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Simulations and techno-economic analysis of solar cooling system

Jacek Kalina[a*], Michał Rabiej[a*], Carlos Santos Silva[b]

[a]Silesian University of Technology, Faculty of Energy and Environmental Engineering, Konarskiego 18, 44-100 Gliwice, Poland
[b]Technical University of Lisbon, Mechanical Engineering Department, Alameda da Universidade, 1649-004 Lisboa, Portugal
*Corresponding author email: jacek.kalina@polsl.pl

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Abstract

In this paper, a solar absorption cooling system with a chilled water storage tank and peak load compression system was considered for cooling the Instituto Superior Tecnico Tower building in Lisbon, Portugal. To fulfill this task, a dynamic simulation of the building was performed using the DesignBuilder software, then a solar collector field was designed. The next step was to build a computational model of the absorption chiller in the Engineering Equation Solver software, which allowed for further simulation of the annual operation of the system supported by the chilled water tank and the backup system with compressed air conditioning. The last stage of the work was the economic analysis of such a system in comparison with conventional compressed air conditioning. The simulation results and economic analysis showed that the solar absorption cooling system could be a beneficial cooling solution for the Instituto Superior Tecnico Tower building. However, it would have to operate with an energy storage system and a peak load compression backup system to be able to cool the building efficiently all year round. Additionally, such a solution could have a significant positive impact on climate through considerable annual savings in electricity consumption. Results revealed that the proposed system meets the cooling demand of the building, mainly by solar-energy-driven absorption chiller. The annual contribution of a backup compression chiller ranges from 20% to 36% depending on the size of chilled water storage tanks. Financial calculations revealed discounted payback periods in the range of 4.5 to 12.5 years depending on the system configuration.

Keywords: Solar cooling; Building simulation; Absorption chillers, Solar thermal collectors; Thermal energy storage

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1. Introduction

In times of climate crisis, depletion of fossil energy sources, and global energy transition, in all branches of the global energy system solutions are sought for the reduction of fuel consumption and environmental impacts. The cooling sector is one of the sectors where the integration of renewable energy sources has been constantly increasing over the past several years [1]. Conventional and widely used grid-connected compression cooling systems can be replaced with heat-driven systems using absorption or adsorption chillers, PV-driven compression or thermoelectric technologies, and several other solutions [2]. Considering technology maturity and financial aspects of projects, in practice, absorption technology is usually taken into account as a feasible

Nomenclature

A – total aperture area, m^2
a_1 – first- order loss coefficient
a_2 – second-order loss coefficient
COP – coefficient of performance
G – solar irradiance, W/m^2
h – specific enthalpy, kJ/(kg K)
$\dot{m}$ – mass flow, kg/s
p – pressure, Pa
P – power, kW
$\dot{Q}$ – heat flux, kW
$\dot{Q}_{E,nom}$ – nominal cooling capacity, kW
$\dot{Q}_{G,nom}$ – nominal driving heat flux, kW
x – mass fraction, kg/kg

Greek symbols

η_0 – zero loss efficiency
ΔT_{sol} – temperature difference, K
υ – specific volume, m^3/kg

Subscripts and Superscripts

1, 2, … , 18 – specific points in the plant scheme
ch – cooling
C – condenser
E – evaporator
G – generator
nom – nominal
max – maximum
w – water

Abbreviations and Acronyms

COP – Coefficient of Performance
EES – Engineering Equation Solver
IST – Instituto Superior Tecnico
NPV – Net Present Value
PV – Photovoltaic
SPB – Simple Payback

solution. Although the coefficient of performance (COP) of the absorption cooling devices (typically in the range of 0.7 to 1.2) is significantly lower than in the case of conventional vapour compression chillers (typically above 3.0), the key advantage of absorption technology is much lower electricity consumption and peak power demand. As electric grids become affected more strongly by cooling systems due to hotter weather conditions [1], solar cooling projects can also generate positive external systemic effects. Additionally, as sorption chillers use natural refrigerants only, they can effectively support the fluorinated gases (F-gas) phase-out [1].

The single-effect LiBr absorption chillers require hot fluid at a temperature higher than 70−80ºC, which can be achieved by solar collectors. At this temperature level, commercially available technology solutions can achieve a COP of around 0.7. Higher values of the COP can be reached at higher inlet temperatures of the heat carrier, depending on the configuration of the absorption chiller system. The noticeable disadvantage is however relatively large size of the cooling unit. Although sorption cooling can be implemented starting from 100 kW of cooling capacity [1], typical applications are considerably bigger. Typical places of implementation are skyscrapers, large office buildings, shopping centers, industrial facilities, hospitals, etc. Examples are [3]: Surgery Hospital for children in Soba (Sudan) where a 2 × 615 kW absorption chiller and 12 000 m^2 solar field were installed, the United World College in Singapore with 1 470 kW of cooling capacity absorption system and the 3 900 m^2 field of solar collectors, the METRO Cash Carry in Rome (Italy) with absorption chillers of 700 kW of cooling capacity, or the office building of the bank Caixa Geral de Depositos in Lisbon (Portugal), which is cooled by an absorption system of 585 kW cooling capacity driven by hot water from the 1 592 m^2 rooftop system of 158 solar collectors of 845 kW heating capacity.

Although the technologies and implementation examples are already known, solar cooling is still a relatively rare solution. This is mainly due to the low level of dissemination, and lack of relevant information regarding the long-term effects and bankability of projects. According to Delmastro et al. [1], the number of newly installed solar-driven systems can be estimated for 1 800 small units in 2018. Nowadays broad measures are required for affordable, safe, and reliable cooling systems for the sunbelt regions worldwide, including the development of innovations, adaptation of components and systems, demonstration, assessment tools, and dissemination [4]. According to the definition of the research topic "Solar Cooling Technologies: Challenges, Applications, and improvements" of the Frontiers Open Access Publisher and Open Science Platform [5] it is necessary to recognize the main advantages, challenges, disadvantages, and feasibility of different solar cooling technologies, and the area of interest, among other issues, includes simulation, modelling and techno-economic analysis of solar cooling systems.

Regarding research activities in the field of solar cooling different projects and studies have been reported in the published literature. For example, Assilzadeh et al. [6] proposed a solar cooling system with evacuated tube solar collectors and LiBr absorption unit for a building in Malaysia. The system was optimally sized using the TRNSYS software and the typical meteorological year weather data. The optimal key system design parameters were: 3.5 kW (1 refrigeration ton) chiller, 35 m^2 evacuated tubes solar collector sloped at 20º and 0.8 m^3 hot water storage tank. The results revealed that life cycle savings generated by the system against conventional air conditioning were negative, which was due to the high cost of the solar collectors and the low price of electricity.

