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SOLAR SYSTEMS FOR HEATING AND COOLING OF BUILDINGS

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ABSTRACT: Recently, the concept of net zero energy buildings has become a major topic in the R&D work on future buildings. In order to achieve a zero energy balance on annual level energy saving and energy efficiency measures have to be fully exploited. However, a demand for active heating and/or cooling will remain in most buildings and climatic conditions. Solar energy is the main on-site renewable energy source which can be used to achieve a high fraction of renewable energies to cover the remaining energy demand in buildings. Main energy needs in European buildings are due to heating and in particular in the south of Europe also for cooling. In this paper principle ways of covering part of the demand for heating, cooling and domestic hot water by using solar technologies are discussed and a design study of a solar thermally driven heating and cooling system for a virtual hotel located in Malta is presented.

Keywords: Solar heating, solar cooling, solar collectors, thermally driven cooling

1 INTRODUCTION

The European Parliament and the Council of the European Union adopted an update of the 2002 Energy Performance of Buildings Directive (EPBD) on 19 May 2010 [1]. This update includes a significant strengthening of the energy performance requirements of new and existing buildings across the EU. For new buildings it fixes 2020 as deadline for all new buildings to be “nearly zero energy” and for public buildings by the end of 2018. ‘Nearly zero energy’ is defined in a qualitative way: “A ‘nearly zero energy building’ is a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.”

Solar energy is the most important renewable energy source available on-site. Therefore applications of solar energy have to play a major role in covering the energy demand for heating and cooling of buildings. A pre-condition to achieve a ‘nearly zero energy’ standard is to maximize energy saving and energy efficiency of buildings. This minimizes the remaining energy demand such that it becomes realistic to cover it by renewable energy sources. How far this can be achieved in a particular case depends on the building type and form, on its use and on the local climatic conditions.

In this paper general solutions of solar energy systems for buildings are described. The two main technologies discussed are

(1) solar thermal collector systems used for heating and hot water production and for cooling in combination with a thermally driven chiller system and
(2) photovoltaic systems which are used to operate a reversible heat pump which is used for heating, hot water production and cooling.

For the solar thermal solution a detailed energy and cost balance is made for a virtual hotel located in Malta.

2 GENERAL SOLUTIONS

Solar energy can be inverted into electricity by photovoltaic modules or into heat by solar thermal collectors. Both systems can be used for solar assisted heating and cooling using different transformation techniques.

2.1 Photovoltaic system solution

The most straightforward design of solar heating and cooling systems using photovoltaic modules is drawn in Figure 1. A normal boiler using fuel (e.g. natural gas, oil or biomass) is used for heating and hot water production and a vapour compression chiller is used for cooling. In such systems the electricity generated by the photovoltaic system can only be used for cooling. Excess electricity which exceeds the actual electric load of the building might be fed into the electricity grid depending on agreements with utilities. A control in the switchboard can be adjusted such that the use of locally produced electricity within the building is maximized.

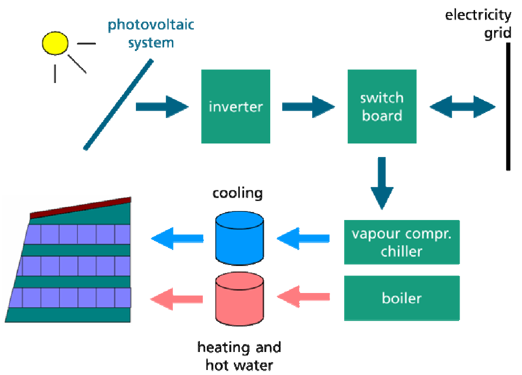

Figure 1: Solar assisted heating and cooling system using photovoltaics for cooling and a conventional boiler for heating and hot water production

A more sophisticated design uses an electrically driven reversible heat pump based on a vapour compression cycle that can be used to produce heat in the heating season and cooling in the cooling season (see Figure 2). The production of hot water, which is also needed in cooling seasons, requires a periodic change of the operation of the reversible heat pump between heating and cooling operation. In this system the boiler is used as back-up in case there is not enough heat from the reversible heat pump available to cover the heating load or the hot water load.

