Performance Simulation and Monitoring Methodology of a Solar Cooling Installation in Aqaba, Jordan

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Abstract

This work presents the results of the energy performance simulation of a solar cooling system that is currently under installation in the Aqaba Chamber of Commerce office building in Jordan, as well as the monitoring methodology for the system's operation. The main components of the system are the flat plate solar thermal collectors (160m^2), the single-effect absorption chiller (35kW), the two hot water storage tanks and the chilled water storage tank. The solar thermal cooling system is coupled with the existing central cooled water system and it is designed to cover approximately half of the cooling load of the building. Key Performance Indicators of the specific solar cooling system are defined and provide the basis of the monitoring system. Key Performance Indicators are defined according to IEA-SHC Task 38 and regard the solar field efficiency, the thermal and electrical coefficient of performance and the cooling solar fraction. The simulations show that the thermal energy produced by the collectors' field is 131,103 kWh/y, the cooling energy production is 79,525 kWh/y and the auxiliary electricity consumption is 4,979 kWh/y. The efficiency of the solar field is estimated at 0.38. The solar cooling system can cover the 0.52 of the building's cooling energy demand. The simulated thermal coefficient of performance of the whole solar cooling system is 0.61 and its electrical counterpart is 15.5. The simulation are reasonable, indicating that the correct design of the system and dimensioning of the components produce a well operating system with high energy saving potential.

Keywords: solar cooling, absorption chiller, energy simulation, solar fraction.

1. Introduction

Today, heating and cooling consume the most energy of all end uses, accounting for nearly half of global final energy consumption. The energy consumed for heating and cooling is a significant contributor to air pollution and carbon dioxide emissions, since the 77% of the heating and cooling demand is met by fossil fuels and non-renewable electricity (IEA 2020, IRENA 2021a).

Due to global warming, cooling and refrigeration demand is under rapid growth and several hundred million air conditioning units are expected to be sold per year by 2050 (IEA 2021). Indeed, by that date, the 37% of the electricity demand growth will be due to the growth of cooling and refrigeration demand. An enormous potential for cooling systems that use solar energy arises.

A major argument for using solar thermally driven cooling systems, instead of other technologies, is that they consume less conventional energy and use natural refrigerants, as appointed by the European F-gas Regulation (EU, 2014). But their most important advantage is that they can deliver cooling during the peak demand in summer. Therefore, purchase of electricity at its highest cost is avoided. In this way, solar thermal cooling reduces peak electricity demand and this is particularly important for countries with significant cooling loads (IRENA et al 2020). Additionally, solar thermal cooling can easily store heat and thus, shift the demand. These assets enable solar thermal cooling systems to reduce the electric demand for cooling in a building by more than 80%, compared to conventional cooling and air conditioning equipment (IEA 2021).

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The market of solar thermal collectors is well established and growing; the global solar thermal capacity of solar thermal collectors in operation has grown from 62 GWth (89 million m^2) in 2000 to 501 GWth (715 million m^2) in 2020 and the corresponding annual solar thermal energy yields amounted to 51 TWh in 2000 and 407 TWh in 2020. The translation into savings for 2020 are 43.8 million tons of oil and 141.3 million tons of CO_2 (IEA 2021). Especially in the MENA region (Israel, Jordan, Lebanon, Morocco, Palestinian Territories, Tunisia), the total capacity of glazed water collectors in operation in 2019 is 7,361MW_{th} in total or 96.1 kW_{th} per 1,000 inhabitants. In terms of market penetration per capita, China is the leader, but MENA countries are remarkably ahead of Europe and Australia (IEA 2021).

Despite the clear advantages of solar thermal cooling, it is still a niche market, with about 2,000 systems deployed globally as of 2020 (IEA 2021). The main barriers of the limited market uptake can be attributed to costs, technical limitations and the need for further research and development (IRENA et al 2020). Even today, solar cooling technology is relatively expensive when compared to most electric alternatives. Finally, limited awareness of available technology options, their maintenance requirements and potential benefits impede their deployment.