Narayanan [7] presented a simulation-based study on absorption solar cooling systems and their application in commercial/office buildings in India. A typical Indian commercial building of 1 156 m^2 floor area and 289 m^2 roof area was simulated using TRNSYS software in order to examine feasibility and operational strategy of the cooling system. The results revealed that the proposed solar absorption cooling system in comparison to a traditional air conditioner unit will achieve full payback time after 15.5 years. According to the author, this period may vary depending on climate and the cooling demand.

However, the author drew attention to the high initial installation costs, which for the system with 105 kW cooling capacity chiller, 20 m^3 heat storage tank, and 42 evacuated tube collectors of 220 m^2 total area was estimated at 81 650 USD.

Similarly, Praene et al. [8] considered the possibility of implementing a single-stage solar absorption system for classroom cooling in Reunion Island, where the yearly average solar radiation and is 5.4 kWh/m²/day. The system simulation and optimization were performed using TRNSYS to determine the optimum solar energy collector area, storage tank volume and absorption chiller nominal capacity of 60 m^2, 0.8 m^3 and 33 kW, respectively. The author did not provide information on system economics.

Iranmanesh et al. [9] presented results of the optimization of a solar cooling system with a 350 kW (100 t of cooling capacity) double-effect LiBr–H_2O absorption chiller using a combined EES - MATLAB software environment. It was infeasible to operate a solar double-effect absorption chiller without any auxiliary energy source to provide the required energy for the chiller at most hours during the day. Therefore, two objective functions were defined, namely the amount of auxiliary energy consumed and net profit. The input parameters taken into account in the sensitivity analysis are the volume of the storage tank, the area of the evacuated tube collector, and mass flow rates of water passing through the collector and generator. The results revealed very positive financial performance with the investment return period from 1.79 to 2.75 years.

Pinamonti et al. [10] investigated different configurations of solar-assisted heat pump systems in combination with energy storage for a typical single residential dwelling in Italy of 140 m^2 heated floor area and a ratio of heat dispersion area over conditioned volume (S/V) of 0.59. The study was focused on factors influencing energy demand of the system, self-consumption of solar energy, and installation cost. Several configurations of the system were simulated using the TRNSYS software. The proposed solution was compared to a standard air-source heat pump. The results revealed that for a highly insulated building, a maximum reduction of energy consumption at the level of -30% could be achieved in the case of photovoltaic (PV) panels and battery storage. On the other hand, in the case of solar thermal (ST) panels the achievable energy savings are lower (−24%), however, financial benefits are more advantageous over a 20-year period. The solution based on ST panels appeared to be the most profitable solution also for a low-insulated building. The results also revealed that the role of energy storage is essential.

Altun et al. [11] investigated the parameters of a 10 kW solar-powered absorption cooling system using dynamic modelling under the weather conditions of Mugla, Trabzon, Izmir, Konya, Canakkale and Istanbul using the TRNSYS software. In most of the studied cases, the results of the financial analysis revealed the payback periods between 10.7 and 15.0 years.

Drosou et al. [12] proposed the implementation of an integrated solar cooling system using parabolic trough solar collectors and a double-effect chiller is discussed, used to cover the cooling needs of a typical office building in Greece. The results of the study revealed that concentrating solar collectors give significantly higher output temperatures that can enable the use of two-stage absorption chillers with a higher COP. Unfortunately, although the costs of major system components were assessed, the level of project profitability was not determined.

Eicker et al. [13] presented the results of a systematic solar cooling system design study covering most climatic regions worldwide and different cooling technologies. According to the study, single-effect absorption cooling systems easily reach 80% solar cooling fraction for all but very humid climates, and primary energy savings between 30 and 79%, depending on system design and cooling load data. The economic analysis revealed that solar thermal cooling and heating are more viable in hot climates than in moderate European climates, and in order to obtain reasonable payback periods in the range of 10 years significant investment cost reductions are required.

Casals [14] performed a detailed TRNSYS dynamic simulation of some of the first commercial solar heating and cooling installations implemented in Spain. He claims that due to the low fraction of profitable thermal storage capacity in the cooling season, very high storage volumes would be required to significantly decouple the solar field and the absorption chiller. He also concluded that limited effective storage capacity should be compensated as far as possible with appropriate design choices (solar multiple and solar field mass flow), and implementing high inertia air conditioning distribution systems like radiant floors or walls which regularize the cooling load imposed on the solar absorption system.

Ge et al. [15] presented a literature review summarizing the current situation of solar heating and cooling and discussed new achievements in related areas and potential future market penetration. According to the authors, the investment payback period is widely adopted to evaluate economic performance. Results reveal that solar cooling systems can be economically attractive with payback periods varying from 3 to 15 years.

Palomba et al. [16] developed. an advanced hybrid solar cooling system, which consists of a thermal and an electric unit in parallel integrated into a single unit with the dry cooler. They also presented the results of sizing for the same building in three different climates (Athens, Berlin and Ryiad). The configuration of the solar cooling system included a solar field of 40 m^2 in combination with a 1 000-litre hot water tank corresponding to a specific storage ratio of 25 l/m^2. The authors claimed that larger storage volumes do not affect the performance of solar cooling systems significantly. The results revealed annual energy savings in the range from 35% in Riyadh to 89% in Berlin, which well justified replacing traditional cooling systems with solar-powered ones.

The aim of this study is to assess whether an absorption cooling system with solar collectors as a heat source would be an advantageous solution for a university building compared to a typical vapour compression cycle air conditioning system. To examine this, the annual simulations of both the solar absorption cooling system and the vapour compression cooling system were carried out for the Instituto Superior Tecnico (IST) Tower in Lisbon using the DesignBuilder software [17]. In the first step, the dynamic model of the building was created, which resulted in cooling demand data on hourly basis. In the next step, a field of solar thermal collectors was simulated to determine possible heat output profile. Then a calculation model was prepared which firstly calculated the design parameters of the absorption chiller and later simulated the annual performance of the system. Within the model the chiller correction curves and solar field data of commercially available equipment were used. Subsequently, the energy storage system was modelled and sized for the installation. In the case of the solar cooling system, a backup vapour compression chiller was taken into consideration, which allowed the system to operate in the absence of solar energy or insufficient cooling capacity produced by the absorption chiller. Dimensions and costs of the whole installation were assessed for 2020 energy prices. Finally, the two alternative solutions of the building cooling system were compared using economic indicators, such as net present value (NPV), net present value ratio (NPVR), internal rate of return (IRR), discounted payback period (DPB), and simple payback (SPB), which presented economic justification for the project.

