Thermo-economic evaluation of solar concentrating technologies for industrial process heat production in Uruguay

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Abstract

This work aims to identify the existing potential of solar energy for process heat production in Uruguay. Both Parabolic Trough Collector (PTC) and Linear Fresnel Technology (LFT) are considered as candidate tecnologies for their application in the Uruguayan industrial sector, and their performance evaluated as if installed in five different locations. Simulations using TRNSYS were carried out in order to obtain the annual power produced and efficiency –among other results – for the two technologies, five locations and various working temperatures considered. Furthermore, an economic analysis was performed, in which the Levelized Cost of Heat (LCOH) was calculated for all the cases. Since most steam generators in Uruguay work with Fuel Oil and Firewood as fuel, comparison against these two energy sources is performed.

Key-words: Concentrating solar, Process heat, Uruguay

1. Introduction

Solar energy is a potential candidate for the replacement of fossil fuels, generating a decrease in CO2 emissions, and mitigating the dependence on heat generation from non-renewable sources. The evolution of the global industry is accompanied by an increase in energy demand. For industrial purposes, heat constitutes a large part of this energy. The application of solar technologies is potentially broad, since it allows the fluid heat carrier reach temperatures ranging from 45ºC to 400ºC.

This same analysis has been carried out for different countries (Lauterbach et al. 2012; Lillo et al. 2017; Parthiy et al. 2015; Schweiger et al. 2011; Rittman et al. 2017;), this being the first thermo-economic study of solar concentration technology for process heat production in Uruguay.

In this study, the industrial heat demand in Uruguay was analyzed from the perspective of its suitability for concentrating solar technologies utilization. Heat demand is supplied mostly with steam generation, and the main sources for its production are Fuel Oil and Firewood, as seen in Fig. 1.

A typical temperature range of the steam produced in the industrial processes, which cannot be achieved with solar technologies without concentration, is between 100 and 180ºC. Thus, this is the working temperature range for the solar technologies considered in this study.

Three sizes of solar fields were considered –based on the typical capacity of steam generators installed in Uruguay (URSEA, 2017)–, with the aim to represent small, medium and big solar plants. From this source of data, it is also observed that most steam generators produce saturated steam at 100 - 200ºC, which is in agreement with previous works. It should be pointed out that a high portion of these boilers are installed in meat, milk and other food industries.

The geographical locations within the country selected for this study were Montevideo and Salto, since Typical Meteorological Years (TMY) [LES, 2018] of all the relevant meteorological variables (DNI, ambient temperature, etc.) are available for these locations (Table 1).

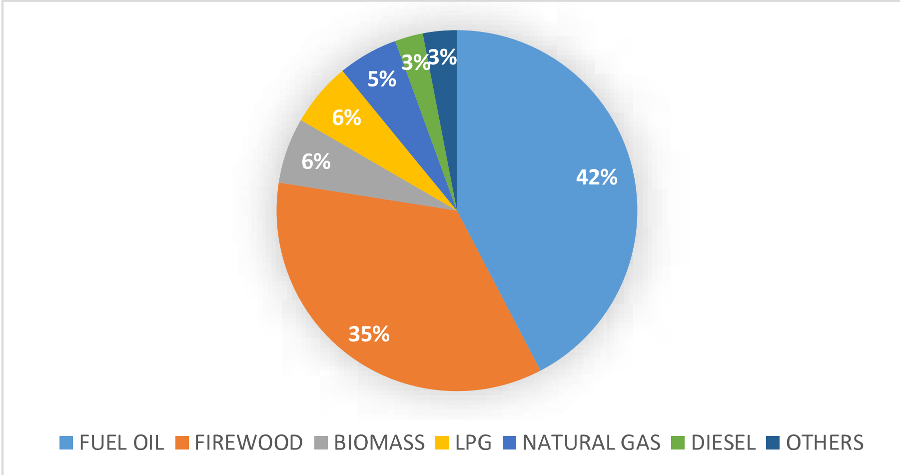

Fig. 1: Distribution of fuels used in the steam generators of Uruguay

Tab. 1: Location where the typical meteorological year is avaible.

Location	Latitude	Longitude	DNI (kWh/m^2.yr)
Montevideo	-34.83	-56.01	1862.5
Salto	-31.43	-57.98	1897.5

2. Model

A model was implemented in TRNSYS to simulate the behavior of PTC and LFT solar plants. The thermal efficiency of both technologies was modeled using the empirical model (eq. 1).

$$\eta = \eta_0 - (C_1 + C_2 \Delta T)\left(\frac{\Delta T}{DNI}\right) \qquad \text{(eq. 1)}$$

2.1 Incidence angle and optical efficiency

The direct radiation of the sun does not usually fall in the normal direction above the aperture area of the collector, but with an incidence angle, called θ.

