Optimization of solar cooling system in Greek hotelincluding cooling production and rejection heat recovery

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Abstract

Cooling systems in buildings currently represent an issue in terms of energy consumption. The electrically driven chillers are used in most cases while cooling loads cause overloading of the electricity distribution system during summertime. This situation is significantly energy consuming in the case of hotels, where domestic hot water (DHW) consumption appears, often simultaneously.
Solar cooling systems (SCS) designed for full or partial coverage of the cooling load can decrease electric consumption peaks in buildings and consequently also consumption of non-renewable primary energy. Even more significant savings can be achieved by using the rejected heat of solar chillers for DHW preheating or for heating of open pools in Mediterranean coastal type hotels so that to maximize the overall EER and COP of the whole installation.
DHW consumption and pool heating load profiles combined with the cooling peak load profiles are significant parameters for optimizations. Furthermore, the penetration ratio of a solar chiller capacity related to the summer cooling peak load value is a decision tool to achieve significant overall energy efficiency.
In this paper, energy performance of SCS with rejection heat recovery in Greek hotel is evaluated using transient simulation program (TRNSYS) and energy savings are calculated in comparison to compression-based cooling system and gas heater. The optimized overall efficiency of a typical Mediterranean hotel situated in the Rhodos Island has been found according simulated scenarios equal to 7.45. This efficiency is announced for a solar cooling penetration ratio of 28 % referred to the summer cooling peak load.

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*Keywords:*Solar cooling system; heat recovery; domestic hot water preheating; pool heating; hotels

1. Introduction

The need for utilization of renewable and clean energy sources is growing in past few decades because of increasing effort to reduce the concentration of greenhouse gases and sustainability of energy production. Use of thermal solar systems for heating and cooling can create appreciable environmental benefits [1] but the economic feasibility compared to conventional cooling systems is questionable with today's prices of energy [2]. Initial investments have a strong influence on the payback and cost of saved primary energy and reduction of these costs is necessary to increase feasibility of solar cooling systems [3].

Use of rejected heat from chiller for preheating of domestic hot water (DHW) can increase energy savings, especially in buildings with high DHW consumption like hotels. Several studies of solar cooling systems has been already done [3-5, 9] however none of them included heat recovery from chiller. The objective of this work

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was to simulate a solar cooling system for partial coverage of the cooling load including heat recovery of rejected heat from sorption chiller and determine primary energy savings.

2. Methodology

In the simulation were considered three variants of building with 400 m^3 outdoor pool, 200 m^3 outdoor pool and without pool. All variants were evaluated in two different occupancy scenarios regarding to costal and city type hotel and with five different solar cooling systems, therefore, the total number of simulations was 30.

2.1. Description of the building model

To provide consistent baseline of comparison, the model of standard hotel building situated in Rhodosisland (Greece) was used in this study. The building model consists of 7 zones with the total floor area 6486.8 m^2. It includes lobby, restaurant, kitchen, offices, facilities and common rooms in the first floor and guest roomsfrom first to six floor. The building was chosen because of high cooling load and simultaneous high consumption of DHW. Combination of these two demands is favorable for solar cooling system (SCS)because rejected heat can be used for DHW preheating.

The model was built in TRNBuild software and the building constructionsused in thermal behavior simulation are shown in Table 1[6].

Table 1. Building constructions thermal properties

Construction	Construction materials	Thermal capacitance [kJ/(m^2K)]	Heat transfer coefficient [W/(m^2K)]
External wall	Plaster (1 cm), concrete (19 cm), insulation (9 cm), plaster (1 cm)	547.61	0.476
Panel wall	Plaster (1 cm), wooden board (1 cm), insulation (9 cm), wooden board (1 cm), plaster (1 cm)	52.14	0.475
External floor	Wooden floor (1 cm), concrete (4 cm), insulation (9 cm), concrete (35 cm), plaster (1 cm)	1059.23	0.442
Roof	Plaster (1cm), concrete (34 cm), insulation (10 cm), ceramic tiles (1 cm)	934.13	0.419
Internal wall	Gypsum board (1 cm), insulation (18 cm), gypsum board (1 cm)	90.56	0.264
Internal floor	Wooden floor (1 cm), concrete (4 cm), insulation (9 cm), concrete (35 cm), plaster (1 cm)	1059.23	0.442
Windows	Wooden frame, double glazing	-	2.99

