Plant in Jordan

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Abstract

A polygeneration concentrated solar plant is designed and analyzed to investigate its techno-economic performance, and to investigate the different components that can be effectively combined in zero or positive energy districts, both in built and rural environments. The design was based on the results of an energy audit performed on the site which showed the prevalence of the summer cooling demand. The design is characterized by using Parabolic Trough Collectors as solar collecting technology installed on the roof of a building. The installation constraints, such as the size and the orientation of the available space, have driven the design of the plants and the selection of the possible storage and conversion technologies. The design includes a steam circuit that feeds a steam turbine manufactured at a very small scale, solar driven absorption chiller, direct heating system and water distillation unit. Conclusions are drawn and documented about the potential impact of solar polygeneration in the Mediterranean solar belt and the future development of the involved technologies. Results showed that the polygeneration plant has a Utilization Factor of 0.66, while, the economics of such technology needs improvement as indicated by the Benefit-Cost-Ratio (BCR) of 0.62 due to the high cost of the small-scale components of this technology.

Keywords: *CSP, Polygeneration, Energy Audit, Renewable Energy.*

1. Introduction

In the framework of the STS-Med Project, an EU-funded project by European Commission under the ENPI CBCMED program, four solar polygenerative plants have been designed to be connected with public buildings in four different Mediterranean countries, respectively Italy, Cyprus, Egypt, and Jordan. All the plants are characterized by an innovative application of concentrating solar collectors with the aim to generate a balanced answer to the energy demanded by the buildings: electricity, heat and cold, as well as other energy-driven services like the supply of purified water.

Energy demand for cooling and heating requirements has increased significantly over the last years. Global space cooling energy consumption increased by 60% in the period between 2000 and 2010 reaching 4% of global consumption in 2010 [1]. On the other hand, heat consumption accounts for more than 50% of the global consumption [2].Therefore, alternative heating and cooling systems derived from renewable or recovered energy have driven the interest of many researchers worldwide. The generation of electricity using renewable energy technology may cause problems to the electricity grid [3], thus, thinking of generating essential energy demand is a solution that avoids the pressuring use of national electricity grid.

Many researchers [4-8] have carried out experimental and theoretical studies of using CS technology for Solar Heating Cooling (SHC) systems and/or power generation. Sakhriehaet al. [9], for example, carried out modeling investigation for the hybridization of CS technology with geothermal energy to produce electricity using organic Rankine cycle. For this paper, the work of [9] and [11] is of interest. They used the concentrated energy for polygeneration. Absorption heating and cooling systems were studied more than any other systems. These systems have many advantages over other refrigeration systems [11]: such as quiet operation, high reliability, long service life, meeting the variable load efficiently, minimum mechanical moving parts, no lubricants needed, and no atmosphere-damaging refrigerants .There are not many tools available for accurate dimensioning and evaluating the solar thermal contribution to the total energy requirements. The dynamic simulation tool is used by

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many researchers [12-14]. Fong et al. [15] made a theoretical, comparative study of five different solar cooling systems; Solar electrical compression, solar mechanical, solar absorption, solar adsorption and solid desiccant cooling system. The results show that solar electrical compression alongside solar absorption system has the best performance results. Moreover, the advantages of two-stage systems over other systems are investigated by [17]. They concluded that the cooling system could work steadily in spite of unsteady solar input, lower generator input, and outlet temperature. However, they demand higher temperature heat.

The primary goal of using poly-generation systems is to maximize the utilization of the collected solar energy to the maximum possible extent. However, there are several challenges facing this approach: those challenges are mainly economical; first of all, the cost of the components of the systems are still high. Second, no available commercial technology for some components of the system, and the third challenge is to match the building load with the system output especially in winter and night which needs special treatment. The concept of storage using the innovative solution presented by [17] is applied.

In this paper, the case of designing and simulating a small scale poly-generation system to match the load for a building in Italy is presented. The techno-economic performance indicators are presented.

