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Life-Cycle Cost-Optimized Cooling Systems for European Office Buildings

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Abstract

This study compares the life-cycle costs of various conventional and emerging cooling systems in representative European climates and energy markets. Firstly, cooling demands and energy requirements of a multi-story office building are determined in compliance with local building codes in six different European locations. Life-cycle costs of various cooling systems are then calculated using location-specific market prices and economic data. The results indicate that no single cooling system is an optimal choice for all locations. In cold climates, conventional vapour compression systems are shown to have the lowest life-cycle costs. In moderate and warm climates, solar electricity driven vapour compression systems have the lowest life-cycle costs. Absorption and solar thermal cooling systems are shown to be economically infeasible under current market conditions.

Keywords – LCC; Cooling systems; Office building; Solar cooling; Energy markets

1. Introduction

The use of active cooling systems for office buildings remains largely inevitable despite tightening building regulations, improving energy efficiencies and rising energy prices throughout the European Union. Several conventional and emerging cooling technologies are available for space conditioning in buildings. These include, among others, conventional vapour compression and absorption systems, district cooling, solar electricity driven vapour compression systems, and solar thermal driven absorption systems. With so many available options, determining the most efficient and economical system solution is quite challenging.

Few recent research studies have investigated the life-cycle costs (LCCs) of some of the above-mentioned cooling systems at a local or a regional level. Kohlenbach et al. [1], for example, compared LCCs of solar thermal driven absorption and solar electricity driven vapour compression systems with grid electricity driven vapour compression systems for Australian conditions. Others [2, 3, 4, 5, 6] have compared the LCCs of solar thermal and photovoltaic cooling systems in certain economic settings and climatic conditions. However, as most of the above-mentioned studies have been conducted for specific conditions, their results are thereby limited and not generalizable to other economic settings and climatic locations.

This study investigates and compares the life-cycle costs of both conventional and emerging cooling systems in different European climates. The aim is to establish recommendations and guidelines for planners, designers and engineers involved in the design and selection processes of the cooling systems with regards to the most appropriate and cost-effective cooling solutions in specific climates and market conditions.

2. Method

The study has been carried out in two main parts. The first part deals with the calculation of cooling loads and energy demands in representative European climates. A state-of-the-art building energy simulation software, DesignBuilder, has been used to determine building thermal loads in accordance with the building codes of each location. The calculated loads are then used in Polysun – a dynamic design tool for building energy systems – to determine the annual energy demands for the studied cooling systems. In order to optimize the performance of the solar cooling systems, a solar access analysis of the studied building has also been performed in DIVAforRhino – a Radiance-based daylighting and energy modelling tool. The second part of the study deals with the cost efficiency and economic feasibility of all studied systems. Detailed LCC analysis has been carried out for each location using location specific energy and economic data. Sections 2.1 and 2.2 describe the two steps in more detail.

2.1 Energy simulations and cooling systems

The studied object is a six-story, box shaped office building with the main facades facing north and south and with windows on all façades. Fig.1 shows 3D-images of the building. The building has an open-plan layout and an occupied floor area of approximately 5,920 m² with a window-to-wall ratio of 39 %. It is assumed to be completely unshaded throughout the year.

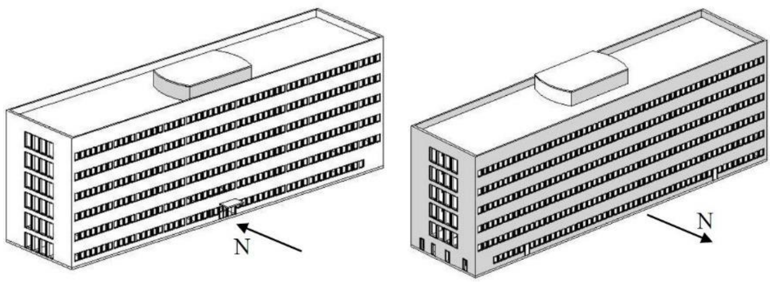

Fig. 1 3D-images of the case-study office building.

