Article

PERFORMANCE RESULTS OF A SOLAR ADSORPTION COOLING AND HEATING UNIT

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Abstract: The high environmental impact of conventional methods of cooling and heating has increased the need for renewable energy deployment for covering thermal loads. Towards that direction, the proposed system aims at offering an efficient solar powered alternative, coupling a zeolite-water adsorption chiller with a conventional vapor compression cycle. The system is designed to operate under intermittent heat supply of low-temperature solar thermal energy (<90 °C) provided by evacuated tube collectors. A prototype was developed and tested in cooling mode operation. The results of separate components testing showed that the adsorption chiller was operating efficiently, achieving a maximum coefficient of performance (COP) of 0.65. With respect to the combined performance of the system, evaluated on a typical week of summer in Athens, the maximum reported COP was approximately 0.575, mainly due to the lower driving temperatures at a range of 75 °C. The corresponding mean energy efficiency ratio (EER) obtained was 5.8.

Keywords: Solar Cooling; Adsorption; Evacuated tube collectors; Experimental testing.

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1. Introduction

The depletion of fossil fuel reserves and the growing concerns over the environmental impact of conventional cooling and heating technologies has turned attention towards alternative methods utilizing renewable energy sources. In this context, solar energy presents the most promising candidate to drive sustainable cooling and heating systems. In fact, given the concurrence between the solar availability and the peak building demands makes such systems as a field of great potential [1].

With respect to solar driven heating/cooling there are two main technologies: photovoltaic driven reversible heat pumps and solar thermally driven sorption heat pumps [2] [3]. Currently, the PV driven cooling/heating systems dominate the market, thanks to overall growth of the PV market, which is expected to gain a share of 16% of the total energy production by 2050, according to International Energy Agency [4]. This expansion of the PV market, along with the respective increased use of reversible heat pumps has resulted in low specific capital costs for the PV driven cooling/heating systems, making this technology the most competitive solar driven cooling/heating technology [5].

On the other hand, the majority of commercially available solar thermally driven cooling/heating setups implement an absorption heat pump, mainly due to the fact that absorption is the most mature thermally driven cooling/heating technology [6]. Several solar absorption applications have been developed and are currently in operation across the world. For instance, a solar driven absorption system has been installed at the Centre for Renewable Energy Sources and Saving (CRES) in Pikermi, Athens, Greece, and is in operation since December 2011. The solar field consists of flat plate collectors with a total surface of 149.5 m², while an underground energy storage

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system with a total volume of 58 m³ has also been installed. The LiBr-H_2O absorption chiller has a nominal capacity of 35 kW, while a 18 kW conventional heat pump is installed as a backup. According to measurements conducted by Drosou et al. [7], the achieved solar fraction is around 70%. The annual cooling demands were estimated to be 19.5 MWh/a, which refers to the period May-September, while the respective heating loads were 12.3 MWh/a for the period October-April [8].

On the other hand, adsorption technology has gained attention over the past years, thanks to its potential to exploit very low-grade heat sources, the absence of crystallization issues and the simplicity of the involved equipment due to the absence of solution pump and rectifier [9] [10]. Furthermore, compared to conventional electrically driven systems, the adsorption technology advantages in the lower operating costs, the absence of moving parts and the absence of vibrations [11]. On the other hand, a key drawback for adsorption technology is the relatively low coefficient of performance (COP) [12].

Solar adsorption systems have already been investigated thoroughly in terms of both their theoretical and experimental performance [13] [14].

In [15] authors introduce an innovative thermodynamic cycle based on a four-bed layout and three-stages which can be powered by low temperature heat. The mathematical simulations conducted have shown that the maximum coefficient of performance of the system can be achieved for a regeneration temperature at 55 °C while the optimal cycle time was dependent on the corresponding heat source temperature thus proving the possibility to employ adsorption chiller for solar applications. Habib et al. [16] simulated the performance of a two stage four bed silica gel-water adsorption system, powered by evacuated tube collectors. For the needs of the simulations, the heat source temperature varied from 40 to 95 °C. In single stage mode (driving temperature of 80 °C, cooling water temperature of 30 °C and chilled water inlet temperature 14 °C), the COP was around 0.48. On the other hand, when the driving temperature is lower (50 °C), the system operates in two stage mode, with a COP of approximately 0.27. Lemmini and Errougani [17] tested a single-bed methanol- activated carbon (AC-35) adsorption unit powered by a flat plate collector. Several experiments were conducted, achieving a maximum solar COP of 0.078 with a second law efficiency of 71%. Aristov et al. [18] evaluated by simulations and developed a solar refrigeration system based on a closed adsorption cycle. Among several chemisorbents, CaCl2 in silica gel composite sorbent was found to be the most efficient sorbent for water adsorption, resulting in a cycle's COP equal to 0.6-0.8 (T_e=5 °C, T_c=35 °C and T_{des}=80 °C). evaluated experimentally a silica-gel single bed adsorption chiller driven by 4 m² evacuated tube collectors under the climatic conditions of Baghdad, Iraq. The nominal driving heat temperature was set at approximately 90 °C. Under varying experimental conditions, the optimal working point of the chiller was determined to be achieved at an evaporator temperature of 6.6 °C, which corresponded to a COP of 0.55. Chorowski et al. [19] investigated the performance effects of the control strategy on a three-bed, two-evaporator adsorption chiller. Authors demonstrated that changes to the control system can improve the performance of the chiller, especially in terms of COP. However, improvements were still limited: average COP was improved by 7.5% while the peak COP was improved by 11% up to 0.71. Due to the aforementioned drawbacks of adsorption technology, there are fewer applications of solar adsorption cooling. One of the earliest solar thermal system based on a 5.5 kW adsorption chiller was developed and installed at Institute for Solar Energy System (ISE) in Freiburg, Germany. The measurements conducted between August 2008 and July 2009, revealed an average COP of 0.43 [20].

