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Research article

Solar-powered chilling: Technical and economical analysis on individual air-conditioning with different solar collectors for Tunisian climate

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Abstract

This paper aims to analyse the technical and economical feasibility of solar driven air-cooled single effect LiBr-H_2O absorption domestic chillers adapted to Mediterranean climatic conditions in Tunisia. The solar cooling system is dynamically simulated in TRNSYS. The analysis is performed for two types of solar collectors (flat plate collectors and evacuated tube collectors). A parametric analysis is carried out in order to evaluate the sensitivity of the optimum collector area to relevant economical parameters. the technical and economical investigation show that the solar system coupled to the flat collectors is more economical than the system coupled to the evacuated tube collectors although the best efficiency of these collectors. In fact, the optimum evacuated tube collector area is 32 m² with a solar fraction of 72.6% and total annual cost, 1935.6 €. The optimal flat collector area is 50 m², the corresponding solar fraction, 62.7% and the amount of annual total cost is 1862 €. The results depend on fluctuant economical parameters. The sensitivity study shows that the optimum solar collector area is so sensitive to the unit price of the collectors and the discount rate.

Keywords: Solar-cooling, air-cooled LiBr-water chiller, TRNSYS, economical assessment, sensitivity analysis.

I. Introduction

Residential Buildings are increasingly air-conditioned caused a significant increase in demand of electric power reaching the capacity limits of network and causing the risk of blackouts (take place on July 2011 and August 2014 in Tunisia). Solar cooling is particularly promising because of primary energy saving and environmental concerns [1 – 5]. According to H.M. Henning [6] and R.Z. Wang [7], absorption chillers are the most used thermally driven cooling systems and the most dominant technology in solar cooling applications. The development of this technology is limited by the relatively high installation cost compared to the compression system. For arid and semi-arid regions with generally high solar radiation, but where water is scarce, the development of solar air-cooled chiller technology is the solution [8]. El May *et al.* [9] have investigated the technical feasibility of solar chilling using a single effect LiBr/H_2O air-cooled machine for Tunisian climate conditions. The appropriate operating conditions for the chiller have been found. A number of studies have assessed solar cooling technology based on its economic analysis and energy performance [10 – 11].

Hang *et al.* [12] presented a systematic energetic, economic, and environmental assessment on a solar cooling system for a medium-sized office building in Los Angeles, California by system modeling. The studied solar cooling system primarily consists in evacuated tube solar collectors, a hot water storage tank, a single-effect LiBr/H_2O absorption chiller, and a gas-fired auxiliary heater. Results show that a trade-off exists between economic and energetic / environmental performances indicated respectively by the equivalent uniform annual cost (EUAC) and the solar fraction / CO_2 reduction percentage.

Calise [13] demonstrated that solar heating and cooling systems can be competitive although the economic profitability is higher for the hottest climates. Eicker *et al.* [14] investigated an economic study and showed that solar thermal cooling is more viable in hot climates than in moderate European climates. Annual costs strongly depend on the locations. The specific costs per kWh cooling in German locations varies between 0.25 and 1.01 €/kWh and in Spanish locations between 0.13 and 0.30 €/kWh. Liqreina *et al.* [15] concluded that dry cooling of steam power blocks of concentrating solar power plants in sites with significant high direct and normal irradiation values is an attractive economic and technical option to be considered in the future for new projects planning.

In this paper, we will present a dynamic model of solar cooling system, using the solar applications software TRNSYS. The system is composed of solar collector field, a thermal make-up source provided by a gaz heater and hot water storage tank which is connected to single effect air-cooled LiBr-H_2O absorption chiller. The air-conditioner is designed for a middle class family house (100 m^2) under the climatic conditions of Tunis City. The objective of this study is to compare the technical and economical feasibility of solar absorption cooling system connected to: flat collectors in the first case and tube evacuated collectors in the second case. The economical investigation depends on the fluctuant economical parameters. Therefore, this study is completed by a sensitivity analysis in order to identify the most sensitive parameters to the optimum collector area.

II. Solar cooling system

A solar assisted air conditioning system is based on the coupling of an air-cooled LiBr / H_2O absorption chiller with a solar thermal system including solar collectors, thermal storage tank, pumps, thermostat controllers and auxiliary thermal energy source (Fig. 1). The air-conditioner is designed for a middle class family house (100 m^2) under the climatic conditions of Tunis City.

III. System simulation

The building's cooling loads for a period extending from May to October and indoor temperature of 26°C is calculated using the software TRNSYS. Based on the evolution of cooling demand illustrated in Fig.2, a peak cooling load of 10.7 kW is detected at hour: 5035 (on July). We adjust the nominal cooling capacity of the air-conditioner to 10 kW. The energy needs that must be supplied to the generator are fixed to 11.87 kW for a nominal *COP* of 0.67. The hot water storage tank volume is 1m^3 [9]. The temperature of the hot water in the top of the storage tank is maintained at 110°C and a mass flow rate of 0.7 kg/s. The heat to be supplied in the auxiliary heat exchanger depends on the inlet temperature of the fluid and on the set-point outlet temperature.

The TRNSYS main components (Fig.3) used in the simulations are:

- Weather data unit : Type 109 - TMY2 ;
- Psychometrics data : Type 33 ;
- Sky temperature : Type 69 ;
- Evacuated tube collectors (Type 71) and flat collectors (Type 1) ;
- Pump : Type 3 ;
- On/off differential control : Type 2 ;
- Thermal storage tank : Type 4 ;
- Auxiliary Heater : Type 659 ;
- Building: Type 56.

IV. Simulation results

Figure 4 shows the influence of the collector area on the solar gain and auxiliary heat required for flat collectors and evacuated tube collectors. The technical features of collectors are reported in table 1 .The auxiliary heat power varies between 1.93 kW and 10.56 kW for flat collectors and from 3.43 kW to 13.4 kW for evacuated tube collectors. The maximum solar fraction ($f = 1 - \frac{Q_{AUX}}{Q_{GEN}}$) is 0.74 with 56 m² of flat collector area and 0.84 with 40 m² of evacuated tube collector area (Fig.5). Then energy made from fossil fuel is always necessary to heat the pressurized water to the required set-point temperature of 110°C. The performance of evacuated tube collectors is better compared to flat plate collector in high temperature applications. So, the evacuated tube is considered to be an important component in thermal application, particularly in solar water heating systems.

Technical and economical studies are required to find out the optimal solar collector size

V. Technical and economical optimization

Technical and economical optimization is carried out in order to evaluate the optimum collector area of two solar systems.

a. Economic analysis

The total costs represent the sum of the updated capital and the updated operating. It is reported on a yearly base, depending on the expected life of the system and on the discount rate and expressed as

$$C_{tot} = C_{cap,up} + C_{op,up}$$

where the updated capital cost is

$$C_{cap,up} = C_{cap}\frac{i\,(1+i)^t}{(1+i)^t - 1}$$

C_{cap} is calculated by summing the investment cost of each solar system component :

- Unit price of flat plate collectors is 227.3 €/m^2;
- Unit price of evacuated tube collectors is 453.54 €/m^2;
- Unit price of storage tank is 1.5 €/l;
- Pumps, valves, pipes, system control is 20% of C_{cap}.

