The application of concentrating solar thermal systems in hospital buildings

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Abstract

One of the basic objectives of EU is to decarbonize the building sector by the year 2050. To achieve this goal, energy renovation of the building stock across Europe will be initiated in order to improve the energy performance of buildings and reduce greenhouse gas emissions. Hospital buildings are often large scale buildings that accommodate energy intensive uses, such as space heating and cooling with specific thermal comfort settings, high hot water requirements, equipment, lighting. This results to very high energy consumption in hospital buildings and consequently, high energy bills.

The aim of this paper is to investigate the application of concentrating solar thermal for space conditioning needs in hospitals buildings in Greece and enhance their application in the building sector. The paper will present the techno-economic and environmental assessment for a hospital building targeting to reduction of the carbon footprint of these buildings.

Keywords: Net Zero Buildings, Hospitals, Thermal Energy, Concentrating solar thermal systems.

1. Introduction

One of the basic objectives of EU is to decarbonize the building sector by the year 2050. To achieve this goal energy renovation of the building stock across Europe will be initiated in order to improve energy performance of buildings and reduce greenhouse gas emissions.

Hospital buildings are big buildings that accommodate energy intensive uses like space heating and cooling with special comfort settings, high hot water requirements, equipment, lighting. This results to very high energy consumption in hospital buildings and consequently high energy bills (Dimoudi et al. 2022).

Final energy use intensities of health care buildings in EU countries varies from 656,5kWh/m^2 in Bulgaria, 147,8kWh/m^2 in Estonia, 228,2kWh/m^2 in France, 1.124,3kWh/m^2 in Spain and 516,2kWh/m^2 in the United Kingdom (Balaras et al, 2017). In other studies, differences on hospital's energy recordings were found. Energy intensity of 20 hospitals in Spain was recorded at 270kWh/m^2 and of 48 hospitals in UK at 289kWh/m2 (Bawaneh et al, 2019) while at 195kWh/^{m2} in France (Nourdine, Saad, 2020).

The energy intensity per bed or per employee also varies between countries, ranging from an average consumption at 29.000kWh/bed for heating and 6.000kWh/bed for electricity in a survey of 2.100 hospitals in Germany and in Spain electricity recordings fluctuate between 8.888kWh/bed and 10.004kWh/bed for small (under 300 beds) and big hospitals (González et al, 2018), while in France 26.000kWh/bed (Nourdine, Saad, 2020).

A survey on energy consumed in fourteen hospitals in North-West Greece, reported that the average thermal annual consumption was 179kWh/m^2, the average electricity energy consumption was 118kWh/m^2 and the average electricity consumption per bed was at 10.483kWh and per employee at 4.461kWh (Kostadimas et al. 2022).

The aim of this paper is to investigate the application of concentrating solar thermal for space conditioning needs in hospitals buildings in Greece and enhance their application in the building sector. The paper will present the

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techno-economic and environmental assessment for a hospital building targeting to reduction of the carbon footprint of these buildings.

2. Analysis of the energy consumption of the hospital building - simulation

The energy profile of a General Hospital located at the A Climatic zone is used in the study. The simulation for its energy performance were carried out with two collaborating energy simulation tools: the EnergyPlus and the DesignBuilder software.

The General Hospital was built in a site area of 40.000 m^2 which is located in the center of a small city. The total premises of the hospital nowadays consist of 2 buildings which were constructed in different time periods. The construction permission for the main hospital building was issued in 1983 and it was completed almost 5 years later in 1987/8, according to the regulations of the permit year. A new wing which is connected to the main facilities, was added to the building compound later at 2010.

The total area of the General Hospital after the addition of the new building, amounts almost 13.000 m^2, distributed in 5 floors in the main hospital (Basement Floor B', Basement Floor A', Ground Floor, First Floor and Second Floor), and 3 floors in the new building (Basement Floor, Ground Floor and First Floor). Almost 9.000 m2 is conditioned while the other 4.000 m^2 (Basement B' with mechanical equipment, mechanical rooms in both buildings, storage rooms, etc.) is unconditioned.

Due to its complex structural design and its energy consumption diversities between its internal spaces, the General Hospital was separated into four distinct conditioned thermal zones which demonstrate the same use and activity schedules, have the same HVAC systems and operate at the same temperatures set-points. Those four thermal zones, were divided into smaller thermal zones according to their floor or orientation but still following the same attributes as their parent zone. The unconditioned zones which include the floor with the mechanical service room, equipment, storage rooms and auxiliary spaces were designed as well into the software.

The hospital's envelope is insulated and its windows are divided between doubled glazed with old or new aluminum frame.

The facilities are able to hospitalize more than 4.000 patients per year, while there are 120 available beds able to satisfy the needs of the hospital, so occupancy profiles, internal gains for occupants, clothing and activity rate were taken into account for the energy performance simulation. The operation hours of the building differ greatly due to the different activities between the zones. The operating hours of the hospital per day may vary in its different zones between 8 to 24 hours. Therefore, each zone was created with its unique operation schedules and temperature set-points. The lighting and mechanical equipment follow the operation schedules of their zone.