Following assumptions have been also considered in the building model:

- Ventilation of the building was mechanical. Air exchange ratio was specified for each zone regarding to the minimum requirements and air exchange ratio was increased to 3.0 during the night if the outside temperature was lower than interior temperature.
- Automatic shading of the glazed surfaces was used. Shading factor was dependent on the intensity of solar radiation and ranged from 0.2 to 0.5. Shading was used when the intensity of solar radiation exceeded 200 W/m^2.
- Internal heat gains from people and lightning were dependent on occupancy profile. Heat gain from lightning in communications was continuous.
- Internal heat gains from equipment was considered in offices and kitchen during operation hours.
- Cooling system operates from 8:00 to 21:00.

2.2. Pool and DHW consumption profiles

During April, May, September and October was the pool heated to the setpoint temperature 26 °C during day and 24 °C during night. For heating of the pool were used gas boilers or rejected heat from absorption chiller. DHW was supplied at 55 °C.DHW consumption profiles were reflexing following assumptions:

- Occupants in costal type hotel consumes less DHW than occupants in city type hotel, laundry and restaurant increases consumption,as shown in Table 2 [7].

- Hourly day profile and total amount of consumed DHW per day differs in each week day, regarding to Figure 1 [7]. Difference in DHW consumption of costal and city type hotel is in the absolute values (l/day), not in the hourly percentage consumption.
- In summer month is consumed less DHW than in winter, as shown in Figure 2 [8].
- DHW consumption depends on building occupancy, as shown in Figure 3 [7].

For every time step of the simulation was the DHW consumption $V_{DHW,h}$calculated from equation (1).

$$V_{DHW,h} = 0.000001.(V_{H-DHW,d}.c_{h-h} + V_{R-DHW,d}.c_{h-r}).c_m.c_o \qquad [m^3/hr] \qquad (1)$$

Where:

$V_{H\text{-}DHW,d}$	*DHW consumption of hotel [m³/h]*
$V_{R\text{-}DHW,d}$	*DHW consumption of restaurant [m³/h]*
$c_{h\text{-}h}$	*hotel hourly consumption coefficient from Figure 1 [-]*
$c_{h\text{-}r}$	*restaurant hourly consumption coefficient from Figure 1 [-]*
c_m	*monthly consumption coefficient from Figure 2 [-]*
c_o	*occupancy coefficient from Figure 3 [-]*

Table 2. DHW consumption per day

	Costal type hotel	City type hotel
DHW daily consumption per bed	45 l/(day.bed)	78 l/(day.bed)
Beds	216	216
Laundry coefficient	1.25	1.25
Hotel DHW daily consumption ($V_{H\text{-}DHW,d}$)	12 150 l/day	21 060 l/day
DHW daily consumption per meal	11,5 l/(day.meal)	
Meals per day	324	
Restaurant DHW daily consumption ($V_{R\text{-}DHW,d}$)	3 726 l/day	
Total DHW daily consumption	15 876 l/day	24 786 l/day

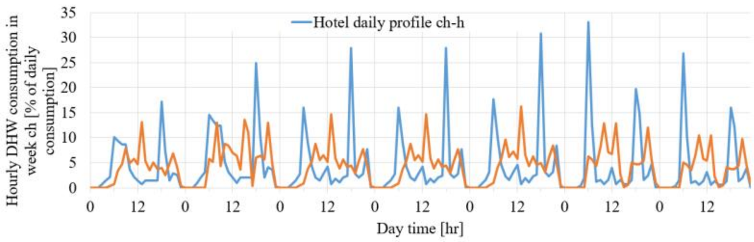

Fig. 1. Hourly DHW consumption coefficients in week (c_h)