The updated operating cost of natural gas is calculated us:

$$C_{op,up} = \frac{i\,(1+i)^t}{(1+i)^t - 1}\sum_t C_{op}\,(1+i)^{-t}(1+\alpha)^t$$

For the evaluation of the operating cost, the natural gas tariff and the corresponding taxes are considered for a Tunisian user:

- The price of 1 kWh of primary energy produced by the combustion of natural gas is 0.013 €;
- i: Discount rate equal to 6.68 %;
- t: Lifespan (25 years);
- α: The increase rate in natural gas price (7.5 %);

b. Results & discussions

Figure 6 shows that the total cost reaches a minimum of 1862 € for a collector area of 50 m^2 and solar fraction of 62.7%. For the solar system coupled to the evacuated tube collectors, this cost leads to minimum fees of about 1935.6 € for 32m² collector surfaces. Such area covers 72.6% of the required heat.

Results show that the minimum cost for a solar installation coupled with flat plate collectors is lower than the system coupled with the evacuated tube collectors while the collector surface is more important.

The simulation software calculates the dynamic trends of temperatures and heat flows for all components of the system. In Fig.7 and Fig.8 are reported respectively temperatures and energy flows for just one random summer day. In the first case, the maximum temperature in the inlet of the generator is around to the set point temperature (110°C) and the maximum solar heat is 17 kW (at 13 hr). It is therefore necessary to use an auxiliary gas natural energy. However, in the solar system coupled to 32 m^2 of evacuated tube collectors (second case), we detect that the maximum solar heat is 19.4 kW which is significantly higher than the first case. The maximum temperature in the outlet of the collector field reaches a value of 126°C, higher than the demanded set point temperature. This is due to the higher efficiency of the evacuated tube collectors.

It is clear that the solar energy provided from evacuated tube collectors is available for a longer period (11hr) than the flat collector solar system (5hr). Its value is also significantly high (Q_{gain} = 145 kWh from evacuated tube field and Q_{gain} = 69.56 kWh from flat collectors).

The solar fraction depends on the solar collector area. The optimum value of the collector surface depends on technical and economical parameters such as the unit price of solar collector which may change from a provider to another (it is possible to consider costs reduction). The discount rate and the increase rate in natural gas price are related to political and economical developments. For that reason a sensitivity analysis is investigated in order to evaluate the effect of these parameters on the optimum collector area and the total cost of the two cases.

VI. Sensitivity analysis

The objective of this study is to identify which parameter is the more sensitive to the optimum solar cooling area.

In Figure 9, we detect that for a lifespan of solar system coupled to the flat collectors and that connected to the evacuated tube collectors respectively less than 18 years and 16 years, the solar cooling system is not economically viable.

For a lifetime of 24 years, the optimal flat collector area is equal to 50 m^2 for a minimum annual total cost of 1861.8 €. In the case of evacuated tube collector the higher the lifespan, the lower the amount of total annual cost.

It is interesting to note that the increase in the lifespan (more than 24 years) of the solar cooling system coupled to the flat plate collectors is not the best economical solution because of the high investment and the low efficiency of the considered collectors. In all cases, the total annual cost of the solar system connected to the evacuated tube collectors is the highest.

The figure 10 illustrates the trends of optimum collector area and the total cost vs. the unit price of collectors. The total annual costs of both cases increase linearly vs. the unit price of collectors, while the optimum collector area decreases. The optimum flat collector area and evacuated tube area range respectively from a maximum of 56 m^2 to a minimum of a 50 m^2, and from a maximum of 38 m^2 to a minimum of a 32 m^2 while the unit price varies respectively between 200 € and 227.3 € and between 227.3 € and 409 €. We deduce that the optimum collector area is too sensitive to the unit price of both types of collectors

Figure 11 depicts that in the a discount rate range 6.6% and 7.8% for flat collectors then 7% and 7.7% for evacuated tube collectors systems, the optimum collector area does not change whereas the total annual cost increase linearly. The optimum collector areas in the two configurations become more sensitive for a discount rate value higher than 7.8%.

Figure 12 shows that for the values of increasing rate in natural gas price less than 5.2% (flat collectors) and 6% (evacuated tube collectors), the solar cooling system is not economically viable. We note also that the optimum collector areas are more sensitive between 5.2% and 6.4% in the case of flat collectors then between 6% and 6.4% for evacuated tube collectors. In addition a slight increase of collector area for value higher than 6.4% is also detected in both configurations. While the total annual cost increase linearly vs. the increase rate in natural gas price.

VII. Conclusion

In this paper, a dynamic model of a solar cooling system for a middle class family house was presented under the climatic conditions of Tunis City. The system evaluated is based on the combination of solar and natural gas energy sources. Two types of solar collectors were considered. In addition the use of single effect air-cooled absorption chiller is proposed. In all cases, primary energy savings higher than 70% were achieved and very interesting economic results were also obtained. In the case of solar cooling system coupled to evacuated tube collectors, the technical and economical investigation showed that the optimum collector area is 32 m² with a solar fraction of 72.6% and total annual cost of 1935.6 €. In The case of flat plate collectors, the optimum area is equal to 50 m², the corresponding solar fraction is 62.7% and the amount of annual total cost is 1862.18 €.

When we compare the annual total cost of the two configurations, it is shown that the solar cooling system coupled to flat collectors is the most economical solution. However, the corresponding optimum collector area is more important, it represents half of the floor area of the villa which causes a problem for the installation of the collectors according to state of the art. In addition the primary energy savings is higher in the case of solar cooling system coupled to evacuated tube collectors. As a consequence, this configuration is better.

Finally, the sensitivity analysis shows that the optimum collector surface is dramatically sensitive to the unit collector price and the discount rate.

Figure captions

Figure 1: Schema of a solar driven LiBr-water single effect absorption air conditioning system.

Figure 2: Evolution of cooling needs during the simulation period (from May to October)

Figure 3: TRNSYS Platform.

Figure 4: Solar and gas energy needs vs. collector area.

Figure 5: Evolution of the solar fraction vs. flat plate and evacuated tube collector area.

Figure 6: Economic results vs. collector area.

Figure 7: Temperature trend for a typical summer day for 50 m^2 of flat plate collector (a) ; 32 m² of evacuated tube collector area (b).

Figure 8: Energy trend for a typical summer day for 50 m² of flat collector area (a) ; 32 m² of evacuated tube collector area (b).

Figure 9: Optimum collector area vs. lifespan solar system.

Figure 10: Optimum collector area trends for different collector’s unit price.

Figure 11: Optimum collector area trends vs. discount rate.

Figure 12: Optimum collector area trend vs. increase rate in natural gas price.

