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

S. Kiwan[1], R. Damseh[2], L. Venezia[3], F. M. Montagnino[3], F. Paredes[3]

[1] *Jordan University of Science and Technology, Irbid, Jordan,* E-mail: kiwan@just.edu.jo

[2] *Albalqa Applied University, Al Huson College, Irbid, Jordan*

[3] *Consorzio Arca, Palermo 90128, Italy,* E-mail: fmontagnino@consorzioarca.it

ABSTRACT

In the framework of the STS-Med Project funded 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. One of the project goals is to investigate the different components that can be effectively combined in zero or positive energy districts, both in built and rural environments. In part A of this work, the designs of the Italian plant is presented while in this the Jordanian plant is presented. Each design is characterized by different collecting technologies, respectively Linear Fresnel and Parabolic Trough, a distinct context of installation of the solar field, on ground and on roof, and a polygeneration balance which has been tuned accordingly with the specificity of the two sites. Both designs were based on the results of the energy audits performed on both sites. They showed the prevalence of the summer cooling demand. The installation constraints, 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. In the Italian plant, an innovative LFC solar field has been introduced, as well as a thermal energy storage unit that is downscaling the molten salts large TES units, typically applied in utility scale CSP plants. The Jordanian designers have introduced a steam circuit that feed a steam turbine manufactured at a very small scale. 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 Italian CS plant has a Utilization Factor of 0.7 and the Jordanian Plant 0.62.

1. INTRODUCTION

Energy demand for cooling and heating requirements has increased significantly during 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 driven by renewable or recovered energy have driven the interest of many researchers. Many researchers [3-6] have carried out experimental and theoretical studies of Solar Heating Cooling (SHC) systems. Of interest the work of [6] and [7] whom 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 [8] :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 many researchers [9-11]. Fong.et al. [12] made a theoretical comparative study between 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 have the better performance results. Moreover, the advantages of two-stage systems over other systems are investigated by [13]. They concluded that the cooling system can work steadily in spite of unsteady solar input, lower generator input and outlet temperature, however, they demand higher temperature heat.

The main goal behind 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: (1) economical in which the cost of the components of the systems are still high partly because (2) 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 [14] 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 a 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 annual useful 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

$$\varepsilon = \frac{Usuful\ Energy\ Collected\ per\ year}{Annual\ Incident\ Solar\ Irradiation\ on\ the\ solar\ field} \qquad (1)$$

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

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

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

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

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

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

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 the 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

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

Where NN is the number of hours in the year when the cooling system is operating. m is the average hourly flow rate of the fluid conveying heat to the 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 simple and comprehensive 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:

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

Where B_A is 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 percentage of the initial system cost. Now, if BCR is greater than one, then the project is success.

3. CS PLANT DESCRIPTION

The Jordan plant, as shown in Fig.1, is simply a 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 PTMx-36 model (net collecting Area = 164 m2) of total nominal capacity of 100 kWth. The Heat Transfer Fluid is 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.