1. The IST Tower building simulation

The IST Tower building is located in Lisbon, Portugal (38º44´N, 9º08´W). This is a 10-story high-rise building of 50 m height. Its facade material is glass. The building is not equipped with external blinds. inside It entered into exploitation in 1994 as a university building. The building is depicted in Fig. 1.

Fig. 1. IST Tower building (Source: Google Earth: https://earth.google.com/web/).

To determine energy demand profiles, the building was modelled using the DesignBuilder software [17]. The software allows creation of complex building models in a user-friendly and intuitive manner. It uses EnergyPlus™ [18] whole building dynamic energy simulation program as calculation engine software and simulates building thermal conditions over a long time. In this work, the annual simulation of the IST Tower building performance was carried out. The building model is depicted in Fig. 2.

The occupied floor area of the designed building was equal to 7 994.5 m^2 and the occupied volume 100 768.5 m^3. Lightweight concrete clad wall was selected as an external walls material. The interior of the building was divided with walls in order to take into account its thermal inertia. Occupancy density was set to 0.111 people/m^2, fresh air flow was 10 dm^3/s per person, and the power density of office equipment was set to 11.77 W/m^2. Light office work was used as the occupation scenario of the building. The cooling setpoint temperature was 24°C and the cooling set back temperature was set to 28°C.

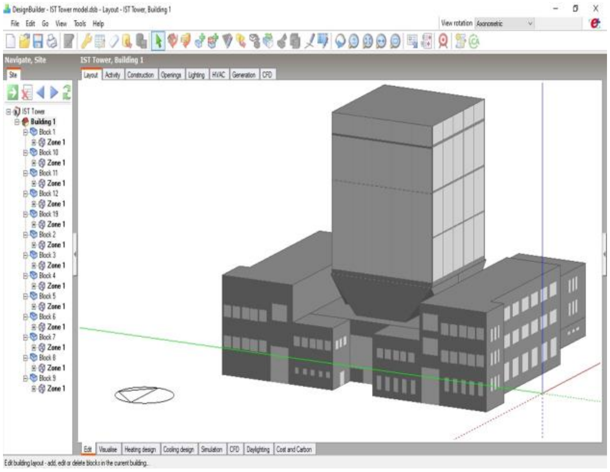

Fig. 2. IST Tower building model in the DesignBuilder.

The weather data for Lisbon in hourly resolution was obtained from a publicly available weather data repository for the typical meteorological year (TMY), which was imported by the weather data import tool of the DesignBuilder software. Figures 3 and 4 depict the annual variability of the ambient temperature and solar irradiation for the site. The analysis of data revealed that the annual values of temperature and solar irradiation are very high and promising for the use of solar technologies to generate energy. The average annual ambient temperature was equal to 16.32°C, while the maximum was 36°C and the temperature did not fall below 4.1°C. As far as irradiation is concerned, the annual average was 397 Wh/m^2 (excluding fully cloudy conditions and nights) or 196.01 Wh/m^2 (taking into account every hour of the year).

As a result of the simulation, the necessary hourly data was obtained for cooling demand and heating demand of the building. The DesignBuilder software also enabled calculation of the demand for electric power for needs for heating system, conventional air conditioning system (vapour compression), and domestic hot water. The annual profile of the cooling demand is depicted in Fig. 5. Figure 6 depicts the annual cooling demand duration curve revealing relatively sort annual time of cooling system operation (in the range of 2500 hours per year).

During the hottest hours cooling demand did not fall below 800 kW and the peak values exceeded 1 550 kW. It was also found that the demand for cooling also occurs during colder months. In January and December, the temperature dropped down to 4°C but sometimes values as high as 17°C registered, and the cooling demand reached at some hours 250 kW. An important factor for the operation of the air conditioning system was that all the spring months (especially May) and early autumn months (especially September) there may occur very high temperatures (up to even 32°C), and at the same time high demands for cooling.

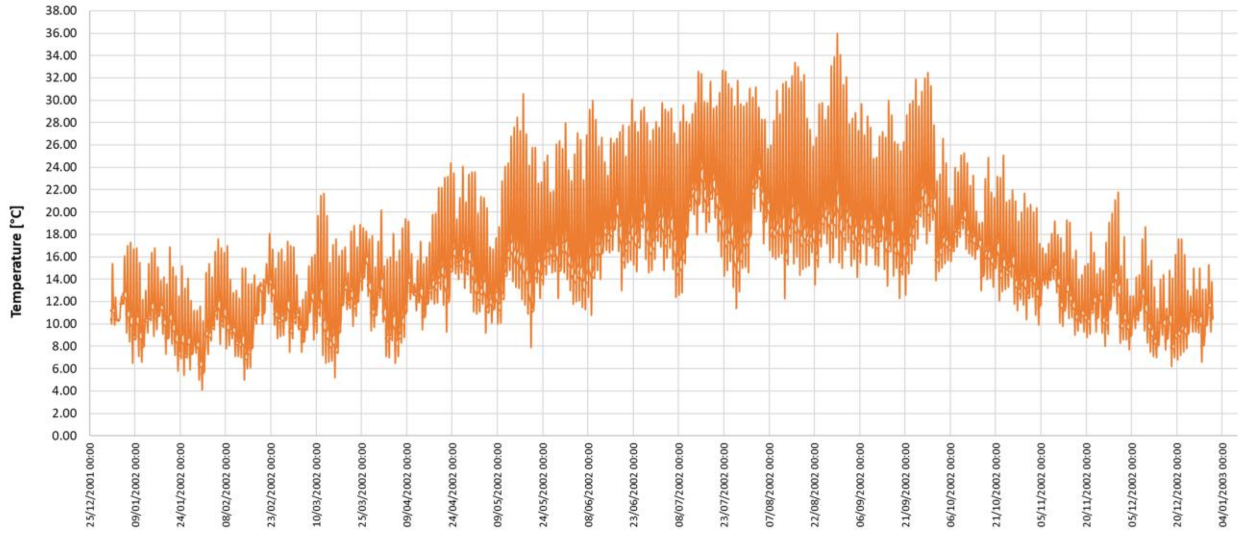

Fig. 3. Annual dry bulb temperature variations in Lisbon.