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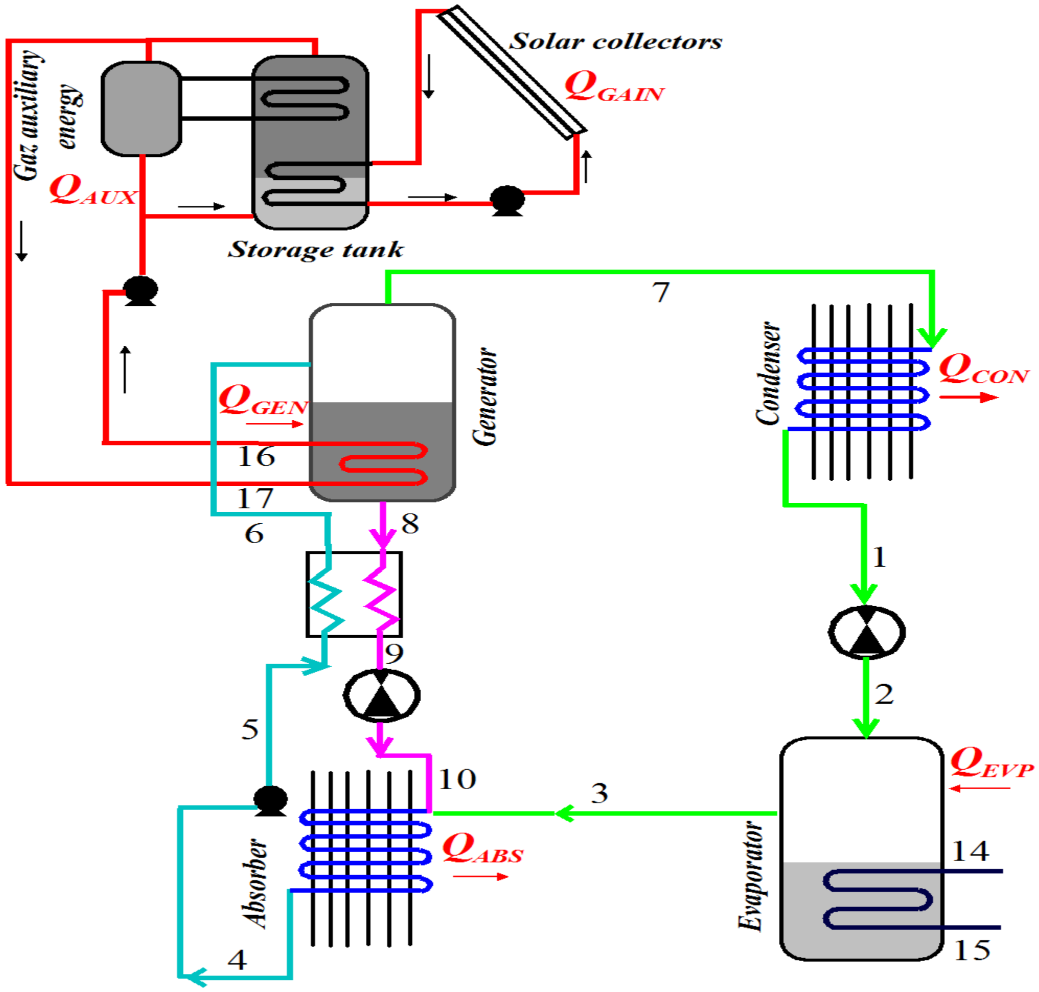

Fig.1: Schema of a solar driven LiBr-water single effect absorption air conditioning system.

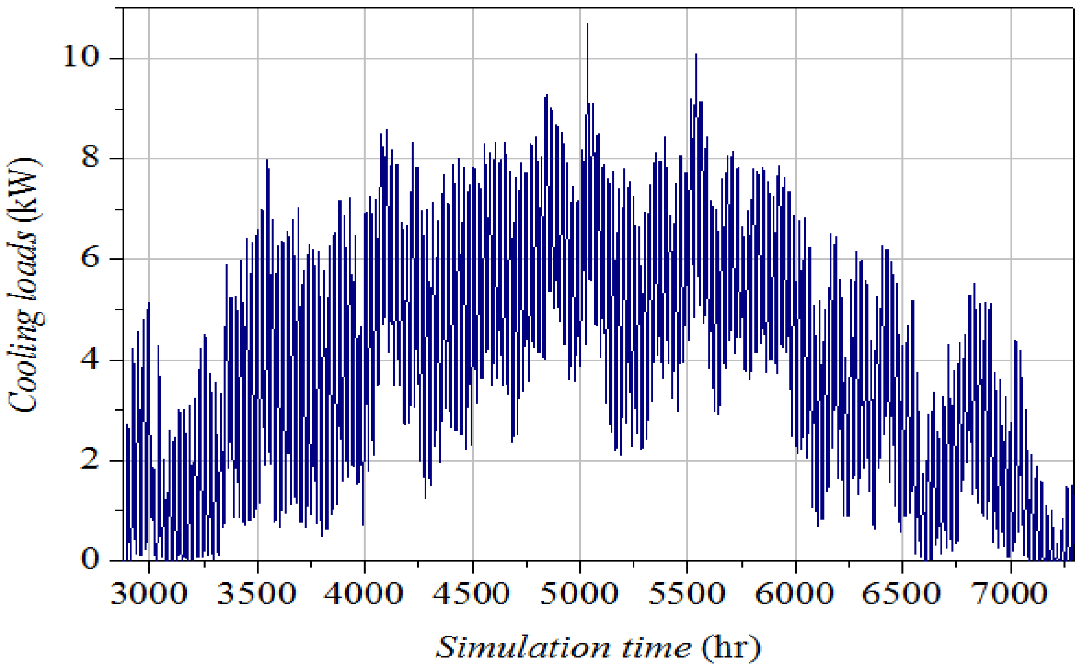

Fig.2: Evolution of cooling needs during the simulation period (from May to October).