2. Analysis

To assess the impact of CS power plant from technical and economic points of view, we need to define technical and economic indicators. The concept of utilization factor is used to assess the technical performance of this poly-generation plant. Since the main idea of the multi-generation is to maximize the utilization of the incident solar energy on the solar field, it will be convenient to use the utilization factor which basically measures the amount of converted useful energy relative to the available energy from the source. It is defined as the ratio of the useful annual energy (thermal and electrical) produced by the system to the total annual incident energy on the system. The useful energy includes the energy produced for heating, cooling, water desalination, and electricity generation. That is

$$\varepsilon = \frac{Useful\ Energy\ Collected\ per\ year}{Annual\ incident\ solar\ irradiation\ on\ the\ solar\ field} \quad (1)$$

$$\varepsilon = \frac{E_h + E_c + E_{ele} + E_w}{\overline{DNI}\ x\ A} \quad (2)$$

where, DNI is the annual average direct normal solar irradiation in kWh/m^2/year incident at the location. The energy used for water desalination is calculated as

$$E_w = M * \left(h_{fg} + cp\ \Delta T\right) / 3600 \quad (3)$$

where, M is the total mass of water desalinated per year (kg/year), h_{fg} (2200 kJ/kg) is the specific enthalpy for vaporization of water at ambient conditions, and ΔT=(100-20)=80 °C.

The energy output of the heating system, E_h, is calculated as

$$E_h = \sum_{i=1}^{N} \dot{m}\, c_p (T_i - T_o) \quad (4)$$

where, N is the number of hours in the year when the heating system is operating. m is the average hourly flow rate of the fluid conveying heat to space in (kg/s) and T_i is the hourly average of the temperature of the fluid entering the heating coil and T_o is the hourly average temperature of the fluid leaving the heating coil.

The energy output of the cooling system, E_c, is calculated as

$$E_c = \sum_{i=1}^{NN} \dot{m}\, c_p (T_{co} - T_{ci}) \quad (5)$$

where, NN is the number of hours in the year when the cooling system is operating.$\dot{m}$, is the average hourly flow rate of the fluid conveying heat to space (kg/s), and T_{ci} is the hourly average of the temperature of the fluid entering the cooling coil and T_{co} is the hourly average temperature of the fluid leaving the cooling coil. The total annual energy from the electricity generation system is E_{ele} in kWh.

The variation of the types of energy harvested from the CS poly-generation systems makes the benefit-cost ratio (BCR) as a comprehensive and straightforward indicator. Benefit-cost ratio is the ratio of the accumulated present value of all the benefits to the accumulated present value of all costs, including the initial investment. The BCR is expressed as:

$$BCR = \frac{B_A \left[\frac{(1+I)^n - 1}{I(1+I)^n} \right]}{C_I \left[1 + m \left(\frac{(1+I)^n - 1}{I(1+I)^n} \right) \right]} \quad (6)$$

where,B_A is the sum of the annual benefits of the system (in Euro), I the real rate of discount, n is the lifetime of the system, C_I is the initial investment of the system, and m is the cost of annual O&M as a percentage of the initial system cost. Now, if BCR is higher than one, then the project is asuccess.

3. CS Plant Description

The plant under consideration is as shown in Fig.1. It is merelya parabolic trough for space heating, cooling, water distillation, and power generation. The solar thermal system loop consists mainly of the: concentrated solar collector of type linear parabolic trough Soltigua concentrating Solutions. The collector model is aPTMx-36 model (net collecting Area = 164 m2) of a nominal capacity of 100 kWth. The Heat Transfer Fluid is the thermal oil“Seriola Eta”by TOTAL. The nominal temperature of the oil at receiver inlet is 200 C, and at receiver outlet is 240 C. The collected heat from the solar field is extracted from the thermal oil in a counter flow heat exchanger and delivered to fan coil units to provide heating to the designated space in winter. While in summer, the extracted heat from the solar field through the thermal oil is used to drive an absorption chiller of 17.2 kW.

