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Energy and economic assessment of a solar air-conditioning process for thermal comfort requirements

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Abstract

This paper investigates the energetic performance of solar air-conditioning by absorption chiller applied for building sector in Morocco. The combined effects of cooling profiles (Morning, Day and Morning), building categories (residential house, building office and hotel) and collector's technology on the potential of solar cooling installation operating under various meteorological conditions (Fez (Z3), Marrakech (Z5) and Zagora (Z6)) were assessed. It is found that it is possible to save in costs of produced cooling energy for the studied zones when electricity is used as auxiliary backup for annual solar fractions between 40% and 70%. A solar fraction of 70% each year can provide between 25% and 50% as a minimization of exploitation costs between 25% and 50%. Taking into consideration the present Moroccan costs of energy resources, it is highly recommended that the costs of solar cooling equipments, especially solar collectors and absorption machines, are more decreased to become more used for both domestic and industrial sectors.

Keywords: Solar cooling; Absorption chiller; Cooling profiles; Economic assessment; Dynamic simulations; Performance optimization.

1. Introduction

Nowadays, the electrical energy consumption takes a huge part in the building sector and a determinant gateway to ecological problems (Pérez-Lombard et al., 2008). Indeed, the building sector represents 25% of total CO_2 emissions (Bouhal et al., 2017a). Progressively, the participation of alternative energies is necessary to reduce CO_2 emissions and achieve the goals of energy saving set by the several authorities. Owing to the expensive cost of fossil fuels and significant greenhouse emissions caused by the high use of air-conditioning installations for both residential and industrial buildings, the use of solar energy to drive refrigeration systems represents an attractive alternative while the cooling load is totally in phase with solar energy potential (Henning, 2007). Solar cooling

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is an advantageous option because it has the possibility of removing the majority of weaknesses of conventional air-conditioning installations and that the peaks of requirements in cooling are coincidence with the availability of the solar radiation (Kim and Ferreira, 2008).

In this way, research community has two main trends. Thus, the first interests in the building itself in order to reduce heat gains through the building covering and optimize the use of natural heat sinks (Santamouris et al., 2007). While the second is dealing with the development of technologies that can allow reductions in energy consumption, energy costs and peaks in electrical demand without decreasing the required level of comfort conditions. While this study is concerned by the solar cooling production, it is vital to consider the impact of solar hot water generation from a system perspective. Several numerical experimental investigations have shown the performance of fully integrated solar air-conditioning systems, and used the overall system performance as an approach of assessment (Sarbu and Sebarchievici, 2013).

Research on the solar cooling systems is numerous and diversified in the literature in terms of experimental and numerical studies. Semmari et al. (2017) conducted a case study to validate experimentally a new scaling tool for closed solar heating, solar cooling and hot water systems. Moreover, Araújo and Pereira (2017) developed a mathematical model for fast evaluation of auxiliary power demands in water heating production with off-on flow rate managment. Their solar thermal modeling take into account the overall flow elements like collector surface, storage heat and solar fraction. In addition, Carotenuto et al. (2017) carried out technico-economic analysis and dynamic simulation of a novel solar cooling and solar-geothermal district and water heating system. Their results show that solar energy and geothermal are only used to match the thermal needs of the district users in winter and a public funding is needed to make the system economically feasible. Several technical and economic studies can be found in the literature dealing with the solar air-conditioning systems and their thermal performance improvement. In Europe, the economic and energy aspects of an solar absorption integrated heating and cooling system in different types of buildings were examined in different locations: Berlin (Germany), Lisbon (Portugal), and Rome (Italy) (Mateus and Oliveira, 2009).

In some Maghreb countries, the technico-economic feasibility of these systems has been examined according to the published reports. Balghouthi et al. (2008) evaluated the performance of solar absorption cooling installation in Tunisia. They assessed a process for a 150 m^2 building area composed of an absorption machine of a capacity of 11 kW using H_2O-LiBr as a working fluid, a 0.8 m^3 hot water storage tank and a 30 m^2 of FPC surface. At Moroccan level, Allouhi et al. (2015) established annual simulations in six Moroccan climatic zones and a financial and environmental assessments of solar cooling systems. The results show that these systems must be possible options to enhance energy savings and reduce CO_2 emissions especially in hot climates. Accordingly, Agrouaz et al. (2017) conducted an energy and parametric analysis of solar absorption air-conditioning cycles in different Moroccan sites. They found that the COP values in some locations have a significant variation from 0.12 to 0.33 all over the year. Recently, Bouhal et al. (2018b) conducted a technico-economic analysis and investment risk assessment of solar DHW production, heating and air-conditioning process for building applications in Morocco. The results indicate that solar contribution has improved from 605 kWh to 705 kWh in summer and winter periods, respectively, while the auxiliary backup has achieved 1450 kWh, 1875 kWh and 2300 kWh for Z1

(Agadir), Z2 (Tangier) and Z5 (Ben Guerir), respectively.

Determining the daily demand profile is inspected as a determinant parameter on the solar air-conditioning designing (Fong et al., 2010). Parametric studies regarding the impact of the cooling load profile on the energy savings of solar cooling systems are less published despite their primordial importance. This paper evaluates the combined impacts of cooling load profiles, building categories and collector's technology (Flat Plate FPC and Evacuated Tube ETC) on the performance of solar air-conditioning process functioning under diverse weather cases. The Transol software tool was used as a basis of simulations. Various building categories were evaluated: residential (residential house), building office and hotel and different Moroccan zones and climates were considered: Fez (Zone 3), Marrakech (Zone 5) and Zagora (Zone 6) known as the hottest regions in Morocco. The study also evidences the influence of the cooling load demand on the annual fractional savings of solar air-conditioning system using energy and economic indicators.

2. Simulation methodology

2.1. Context and background

In the last few years, summer temperatures and rising comfort requirements have led to significant use of traditional cooling in Morocco. This progress in cooling is responsible for important peaks of electricity consumption especially in summer. These possible cooling effects are related to traditional refrigeration techniques, highlighting the brutal cycle of climate change and increasing greenhouse gas emissions (Bouhal et al., 2017c). In addition, the use of cooling technologies in the summer season leads to a high energy consumption which generates inevitable instabilities between the electricity production and the energy demand.

Therefore, the growth of renewable energies is an important preference in Moroccan energy strategy. Indeed, it is the efficient way to optimize the energy use while decreasing our energy invoices. Thus, the objective of this strategy is to accomplish 15% of energy savings by 2020 in terms of energy efficiency (Bouhal et al., 2018a). Accordingly, the energy consumption in Moroccan building sector accounts for 35% of the total energy used which has been rised in current years with the development of the national economy.

The solar air-conditioning system configuration consists of a solar air-conditioning absorption machine with a distribution circuit of cold/hot water to the load using solar collectors and a hot water storage tank. When there is no insolation, an electric or a gas boiler backups were used to provide hot water which directly used to drive the absorption water chiller as presented in Fig. 1-(a). The energy interaction of the solar air-conditioning absorption chiller with linked components and their typical boundary temperatures with the absorption machine (RXZ - 11.5 kW) implemented in Green Energy Park (gre) is presented in Fig. 1-(b).

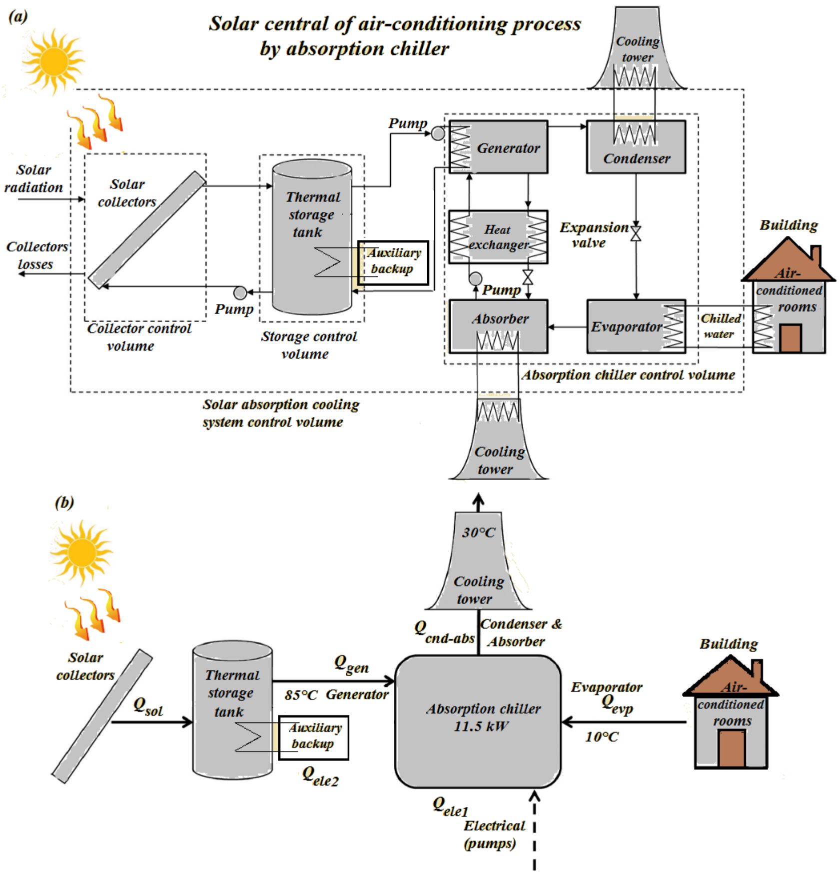

Figure 1: Schematic of solar central absorption cooling system (a) and energy interaction with linked components (b) for indoor space air-conditioning in Morocco (gre)

At the Moroccan level, a solar cooling prototype has been funded by the Research Institute for Solar Energy and New Energies (IRE) and focuses on the integration of solar air-conditioning technologies in Moroccan building sector using low power refrigeration systems in the range of 11.5 kW which is the first solar cooling prototype implemented in Morocco.