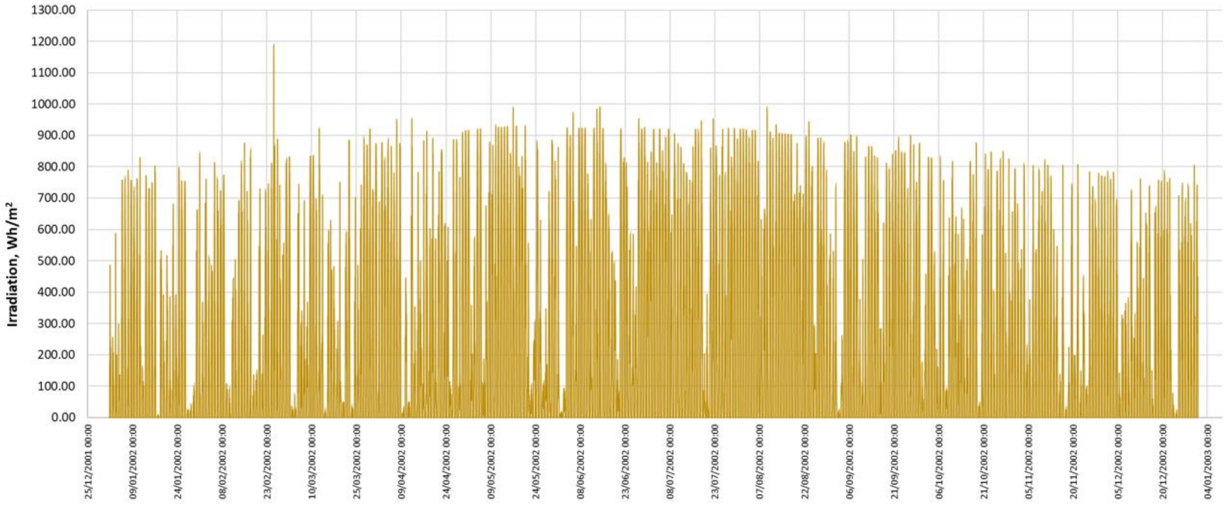

Fig. 4. Annual variations of solar irradiation in Lisbon.

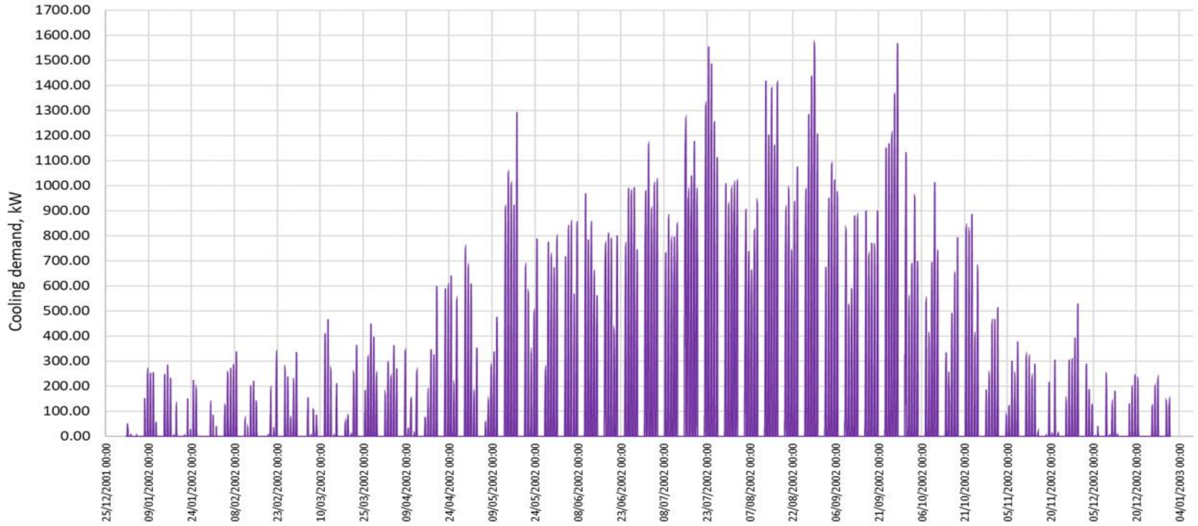

Fig. 5. Annual cooling demand profile.

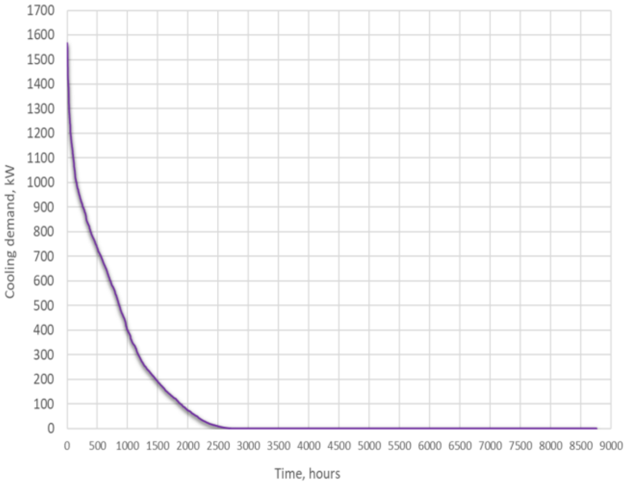

Fig. 6. Cooling demand duration curve.

2. Design and characteristics of solar collectors and solar field

It was assumed that the driving heat for the absorption chiller would be generated by solar collectors. The solar field was designed on the roofs of the IST buildings. The obtained value of the available space for the solar collectors' field was 3 056.8 m^2. For the calculation of the total aperture area, the land use coefficient was assumed to be 2.5. Arcon-Sunmark A/S HT- SolarBoost 35/10 collectors [19] were adopted as the solar collectors for the entire installation. Technical specification of the collector is given in Table 1.

The available roof area allowed for the placement of 225 solar collectors, which gave 3 053.25 m^2 of collector aperture area. The peak power of such a field at solar irradiance G = 1 000 W/m^2 would be around 2 366.8 kW. The heating power of the solar collector was calculated using the formula:

$$\dot{Q} = A \cdot (\eta_0 G - a_1 \Delta T_{\text{sol}} - a_2 \, \Delta T_{\text{sol}}^2), \qquad (1)$$

where: A – total aperture area, η_0 – zero loss efficiency, G – solar irradiance, a_1 – first- order loss coefficient; a_2 – second-order loss coefficient; ΔT_{sol} – temperature difference between the average temperature of the solar fluid and ambient temperature.

Table 1. Parameters of Arcon-Sunmark A/S HT-SolarBoost 35/10 solar collector.