At the same time, the legally binding international treaty on climate change “Paris Agreement” for limiting global warming by 2050 to 1.5°C (UNFCCC, 2015) can be only achieved through the energy transition grounded in renewable sources of energy and efficient technologies. But for the moment, the speed of this energy transition falls short of the 1.5ºC goal (IRENA, 2021b). Especially for the Sun Belt countries, solar thermal energy has great potential to contribute towards decarbonisation of energy intensive processes, thus ensuring a rapid decline in emissions and contributing to net zero emissions by 2050.

This work aims at unveiling the energy saving of a solar cooling system, by presenting the energy performance simulation results for a typical office building in Aqaba, Jordan as well as the monitoring methodology for the system’s operation. The results of this study are useful to mechanical engineers and companies designing and installing solar cooling systems, to manufacturers of solar cooling components, as well as to the final end users of the technology, especially in the countries of MENA region

2. Description of the Solar Cooling and Monitoring System

2.1. End User Description

The Aqaba Chamber Of Commerce Building is in Aqaba, Jordan and consists of a two-level basement, a ground floor and three floors of 450 m^2 each. The total air conditioned area is 1,848m^2 at a cooling set point temperature 26.5ºC. The building is occupied from 8:00 am to 3:00 pm from Sunday to Thursday. The building has no heating load. The cooling needs of the building, typically from March until October, are covered partially by two conventional vapor compression electric chillers, with total nominal capacity 344 kW (2*172 kW). The cooling energy of the building has been estimated at 146,510 kWh/y. The chillers are connected with a central piping network system (with estimated flow rate 5.5 m^3/hr) distributing chilled water to the building. The terminal units of the chilled ceiling system are 46 fan coil units. There is also one air-handling-unit in the building, used for providing fresh air in the auditorium. Additionally, several autonomous air-conditioning split-units are installed in the building.

2.2. System Components

A solar cooling system will be installed in the terrace of the building and will be assisting the cooling production of the vapor compression chillers. The simplified system configuration is shown in Fig. 1. The solar cooling system was simulated with Polysun Designer (Polysun 11.2, 2020) simulation tool (Fig. 2). Considering the available free space in the terrace, the solar cooling system consists of the main following parts:

- 144 m^2 (aperture area) flat plate collectors
- 2 hot water storage tanks, 1,500lt each
- 35kW closed loop absorption chiller and
- 1 chilled water storage tank, 1,500lt that serves as the central chilled water provider for the air conditioning system of the building