The building is studied in six representative locations from three European climate zones: cold, moderate and warm. For each climate zone, one coastal and one continental location has been investigated. The studied locations for the three climate zones are Stockholm (cold, coastal) and Tampere (cold, continental), London (moderate, coastal) and Berlin (moderate, continental), and Athens (warm, coastal) and Zaragoza (warm, continental). The building exterior has been modified to comply with the location-specific building regulations. The average U-value of the building in cold, moderate and warm climates is 0.54, 0.66 and 0.82 W/(m²-K), respectively. The glazing used for cold climates has three low emissivity (Low-E) coating panes and a SHGC of 0.36, whereas the glazing used for moderate and warm climates has three clear panes and a SHGC of 0.69. The thermal capacity of the building structure is 407.2 kJ/(K-m²) in cold climates and 405.7 kJ/(K-m²) in moderate and warm climates. The building is assumed to be occupied during weekdays between 8 a.m. and 5 p.m. The considered lighting and equipment loads are 14.5 W/m². The heat gains from occupants are taken to be 5.8 W/m². All the loads and gains are based on SVEBY [7] recommendations. The mechanical ventilation rate is set to be 0.35 l/(s-m²) and 7.0 l/(s-person), with a heat recovery efficiency of 70 %. The infiltration rate is considered to be 0.15 ACH for all locations. The heating and cooling set point temperatures used in all locations are 21 °C and 25 °C, respectively.

The cooling systems simulated in Polysun include conventional vapour compression (VC) systems, district heating driven sorption (So) systems, district cooling (DC) systems, solar thermal (ST) systems and solar photovoltaic (PV) systems. The capacities and COPs of the equipment used for this study have been obtained directly from the suppliers/manufacturers. The cooling capacity and the coefficient of performance (COP) of the used vapour compression chillers is 185 kW and 4.5, respectively, in the cold climates; 222 kW and 4.17, respectively, in the moderate climates; and 306 kW and 4.58, respectively, in the warm climates. Solar photovoltaic cooling systems also use the same vapour compression chillers but are mainly driven by electricity produced from the photovoltaic system. The cooling capacity and COP of the used sorption chillers is 175 kW and 0.75, respectively, in the cold climates; 281 kW and 0.75, respectively, in the moderate climates; and 351 kW and 0.75, respectively, in the warm climates. Solar thermal cooling systems also use the same absorption chillers but are mainly driven by the hot water produced from the solar system. A detailed description of the system layouts and their functionality is available in [8].

2.2 LCC analysis

The LCC analysis of the above-discussed cooling systems has been carried out using the net present value (NPV) method for a projected system lifetime of 25 years. The analysis has been performed assuming annual payments for materials, labour and connection fees of energy supply companies, and assuming geometric gradient growth rates for purchased energy including the auxiliary energy for fans and pumps. The costs of various system components have either been obtained directly from the manufacturers or from an engineering budgeting guidebook [9]. Energy prices and photovoltaic feed-in tariffs of Fig. 2a, as well as interest rates and price growth rates of Fig. 2b, have been determined from a number of sources [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21]. The average labour costs have been obtained from [22] and are 37.4 €/h in Stockholm, 32.2 €/h in Tampere, 22.2 €/h in London, 31.4 €/h in Berlin, 14.6 €/h in Athens and 21.3 €/h in Zaragoza. More information on the economic inputs to the LCC analysis can be found in [8].