Parameter, unit	**Value**
Gross area, m^2	13.57
Gross length, m	26
Gross width, m	26
Gross height, m	0.24
Zero-loss efficiency (η_0)	0.773
First order loss coefficient (a_1), $W/(m^2K)$	2.27
Second order loss coefficient (a_2), $W/(m^2K^2)$	0.018
Peak power (at G = 1000 W/m^2), kW.	10.519

Solar collector field simulation was performed in MS Excel to determine the heat flux that can be transferred to the absorption chiller generator. The collector water inlet/outlet temperature was assumed 80/90°C taking into consideration the requirements of the absorption chiller. Results are depicted in Fig. 7. The maximum value of the collector field throughout the year was 2 080.15 kW. The annual average of obtained heat was equal to 240.68 kW (770.87 kW – excluding hours during the night and periods without any thermal energy obtained from solar collectors).

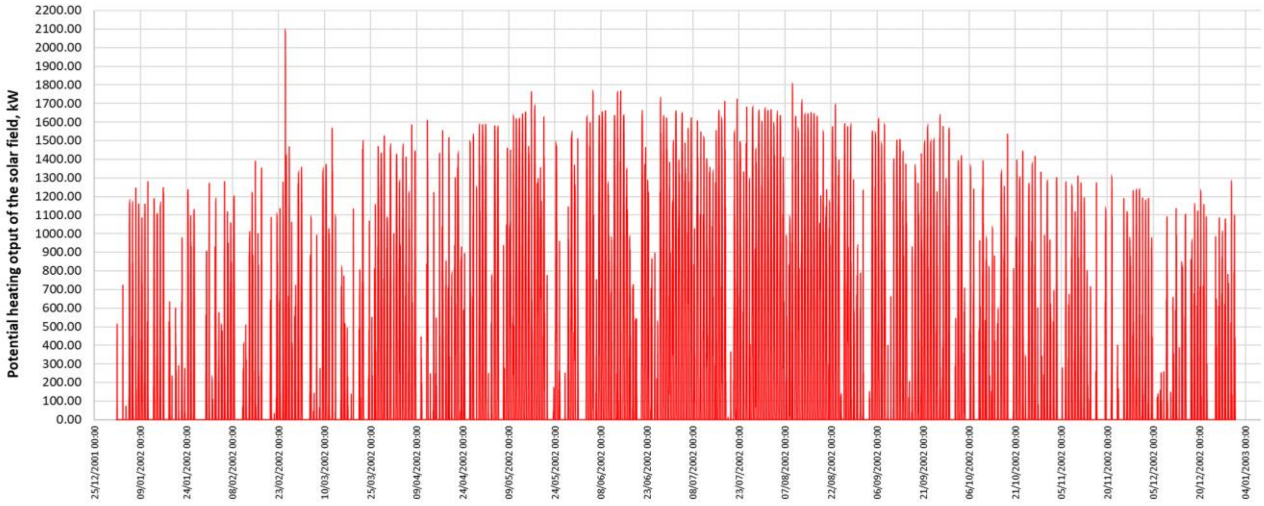

Fig. 7. Results of solar collector field simulation – hourly.

3. Sizing of solar absorption cooling system

The proposed cooling system is depicted in Fig. 8. The main part of the installation is the absorption chiller. A hot water-driven lithium bromide/water (LiBr/ H_2O) system was assumed as a typical solution for air conditioning applications [20]. The chiller is interconnected with the field of solar collectors, a chilled water cycle with cold storage reservoir and cooling water cycle. For cooling the absorber and condenser of the chiller, a wet cooling tower is taken into consideration. The cooling water temperature for Portugal was set to 31°C [21]. The constant chilled water inlet/outlet temperature of 12.2°C/6.7°C was assumed according to technical specifications [22]. To provide cooling during unfavourable weather conditions and exceptionally high cooling demand, chilled water storage was designed. The reservoir sizing was performed taking into account cooling demand as well as the financial profitability of the project.

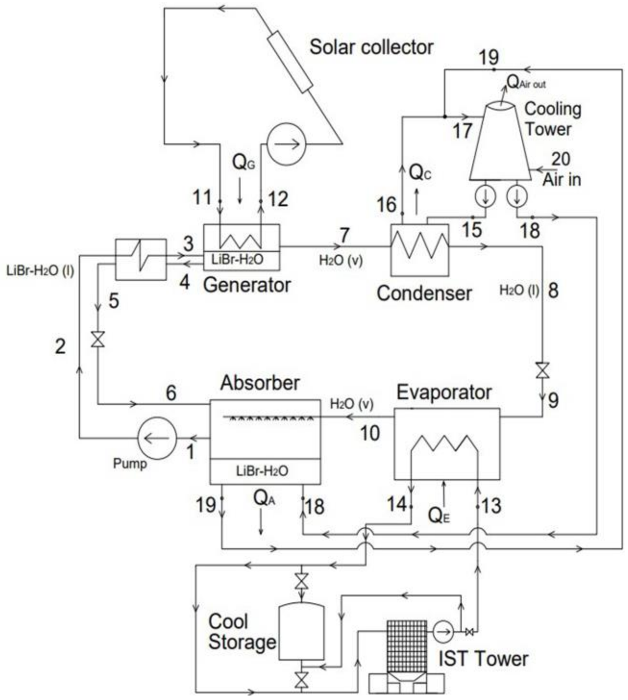

Fig. 8. Technological scheme of solar absorption cooling system with cold storage.

The absorption chiller was modelled using Engineering Equation Solver (EES) software and its built-in LiBr/H_2O thermodynamic properties library. Energy balance for the absorber is:

$$\dot{Q}_A = \dot{m}_{10}h_{10} + \dot{m}_6h_6 - \dot{m}_1h_1. \tag{2}$$

The heat of absorption is removed by cooling water, what gives:

$$\dot{Q}_A = \dot{m}_{19}h_{19} - \dot{m}_{18}h_{18}. \tag{3}$$

The energy balance of generator:

$$\dot{Q}_G = \dot{m}_4h_4 + \dot{m}_7h_7 - \dot{m}_3h_3. \tag{4}$$

In the condenser where the H_2O vapour from generator is cooled down and subjected to the condensation process, energy balance was as follows:

$$\dot{Q}_C = \dot{m}_7h_7 - \dot{m}_8h_8. \tag{5}$$

And from the side of cooling water it is:

$$\dot{Q}_C = \dot{m}_{16}h_{16} - \dot{m}_{15}h_{15}. \tag{6}$$

Energy balance of the evaporator, where cooling effect occurs is:

$$\dot{Q}_E = \dot{m}_{10}h_{10} - \dot{m}_9h_9. \tag{7}$$

Energy balance of the regenerative heat exchanger is:

$$\dot{m}_4h_4 - \dot{m}_5h_5 = \dot{m}_3h_3 - \dot{m}_2h_2. \tag{8}$$

The mass flow of chilled water was calculated from energy balance:

$$\dot{m}_{w,ch} = \frac{\dot{Q}_E}{h_{13}-h_{14}}. \tag{9}$$

The required mass of water from the solar collectors to the generator was calculated as:

$$\dot{m}_{w,G} = \frac{\dot{Q}_G}{h_{11}-h_{12}}. \tag{10}$$

The thermodynamic model also takes into account the operation of the pump in the absorption chiller:

$$P_{\text{pump}} = \dot{m}_1v_1(p_2 - p_1). \tag{11}$$

Moreover, considering steady state energy for expansion and refrigerant valves and mass conservation equations, the following enthalpies relations are:

$$h_5 = h_6, \tag{12}$$

$$h_9 = h_8. \tag{13}$$

LiBr concentration balance for generator is:

$$\dot{m}_3x_3 = \dot{m}_4x_4. \tag{14}$$

Concentration in other points of the system is:

$$x_2 = x_1, \tag{15}$$

$$x_3 = x_1, \tag{16}$$

$$x_5 = x_4\ , \tag{17}$$

$$x_6 = x_4, \tag{18}$$

$$x_8 = x_7, \tag{19}$$

$$x_9 = x_7, \tag{20}$$

$$x_{10} = x_9. \tag{21}$$

Additionally, the following parameters were assumed:

- temperature difference between the cooling water before/after condenser: 6 K,
- pinch temperature difference in the absorber, generator, condenser, and evaporator: 3 K.

The coefficient of performance is defined as:

$$COP = \frac{\dot{Q}_E}{\dot{Q}_G}. \tag{22}$$

From the thermodynamic point of view the definition of COP should also account for the pump work P_{pump}. However, the standard approach used by manufacturers is to present COP as the ratio of the cooling effect to the heat input, where the work used by the pump is neglected, the same as power used by electronics. This is mainly because relatively low electricity consumption. The EES model results for design parameters of the absorption chiller are presented in Table 2.

Table 2. Key design parameters of the absorption chiller.

Parameter	Symbol	Unit	Value
Nominal cooling capacity	$\dot{Q}_{E,nom}$	kW	622.5
Absorption heat flux	$\dot{Q}_A$	kW	826.1
Condensation heat flux	$\dot{Q}_C$	kW	660.0
Nominal driving heat flux	$\dot{Q}_{G,nom}$	kW	863.7
Pump work	P_{pump}	kW	0.02
Total heat inlet	$\dot{Q}_E+\dot{Q}_G$	kW	1 486.0
Total heat outlet	$\dot{Q}_C+\dot{Q}_A$	kW	1 486.0
Design coefficient of performance	*COP*	–	0.72

An important aspect of the system design is sizing the absorption chiller in relation to the heating output of the solar field. The number of working hours of the chiller results from availability of the driving heat flux and the demand for cooling. It can be observed in Fig. 7 that the maximum heating output of solar collectors occurs in a very short annual time as a peak value. The minimum thermal load of the absorption chiller was set to 55% of nominal heat input. It has to be emphasised that sizing of the absorption chiller was performed assuming that its nominal of heating power input (output from the solar field) is:

$$\dot{Q}_{G,nom} = 0.4\dot{Q}_{max}. \tag{23}$$

This assumption results in 1871 chiller working hours per year. The operation window of the absorption chiller is depicted in Fig. 9. The higher is the nominal capacity of the chiller, the shorter is its annual time of operation. The heat which is not used by the chiller is presented in the results of the study as the unused heat. Actually, the nominal cooling capacity of the chiller should by subject to optimisation, which is foreseen as a future work. The study also reveals the demand for heat management and storage of hot water from the solar field.

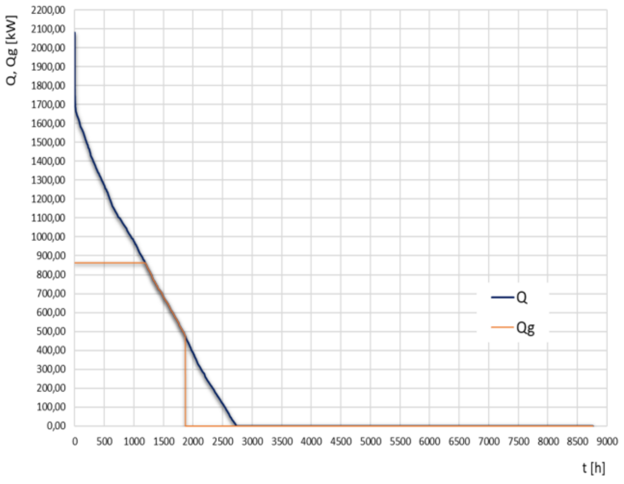

Fig. 9. Duration curves of heat output from the solar field and heat input to the absorption chiller.

In off-design calculations of the absorption chiller correction curves were used. Those were adopted from manufacturer data of the WFC-M100 Yazaki Energy absorption chiller [22]. The cooling capacity of the unit was then:

$$\dot{Q}_E = (0.0048 \cdot \dot{m}_{w,G} + 0.534)\dot{Q}_{E,nom}, \tag{24}$$

where $\dot{m}_{w,G}$ is the actual mas flow of hot water into the generator.

3. Simulation of integrated cooling system

Using design calculations, correction curve and solar collector field simulation, it was possible to perform an annual simulation of the absorption cooling system performance. The key parameters determining the efficiency as well as the legitimacy of using such an installation were the COP values and the generated cooling effect which should meet the building's demand. Sample daily COP values for the absorption system, which result from weather conditions are depicted in Fig. 10.