The effective reflection area can be calculated from the aperture area (eq. 2)

$$A_\theta = A_{ap} \times \cos(\theta) \qquad \text{(eq. 2)}$$

The optical performance at different angles of incidence ($\eta_{opt,\theta}$) is obtained from optical and thermal measurements and comparing them with optical efficiency at normal incidence, $\eta_{opt,0º}$ (Wei, 2014).
The total optical performance (first term on the right in eq. 1), which includes the effects of reducing effective reflective area and modifying the angle of incidence, can be expressed as follows:

$$\eta_0 = \eta_{opt,0} \times \cos(\theta) \times \text{IAM}(\theta) \qquad \text{(eq. 3)}$$

Due to their differences in geometry and tracking system, IAM calculation is performed differently for PTC and LFT. In the latter, it is necessary to consider longitudinal and transverse direction IAM, while in the former only a longitudinal direction IAM is needed, since in this, the opening surface does not follow the sun and remains horizontal. Because both components of the angle of incidence are different from zero, there is a longitudinal and transversal incidence angle modifier, which multiplies to obtain the IAM.

It should be pointed out that there is no general consensus on how to present the efficiency of a solar collector and the definition of the IAM. It is possible to find IAM values which already include cos(θ), i.e. which correspond to the $\cos(\theta) \times \text{IAM}(\theta)$ product. For further insight see e.g. Eck et al., 2014.

2.2 Concentration ratio

The concentration ratio, *Cr*, can be determined geometrically as the quotient between the solar aperture area A_{ap} and the absorber area A_{abs}. The absorption tube must have a small diameter to keep the thermal losses at low levels, but large enough to allow a high interception factor of the incident solar radiation. The dependence of the thermal losses with this parameter is observed in (eq. 4) (Duffie and Beckmann, 1974).

$$q'' = \frac{1}{Cr}\left(h_w(T_r - T_a) + \varepsilon\sigma\left(T_r^4 - T_{sky}^4\right) + U_{cond}(T_r - T_a)\right) \quad \text{(eq. 4)}$$

3. Case studies

3.1 Selection of collectors

After having available information of several technologies (Tables 2 and 3) the optical and thermal behavior of both PTC and LFT were analyzed in order to choose a manufacturer and model of each technology (Figs. 2 to 5).

Tab. 2: PTC models.

	Technology	η_0	C_1 (W/m²K)	C_2 (W/m²K²)	C_r	T_{max} [ºC]
1	(Lillo et al. 2017)	0.718	0.500	0.0005	--	--
2	Solitem (IEA, 2015)	0.75	0.1123	0.00128	15	250
3	Trivelli (IEA, 2015)	0.70	0.7	0	--	250
4	Abengoa PT-1 (IEA, 2015)	0.71	0.437	0.0029	50	288
5	Abengoa RMT (IEA, 2015)	0.65	0.404	0.0027	50	205
6	Solarite 2300 (IEA, 2015)	0.641	0.4201	0.00119	57.5	250
7	Solarite 4600 (IEA, 2015)	0.757	0.0191	0.00006	66	400
8	Nep (IEA, 2015)	0.689	0.36	0.00110	17	230

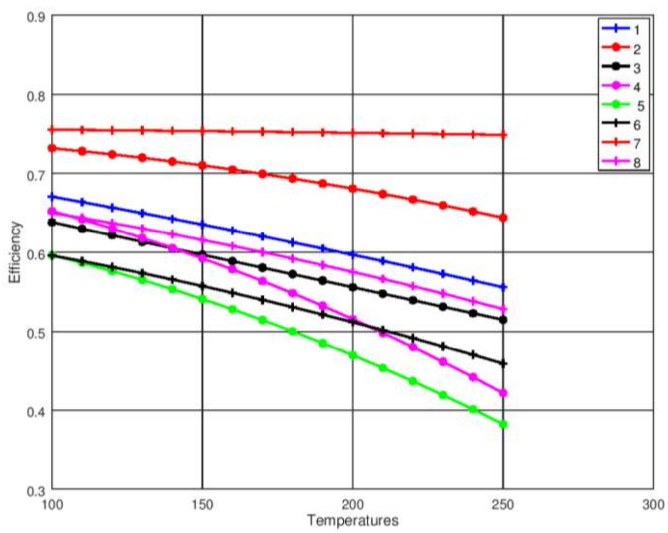

Fig. 2: Efficiency curves for PTC Technologies from Tab. 2.

