Solar energy for combined production of electricity and industrial process heat

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Abstract

Industrial process heat represents a large part of energetic demand in industries. A parabolic-trough collector solar power plant working on cogeneration mode may meet the thermal and electrical demand of these industries, especially at average and low temperatures (<250°C). Simulations were performed to attend the demand of a food processing plant installed at three locations in Northeastern Brazil with different Direct Normal Irradiances (DNI). The solar power plant was simulated using different receiver settings with and without vacuum for the generation of 1 MWe and the supply of industrial process heat. A comparison between organic Rankine cycle (ORC) and steam Rankine cycle (SRC) was also performed to confirm the best power cycle to be applied to those plants. The results showed that the ORC allows higher efficiencies than the SRC, regardless of the receiver used (i.e. evacuated or not). When evacuated receivers are used, the ORC allows a gain in solar-to-electric efficiency of 1.2-1.3 percentage point (i.e. from 10% to 13% in relative value) as well as a correspondingly lower land footprint. Furthermore, the study showed that the design with non-evacuated receivers covered with glass tubes is feasible despite its lower efficiency.

Keywords: solar thermal energy, process heat, cogeneration, parabolic-trough.

1. Introduction

About one third of the total energy demand for industries in southern European countries is heat (Urban and Werner, 2015). Within important sectors such as textile, beverages, and food, this demand is, for the most part, for processes requiring heat at temperatures lower than 250 °C. Solar thermal energy has great potential to meet this demand and part of the thermal provided by the solar field at higher temperatures can be directed to generate electricity using the Rankine Cycle.

The replacement of large collectors with smaller ones, although less efficient, is an important item of this study in the search for system costs reduction and the possibility of full integration with the industrial park currently available in Brazil. These smaller collectors fit the operation for combined generation of process heat and electricity, provided they meet the required heat demand at enough (however lower) temperature. Some authors showed the feasibility of electricity generation with organic Rankine cycle in comparison with the steam cycles for low temperatures and small-scaled systems (Mcmahan, 2006; Orosz et al., 2009), others mention that only a cogeneration mode would be of economic interest (Krüger et al., 2015). We propose an ORC-solar cogeneration system with an energy peak supply ratio of 2/3 of the heat for processes and 1/3 of the heat for electricity generation, fractions based on the demands of the European food industry (Desbrosses, 2012).

The organic Rankine cycles use organic working fluids instead of water/steam from more common Rankine cycles. The organic fluids are ideal for lower temperatures; most degrade at temperatures higher than 300 °C, although they might allow greater efficiency those achieved with a steam cycle under these lower temperatures. Furthermore, their latent heat of vaporization is lower, and they do not necessarily need superheating (Vanslambrouck et al., 2012).

The solar field proposed in this study supplies heat at a maximum design temperature of 250°C to generate electricity and 80-110ºC to industrial process heat. This paper is based on simulations using the System Advisor Model (SAM) (NREL, 2019) for the solar field. The thermal output data obtained from SAM was used as input data for the power cycle, which was modeled with the Engineering Equation Solver (EES) (F-Chart, 2019), allowing the performance comparison between ORC and steam cycle at low temperatures.

1.1. Application in the Dairy Industry

doi:10.18086/swc.2019.08.09 Available at http://proceedings.ises.org

The initial idea is to dedicate the plant to the dairy industry which is an important sector in the Northeastern Brazil. Dairy industry demands low and medium temperature heat. Fig. 1 was obtained (with some adaptations) from a study about the integration of solar field to the dairy industry (Quijera et al., 2010) for a plant processing 20 thousand liters of cow milk per day located in the Basque Country where 95% of the milk is destined for the production of yogurt and cheese. Although the final products vary from plant to plant, the intermediate processes keep similar energetic demands and are common to most plants. In the figure, we can see the processes and their temperatures, such as water heating in the boiler, pasteurization and hot water for washing and cleaning in place requiring temperatures lower than 100°C. The boiler represents the input of the heat obtained from the solar thermal energy that will be supplied for the rest of the plant. There are also other plants with the option for milk treatment with ultra-high temperatures (UHT), which still demands temperatures below 150°C, value that solar thermal energy can reach. Solar thermal energy may also be applied in the steps that require water cooling for milk refrigeration and cold storage using refrigeration cycles operated by heat. As the intended is a cogeneration system, the electrical need of the plant can also be met: water and milk pumping, homogenization of milk, filtration, final packaging and even building lighting. The possibilities are numerous for dairy industry as well as several other sectors.