Transol software was used to carry out the dynamic simulations which uses the transient simulation tool TRNSYS power (TRN) to size the solar thermal systems connected to the building. Besides using Transol existing system components, technical parameters for absorption chiller using real COP values taken from the manufacturer data base (luc) were introduced allowing the model to operate for a whole year operating in cooling mode.

The technical characteristics of the solar cooling absorption machine implemented in Green Energy Park (GEP) are included in the Table 1.

Model		RXZ – 11.5	
Cooling power		11.5 kW	
	Hot water	Chilled water	Cooling water
Flow rate	2.8 m^3/h	2.0 m^3/h	4.8 m^3/h
Inlet/Outlet Temp.	90°C/85°C	15°C/10°C	30°C/35°C
Linking diameter	DN40	DN32	DN40
Loss of pressure	50 kPa	40 kPa	50 kPa
Power consumption		0.3 kW	
Cooling capacity adjusting range		20 - 100%	
Dimension	Length	1010 mm	
	Width	785 mm	
	Height	1622 mm	
Shipping weight		700 kg	

Table 1: Technical characteristics of solar cooling absorption chiller (luc)

For this absorption machine, the fouling factor is 0.086 m^2K/kW and the standard manometric pressure limit for cooling/chilled water is below 0.8 MPa.

The performance and the intrinsic characterestics of the absorption chiller for solar cooling (11.5 kW) including the curves of cooling capacity at different temperature points (generator, absorber and evaporator) are presented in Fig. 2. When performing the numerical simulations, the absorption chiller behavior is considered as variable knowing that the cooling capacity changes depending on both the cold and hot sources (see Fig. 2).

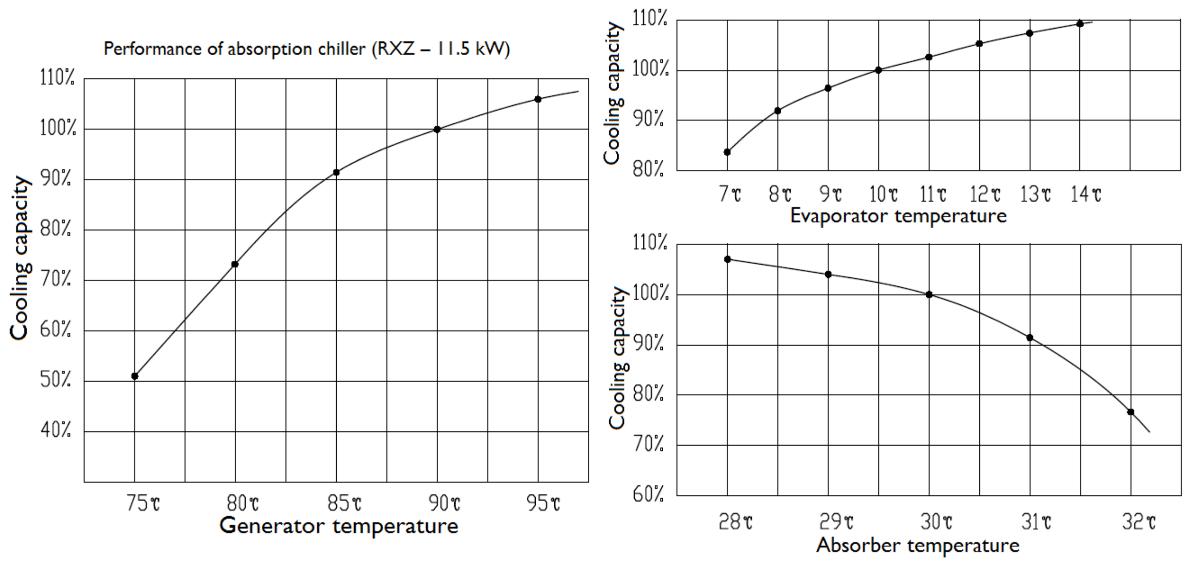

Figure 2: Performance and the intrinsic characterestics of the absorption chiller for solar cooling (Model RXZ – 11.5 kW, (luc))

In the present work, the solar collector types investigated are Evacuated Tube Collectors (ETC) without concentration and Flat Plate Collectors (FPC) with selective coating. Table 2 lists the technical characteristics adopted for both collector types in the simulations.

Parameters	Value		Unit
	FPC	ETC	
Collector absorber area	2.67	2.67	$[m^2]$
Optical efficiency η_0	0.735	0.821	[-]
Loss coefficient k_1	4.6	2.82	$[\text{W}/m^2.°\text{C}]$
Loss coefficient k_2	0.0164	0.0047	$[\text{W}/m^2.°C^2]$

Table 2: Technical parameters of solar thermal collector's (Agrouaz et al., 2017; vie)

The objective of this paper is to perform a technico-economic optimization based on dynamic simulations to upgrade the "cost/efficiency" ratio of a standard solar cooling absorption chiller (see Fig. 6) an 11.5 kW cooling capacity adopted as a prototype for solar cooling generation in a green energy park (GEP) in Ben Guerir (gre). As a result, the combined impacts of climate data, cooling demand profiles, sensor technology and the technical characteristics of the other components on the potential of the solar cooling system under Moroccan conditions were examined. The numerical simulations were carried out using Transol which is a sizing tool for solar thermal systems based on TRNSYS platform (TRN).

2.2. Description of building categories

The Kingdom of Morocco is facing increasingly high electricity consumption which is largely of fossil origin With an estimated increase of an average 5.3% (one). The country is experiencing a very high rate of dependence on energy about 93% (Bouhal et al., 2018a). However, Morocco has enormous potential for solar energy represented by an average solar insolation of 5 kWh/m^2/day and more than 3000 h/year of sunshine. Hence, this possibility can be exploited to ensure the convenience of air conditioning by reducing energy bills and preserving the environment. In the context of this investigation, three categories of building were investigated in the simulations as they have different thermal output ranges: a residential house representing a lower power scale, an office building and a hotel accounting for middle power range as shown in Fig. 3. The air-conditioning system was defined based on the climatic data of the considered cities namely; Marrakech (Z5), Fez (Z3) and Zagora (Z6).

Figure 3: Categories of building considered in the present work located in Morocco: (a)- Residential house, (b)- Office building and (c)- Hotel

The main characteristics of these building categories which fit to the requirements of the thermal regulations in Morocco (ame) are listed below:

- **The residential house** has a global area of 200 m^2 with a floor's height of 2.3 m. The glazing surface for the South and North façades accounts for 8% of façade surface. In West and East walls don't contain any glazing.
- **The office building** is designed by one floor with a global area of 400 m^2 with a height of 2.54 m and an East West main axis. The glazing area accounts for 35% of the South and North façades and 8% of the East façade and West façade is considered without glazing.
- The **hotel** is constructed by two floors and each one with an area of 360 m^2 with a height 2.6 m and where the main building axis is North South. The glazed area for the South and North façades accounts for 3% for the East and West façades and 20% of façade surface while the cooled rooms has 55% of the total area. Only one floor is considered for the thermal load for the air-conditioning system.

2.3. Weather data and cooling loads for simulations

Six climatic regions have been defined by AMEE (Moroccan Agency for Energy Efficiency) where each region is referred by a representative city for the application of a new thermal regulation for construction in Morocco (ame). For an efficient investigation, three reference cities are considered in the present study which are Fez ($34°03'$ N $4°58'$ W, Zone 3), Marrakech ($31°$ $37'$ N $8°$ $00'$ W, Zone 5) and Zagora ($31°$ $55'$ N $4°$ $25'$ W, Zone 6) because they have a very hot weather during summer which mean that the cooling requirements are important. The main weather data regarding the average values of solar radiation incident on the solar field, the ambient temperature of the climatic zones is provided in Fig. 4-(a), (b) and (c) as they have produced by Meteonorm Software 7.0. The estimated cooling needs (taking into account several factors such as internal and external gains and occupancy) are depicted in Fig. 4-(d).