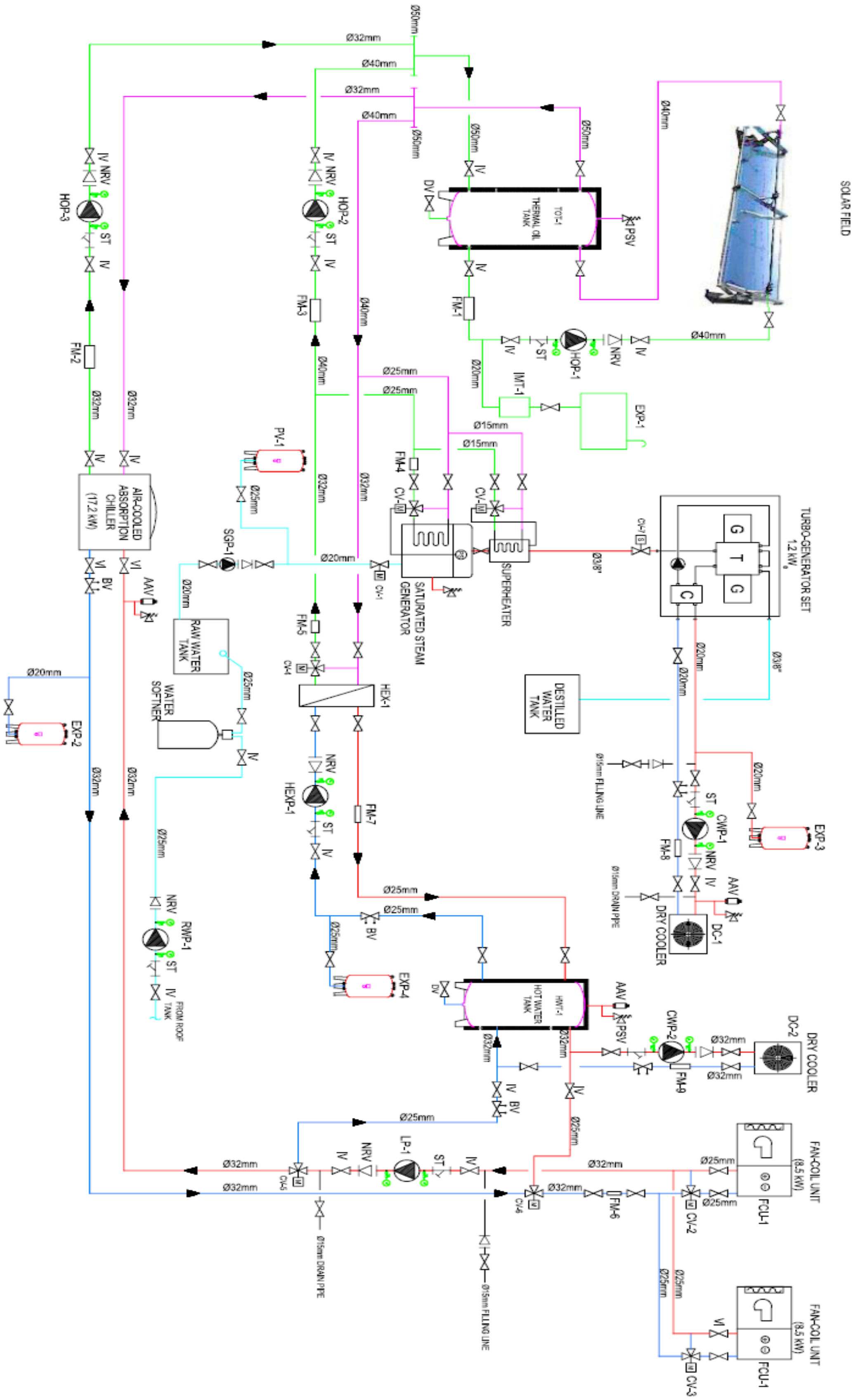

Figure 1: System Layout of the CS Polygeneration Plant in Jordan

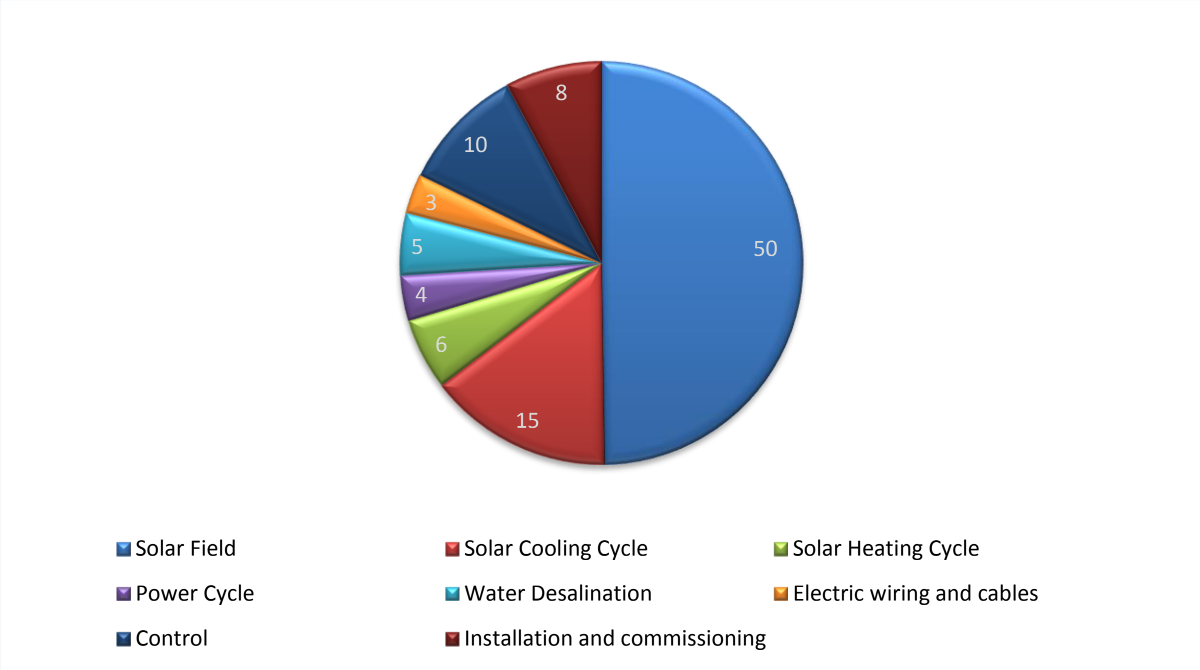

Figure 2: Percentage of cost for the CS-Polygeneration system in Jordan's pilot project

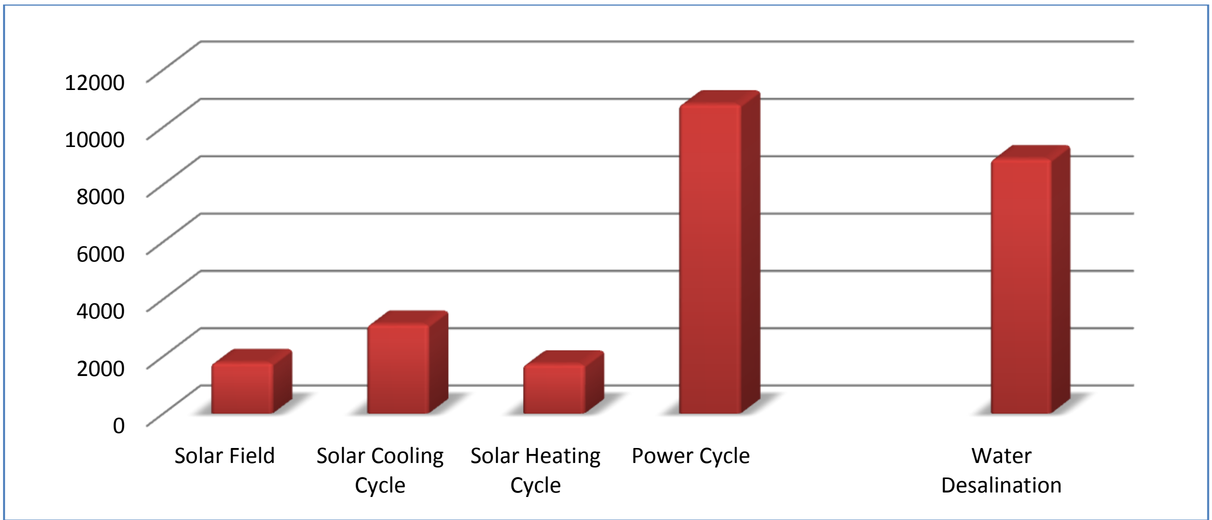

Figure 3. Normalized Cost (€ per Unit Output) for system components in Jordan's project

The chiller is Robur with inlet oil temperature at 240°C, and outlet temperature at 190 °C. It is a single effect Ammonia absorption chiller with COP of 0.5. Part of the hot thermal oil is extracted to generate steam at 200 °C, 5.2 bar through a locally made steam generator. The generated steam is fed to a small steam Turbine of 1.2 kW nominal power output. The condensate of the steam leaving the turbine is used as adistillate at a rate of 18 kg/hr.

The cost of subsystems is evaluated and analyzed. Table 1 shows the summary of the cost based on subsystems/components classified according to the nature of the energy outputs from the system.