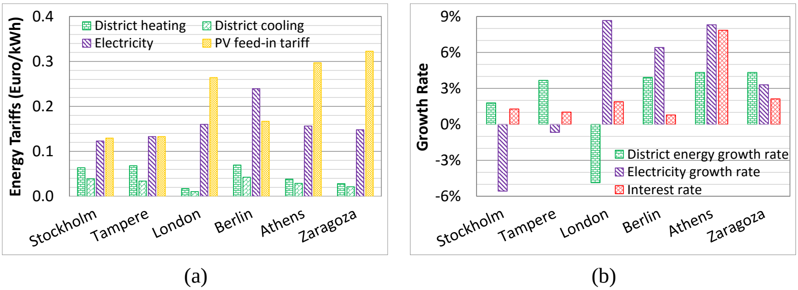

Fig. 2 a) Energy prices and feed-in tariffs (including subsidies), and b) Real growth rate of energy prices and real interest rate for each location.

2.3 Limitations

This study is based on methodological as well as statistical assumptions and limitations that may have an influence on the results. First and foremost, like any other life-cycle analysis, the future scenarios in this study have been extrapolated from current financial prices, economic variables and growth rates. Secondly, actual energy prices for some locations are not available. The missing prices have been estimated using the European Commission's statistical data [10] on energy prices. Thirdly, there is currently no district heating infrastructure in Athens. The district heating prices for Athens have instead been obtained from an energy supply company in Northern Greece. Finally, the energy demand for space heating, electrical appliances and lighting has not been considered for this study. It is assumed that the solar energy collected from the thermal collectors and photovoltaic modules is used only for cooling purposes. Hence, additional economic and energy savings from solar-systems in non-cooling times have not been taken into account.

3. Results

This section presents the results of both the building thermal and energy simulations as well as the LCC-analyses. Thermal and energy demands of the studied building are presented in Table 1 for each location. Peak heating loads and heating demands are lower in more-southern location. Naturally, the opposite effect can be identified for peak cooling loads and cooling demands. A small difference in energy demands and peak loads can be identified between coastal and continental locations, with continental climates being higher on average.

Table 1. Simulated energy peak loads (DesignBuilder) and annual energy demands (Polysun).

Location	Peak heating load (W/m^2)	Peak cooling load (W/m^2)	Heating demand ($kWh/m^2/year$)	Cooling demand ($kWh/m^2/year$)
Stockholm	51.0	27.8	24.5	5.8
Tampere	65.1	27.6	32.8	2.8
London	39.7	32.7	33.9	8.7
Berlin	52.3	35.3	43.4	11.4
Athens	32.5	42.6	11.6	50.5
Zaragoza	39.4	43.4	20.6	29.9

Results of the annual solar radiation analysis for the three considered climate zones indicate relatively higher solar potential of the roof in comparison to facades. Annual solar radiation on the horizontal roof surface are found to be approximately 1250 $kWh/m^2/year$ in the cold and moderate climate zones and nearly 2500 $kWh/m^2/year$ in the warm climate zone. As the roofs receive significantly higher annual solar radiation, all solar systems for this study have been assumed to be installed on the roof. Moreover, a parametric study has been carried out to optimize the energy output from the solar systems. Based on the results of the study, a south-facing solar photovoltaic system consisting of 162 modules with a gross aperture area of 264 m^2, a row-spacing of 1.5 m and a module efficiency of 0.156 has been selected for the solar photovoltaic cooling system. Likewise, a solar thermal system consisting of 50 south-facing vacuum tube collectors with a gross area of 139 m^2 and a peak efficiency of 0.757 has been selected for the solar thermal cooling system. In order to achieve the optimum energy output, the collectors and modules are assumed to be tilted equal to the latitude of the location they are installed in.

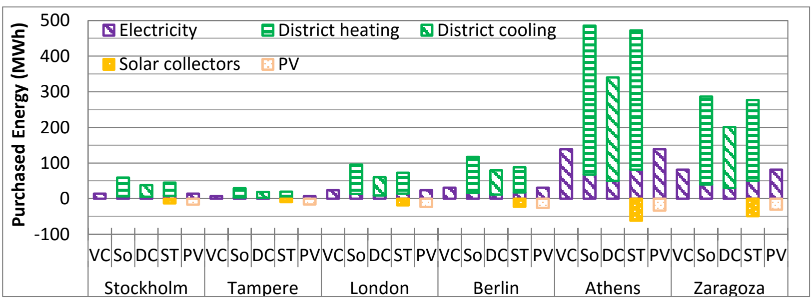

Fig. 3 Energy balance for each system, location and energy source.