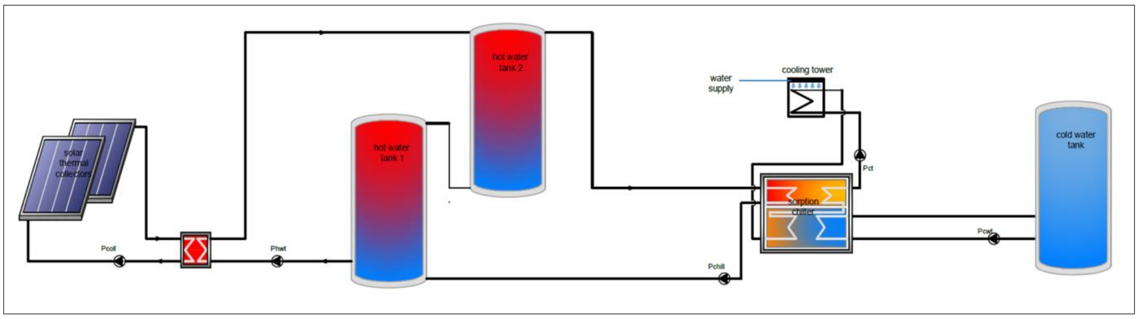


Fig. 1: Solar cooling system configuration

The solar system operates every day during the cooling season, even when there is no occupancy or in weekends (Friday and Saturday). During these days without occupancy, the building turns into a 'solar only' mode, the solar system operates normally and chilled water is driven into the building in order to prevent excessive temperature increase and to retain the thermal comfort inside the offices. Two hot storage tanks are employed instead of one because there are height and space limitations in the site. The chilled water storage tank is not a standard subcomponent of solar cooling systems, but in the specific case it serves as a temporary storage to match the flow rates of the absorption chiller and the conventional vapor compression chiller. Therefore, its role is to facilitate the combination of the conventional chiller and the absorption chiller and not to store chilled water for a specific amount of time. This system is built in *Polysun* software, in order to elaborate the annual energy performance analysis.

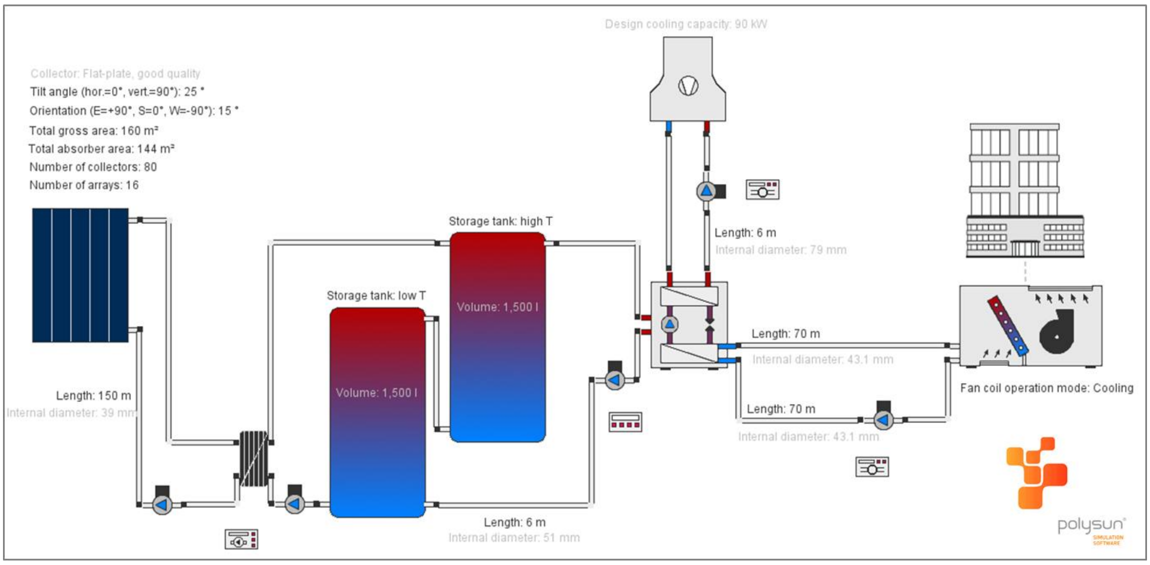


Fig. 2: Solar cooling system simulated in Polysun software

The dimensions of basic components are shown in Tab. 1.

Tab. 1: Dimensions of basic components

Geographical data	Longitude: 35.01°, Latitude: 29.536°
	Global irradiation, annual sum 2197 kWh/m²
	Diffuse irradiation, annual sum 542 kWh/m²
Flat plate solar thermal collectors	Area: 160 m² gross, 144 m^2 aperture
	Tilt angle 25° (hor.=0°, vert.=90°)
	Orientation 15° (E=+90°, S=0°, W=-90°)
	Heat transfer fluid: 30% propylene glycol solution
Thermal chiller cooling capacity	35 kW, absorption closed loop
Hot water storage tanks	2 tanks, 1500 lt each
Chilled water storage tank	1500 lt
Cooling tower	Wet cooled, Cooling capacity 90kW

2.3. Monitoring System

Monitoring of solar cooling systems is a fundamental tool to optimize the system operation and to enable the maximum energy yield with the minimum operational cost.

