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Evaluation of the solar cooling and heating system of the CUT mechanical engineering laboratories

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Abstract-- The main objective of this paper is to describe and analyze the experimental system of solar cooling and heating, installed at the Mechanical Engineering laboratories of the Cyprus University of Technology (CUT). For this purpose, the behavior and performance of the system was studied over a period of one year, both for the cooling and heating modes using the Building Management System records. Furthermore, the performance of absorption chillers during the summer months was examined, and suggestions are made to reduce further the power consumption and to increase the overall efficiency of the system. The mean value of the coefficient of performance of the chiller was 0.68, which is quite high, even though the water entering the chiller was at a relatively low average temperature of 68°C. From the measurements it was also observed that there was excessive indirect energy consumption. Its main cause was related to the general pump over-sizing and the management of the un-used solar energy. Suggestions are given to reduce this consumption. The results of this study are very important because through our suggestions it is possible to increase efficiency, reduce energy consumption and make the system economically attractive to users.

***Index Terms*—Absorption chillers; Coefficient of performance; Solar cooling**

I. INTRODUCTION

In recent years, as reported by the Intergovernmental Panel on Climate Change (IPCC), the power consumption increased dramatically, resulting in a deterioration of the environment, which results in global warming and environmental pollution.

The negative environmental impact of climate change requires the immediate adoption of technologies that support the rational use of energy sources.

The use of solar energy for cooling of buildings is currently an attractive solution, especially for the climate of islands. The solar air conditioning, contributes positively to the energy reduction and environmental protection, while providing significant economic benefits [1].

In this paper, we will deal only with solar absorption cooling systems, and especially with the single stage lithium bromide - water absorption system that was installed in the Mechanical Engineering laboratories of the Cyprus University of Technology (CUT).

A refrigeration cycle by absorption is a process in which the cooling effect is produced through the use of two fluids and a heat source as input to the system [2].

The performance of an absorption refrigeration system depends to a significant extent on the chemical and thermodynamic properties of the fluid pair that is used [3].

There are a large number of cooling-absorbent pairs that can be used but the couple chosen should meet some important requirements such as absence of solid phase, volatility ratio, affinity, pressure, stability, corrosion, safety and latent heat.

None of the pairs meet all the requirements listed above, but the most common pair of fluids used is LiBr-H_2O (Water-Lithium Bromide) and H_2O-NH_3 (Ammonia-Water) [4].

The system employed in the CUT laboratories is of the single effect LiBr-H_2O technology. Absorption systems are similar to vapour-compression air conditioning systems but differ in the pressurisation stages. In general an absorbent on the low-pressure side (in this case the LiBr), absorbs an evaporating refrigerant (H_2O). The pressurisation is achieved by dissolving the refrigerant in the absorbent in the absorber section. Subsequently, the solution is pumped to a high pressure with an ordinary liquid pump. The addition of heat in the generator is used to separate the low-boiling refrigerant from the solution. In this way, the refrigerant vapour is compressed without the need of large amounts of mechanical energy that a vapour-compression air conditioning system demands. The remainder of the system consists of a condenser, expansion valve and an evaporator, which function in a similar way as those in a vapour-compression air conditioning system.

II. LITERATURE REVIEW

Literature regarding applications of absorption refrigeration systems is scarce. Bermejo et al. [5] analyzed a solar cooling system in the Faculty of Engineering of Seville in Spain. The system consists of a double effect LiBr - H_2O absorption chiller and linear concentrating collectors with a total collector area of 352 m^2. The average efficiency of the collectors was 35% and the coefficient of system performance (COP) ranged from 1.1-1.25. Also Lizarte et al. [6] analyzed a solar cooling system, applied in Madrid which consists of a single stage LiBr - H_2O absorption chiller of 4.5 kW cooling capacity and flat plate collectors