The HVAC systems of the General Hospital consist of equipment that was installed in the old building during its construction, along with the equipment that was provided at later stages which are diesel boilers, air cooled chillers and air handling units (AHUs).

The General Hospital has two separate Heating, Cooling and Ventilation systems, in its two buildings (old building and new wing). The hospital consists of two separate heating systems with diesel boilers and two separate cooling systems with air cooled chillers which are used for the two buildings. The mechanical ventilation equipment of the hospital consists of air handling units conditioning all 4 thermal zones. The AHUs are operating following the working profile of the occupants of the thermal zones and are separated into two different categories according to their characteristics. The needs for domestic hot water are satisfied by the diesel boilers in both buildings throughout the year.

The main heating system of the old building that operates separately from the new building, consists of two diesel boilers of 1.046,00 kW power (900.000 kcal/h), operating simultaneously, according to the needs of the hospital (Fig. 1). The hot water loop consists of a two-pipe system of supply and return, distributed from the heating collector to the thermal heating units (convectors) located in all areas of the building areas, and also to the heating coils located to the air handling units and the reheat coils in their terminal units inside the zones. So, the air handling units can be used for heating purposes as well.

Two diesel boilers of 407,00 kW power (350.000 kcal/h) located in the mechanical room of the new wing basement, operate alternately and not at the same time, covering the needs of the new wing of the hospital (Fig 2).

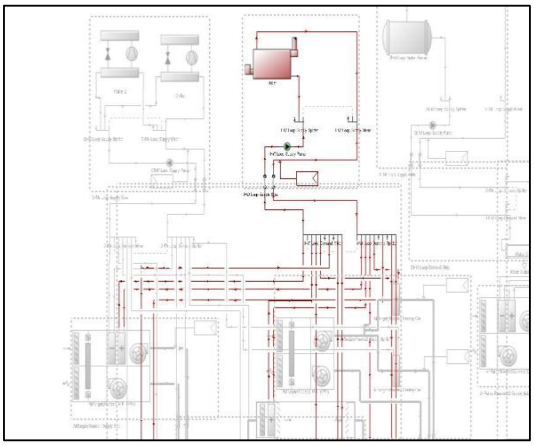

Fig. 1: Schematic of the heating system of the General Hospital (new wing)

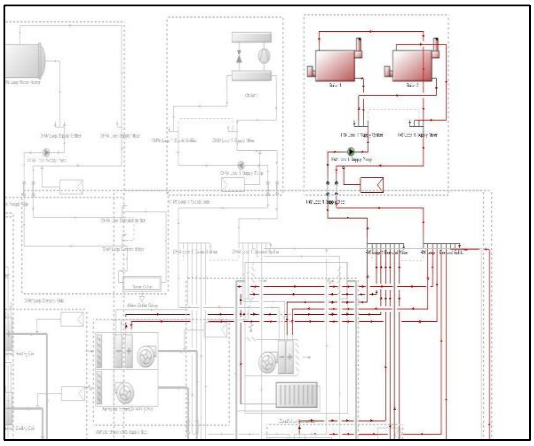

Fig. 2: Schematic of the heating system of the General Hospital (old building)

Three air cooled chillers are installed in the hospital to cover the needs for the cooling loads. Two of them, of 440 kW with refrigerant R134a, are located in the roof of the new building (Fig. 3) while the older one is found in the old building (Fig. 4). Those air cooled chillers are connected to the chilled water loop of their wing respectively. The chilled water loop includes a two pipe system of supply and return which provides chilled water to cooling coils located in the air handling units.

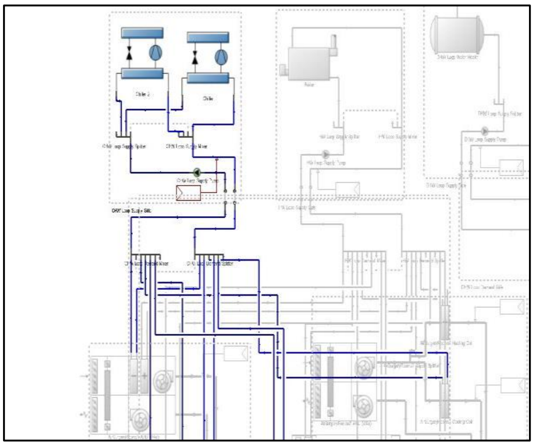

Fig. 3: Schematic of cooling system of the General Hospital (new wing)

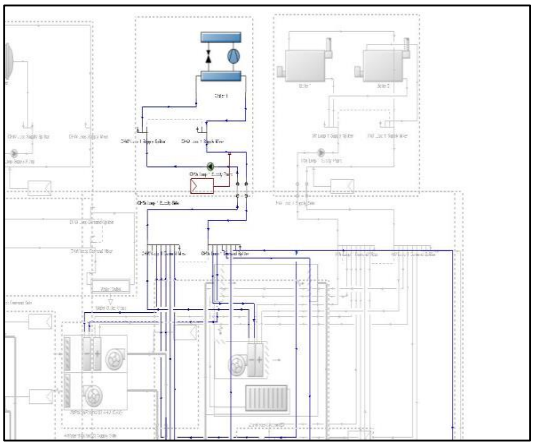

Fig. 4: Schematic of cooling system of the General Hospital (old building)