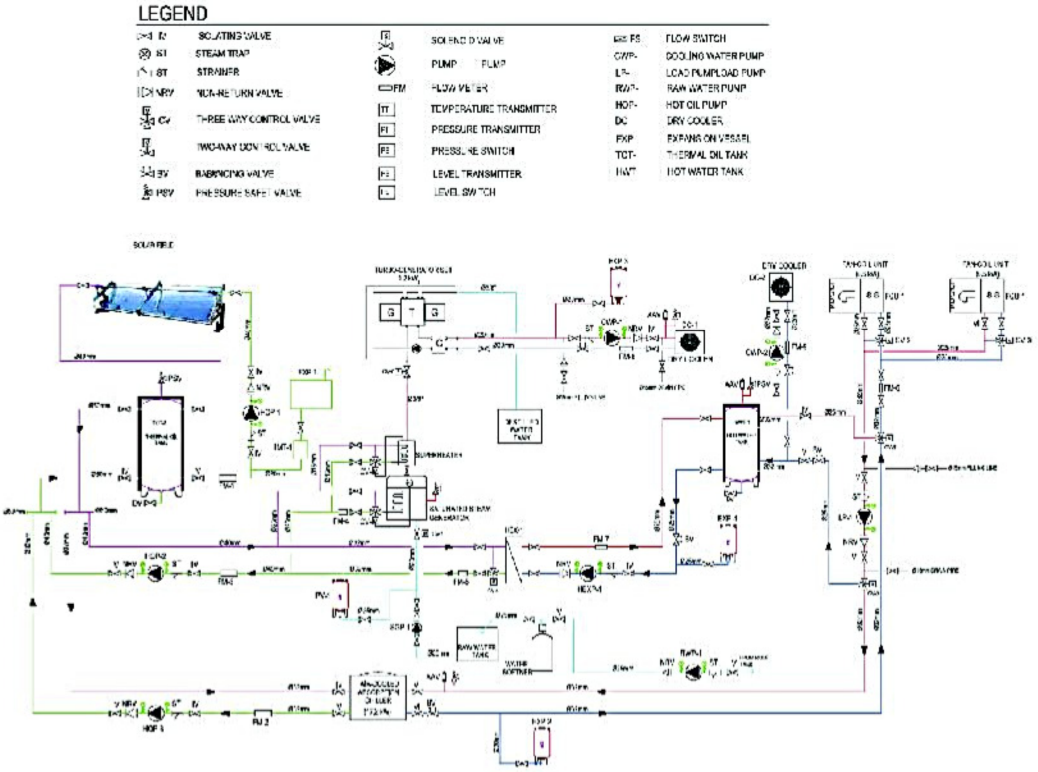

Fig. 1. System Layout of the CS Polygeneration Plant in Jordan

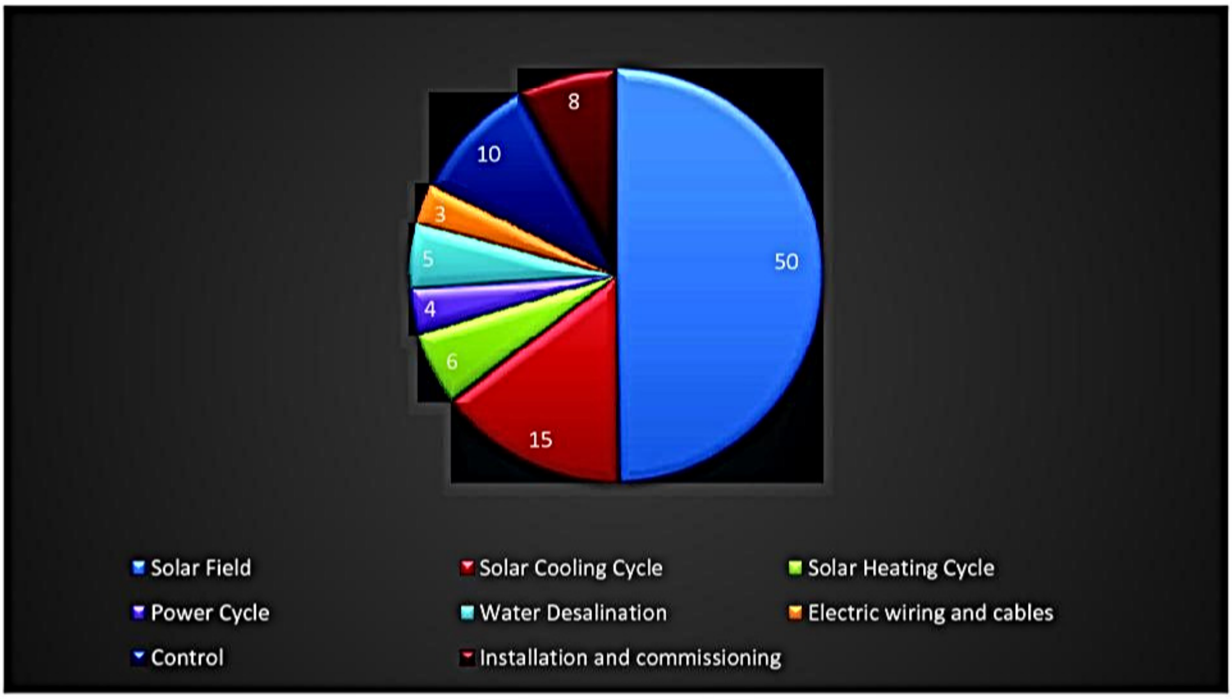

Fig. 2. Percentage of cost for the CS-Polygeneration system in Jordan's pilot project

