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Economic-environmental performance indexes for solar-powered absorption cooling system in Mediterranean area

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Abstract
The most recent European (Directive 2006/32/CE of April 5/2006 relating to the efficiency of the final uses of the energy and the energetic services) and national (Decree 311/06) normatives impose the use of energetic systems more efficient that minimize the use of fossil fuels in comparison to the use of renewable energy. In this research a comparison was developed between the traditional electric equipments (which use vapour compression) and the absorption equipments (powered by solar thermal energy). This comparison was implemented considering the energetic, economic and environmental aspects.
This research explores the technical - economic potentialities of solar HVAC systems, with particular reference to those based on the absorption cycles, verifying the possible applications in regions of the Mediterranean area (in particular Madrid, Palermo and Athens). In particular we define an economic index and an environmental-energetic index.

Keywords: Cooling absorption system, Economic index, Environmental index, Mediterranean area, Solar system.

1. Introduction

In the last years we had a considerable increase of the number of air-conditioning system (especially for the air cooling) in the domestic and industrial sector. In fact, especially in buildings with many windows, there is a disagreeable condition of overheating in the summer. In this way the indoor comfort of the people present in the room decrease notably. In these cases, the air-conditioning system of the environments results the only solution acceptable for maintaining the air temperature and the relative humidity indoor within admissible limits. Such effect is obtained with a ventilation plant combined with a refrigeration unit. The traditional air conditions system, based on the use of the vapour compression cycles, is powered through electric energy, normally produced by fossil fuels.
In consequence of the use an ever-increase of the conventional technologies is the exponential increase of the average and maximum electric consumptions during summer. It initiated about ten years ago with the thick diffusion of domestic air-conditioning. For example in the period 2000-2005 seven million of air-conditioners have been sold in Italy, this allow to affirm, that exists one correlation between the peak electric demand in summer and the diffusion of the air-condition system.
The cooling using heat produced by solar radiation could seem a mad idea; nevertheless, air-conditioning systems not conventional exist, called "absorption machine" that use the solar radiation as principal

energy source for developing a process for cooling the room. In fact, the absorption systems differ from the traditional mechanical refrigerator because they use a "thermal compressor" rather than “mechanical compressor”. A description of the principles of absorption system is defined in [1] and [2]. The papers dealing with the solar absorption system can be divided in three categories. In the first group we have different simulation models applied to distinct typologies of absorption system [3], [4], [5], [6] and [7]. The second group includes experimental researches [8] and [9]. In the last group economic-viability analysis have been carried out [10] and [11]. In this paper a technical economic comparison will be developed among traditional air-conditioning systems and integrated absorption systems powered by solar thermal energy for different Mediterranean places. In particular we define an economic index and an environmental-energetic index. The software SolAC (Solar Air Conditioning, IEA-Task 25) was used to identify the optimum solution among the different solar absorption system studied [12] and [13].

2. Plant configurations and performance parameters

In this research was determined the energetic-economic performances of air-conditioning systems powered by solar energy and to compare with the energetic-economic performance of conventional compression system. The result was realized by the study of different plant configurations and changing some parameters: the site of system installation, the solar collector type, the cost of the components, the surface of the solar field, the volume of thermal storage etc..
The plant of reference, whose scheme is in Figure 1, is characterized by the parameters reassumed in tables 1 and 2, relative to technological and economic aspects. They are often described in terms of specific costs, for example, cost for kW of installed power or for m2 of collector etc.

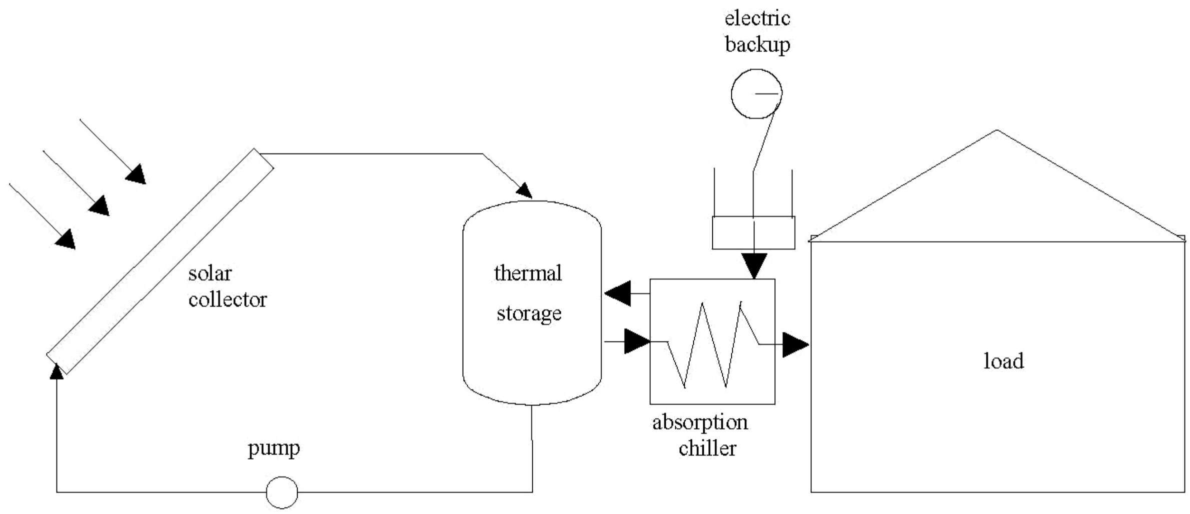

Figure 1. Absorption system scheme with electric backup

Solar collector employed are: FPC, the plate collectors with selective surface, CPC, the static parabolic collectors, and ETC, the evacuated tubes collectors without concentrator.
The specific cost, in this research, is only referred to the equipment, in particular its refers to kW installed of cooling so it doesn't include the costs of plant installation.
The values shown in the preceding table are identical for all the solar systems, which ever is the solar thermal collector used. In the case of the conventional system was considered, only the secondary pump of the refrigeration circuit.