Fig. 3 and Fig. 4, respectively, show the annual energy balance and the net cost of purchased energy for each system. As expected, the annual energy costs for locations with large cooling demands are significantly higher. It is interesting to observe that among all cooling systems district cooling has the highest annual operating cost in all locations. A likely explanation for this lies in the high connection fees charged by the district cooling supply companies. Another interesting observation is that in Stockholm, Tampere and London solar photovoltaic cooling systems produce a positive cash-flow. This is because solar fractions, i.e. the percentage of yearly cooling demand covered by the solar system, are relatively higher in cold and moderate climate zones due to low cooling demands.

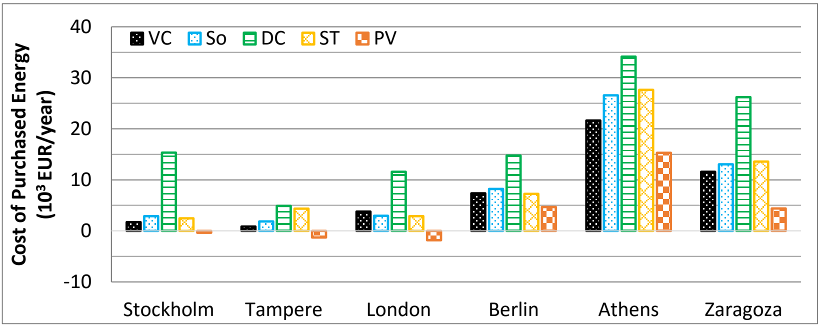

Fig. 4 Annual energy costs for each investigated cooling systems.

Fig. 5 shows the accumulated LCCs for vapour compression, district heating driven sorption, district cooling, solar thermal, and solar photovoltaic cooling systems. In the cold climate zone, conventional vapour compression systems turn out to be the most economical cooling system for both Stockholm (coastal) and Tampere (continental) after 25 years. Even though the district cooling system has the lowest investment cost in both locations, the vapour compression system breaks even after 4 and 15 years, respectively. In the moderate climate zone, the solar photovoltaic cooling system has the lowest LCCs for both London (coastal) and Berlin (continental) after 25 years. The system has the second highest investment cost in both locations, but breaks even after 15 years in London and after 24 years in Berlin. In the warm climate zone, district cooling and solar photovoltaic cooling systems are the most economically feasible options for Athens (coastal) and Zaragoza (continental), respectively, after 25 years. In both locations, district cooling has the lowest investment cost whereas the solar photovoltaic cooling system has the second highest investment cost. In Zaragoza, solar photovoltaic cooling breaks even after 15 years to have the lowest LCCs but in Athens the break-even does not occur within 25 years.