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with a total collector area of 42.2 m^2. The COP was 0.62. A similar analysis was performed by Monne et al. [7] for a solar cooling system applied in Zaragoza, Spain. The system consists of a single stage LiBr - H_2O absorption chiller of 4.5 kW cooling capacity and flat plate collectors with a total collector area of 37.5 m^2. The coefficient of performance of the system was 0.6. Furthermore Balghouthi et al. [8] analyzed a solar cooling system applied in Tunisia in a building which covers 150 m^2. The system includes a single stage LiBr - Water absorption chiller of 11 kW cooling capacity and flat plate collectors with a total collector area of 37.5 m^2. The COP of the system was 0.72. Moreover Yin et al. [9] analyzed a solar cooling system in a 50 m^2 area installed in Shanghai, China. The system consists of a single stage LiBr - H_2O absorption chiller of 8 kW cooling capacity and evacuated tube collectors with a total collector area of 96 m^2. The COP of the system was 0.31, which is very low for the solar radiation absorbed by the collectors throughout the day.

III. DESCRIPTION OF THE BUILDING

The building was used for many years as a warehouse and its area covers 1400 m^2. In 2010, the building was renovated and is now used as classrooms and laboratories as well as a workshop (half of the building) of the Department of Mechanical Engineering and Materials Science and Engineering of the CUT. The renovation did not affect the external walls of the building, which were built in 1950 and consist of limestone blocks 50 cm in thickness. Double-glazing was fitted and the roof was rebuilt from scratch using thermal Rockwool insulation of 200 mm thickness. The building has a double pitched roof, which has a minimum height of 6m and a 20° slope. The solar panels have been installed on the two south facing areas of the building roof. The total cooling load of the building is estimated to be 250 KW [10]. In the building a solar central air conditioning system (heating and cooling) has been installed and is operating. Additionally, a cooling tower is employed to cool down the condenser of the absorption chiller. The cooling tower is also assisted by a geothermal system. The solar cooling system is installed to cover the cooling needs of the building with renewable energy and is fully monitored through the building management system, which also records all the temperatures and energy flows of the system.

The system diagram shown in Fig. 1 and Fig. 2, consists of three absorption chillers each having a cooling capacity of 95 kW, three hot water storage tanks with a total capacity of 14,100 liters, two oil fired boilers of 155 kW capacity each, a closed type water cooling tower with a capacity of 425 kW and 69 evacuated tube solar collectors having a total absorber area of 310.5 m^2 (see Fig. 3).

IV. DESCRIPTION OF THE SOLAR COOLING SYSTEM OF THE BUILDING

According to Figs. 1 and 2, solar energy is collected by the solar panels located on the roof and stored in 3 hot water storage cylinders with 4700 liters capacity each. The system is controlled by a differential thermostat, which compares the temperature of the water in the cylinders with the temperature of the water from the solar panels. When the temperature of the water from the solar panels is greater by a predetermined difference (DT) then energy is transferred from the solar panels to the storage cylinders. The hot water from the solar panels transfers the heat to the cylinders through heat exchangers located in the cylinders.