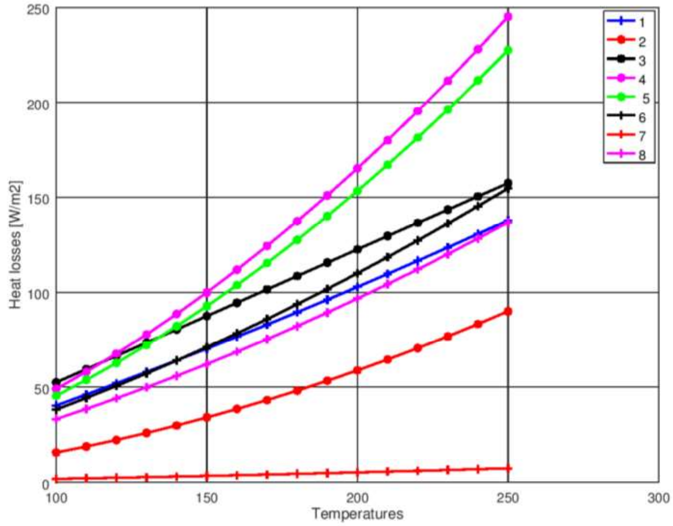

Fig. 3: Heat losses curves for PTC Technologies from Tab. 2.

Tab. 3: LFT models.

	Technology	η_0	C_1 (W/m^{2}K)	C_2 (W/m^{2}K^2)	C_r	T_{max} [ºC]
1	(Lillo et al. 2017)	0.667	0.1020	0.0002	--	--
2	IS-LF11 (IEA. 2015)	0.635	0.0265	0.00043	25	400
3	Novatec (Mills, 2012)	0.67	0.056	0.000213	52	270
4	Fresdemo (Bernhard, 2009)	0.62	0.0366	0.000707	34	270

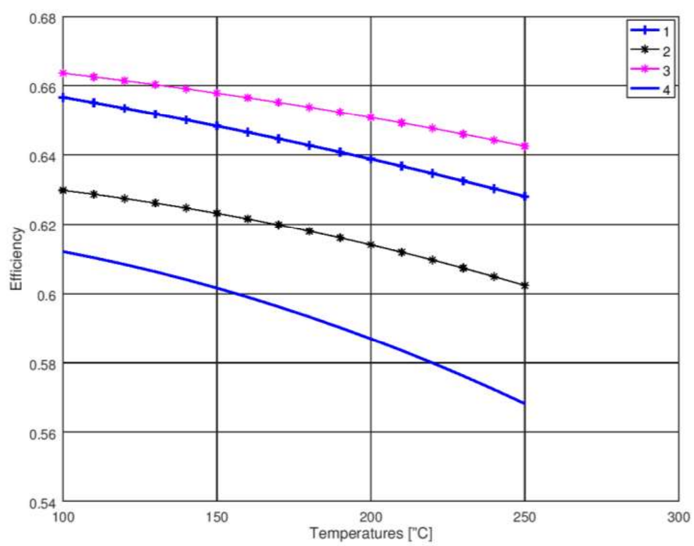

Fig. 4: Efficiency curves for LFT Technologies from Tab. 3.

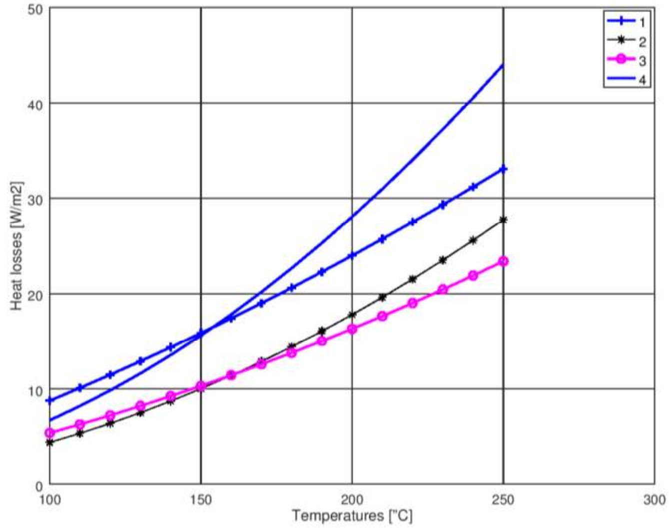

Fig. 5: Heat losses curves for LFT Technologies from Tab. 3.