There are totally 10 AHUs installed in the hospital, located in different sections, meeting the required conditions of each specific space, with total 410,13 kW cooling capacity and 347,82 kW heating capacity. All of them are variable speed units with preheat and reheat in order to reduce energy consumption but they are separated in two types: a) AHUs with a two-pipe system of supply and return (Fig. 5), b) AHUs with a dual duct air loop consisting of a four-pipe system, where the heating and cooling is mixed (Fig. 6).

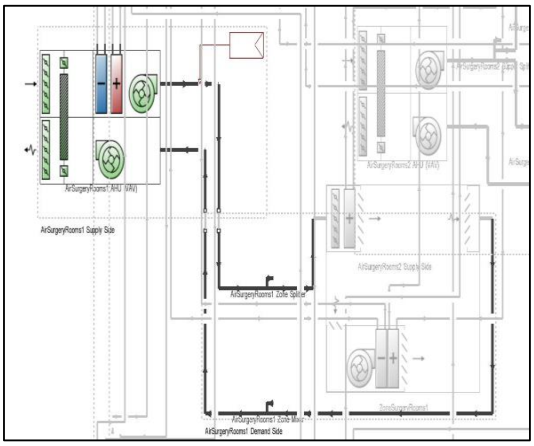

Fig. 5: Schematic of AHUs with a two-pipe system of supply and return

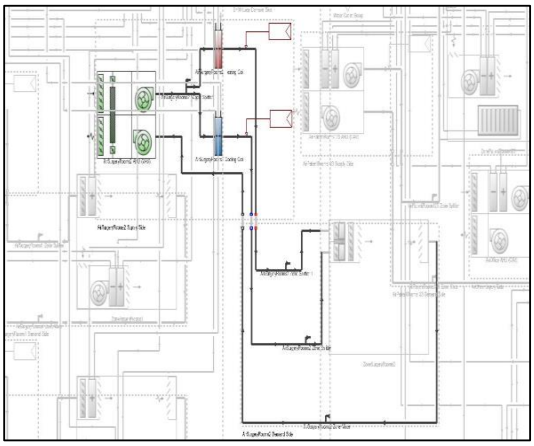

Fig. 6: Schematic of AHUs with a dual duct air loop consisting of a four-pipe system

The simulation was performed with four time steps per hour, evaluating the energy consumption of the building.

After the simulation of the energy performance of the existing base building, results about the electricity and heat consumption were extracted. The total net energy consumption of the hospital is 1.866,6 MWh, out of which 1.320,2 MWh is the electricity consumption (cooling, lighting, equipment and other appliances) and 546,4 MWh is the diesel consumption (heating and DHW). The total source (primary) energy is 4.429,5 MWh, out of which 3.828,5 MWh is the source electricity consumption and the 601,0 MWh is the source diesel consumption (ZenH Balkan, 2021).

Figures 7 and 8 present the percentage distribution (%) of each consumption per use and per category. The source diesel consumption has 14% of the total source consumption, while source electricity consumption covers the 86%, and out of the electricity total, the interior lighting has 22%, the interior equipment has 7%, the cooling has 44%, the other appliances have 13%.

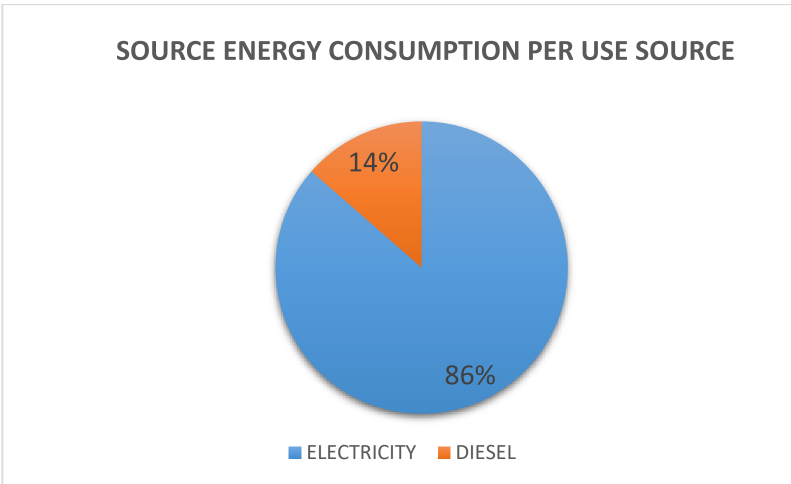

Fig 7: Distribution of source energy consumption per use, in percentage (%)