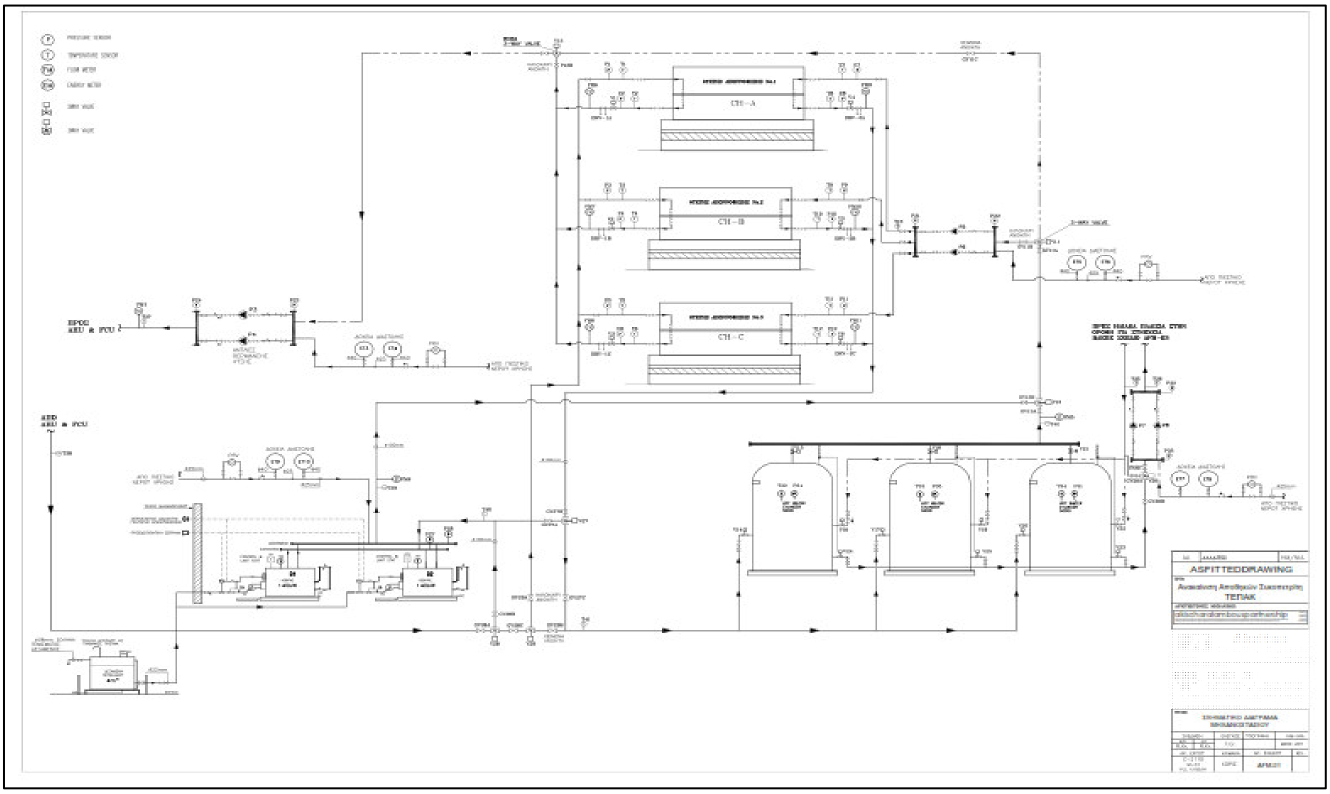

Fig. 1. Schematic diagram of the solar cooling system – connection with boilers and hot water cylinders