Despite the attractiveness of the aforementioned solutions, the need to cover thermal loads on the absence of solar irradiance, results in the use of conventional backup systems. In order to overcome this issue, recently, several hybrid adsorption/compression solutions have been proposed [21] [22]. In this context, ZEOSOL project is based on the hybridization of an adsorption chiller with a conventional vapor compression cycle. The implementation of the vapor compression cycle allows for covering of the peak loads allowing the adsorption chiller to operate at higher COP, while on the absence of the solar irradiance the conventional system is able to fully cover the loads of the residential building [23].

The system has been designed with particular attention on the environmental impact of the developed system, compared to conventional alternatives, as presented by Kallis et al. [24]. The life

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cycle assessment (LCA) of the investigated system, using the ReCiPe 2016 method, outlined the significant reduction in the system's impact on global warming and ozone depletion with respect to conventional reversible heat pumps.

In the present study the authors investigate the preliminary experimental performance of a solar driven hybrid cooling and heating system based on a small-scale zeolite-water adsorption chiller at adsorption only mode. The prototype system has been designed to fully cover the thermal loads of a residential building of 12.5 kW peak cooling load.

2. System description

The proposed project focuses in the coupling of a zeolite-water adsorption chiller with solar thermal collectors. The cooling capacity of the developed sorption chiller is exceeding 10 kW with a maximum reported COP of 0.65. To reduce the chiller's capacity and thus the required solar field area, enhancing simultaneously the efficiency on part-load operation, a backup electrically driven heat pump is coupled with the adsorption chiller. The backup heat pump has a nominal cooling capacity of 10 kW and is used mainly to cover peak loads. The solar field consists of three rows of advanced evacuated tube collectors with a total surface of 40 m^2.

To enhance solar collector's performance and allow risk-free operation on low ambient temperatures, a propylene glycol solution is used as the working medium for the solar subsystem. Moreover, all secondary circuits of the adsorption chiller are using pure water. The 1 m^3 heat storage tank is equipped with heat coils, via which heat is transferred from the glycol solution towards the hot water, which in turn drives the adsorption chiller. A "V shaped" dry cooler is implemented as the heat rejection unit for both the adsorption chiller and the backup heat pump, retrofitted for the specific application. An overview of the prototype, including the installed measuring devices is shown in Fig. 1 and Fig. 2, while images of the actual setup are also provided in Fig. 3.

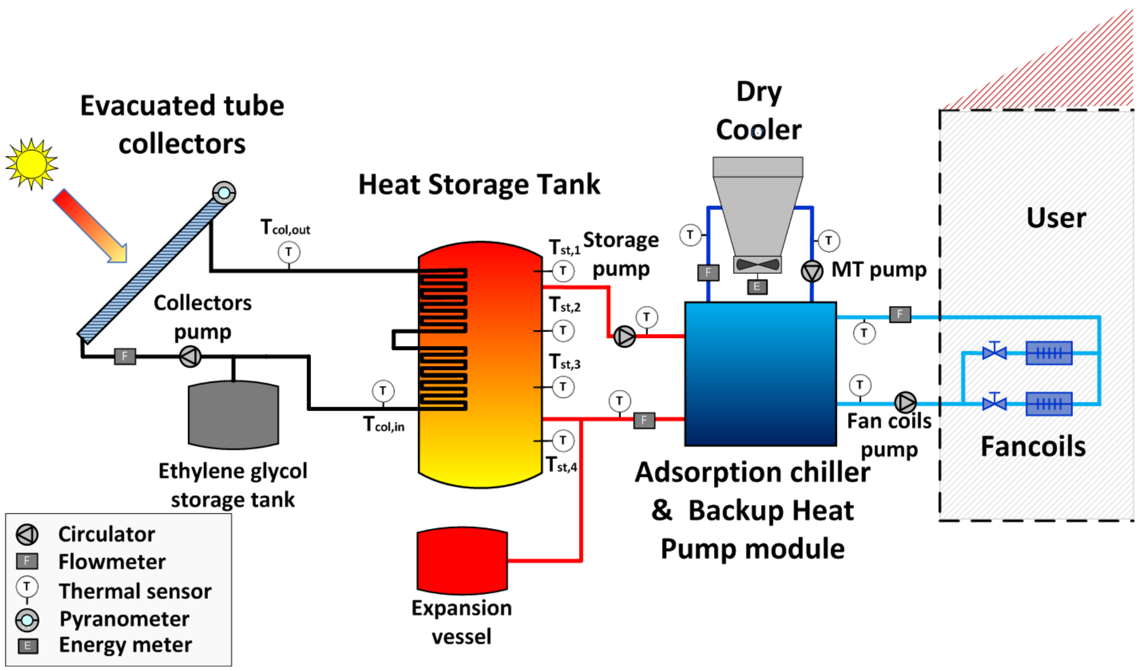

Fig. 1 - Schematic of system prototype with all the involved measuring devices.

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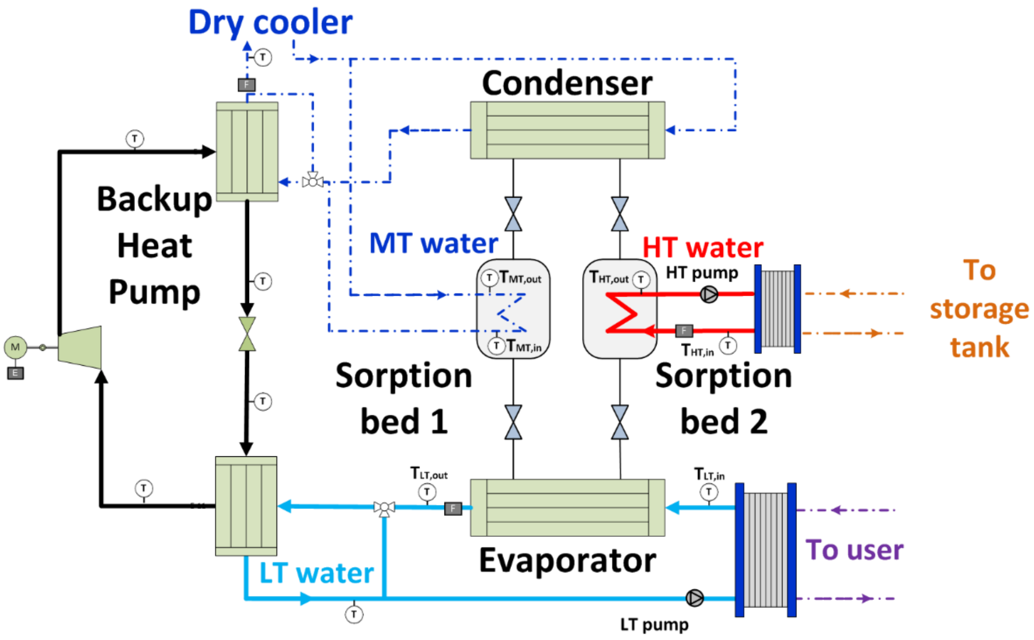