This selection was made under the following criteria: minimizing thermal losses, prioritizing that the technology was intended for process-heat generation (and not for electricity generation), similar concentration ratio between PTC and LFT models. Selected models are presented in Table 4.
Both the incidence angle modifier (IAM) and the concentration ratio (*Cr*) have a great influence on the performance of the technologies, so they are given special attention in this work.

Tab. 4: Selected models.

Technology	Model	η_0	C_1 (W/m²K)	C_2 (W/m²K²)	C_r	Aperture (m²)
PTC	Nep	0.689	0.360	0.011	17	18.45
LFT	IS-LF11	0.635	0.0265	0.00043	25	22

Regarding the values of IAM of the selected models (Figs. 6 and 7), which were obtained from their technical datasheets, it can be observed that those of PTC Nep model do not include cos(θ), while those of LFT IS LF-11 do. This can be concluded by observing that the values of IAM of the PTC model are higher than cos(θ) while longitudinal IAM values of the LFT model are lower. Furthermore, if the values of longitudinal IAM of LFT are divided by cos(θ), a curve close to that of Fig. 6 is obtained, with somewhat lower values, which is what is expected for a LFT module.

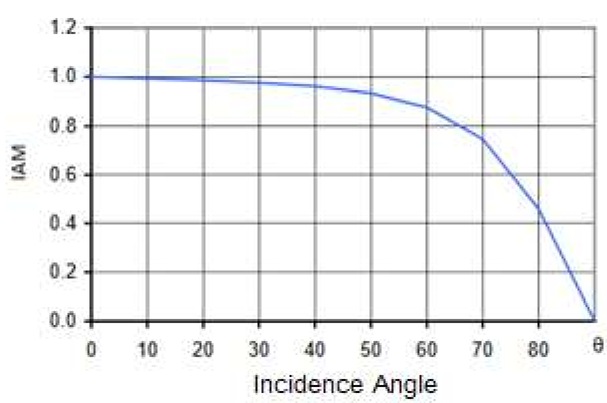

Fig. 6: Incident angle modifier, IAM, for PTC technology [Sol, 2018]

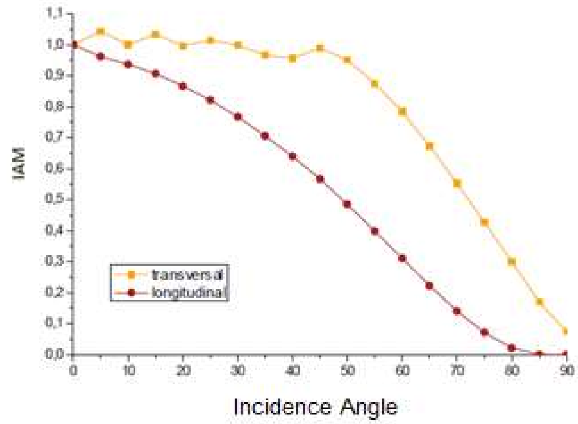

Fig. 7: Incident angle modifier, IAM, for LFT technology [Tec, 2018].

3.2. Plant operating modes

Two different limiting situations are evaluated from the point of view of the operating regime of the solar plant:

- Option 1: Normal operation continues throughout the night (when there is no solar radiation but there are thermal losses).
- Option 2: No night losses (limiting case of draining the receivers and storing the fluid in an adiabatic vessel).

3.3 Typical sizes of steam generators and solar fraction

From the list of boilers installed in Uruguay (URSEA, 2017), three different sizes were chosen to represent the power heat consumption industrial boilers (see Tab. 5). From the installed power and assuming a working regime of the plant of 12 hours per day, 6 days a week, for small and medium sizes, and 16 hours per day, 6 days a week, for the large size, the annual energy produced by each boiler was estimated.

Tab. 5: Representative sizes and annual energy production of steam generators in Uruguay.

Size	Power generated (kW)	Estimated anual energy (kWh)
Small	70	240000
Medium	4200	14650000
Large	13000	58000000

The solar fraction is defined as the amount of energy produced from solar, divided by the total energy demanded by the plant:

$$f_s = \frac{E_{solar}}{E_{demand}} \qquad \text{(eq. 5)}$$

This value depends on the relative size of the solar field, but also on the size of the storage system —which allows saving energy in times of surplus for later use—. Since in this work, a storage system is not considered, somewhat low values of fs need to be adopted in order to assure that no surplus power is produced. It is observed that for fs = 26%, the power generated in the field is lower than that of the boiler at any time of the year. Therefore, a value of 26% is adopted for sizing the solar plants located in Salto. In the rest of the locations, the same sizes are considered, which results in slight variations of the solar fraction.