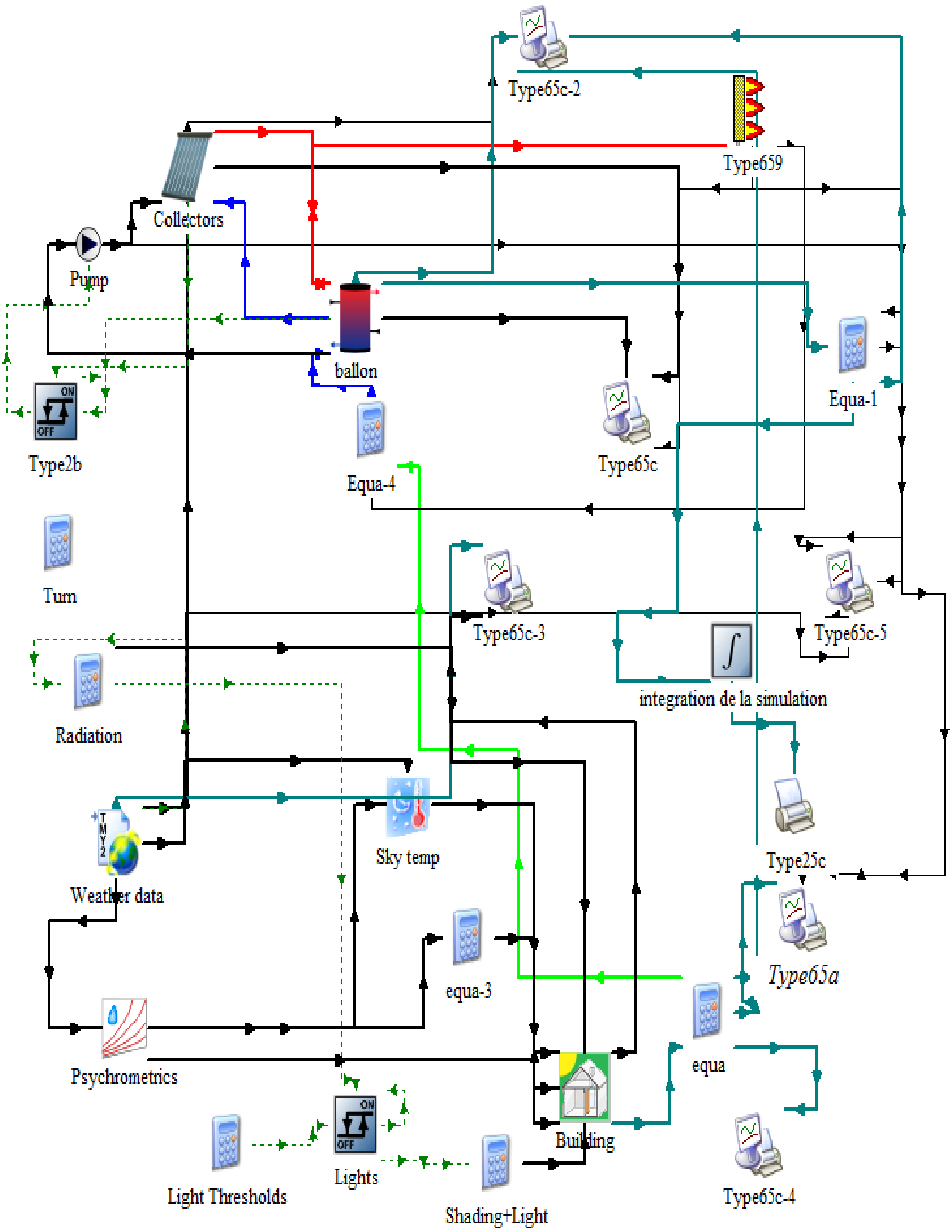

Fig.3: TRNSYS Platform.

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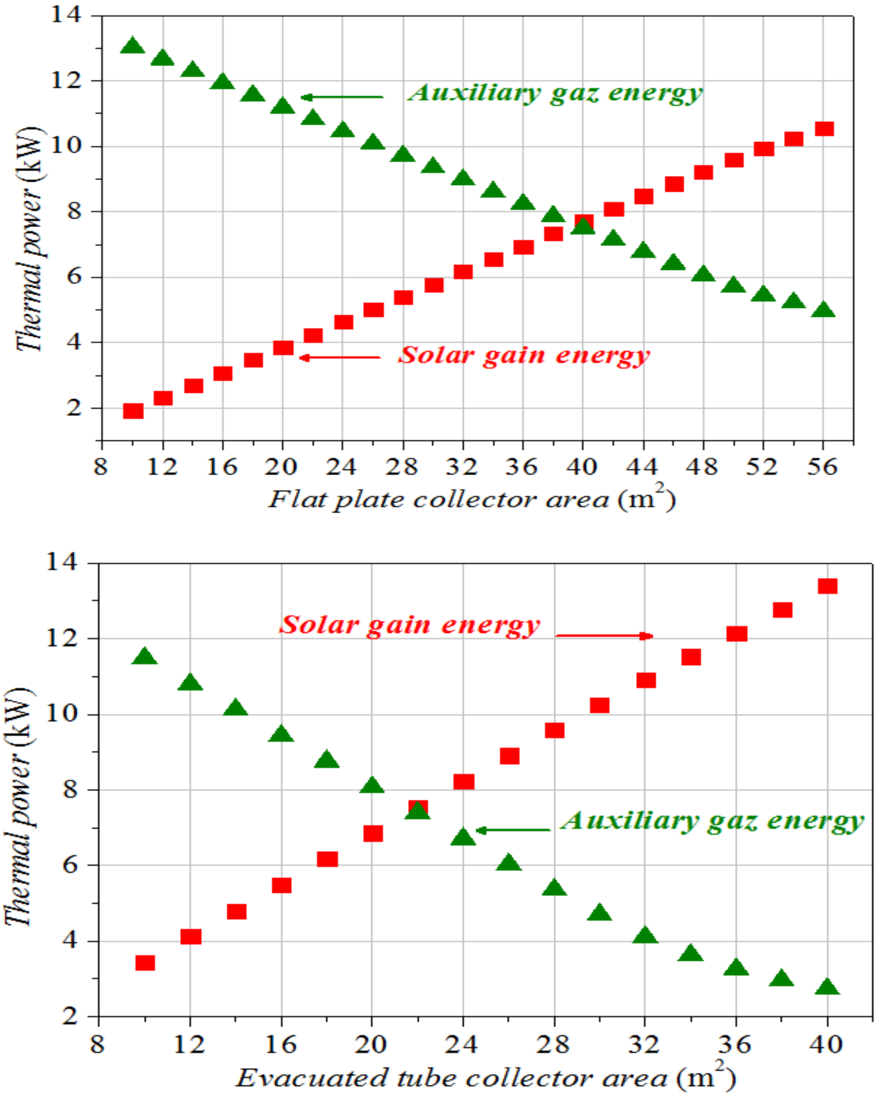

Fig.4: Solar and gas energy needs vs. collector area.

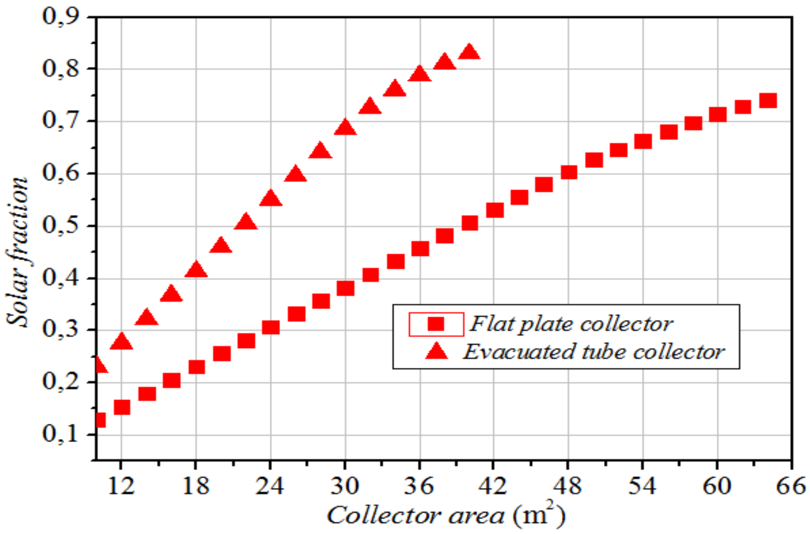

Fig.5: Evolution of the solar fraction vs. flat plate and evacuated tube collector area.