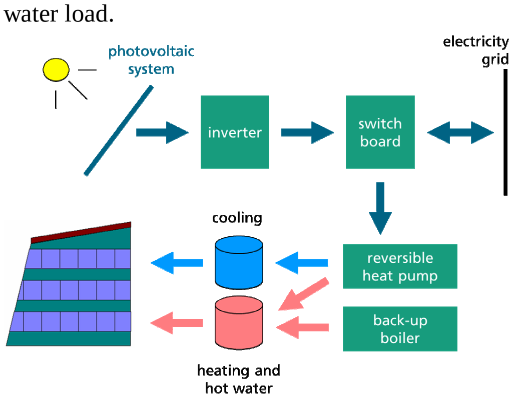

Figure 2: Solar assisted heating and cooling system using photovoltaics for heating and cooling with a reversible heat pump; a boiler is used to cover heating loads and hot water loads that cannot be covered by the reversible heat pump driven with PV electricity

The reversible heat pump might also be used to completely cover the heat demand of the building. In cases where not enough electricity from the photovoltaic generator is available the electricity from the grid is used to operate the reversible heat pump not only for cooling but also for heating. A control in the switch board can be adjusted such that the use of locally produced electricity by the photovoltaic system is maximized. A sketch of such system is shown in Figure 3.

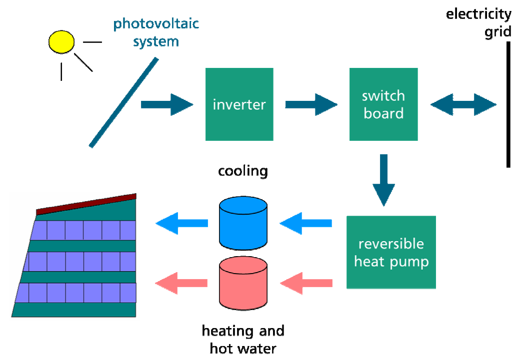

Figure 3: Solar assisted heating and cooling system using photovoltaics for heating and cooling with a reversible heat pump

Today almost no complete system solutions using photovoltaics for energy supply in buildings (as shown in Figures 1 to 3) are available on the market. The main reason is that the installation of photovoltaic systems is most interesting in countries that provide a feed-in tariff for electricity from renewable energy sources. In countries such as Germany and Italy very attractive PV feed-in tariffs with a 20-years guarantee of the price of the electricity fed into the grid led to strongly growing market for PV installations [2]. However, almost all these systems are simply connected to the grid and do not at all interact with the building energy system. This may change in future with an increasing drop of the price for PV modules and reduced feed-in tariffs. As soon as the price for electricity fed into the grid is getting lower than the price for electricity purchased from the utility it becomes interesting to make local use electricity produced locally. Then electrically driven heating and cooling equipment such as vapour compression heat pumps, chillers or reversible heat pumps in connection with heat and/or cold storage will be interesting options for the energy supply in buildings.

2.2 Solar thermal system solution

Today solar thermal collectors are the most common way to cover hot water loads in buildings. In some European countries – in particular Austria and Germany – also a significant share of the market is covered by so called solar combi-systems which cover part of the heating load of the building [3][4]. These systems are typically installed in single-family houses and use large buffer storages of about 1000-2000 litres and a solar thermal collector field of 10-20 m².

A solar thermal collector system can also be used for cooling by integrating a thermally driven cooling device [5]. Different types of thermally driven cooling systems are available on the market, most of them employ the physical phenomena of sorption, either absorption or adsorption. More details can, for instance, be found in [6].

If a solar thermal collector system is used for both heating and cooling two main options exist for a system back-up which is used in cases without enough solar heat available:

(1) A back-up boiler is used for both, heating and cooling. Then the thermally driven chiller has to be designed such that it is able to cover all cooling loads, i.e. the capacity of the thermally driven chiller is determined by the maximum cooling load. A sketch of such system is shown in Figure 4. The main disadvantage of this solution is that the conversion efficiency from primary energy to cooling in the case of using the back-up boiler is rather low, at least if the thermally driven chiller is a single-effect system (for more details see [7]).

(2) A vapour compression chiller is used as a back-up device for cooling and the boiler is only used as back-up device for heating (see Figure 5). In case there is not enough solar energy available to completely cover the cooling load the vapour compression chiller operating in the conversion efficiency is the same as in a conventional system which does not use any solar energy. The disadvantage of such solution is that more components are needed. However, the thermally driven chiller may be sized with a significantly smaller capacity since it has not to cover peak cooling loads.