Fig. 2 - Detailed schematic of the hybrid adsorption chiller/backup heat pump module.

(a)

(b)

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(c) **(d)**

Fig. 3 - Overview of the experimental setup components: (a) the ETCs solar field, (b) the hybrid chiller-dry cooler setup, (c) the solar station and the storage tank and (d) the hydronic ducted fan coil unit

3. Experimental measuring of separate components

The preliminary measuring of the proposed system was divided in three parts: (a) the experimental assessment of the solar collectors and the storage tank, (b) the performance testing of the hybrid adsorption chiller and (c) the dry cooler along with all the involved auxiliary equipment (e.g. circulations pumps).

The solar collectors used in the system are heat pipe evacuated tube collectors, manufactured by Akotec specifically for ZEOSOL system and being able to operate efficiently between 65-95 °C. The collectors were tested by a certified institute according to ISO 9806. The results of the testing with respect to the characteristic curve of the solar collectors are shown in Fig.3. The collector efficiency, shown in Fig. 4, is calculated as follows:

$$\eta = \eta_0 - c_1 \frac{T_{col} - T_a}{G} - c_2 \frac{(T_{col} - T_a)^2}{G} \quad \text{(eq. 1)}$$

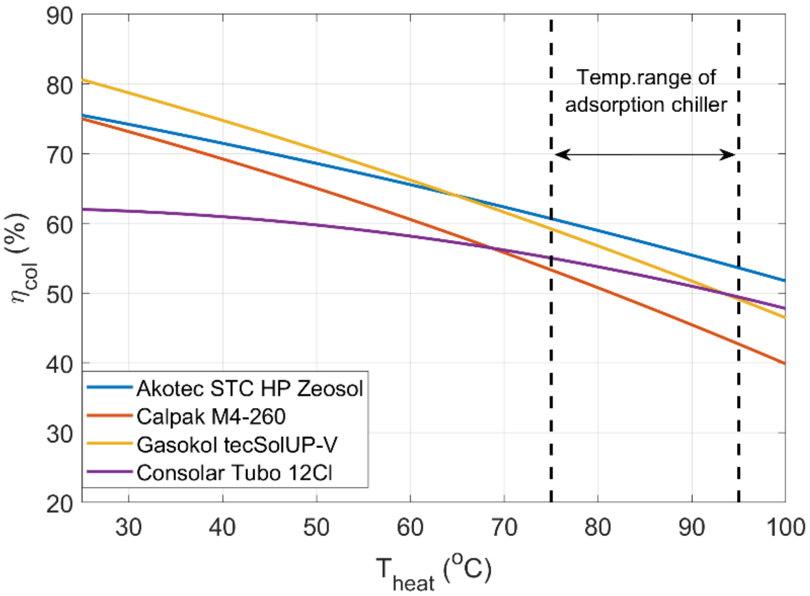

Fig. 4 - Performance curve of the developed solar collectors for ZEOSOL system (blue line) in comparison to other commercial solar collectors

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On the other hand, the adsorption chiller was developed and experimentally tested by the respective manufacturers, Fahrenheit GmbH. The performance results of the separate testing of the adsorption chiller, revealed a maximum thermal COP of 0.65, corresponding to an energy efficiency ratio (EER) as high as 45 for a driving temperature of 85 °C [22]. The aforementioned COP for the adsorption chiller is defined by eq.2:

$$COP = \frac{\dot{Q}_{LT}}{\dot{Q}_{HT}} \qquad \text{(eq. 2)}$$

With HT referring to the driving heat supplied to adsorption chiller and LT to the low temperature stream which provides the cooling effect. On the other hand, the EER is defined as the ratio between the cooling capacity $\dot{Q}_{LT}$ and the total electric power consumption of the system $\dot{W}_{el}$:

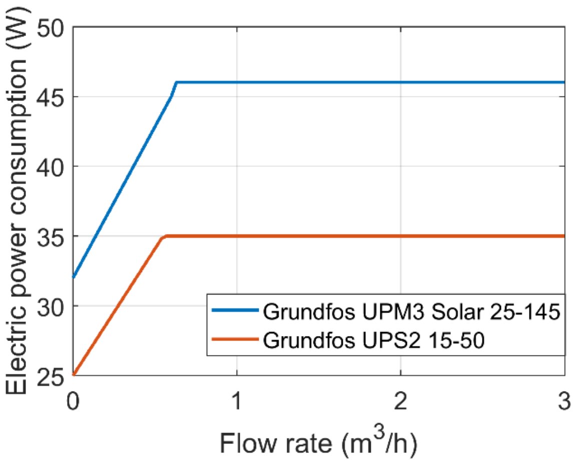
$$EER = \frac{\dot{Q}_{LT}}{\dot{W}_{el}} \qquad \text{(eq. 3)}$$

For the determination of the total electric power consumption of the system, apart from the electrical consumption of the dry cooler, $\dot{W}_{el,dc}$, are contributing also (i) the power consumption of the heat pump's compressor, $\dot{W}_{el,com}$, and (ii) the electrical consumption for the six pumps of the system, as shown in Fig.1. The total electrical power consumption is calculated as follows:

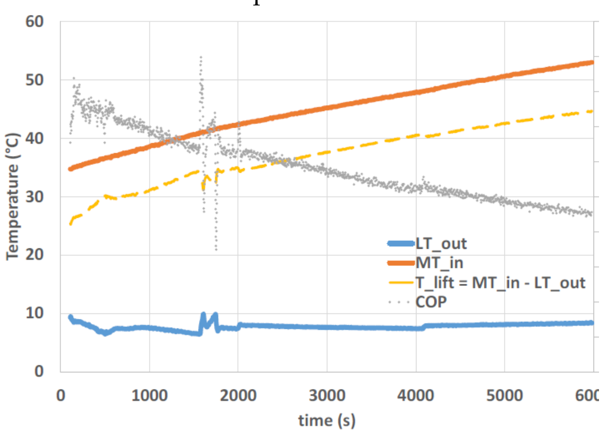
$$\dot{W}_{el,tot} = \dot{W}_{el,com} + \dot{W}_{el,dc} + \sum \dot{W}_{el,pumps} \qquad \text{(eq. 4)}$$

The equations for the power consumption of the HT, MT and LT pumps of Fig.1 can be found at [22]. Moreover, the fan coils pump is identical to the LT pump, thus the same power consumption profile is realized. The solar collector's circuit pump, installed at the solar station of the setup, Fig.2(c), is a Grundfos pump, model UPM3 Solar 25-145. On the other hand, the storage pump is a pump from the same manufacturer, model UPS2 15-50. The electric power consumption curves, as provided by the manufacturer, of the aforementioned pumps are shown in Fig. 5 (a).

The backup heat pump is a custom-made module developed for this specific application and a series of experiments were conducted at CNR-ITAE to evaluate its performance in coupling with the dry cooler of the system. Fig. 5 (b) and (c) show that the performance of the backup heat pump, operating with R134a at a cooling water temperature of 7 °C, is considered satisfactory, achieving COP values as high as 4.0. On the other hand, Fig. 5 (d) presents the power dissipated by the dry cooler as a function of the temperature difference between the water input and air.



(a)



(b)

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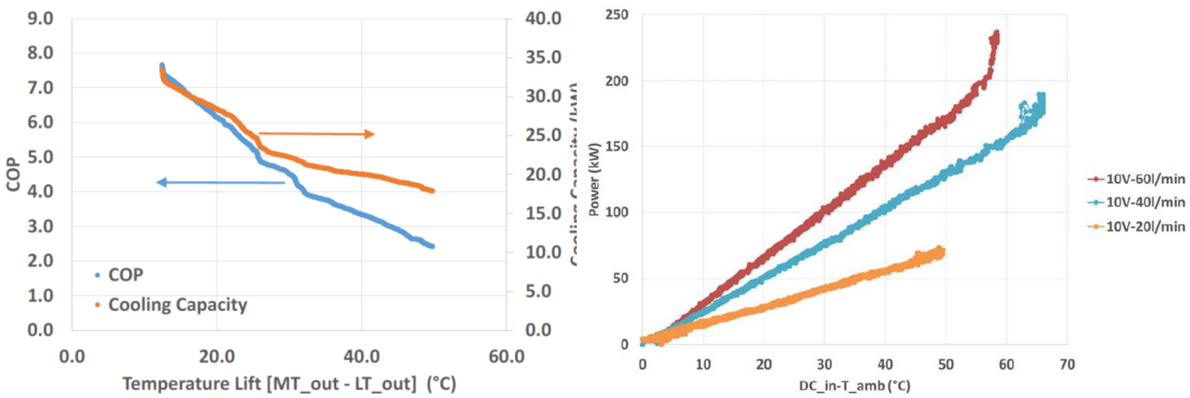

(c) (d)

Fig. 5 - Experimental results of (a) the electrical consumption of the pumps, the developed backup heat pump performance (b) at maximum flow rate and (c) as a function of the maximum temperature lift and (d) cooling map of the dry cooler for variable flow rates at maximum fan speed.

Regarding, the performance of the backup heat pump, its COP is defined by eq.5:

$$COP = \frac{\dot{Q}_{LT}}{\dot{W}_{el,com}} \qquad \text{(eq. 5)}$$

4. Results of solar adsorption cooling unit performance

In this section are presented the experimental results of the developed setup operating solely with the adsorption chiller. All temperature measurements were obtained using Pt1000 thermal sensors, class A according to DIN/EN 60751. The flow sensors used are ultrasonic in-line flow meters with a 2% accuracy. The electrical power consumption of the dry cooler, the compressor and the circulation pumps was measured using energy analyzers. Finally, the solar radiation and the ambient conditions were monitored via a solar weather station, equipped with a second class (as ISO 9060) pyranometer, a Pt1000 thermal sensor, an air humidity sensor and an anemometer.

Fig. 6 shows the temperature trend and performance measured in a typical summer day. In particular Fig. 6 (a) presents an overview of the ambient conditions, with respect to the temperature and the solar irradiance for the week of the measurements.

As shown in Fig. 6 (a), the solar irradiance in the evaluated week –first week of August 2019- is a rather lower than the average peak values for the summer of the typical year in Athens, not exceeding 1000 W/m². On the other hand, the simultaneous higher ambient temperatures that occurred in the investigated days resulted in operating all the components at higher temperature levels, which decreased their efficiency. Fig. 6 (b) and (c) present the temperature profiles for the solar collectors-storage tank module and for the adsorption chiller secondary streams, respectively. The adsorption chiller was set to start its operation at 65 °C for the HT in stream, resulting -in combination with the available solar irradiance- in operating only a few hours per day close to the solar noon. Despite the less optimal conditions, the system is able to cool down the water to 7.5 °C, which is the setpoint for the low temperature circuit, even though the driving temperature was less than 80 °C on all cases. The profiles of Fig. 6 (c) outline the necessity for a modification of the control strategy for the involved circulating pumps so that higher driving temperatures are obtained ensuring maximum efficiency of the chiller. At this point, it has to be highlighted that Fig. 6 refers to adsorption only mode, thus at the absence of driving solar heat the system is off, which results in no operation at night.