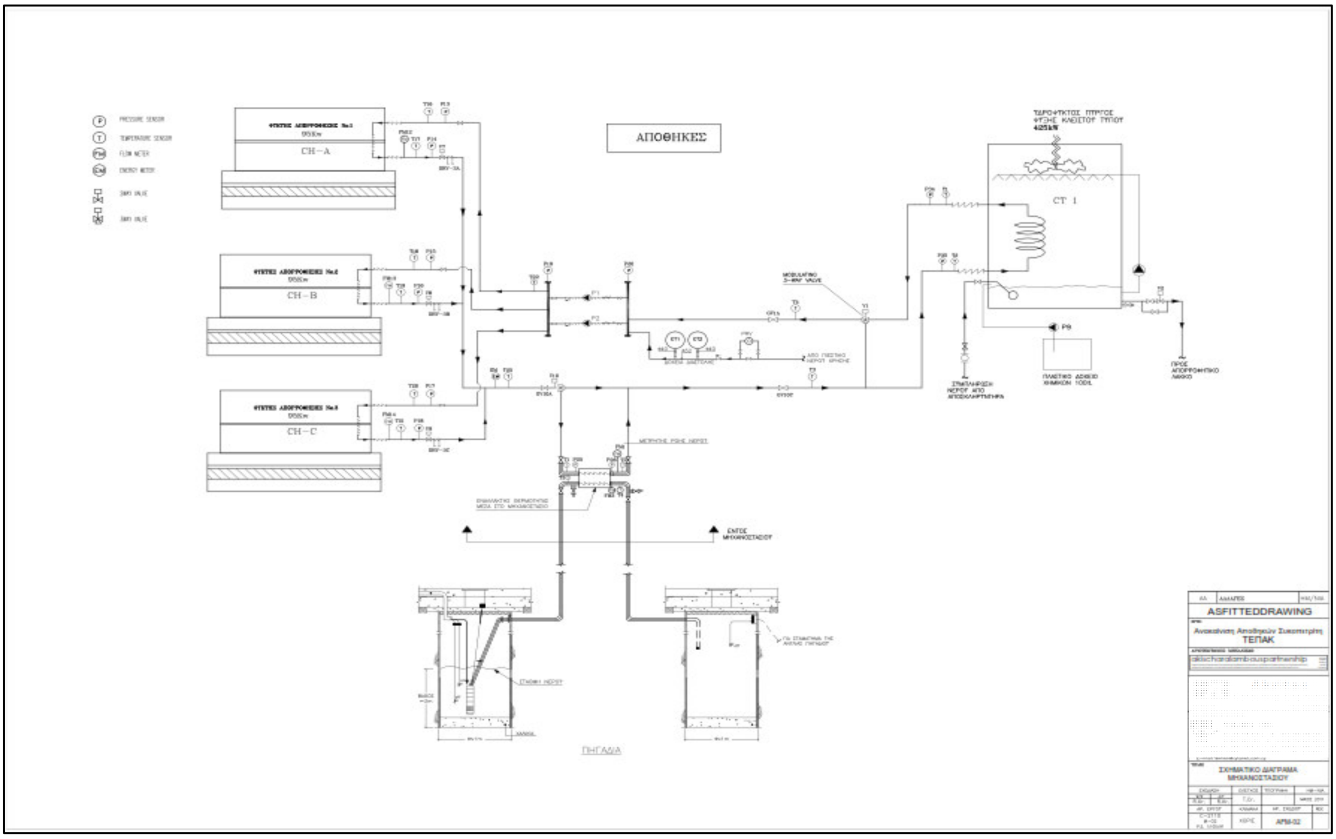

Fig. 2. Schematic diagram of the solar cooling system – connection with cooling tower and geothermal wells.

The stored hot water is circulated through pipes to the absorption chillers where the solar collected energy is used to produce refrigeration by the chillers. In the case where the stored hot water is not enough to meet the required needs of chillers, valves 4 and 5 open to allow the hot water boilers B1, B2, to give additional energy directly to the chillers (i.e., without heating the water content of the cylinders) and meet the demand.

The cold water produced by the chillers is transferred by piping to the air conditioning units (fan coil units-FCU and air handling units-AHU) which are used for cooling the building.

The hot water coming out from the chillers goes back to the hot water storage cylinders. Cold water from the cooling tower extracts heat from the absorber and the condenser of the chiller and then passes through the heat exchanger, which cools the water using two wells. This is a significant originality of the system, i.e., the combination of the cooling system with geothermal energy. Water from well 1 feeds the heat exchanger to cool the water that comes from the chillers and then is discarded in well 2. Then the water passes from the chillers of the cooling tower to further remove energy and cool it to the required temperature (Figure 2).

During the winter, chillers have no use since the demand is for heating. The solar heating system works in exactly the same manner as in summer by storing hot water in the storage cylinders.

In winter, the three way valves 6, 7 and 8 change setting so that the stored hot water does not pass through the chillers but is diverted directly to the air units (FCU and AHU) and back to the hot water storage.

In the case where the stored hot water is not enough to meet the requirements of the building, valves 4 and 9 open and hot water from the boiler is supplied directly to the air units and returns back to the boilers.