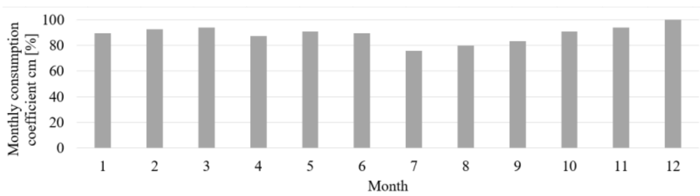

Fig. 2. Monthly consumption coefficients (c_m)

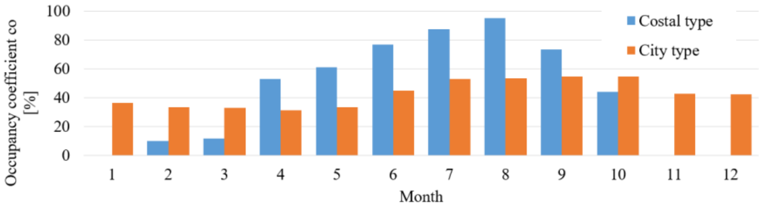

Fig. 3. Occupancy in the costal and city type hotel during year (c_o)

2.3. Description and parameters of the compared systems

The comparison of four solar cooling systems and one conventional system was carried out using two different programs. The program TRNBuildwas used for simulation of the dynamic thermal behavior of modeled building and the program TRNSYS for simulation of the solar cooling systems and also for the system used as reference.

2.3.1. Reference system

This system was composed of five vapor compressor chillers of 50 kW which were operated in dependence on cooling load while no cooling water storage tanks were used. System also included four gas boilers of 100 kW for pool and DHW heating supplemented by seven DHW storage tanks of total volume 10.5 m^3.

It was assumed that all electricity demand for the condenser fans, vapor compressors, controllers and circulation pumps was covered by the public grid.
The seasonal energy efficiency ratio (*SEER*) of the compressor cooling system was assumed equal to 3.39.Gas demand for gas boilers was covered from public grid and boilers efficiency (n) was equal to 90 %.Schematic diagram of the reference system is show on Figure 4.

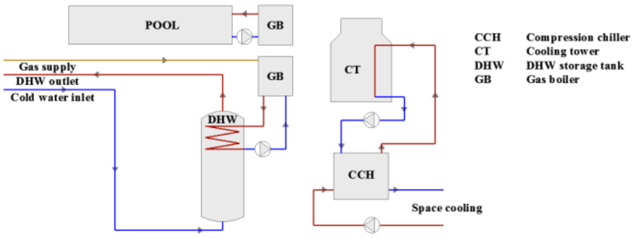

Fig. 4. Schematic diagram of reference system

2.3.2. Solar cooling system

Compared to the reference system, in solar cooling system part of the cooling load was covered by absorption chiller supplied by heatfrom evacuated tube collectors. To increase overall efficiency of the whole system, rejected heat from absorption chiller was used for preheating of DHW and pool, so additional storage tank for preheated DHW and heat exchanger for pool heating had to be added to the cooling water circuit. On the cooling water circuit was also placed backup closed-circuit cooling tower used in cases when the temperature of cooling water entering the absorption chiller was too high.When the cooling load was low, the heat from thermal collectors was used for second stage preheating of DHW. It typically happened during spring and autumn when the heat production was higher than heat demand from absorption chiller, however this principle was also applied during winter when there was no cooling demand.

Simulations of four representative absorption chillers available on market were carried out. Efficiency curves of all used absorption chillers are shown on Figure 5, further specification is shown in Table 3. Efficiency curves of chillers were modeled in simulations using approximation curves. Specification of evacuated tube collectors is shown in Table 4.