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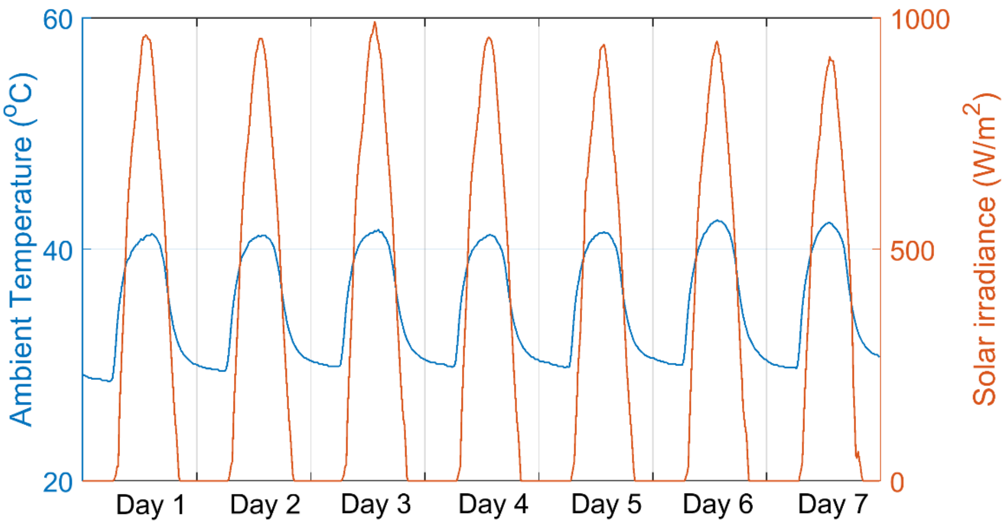
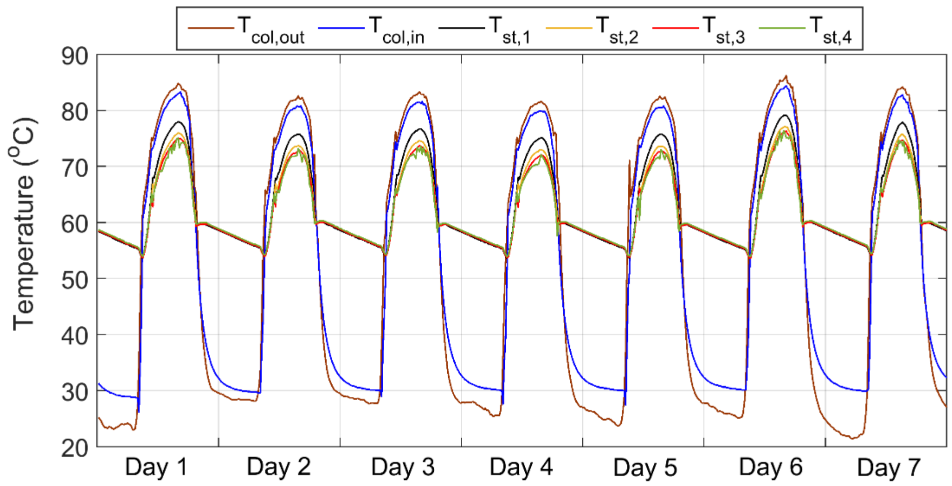


(a)



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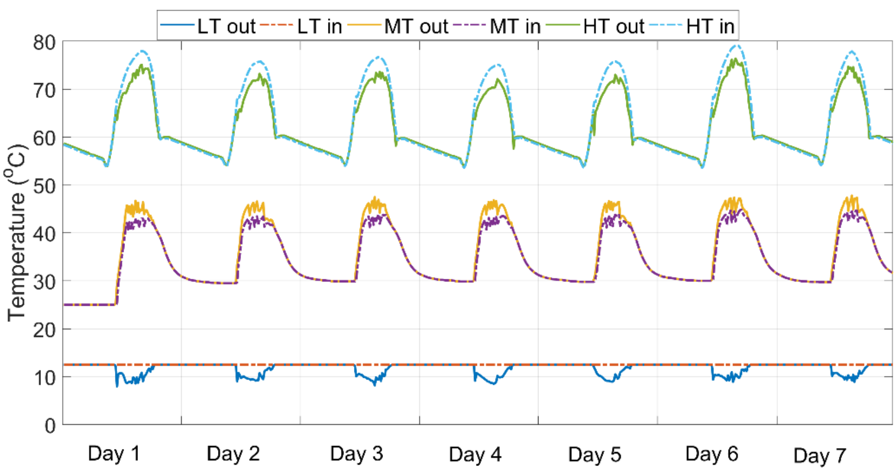

(c)

Fig. 6 - (a) Ambient conditions at the period of the experiments (b) experimental results with respect to the solar sub-circuit temperatures and (c) with respect to the chiller's secondary streams' temperatures

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Fig. 7 presents the performance results for the entire ZEOSOL system, on adsorption-only mode, based on the definitions of eq. (2)-(3) in a typical summer day. Fig. 7 (a) shows the cooling power production of the chiller during the investigated week and the total electrical power consumption, as defined by eq. (4). As shown in Fig. 7 (a) the maximum obtained cooling power output is around 5 kW, which is approximately 40% of the nominal chiller's cooling capacity and is mainly attributed to the lower driving temperatures during the period of the measurements. On the other hand, the electrical power consumption is significantly low, with a maximum of 900 W, mainly due to the operation of the dry cooler, which accounts for more than 60% of the total power consumption of the system, on adsorption-only mode. The corresponding performance indicators are presented in Fig. 7 (b). The maximum obtained thermal COP is approximately 0.575, for a maximum reported driving temperature of 79 °C, while the corresponding maximum EER was as high as 12, with an average operation at approximately 5.8. As these figures present only preliminary results of the system's performance on real-time conditions, there cannot be conclusive outcomes at this point. However, the first results with respect to the COP and the EER, at driving temperatures more than 10 °C lower than the nominal driving temperatures are rather promising. Furthermore, as a next step in the experimental evaluation of the system is also considered the operation of the backup heat pump as either an efficiency boost to the adsorption chiller as well as to cover the thermal loads at periods with no solar availability.