The designed monitoring system monitors the heat and electricity flow of all subsystems individually, according to the suggestions of IEA-SHC Task 38 (IEA, 2011). This procedure is performed by measurements of the temperature of the water in specific points, the water flow, the incident irradiation to the collector field and the electricity consumption of the components (pumps, fans, chiller, control). The aim of the monitoring process is to calculate the Key Performance Indicators (KPI) as defined in Tab. 2.

Tab. 2: Key Performance Indicators of the solar cooling system

Key Performance Indicator	**Equation**
KPI 1 Solar Field Efficiency	$n_{sf} = \frac{Collectors' \; yield}{Solar \; Irradiation \; onto \; collectors \; area}$ This equation is relevant to the eq. 20 of the 2nd monitoring level in IEA, 2011. Collectors' yield $Q_{coll} = m_{coll} * C_p * (T_{coll\_out} - T_{coll\_in})$ kWh Solar Irradiation onto collector's area Q_{irr} = Aperture * Global irradiation on tilted surface, kWh
KPI 2 Coefficient of Performance, Thermal	$COP_{th} = \frac{Cooling \; energy \; yield}{Heat \; supplied \; by \; storage \; tanks}$ This equation is relevant to the eq. 57 of the 3rd monitoring level in IEA, 2011. Cooling energy yield $Q_{cwt}=m_{cwt}*C_p*(T_{cwt\_out} - T_{cwt\_in})$ kWh
KPI 3 Coefficient of Performance, Electrical	$COP_{el} = \frac{Cooling \; energy \; yield}{Electricity \; consumption}$ This equation is relevant to the eq. 59 of the 3rd monitoring level in IEA, 2011. Electricity consumption = $E_{Ptank} + E_{chill} + E_{ct} + E_{Pcoll} + E_{Pchill} + E_{Pct} + E_{pfc}$, kWh
KPI 4 Solar Fraction, Cooling	$SF_{cool} = \frac{Cooling \; energy \; yield}{Building \; cooling \; demand}$ This equation is similar to the eq. 11 of the 1st monitoring level in IEA, 2011. The authors adjusted this relationship to convey the contribution of the solar energy to the building cooling demand. Therefore, there is a difference in the denominator: instead of using the primary energy demand, the authors have used the cooling demand of the building.

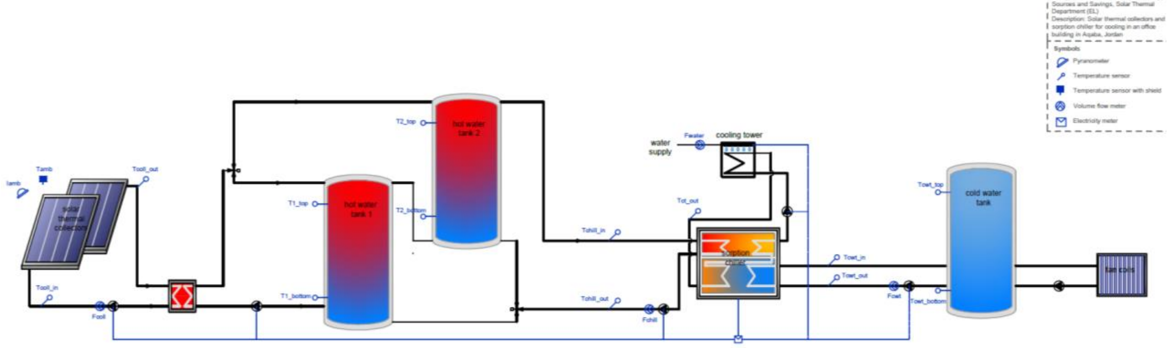
The inputs necessary for the achievement of this monitoring procedure are listed below.