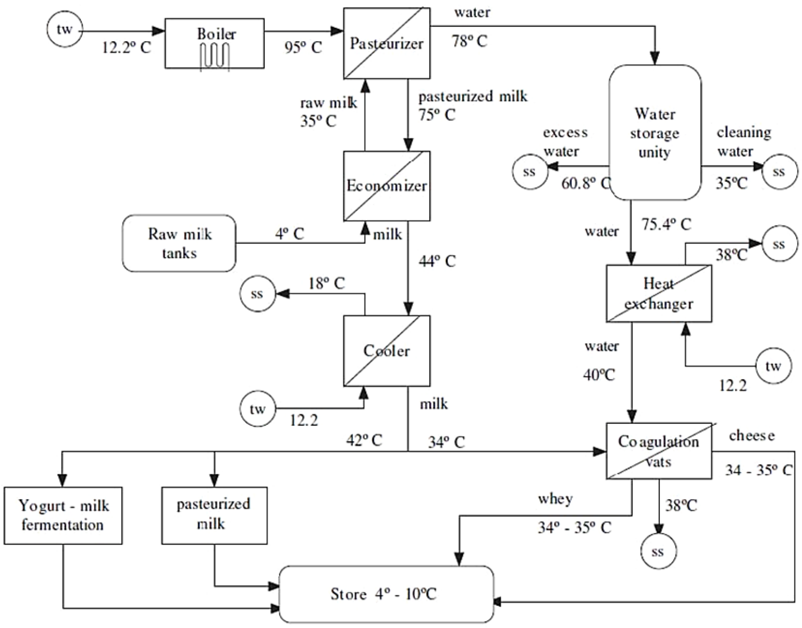

Fig. 1: Adapted scheme of a dairy facility (tw: tap water; ss: sewage system) [9].

1.2. Plant Specifications

We chose the PTMx-18 collectors from Soltigua (Fig. 2), which are small, light, allow automatic operation and are cheaper than the large ones. These collectors have an aperture width of 2.37 m, a length of 19.7 m and a reflective aperture area of 41 m². The receiver used was the Solel UVAC 3 for being quite widespread and used in important CSP plants such as Andasol-1 (Ferrer and Mehos, 2013) in Aldeire, Spain. The simplified scheme of the system proposed is presented in Fig. 3. In this system, all thermal energy is supplied directly by the solar field to the thermal storage system.

The Heat Transfer Fluid (HTF) used in the simulations for the solar field was the Dowtherm A, which was chosen for this work because it was the oil used successfully in the Andasol-1 plant (Ferrer and Mehos, 2013) and is applicable in the interval of temperatures between 15°C to 400°C and pressures between 1.0 bar e 10.6 bar (Urban and Werner, 2015). Other types of HTF with lower cost and applicable in smaller temperature ranges can also be tested but it is not the aim of this work.

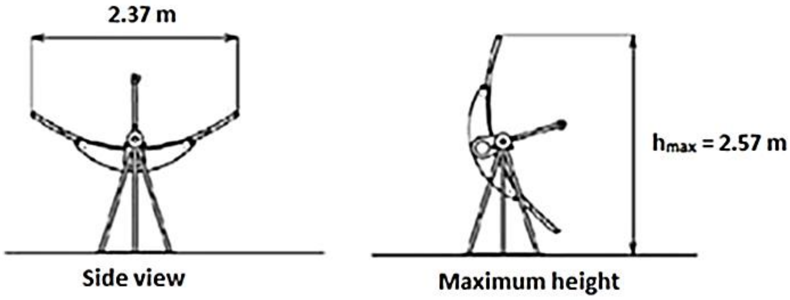

Fig. 2: Section of the collector: maximum width and height [11].

The thermal storage was treated generically and, despite the representation in a single block, it may have one or two tanks. It was included in the system with the main purpose of guaranteeing the stability of the thermal supply regardless the variations of the solar resource. Then, the stored energy can be supplied to the Rankine cycle and the process heat in a constant way. To this end, this supply will occur from the moment the thermal power reaches the necessary value for the cycle to generate 1 MWe. The heat exchanger train is commonly divided into three parts that are not represented in the scheme: pre-heater, steam generator, and superheater. The exceeding thermal power will meet the demand for process heat.