Table 1. Parameters, characteristics and cost of the system analysed [14]

Component characteristics				Component cost		
Solar collector	FPC	CPC	ETC	Solar collector	FPC	280 €/m²
Optic efficiency, c_0	0.789	0.94	0.86		CPC	400 €/m²
Coeff. linear loss, c_1 ($Wm^{-2}K^{-1}$)	2.88	2.20	2.02		ETC	620 €/m²
Coeff. quadratic loss, c_2 ($Wm^{-2}K^{-1}$)	0.0180	0.0330	0.0022	primary Pump solar circuit (nominal electric power 0.002 kW/m² cool)		400 €
Longitudinal IAM (50° incidence)	0.92	0.9	0.9	secondary Pump solar circuit (nominal electric power 0.002 kW/m² cool)		250 €
Transversal IAM (50° incidence)	0.92	0.8	0.9	Thermal storage (loss coeff. 0.8 w/mK		600 €/m³
System air-condition	Absorption to single effect	Electric to compression		Primary Pump refrigeration circuit (Nominal electric power 0.3 kW)		550 €
Specific cost	400 €/kW	310 €/kW		secondary Pump refrigeration circuit (Nominal electric power 0.3 kW)		550 €

Table 2. Financial and use energy parameters

Investment cost	Value	Management costs	Value
Hydraulic systems installation of compressor system	20000 €	Electricity cost - energy	0.1044 €/kWh
Hydraulic systems installation of solar-thermal system	15000 €	electricity cost - installed power (peak loads)	75 €/kW
Hydraulic systems installation of traditional backup	5000 €	Annual maintenance costs of thermal solar system	10 % inv. cost
		Annual maintenance costs of other components	20 % inv. cost
Financial parameters			
Plant operative Life	20 years	Electric production Efficiency	0.36 kWhel/ WhEP
Rate of interest	6 %	CO_2 Specific emissions from power	0.8 kg/kWhel

The parameters of performance evaluated, for the different plant configurations and the different site, are:

- The primary energy saving, EPsav, defined as the difference between the annual consumption of primary energy of the compression system and that of the solar system. In the results, this value, is cited in percentages terms in comparison to the conventional system, that is:

$$EP_{sav} = \frac{EP_{cons,ref} - EP_{cons,sol}}{EP_{cons,ref}} \quad (1)$$

Since we have considered only the cases with a primary energy consumption superior to that of the traditional system of reference, the parameter so defined always results positive.

- The net annual efficiency of the collectors, equal to the ratio between the useful thermal energy produced by the solar field within the year and the incident radiation on the collectors in the same time-frame.

- The cost of the saved electric energy through the employment of the absorption plant powered by solar energy is defined as:

$$C_{el,sav} = \frac{C_{ann,sol} - C_{ann,ref}}{E_{el,sav}} \tag{2}$$

where, $C_{ann,sol}$ represents the annual cost of the solar plant elioassistito, $C_{ann,ref}$ that of the compression system of reference, and $E_{el,sav}$ is the electric energy saved in one year [kWh]. From the comparison of this parameter with the market price of the electric energy, it is possible to obtain the saving energy in kWhel.

- The percentage annual cost of the absorption system in comparison to the compression system:

$$\frac{C_{ann,sol}}{C_{ann,ref}} \cdot 100 \tag{3}$$

The percentage first cost (of investment) of the solar system in comparison to the same cost related to the traditional system:

$$\frac{C_{Inv,sol}}{C_{Inv,ref}} \cdot 100 \tag{4}$$

For every analysed configuration, the parameters defined before, were calculated in function of the solar collectors surface of the solar field and the heat storage of the same solar system. Particularly, the area of collectors was varied as percentage fraction of the building surface from air-condition. This percentage varied from a 10% minimum (0.1 m^2 of collector surface over m^2 of building surface) to a maximum of 100% (1 m^2 of collector surface over m^2 of building surface). While, the solar thermal storage can be express both as number of hours in which the solar system results able to autonomously feed the absorption cycle in absence of incidental radiation on the collectors, that in terms of meters cubes of storage required for the same purpose. The presence of certain heat storage avoids that the auxiliary electric system begins to work when the incidental radiation results insufficient to sustain the absorption process. It also allows getting a great saving of primary energy and a more efficient employment of the whole solar system.
The storage heater capacity, express in times, can be defined as:

$$CA = m_{fl} \cdot c_{p,fl} \, \frac{T_{acc,m} - T_{ch}}{P_{ch} \cdot 3600} \cdot COP_{ch} \tag{5}$$

In this formula: m_{fl} is the stored fluid mass [kg], $T_{acc,m}$ is the maximum temperature in the tank [°C], T_{ch} is the operative temperature of the absorption cycle [°C], P_{ch} is the nominal power of the absorption system [kW], and the COP_{ch} is the coefficient of performance of the absorption cycle.
In the paragraphs that follow are describe the results some systems characterized optimal ideal, for every of select district of the Mediterranean area. The result was obtain in proportion to restriction imposed above solar field efficiency value and on the real primary energy saving. Particularly we considered competitive those configurations, that, have shown an annual net efficiency superior to 20% (this for not to penalize too much the expensive solar technology) and, contemporarily, have allowed an primary energy saving superior to 25% in comparison to demands of the conventional plant. Finally, among all the cases that respected limits, we choose, for every collector typology and for every district, that with the least cost of the saved electric energy.

3. Summer thermal load of the districts considered

All the evaluations were carried using meteorological hour data of three Mediterranean places: Palermo, Madrid and Athens. They were held representative of typical climatic conditions of this area relating to summer air-conditioning. The following table reports a description a of the climatic regime for these three cities.

Table 3. Climatic trend of the three Mediterranean places

City	Lat.	Horizontal global radiation	Global radiation on the collectors plan	Climatic trend
Palermo	38.1°	1690 kWh/m^2year	1879 kWh/m^2year	Maritime climate, with elevated humidity and high summer temperatures. Typical season for the conditioning is from April to October.
Madrid	40.4°	1664 kWh/m^2year	1711 kWh/m^2year	Continental Mediterranean climate with high temperatures but moderated humidity in the summer.
Athens	39.0°	1566 kWh/m^2year	1710 kWh/m^2year	Mediterranean maritime climate with elevated summer temperatures. Typical season for the conditioning is from April to October.

We presumed to orient the collectors to South with an inclination of 30° relating to the horizontal plan in oder to maximize the useful solar energy. The meteorological data, represented by hour temporal series, were produced by the Meteonorm [14] software, this have allowed to calculate the radiation on the collectors plan (30° of inclination).
Athens present the great summer temperatures. The highest humidity and the greatest solar radiation are found in Palermo.