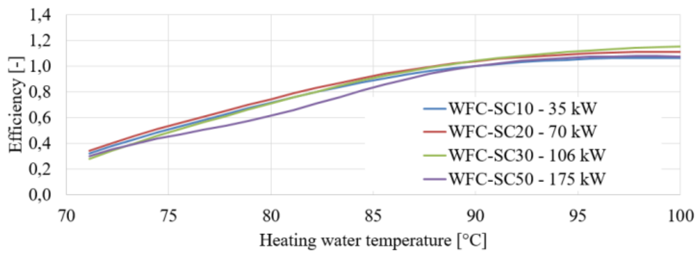

Fig. 5. Efficiency of used absorption chillers for cooling water inlet temperature 31 °C and cooled water outlet temperature 7 °C

Table 3. Specification of absorption chillers

Chiller			SC10	SC20	SC30	SC50
Cooling capacity		kW	35.2	70.3	105.5	175.8
Chilled water	Cooling temperature	°C	12.5 Inlet / 7 Outlet			
	Rated water flow	m^3/h	5.5	11.0	16.5	27.5
Cooling water	Heat rejection	kW	85.4	170.8	256.2	427.0
	Temperature	°C	31 Inlet / 35 Outlet			
	Rated water flow	m^3/h	18.4	36.7	55.1	91.9
Heat medium	Heat input	kW	50.2	100.4	150.7	251.1
	Temperature	°C	88 Inlet / 83 Outlet			
	Rated water flow	m^3/h	8.6	17.3	25.9	43.2
Electrical power	Consumption	W	210.0	260.0	310.0	670.0

Table 4. Specification of evacuated tube collectors

Optical collector efficiency (η_O)	-	0.368
Linear heat loss coefficient (a_1)	$W/(m^2.K)$	0.61
Quadratic heat loss coefficient (a_2)	$W/(m^2.K)$	0.0046
Gross area	m^2	2.206

Slope of the collectors was chosen considering optimized tilted angle for solar cooling by Duffey and Beckman (Solar Engineering of Thermal Processes) as local latitude minus 15 ° for summer use. However, a tilted angle of 30 ° was chosen because thermal collectors were used during whole year for preheating of DHW. Total collectors area varies from 139 to 690 m^2, depending on absorption chiller rated power. According to Hang, Q_u and Zhao [9], storage tank size of 0.05 m^3/m^2 was chosen.

Very limited gain in solar fraction can be achieved when the ratio is higher than 0.04.

The schematic diagram of the solar cooling system for the selected building is shown on Figure 6.

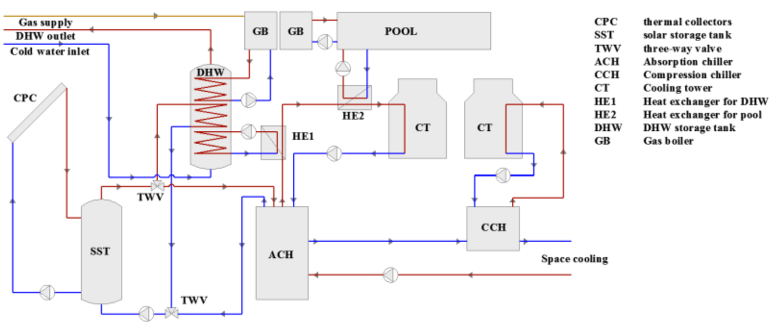

Fig. 6. Schematic diagram of solar cooling system

2.4. *Energy performance indicators*

Regarding the complicated energy flows in the simulations, energy performance indicators which summarizes quality of energy use in the building have to be established.

2.4.1. *Solar penetration ratio*

As solar penetration ratio(SPR) was considered as the ratio between solar chiller power and highest cooling peak load, as shown on equation (2).

$$\text{SPR} = \frac{P_{cool}}{P_{load}} \quad [-] \qquad (2)$$

Where:

P_{cool}	*solar chiller power[kW]*
P_{load}	*highest cooling peak load(248.1 kW) [kW]*

2.4.2. *Overall seasonal energy efficiency ratio*

For comparison of all simulated scenarios the overall seasonal energy efficiency ratio ($SEER_O$) was determined according to equation (3). DHW consumption and pool heating profiles are taken into consideration in the calculation of the $SEER_O$. This calculation includes consumption of gas by the gas boilers.

$$SEER_O = \frac{Q_{cooling} + Q_{DHW} + Q_{pool}}{Q_{electricity} + Q_{gas1} + Q_{gas2}} \quad [-] \qquad (3)$$

Where:

$Q_{cooling}$	*produced cold[kWh]*
Q_{DHW}	*produced heat for DHW [kWh]*
Q_{pool}	*produced heat for pool heating [kWh]*
$Q_{electricity}$	*consumption of electricity [kWh]*
Q_{gas1}	*consumption of gas for the production of DHW [kWh]*
Q_{gas2}	*consumption of gas for the production of pool heating [kWh]*

According to equation (3), the $SEER_O$ considered as reference, (with no solar mixing), systems are listed in Table 5.