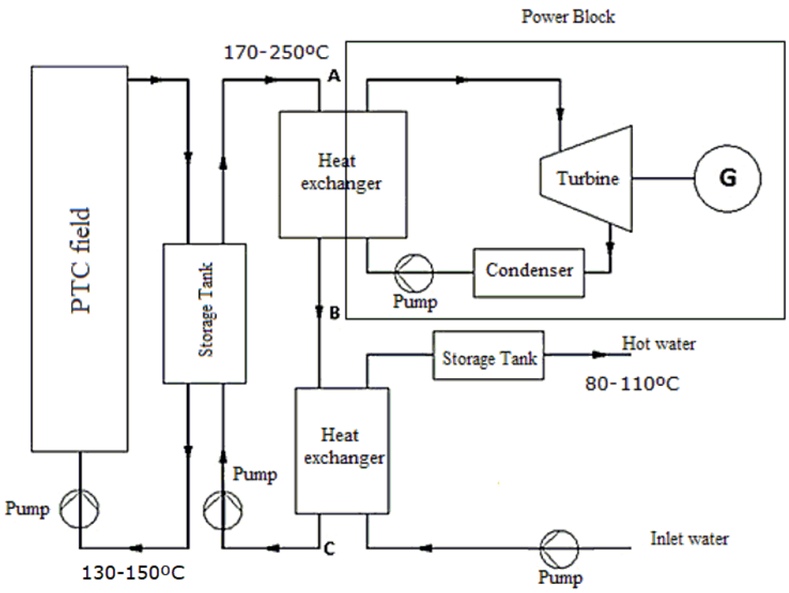

Fig. 3: Simplified scheme of a cogeneration system.

The power cycles compared were the steam Rankine cycle and the organic Rankine cycle. The organic fluid used was toluene, which, provides the best performance, i.e. higher cycle efficiencies (Vanslambrouck et al., 2013), when compared to other organic fluids commonly used such as R245fa, pentane, cyclopentane, and Solkatherm.

1.3. Location and Weather Data

The chosen cities were Recife (DNI equal to 1520 kWh/m²/year), Petrolina (DNI equal to 1834 kWh/m²/year) and Bom Jesus da Lapa (DNI equal to 2200 kWh/m²/year), all located in Northeastern Brazil, region with the best irradiance values of the country. Recife is located on the coast and the other two cities are in the Brazilian backlands. Some important location and weather data can be seen in Tab. 1. The environmental data used were obtained from SAM's own library, which, although somewhat inaccurate regarding weather files, allow to predict the annual energy output proportionally to the expected values (Ferrer and Mehos, 2013). The SAM model used for the simulations was "Process Heat Parabolic Trough" and the receiver tube was varied in three ways: protected by glass envelope and evacuated, protected by glass envelope without vacuum, and without glass envelope (tube exposed to the environment). The thermal output target was also changed for each case so that the 1 MWe electric output was obtained and the proportion of 2/3 for thermal processes and 1/3 for electricity generation at the maximum thermal supply point of the solar field was respected.

Tab. 1: Location and weather data summary.

	Recife	Petrolina	Bom Jesus da Lapa
Latitude	-8.07°N	-9.35°N	-13.27°N
Longitude	-34.85°E	-40.55 °E	-43.42°E
Temperature (annual average)	27.1°C	26.8°C	26.1°C
Wind Speed (annual average)	3.2 m/s	4.1 m/s	1.6 m/s
Solar Resource (Direct Normal)	1520 kWh/m²/year	1834 kWh/m²/year	2200 kWh/m²/year

2. Results and discussion

It was simulated three cases for each location, where the basic difference was the configuration of the receiver used. For each case, the design parameters of SAM were changed in ways to meet: the thermal demand of generating 1 MWe, the proportions of 1/3 electrical and 2/3 thermal at the maximum thermal supply point of the solar field and the thermal losses estimated for each configuration of the receiver, where the lowest ones are for the evacuated receivers and the highest ones for exposed tubes.

Table 2 shows the cases and their thermal demands obtained through the EES model of the Rankine cycle, with both an ORC and a SRC power cycle. In addition, it shows the surplus average thermal power that will be supplied for industrial processes. The larger thermal losses make the receivers reach lower temperatures, which influences electrical generation, causing the enhancement of the thermal demand to compensate the lower temperature, which can also be seen in Table 2. In the cases where the tube is protected by glass envelope and vacuum, a lower thermal demand can be observed, increasing when the vacuum is replaced by air. For the exposed tube, the electrical generation is only possible in Bom Jesus da Lapa, city with higher direct normal irradiance. In the other cities, the thermal losses are so high that almost match the energy absorbed by the receiver. When the studied cities are compared, we observe that the higher the direct normal irradiance, the lower the thermal power demanded to generate 1 MWe, because the temperatures reached are higher, which allow better efficiencies. It is also possible to observe that the thermal demand of the steam Rankine cycle is greater than the organic Rankine cycle when both are compared in the same case, which was expected because the efficiency of the first is inferior at lower temperatures (Vanslambrouck, 2012).