Tab. 3: List of monitoring sensors and their position

Name	**Description**
I_{amb}	Total irradiation on tilted surface, W/m^2
T_{coll_out}	Solar field outlet temperature (glycol), ^oC
T_{coll_in}	Solar field inlet temperature (glycol), ^oC
T_{chill_in}	Chiller inlet temperature from hot tanks (water) , ^oC
T_{chill_out}	Chiller outlet temperature to hot tanks (water), ^oC
T_{cwt_in}	Chilled tank inlet temperature from chiller (water), ^oC
T_{cwt_out}	Chilled tank outlet temperature to chiller (water), ^oC
T_{amb}	Ambient air temperature, ^oC
F_{chill}	Water volumetric flow from chiller to tank, m^3/hr
F_{cwt}	Water volumetric flow from chiller to chilled water tank, m^3/hr

F_{coll}	Glycol volumetric flow from heat exchanger to collectors, m^3/hr
E	Electricity meter of the whole system, kWh

The exact positioning of the above temperature sensors, pyranometer, flow rate sensors and electricity meters can be seen in Fig. 3, where the additional sensors of the control system are also shown.



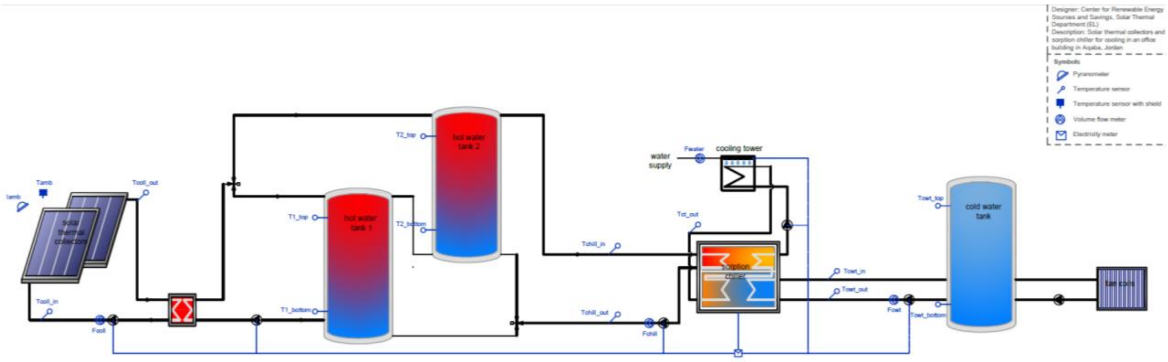


Fig. 3: Positioning of temperature sensors, flow rate sensors and valves for the monitoring and control system.

3. Energy Performance Results

Tab. 4 shows the annual values of the energy performance simulation results. The annual irradiation reaching the whole collector field is 347,892 kWh and the thermal energy produced by the solar collectors (total annual field yield) is 131,103 kWh, so the efficiency of the solar field becomes $n_{sf} = 0.38$.

Regarding the chiller performance, the total annual cooling energy yield is 79,525 kWh. The net energy subtracted from the building, through the fan coil cooling modules, is 76,687 kWh. This value includes the heat losses from the delivery system and components. Taking into consideration that the annual cooling energy demand of Aqaba Chamber of Commerce office building is 146,510 kWh, the SF_{cool} becomes 0.52, meaning that the solar cooling system can cover the 0.52 of the building's cooling energy demand.

The annual electricity consumption for the operation of the whole solar system is 4,979 kWh, 273 kWh of which are attributed to the electricity consumption of the pumps.