3.4 Costs and economic parameters

The levelized cost of heat (LCOH) is a measure based on the concept of the levelized cost of energy (eq. 6). Basically, it is about finding the “sale” price of heat, which would make the project profitable, for the discount rate and the evaluation period considered.

Since the produced heat will not be considered as a product to be sold, the LCOH in this case can be seen as the effective price of the substituted fuel (in this work, Fuel Oil or Firewood) that would make the investment profitable, due to the fuel savings obtained.

$$LCOH = \frac{I_o - S_o + \sum_{t=1}^{T} \frac{O\&M_t - S_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}} \qquad \text{(eq. 6)}$$

Here, LCOH is the levelized cost of heat (in US$/kWh), I_o is the initial investment in US$, S_o are the subsidies and incentives at the beginning and S_t at year t (in US$), *O&M* are the costs associated with the operation and maintenance (in US$), r is the discount rate (in %), E_t is the generated energy in year t (in kWh) and T is the analysis period (in years).

Unlike what normally happens in power generation plants, the energy produced in the solar plant is not the product to be sold, and this represents a problem for the estimation of the applicable tax exemptions. In Uruguay, there is a potential tax exemption for promoted investment projects, such as those related to renewable energy. The total tax exemption is a percentage of the initial investment of the project, which depends on the characteristics of the project (e.g. location, invested amount). As it cannot exceed 60-80% (existing-new) of the taxes paid in each year by the company, the total exemption can be distributed over a certain maximum number of years. Table 6 shows some of the tax-exemption parameters used in this work.

Tab. 6: Initial investment (I_0), tax exemption (as % of I_0) and maximum period in which tax exemption can be distributed.

Location	Size (m2)	Technology	Initial Investment (US$)	Percentage (%)	Maximum number of years
Salto	5736	Fresnel	1.76E6	78	10
Montevideo	5736	Fresnel	1.76E6	69	9
Salto	4650	PTC	1.92E6	78	11
Montevideo	4650	PTC	1.95E6	69	9

Three different situations are chosen, corresponding to different possible scenarios of tax exemptions in Uruguay, “Option 1” is the best-case scenario, in which the total possible tax-exemption amount is obtained in the second year of operation. This option could be possible if it is a big company and the initial investment is lower than the taxes payed in one year. “Option 2” is an intermediate situation, in which the whole possible tax exemption is obtained, but distributed in the maximum amount of years allowed. Finally, the worst-case scenario is one in which no tax exemptions are applied, denoted “Option 3”.

Regarding the evaluation period and discount rate (T and r in eq. 6), two sets of parameters were considered:

- 20 years and 8%, which approximately correspond to the expected lifetime of the technology and a discount rate usually applied to big power generation plants.
- 10 years and 12%, which correspond to more usually applied parameters for investments by local industry. In this case, since the period is lower than the expected lifetime of the technology, a residual value (RV) should be considered at the end of the evaluation period. In this work, a RV equal to half of the initial investment is considered, as an income in year 10.3.4.1 Cost of Linear Fresnel.

For estimating the cost of the LFT plant, two different sources were considered, a previous work from Spain (MPE, 2015) and Solatom manufacturer’s website (ESP, 2018). The latter not only gives information about the cost, but also about energy yield, solar fraction, and other useful information. Tab. 7 shows the initial investment for different sizes of solar plant, from both sources.

Tab. 7: Specific initial investment for two representative sizes of LFT fields

MPE [MPE, 2015]		Solatom [ESP, 2018]	
Size (m^2)	Initial Investment (USD/m^2)	Size (m^2)	Initial Investment (US$/$m^2$)

100	370	237	277
15000	182	9504	190
		34214	190

The efficiency of the IS-LF11 model (used in this work for the simulations), seems to be higher than that of Solatom's model, since the annual energy yield resulted respectively higher, for the same size of plant. Therefore, and in order to adopt a conservative criterion with respect to cost estimation for big-sized plants, a somewhat higher cost compared to Solatom's was adopted. Furthermore, following the conservative criterion, the highest of both prices in Tab. 7 was adopted for small-sized plants (which is already higher than that of Solatom). Tab. 8 resumes the specific costs used in this work. For sizes between 100 and 15000 m^2, a linear correlation was used, while for sizes smaller than 100m^2 and bigger than 15000 m^2 the prices were considered not to change.