Regarding the solar field, SAM supplied the data in Table 3. The loop aperture area is the same for all cases, with 492 m², where twelve single collectors with 41 m² of reflective aperture area form each loop. The target thermal power was the input value defined for each case. This value refers to the thermal output of the solar field necessary to achieve the desired design power according to the thermal supply proportion previously mentioned. Cases 2 and 5 (exposed tube for Recife and Petrolina) were removed from the table because not enough energy was generated.

The thermal power for the ORC is lower than for the SRC when we compare the same case due to its greater efficiency. For example, in Recife, the target thermal efficiency of the receiver with evacuated tube is 36.5 MWt when we simulate the system with SRC; when it comes to ORC, the target thermal power is 32.7 MWt. Once again, for larger thermal losses or lower DNI (for the same receiver setting), the values of target thermal power are higher. The need of larger areas of solar fields is a direct consequence of the increase of target power, because for equal collectors it is necessary to enlarge the total area of reflective aperture to reach the desired thermal power. Which also leads to the increase of the solar field area. Making the same previous comparison for Recife, with SRC the reflective aperture area is 71,340.0 m², while for ORC is 63,960.0 m². Since as the loops have the same dimensions and quantity of collectors, the total efficiency conversion of the loop (including optical losses and estimated thermal losses) will depend solely upon the type of receiver (higher efficiencies for receivers with evacuated tube) and the DNI.

As expected, Bom Jesus da Lapa has the smallest land footprint, followed by Petrolina and then Recife. In the best-case scenario presented in Table 3, when the tube is evacuated, the solar field land area is 28 acres (113,312.0 m² corresponding to a reflective aperture area of 54,120.0 m²) using SRC and 25 acres (101,171.0 m² corresponding to a reflective aperture area of 48,216.00 m²) using ORC. A comparison can be made with the real case of the 1 MWe parabolic trough plant located in Arizona/USA, APS Saguaro. The location has annual average DNI of 7.22 kWh/m²/day, the plant uses an ORC power block and LS-2 collectors [9] with a 5 m aperture with a 235 m² of reflective aperture area. The output temperature of the collectors is 300°C. For Saguaro, the reflective aperture area is 10,340.0 m², a little more than 19% of the area obtained for Bom Jesus da Lapa with evacuated tubes and SRC (or 21.4% when using ORC). However, it is important to emphasize that the plant in Arizona is exclusive for electrical generation, while in Bom Jesus da Lapa there is also thermal supply. Making a simplified projection following the standard of thermal/electric proportion of the plants of this study, we found the reflective aperture area expected for Saguaro, 31,020.0 m², which is equivalent to 64.3% of the area for Bom Jesus da Lapa. Other factors might justify the differences of the areas: Saguaro has larger collectors with greater solar concentration, which allows its working temperature to be higher; these collectors are also more optically efficient (peak of 87.1% against 74.7% for the Soltigua collectors); also, the plant is located in a region with higher DNI. These results show that the size of the plant in Bom Jesus da Lapa is consistent as the calculated for Saguaro Power Plant.

Tab. 2: Thermal output for different locations and types of receivers using plants with ORC and SRC.

Case	**Location**	**Type of receivers**	**Thermal power demanded for generation of 1 MWe (MWt)**		**Remaining thermal power for process heat (MWt)**		**Receiver Thermal efficiency (%)**
			Plant with ORC	Plant with SRC	Plant with ORC	Plant with SRC	
Case 1	Recife	Tube with evacuated glass envelope	6.1	6.8	8.0	8.86	65.6
Case 2	Recife	Exposed tube (without envelope)	Generation of insignificant thermal energy in a very large solar field.				
Case 3	Recife	Tube with glass envelope and interior with air at atmospheric pressure	7.1	8.7	8.0	9.6	56.3
Case 4	Petrolina	Tube with evacuated glass envelope	6.0	6.75	7.7	8.65	64.1
Case 5	Petrolina	Exposed tube (without envelope)	Generation of insignificant thermal energy in a very large solar field.				
Case 6	Petrolina	Tube with glass envelope and interior with air at atmospheric pressure	7.0	8.4	8.45	10.19	60.4
Case 7	Bom Jesus da Lapa	Tube with evacuated glass envelope	5.95	6.7	8.2	9.2	68.9
Case 8	Bom Jesus da Lapa	Exposed tube (without envelope)	8.05	9.6	8.05	9.6	50
Case 9	Bom Jesus da Lapa	Tube with glass envelope and interior with air at atmospheric pressure	6.75	7.75	8.45	9.73	62.6