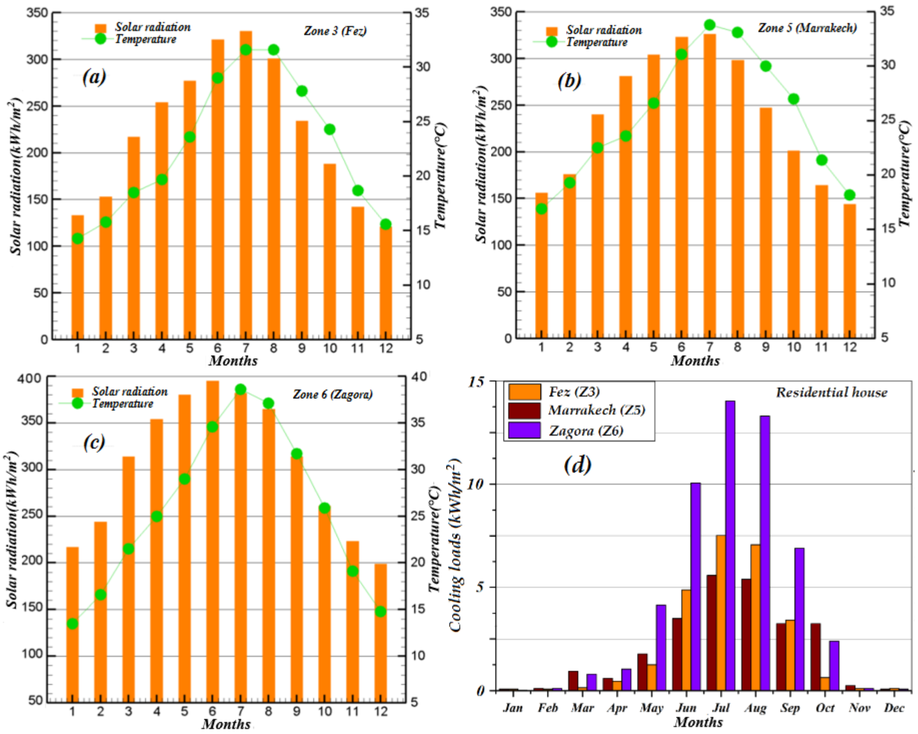

Figure 4: Weather data and monthly cooling loads of the studied Moroccan zones for residantial house ame

It is interesting to mention that annual simulations were carried out hour by hour using Transol which is a numerical tool used to size solar thermal systems based on TRNSYS software (TRN). Indeed, the model develops hourly simulations even though the ambient conditions and cooling loads are presented from mean monthly data as shown in Fig. 4. The numerical models are able to run for a whole year (365 days), according to control rules operating in cooling modes and considering that the ambient conditions and the building loads are variable along the day.

The maximum loads for each building category and its energy requirements are given in Table 3.

Building category	Zone	Cooling		
		Energy demands (kWh/m^2)	Required power (W/m^2)	Number of hours (h)
Residential house	Fez (Z3)	18	19	1286
	Marrakech (Z5)	20	22	1408
	Zagora (Z6)	24	28	1674
Office building	Fez (Z3)	32	34	1024
	Marrakech (Z5)	33	35	1032
	Zagora (Z6)	38	39	1112
Hotel	Fez (Z3)	35	37	1065
	Marrakech (Z5)	38	40	1085
	Zagora (Z6)	41	42	1103

Table 3: Energy requirements and thermal loads in the studied Moroccan regions

The cooling demand profile depends on user's behavior and the location where the simulation is performed. We have estimated the cooling consumption profiles for a typical residence (residential house). A simple user load profile is considered which concentrates air-conditioning needs during three moments per day (Morning, Evening and Day) as shown in Figs. 5. Solar air-conditioning systems reported in the reviews used in general constant cooling consumption during the night and day Syed et al. (2005) but several profiles are possible depending on the building function and the user needs. According to the solar radiation profile, the cooling demands are selected to be in phase simulating daytime cooling (Morning profile), on of phase cooling profile representing nighttime air-conditioning (Evening cooling) and flat demand profile simulating constant cooling (Day profile).

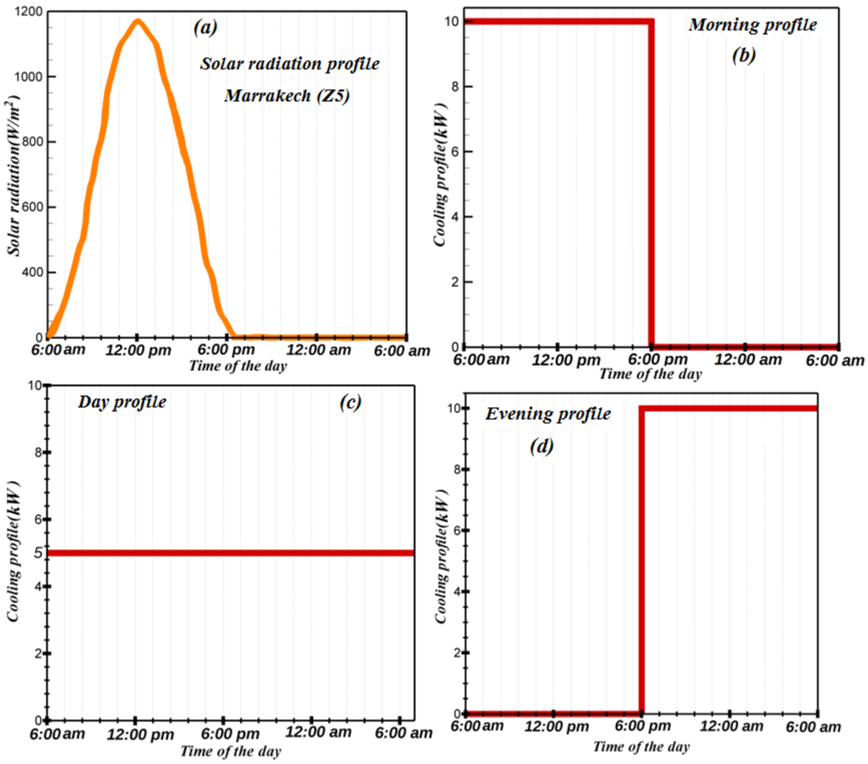

Figure 5: Solar radiation (a) and cooling loads profiles considered in the simulations: (b): Morning, (c)- Evening and (d)- Day

3. Mathematical formulation of solar air-conditioning system

The solar air-conditioning installation designed in the framework of the project of Solar Cooling Process in Morocco (IRE) is showed in Fig. 6.

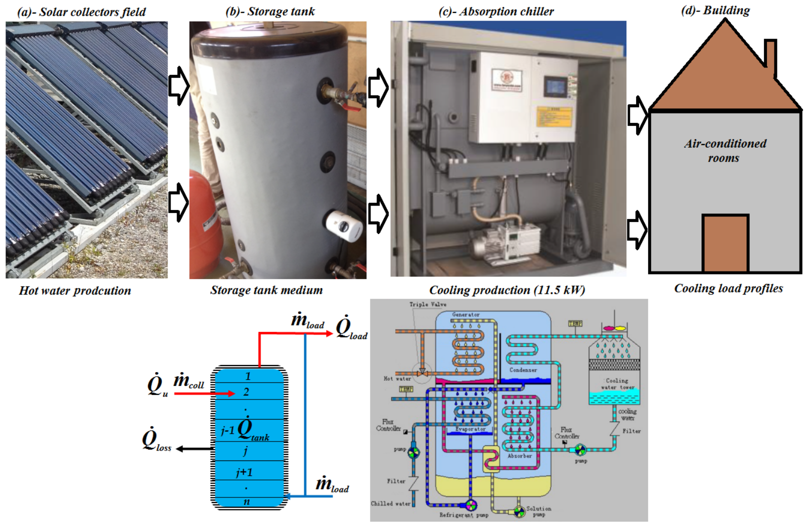

Figure 6: Solar prototype: (a)- Thermal collector's field, (b)- Solar storage tank model and (c)- Absorption machine (RXZ-11.5 kW) and (d)- Building constructed in Green Energy Park, Ben Guerir, Morocco, (gre; iut)

The efficiency of the thermal collector (see Fig. 6-(a)) is generally used to evaluate the energy efficiency of the sensor as described in Eq. 1.

$$\eta = \frac{\dot{m}C_p(T_{out} - T_{in})}{A_c I_{rad}} = \eta_0 - k_1 \frac{(T_m - T_a)}{I_{rad}} - k_2 \frac{(T_m - T_a)^2}{I_{rad}} \tag{1}$$

The energy model of the thermal storage tank contains N segments, fully mixed with equal volume, (Bouhal et al., 2017b), as shown in Fig. 6-(b). The energy balance for the storage tank can be formulated as the following:

$$\dot{Q}_{tank} = m_w C_w \frac{dT_j}{dt} = \dot{Q}_u - \dot{Q}_{load} - \dot{Q}_{loss} + \chi_j C_w \Delta T_\chi \tag{2}$$

In Eq. 2, χ_j has the following form: $\chi_j = \dot{m}_u \sum_{k=1}^{j-1} \epsilon_k - \dot{m}_{load} \sum_{k=j+1}^{n} \delta_k$ where

$$\epsilon_k/\delta_k = \begin{cases} 1 & \text{fi } k^{th} \text{ layer} \in \text{top/bottom of the storage tank} \\ 0 & \text{ailleurs} \end{cases}$$

The other parameters defined in Eq. 2 are expressed as follow:

- Temperature difference: $\Delta T_\chi = \begin{cases} T_{j-1} - T_j & \chi_j > 0 \\ T_j - T_{j+1} & \chi_j < 0 \end{cases}$
- Useful energy provided by the collector's field: $\dot{Q}_u = \epsilon_k \dot{m}_{coll} C_w (T_{out} - T_j)$
- Energy delivred to the generator of the absorption chiller: $\dot{Q}_{load} = \delta_k \dot{m}_{load} C_w (T_j - T_{load})$
- Heat losses to the environnement: $\dot{Q}_{loss} = h_a A_j (T_j - T_\infty)$

The operation mode of the machine and the internal process of the absorption cycle is displayed in Fig. 6-(c). The absorption machine operates with water (H2O) as refrigerant and lithium bromide (LiBr) as sorbant. The important technical indicators of the absorption chiller are listed in Table 4.