Tab. 4: Energy Performance Simulation Results

Solar thermal energy	
Global irradiation, annual sum	2,197 kWh/m²
Irradiation onto collector area	347,892 kWh
Total annual field yield	131,103 kWh
Collector field yield relating to gross area	819.4 kWh/m²/Year
Collector field yield relating to aperture area	910.4 kWh/m²/Year
Thermal chiller	
Cooling energy demand	146,510 kWh
Heat supplied by generator	106,030 kWh

Total cooling energy yield	79,525 kWh
Net energy from/to heating/cooling modules	-76,687 kWh
System overview	
Total energy consumption	77,442 kWh
Total fuel and/or electricity consumption of the system	4,979 kWh
Total annual electricity consumption of pumps	273 kWh
Key Performance Indicators	
KPI 1 Solar Field Efficiency, n_{sf}	0.38
KPI 2 Coefficient of Perfomance – Thermal COP_{th}	0.61
KPI 3 Coefficient of Perfomance – Electrical COP_{el}	15.5
KPI 4 Solar Fraction in Cooling SF_{cool}	0.52

It has to be noted here that the KPI 3 and KPI 4 refer to the whole solar thermal system and not to the chiller alone. To evaluate the Coefficient of Performance, thermal and electrical, of the chiller only, then the equations become:

$$COP_{th\_chiller} = \frac{Cooling\ energy\ yield}{Heat\ supplied\ by\ generator} \qquad \text{(eq. 1)}$$

$$COP_{el\_chiller} = \frac{Cooling\ energy\ yield}{Chiller's\ electricity\ consumption} \qquad \text{(eq. 2)}$$

Accordingly, the COP values for the chiller only, considering the results of Tab. 2, are: $COP_{th\_chiller}$= 0.75 and $COP_{el\_chiller}$= 2.91.

Fig. 4 shows the annual distribution of the solar irradiation (yellow line), the yield of the total collector area (red line) and the cooling energy produced by the solar thermal chiller (blue line). This figure visualizes the solar system efficiency, which has been estimated at 0.38, as well as the thermal coefficient of performance of the system, which has been estimated at 0.61.

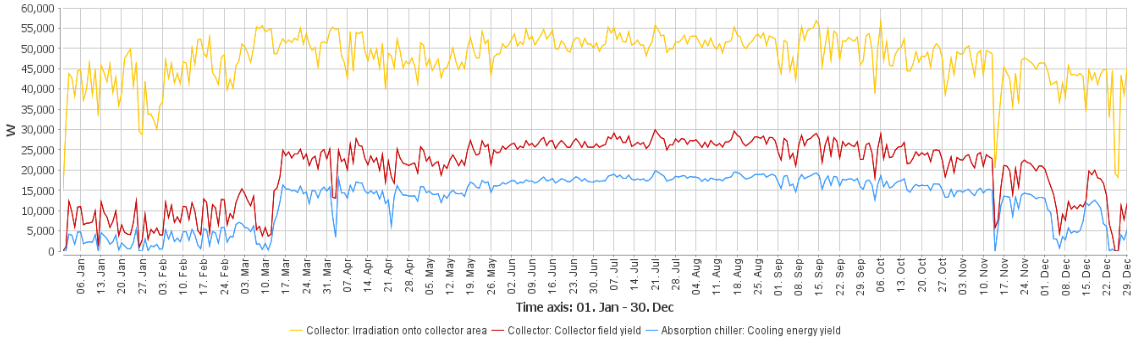


Fig. 4: Annual energy yields of solar cooling system

Fig. 5 provides the same energy yields with Fig. 4, but it focuses on an indicative week in July. The time coincidence of the curves show the smooth operation and control of the system; when solar irradiation becomes available, the system starts to operate, stores thermal energy and produces chilled water, which is either directly consumed or stored in the chilled water tank for future use. A small time lag is also obvious between the availability of solar energy and the chilled water production, which is reasonable.