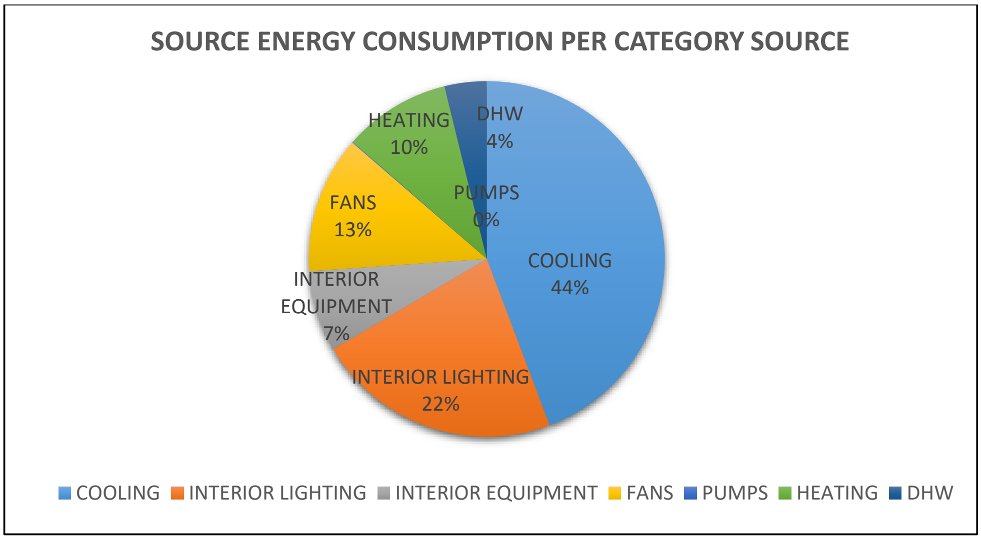

Fig 8: Distribution of source energy consumption per category, in percentage (%)

After the energy evaluation of the case study building and simulation of its energy performance, 9 different energy efficiency scenarios were examined in order to reduce the energy needs of the building. Those scenarios were categorized according to the source they targeted and they included insulation of the external walls and roof of the building with mineral wool insulation, replacement of its windows with new PVC framed ones, double glazed with low-e coating, replacement of old lights with led lights, installation of a Building Energy Management System (BEMS) to control the lighting system according to occupancy profiles and illuminance level (lux set-points), addition of shading devices at the windows and control of them according to solar radiation, natural ventilation control according to occupancy schedules for temperature reduction during summer period, and implementation of cool roof material.

After the simulation of all examined scenarios, the source (primary) electricity energy consumption is reduced by 33.3%, corresponding to 1.273,6 MWh and the diesel consumption is reduced by 25,5% (Tab. 1). The total reduction of primary energy consumption, considering all scenarios from 1 to 9 is 1.426,6 MWh, corresponding to 32,2%. The specific total primary energy consumption is reduced by 162 kWh/m^2, corresponding to specific total primary energy consumption of 341,4 kWh/m^2 (Tab. 2, Fig. 9).

Tab. 1: Source energy consumption (in MWh) and energy savings (in %) from scenarios 1 to 9

	Case building consumption	**Scenarios 1-9 consumption**	**Energy savings**	
	Source energy, MWh	Source energy, MWh	MWh	%
Electricity	3.828,5	2.554,9	1.273,6	33,3%
Diesel	601,0	448,1	153,0	25,5%
Total	4.429,5	3.002,9	1.426,6	32,2%

Tab. 2: Specific source energy consumption (in kWh/m2) and energy savings (in %) from scenarios 1 to 9

	Case building consumption	**Scenarios 1-9 consumption**	**Energy savings**	
	Source energy kWh/m^2	Source energy kWh/m^2	kWh/m^2	%
Electricity	435,2	290,4	144,8	33,3%
Diesel	68,3	50,9	17,4	25,5%