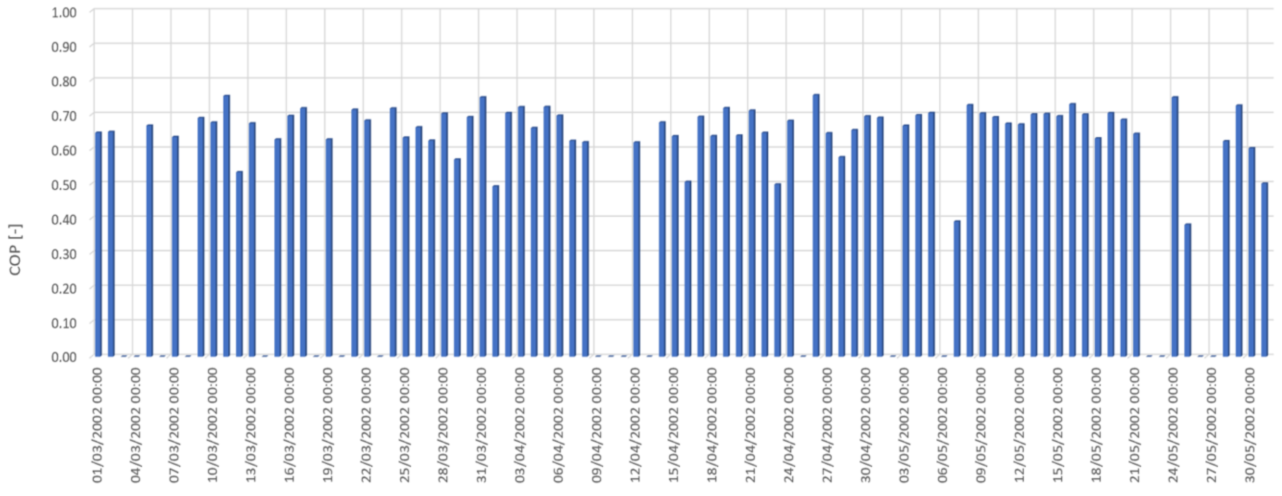

Fig. 10. Achievable values of COP in the spring period (March – May).

It was found that the absorption cooling system with solar collectors as a heat source was not able to provide cooling for the building every hour of the year. To solve this issue heat storage or cold storage system was necessary. In this work, the system with chilled water storage and additional compressor chiller as a backup unit was considered. Three different maximum energy storage tank capacities were considered: 2 500 kWh (392 m^3), 5000 kWh (784 m^3) and 12 500 kWh (1 958 m^3). It must be emphasised that the study does not present an optimization problem but only enables the identification of potential issues related to the operation of the proposed system. Therefore the proposed sizes are just trial values, which enable observation of the trends. The optimisation task has been left for the future work.

As for the principle of operation of the entire solar absorption cooling system with a chilled water storage and backup system of a compressor chiller, the cooling capacity required for the building was the main input to calculate the compressor energy balance. Priority was given to the system of the absorption chiller and chilled water tank, and the compressor chiller balanced the cooling capacity with the cooling capacity required by the building. Results of annual simulation for 5 000 kWh storage tank are depicted in Fig. 11. Summary of annual results for three different systems is given in Fig. 12.

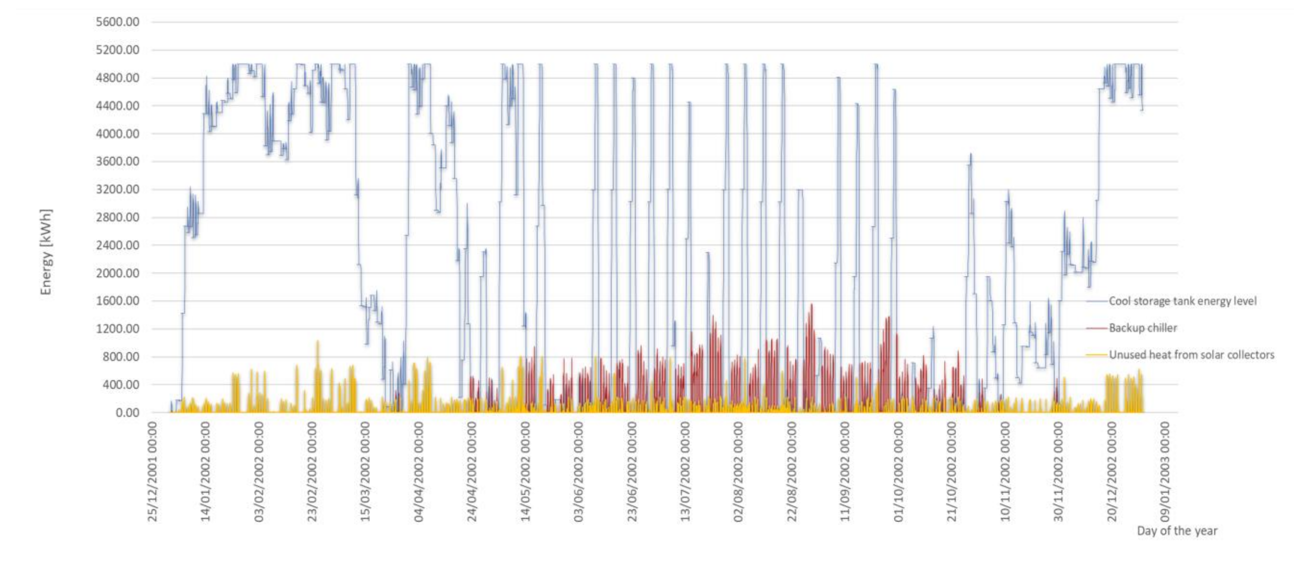

Fig. 11. Key simulation results for the system with 5 000 kWh cold storage.

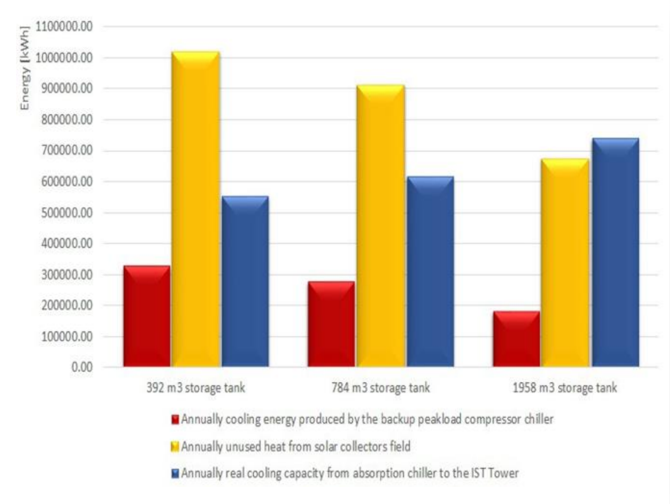

Fig. 12. Summary of key results of annual energy simulation.

In order to limit the unused solar energy throughout the year, a configuration with a smaller collector field (the number of solar collectors has been reduced to 112) and 784 m^3 storage tank was simulated and economic indicators were calculated. This configuration resulted in the reduction of the active field area of the solar collectors to 1 519.84 m^2. The cooling capacity of the absorption chiller was downsized from 622.5 kW to 331.9 kW.

The solution also takes into account the situation in which the conventional air conditioning system has been already installed, so it could be used as backup system, and its initial capital cost would be 0. The key to such a system was to calculate again design parameters of the absorption chiller, which had to be lower than originally assumed due to the operating range of the absorption chiller. Simulation results for this case are presented in Fig. 13.