Tab. 8: Specific initial investment for two representative sizes of LFT fields

Size (m^2)	Initial investment, without accumulation (USD/m2)
100	370
15000	200

Regarding operation and maintenance costs (O&M in eq. 6), 3% of I_0 is considered here, as used in [MPE, 2015].

3.4.2 Cost of Parabolic Trough

For PTC, no investment values nor maintenance costs were found of a plant for thermal energy generation, from manufacturers. Therefore, the cost estimation used here is solely based on the Spanish study [MPE, 2015], where an analysis of the thermal generation is also made by making a breakdown of the costs associated with a type plant and acquiring the relevant data for a plant of thermal generation without accumulation. Table 9 summarizes the data used.

The situations evaluated are the same as in the case of Fresnel technology, working with the same sizes of solar field. The solar energy collection and solar thermal energy conversion system where considered in the initial investment [MPE, 2015], but no heat accumulation system was included. The solar energy collection system includes: mirrors, metal structures, positioning system, earthworks, foundations, assembly and assembly hall; while the solar thermal energy conversion system refers to thermal oil, absorber tubes, rotating joints, pipes and oil transfer system [MPE, 2015].

Tab. 9: Specific initial investment for two representative sizes of PTC fields [MPE, 2015].

Size (m^2)	Specific initial investment, without accumulation (€/m2)	Initial investment, without accumulation (USD/m2)
100	400	456
15000	275	314

For sizes between 100 and 15000 m^2 it is decided to perform a linear interpolation. Price values of 100 and 15000 are assumed to be the lowest and highest, respectively, without extrapolation for smaller or bigger sizes.

O&M costs for PTC technology were considered as 4% of I_0 [MPE, 2015]. The percentage is higher than that of Fresnel given the higher complexity in the assembly and tracking system of the PTC.3.4.3 Substitution of other energy sources

Another parameter to consider is the price of the fuel used by the conventional boiler, which in Uruguay are Fuel Oil and Firewood. Their respective costs are presented in Table 10, where typical low heating values are indicated, as well as the assumed conversion efficiency of the boiler. The effective price indicated in Tab. 10 is the actual cost of the energy contained in the produced steam, taking into account the conversion efficiency of the equipment.

Tab. 10: Current price of the main fuels used in steam generators in Uruguay.

Fuel	Market price (USD/kg)	Low Heating Value (MJ/kg)	Conv. Efficiency (%)	Effective price (USD/KWh)
Fuel Oil	0.648	40.9	85	0.0672
Firewood	0.0724	11.3	85	0.0271

4. Numerical results

In terms of annual energy generation, a relevant aspect to be considered is the occurrence of thermal losses at night. Since selected LFT has lower thermal losses and somewhat higher Cr than selected PTC (see Table 1), if normal operation continues throughout the night (when there is no solar radiation but there are thermal losses), LFT annually produces more thermal energy than PTC if the working temperature exceeds a certain value in the 100-180°C range. However, if there are no night losses (ideal case of draining the receivers and storing the fluid in an adiabatic vessel), PTC produces more energy (annually) than LFT, for all working temperatures in the studied range. This is due to the higher optical efficiency and the lower incidence angles achieved by the PTC.

Table 11 shows the results of size, gross and net production, efficiency and solar fraction, of both PTC and LFT plants, working at a temperature of 140ºC, in the locations of Salto and Montevideo. These locations are selected due to being where the best results are obtained (Salto) and where most of the Uruguayan industries are located (Montevideo). The difference between gross and net values, in this context, comes from the fact that 6-day operation per week has been assumed, and since there is no storage, it is not possible to take advantage of the total (gross) solar production of the 7 days in the week, so the net production (useful) is 86% (6/7) of the latter.

Tab. 11: Main results for selected PTC and LFT in Salto and Montevideo, with a working temperature of 140ºC.