Parameter description	Value
Thermal chiller	
Nominal cooling power	11.5 kW
Nominal COP	0.7
Electric power of auxiliaries	216 W
Electric chiller	
Nominal cooling power	7.5 kW
Nominal COP	3
Set point temperature	7 $°C$
Cooling tower	
Air flow rate	1900 m^3/h
Mass transfer constant	2.3
Mass transfer exponent	-0.72
Fan electric consumption	0.93 kW
Fan minimum capacity	30 %

Table 4: Main system input technical characteristics (luc)

The governing equations modeling the physical phenomena of the absorption chiller are formulated and energetic indicators are defined to evaluate its performance.

- Coefficient of Performance of the absorption machine (COP):

  The Coefficient of Performance (COP), defined as cooling capacity divided by solar input as expressed in Eq. 3:

$$COP = \frac{\dot{Q}_{evp}}{\dot{Q}_{gen} + \dot{Q}_{ele1}} \tag{3}$$

  where $\dot{Q}_{ele1}$ is the electricity consumption of the absorption chiller (see Fig. 1).

- Solar COP Sol_{COP}:

  The solar COP (Sol_{COP}) is an indicator describing the system efficiency regarding the ratio the solar field efficiency and the chilling capacity.

$$Sol_{COP} = \eta_{sc} \times COP \tag{4}$$

  It's interesting to note that $\eta_{sc} = \frac{\dot{Q}_{sc}}{\dot{Q}_{rad}}$ where $\dot{Q}_{sc}$ is equal to the total solar insolation absorbed by collector's field and $\dot{Q}_{rad}$ is the solar insolation. Using an Evacuated Tube Collectors (ETC) and for a temperature in the range of 80–90 °C, the solar COP achieves 44%.

- Solar fraction S_f :

The solar fraction S_f is expressed as the total energy supplied by the solar thermal collector field to deliver the hot water needed for cooling. It is expressed as the ratio of system energy needs that is delivered by solar energy and the auxiliary energy supply the rest of energy. The solar fraction is a key indicator of the thermal efficiency of the solar cooling system compared to the other parameters mentioned above, because it does not take into account one component but the global performance of the system as expressed in Eq. 5.

$$S_f = 1 - \frac{\dot{Q}_{aux}}{\dot{Q}_{gain}} \tag{5}$$

where $\dot{Q}_{gain} = \dot{Q}_u - \dot{Q}_{loss}$ is the total energy supplied by the collector field to meet water heating needs, and $\dot{Q}_{aux} = \dot{Q}_{ele1} + \dot{Q}_{ele2}$ is the global auxiliary energy supplying the devices to support the unsatisfactory portion of the global solar energy load(see Fig. 1).

4. Economic indicators

Several economic indicators were defined in order to evaluate the economic viability of the solar cooling system.

4.1. Cost of energy saving C_{es}

In our investigation, the cost of energy saving C_{es} is adopted as an economic indicator because it compares the economic gains when the solar absorption system substitutes a conventional cooling unit (a vapor compression unit). The C_{es} is formulated as follows:

$$C_{es} = C_{cv} - C_{sol} \tag{6}$$

where C_{cv} and C_{sol} represent the costs of electricity consumption in the cases of conventional and solar cooling systems, respectively. The cost of electricity consumption C_{el} varies annually during the lifetime of the project as a results the inflation rate of electricity is considered using Eq. 7:

$$C_{el} = C_0(1 + r\%)^T \tag{7}$$

In Eq. 7, C_0 is the amount of the annual electricity bill for the first year of operation, $r\%$ the rate of change (%) which is the variation in energy prices related to energy inflation in Morocco and T the period of operation.

4.2. Payback period P

The payback period P represents the time required to recover the initial investment cost paid for the complete thermal installation. The payback period P is formulated as:

$$P = \frac{log(1 + \frac{I_0.r\%}{100.C_{es}})}{log(1 + \frac{r\%}{100})} \tag{8}$$

In Eq. 8, $r\%$ is the rate of inflation of electricity, C_{es} is the amount of energy savings in is the initial investment cost which is the sum of the costs of the various components, including: the assembly (installation) costs C_{inst}, the solar collectors (A_c, C_{coll}), the storage tanks volume

(V_{st}, C_{tank}), the absorption chiller (Q_{abs}, C_{abs}) and the mechanical compression refrigerator (Q_{mec}, C_{mec}), constituting the main components of the system which must be taken into account when calculating the total costs. Installation costs C_{inst} are considered to be included in these measures. Eq. 9 describes the method of calculating the initial capital budget in all cases:

$$I_0 = C_{inst} + C_{abs} \times Q_{abs} + C_{mec} \times Q_{mec} + C_{coll} \times A_c + C_{tank} \times V_{st} \tag{9}$$

A literature review found that there is a wide differentiation in the costs of thermal constituents. These loads depend on the manufacturer, the country and the power range. (Tsoutsos et al., 2003). Therefore, the major economical inputs to the solar refrigeration station under study are presented in the following Table 5.

Parameter description	Value
Average cost of absorption chiller	352-520 €/kW (Allouhi et al., 2015)
Cost of the solar collectors	250 €/m^2 (ETC) and 200 €/m^2 (FPC) (Bellos et al., 2016)
Cost of the heat storage tank	1200 €/m^3 (Allouhi et al., 2015)
Cost of the cooling tower	150 €/kW (Allouhi et al., 2015)
Installation costs	12% of the total equipment cost (Tsoutsos et al., 2003)
Maintenance cost of the solar system	1% of the initial investment cost (Allouhi et al., 2015)
Maintenance cost of the conventional system	30 €/yr (Mateus and Oliveira, 2009)
Average Moroccan electricity cost	0.09 €/kWh (one)
Market discount rate	r =4 % (Year 2017) (hcp)
Moroccan energy inflation	i% =2.5 % (Year 2017) (hcp)

Table 5: Economic input data used in our investigation (Tsoutsos et al. (2003); Wang et al. (2016); Bellos et al. (2016))

4.3. Cost of produced cooling energy $C_{prod.energy}$

Another important economic indicator in this case of system is the cost of produced energy $C_{prod.energy}$ which was obtained by dividing the total costs C_{tot} (initial costs: installation costs, energy, maintenance and other running costs) by the total energy produced by the air-conditioning system $Q_{prod.energy}$.

$$C_{prod.energy} = \frac{C_{tot}}{Q_{prod.energy}} \tag{10}$$

The local natural gas and electricity costs were identified taking into consideration their present value in Morocco and building sector considering an energy inflation (between 2% and 6%/year). Table 6 indicates the local costs used for 2017 according to High Commission for Planning (hcp).

Auxiliary backup	Electricity		Gas	
	Residential	Professional	Residential	Professional
Cost (e/kWh)	0.09	0.1	0.06	0.08

Table 6: Energy costs in Morocco used in the economic analysis for the year of 2017 hcp; mem

The financial cost results with the solar cooling system are presented in the following table 7.

Components	Costs (€)
Thermal collector's field	6000
Absorption chiller	4050
Cooling tower	750
Back-up chiller	300
Cold storage tank	300
Hot storage tank	720
Pumps	600
Installation costs	1530
Initial investment I_0	14245
Maintenance cost of the solar system	142
Mean cost of energy saving	406
Payback period	25 years

Table 7: Financial costs of the solar cooling installation

5. Simulation results

Various parametric studies were performed and a focus on the main results is given including an assessment of the impact of the system characteristics and their optimizing values. The examined costs of the system and auxiliary supplement are compared and an optimization analysis for system sizing are presented for various building categories and Moroccan climates zoning.

5.1. Impact of collector surface and volume of storage tank

Figs. 7-(a) and (b) show the solar fraction variation for cooling with storage volume and collector area for the residential house located in Marrakech (Z5). As shown in Figs. 7-(a) and (b), the optimal results arise for a storage volume in the range of 400-1 000 L of collector area but there is no important change of total cost or solar fraction above 600 L in the residential house.

Figs. 7-(c), (d) and (e) represent the sufficient collector area for a required annual solar fraction for both FPC and ETC solar technologies for residential house, office building and hotel, respectively. We note that for a given collector area, cooling loads in Marrakech city (Z5) are significant compared to Fez (Z3). As shown in Figs. 7-(c), (d) and (e), using FPC technology supplied either with electric or gas backups requires an important collector's area compared to ETC technology for different building typologies. ETC technology shows the best performance, thanks to its efficiency, because low area is required using electric backup in Fez (Z3) and Marrakech (Z5). For a residential house under 70 % of solar cooling fraction, 24 m^2 is necessary for ETC technology while 32 m^2 for FPC technology is required (see Fig. 7-(c)). Concerning the office building, under 70 % of solar cooling fraction, 35 m^2 is required for ETC technology while 55 m^2 for FPC technology is required (see Fig. 7-(d)). Regarding the hotel, under 70 % of solar cooling fraction, 68 m^2 is required for ETC technology while 110 m^2 for FPC technology is required (see Fig. 7-(e)).