Also, in Table 3, we observe that is possible to supply the thermal demand using non-evacuated receivers. However, for the collector used in the present study, the reflective aperture area needed is very large. That way, only a detailed cost benefit study and the levelized cost of electricity (LCOE) calculation for this setting will say if the alternative is valid. The same occurs for the receiver with exposed tube, however, this case would only be possible for Bom Jesus da Lapa, and it still would demand an extremely large aperture area, making its feasibility very unlikely.

Tab. 3: Data supplied by SAM for the solar field of three studied cities case by case.

	Recife		**Petrolina**		**Bom Jesus da Lapa**		
	Case 1	Case 3	Case 4	Case 6	Case 7	Case 8	Case 9
Steam Rankine Cycle							
Target receiver thermal power (MWt)	36.5	109.0	36.0	96.5	33.0	120.0	72.0
Total loop conversion efficiency	0.6422	0.5797	0.6437	0.5881	0.6443	0.2446	0.5916
Total aperture reflective area (m^2)	71,340.0	235,176.0	62,484.0	182,532.0	54,120.0	516,600.0	128,412.0
Solar Field Area (acres)	37	123	33	95	28	269	67
Receiver estimated avg. heat loss (W/m)	33.3	192.2	33.3	192.2	33.3	1268.7	192.2
Solar field outlet temperature (°C)	223.0	170.6	225.7	179.6	227.8	146.5	189.8
Organic Rankine Cycle							
Target receiver thermal power (MWt)	32.7	90.0	32.0	80.0	29.5	100.5	62.5
Total loop conversion efficiency	0.6422	0.5797	0.6437	0.5881	0.6443	0.2446	0.5916
Total aperture reflective area (m^2)	63,960.0	194,340.0	55,596.0	151,536.0	48,216.0	432,960.0	111,684.0
Solar Field Area (acres)	33	101	29	79	25	226	58
Receiver estimated avg. heat loss (W/m)	33.3	192.2	33.3	192.2	33.3	1268.7	192.2
Solar field outlet temperature (°C)	223.0	170.6	225.7	179.6	227.8	146.5	189.5

Comparing the Design Point Solar-to-Electricity Efficiency obtained for receivers with evacuated tube in the three Brazilian cities studied and at APS Saguaro, we found the results showed in Tab. 4. The obtained values are close to the Arizona plant that works at a slightly higher temperature and, as expected, the obtained efficiencies with ORC are better than with SRC.

Considering the simplified scheme of the Rankine cycle shown in Fig. 4, the Solar-to-Electricity Efficiency can be calculated from the following physical description. The thermal power supplied to the thermodynamic cycle is calculated by:

$$Q_0 = \eta_{exc} Q_s \qquad \text{(eq. 1)}$$

Where η_{exc} is the heat exchangers efficiency and Q_s is the power total solar field supplied in MWt. The pump work is calculated by:

$$\dot{W}_p = (h_1 - h_2)\dot{m}_a \eta_p \qquad \text{(eq. 2)}$$

Where η_p is the isentropic pump efficiency, $\dot{m}_a$ is the mass flow rate (kg/s), h_1 e h_2 are the enthalpies (J/kg) in points 1 and 2. The turbine work is calculated by:

$$\dot{W}_t = (h_3 - h_4)\dot{m}_a\eta_t \qquad \text{(eq. 3)}$$

Where η_t is the isentropic turbine efficiency and h_3 and h_4 are the enthalpies (J/kg) in points 3 and 4. The heat supplied by the boiler is calculated by:

$$\dot{Q}_b = (h_3 - h_2)\dot{m}_a \qquad \text{(eq. 4)}$$

The rejected heat in condenser is calculated by:

$$\dot{Q}_c = (h_1 - h_4)\dot{m}_a \qquad \text{(eq. 5)}$$

The cycle efficiency is calculated by:

$$\eta_t = \frac{\dot{W}_t - |\dot{W}_p|}{\dot{Q}_b} \qquad \text{(eq. 6)}$$

The Solar-to-Electricity Efficiency is calculated by:

$$\eta_s = \eta_g \frac{\dot{W}_t - |\dot{W}_p|}{\dot{Q}_b/\eta_{exc}} \qquad \text{(eq. 7)}$$

Where η_g is the generator efficiency.