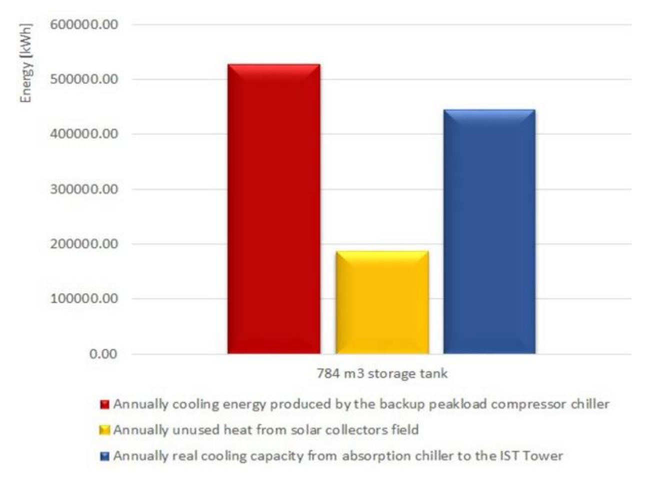

Fig. 13. Summary of key simulation results for downsized solar field.

4. Project profitability assessment

Undoubtedly, the initial capital costs of classic air conditioning system are lower than absorption cooling systems. However, savings in electricity consumption due to the new cooling system could be so significant that, with a long-term investment, the absorption solar cooling system can turn out to be a profitable investment, especially for a large-scale building, such as the IST tower. The economic analysis of the solar absorption cooling system was carried out with reference to the conventional vapour compression cycle air conditioning system. Thus, the annual cash flow was due to the lower operating costs of the system. The considered lifetime of the project was 20 years. The cost of electricity was assumed € 0.147/kWh. The capital costing model was adopted from [23]. The absorption cooling system cost was assessed to be € 159 982.50 and in the case of vapour compression refrigeration units it amounts to € 491 222.88. Additionally, for the absorption cooling system the costs of 784 m^3 chilled water reservoir (€ 98 000.00), cooling tower (€ 99 447.38), solar collectors installation (€ 405 000.00), piping, valves, controllers, pumps (€ 66 298.25) and evaporative condenser installation (€ 47 040.85) were added. Key results of the profitability assessment for the three initial cases are shown in Figs. 14 to 16.

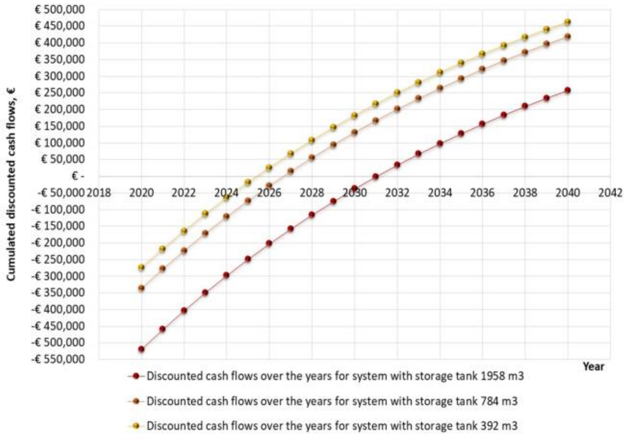

Fig. 14. Change of project discounted value over years.

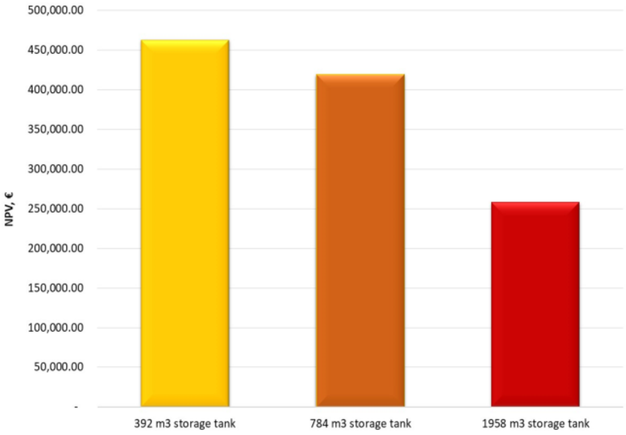

Fig. 15. NPV assessment results.

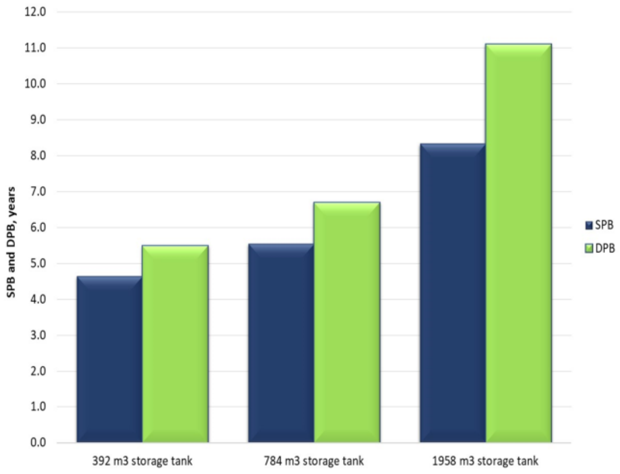

Fig. 16. Simple and discounted payback periods.

The discounted cash flow rate used in the analysis was 5%. In the case of the downsized system the NPV is € 189 770.04, SPB is 9,1 years and DPB is 12.5 years.

Another aspect of the project is that it would have a significant impact on greenhouse gas emissions into the atmosphere as the CO_2 per MWh of electricity indicator for Portugal is equal to approximately 248.57 kg of CO_2 per MWh of electrical energy [24].

4. Conclusions

In this detailed energy simulation and financial analysis were performed for the solar cooling system for the IST Tower in Lisbon, Portugal. Atmospheric and sunlight conditions in Lisbon are ideal for testing this type of solution. After analysing a classic air conditioning compression system, it turned out that such a system would consume approximately 549 238.21 kWh per year. Such amount of electricity consumption could result in really high costs (approximately € 80 738.02 per year).

Results revealed that the proposed system meets the cooling demand of the building, mainly by solar energy-driven absorption chiller. The annual contribution of backup compression chiller ranges from 20% to 36% depending on the size of chilled water storage tanks. Financial calculations revealed discounted payback periods in the range of 4.5 to 12.5 years depending on system configuration. The best solution appeared to be the system with 3 053.25 m^2 of solar collector aperture area, an absorption chiller of 622.5 kW cooling capacity and a relatively small cold water storage tank of 392 m^3. The results of the profitability analysis are very encouraging. As the project has also a considerable impact on the environment, the Life Cycle Assessment (LCA) is considered for future work.

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