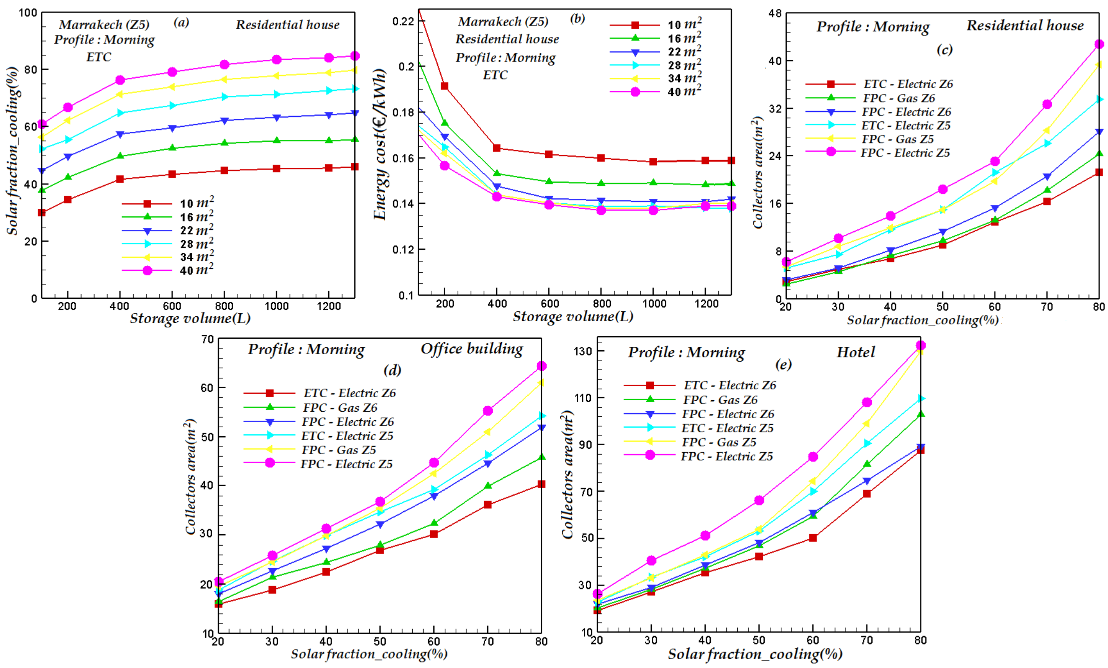

Figure 7: Solar fraction variation with storage volume (a) and collector area (b) and required solar collector's area for residential house (c), office building (d) and hotel (e) using electric and gas as auxiliary backup in Fez (Z3) and Marrakech (Z5)

Annual solar fraction values for cooling period are given in Table 8. The thermal performance results including collector area (ETC) Vs. solar fraction and also tank storage volume and mean collector efficiency for the three studied buildings with the various climates are listed (see Table 8).

Building localisation		Fez (Z3)				Marrakech (Z5)				Zagora (Z6)			
Residential house													
Solar fraction	Cooling (%)	20	40	60	80	20	40	60	80	20	40	60	80
Size	A_c (m^2)	4	6	12	22	6	12	22	32	3	5	10	22
	Vol (m^3)	0.15	0.3	0.6	1.2	0.4	0.8	1	1.1	0.1	0.2	0.5	1
Efficiency	Collectors (%)	51	40	33	26	49	39	31	25	55	42	35	29
Energy saving	E_s (kWh)	950	1100	1600	1800	1000	1200	1700	2000	1200	1500	2100	2900
CO_2 avoided	CO_2 (Tons)	18	23	30	37	19	24	32	40	22	27	41	47
Office building													
Solar fraction	Cooling (%)	20	40	60	80	20	40	60	80	20	40	60	80
Size	A_c (m^2)	15	22	29	40	19	30	39	54	14	20	26	38
	Vol (m^3)	1.5	2	3.3	5.5	1.6	3.4	5.3	1.7	1.3	1.8	3.1	5.4
Efficiency	Collectors (%)	29	27	25	23	28	26	24	21	30	28	26	25
Energy saving	E_s (kWh)	1500	2100	2900	3500	1700	2300	3000	3200	2100	2800	3500	4000
CO_2 avoided	CO_2 (Tons)	95	110	130	150	115	130	170	200	130	180	220	260
Hotel													
Solar fraction	Cooling (%)	20	40	60	80	20	40	60	80	20	40	60	80
Size	A_c (m^2)	20	38	50	88	25	40	70	110	18	37	48	87
	Vol (m^3)	1.6	3.6	5.8	6.7	1.7	3.8	5.9	6.8	1.4	3.4	5.6	6.6
Efficiency	Collectors (%)	35	29	26	22	33	28	25	20	26	30	27	25
Energy saving	E_s (kWh)	2100	2600	3000	3200	2500	2900	3400	3600	2800	3300	3900	4200
CO_2 avoided	CO_2 (Tons)	310	330	370	390	340	380	410	460	360	420	490	540

Table 8: Optimization of system size, storage volume, efficiency of ETC technology, energy saving and tonnes of CO_2 avoided for different solar fractions during cooling season

The solar cooling fraction is adopted as a thermal performance indicator and storage volume is the determinant parameter being investigated to evaluate the solar air-conditioning's thermal performance system taking into account the cooling load profiles. The results are identified to examine the optimal values by switching one main parameter at a time i.e. the degree of instantaneous difference of cooling load and solar availability, varying load consumption profile (Morning, Day and Evening) and the effect of system temperature range. The annual solar cooling production for Fez (Z3), Marrakech (Z5) and Zagora (Z6) is depicted in Fig. 8-(a). Concerning Fig. 8-(b), the annual amount of consumption of the auxiliary supplement is estimated over the year. The results show that solar cold production is maximum during the summer months thanks to a high level of sunshine. As an example, cold production was 410 kWh for the city of Fez (Z3), 630 kWh for the city of Zagora (Z6) and 610 kWh for the city of Marrakech (Z5) in July. There has been an interest in maximising cold production during the summer months to assure the inhabitants' comfort and at the same time reduce the electricity/gas bills used to meet consumer needs when solar radiation is not sufficient (ed Dîn Fertahi et al., 2018). As indicated in Fig. 8-(b), the auxiliary electrical back-up does not work during the months of summer, i.e. : June, July, August and September due to the availability of solar irradiation. However, it is maximum in the winter season. For example, for the month of January, it reached 1 255 kWh in the city of Fez, 1 875 kWh in the city of Marrakech and 2 230 kWh in the city of Zagora (Z6). Fig. 8-(c) shows the solar fraction versus storage tank volume under the various cooling demand profiles. As we can notice, the cooling profile has a strong impact on the system performance. For low storage volume (less than 100 L), the system is always at its minimum performance especially for Evening load profile (e.g. night time cooling), which can reach near zero cooling. Regardless of the amount of temporal mismatch between the loads cooling profiles and solar source there is a linear relationship between the storage volume and solar cooling fraction, with a near constant slope for all three cooling demand profiles examined. It is noticed that in Fig. 8-(c) the simulated system never reaches a solar fraction of 100 %. This is because the simulated system uses average values for collector efficiency which takes into account the nonlinear nature of collector efficiency and its changes with time. Indeed, Morning profile provides the higher solar cooling fraction thanks to the correspondence between the cooling requirements and the availability of solar sunshine. Day profile indicates solar cooling fraction values better than those of Evening profile.

Figs. 8-(d), (e) and (f) show the annual contribution of solar energy for air-conditioning production under the studied Moroccan regions, namely: Fez (Z3) presented in Fig. 8-(d), Marrakech (Z5) shown in Fig. 8-(e) and the city of Zagora (Z6) depicted in Fig. 8-(f) for different cooling demand profiles. The variations in the observed solar contribution for each area are due to the climatic impact in the solar incident irradiation on the field of collectors. Concerning the solar cooling during the month of June, it was noted that the solar power contribution amounts achieves 950 kWh, 690 kWh and 890 kWh respectively in the three zones of Fez, Marrakech and Zagora. It was judged that the solar collector's field should be sized in accordance with the quantity of incident solar radiation available per region and the requirements of consumers in terms of cooling loads. Furthermore, it was also observed that the solar gain of the absorption chiller is insignificant in the summer period for the Evening profile, but it is maximum for the Day cooling profile. From Figs. 8, the cooling load profiles directly affects the average efficiency of the solar air-conditioning system.