Total	503,5	341,4	162,2	32,2%

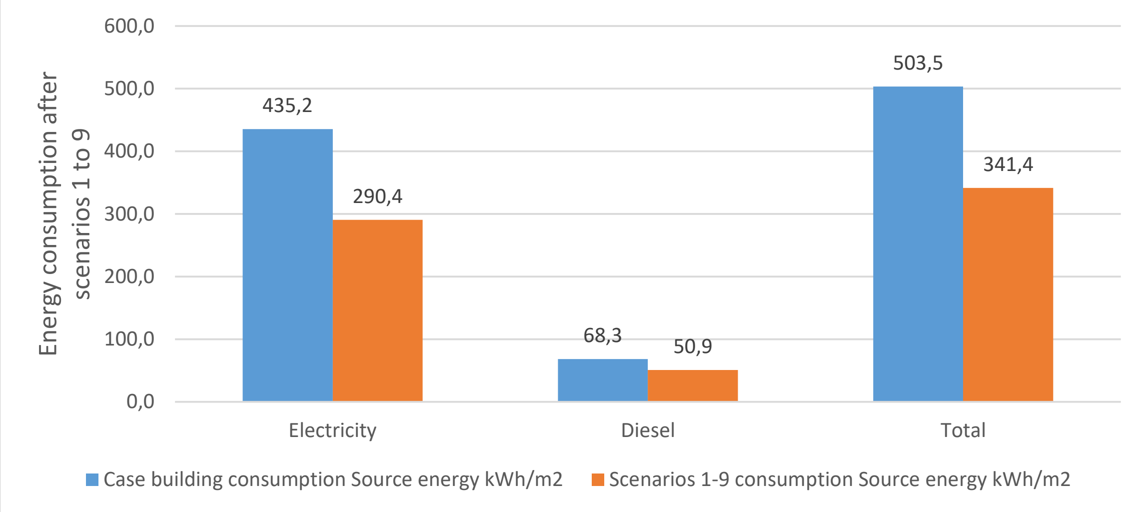

Fig. 9: Specific source energy consumption (in kWh/m²) per energy source from scenario 1 to 9

Table 3 presents the distribution of the source (primary) energy consumption (in MWh) and the energy savings for each separate category use (in MWh and %) for all scenarios. The diesel energy consumption is decreased by 153,0 MWh (35,5%) while the electricity consumption for cooling is decreased by 381,3 MWh (19,4%).

With the aim of achieving a nearly zero energy building, after the implementation of the 9 energy efficient scenarios and reduction of the energy needs of the building, exploitation of RES systems was investigated. The current study focus on investigating exploitation of solar energy for space cooling with concentrated solar thermal collectors.

Tab. 3: Source energy consumption (in MWh) and energy savings (in %) per category from scenario 1 to 9

	Case building Energy consumption	**Scenario 1-9 Energy consumption**	**Energy Savings [Scenario 1-9]**	
	Source energy, MWh	Source energy, MWh	MWh	%
Cooling	1.960,8	1.579,5	381,3	19,4%
Interior Lighting	986,0	218,9	767,1	77,8%
Interior Equipment	326,3	326,3	0,0	0,0%
Fans	552,2	427,7	124,5	22,5%
Pumps	3,3	2,5	0,8	23,7%
Heating	431,4	278,4	153,0	35,5%
DHW	169,7	169,7	0,0	0,0%
Total	4.429,5	3.002,9	1426,6	32,2%

3. Performance Analysis of the solar cooling system

In this section, the energy performance of a concentrating solar thermal system for covering part of the cooling loads of the aforementioned hospital building is described. The energy performance assessment is elaborated in Greenius - The Green Energy System Analysis Tool, developed by German Aerospace Center DLR - Institute of Solar Research, Solar High Temperature Technologies. Meteorological data for Kefalonia, Greece in the form of typical meteorological year record (TMY) are extracted from Meteonorm and inserted into the Greenius tool, as it can be seen in Fig. 10. The cooling loads of the hospital, as presented in the previous section “case building energy consumption”, are inserted into the Greenius tool.

Load Curve and OS : Hospital load

The annual sum of the load is 525,65 MWh and the average load 60,01 kW,
whereas the annual load minimum is 0,00 kW and the maximum 470,00 kW.
January 1st of the typical refence year is a Monday.
Operating strategy is: Hospital load

Meteo : Kefalonia_Hospital

It is located at 38,17°N 20,50°E, 177 m (timezone 2,0 h).
Temperature min. is 2,1 °C, max. 36,2 °C, mean 18,3 °C.
The annual sum of global irradiation GHI is 1754 kWh/m² and the sum of direct normal irradiation DNI is 1908 kWh/m²
The annual sum of diffuse irradiation Diff is: 603 kWh/m²
Max wind speed is 15,5 m/s, mean is 3,0 m/s.

Fig. 10: Input data for the project site; cooling load and meteorological data

The solar thermal system is comprised of concentrating parabolic collectors, thermal chiller, hot water storage tank and the auxiliary hydraulic equipment. The technical characteristics of the selected solar collectors are seen in Fig. 11. The solar collectors’ field consists of 3 rows with 15 solar collectors each, resulting in 594m^2 total collectors’ area (Fig. 12). The selected fluid in the field is Dowtherm A and the temperature exiting the field depends on the chiller operational temperature and it is set at 180^{o}C. Thermal storage of 2.000kWh is also foreseen, that results in 3 hours of full load storage, on an average summer day. The selected thermal chiller is double effect, utilizes absorption technology and the cooling capacity is 583kW. Detailed technical characteristics of the chiller are shown in Fig. 13.