Fig. 3 Photo of one of the two banks of solar evacuated tube collectors

V. ANALYSIS OF THE SOLAR SYSTEM

A. *System analysis methodology*

The installed Building Management System (BMS) was used to record all system parameters through the whole year of study, which were then analyzed and recorded in charts using Excel. The BMS is linked with appropriate sensors and is designed to monitor, control and optimize the building installations. The system is fully monitored so as to be able to evaluate its performance as a whole and also the performance of each component of the system individually. A snapshot of the screen of the BMS, of the absorption chillers, is shown in Fig. 4. The figure shows that at that time only the second absorption chiller was operating.

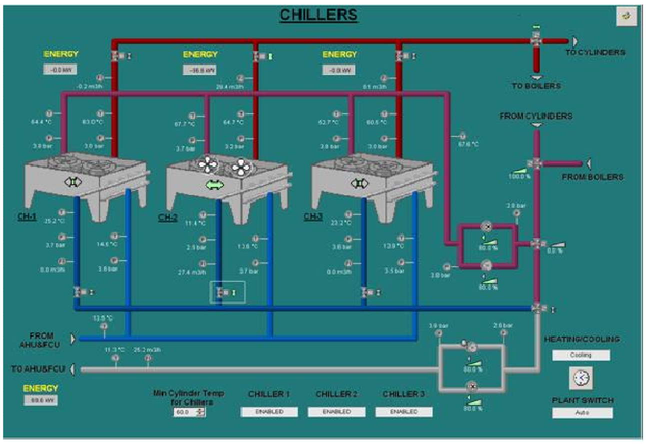

Fig. 4 BMS system showing the conditions of the absorption chillers.

To examine the performance of the absorption chillers during the summer months the records of power flow coming from the solar domestic hot water cylinders entering the chiller, and the power flow exiting the chiller and going to the air units (fun coil units and air handling units), were used. Figure 5 shows the power flow into and out of the chillers for the period of 01/06/12 to 29/06/12 on a daily basis from 8:00 in the morning until 16:00 in the afternoon. It is observed that the input power varies between 70 kW and 125 kW and the output power is between 45 kW and 90 kW. The quotient of outgoing power to the incoming one gives the performance of the chillers and as shown in the figure it varies between 52% and 73%. Additionally, Fig. 5 shows the average temperature of water entering the chiller from 8:00 in the morning until 16:00 in the afternoon, which varies between 60°C and 78°C.

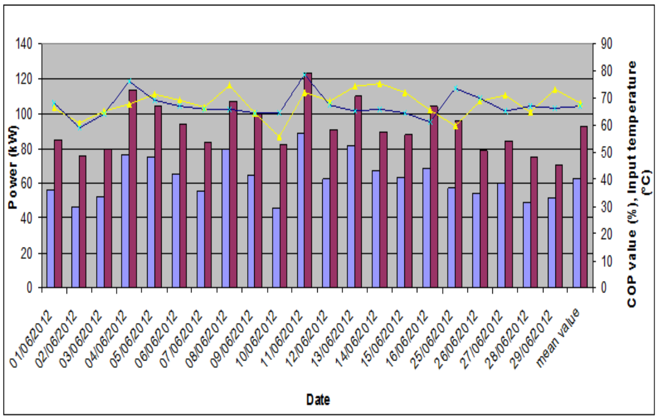

Fig. 5. Graph showing the outgoing power from chillers (blue color), the incoming power to the chillers (RED color), the incoming water temperature to the chillers (blue color line) and the coefficient of performance (yellow color line) for the period 01/06/12 – 29/06/12

B. Performance of absorption chillers during the summer months

Based on the manufacturers technical details, the absorption chillers should operate on input water temperatures of about 85^{o}C to achieve maximum C.O.P. In our system even though the input temperatures where around 70^{o}C, as shown in Table I, the achieved C.O.P was relatively high because the required cooling load was low compared to the size of the chiller.