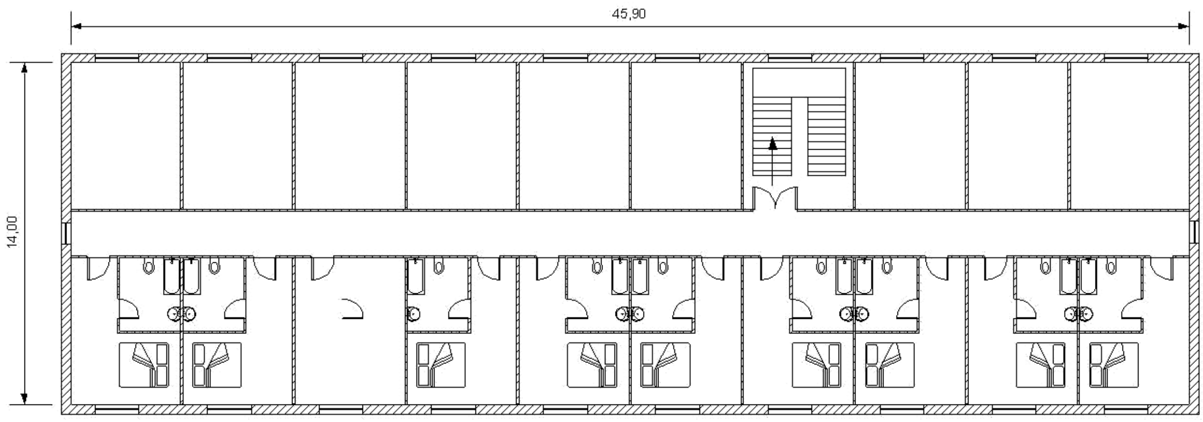

Figure 2. Building plan of the analyse building

The selected building is composed by three floors, with a surface of 643 m^2 all to be conditioned, equal to the area of one level (Figure 2). It is oriented along the direction Nord-Sud and present, on every floor, a central corridor. The windows surfaces on North and South fronts are the 25% of the total to the front. The windows surface on East and West is the 4%. The destination usage is Hotel. This buildings are realized in reinforced concrete with a good thermal isolation that minimize the thermal losses in winter and the thermal gains in summer.
The envelope thermal characteristics are: the walls thermal transmittance 0.45 W/m2K and the windows thermal transmittance 1.8 W/m2Ks. The summer thermal load considered are essentially characterize by solar gains and by internal load (Figure 3).
The software SolAC (Solar Air Conditioning, IEA-Task 25) allowed, for every of the select places, a comparison among different system configuration. This, have permitted of individuation the optimal configuration in regard to the energetic and economic limits.
In the follow paragraphs are described the result of the energetic and economic performances of the three places. Contextually to be analysed a series of hypothesis finalized to the reduction of the annual cost of the solar air-conditioning, purposive to increase the competitiveness of this system towards the conventional technologies.

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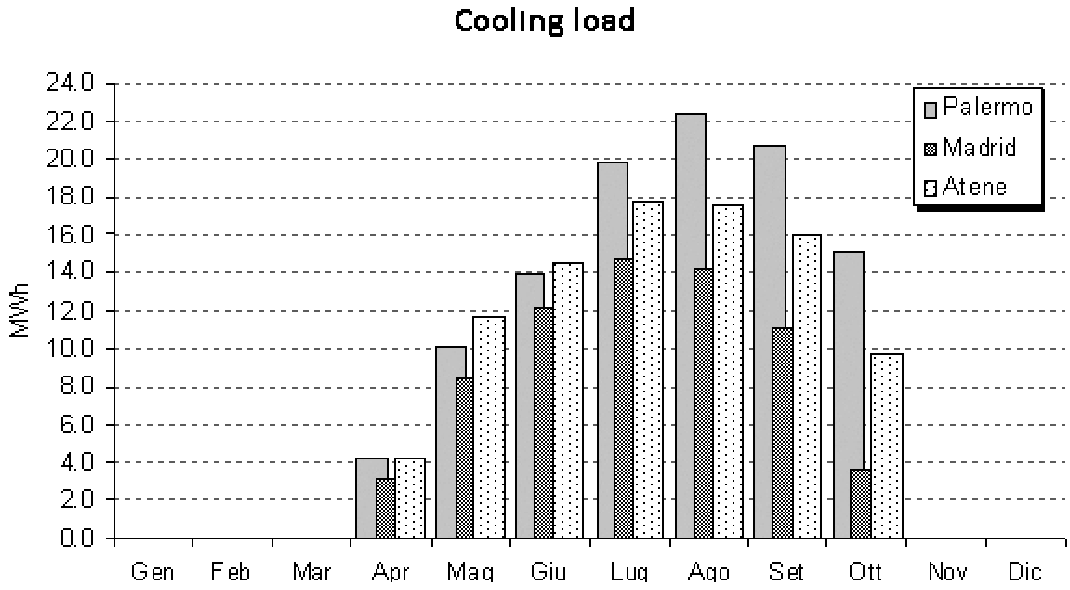

Figure 3. Summer thermal load of the tree studied places

4. Methodology of evaluation of energetic-economic performances
We consider as example the case of the Palermo city. The annual energetic requirements for air-condition an m^2 of building results equal to around 196 kWh/m2. This correspondent at the most value among the analysed places.

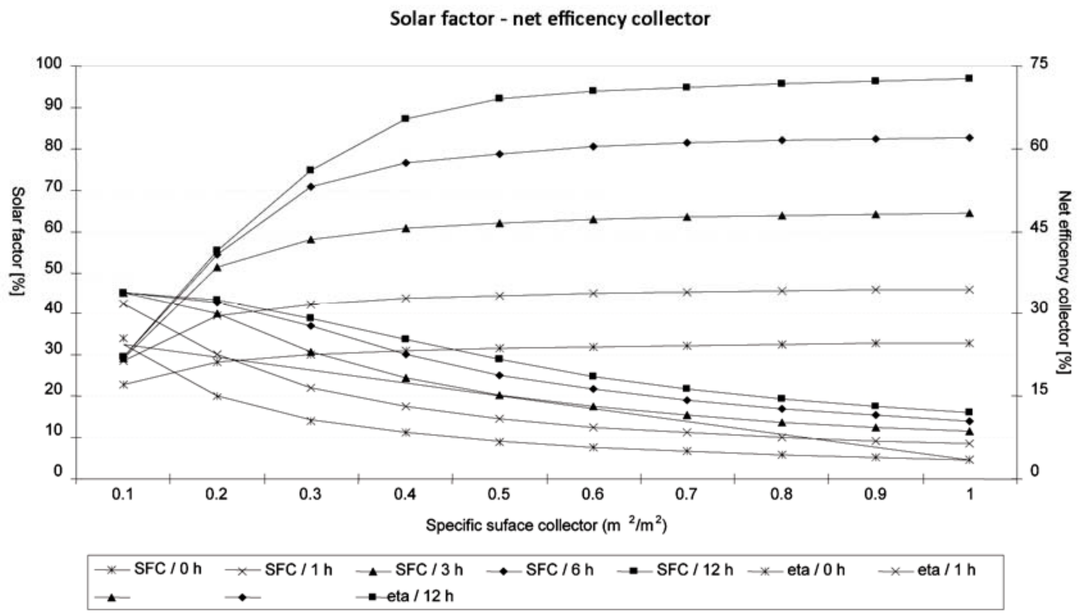

Figure 4. Solar factor and collectors net efficiency against the solar field surface

In the Figure 4 is represented the solar factor and collector net efficiency against the solar surface-building surface ratio. The ratio value equal to 0,1 and 0,2 represent a good compromise.
Figures 5 and 6 illustrate the value of the useful energy produced (expressed in hours) by the solar field and of the solar factor in connection with the employed collector types and the heat storage system. As is obvious, the result obtained are increase of the some solar system performances and increase the annually useful thermal energy produced by 1 m^2 of active surface. Between the solar factor and the efficiency (in correspondence of an increase of the first parameter correspond a reduction of the useful energy produced for effect of the net efficiency diminution) exists a inverse proportionality relationship.