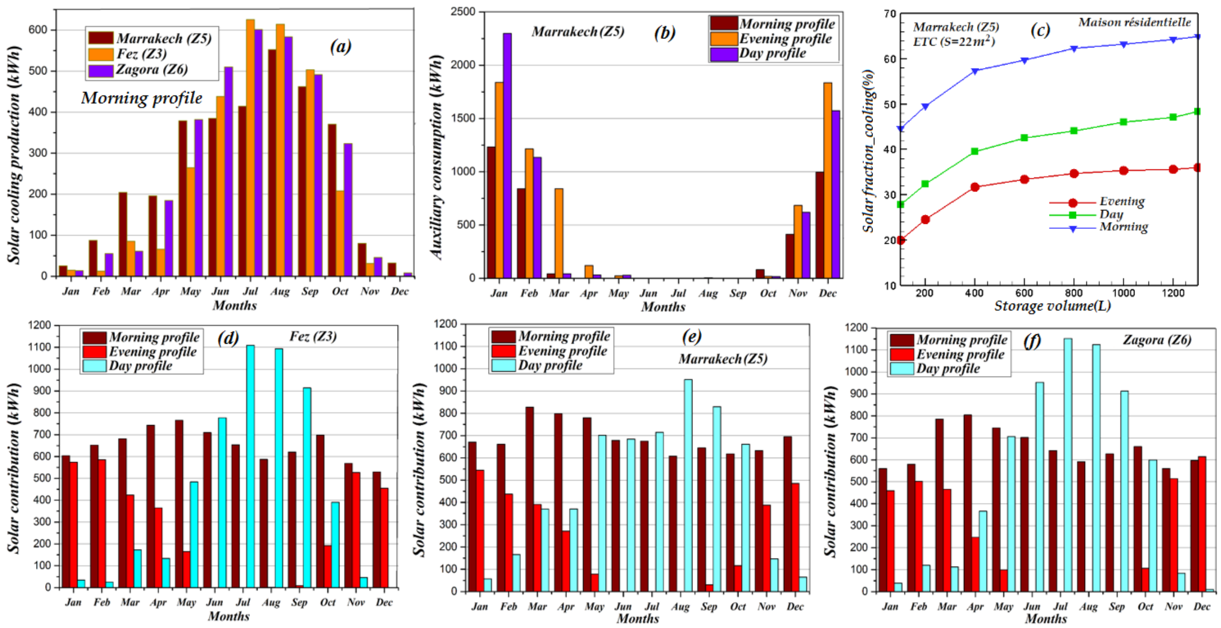

Figure 8: Solar cooling fraction vs. Storage volume at various and solar contribution for various cooling demand time requirements in different regions (Collector's area of 22 m^2, Absorption chiller capacity of 11.5 kW and average COP of 0.7)

5.2. Thermal performance assessment of solar cooling absorption chiller

In this section, the thermal behaviour and overall solar air-conditioning system performance were examined. The examined parameters include the storage tank volume, solar collector area and driving temperature. Accordingly, Fig. 9-(a) indicates the temperature evolutions of the system for two consecutive days of summer (July 1-2) in Marrakech (Z5). Indeed, Fig. 9-(a) shows the two days (48 hours) variation of the top of the storage tank (linked to generator) and bottom layers temperatures, the ambient temperature and outlet temperature from the collector (ETC technology) and temperature of the evaporator. During these 48 hours, it is important to indicate that the ambient temperature reaches high annual values. In the night, the ambient temperature goes down from 40 °C to 20 °C while during the morning it decreases gradually to achieve its maximum value of 42 °C and goes down in the evening. Moreover, the collector outlet temperature keeps the same variation of the ambient temperature and the incident solar irradiation. As showed in Fig. 9-(a), it is interesting to mention that the solar tank temperatures, i.e. outlet collector and different tank layers, varies when the cooling profile loads exists at 12 am (see Fig. 5). During the afternoon, the temperature of the generator has a temperature requirement up to 80 °C, the absorption chiller generates cooling effects during the day between 11 am and 6 pm because the outlet tank temperature is up to 80 °C. The temperature of the evaporator is constantly equal to 10 °C.

Fig. 9-(b) indicates the influence of solar collector's area on the collector efficiency and both mean solar and absorption chiller COPs. When the solar collector area takes values between 10 m^2 and 40 m^2, the absorption chiller average COP grows from 0.63 to 0.8 and the overall collector efficiency decreases from 50 % to 42%. This is due to high collector area that enhances the mean storage tank temperatures which then increases the mean absorption chiller COP and decreases the average collector efficiency. Moreover, the high collector area enhances the solar COP from

0.23 to 0.38.

Fig. 9-(c) shows the impact of solar collector area on the air-conditioning output and absorption chiller operation time. When the collector's area increases from 10 m^2 to 40 m^2, the total cooling output enhances from 110 kWh to 265 kWh and the operation time of the absorption chiller increases from 6.9 h to 10.9 h. Further, the absorption cooling output and solar COP increase with important solar collector's area but, when the collector area exceeds 22 m^2, the both parameters increase slowly.

As the collector surface is an important parameter impacting the economic viability Kalogirou (2004), economic considerations under various collector's areas is analyzed. Several economic criteria were found in the literature including the annual operation cost, cost of energy saving, payback period and intern rate of return (Moore, 2017). In our study, the payback period is considered which indicates the time required for the supplementary electricity savings to equal the initial investment Al-Alili et al. (2012). The main cost's data for absorption chiller, cooling tower, solar collectors (FPC and ETC) and storage tank are listed in Table 5. The electricity prices of 0.08 €/kWh, 0.09 €/kWh and 0.1 €/kWh are considered to carry out the economic calculations (Moore, 2017; hcp) and the annual simulations were performed. Indeed, the absorption chiller achieves an average COP of about 0.7 when it is driven by electricity. For this case, the owned electricity consumption is determined from annual absorption air-conditioning output divided by COP of 0.7. Fig. 9-(d) shows the payback period for various electricity prices and solar collector's area. When the collector's area increases from 10 m^2 to 40 m^2, the payback period decreases slowly because important solar collector's area enhances the mean system efficiency and the operation time of the absorption chiller, as a result more electricity consumption is economized. In other hand, when the collector's area is higher than 26 m^2, the payback period of the system becomes longer which means that the solar collector's area of 26 m^2 is sufficient for the solar cooling system. More enhancement of solar collector's area increases considerably the initial investment costs. Indeed, collector's area values between 22 m^2 and 26 m^2 are the suitable range for solar collector's field.

Fig. 9-(e) shows the effect of storage tank volume on the solar cooling system performance. Indeed, when the storage tank takes values between 0.5 m^3 and 4 m^3, the mean collector efficiency enhances from 44% to 48% while the average absorption chiller COP is reduced from 0.82 to 0.65. These changes are due to the heat losses and inertia of the tank because an important tank volume involves higher tank heat losses and lower mean tank temperature. Accordingly, when the storage tank temperature is in its lower values, the solar collectors have lower working temperature and higher efficiency while the absorption chiller has lower efficiency and lower heat source temperature. Moreover, when the storage tank volume drops from 0.5 m^3 to 2 m^3, the solar COP increases from 0.30 to 0.38 but it decreases from 0.38 to 0.29 when the tank volume increases from 2 m^3 to 3.5 m^3 due to the thermal heat losses. Fig. 9-(f) presents the influence of storage tank volume on the cooling output and operation time of the solar absorption machine. In fact, the cooling output takes values in the range of 180 kWh and 260 kWh and the operation time varies between 8.9 h and 10.5 h. The largest cooling output and the longest operation time are obtained with storage tank volume of 2 m^3 corresponding also to the larger solar COP. The change of cooling output, operation time and solar COP can be explained by the fact that when the storage tank volume increases from 0.5 m^3 to 2 m^3, the water heating storage is improved and solar cooling system operates longer and provides more air-conditioning output. Besides, both thermal losses and temperature of storage tank are reduced due to slight temperature difference with the environment.

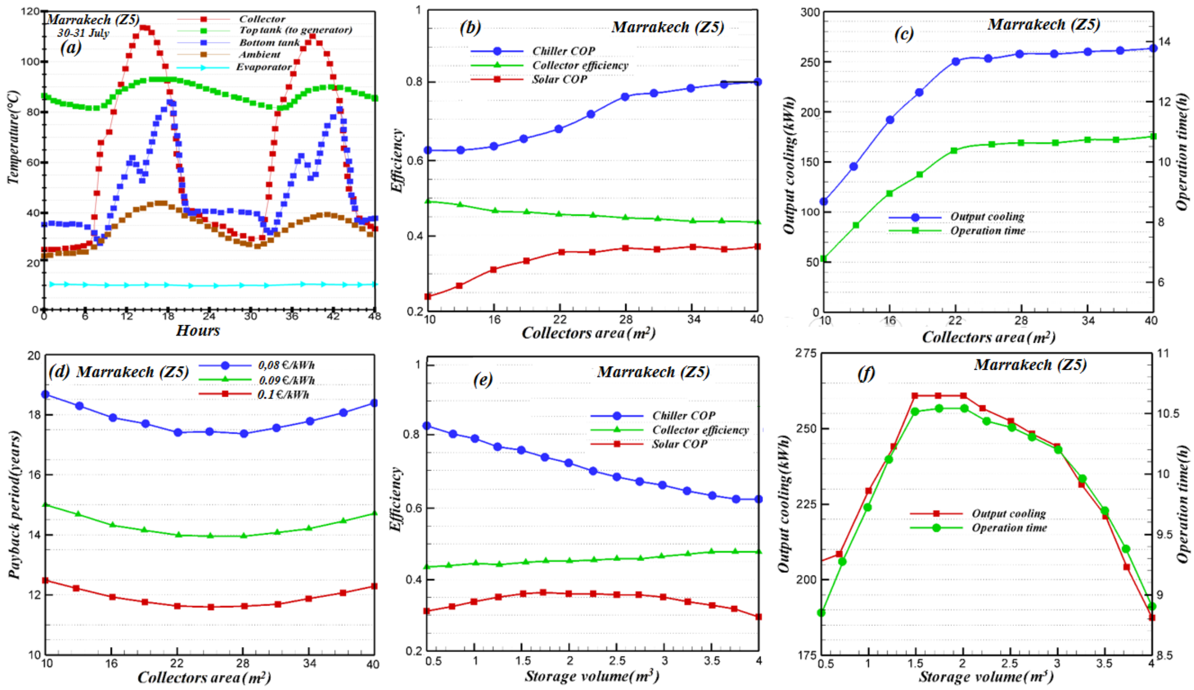

Figure 9: Impact of the surface area of the solar collectors and the volume of the storage tank on the efficiency of the solar cooling system and payback period