Table 5. $SEER_O$ for all reference systems

	Costal type hotel	City type hotel
$SEER_O$ without pool [-]	1.29	1.18
$SEER_O$ with 200 m^3 pool [-]	1.12	1.08
$SEER_O$ with 400 m^3 pool [-]	1.09	1.06

2.4.3. Solar seasonal energy efficiency ratio

If we consider the energy balance for the boundary of the solar assisted cooling system (comprising all produced forms of energy that appear in both cooling production and heat rejection), we may also introduce the solar seasonal energy efficiency ratio ($SEER_S$) as per the equation (4). This ratio includes, apart cooling production, production of heat for DHW and pool heating by cooling system while it does not include heat production of gas boilers and consumption of gas, therefore it is a better indicator of the cooling system use.

$$SEER_S = \frac{Q_{cooling} + Q_{DHW,s} + Q_{pool,s}}{Q_{electricity}} \, [-] \qquad (4)$$

Where:

$Q_{cooling}$	*produced cold [kWh]*
$Q_{DHW,s}$	*produced heat from solar field and absorption chiller for DHW [kWh]*
$Q_{pool,s}$	*produced heat from absorption chiller for pool heating [kWh]*
$Q_{electricity}$	*consumption of electricity [kWh]*

2.5. Weather data

The climatic data for typical meteorological year in Rhodos by Meteonorm were used in simulations. The global solar irradiation is high and stable throughout a year (Figure 6) and it makes Rhodos suitable place for solar cooling.

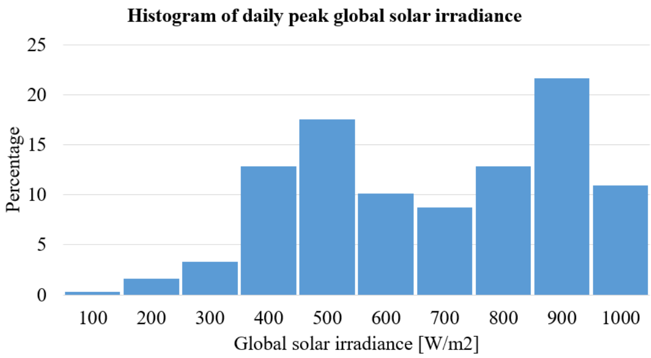

Fig. 6. Daily peak solar irradiation of Rhodos

3. Simulation results

3.1. Cooling and heating demands

Space cooling and space heating energy demands were simulated in TRNBuild software and they took into account building parameters described in chapter 2.1 and weather data presented in chapter2.5. Monthly heating and cooling energy demand is shown on Figure 7.

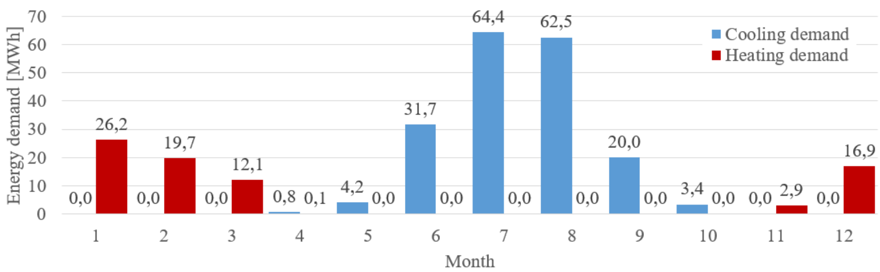

Fig. 7. Monthly cooling and heating energy demand

Figure 8 shows annual load duration curve for cooling of the building. The maximum cooling load is 248.1 kW and the building needs to be cooled for 1800 hours per year. Maximum power is needed only few hours in summer. Solar cooling system, in partial load, covers basically the lowest part of the graph and for the peak loads, conventional compressor chillers must be connected.