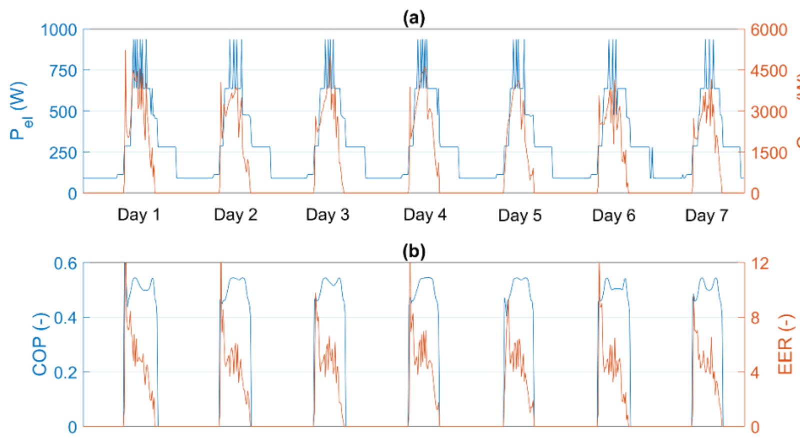
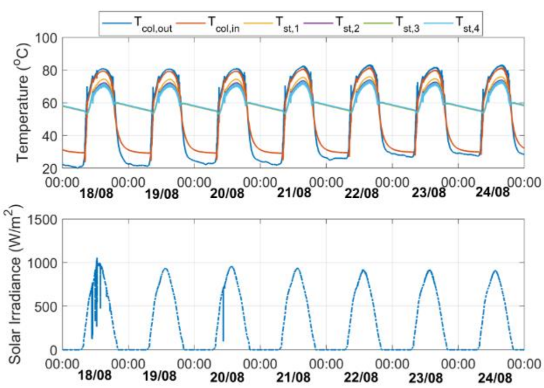
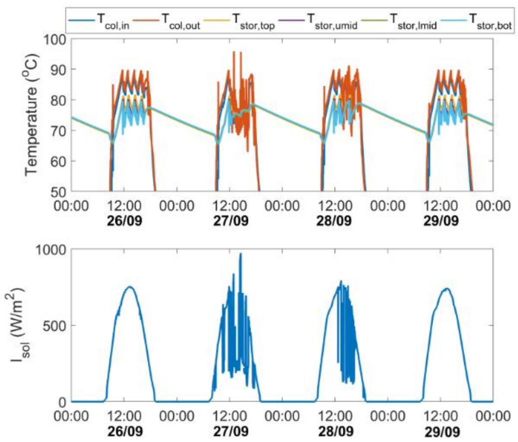


Fig. 7 - Performance results of proposed system prototype with respect to (a) the produced cooling output and the respective electrical consumption and (b) the corresponding COP and EER values.





a) *b)*

Fig. 8 – ZEOSOL System behaviour in hot summer days (a) and in cloudy days (b).

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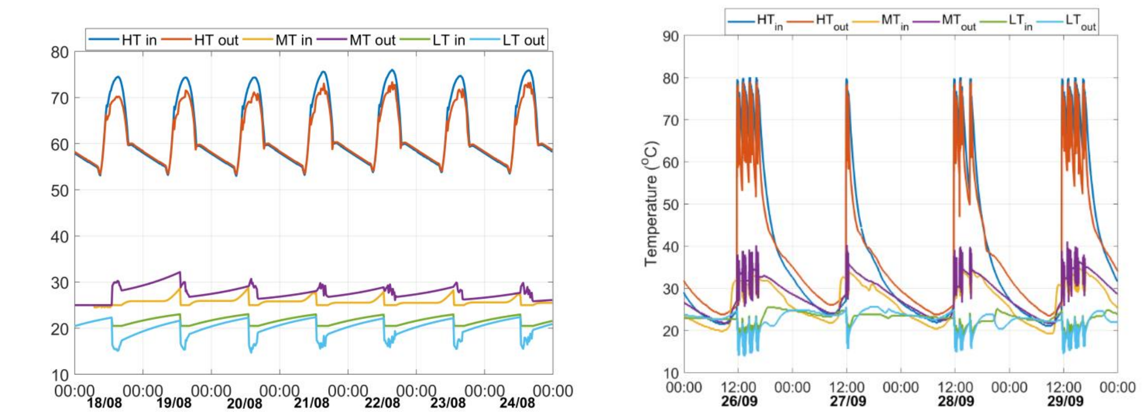
Fig. 8, Fig. 9 and Fig. 10 present, instead, the performance results for the ZEOSOL system, in a hot summer week and in cloudy days (September).

As shown in Fig. 8 (a) the solar field is capable to provide hot water at good thermal level when the solar radiation ranges between 800 and 1000 W/m² while the pump of the solar loop continuously switches off and on to preserve water stratification in the storage tank in cloudy days or when the solar radiation drops below 800 W/m² (Fig. 8 (b)).