5.3. Energy and economic analysis

In addition to the energy analysis, the results of the economic assessment are presented in the Moroccan conditions applicable to the cooling system of the Fig. 1. A combination of economic factors was employed to examine the economic sustainability of the solar air-conditioning system. Thus, the annual energy savings cost was considered as a currency indicator to determine the fractional economy in terms of money saved in three Moroccan zones, namely: Fez (Z3), Marrakech (Z5) and Zagora (Z6) for the residential house. Furthermore, its evolution was presented using a diagram with a stick as shown in Fig. 10 based on the Eq. 6. It can be observed that the energy savings curve is significant during the summer season of the year, since the absorption chiller's efficiency in producing a cooling effect is high (see Fig. 10). For July, the energy saving costs indicate the following amounts: 311, 313, 322 € for the regions of Fez (Z3), Marrakech (Z5) and Zagora (Z6), respectively. However, for the winter period (January for example), the cost of saving energy is as follows: 23, 26 and 32 € for the cities of Fez (Z3), Marrakech (Z5) and Zagora (Z6), respectively. Thus, the results indicate that the contribution of the solar radiation to the performance of the absorption chiller, as well as the operating hours of the electrical/gas backup systems, impact the global balance sheet, which has been quantified in € by the Cost of Energy Savings. Basically, the higher the yearly solar fraction of the absorption chiller, the lower the consumption of auxiliary backup power, generating a significantly higher annual cost optimization of the energy savings achieved, especially when the cooling requirement increases during the summer season in order to meet the comfort needs of end users.

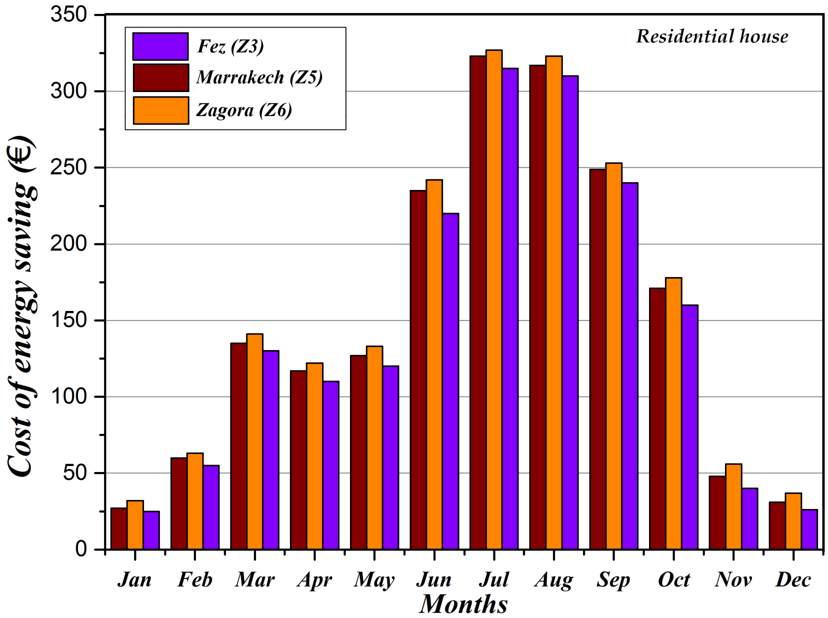

Figure 10: Cost of energy saving in different studied zones

Table 9 presents the various costs counted for each of the examined regions for a solar cooling system with a yearly solar fraction of 70%. The initial investment (including installation cost), maintenance, energy supply and the different backup alternatives of electricity and gas have been identified. Thus, the ETC technology seems to be installed in Fez (Z3) and Marrakech (Z5) while FPC is seems to be implemented in Zagora (Z6) thanks to the high solar energy scope of this region.

Zone	Collector technology	Backup type	Solar investment (*ke*)	Backup Investment (*ke*)	Electricity (1st year) (*ke/year*)	Gas (1st year) (*ke/year*)	Maintenance (1st year) (*ke/year*)
Fez (Z3)	ETC	Electric	16	5	0.414	0.022	0.324
	ETC	Gas	15	9	0.104	0.231	0.121
Marrakech (Z5)	ETC	Electric	15	6	0.423	0.026	0.365
	ETC	Gas	13	8	0.107	0.236	0.124
Zagora (Z6)	FPC	Electric	12	4	0.301	0.014	0.267
	FPC	Gas	10	6	0.095	0.187	0.105

Table 9: Costs generated of solar air-conditioning system for the different Moroccan regions and backup systems by item for an annual solar fraction of 70%

Figs. 11 present the costs of produced energy for different building categories and solar fractions. Hence, Figs. 11-(a) and (b) show the costs of produced energy for a residential house for both electric (a) and gas (b) backups. As it can be noticed, the solar cooling system located in Fez (Z3) and Marrakech (Z5) is economically interesting for solar fractions between 40 and 80% either with electric or gas backup. With solar fractions between 20 and 80%, solar systems installed in Fez (Z3) and Marrakech (Z5) are economically viable than traditional ones in cases where it is not possible to have an electrical or gas backups. For Zagora (Z6), the profitability takes place just with the use of FPC technology and solar fractions between 40 and 80%. A gas boiler as option, instead of an electrical auxiliary backup delivers a reduction in collector's area up to 15% for the same solar fraction. In Marrakech (Z5), FPC technology offers a reduction of total costs compared to ETC one. In Fez (Z3), for a gas backup both collector technologies (FPC and ETC) indicate similar results, but for an electric backup FPC technology shows better results. ETC technology allows a reduction of collector area between 6 and 20%. Table 10 shows the results of the solar cooling system size (including the collector area and storage volume capacity) for a residential house that drives to the minimum total cost of produced energy for the various regions, energy backup solutions and for an annual solar fraction of 70%. Table 10 also compares investment in a residential house and total costs for the solar cooling system and auxiliary system using electricity and gas backups for a period of 25 years.

Zone	Collector technology	Backup type	A_c (m^2)	Vol (m^3)	A_c per kW cool. (m^2/kWc)	Solar cooling system investment (ke)	System investment: sol vs. conventional (%)	Cost of produced energy: sol vs. conventional (%)
Fez (Z3)	ETC	Electric	16	0.6	1.2	18	+266	+12
	ETC	Gas	14	0.5	1	14	+165	+16
Marrakech (Z5)	ETC	Electric	15	0.5	1.1	17	+245	+13
	ETC	Gas	13	0.4	0.9	13	+137	+17
Zagora (Z6)	FPC	Electric	18	1.2	1.7	1.8	+315	+19
	FPC	Gas	20	1.4	1.8	2	+ 316	+20

Table 10: Solar cooling system scheme allowing minimum total cost for the residential house for a yearly solar fraction of 70%

For the office building (see Figs. 11-(c) and (d)), based on economic considerations only and with the current energy costs, the solar air-conditioning system is not proved in any Moroccan zone. The economic viability of the solar air-conditioning system is higher for Fez (Z3) and very low for Zagora (Z6). An electric backup, instead of a gas backup option delivers a diminution in collector surface between 2% and 8%, for the same solar fraction. In Zagora (Z6), the use of FPC technology compared to ETC one provides a reduction of total cost of produced energy. In Fez (Z3), both collector technologies show similar results. ETC technology offers a reduction of collector area between 15 and 20% (see Figs. 11-(c) and (d)).

Table 11 presents the results of the solar air-conditioning system size (including the collector area and storage volume) for the office building that provide the minimum total cost of generated energy for the various zones, energy backup options and for an yearly solar fraction of 70%. Table 11 also compares investment in an office building and total costs for the solar cooling process and auxiliary solution using electricity and gas boiler backup for a period of 25 years.