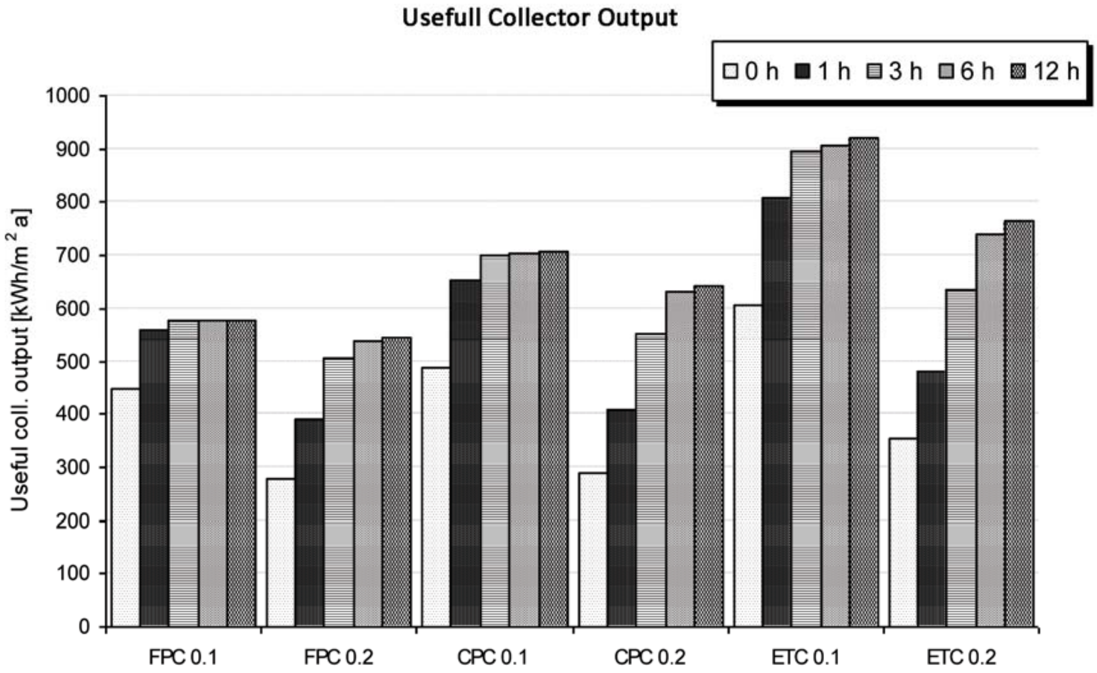

Figure 5. Useful annual energy produced by one m^2 of collector against thermal storage typology system

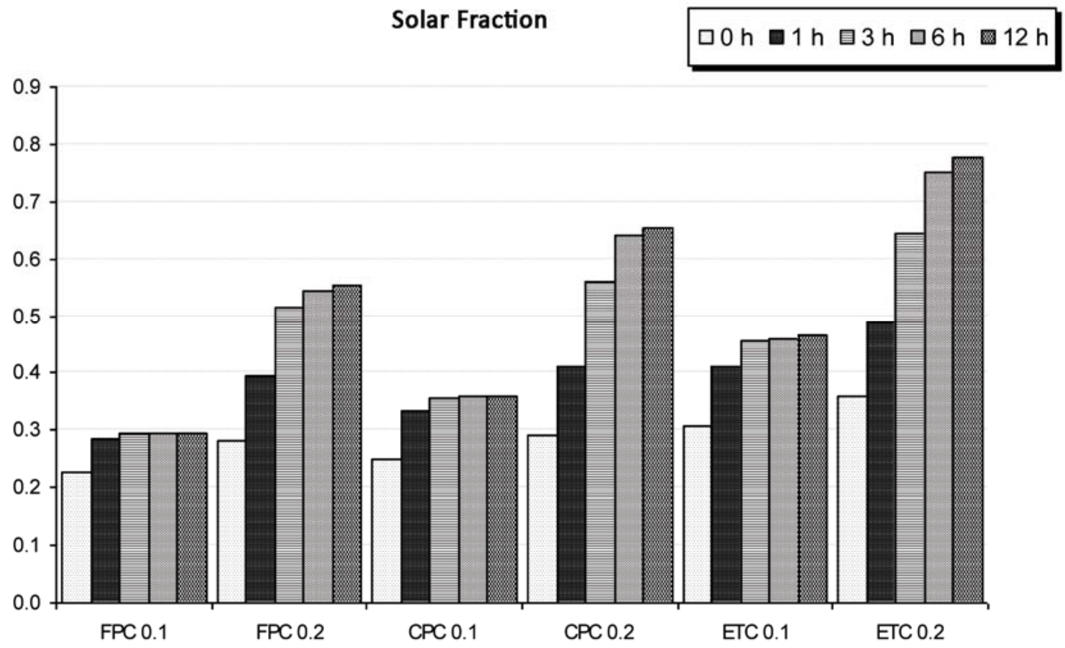

Figure 6. Solar factor against the collector type and the thermal storage capacity of the system

Using the flat collectors is necessary an active area double in comparison to evacuated collectors area. (0.2 and 0,1 m^2/ m^2 of building surface - collector surface ratio).
The table 4 synthesize the results related to the three configurations consider optimal respect to the imposed limits on the collector efficiency (> 20%) and on the primary energy saving in comparison to the traditional configuration (> 25%).
Despite an investment to around 86 k€ for the typology FPC, in the case of the ETC the investment is 88 k€ for have the half active surface. Only thanks to the efficiency of the evacuated collector (ETC), saved annual energy is similar (45.5% against the 51.47 %). Then, further advantage of the systems realized on evacuated collector is represented by a smaller surface for the solar field installation. This possibility is

always pleasant, because in the greatest part of the existing buildings, doesn't exist a special area to the possible installation of solar system.