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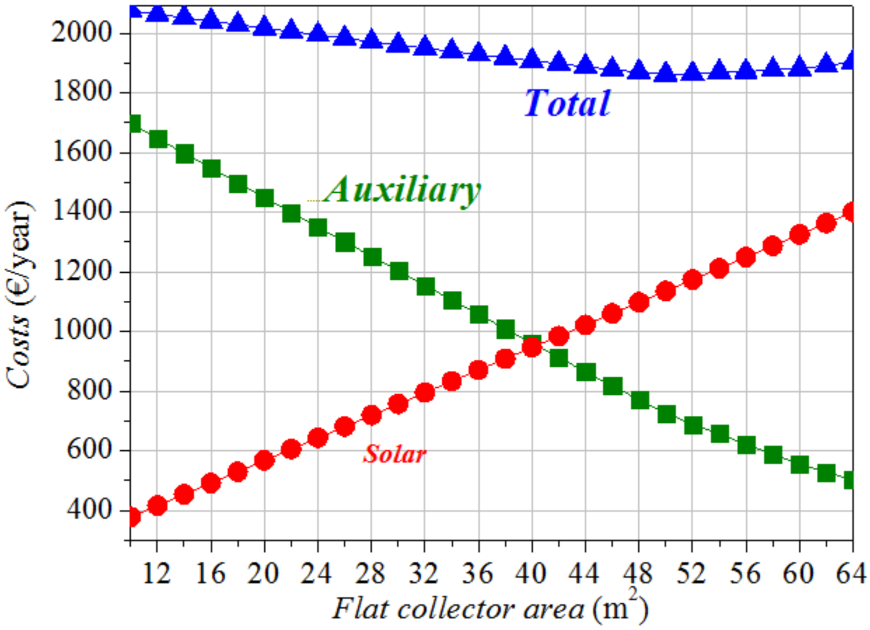

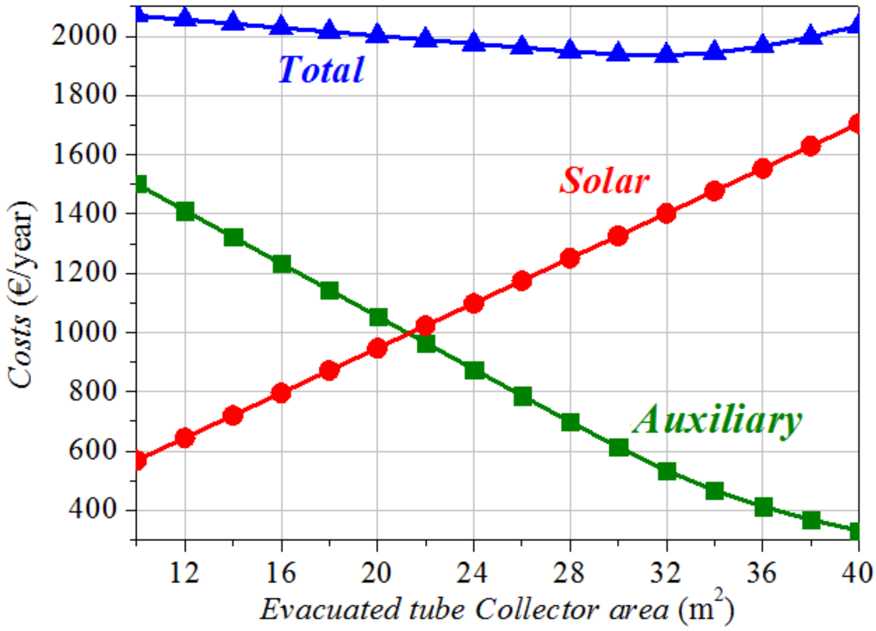

Fig.6: Economic results vs. collector area.

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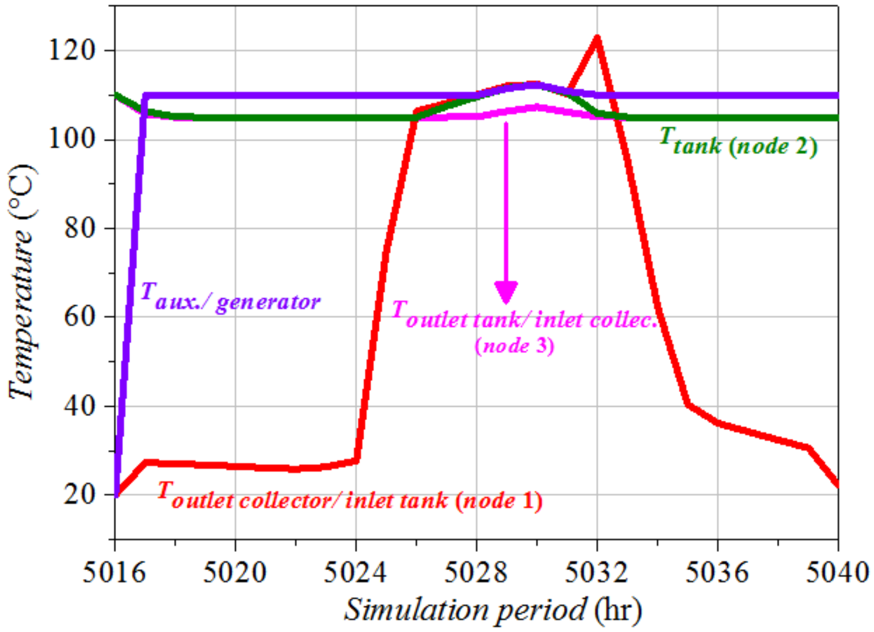
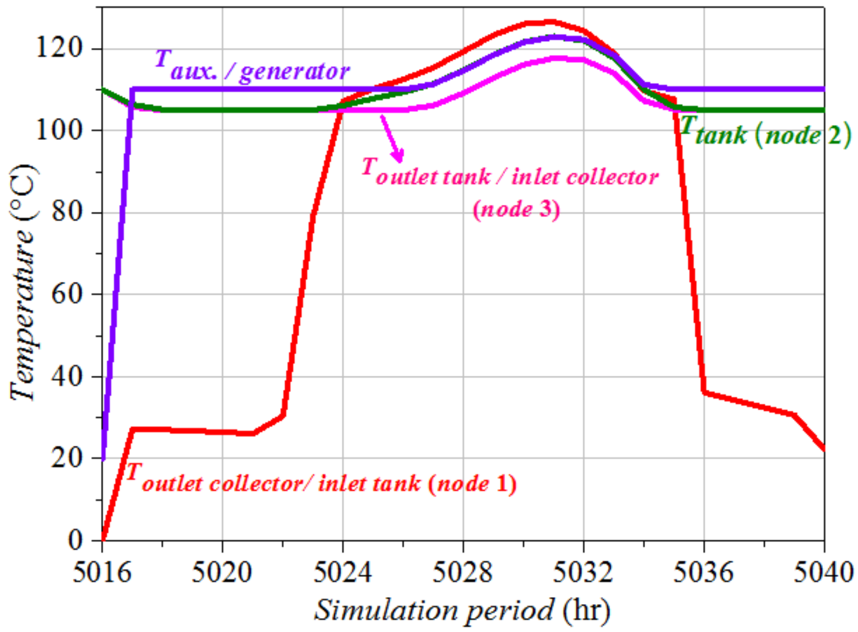