Zone	Collector technology	Backup type	A_c (m^2)	Vol (m^3)	A_c per kW cool. (m^2/kWc)	Solar cooling process investment (ke)	System investment: sol vs. conventional (%)	Cost of produced energy: sol vs. conventional (%)
Fez (Z3)	ETC	Electric	35	6.5	1.2	35	+140	+20
	ETC	Gas	32	6.3	1.1	33	+135	+18
Marrakech (Z5)	ETC	Electric	40	6.8	1.4	38	+125	+17
	ETC	Gas	42	6.9	1.5	39	+128	+19
Zagora (Z6)	FPC	Electric	34	6.4	1.1	33	+165	+30
	FPC	Gas	33	6.3	1	32	+163	+28

Table 11: Solar cooling system scheme allowing minimum total cost for the office building for a yearly solar fraction of 70%

For the hotel (see Figs. 11-(e) and (f)), the solar cooling process has minimum costs in Marrakech (Z5) and Zagora (Z6) if gas is served as backup for solar cooling fractions between 20% and 60% (see Figs. 11-(e) and (f)). For the same yearly solar fraction, an electric backup instead of gas solution delivers a diminution in collector area up to 10%. In Fez (Z3), ETC technology allows a reduction of total cost compared to FPC ones. In Zagora (Z6), both collector technologies (FPC and ETC) provides similar results with a slight advantage to FCP technology. ETC technology offers a reduction of collector's area between 10 and 20% (see Figs. 11-(e) and (f)).

Table 12 indicates the results of the solar cooling system size (including the collector area and storage volume) for the hotel that leads to the minimum total cost of generated energy for the various sites, energy backup solutions and for an yearly solar fraction of 70%. Table 12 also compares investment in a hotel and total costs for the solar cooling system and auxiliary system using electricity and gas boiler backup for a period of 25 years.

Zone	Collector technology	Backup type	A_c (m^2)	Vol (m^3)	A_c per kW cool. (m^2/kWc)	Solar cooling process investment (ke)	System investment: sol vs. conventional (%)	Cost of produced energy: sol vs. conventional (%)
Fez (Z3)	ETC	Electric	72	5.7	1.3	65	+207	+14
	ETC	Gas	70	5.5	1.2	62	+115	+18
Marrakech (Z5)	ETC	Electric	71	5.8	1.2	72	+210	+15
	ETC	Gas	73	6	1.1	74	+208	+10
Zagora (Z6)	FPC	Electric	75	6.7	1.6	84	+400	+55
	FPC	Gas	78	6.9	1.8	86	+450	+60

Table 12: Solar cooling system scheme allowing minimum total cost for the hotel, for an yearly solar fraction of 70%

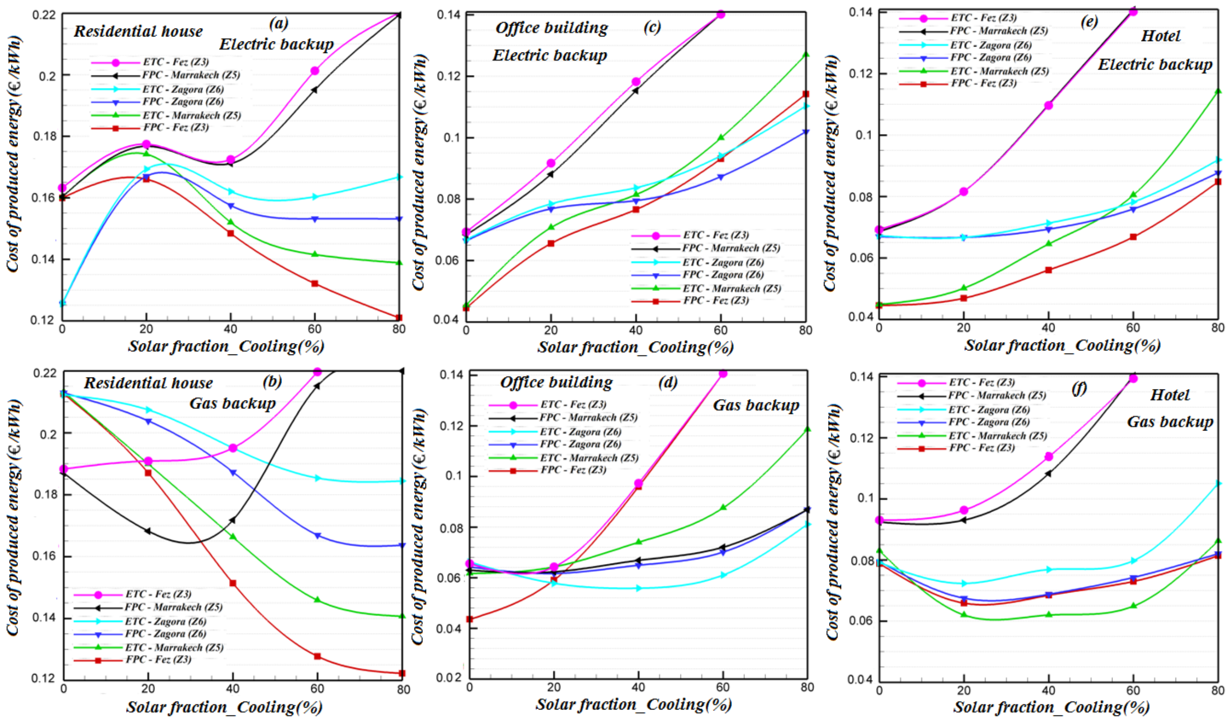

Figure 11: Costs of produced energy evolution with solar fraction for Gas and Electric backups for various building categories for a period of 25 years

6. Conclusions

The optimization and design of a solar air-conditioning process in Morocco was investigated based on energy and economic indicators. Hence, the thermal performance of a LiBr-H_2O absorption chiller coupled to solar thermal collectors was numerically evaluated using annual dynamic simulations for various building categories and different Moroccan climates. It is achieved that minimum costs are controlled by climate zones and building category. Hence, it is possible to save in costs of produced cooling energy for the zones of Fez (Z3), Marrakech (Z5) and Zagora (Z6) when electricity is used as auxiliary backup for a yearly solar fractions between 40% and 70%. The hotel and the residential house are the buildings where the solar air-conditioning system has a larger economic viability especially for Marrakech (Z5) and Zagora (Z6). Moreover, ETC technology provides a reduction in collector's area between 20% and 45% compared to FPC one although, due to their initial costs, FPC allows a higher economic feasibility especially for Zagora (Z6). An annual solar fraction of 70% can only represent a reduction of exploitation costs between 25% and 50% due to significant maintenance and operation costs.

Using the analytical predictions and numerical results, it was also shown that the residential house and office building integrating an ETC technology with gas backup is the best solution especialy for Fez city (Z3). For the touristic cities Marrakech (Z5) and Zagora (Z6), the hotel building using FPC system and electricity backup is the optimal solution in terms of efficency, economic viability and social integration.

Taking into account the present Moroccan costs of energy resources (electricity and gas), it is mandatory that initial costs of solar collectors and absorption chillers are more decreased for solar air-conditioning installations to become more competitive and accessible for domestic and professional users.

7. Acknowledgment

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Nomenclature

A_c	collector area [m^2]	T_L	temperature of the fluid replacing that extracted to supply the load [K]
A_i	surface area of the ith tank layer [m^2]	T_m	mean temperature [K]
C_p	specific heat at constant pressure [J$K^{-1}kg^{-1}$]	T_{out}	outlet temperature [K]
C_{pf}	specific heat of the tank fluid [J$K^{-1}kg^{-1}$]	T_{in}	inlet temperature [K]
$C_{prod.energy}$	cost of produced energy [€kWh^{-1}]	U_i	loss coefficient between the tank and its environment (per unit area) [W$K^{-1}m^{-2}$]
C_{es}	cost of energy saving [€]	V_t	tank volume [l]
I_{rad}	the total horizontal radiation [Wm^{-2}]	***Abbreviations***	
$\dot{m}$	flow rate [kgs^{-1}]	COP	Coefficient of Performance
$\dot{m}_L$	fluid mass flow rate to the load and/or of the makeup fluid [kgs^{-1}]	ETC	Evacuated Tube Collector
N	number of fully mixed (uniform temperature) tank layers (N 15)	FPC	Flat Plat Collector
k_1	first order heat loss coefficient [W$K^{-1}m^{-2}$]	S_f	solar cooling fraction [%]
k_2	first order heat loss coefficient [W$K^{-2}m^{-2}$]	P	Payback period [year]
$\dot{Q}_i$	rate of energy input by the heating element to the i_{th} segment [W]	***Greek symbols***	
$\dot{Q}_s$	rate at which sensible energy is removed from the tank to supply the load [W]	α_l	control function defined by $\alpha_i = 1$ if $i = S_h$; 0 otherwise
$\dot{Q}_{aux}$	auxiliary energy of the backup system [W]	β_i	control function defined by $\beta_i = 1$ if $i = S_L$; 0 otherwise
$\dot{Q}_{load}$	energy to load [W]	ΔE	internal energy change of the tank [J]
$\dot{Q}_u$	useful energy [Wm^{-2}]	η	collector efficiency [-]
T_a, T_{amb}	ambient temperature [K]	η_0	zero loss efficiency [-]
T_{env}	temperature of the environment surrounding the tank [K]	γ_f	control function that defines if the auxiliary heater is off or on. 1 is off, 0 is on
T_h	temperature of the fluid entering the storage tank from the heat [K]	γ_i	control function defined by $\gamma_i = \dot{m}_h \sum_{j=1}^{i-1} \alpha_j - \dot{m}_L \sum_{j=i+1}^{N} \beta_j$
T_i	temperature of the ith tank segment [K]	ρ_f	fluid density [kgm^{-3}]

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