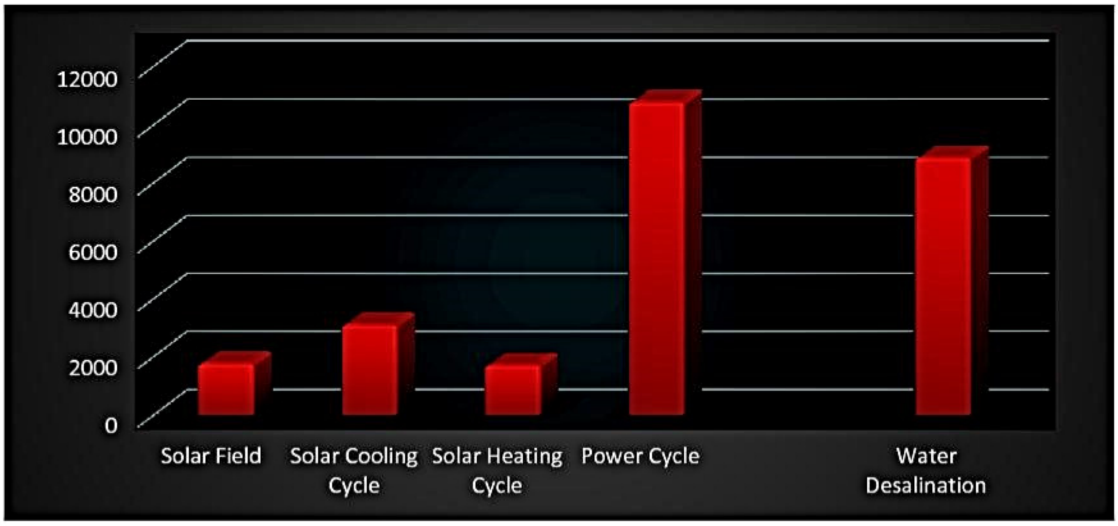

Fig. 3. Normalized Cost (€ per Unit Output) for system components in Jordan's project

The chiller is Robur with inlet oil temperature at 240C, outlet 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 local 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 distillate at a rate of 18 kg/hr.

The cost of subsystems is evaluated and analysed. 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 costs about 6%. It is worth mentioning most of heating system cost goes to the fan coil units. These unit were not available in the space.

Figure 3 shows the normalized cost of subsystems and components deeded to produce certain type of energy. For example, the cost of the solar chiller and the dry cooler compromise the main components for the solar cooling system. Their cost share is 15 %, as shown in Table 2, and their cost 3120 Euro/kW.

4. SYSTEM OUTPUT

The system is simulated using TRNSYS where the weather data for the site (Irbid, Jordan) was input to the simulation software in addition to the performance characteristics of each component in the system. The results of the simulation indicated the outputs are listed in Table 2.

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**

The data in the above 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 cos 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). Based on the data given in the above table and applying Eqns (1) and (6) respectively, we obtain

The utilization factor is ε= 0.66 and the Benefit Cost Ratio (BCR)= 0.62.

Figure 3 shows that the income drawn from selling distilled water contributes about 80% to the total Benefits of the system.