Location	Technology/size	Size (m^2)	Gross energy generated (Op. 2) (kWh/yr)	Net energy generated (Op. 2) (kJ/yr)	η	f_s
Salto	PTC small	76	2.60E8	2.24E8	0.503	0.26
	LFT small	93	2.59E8	2.22E8	0.408	0.26
	PTC medium	4650	1.60E10	1.37E10	0.503	0.26
	LFT medium	5736	1.60E10	1.37E10	0.408	0.26
	PTC large	18315	6.30E10	5.40E10	0.503	0.26
	LFT large	22720	6.34E10	5.43E10	0.408	0.26
Montevideo	PTC small	76	2.50E8	2.14E8	0.490	0.25
	LFT small	93	2.47E8	2.12E8	0.396	0.25
	PTC medium	4650	1.53E10	1.31E10	0.490	0.25
	LFT medium	5736	1.52E10	1.30E10	0.396	0.25
	PTC large	18315	6.02E10	5.16E10	0.490	0.25
	LFT large	22720	3.04E10	5.18E10	0.396	0.25

Figure 8 and 9 show the LCOH of LFT fields located in Salto (left) and Montevideo (right). Fig. 8 show results obtained for a discount rate of 8% and 20 years of evaluation, while in Fig. 9, r=12% and T=10 years were used. Both figures also show effective prices of conventional fuels for comparison. There are three different situations represented, corresponding to different possible scenarios of tax exemptions in Uruguay, "option 1" being the best-case scenario (exemption of the total amount produced in year 1) and "option 3" the case with no tax exemptions, as described in section 3.4.

It can be observed that in certain scenarios, the cost of the solar kWh is lower than that of conventional energy if compared against Fuel Oil. This is especially true for large LFT plants both in Salto and Montevideo. These can also compete against Firewood, in tax exemptions situations 1 and 2 and with r=8% and T=20 years. Furthermore, it is observed that with the less rigorous financial parameters (r=8%, T=20)

LCOH of LFT is lower than Fuel Oil cost even without tax exemptions, for medium and large sizes. This is also true for the more rigorous parameters (r=12%, T=10 years) only for the large plant size.

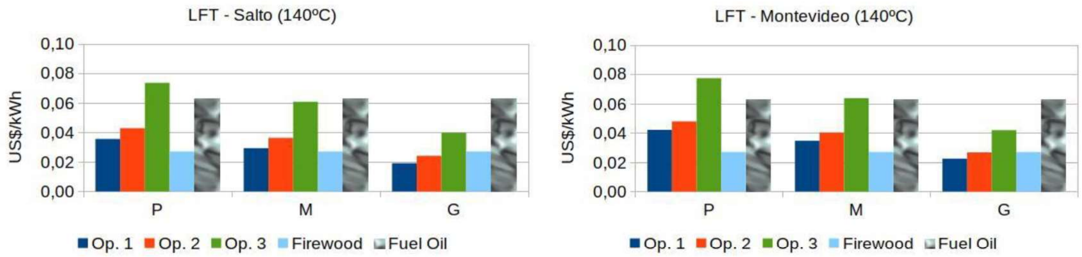

Fig. 8: LCOH of Solar Thermal Energy of a Fresnel field in Salto (left) and Montevideo (right), working at a mean temp. of 140ºC, with <u>*r*=8% and *T*=20 years</u>. Effective prices of Firewood and Fuel are included. The options 1,2 and 3 indicate the different possible situations of tax exemptions described in 3.4. S, M and L indicate the plant sizes (small, medium and large).

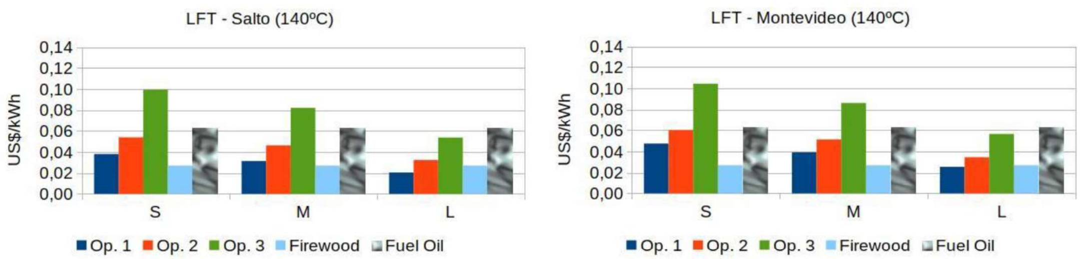

Fig. 9: LCOH of Solar Thermal Energy of a Fresnel field in Salto (left) and Montevideo (right), working at a mean temp. of 140ºC, with <u>*r*=12% and *T*=10 years</u>. Effective prices of Firewood and Fuel are included. The options 1,2 and 3 indicate the different possible situations of tax exemptions described in 3.4. S, M and L indicate the plant sizes (small, medium and large).