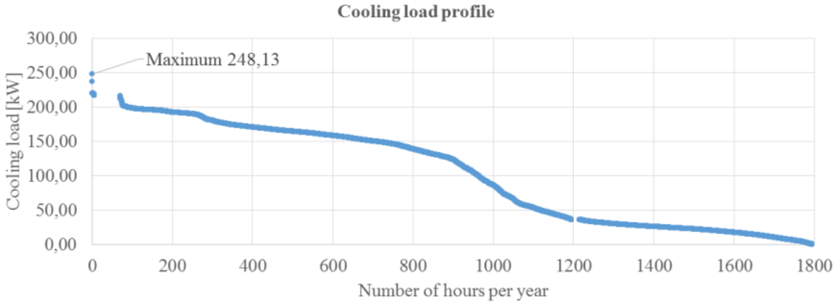

Fig. 8. Annual duration curve for cooling

Heating load for DHW and pool is shown on Figure 9. Differences between DHW consumption of costal and city type hotels are visible from this graph. The city type hotel can benefit from collectors heat production even in winter and potential energy saving can grow higher.

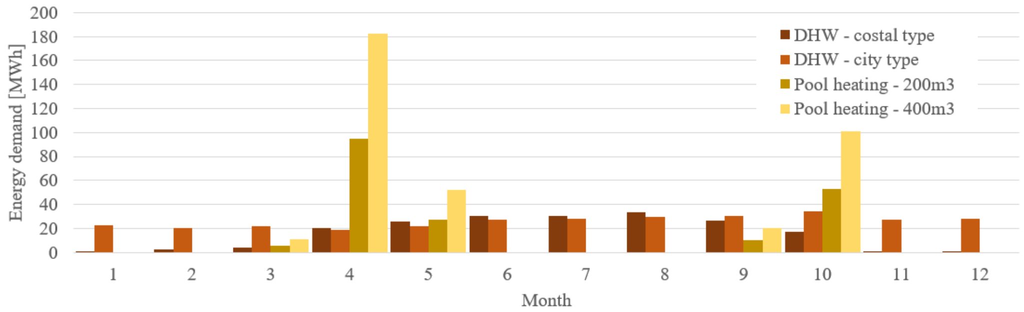

Fig. 9.Monthly DHW and pool heating demand

Average day for cooling and DHW heating is shown on Figure 10. Only days with cooling/heating were taken into account for calculation of average day. Annual cooling demand, DHW and pool heating demand carried out by simulations are shown in Table 6.

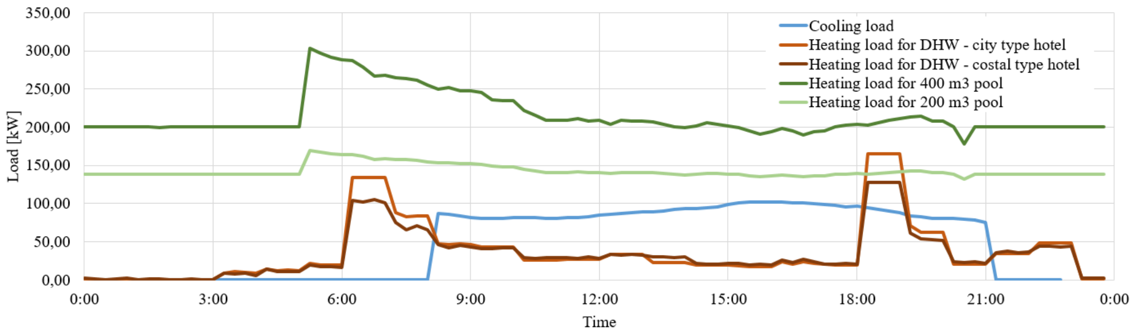

Fig. 10. Loads for the average day for cooling, DHW and pool heating

Table 6. Annual cooling demand, DHW and pool heating demand

Energy demand	Costal type hotel	City type hotel
Cooling demand $Q_{cooling}$ [MWh]	186.9	186.9
Heating demand for DHW Q_{DHW} [MWh]	191.4	310.8