Table I shows the chiller performance for May to October as well as the incoming hot water temperature to chillers. The calculated average performance (COP) of this period is 0.68 and the average incoming hot water temperature is only 67.8°C, which is low.

The system was set up in such a way as to avoid stored water temperatures to reach 75°C because there was no need for extra energy. This resulted in a low performance of the chillers. However if the whole building was operating (see section IV) the chillers would not have been able to cover the cooling load satisfactorily. Therefore, the study was focused on ways to reduce auxiliary energy consumption (e.g. electricity) but at the same time to achieve maximum system efficiency.

TABLE I
SUMMARY OF PERFORMANCE AND INLET HOT WATER TEMPERATURE OF CHILLERS DURING THE SUMMER MONTHS

Period	**Chiller Performance (COP)**	**Incoming hot water temperature to chillers**
May	0.69	71.7°C
June	0.68	67.1°C
July	0.68	67°C
August	0.68	67.1°C
September	0.69	67.3°C
October	0.66	66.3°C
Mean value	**0.68**	**67.8°C**

VI. RESULTS AND SUGGESTIONS

In general, the system as a whole is operating effectively, since during the year no fuel was needed to cover the cooling or heating loads of the building. A drawback is that the whole system is oversized, although during the examined period only half of the building was operating. In fact, the workshop part of the building, which draws half of the total load, was not conditioned during the evaluation period for various reasons.

The only energy consumed by the system was electricity and attention was given to reduce its consumption to the minimum with the suggestions that follow.

A detailed study of the technical specifications of the installed solar evacuated tube collectors proved that a much lower water flow rate than the one used was required in order to achieve higher water temperatures. Therefore, the installed pump for this purpose was oversized consuming more electrical energy than needed.

Additionally, on the same pumping system it was noted that the differential temperature controller was set up with a very small temperature differential. This caused the pump to work more often than required, thus consuming more unnecessary power and not allowing the solar system to attain high temperatures. The differential set point should have been set at 10^{o}C.

It is suggested to correct the temperature differential and during the summer period, to account for days with low required cooling load and thus possible overheating, it is suggested to install a heat rejection system to avoid overheating. The heat rejection system operates with a much lower energy consumption rate than running the cooling system at full load, which is what is done now to avoid this problem.

The chilled water pump installed was sized for a system where all three absorption chillers would be in operation. This means that during the operation of our system with only one chiller in operation, the pump was consuming much higher energy than a pump sized for one chiller only. Therefore, it is suggested that the pump is replaced by smaller pumps each operating with its own chiller.

An economic analysis showing the savings that would result if the current pumps are replaced with appropriate ones, is shown in Table II. As it is shown, a total cost of €4868 will be needed for the replacement of the pumps. The pay-back period for this investment will be only about eight months and the savings that would results for each year would be €7125. It should be noted that this will also increase the efficiency of the complete system.

TABLE 2
RESULTS OF ECONOMIC ANALYSIS

<table>
<tr><th colspan="5">Pump over-sizing</th></tr>
<tr><th>Current pump</th><th>Suggested pump</th><th>Cost</th><th>Pay-back period</th><th>Saving</th></tr>
<tr><td>Pumps circulating water in solar panels.
TP 80-270/4</td><td>TP 32-320/2</td><td>€1250</td><td>4 months</td><td>€4310 per year.</td></tr>
<tr><td>Pumps circulating hot water in chillers.
TP 80-240/4</td><td>TP 50-240/2 for each chiller</td><td>€1330</td><td>7 months</td><td>€800 per year.</td></tr>
<tr><td>Pumps circulating cold or hot water to air units.
TP 80-240/4</td><td>Circulating cold water.
TP 32-320/2
Circulating hot water.
TP 32-200/2</td><td>€1250
€1038</td><td>6 months
4 months</td><td>€935 per year.
€1080 per year.</td></tr>
<tr><td colspan="4">Total cost of the suggested pumps</td><td>€4868</td></tr>
<tr><td colspan="4">Approximate pay-back period for all pumps</td><td>8 months</td></tr>
<tr><td colspan="4">Savings for the operation of the suggested pumps per year</td><td>€7125</td></tr>
</table>

VII. CONCLUSION

The building in which the system was installed is not the best application for energy savings due to the nature of its operation (operating hours between 8:00 – 16:00).