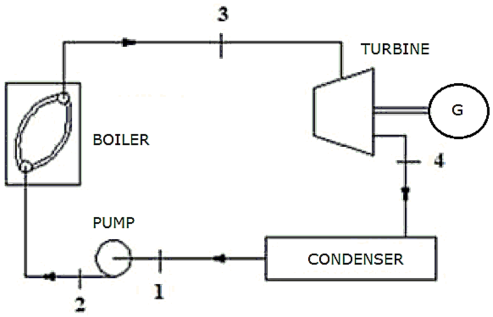

Fig. 4: Simplified scheme of a Rankine cycle.

The optical efficiency (η_o) of the loop is the product of the collector's optical efficiency by the loss of the optical capacity of the collectors due the connection between the pipes, dirt, tube absorptance and glass envelope transmittance.

Tab. 4: Design-Point Solar-to-Electricity Efficiency for ORC and SRC at different localities using evacuated tubes.

Location	Design-Point Solar-to-Electricity Efficiency			
	Tube with evacuated glass envelope		Tube with air glass envelope	
	ORC	SRC	ORC	SRC
Recife	10.0%	8.9%	7.8%	6.4%
Petrolina	10.1%	9%	8.0%	6.7%
Bom Jesus da Lapa	10.2%	9.1%	8.3%	7.2%
Saguaro	12.1%	-	-	-

Analyzing simply the cycle efficiency for evacuated tube and tube with air (Tab. 5), once more the advantage of the organic Rankine cycle is proven, obtaining efficiencies greater than 16% in the three localities with evacuated tube, meanwhile, the steam cycle reached values slightly below 15%. For the tube with air receiver, the difference of the efficiencies is even greater because the temperatures reached by the receivers are lower, being approximately 170°C in Recife and 190°C in Bom Jesus da Lapa, temperatures seen previously in Table 3, which makes the application of the organic Rankine cycle even more suitable.

Tab. 5: Cycle efficiencies for evacuated tube and tube with air at different localities. Comparison between ORC and SRC.

Location	Tube with evacuated glass envelope		Tube with air	
	ORC	SRC	ORC	SRC
Recife	16.3%	14.6%	14.1%	11.6%
Petrolina	16.5%	14.7%	14.2%	12.0%
Bom Jesus da Lapa	16.6%	14.8%	14.7%	12.9%

3. Conclusion

The results indicate that the combined generation of electricity and process heat is possible for Recife, Petrolina and Bom Jesus da Lapa using evacuated or non-evacuated receivers with glass envelope, with solar field HTF outlet temperatures between 220°C and 230°C for evacuated tubes and between 170°C and 190°C with atmospheric tubes. However, for a more realistic assessment of the feasibility of the utilization of less sophisticated parabolic troughs using non-evacuated receivers with glass envelope (instead of evacuated ones), a more detailed LCOE calculation is necessary for both cases. For the cases simulated with exposed tubes receivers, the only location where there might be some generation is Bom Jesus da Lapa due to its higher direct normal radiation. However, this configuration must be discarded because the necessary area would be nearly ten times that required with evacuated receivers.

When we compared the efficiencies, we obtained values close to the real APS Saguaro plant for the Design-Point Solar-to-Electricity Efficiency, between 11.6% and 11.8% for the studied cities and 12.1% for the plant in Arizona, the higher values corresponding to the cities with higher DNI. It was possible to prove the advantage of the organic Rankine cycle (using toluene as working fluid for this study) when compared to the steam Rankine cycle for medium and low temperatures, the gain in efficiency being higher when the turbine inlet fluid temperatures are lower.

4. Acknowledgments

The authors would like to acknowledge the support of the National Council for Scientific and Technological Development (CNPq), process 302251-2017-0, the P&D named “Desenvolvimento de Tecnologia Nacional de Geração Heliotérmica de Energia Elétrica, PD-ANEEL 2290-0051/2016, Termopernambuco S.A”, and the Federal University of Pernambuco (UFPE) for supporting the solar energy research projects and providing the material means and the scientific environment for the execution of this research.

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