Table 4. Parameters results of the optimal configuration

Collector type	Surface collectors ratio installed kW	heat storage volume	Net efficiency	Annual cost respect traditional case	electric saved energy respect traditional case	Electric saved energy Cost
FPC - (0.2)	4.80 m^2/kW	5.98 m^3	29.02 %	124.70 %	51.47 %	0.139 €/kWh
CPC - (0.1)	3.48	4.09	40.11	121.46	35.52	0.175 €/kWh
ETC - (0.1)	2.71	4.14	52.0	130.80	45.50	0.196 €/kWh

The Figures 7 and 8 illustrate the trend of the cost and efficiency against the saved primary energy (always in the case of flat collectors).
The minimum point is represented in both the Figures and it indicates a good energetic-economic combination for the optimal FPC configuration. We have increase of the saved electricity energy cost with a increasing the investment cost. In correspondence of least cost, the efficiency becomes constant (Figure 8).

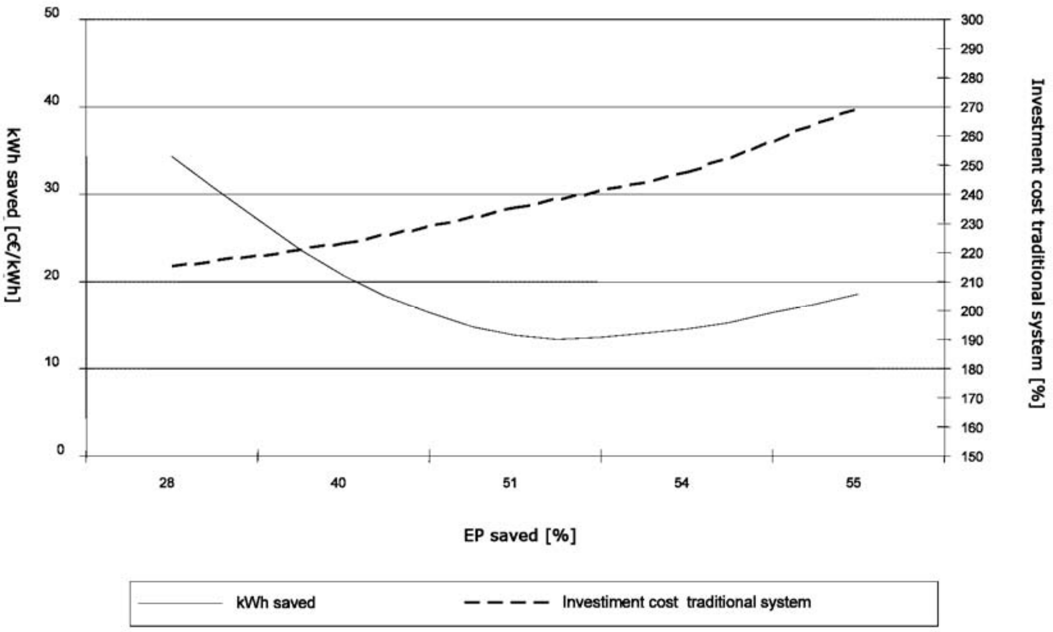

Figure 7. Collectors surface: 0,2m^2 and collector type FPC

The annual present rate of the investment cost was calculated, for each of the examined configurations, using the typical formula of the present coefficient:

$$F_a = \frac{i \cdot \left[(1+i)^n\right]}{\left[(1+i)^n - 1\right]} \quad (6)$$

in which, is the rate of interest (fixed to 6%) and n is the service life of the solar system (fixed to 20 years). Multiplying F_a by the general investment, the annual present rate of the investment cost $C_{inv,ann}$ is obtained. Adding to the annual management and maintenance costs, $C_{o\&m}$, furnishes the already defined annual plant cost of the system: $C_{ann,ref}$, for the traditional case and $C_{ann,sol}$ for the different solar absorption configurations.

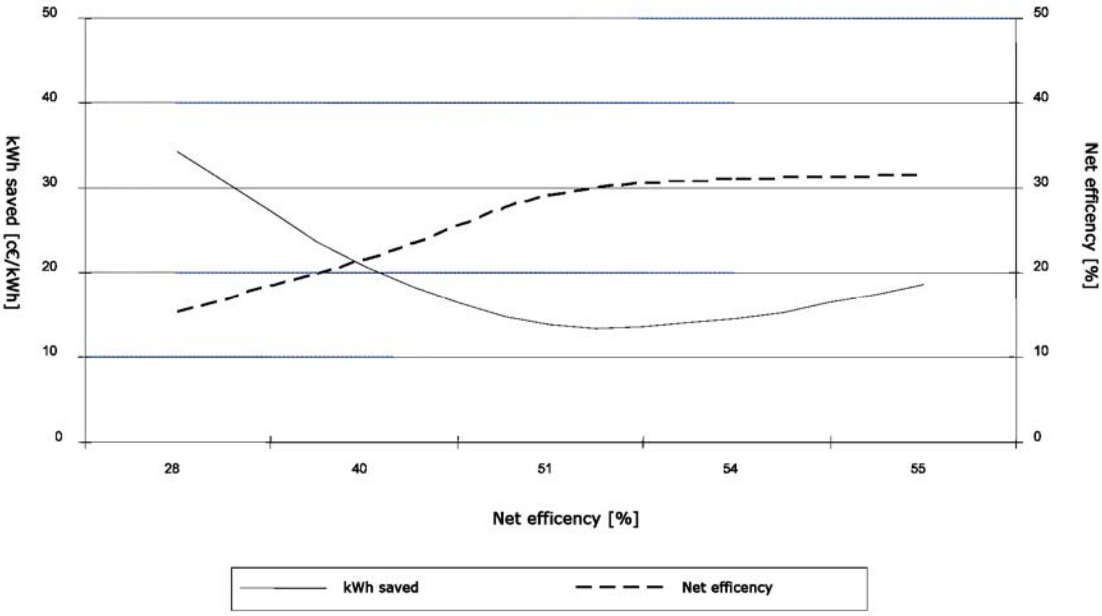

Figure 8. Collectors surface: 0,2 m^2 and collector type - FPC

The table 5 synthesizes the economic results of the optimal configurations for each specific solar technology. The employment of a vapour compression cycle (traditional case power 50 kW) implies an annual consumption of electricity energy equal to 42210,81 kWh , corresponding to an emission of 33768,65 CO_2kg.