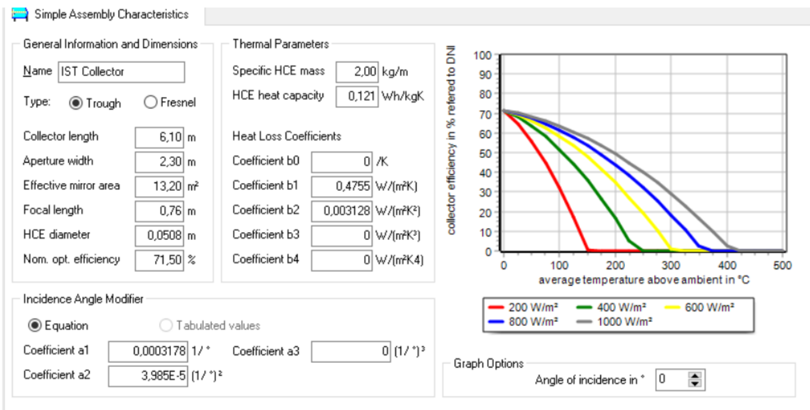

Fig. 11: Input data for the solar collectors

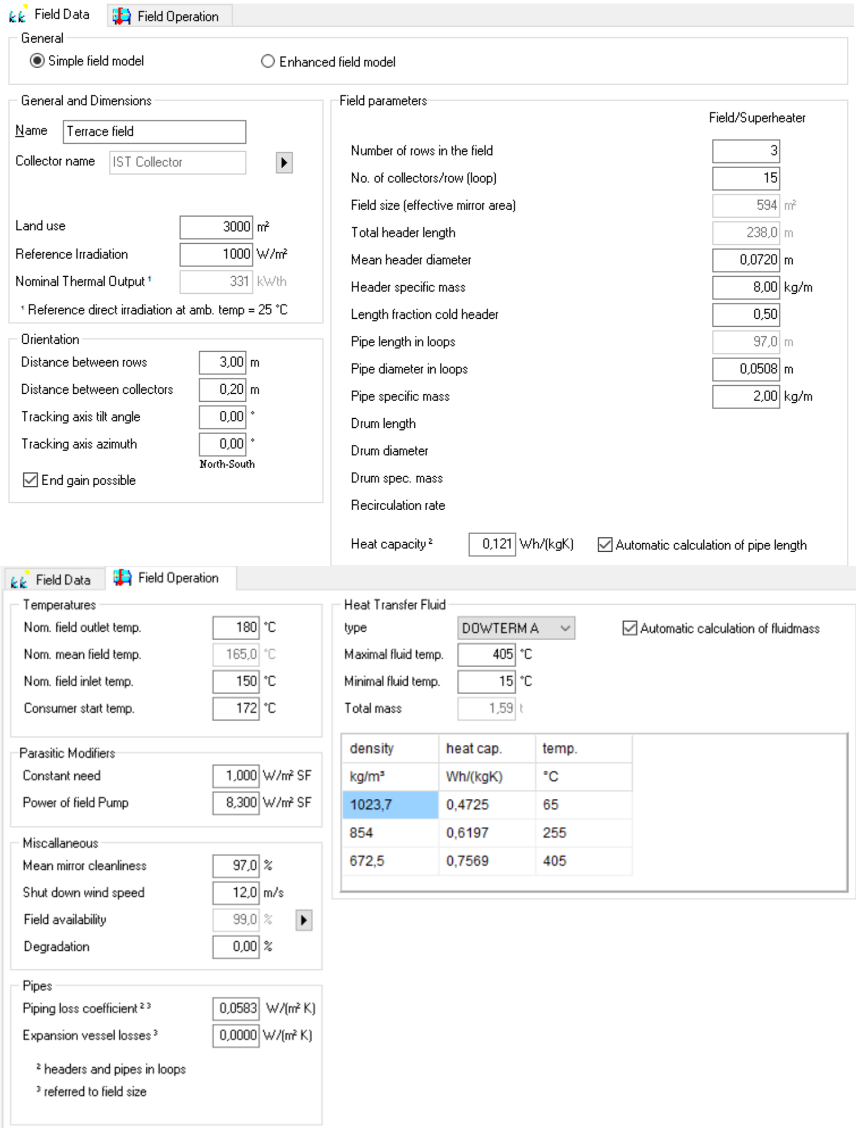

Fig. 12: Input parameters for the solar collectors' field

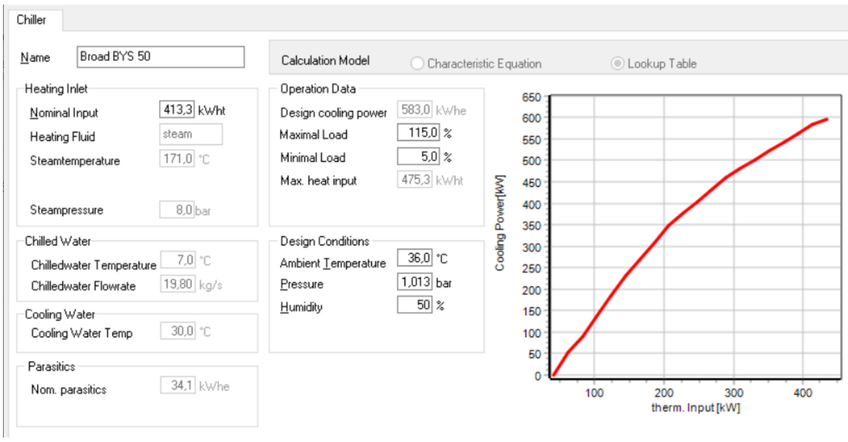

Fig. 13: Input data for the absorption chiller

Following the data input of all operational parameters regarding the site, the building load and the cooling system, the simulation procedure follows. The results of the simulation for each month are shown in Table 4. The annual sum of the Direct Normal Irradiation onto the collectors' area is 1.133MWh. Taking into consideration the thermal and optical losses, the thermal energy produced by the collectors is 334MWh, whereas that of the solar field is 272MWh. The double effect solar thermal chiller produces 240MWh of cooling energy and an amount of 172MWh of thermal energy is stored. The annual average solar fraction of this solar thermal system is 39%, which means that the designed solar cooling system can provide the 39% of the cooling load of the building. The average annual field efficiency is 19% and the average annual collectors' efficiency is 26%.