Heating demand for 200 m3 pool heating Q_{pool1} [MWh]	230.3	230.3
Heating demand for 400 m3 pool heating Q_{pool2} [MWh]	344.9	344.9

3.2. Calculated primary energy consumption

All simulated systems were covering demands shown in Table 6. Primary energy was calculated by multiplying energy consumptions by primary energy conversion factors by [6]. The conversion factor in Greece is 1.05 for natural gas and 2.90 for electricity. Conversion factor for thermal collector heat production is 0. Figure 11 shows primary energy consumptions for six simulated scenarios. Increasing solar penetration ratio causes in all scenarios decreasing of primary energy consumption for cooling and also for DHW and pool heating.

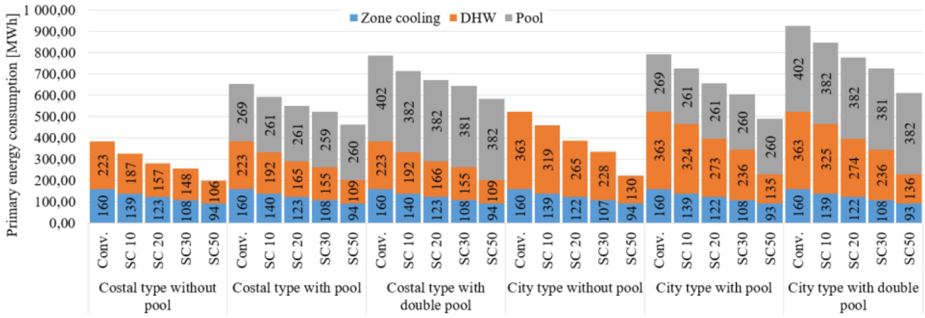

Fig. 11. Calculated energy consumptions

3.3. System efficiency

DHW consumption and pool heating profiles plays major role in energy efficiency ratio calculationbecause solar absorption cooling provides large amount of rejected thermal energy which can be used for preheating. However, it was necessary to optimize size of storage tank for preheated water for a better utilization of heat when the DHW consumption profile dismatch cold production or thermal collector heat production.

$SEER_S$ and $SEER_O$ for all simulated scenarios are shown respectively on Figure 12 and Figure 13. Better utilization of heat from solar cooling system is observed in city type hotel even when $SEER_O$ of costal type hotel is higher (for lower solar penetration ratio). This effect is due to the higher DHW consumption in city type hotel. Heat was basically produced by gas boilers with efficiency 0.9, so higher heat production by gas boilers causes that $SEER_O$ was getting closer to this value. On the other hand, with higher solar penetration ratio the gas boilers produced much less heat and $SEER_O$ of the city type hotel was growing faster.

Similar effect was observed in hotels with pool heating. High production of heat decreases $SEER_O$, however, increasing solar penetration ratio didn't help to pool heating like it did to DHW production because pool heating demand was not consistent in the year as this is visible from Figure 9. Consequently, the solar cooling system wasn't able to produce such high amount of heat in the short period and it had to be delivered from gas boilers.

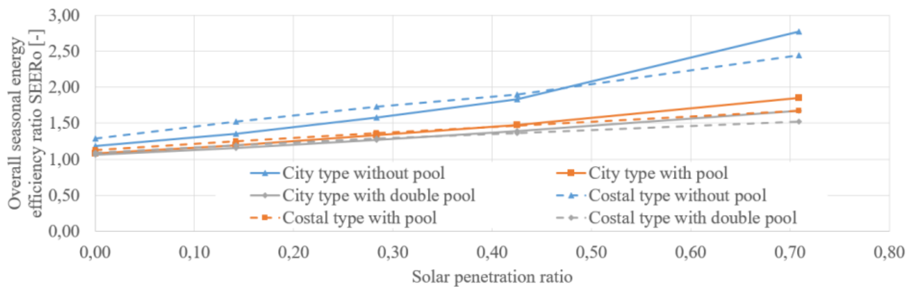

Fig. 12. Overall seasonal energy efficiency ratio ($SEER_O$) for simulated scenarios