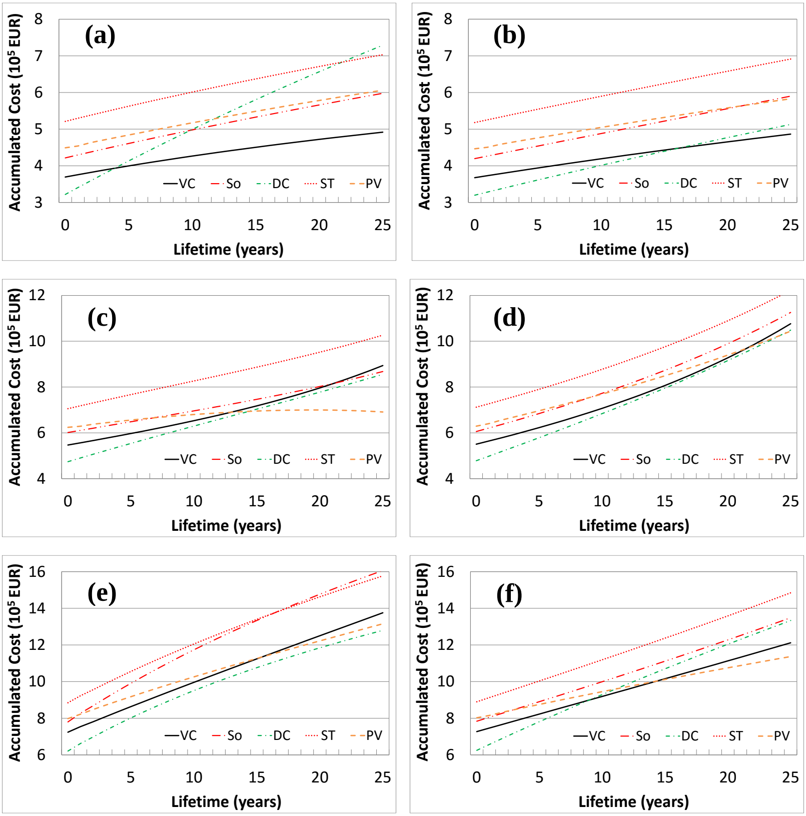

Fig. 5 Accumulated LCCs for investigated cooling systems in a) Stockholm, b) Tampere, c) London, d) Berlin, e) Athens and f) Zaragoza.

It can also be observed from Fig. 5 that the LCCs of vapour compression systems remain competitive in all three climate zones. This can be attributed to the relatively low investment and operating costs combined with high COPs of the vapour compression systems. The LCCs of photovoltaic cooling systems indicate that these systems are more competitive in moderate and warm climate zones. As expected, these systems are economically more feasible in locations with high electricity prices and feed-in tariffs. However, despite high solar fractions, these systems do not break even in cold climates. The LCCs of district cooling systems are also competitive in some locations. However, what is interesting to note is that despite having the lowest investment (Fig. 6) and energy costs (Fig. 2a) in all locations, the LCCs of district cooling systems after 25 years are lowest only in one location. This can be ascribed to the high annual connection fees charged by the district cooling supply companies. The LCCs of sorption chillers are not competitive in any location except Stockholm. This is despite the low district heating prices during summer when cooling is needed. The main reason behind the economic infeasibility of the sorption systems can be explained by their high investment costs and their low COP values. For similar reasons, the LCCs of solar thermal cooling systems using sorption chillers with solar collectors are even higher in all locations.

Fig. 6 presents the accumulated LCCs of the studied cooling systems in all locations after 25 years. What is particularly interesting to observe is the share of initial investment and the operating costs in the total LCCs. In cold climates, the largest portion of the LCC is formed by the initial system costs, while running costs constitute only a minor share. In warmer climates, the share of running costs in the LCCs is significantly larger than those in colder climates. This is because the investment costs do not increase linearly with cooling demands and are only marginally higher in warmer climates. On average, initial investment costs account for approximately 70 % in cold climates, 61 % in moderate climates and 56 % in warm climates. It can also be observed that solar cooling systems, in general, have lower running costs. This is particularly the case for solar photovoltaic cooling systems. These systems have a positive cash-flow in locations with high electricity prices e.g. London and Zaragoza.

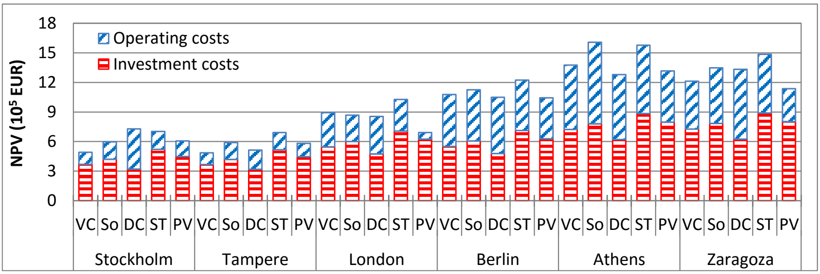

Fig. 6 LCCs of the studied systems.