Tab. 4: Simulation results in tabular form

	DNI	**DN_c**	**H_{dn}**	**T_{amb}**	**Q_{load}**	**Q_{cool}**	**Q_{field}**	**Q_{col}**	**$Q_{Storage}$**	**Solar Cooling Fraction**
	W/m²	W/m²	MWh	°C	MWh	MWh	MWh	MWh	MWh	%
Average				**18**						**39%**
Sum	1.908.109	1.695.066	1.133		526	240	272	334	172	
January	105	68	46	11	0	0	2	6	3	
February	125	91	50	11	0	0	3	7	4	
March	177	154	78	13	0	0	14	19	22	
April	254	239	109	16	0	0	29	35	46	
May	290	283	128	20	59	10	39	46	42	0.17
June	311	305	133	24	117	66	45	51	5	0.56
July	353	345	156	27	141	84	55	61	4	0.60
August	328	313	145	27	146	71	45	52	1	0.49
September	237	212	101	23	63	10	24	30	20	0.16
October	179	142	79	20	0	0	11	17	18	
November	137	92	59	16	0	0	3	7	4	
December	111	69	49	13	0	0	1	5	2	

Graph 14 shows the annual distribution of the building's cooling load (red line) in comparison to the Direct Normal Irradiation on the collectors' area. This graph visualizes the advantage of the solar cooling concept; that is the time coincidence of the cooling loads with the availability of solar irradiation.

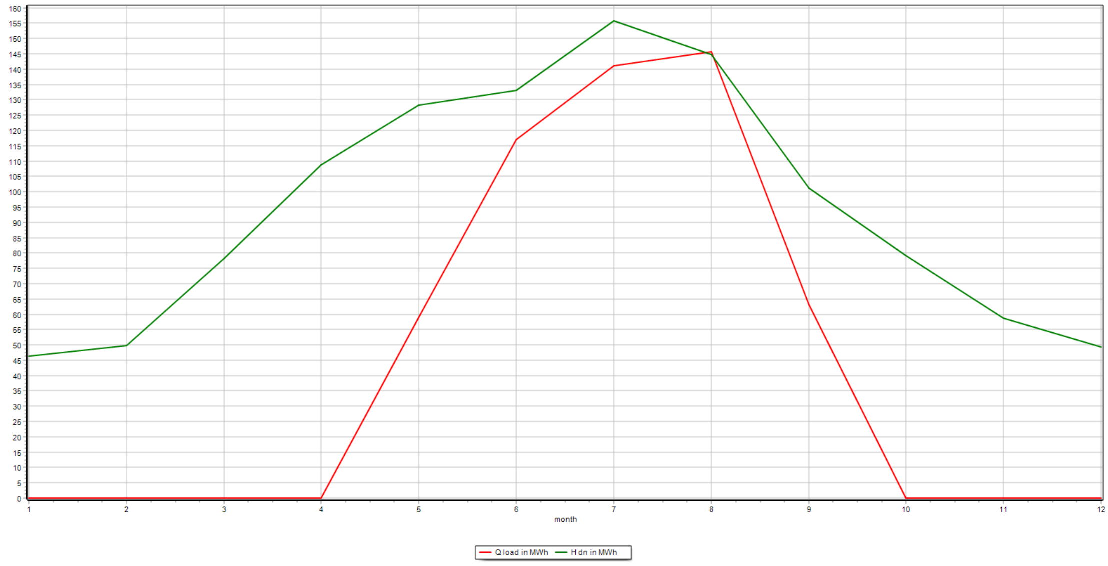

Fig. 14: Direct Normal Irradiation on the collectors' area (green line) and annual distribution of the hospital's cooling load (red line), in MWh

Fig. 15 shows the annual distribution of the cooling load (red line), in comparison to the cooling energy produced from the chiller (green line). The areas that occupy these two lines show that the selected capacity of the chiller and the parameters of the solar system are sufficient to cover approximately half of the cooling energy demands. Moreover, this graph illustrates the stored thermal energy happening during the spring and autumn periods, whereas in summer, the stored energy is minimized, due to its direct use in the thermal chiller. The blue line shows the heat produced by the solar field.