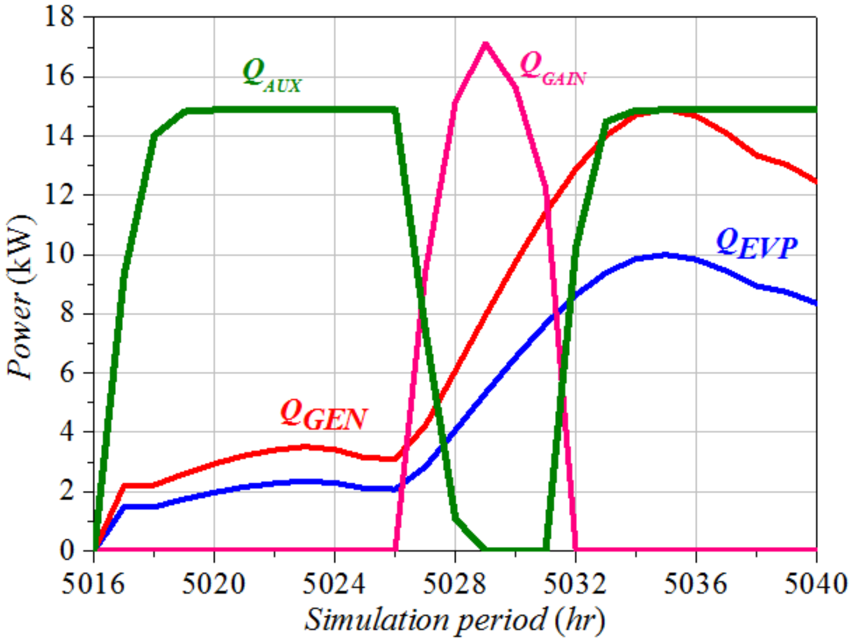
(a)

(a)

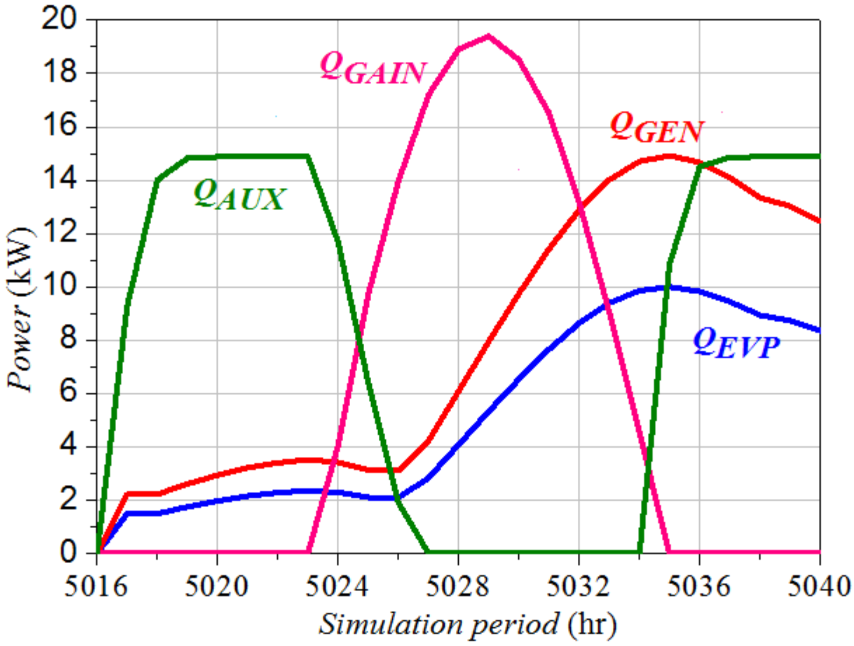


(b)

Fig.7: Temperature trend for a typical summer day for 50 m^2 of flat plate collector (a) ; 32 m^2 of evacuated tube collector area (b).



(a)



(b)

Fig.8: Energy trend for a typical summer day for 50 m² of flat collector area (a); 32 m² of evacuated tube collector area (b).