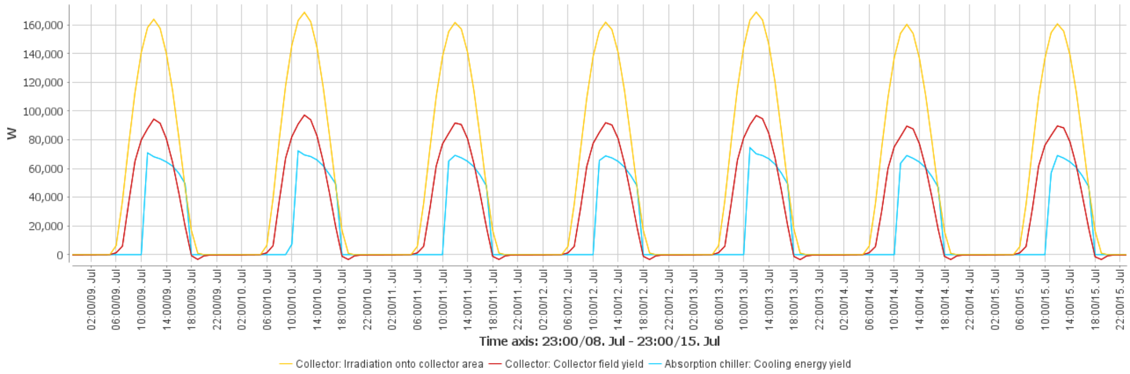


Fig. 5: Energy yields of solar cooling system during a week in July

Fig. 6 shows the most important temperatures inside the system, during another indicative week, in June. The outdoor temperature reaches 45°C at midday and the indoor temperature is steadily slightly above 30°C. The maximum temperature of the collector is 109°C, but without observing any stagnation due to the specific technical characteristics of the selected solar thermal collector as well as due to the continuous heat consumption profile. The temperature of the hot water inlet to the absorption chiller follows the pattern of the collector outflow temperature, being slightly below it, due to heat losses. It is also seen that the temperature of the chilled water produced by the absorption chiller totally depends on the hot water inlet, being inversely proportional.

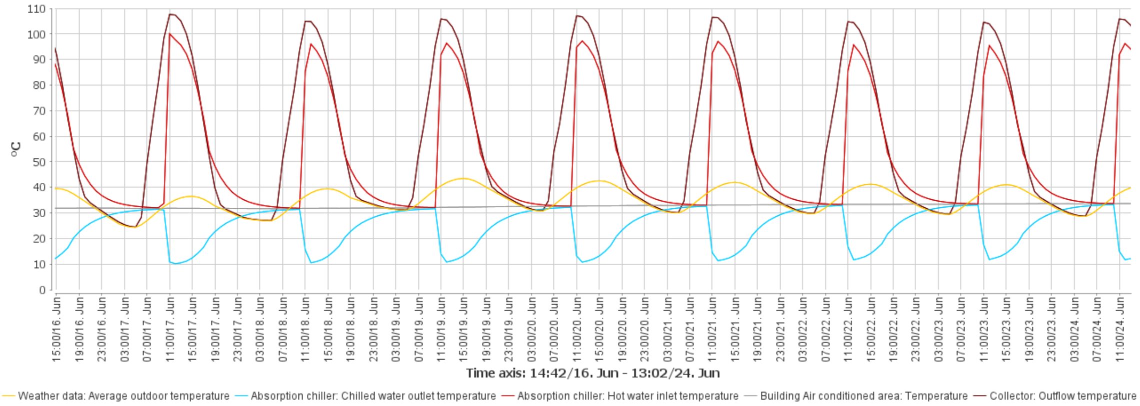


Fig. 6: Basic system temperatures during a week in June

The system diagram along with simulated operation parameters for 29th March at midday, is shown in Fig. 7. The temperature output of the collectors is at 98.6°C. Due to heat losses and the presence of the heat exchanger, this is translated to 95.3°C inlet to the hot water tank. The system of two tanks has sufficient temperature stratification and seems to be working properly, since the right tank has higher temperature than the left tank. The hot water inlet to the thermal chiller is at 94.9°C. The hot water outlet from the chiller to the tanks is 85.7°C and corresponds with the lowest temperature of the left tank. The cooling water loop of the cooling tower, which is a crucial parameter at the design and dimensioning phase, is also working properly. The chilled water inlet to the building is at 7.2°C and the outlet is at 13.4°C, subtracting 58,559W from indoors.