A technological change toward solar system involves an increase of the total annual cost; this is obtained essentially because of the greatest investment in equipments. Contrarily, the management costs show a drop, in comparison to the traditional system. This is connected to the smaller annual electric consumption of the solar absorption system. In fact, in this last case, only the electric backup system gets energy by the electric net, in case of necessity

Table 5. Economic and emission related to optimal configurations [A = specific area]

Plant Type (To)	$C_{inv, ann}$	$C_{o\&m}$	C_{ann}	Saved electric energy	Avoided CO^2 emission
Traditional	3197.06 €	9040.21 €	12237.27 €	-	-
FPC - (0.2)	7514.49 €	7743.60 €	15258.08 €	21724.83 kWhel	17379.86 Kg
CPC - (0.1)	6300.10 €	8563.25 €	14863.35 €	14992.62 kWhel	11994.09 Kg
ETC - (0.1)	7674.24 €	8331.76 €	16006.00 €	19204.27 kWhel	15363.41 Kg

In Figure 9 the horizontal continuous line delineate the reference condition (100% of the annual cost corresponding to the traditional system). The black circle corresponds to the solar configuration (FPC, Palermo); with an annual cost equal to 124.7% (ordinate) and a total investment cost of 235% (abscissa) in comparison to the reference condition. The point indicated by the triangle represents the condition for which the cost of the saved electric in kWh succeeds to equalize the electricity market price (0,104 € / kWh). This price, thanks to the employment of the solar energy changes from 0,139 € to 0,104 €. For obtain this price is necessary to reduce the investment costs of 211,5%, and annual cost 118,5%. Moreover, we consider an incentive for any avoided CO_2 emission. This incentive is very important to amortize the cost of a plant. For example, we consider an incentive of 45 €/ton avoided CO_2 emission to amortize the FPC collector system, an incentive of 85 €/ton avoided CO_2 emission to amortize CPC collector system and an incentive of 115 €/ton avoided CO_2 emission to amortize ETC collector system.

In these last two cases, besides the importance of the smaller avoided CO_2 quantity because of the reduction of the employed active surface, the superior cost of technological investment plays a fundamental role.

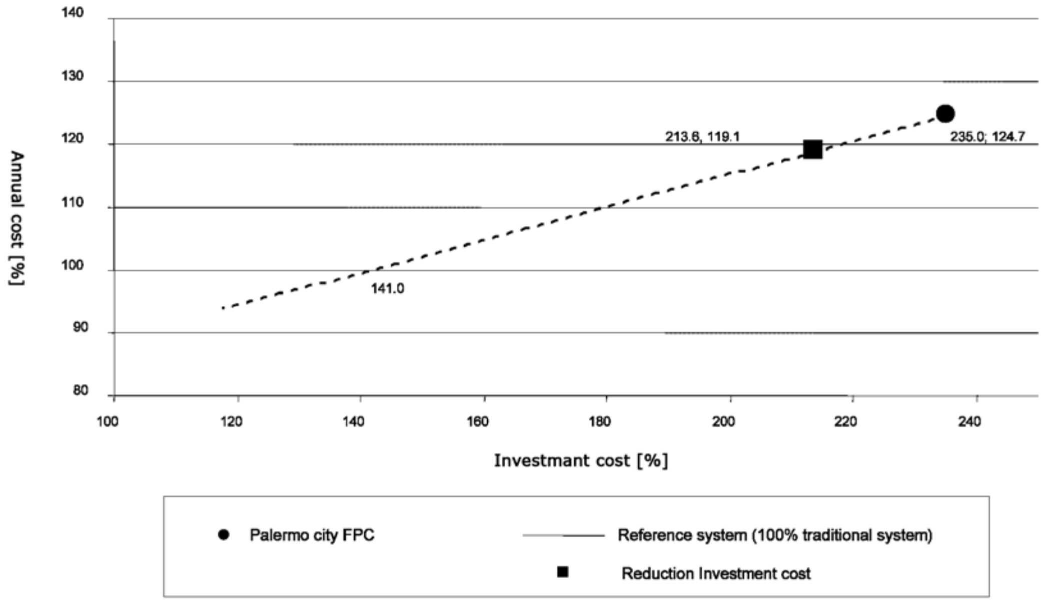

Figure 9. Annual cost and investment cost [FPC]

Simultaneously we consider the effect of the electricity price increment. Particularly, was considered increase of the electric energy market price from a reference of 0,14 €/kWh up to the value of 0.21 €/kWh (200%). Moreover, we have an increase of electric equipments management costs from a reference of 75 €/kW installed to 150 €/kW installed. This hypothesis considers the peak electric consumptions in summer air-conditioning.
From the Figure 10 we observed that, in the FPC-150 case, we archive the break-even point in correspondence of an increase of the electricity price around 40%.

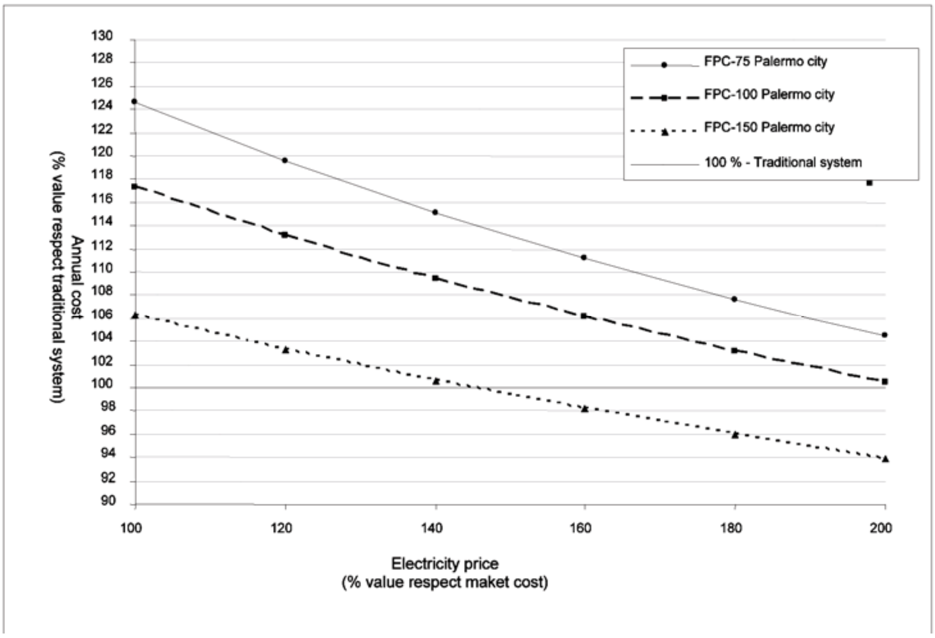

Figure 10. Effect of the electricity price increase and electric equipments management cost [FPC]

The considerations describe in the preceding paragraphs for the Palermo city, are repeated identically for the other two studied cities. Obviously, only differences are in the numerical results, because of the different environmental conditions and of the different energetic demand of air-conditioning

5. Economic-environmental performances indexes for Palermo, Madrid and Athens

These indexes consider, either the investment and exercise costs of the absorption system, also the environmental performances in comparison to the traditional system. First of all, the Figure 11 and Figure 12 show a general vision of the results for the different site and solar technologies, in terms of the installation system costs and electricity saved costs with the absorption system.