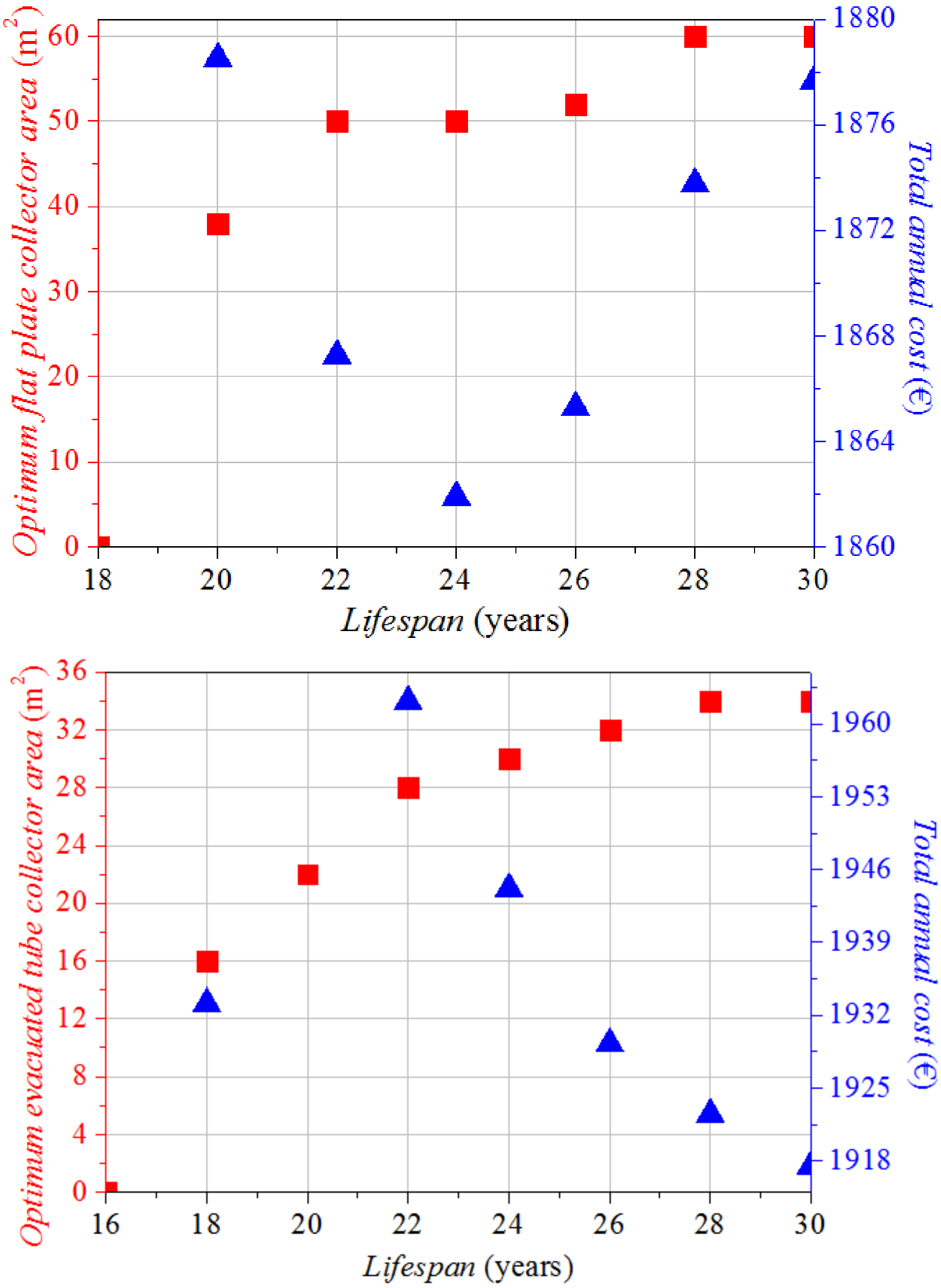


Fig.9: Optimum collector area vs. lifespan solar system.

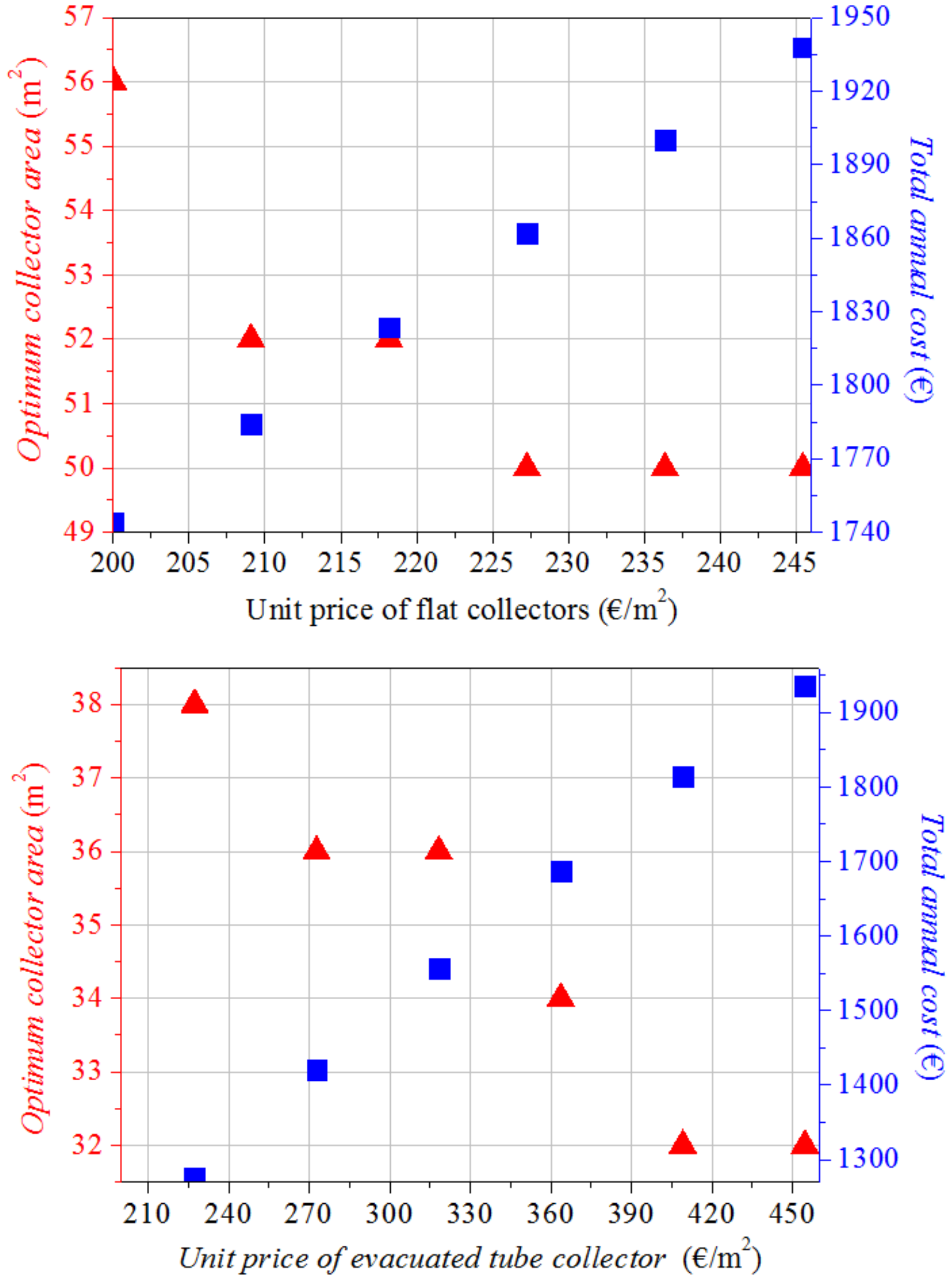


Fig.10: Optimum collector area trends for different collector's unit price.