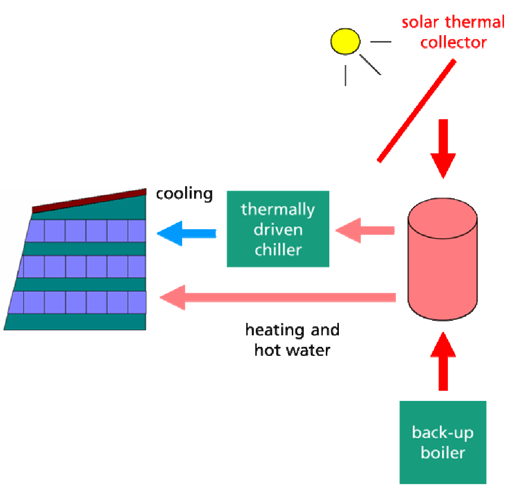

Figure 4: Solar assisted heating and cooling system using a solar thermal collector for heating and cooling with a thermally driven chiller

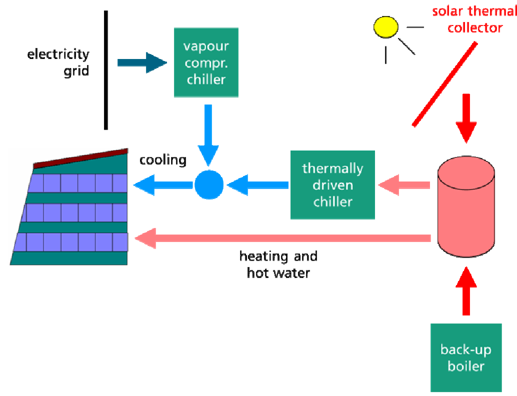

Figure 5: Solar assisted heating and cooling system using a solar thermal collector for heating and cooling with a thermally driven chiller; a conventional vapour compression chiller is used as back-up for cooling

In principle a third option exists in which a reversible heat pump is used as back-up for both, cooling and heating. Such a design reduces the number of components, since only one back-up component is employed for both heating and cooling. A sketch is shown in Figure 6.

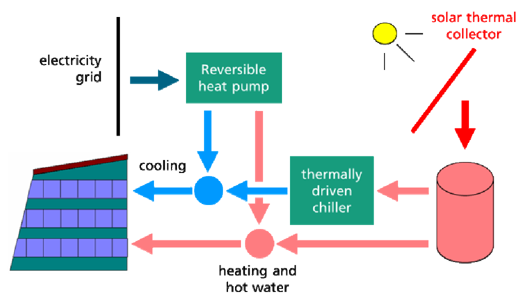

Figure 6: Solar assisted heating and cooling system using a solar thermal collector for heating and cooling with a thermally driven chiller; a reversible heat pump is used as back-up for cooling and heating

It should be noted that all figures in this chapter are simple energy flow charts and are not meant as hydraulic schemes. For instance the heat rejection unit which is an important component for all thermally driven chillers has not been displayed. Also the electricity consumption of all components (e.g. pumps, control units) and the corresponding connection to the grid is not shown for simplicity reasons. However, this electricity consumption has been considered in the parametric study described below (chapters 3 and 4).

2.3 Comparison of the different solutions

In a given project an overall assessment which compares energy saving and cost compared to conventional reference solutions guides the decision for the best suited system. However, some general technical specifications of the different systems exist which are briefly outlined.

Systems which use a boiler and a vapour compression machine as back-up units (systems shown in Figures 1, 2 and 4) are more complex since more components are involved. However, they open a higher flexibility and may be more economic regarding operation cost. Therefor those solutions will mainly be interesting options in case of large installations in either large residential housing complexes or commercial buildings such as e.g. hotels or shopping malls. Systems such as shown in Figure 3 and Figure 4 are more simple in terms of the number of involved components. However, their efficiency may be lower than for the more complex solutions. Therefore they will be more advantageous for installations with small capacities such as offices, small commercial buildings or even private homes.

A general advantage of solar thermal solutions is that a single heat storage can be used as buffer for heating as well as for cooling and solar gains that exceed the actual building loads can be saved to a later point of time in a single heat buffer. In case of PV driven solutions separate storages are needed in order to compensate mismatches between available solar gains and buildings loads, namely a heat storage for heating and hot water and a cold storage for cooling. An additional drawback of PV based solutions which use a reversible heat pump for heating is that the heat storage can only be heated up to temperatures of about 55°C to 60°C since this is typically the upper maximum temperature of heat pumps.

A general advantage exists for PV solutions as long as the local utility allows feed-in of excess electricity. In particular in case of an obligation of the utility to purchase electricity of the PV system at a given feed-in tariff the PV solution becomes highly attractive from the perspective of the building owner. However, this situation will change in future – even in countries which today have a very high feed-in tariff. Reasons are the significant cost reduction for PV modules on the one hand and the increasing grid capacity and management problems in grids with a high and increasing amount of fluctuating electricity generation from renewable sources such solar energy and wind on the other hand.