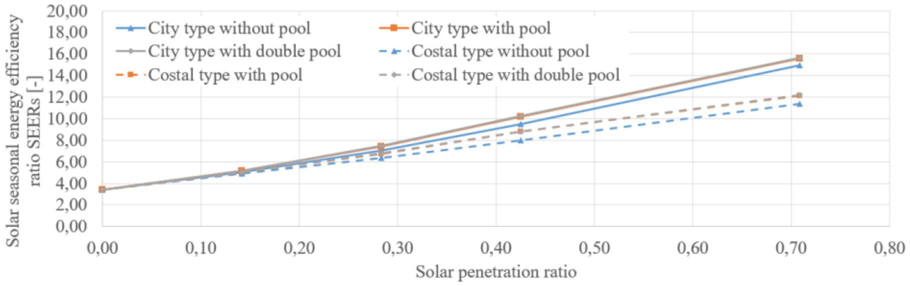

Fig. 13. Solarseasonal energy efficiency ratio ($SEER_S$) for simulated scenarios

For a solar penetration ratio 28 %, solar seasonal $SEER_S$ values reach 7.45 for city type hotel with pool and 6.75 for coastal type hotel with pool. For a city type hotel without pool it is equal to 7.07.

Highest $SEER_O$ was reached in the city type hotel without pool with penetration ratio 71 % and it is equal to 2.77, while conventional systems show an $SEER_O$ equal to 1.18, therefore we proved a 134 % increase in overall energy efficiency.

3.4. Primary energy savings

Primary energy savings compared to reference system are shown on Figure 14. Highest growth of savings is observed for penetration ratio up to 28 %, additional increase of penetration ratio brings smaller energy gain from the solar cooling system, and therefore economical aspect of the whole installation has to be assessed to set right balance between investment costs and operational coast (savings).

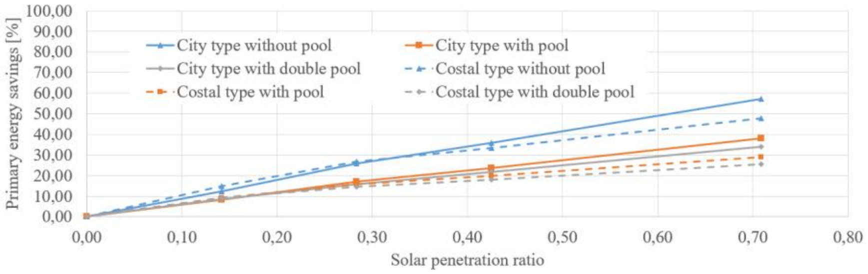

Fig. 14. Primary energy savings compared to the reference system

The most significant primary energy savings (57 %) were achieved in city type hotel without pool for solar penetration ratio 71 % because DHW heating load is consistent in year and heat from thermal collectors can be used for DHW preheating in winter.Even though the percentage savings in lower solar penetration ratios are larger for costal type hotel, absolute savings in kWh are higher for city type hotel, because energy demand for DHW heating is approximately twice higher.

4. Conclusions

Four solar cooling systems in hotel building have been simulated for partial coverage of cooling load and assessed for primary energy consumption in contrast to a typical compression cooling system. Two different scenarios of DHW consumption and three different sizes of outdoor pool have been considered in the simulations. Rejected heat from sorption chiller and surplus heat from thermal collectors was used for DHW and pool heating.

Results of simulations show potential for energy savings in space cooling, DHW and pool heating.Annual primary energy savings for a solar penetration ratio 28 % reached 26.01 % for city type hotel without pool while absolute savings were 135.9 MWh. Solar cooling system performance indicator, $SEER_S$, for this case was 7.07 which is more than twice higher than conventional cooling system.

DHW consumption profile plays major role in the final system efficiency. Constant DHW consumption in the year can benefit from thermal collectors winter heat production like we observed in the simulations of city type hotel. Therefore, utilization of rejected heat should be part of solar cooling system design and buildings with consistent heat demand, such as hotels, are suitable for installation of solar cooling system.

Acknowledgements

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