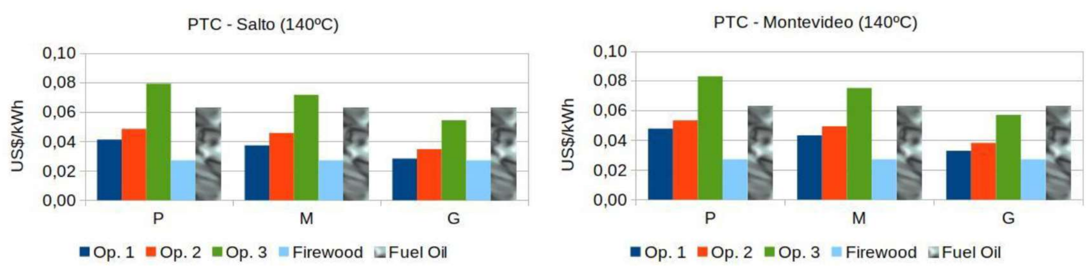

Fig. 10: LCOH of Solar Thermal Energy of PTC fields in Salto (left) and Montevideo (right), working at a mean temperature of 140ºC, with <u>*r*=8% and *T*=20 years</u>. Effective prices of Firewood and Fuel are included. The options 1,2 and 3 indicate the different possible situations of tax exemptions described in 3.4.

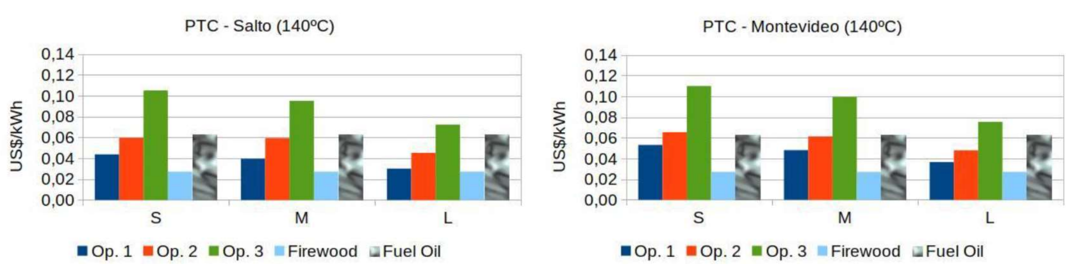

Fig. 11: LCOH of Solar Thermal Energy of PTC fields in Salto (left) and Montevideo (right), working at a mean temperature of 140ºC, with <u>r=12% and T=10 years</u>. Effective prices of Firewood and Fuel are included. The options 1,2 and 3 indicate the different possible situations of tax exemptions described in 3.4.

Figures 10 and 11 show the LCOH for PTC solar fields located in Salto (left) and Montevideo (right) respectively. In Fig. 10, r=8% and T=20 years were used, while in Fig. 11, r=12% and T=10 years were adopted.

The same trends as for LFT technology are observed, but with somewhat higher values of LCOH for all the cases. However, it is possible for PTC to compete against Fuel Oil if tax exemptions are considered (op. 1

and op. 2) for both sets of financial parameters and all plant sizes. Competitiveness against Firewood is only attained for large plant sizes located in Salto (best location) and with the most favorable tax exemption situation (op. 1).

5. Conclusions

Regarding the thermal performance of PTC and LFT technologies for process heat generation, it can be concluded that PTC generally present better optical behavior, both at normal and off-normal angles of incidence. On the other hand, LFT generally have lower thermal losses, due to having a somewhat more isolated absorber from the outside environment and a higher *Cr*. In case of disregarding night losses, PTC model outperforms LFT, for the same size of aperture area.

To complement the production of the different sizes of steam generators considered —70 kW, 4200 kW and 13000 kW—, it could be possible to replace around 25% of the annual production with solar fields with sizes of 75-95 m2, 4700-5700 m2 and 18000-23000 m2, respectively. PTC fields result smaller (in aperture area) than LFT fields. The corresponding investment costs are between US$ 35,000 and US$ 5-6 million.

Analyzing economic viability, it is noted that for all locations, as well for all levels of working temperature and sizes analyzed, Fresnel technology has better return on investment than the PTC. Furthermore, in certain scenarios taken into account in this study, the cost of the resulting solar kWh (LCOH) is lower than that produced by a conventional energy source (Fuel Oil). For the most favorable cases considered (LFT large plants, with high tax exemptions) competitiveness against Firewood is attained.

These results are promising with respect to thermo-economic performance of CSP technologies for process heat production in Uruguay. Further work is needed to refine the analysis, including cost and performance information for several models, as well as load profiles for specific industries. Furthermore, economic analysis including bank loans are also necessary, since these normally result in lower LCOH.

6. Acknowledgements

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