Table 1: Breakdown of the cost of the pilot project in Jordan

Sub System/ Component	Size	Unit	Cost in€ per unit size	% Share
Solar Field	100	kWth	1778	50
Solar Cooling Cycle	17	kW	3120	15
Solar Heating Cycle	12	kW	1726	6
Power Cycle	5	kWe	6148	9
Electric wiring and cables	100	kWth	114	3
Control	100	kWth	358	10
Installation and commissioning*	100	kWth	278	8

*Estimated values

Figure 2 shows the pie chart of the distribution of the percentage of system cost. It is clear from this figure and the above table that the solar field cost 50% of the project, while, the heating system cost is about 6%. It is worth mentioning that most of heating system cost goes to the fan coil units. These unit were not available in the space. Moreover, the unit cost of the solar cooling system per kW is high compared to other components. Its cost is almost 6 times higher than conventional cooling systems such as vapor compression AC units. In spite of this, the cost of the solar chiller and the dry cooler compromise the main components of the solar cooling system, as shown in Fig. (3),in which their cost share is 15 %, as shown in Table 2, and they cost 3120 Euro/kW.Of particular interest in Fig. 3 is the cost of the energy block to produce electricity. The use of steam engine or steam turbine at small scale is unconventional in the market. This made the unit cost is very high. Figure 3 shows the normalized cost of power machine is 6148 Euro per kW. This causes a constraint to the required size of the power production unit in the polygenerative system.

4. System Output

The performance of the system and its components are simulated using TRNSYS where the weather data for the site is (Irbid, Jordan).The model equations for each component or subsystem were taken from manufacturers. The results are listed in Table 3. The output data in this table is calculated using the Eqns. (3-5) and assuming the COP of conventional A/C is 3. The real discount rate of 5%, and the annual operation and maintenance cost 2% of the initial cost. The lifetime of the system is assumed to be 20 years. The cost of electricity is sold to the facility at 0.25 euro/kWh (large consumer Tariff). The results of the simulation indicated the outputs as listed in Table 3 below.

Table 3: Energy and benefits extracted from the system in one year

Sub System	Quantity output/year	Unit	Annual Output kWh_{th}	Annual Benefit (€/year)
Cooling	2618	kWh_{th}	2618	655
Heating	12240	kWh_{th}	12240	3060
Distilled water	360	m^3	220500	18000
Electricity	1825	kWh_{elec}	1825	456
		Total	**237183**	**22171**

Based on the data given in the above table and applying Eqns. (1) and (6) respectively, it is found that the utilization factor is ε= 0.66 and the Benefit Cost Ratio (BCR)= 0.62.

Figure 4 shows that the income drawn from selling distilled water contributes about 80% to the total Benefits of the system.

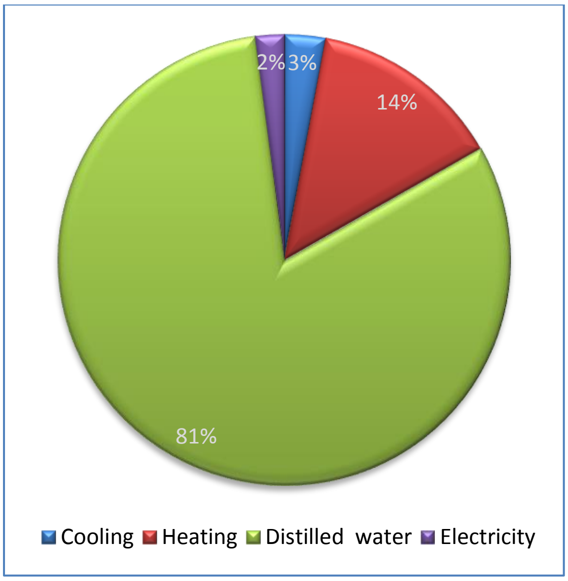

Figure 4: Percentage share of system benefits for Jordan's Pilot Project

5. Conclusion

The STS-Med Jordan pilot project was designed to demonstrate the ability to utilize solar poly-generation systems using CS technology. The project will also serve as a living laboratory to students at the college. On the other hand, the results indicated that the proposed plant would provide the heating and cooling load for the auditorium at the building. The system will cover part of the electric load. It will also provide a considerable amount of distilled water.

The results show that 66% of the incident solar energy at the solar field will be converted into different forms of useful energy. However, the cost-benefit ratio is lower than one. The percentage of the cost of the solar field reaches 50% of the total cost of the plant. Thus, to make such system economically feasible in the future, the cost of the solar field must be reduced at least by 25%. This should be an interesting perspective for the development of polygenerative solar fields in the Mediterranean area. Furthermore, it is found that 81% of the benefits of the studied plant come from water distillation. This is also an interesting future perspective of such plants.

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