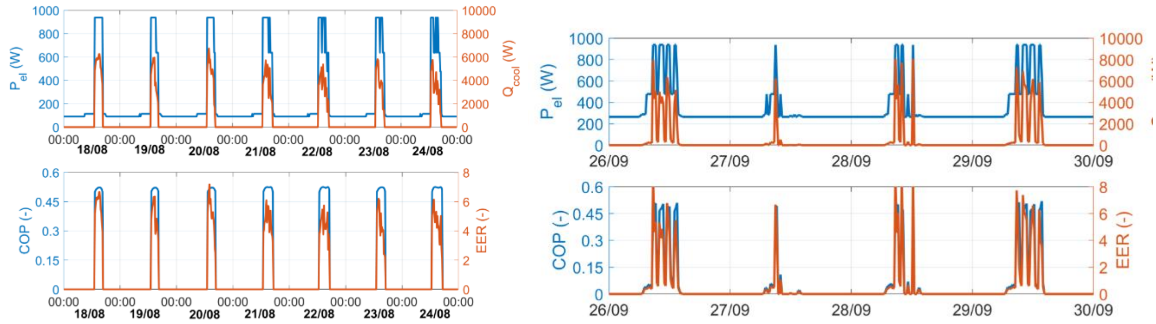
As shown in Fig. 9, the adsorption chiller can produce cold water at 15 °C and release the process heat at 25-30 °C both in a hot day and in cloudy day; however, cold production is not continuous with a lower solar radiation thus demonstrating the need of the operation of the electrical back-up unit.

Finally, as depicted in Fig. 10 the maximum obtained cooling power output is around 6 kW in hot day while it ranges between 2 and 5 kW when it is cloudy, due to the lower driving temperatures. During the same measurements, the electrical power consumption is significantly low, ranging between 50 (electronic consumption) and 900 W (operation of the fans the dry cooler) while the maximum obtained thermal COP is approximately 0.58 for driving temperature of 80 °C, whit the corresponding average EER of 7.



a) *b)*

Fig. 9 – Temperature of secondary chiller's streams: a) hot summer days; b) cloudy days.



a) *b)*

Fig. 10 - Performance results of proposed system prototype: the produced cooling output, the respective electrical consumption and the corresponding COP and EER values: a) in hot summer days; b) in cloudy days.

5. Economic evaluation of solar adsorption cooling unit

Using the performance results of the previous section, an economic analysis was conducted to evaluate the economic viability of the ZEOSOL system for a number of countries in comparison to other commercially available technologies for cooling and heating. For this purpose, a 500 m²

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reference multi-family building was considered. As reference heating system of the building was considered a 30 kW condensing gas boiler, while for the cooling loads single split air conditioning units were considered of a total cooling capacity of 24 kW. Apart from the ZEOSOL system, the other evaluated technologies were:

- A boiler for the heating loads of the building and a solar cooling system for the cooling loads.
- A reversible heat pump powered by the grid.
- A reversible heat pump powered by a photovoltaic panels' field of a 10 kWp capacity.

The investigated locations were namely: Berlin (Germany), Paris (France), Vienna (Austria), Rome (Italy), Athens (Greece), Larnaca (Cyprus), Madrid (Spain), Lisbon (Portugal) and Istanbul (Turkey). The estimation of the annual heating/cooling loads was conducted using data for the buildings per country from TABULA webtool [25], considering in all cases the respective most modern typology. The energy simulations for the building were conducted using EnergyPlus software [26] and the results are summarized in Fig. 11 (a). With respect to the estimation of the capital costs per system, the following assumptions were considered:

- The ZEOSOL system has a specific capital cost of 2 k€/kWc, while the installation costs were considered equal to 1 k€.
- For the reference system, the cost of the boiler was considered equal to 2.8 k€ and the total cost for the single split a/c units equal to 7.3 k€, based on commercial prices from the Greek HVAC market.
- For the solar cooling system a specific cost of 3 k€/kWc was considered with installation costs of 2 k€.
- The reversible heat pump cost was considered to be equal to 11.2 k€ and the specific costs of the PVs equal to 1.1 k€/kWp [27].
- For simplification, all scenarios considered a maintenance cost of 400 €/year, apart from the reference case which was estimated to have 200 €/year.

Based on the above, the capital costs per system were estimated as listed in Fig. 11 (b). As shown, the costs of all systems are comparable, apart from the case of boiler with solar cooling, which has a capital cost exceeding 35 k€.

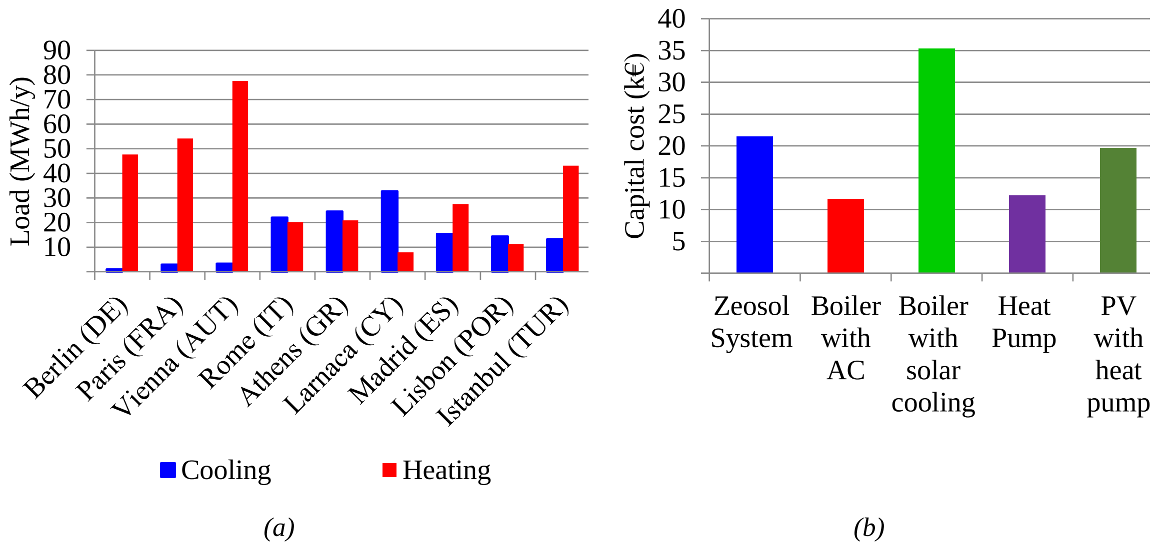

Fig. 11 – (a) Cooling/Heating loads for the considered building in the investigated regions and (b) capital costs for the considered systems