Additionally, during the months of July and August, where there is maximum solar input and thus better performance of the cooling system, the building is under-utilized or closed completely due to summer holidays. In July and August, it was very important to keep the system operating to avoid overheating of the collector system, thus wasting electrical and solar power. A much better application would be in buildings with round the clock requirements for cooling and heating (e.g. hotels, airports, etc.), but the system was installed primarily for experimental reasons.

Based on the techno-economical study of the system it is suggested that all parts of the system are very carefully sized and selected to make the system viable in terms of economy and energy consumption.

It is shown that with a few simple measures the overall system performance would be improved drastically. This reduced electrical energy requirements opens also the idea of installing photovoltaics to cover this load so as to make the system 100% renewable.

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IX. BIOGRAPHIES

Soteris A. Kalogirou was born in Trachonas, Nicosia, Cyprus on November 11, 1959. He is a Senior Lecturer at the Department of Mechanical Engineering and Materials Sciences and Engineering of the Cyprus University of Technology, Limassol, Cyprus. He received his HTI Degree in Mechanical Engineering in 1982, his M.Phil. in Mechanical Engineering from the Polytechnic of Wales in 1991 and his Ph.D. in Mechanical Engineering from the University of Glamorgan in 1995. In June 2011 he received from the University of Glamorgan the title of D.Sc. He is Visiting Professor at Brunel University, UK and Adjunct Professor at the Dublin Institute of Technology (DIT), Ireland. For more than 25 years, he is actively involved in research in the area of solar energy and particularly in flat plate and concentrating collectors, solar water heating, solar steam generating systems, desalination and absorption cooling.

He has 41 books and book contributions and published 264 papers; 109 in international scientific journals and 155 in refereed conference proceedings. Until now, he received more than 4000 citations on this work and his h-index is 35. He is Executive Editor of Energy, Associate Editor of Renewable Energy and Editorial Board Member of another eleven journals. He is the editor of the book Artificial Intelligence in Energy and Renewable Energy Systems, published by Nova Science Inc., co-editor of the book Soft Computing in Green and Renewable Energy Systems, published by Springer and author of the book Solar Energy Engineering: Processes and Systems, published by Academic Press of Elsevier.

Fivos Frangou was born in Limassol (Cyprus), on July 30, 1989. He graduated from the Agia Phyla Lyceum, Limassol, and studied Mechanical Engineering and Materials of Science at the Cyprus University of Technology. He received the top overall performance in all 4 years of his study in university.

He works in his father company as a Mechanical Engineer but he is looking forward to work in the sector of oil and gas energy and with renewable energy.

Georgios Florides was born in Kaimakli, Nicosia, Cyprus on November 26, 1952. He was a Senior Lecturer and is now a researcher of the Department of Mechanical Engineering and Materials Science and Engineering. He received his basic degree in Mechanical Engineering from the Higher Technical Institute and he was awarded an MPhil and a PhD by Brunel University, London, UK. He was employed by the Higher Technical Institute from 1975-2007 in various posts, in the Mechanical Engineering Department and in the Engineering Practice Department. He used to teach the theory and practice of Welding, Machine-shop, Bench-fitting and Plumbing. His research activity focuses on the topic of Energy, which includes studies and analysis of the energy requirements of buildings, measures to lower building thermal loads, design of LiBr-water absorption machines, modelling and simulation of absorption solar cooling systems and earth heat exchangers and heat pumps. He also studies the thermal behaviour of reptiles and scientifically constructs models of extinct animals.