4. Sensitivity Analyses

In addition to the LCC analysis performed with the economic parameters of Fig. 2b, two sensitivity analyses with modified energy market parameters have also been carried out. In Scenario I, the growth rates of energy prices for district energy and electricity are assumed to be fixed at 0 and 2.5 %, respectively. In Scenario II, the interest rate is also assumed to be fixed at 3 % in real terms, in addition to the assumptions of Scenario I.

Fig. 7 and Fig. 8 present the results of the two sensitivity analyses. Under Scenario I, the LCCs of the studied cooling systems generally decrease in all location except Stockholm. The decrease in LCCs is more pronounced in locations like London, Berlin and Athens, which have relatively high electricity price growth rates. Stockholm, on the other hand, has a negative electricity price growth rate. Under Scenario I, the growth rate of electricity price in Stockholm is increased by over 8 %, which consequently increases the LCCs of the considered cooling systems. Scenario II also has a positive effect on the LCCs of the cooling systems in all locations except Athens. The decrease in LCCs is more noticeable in locations like Stockholm, Tampere and Berlin, which have fairly low interest rates. Athens, on the contrary, has comparatively high interest and price growth rates. Under Scenario II, the price growth and interest rates are significantly reduced in Athens. This, in combination with high cooling demands, significantly increase the LCCs of all considered cooling systems.

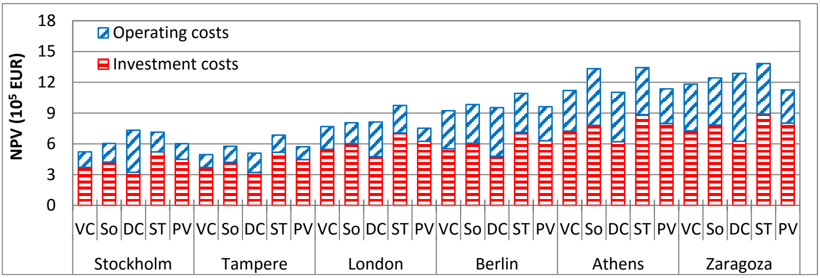

Fig. 7 LCCs of the studied systems under Scenario I.

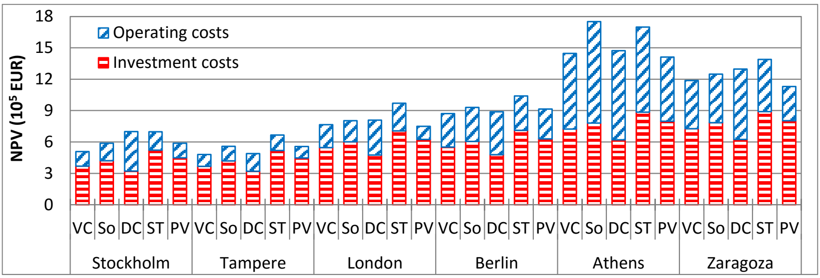

Fig. 8 LCCs of the studied systems under Scenario II.

5. Conclusions

This paper investigates the life-cycle costs of various cooling systems in representative European climatic and economic conditions over a 25 year lifespan. The analysis is based on energy simulations of an office building in six different locations using the programs DesignBuilder and Polysun. It is shown that at present economic conditions and under the given financial and technical assumptions, no single cooling system emerges as the optimal choice for all locations. Conventional vapour compression systems have the lowest life-cycle costs in cold climate zones, whereas solar photovoltaic cooling systems have the lowest life-cycle costs in moderate and warm climate zones. District heating, despite its high annual connection fees, is also a competitive option in many locations. District heating driven absorption and solar thermal cooling systems are not competitive at the current energy prices and subsidy levels, primarily because of their high investment costs.

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