The economic performance for the different scenarios was estimated on the basis of considering as profit from each alternative system, the avoided annual costs of the reference system (maintenance

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and operation) reduced by the respective costs of the selected per case system. The index that was used for this analysis was the payback period:

$$PbP_{system,i} = \frac{(Capital\ cost)+(installation)}{(annual\ cost\ of\ reference)-(annual\ cost\ of\ system,i)} \quad \text{(eq. 6)}$$

For the estimation of the operational costs, the recent prices for electricity were considered based on data from Eurostat for the first semester of 2019 [28]. The results of the analysis are presented in Fig. 12. As shown, ZEOSOL system's performance is favorable than the scenarios of a boiler with solar cooling and a grid-connected heat pump. In terms of the comparison with a PV driven heat pump, ZEOSOL system is favorable in countries with dominant heating loads and lower solar irradiance during heating period. This is because the custom made backup heat pump of ZEOSOL system has a higher efficiency than commercial reversible heat pumps, an effect which is further enhanced by the boost of the sorption chiller when there is solar energy available. In fact, the lowest payback periods are reported for Paris and Vienna, with 7.9 and 7.2 years, respectively.

Quite competitive is considered the economic performance of ZEOSOL also on regions with higher cooling demands, with payback periods of 11.3 years for Rome and 11.9 years for Madrid, respectively. However, the PV-heat pump system has a better performance in such regions in overall. This is mainly justified by the high COPs of the heat pump at the period of maximum production of the PVs, which results in almost zero grid dependent operation. On the contrary, ZEOSOL system is using its backup heat pump to cover peak loads, thus resulting in electrical consumptions and eventually smaller profits. At this point, has to be mentioned that the analysis did not evaluate the use of any system for DHW, which could significantly vary the outcomes.

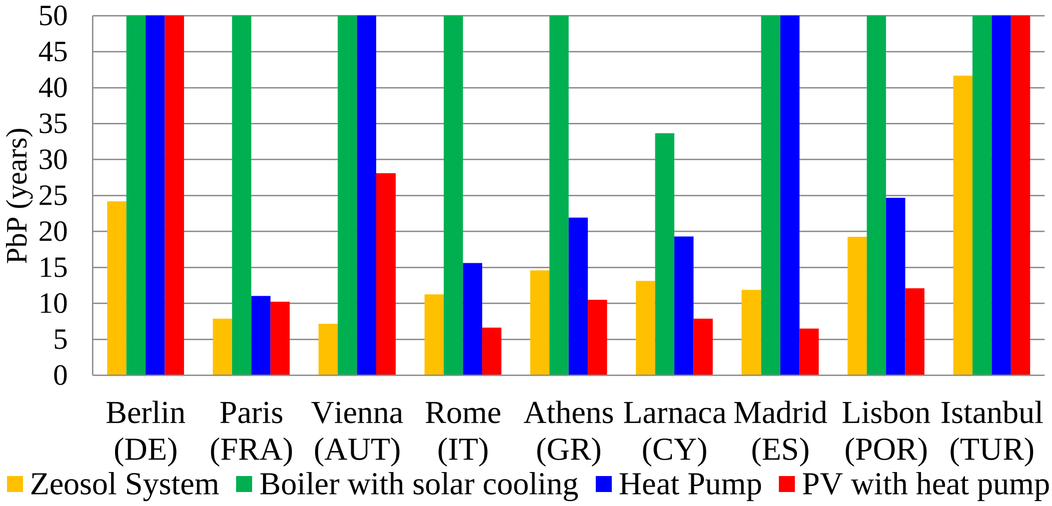

Fig. 12 – Economic performance of considered technologies for the investigated countries

6. Conclusions

In this study, the preliminary performance results of a solar driven hybrid adsorption chiller coupled with a backup heat pump were presented. The experimental analysis of the solar driven adsorption chiller revealed that the system despite non optimal conditions (smaller solar irradiance, high ambient temperatures) operated at a satisfactory level, with a maximum COP of 0.575. The developed system was proven to decrease significantly the electrical power consumption, achieving a maximum EER of 5.83 (with more than 60% of the total consumption coming from the system's dry cooler). These results are considered optimistic for the upcoming phases of the experimental evaluation of the system, not only on cooling but also for heating mode operation. However, as the experimental testing is at preliminary phase, there cannot be objective conclusions towards the system's performance, especially prior to the evaluation of the combined adsorption chiller-backup

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heat pump operation, which allows for even higher EER values under an optimized operational strategy. At the combined operation the system is expected to fully cover the loads of a 12.5 kW peak building, with an optimum solar fraction of around 60%, depending on the climatic conditions of the site of installation. An alternative to further enhance the solar fraction of the system it would be the addition of photovoltaic (PV) panels; however, this option was not evaluated within the framework of this project as it would increase the capital costs and add further complexity to the system. Regarding the economic aspects of this technology, the investigated system has a better economic performance in regions with dominant heating loads, with payback periods as low as 7.2 years for Vienna, Austria. On the other hand, for the countries of Mediterranean region, the system is outperformed by PV-heat pump systems due to the high maturity of the latter.

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8. Nomenclature

Nomenclature	
A	Aperture area, m^2
c_1	Heat loss coefficient $W/(m^2K)$
c_2	Heat loss coefficient $W/(m^2K^2)$
G	Solar radiation, W/m^2
η	Efficiency
η_0	Collectors efficiency, adm
PbP	Pay Back Period, years
$\dot{Q}$	Heating/Cooling Capacity, kW
$\dot{W}$	Power, kW
Subscripts	
a	ambient
col	collectors
com	compression
el	electrical
dc	Dry Cooler
pumps	pumps
Abbreviations	
COP	Coefficient of Performance
EER	Energy Efficiency Ratio
HT	High Temperature
LT	Low Temperature
MT	Medium Temperature

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