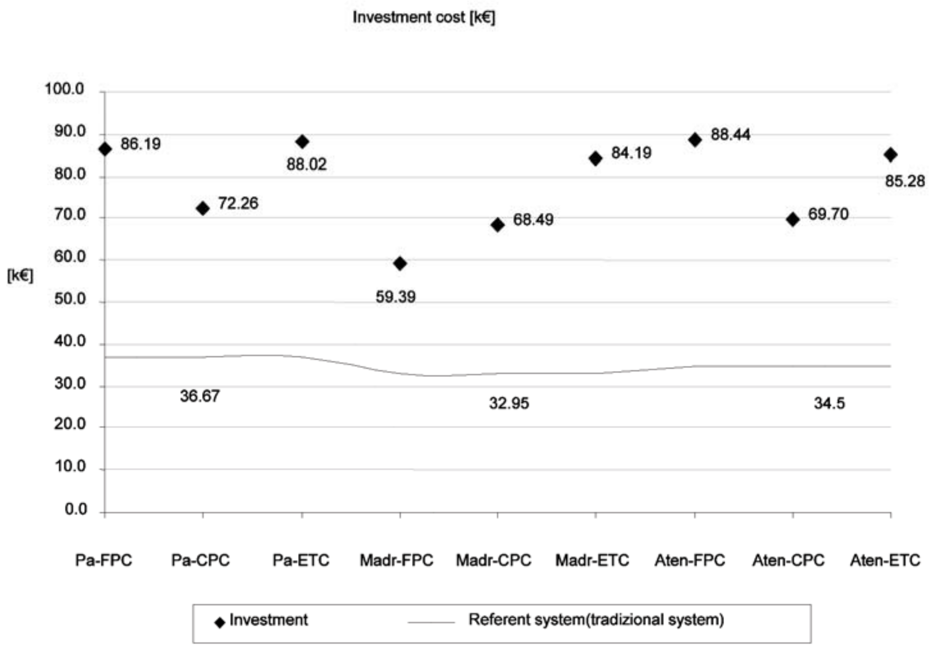

Figure 11. Total cost of the system relative at kWh saved

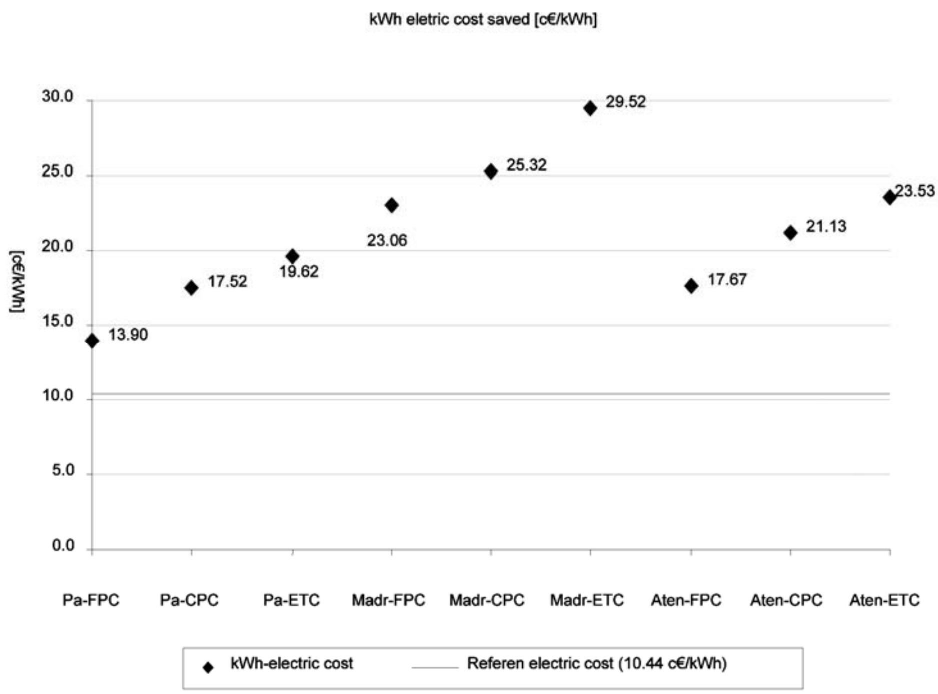

Figure 12. Total cost of the system relative at kWh saved

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Exclusively considering this last parameters, the solution Pa-FPC (Palermo, flat collectors) would seem the best (Figure 12). Instead, if you observe in the Figure 12, the solution Pa-FCP is characterized by the highest investment cost, even though, it uses a low cost technology and little efficient, as the solar flat collectors.
In the end was assess the annual electric kWh saved from each solar configuration (this are strictly linked at the annual quantity of CO_2 saved and not blow in environment). For all solar configurations, was defined the next performance index:

- Economic performance index I_{p1}:

$$I_{p1} = \frac{C_{Inv,\max} - C_{Inv}}{C_{Inv,\max} - C_{Inv,\min}} + \frac{C_{ann,\max} - C_{ann}}{C_{ann,\max} - C_{ann,\min}} \quad (7)$$

where $C_{Inv,max}$ and $C_{Inv,min}$ are, respectively, maximum and minimum investment cost among the configuration system examined; C_{Inv} is the investment cost of the configuration system considered; $C_{ann,max}$ and $C_{ann,min}$ are, respectively, maximum and minimum annual costs among those system examined and C_{ann} is the annual cost of the configuration system examined.
The index can vary between a minimum of zero and a maximum of 2, in correspondence, respectively of the worse and best option. Moreover, the index furnished only an economic and convenience indication. The most competitive option, that correspondent at the low risk investment, is the option associated to the highest value of this index.
Considering also the environment effects, we have introduced a second index, defined as it follows:

- Environmental-energetic performance index , I_{p2} :

$$I_{p2} = I_{p1} + \frac{E_{el,\max} - E_{el}}{E_{el,\max} - E_{el,\min}} \quad (8)$$

where $E_{el,max}$ and $E_{el,min}$ represent, respectively, the maximum and minimum annual saving of electric energy express in kWh between the configurations examined, while, E_{el} is the annual saved associates of the analyse case.
This index can vary between zero and three, with maximum value in correspondence of the best option. With this index we obtain an indication on the environmental performance (electric energy saving, and reduction of CO_2 emission). The two following Figures 13 and 14 show the performance indexes for all the optimal cases.