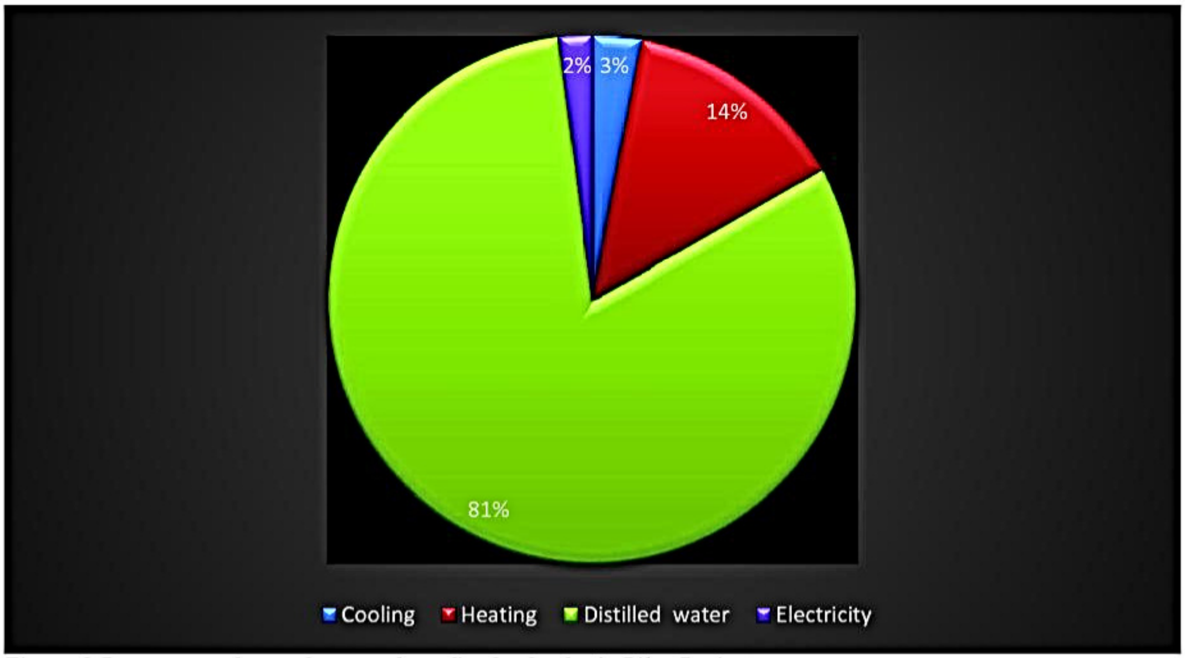

Figure 3 Percentage share of system benefits for Jordan's Pilot Project

5. CONCLUSION

The STS-Med Jordan pilot project was designed to demonstrate the ability of utilizing solar poly-generation systems using CS technology. The project will also serve as life laboratory to the students at the college.

The results indicated that the proposed plant will 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. This should be an interesting perspective for the development of polygenerative solar fields in the Mediterranean area.

6. ACKNOWLEDGMENT

The authors would like to acknowledge the European Commission: ENPI CBCMED program for supporting the project STS-Med under which this work has been conducted.

7. REFERENCES

[1] Report, "Transition to Sustainable Buildings: Strategies and Opportunities to 2050," OECD/IEA, Paris, 2013.

[2] Report "Heating without Global Warming: Market Developments and Policy Considerations for Renewable Heat," OECD/IEA, Paris, 2014.

[3] Kim.D.S, Infante Ferreira.C.A, "Solar refrigeration options – a state-of-the-art review," international journal of refrigeration, vol. 3 I, pp. 3-15, 2008.

[4] Henning.H.M, "Solar assisted air conditioning of buildings – an overview," Applied Thermal Engineering, vol. 27, pp. 1734–1749, 2007.

[5] Saman, W, Krause, M, Vajen, K,, "Solar Cooling Technologies: Current Status and Recent Developments," in Proceedings of 42nd ANZSES Conference Solar, Perth,Australia , 2004.

[6] Neuhäeuser, A, Polygeneration using concentrating solar thermal power, Acts of SolarPACES2009

[7] S. Vasta, A. Frazzica, A. Freni, L. Venezia, A. Buscemi, F. Paredes, F. M. Montagnino, A concentrating – based solar cooling system for agri-food industry, Acts of 5th International Conference Solar Air-Conditioning, Germany, 2013

[8] Freeman.T. L, Mitchell. J. W and Audit.T. E, "Performance of Combined Solar Heat Pump Systems," Solar Energy, vol. 22, no. 2, pp. 125-135, 1979.
[9] Quirante.M and Valenzuela.L, "Dimensioning a small-sized PTC solar field for heating and cooling of a hotel in Almería (Spain)," Energy Procedia, vol. 30, pp. 967 – 973, 2012
[10] Calise.F, Palombo.A, Vanoli.L, "Maximization of primary energy savings of solar heating and cooling systems by transient simulations and computer design of experiments," Applied Energy, vol. 87, p. 524–540, 2010.
[11] Mazloumi.M, Naghashzadegan.M and Javaherdeh.K, "Simulation of solar lithium bromide–water absorption cooling system with parabolic trough collector," Energy Conversion and Management, vol. 49, pp. 2820–2832, 2008
[12] Fong K.F, Chow T.T, Lee C.K, Lin Z, Chan L.S., "Comparative study of different solar Cooling systems for buildings in subtropical city," Solar Energy, vol. 84, pp. 227–244, 2010.
[13] Mittal V, Kasana K.S, Thakur N.S, "The study of solar absorption air-conditioning systems," Journal of Energy in Southern Africa, vol. 16(4), 2005.
[14] W. Gaggioli, F. Fabrizi, F. Fontana, P. Tarquini, L. Rinaldi, An innovative concept of a Thermal Energy Storage system based on the single tank configuration using stratifying Molten Salts as both HSM and HTF and with an integrated Steam Generator". Acts of SolarPACES2013 conference