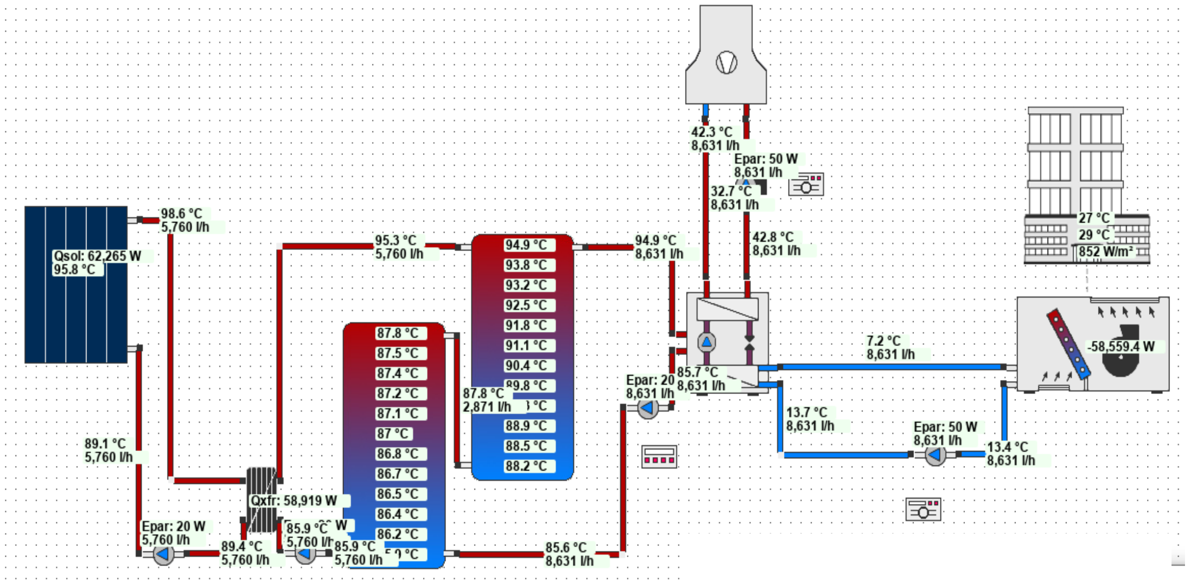


Fig. 7: Solar cooling system state of operation in March 29th

4. Conclusions

Cooling and refrigeration demand is under rapid growth and several hundred million air conditioning units are expected to be sold annually by 2050, leaving enormous space for the market uptake of solar thermal cooling systems. Cooling and air conditioning through solar thermal energy has the outstanding advantage of time coincidence between supply and demand; thus enabling the reduction of peak electricity demand. Furthermore, they can inexpensively store heat and shift the demand, they use natural refrigerants and finally, they reduce the electric demand for cooling in a building by more than 80%, compared to conventional cooling and air conditioning units.

This study unveils the potential of solar cooling systems, by presenting the energy performance simulation results for a specific office building in Aqaba, Jordan. Key performance indicators of the specific solar cooling system are defined and provide the basis of the monitoring system. The monitoring system is in line with the requirements of 1st level monitoring procedure and consists of one irradiation sensor, seven temperature sensors, three flow meters and one electricity meter. The simulations showed that the thermal energy produced by the collectors' field is 131,103 kWh/y, the cooling energy production is 79,525 kWh/y and the auxiliary electricity consumption is 4,979 kWh/y. The efficiency of the solar field was calculated at 0.38. The simulated solar cooling system covers the 0.52 of the building's cooling energy demand. The thermal coefficient of performance of the whole solar cooling system is 0.61 and the electrical is 15.5. The results indicate that the correct design of the system and dimensioning of the components produce a well operating system with high energy saving potential. Further investigation of the system that includes acquisition of monitoring data and validation of the simulation results will be performed upon the completion of the installation that is expected to occur at the end of 2021.

5. Acknowledgments

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