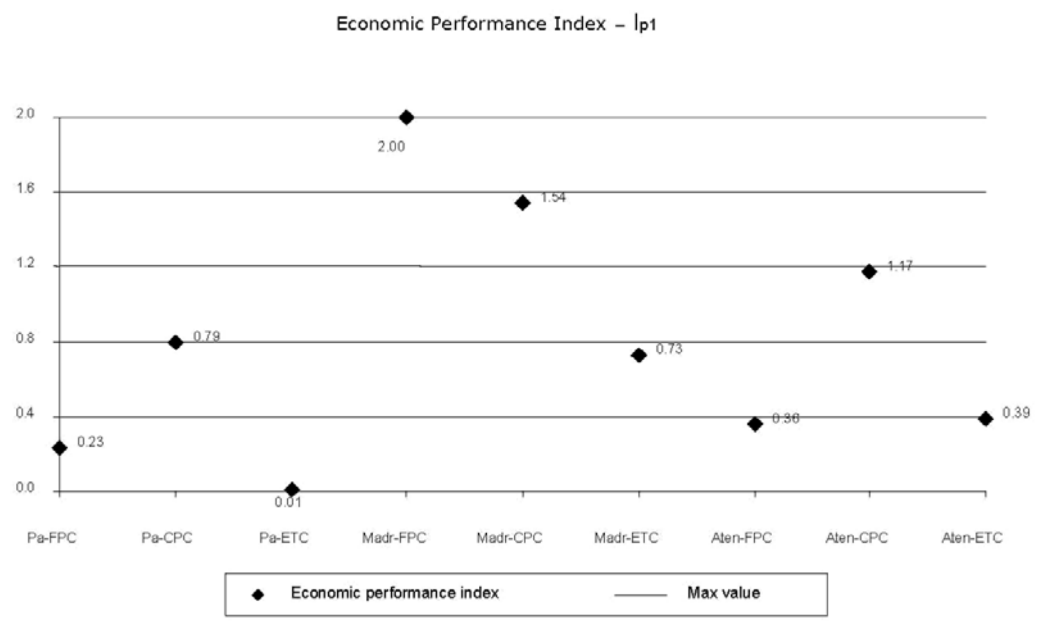

Figure 13. Economic performance index for examined cases

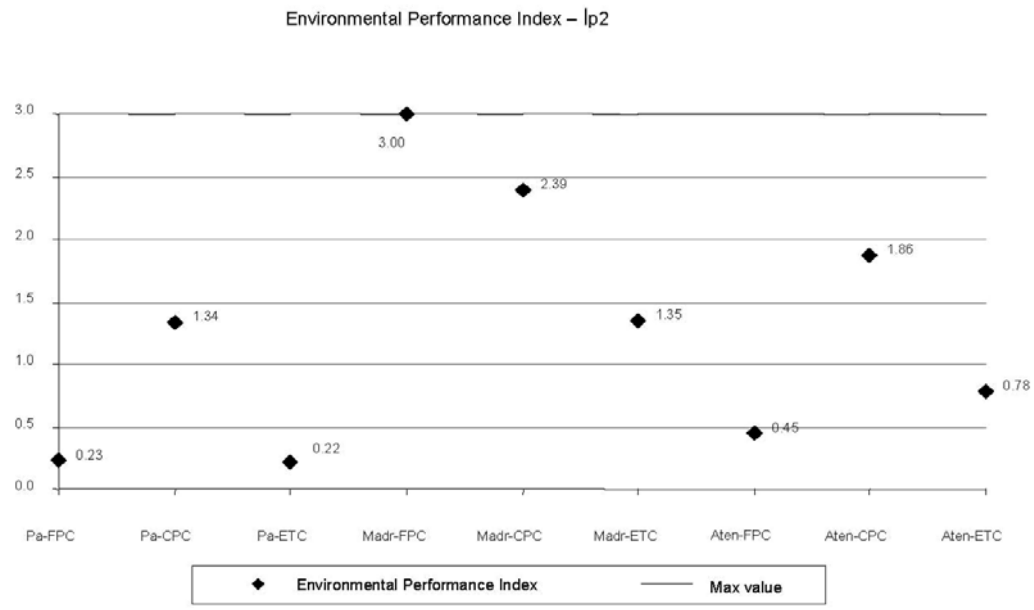

Figure 14. Economic and environmental index

The result of the index calculation on the three cities have indicate that the less expensive solar technology (FPC) It's not result the best. This result is confirmed if we consider the electric energy saving associated to the employment of solar energy. In this way, the configuration with the low cost of the kWh (Pa-FPC) result the worse. The cause is due to the employment of a solar technology with lowest efficiencies, that allow a high annual electricity saving despite the utilize of a double active surface in comparison to surface of the other configurations. In this way we obtain an investment cost doubled.

6. Conclusion

In this study we developed a technical-economic evaluation utilizing the air-conditioning systems powered by solar energy compared with the traditional vapour compression system. Among the different solar technologies, we have chose the technology based on the LiBr-H2O absorption cycles. All evaluations were realized using meteorological data of three places, Madrid, Palermo and Athens, representatives of the typical climatic conditions of the Mediterranean area.
The results of the different system comparison are:

- The competitive solutions have a meaningful saving of primary energy (> 25%) and, contemporarily, a high efficiency of the collectors (> 20%);
- An increase of the solar fraction implicates great environmental benefits in terms of CO_2 emission reduction and energetic saving, but also an unsustainable growth of the investment and annual cost;
- For all the solar systems analysed (FPC,CPC,) resulted an investment and annual cost higher respect the compression vapor system, despite the solar system allows considerable energy saving;
- The annual costs referred to the traditional case increase with the increment of the solar collector surface and it was individuate a minimum specific cost of the electric energy saved, $C_{el,sav}$, for an assigned collectors surface;
- The annually energy saved (electric or primary) depends on the type of solar technology used. The flat collectors have primary energy saving around 40%. The evacuated collector, with higher efficiency, can be to reach and overcome the 50% in comparison to the traditional system. This demonstrate that the solar air-conditioning systems can contribute in meaningful way to the energetic saving and the CO_2 emission reduction;
- The solar scheme by an electric backup has been preferred to a thermal backup because of the scheme by thermal backup necessity of great solar surfaces for to have meaningful benefits of primary energy saving.
- Results essential to maximize the use of the solar system for all year for reward the high investment cost. This is possible using the system in different applications: the air-conditioning, the heating the room and the production of domestic hot water.

- For some component of the air-conditioning solar system (collectors, absorption machines, heat storages), we can anticipate a reduction of the costs caused from a great industrial production. This effect of reduction of the first cost of the system was considered for the optimal system in the different City examined.
- At last, we also considered the effect of the electricity price increase on the economic performances of the solar systems. The hypothesis of investment cost and equipments cost reduction resulted more advantageous for the solar system. Indeed the reference system, using the electric energy, is penalized because the most consistent percentage fraction of management costs depends essentially by electric consumptions. The utilize of the solar absorption system allows a smaller electric demand, balancing, at the same time, the greater investment cost.

At last the global two indexes of energetic-environmental performance have been defined and we have calculated the cost of the saved electric. In such way it was possible to individualize the optimal configurations in dependence from the collector's number for each site.

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