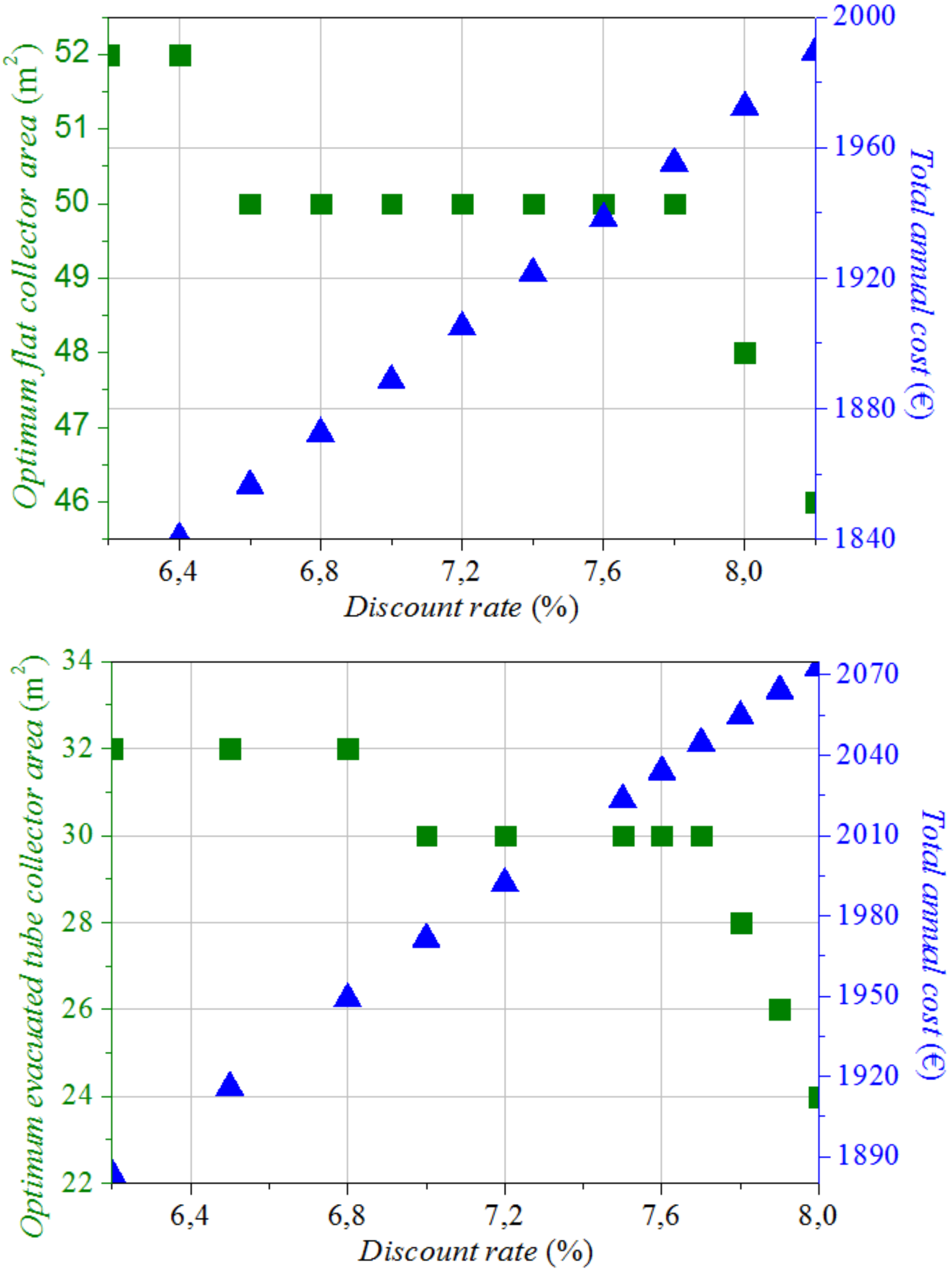


Fig.11 : Optimum collector area trends vs. discount rate.

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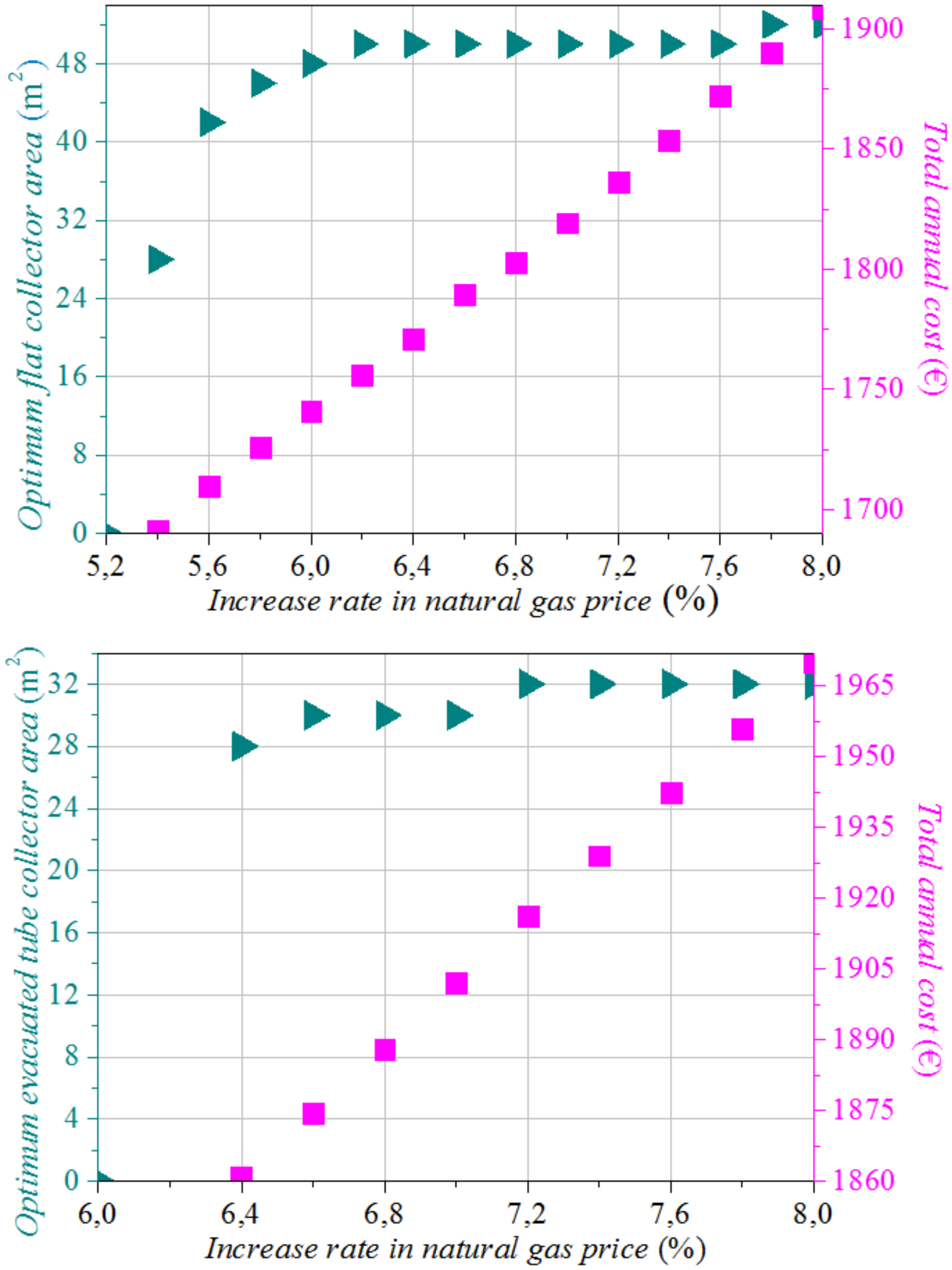

Fig.12: Optimum collector area trend vs. increase rate in natural gas price.

Table 1: Collectors technical features

model	Evacuated tube collector	flat collector
Type	ThermomaxMazdon 20-TMA 600S	C8/8S
Absorber surface (m^2)	2.027	2
$\eta 0$	0.804	0.76
a1(W/m^2K)	1.15	4.003
a2(W/m^2K^2)	0.0061	0.015

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