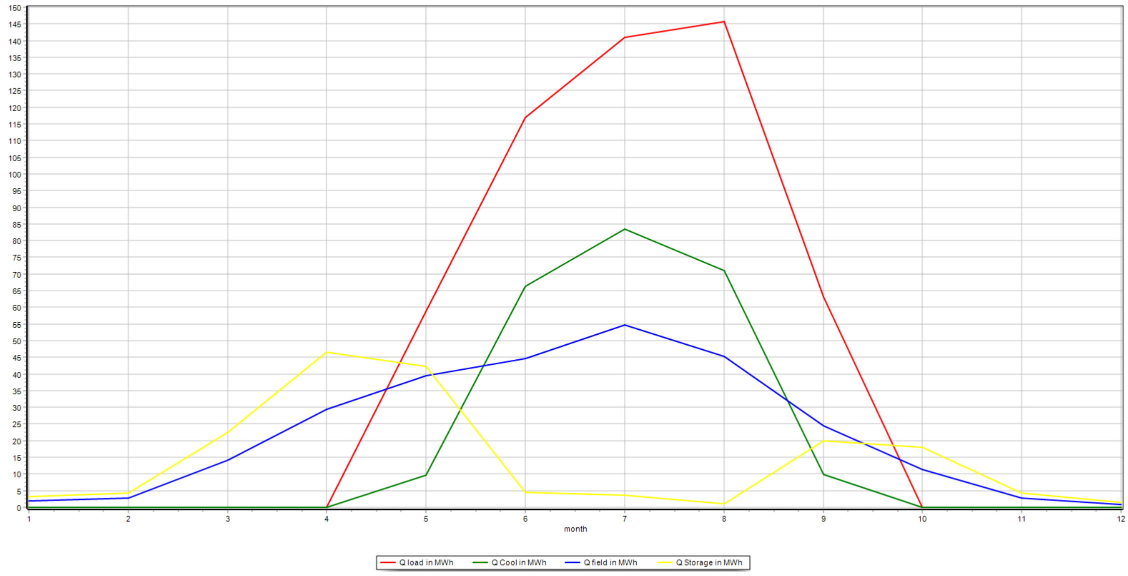

Fig. 15: Annual distribution of the hospital's cooling load (red line), cooling output from the chiller (green line), heating output from the solar collectors' field and stored heat (yellow line), in MWh

The economic evaluation of the system has been based on a previous work of the authors (Drosou et al, 2016) and the most important considerations are shown below. As such, Table 5 provides the initial, operation and maintenance costs of the solar cooling system.

Tab 5: Solar Cooling System Costs

Initial Costs		
Component	**Price**	**Unit**
Solar field	350	€/m^2
Chiller	200	€/kW
Cooling tower, hydraulics, other components	135	€/kW
Installation & Commissioning	15% of components cost	
Total system cost	**463,686**	**€**
Total system specific cost	**781**	**€/m^2**
Annual Operation & Maintenance Costs		
Solar field	4	€/m^2
Chiller	2.8	€/MWh
Cooling tower, hydraulics	0.2% of total system cost	
Total O&M cost	**3,813**	**€/a**
Total O&M specific cost	**6**	**€/m^{2}a**

A preliminary economic analysis based on the aforementioned data shows that the total investment cost sums up to 463,686 €, thus, resulting in a specific cost of 781 € per m2 of net solar collector area. Assuming the current electricity price of large consumers at 0.14€/kWh and considering the total investment cost, the annual energy savings of this system are 9,567 €/a, the IRR is negative and the Levelised Cost of Energy is 0.2672. These figures are far from attractive and indicate that this investment could be acceptable under specific circumstances. For example, the use of incentives could make the system costs more appealing. Additionally, new tighter legislation towards net zero emissions that applies penalties for CO_2 emitters could also fix the economics of this system.

4. Discussion and Conclusion

This work described the energy performance of a concentrating solar thermal system for covering part of the cooling load of a hospital building in Greece. Following a thorough analysis of the building's cooling loads, these were estimated at approximately 525MWh/a. The solar system comprised of 594m^2 concentrated parabolic collectors and a 2.000kWh thermal storage and 413kW double effect thermal absorption chiller. The energy performance assessment of the cooling system was elaborated in the Greenius tool and the results showed that the designed system provided 39% of the cooling loads of the building. The average annual field efficiency was calculated at 19% and the average annual collectors' efficiency was 26%. The annual sum of the Direct Normal Irradiation onto the collectors' area is 1.133MWh. Taking into consideration the thermal and optical losses, the thermal energy produced by the solar field is 272MWh. The double effect solar thermal chiller produces 240MWh of cooling energy and an amount of 172MWh of thermal energy is stored. The economic figures of the system, that is the Levelised Cost of Energy 0.2672 and the negative IRR imply that this system could be economically viable under specific circumstances.

In the direction of the future decarbonization of buildings, the use of RES heating and cooling systems is getting necessary. Peak space cooling needs also coincide with peak solar energy availability and solar thermal systems can contribute to space cooling and avoidance of interior overheating. The results of this analysis can be also useful for engineers and developers during the design and dimensioning process of solar concentrating thermal systems for heat production.

5. Acknowledgements

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