3 CASE STUDY: HOTEL IN MALTA

Today almost all solar heating and cooling systems use solar thermal collectors as main solar energy source and employ a thermally driven cooling cycle to cover cooling loads. It is estimated that up to about 1000 systems are installed worldwide [7]. Since many of these systems were designed and installed in the framework of R&D or demonstration projects, very little solid information on real performance and cost exists. Therefore in the following a computer study will be presented in which energy performance and cost issues of a solar heating and cooling system for a virtual hotel building located in Malta have been assessed.

3.1 Modelling approach

The general approach of this study is shown in Figure 7.

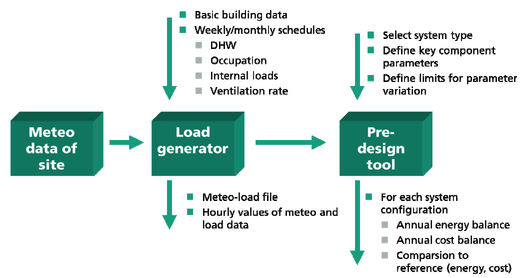

Figure 7: Modelling approach

Meteorological data of the site (Malta, Luga/Qrendi) were generated with the software Meteonorm 6.1 [8]. Based on hourly values of main meteorological parameters (outdoor air temperature, outdoor air relative humidity, global horizontal radiation, diffuse horizontal radiation) load profiles were produced for the heating, cooling and hot water demand of a pre-defined building. For this purpose a so called Load Generator has been used. The Load Generator is a software produced at Fraunhofer ISE which generates a building load file for a multi-zone building with a minimum effort and a minimum of required information; it is based on a 2C-3R-model which is outlined in Figure 8 and described e.g. in [9]. Hourly schedules for every day of the week and every month are used for the main important loads, such as domestic hot water, occupation, internal loads (due to e.g. artificial lighting and other electric appliances) and the building ventilation rate. As a result the Load Generator delivers a meteo-load-file which contains hourly values of buildings loads (heating, cooling, domestic hot water) and meteorological data which are needed for the modeling of the respective technical system.

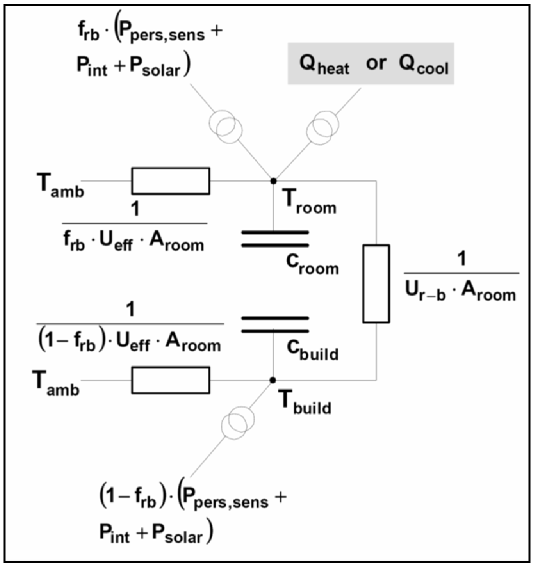

Figure 8: 2C-3R-model for a building zone used in the Load Generator

Based on the meteo-load-file a simulation of a solar heating and cooling system which corresponds to a design as shown in Figure 5 has been made using a pre-design tool which has been developed at Fraunhofer ISE and which is used for a draft design of solar heating and cooling systems. All component models are simple steady-state models except the one for the heat storage. The heat storage by a single mode, i.e. no stratification, is considered. Although the model is comparatively simple it turned out that annual results are very much comparable to the results achieved with much more complex simulation tools [10]. In addition for each component cost curves are included which express their specific cost as a function of their size. For instance the first cost of solar collectors is expressed in € per m² as a function of the collector area in m². The Pre-design tool allows variation of the three key sizing parameters of a system such as shown in Figure 5, namely the collector size, the buffer storage volume and the size of the thermally driven chiller. For each set of parameters an annual simulation using the meteo-load file is carried out and an annual energy balance is calculated. The size of the back-up components, i.e. the boiler and the vapour compression chiller, is automatically determined such that in each single hour the buildings loads are completely covered. Based on prices for conventional energy (electricity, fuel) and other cost parameters (interest rate, lifetime, maintenance cost) a life cycle cost for each parameter set is calculated.

3.2 Load description

For the purpose of this study a virtual hotel was assumed with a total floor area of 3050 m². Four zones were modelled in order to calculate the building loads for each single hour: guest rooms, lobby incl. floors, restaurant and kitchen. The key results of the load calculation are displayed in Table 1 and the annual load duration curves are shown in Figure 9. The shown values and curves correspond to the following loads: the heating demand (denoted "heating" in Figure 9); the cooling demand (denoted "cooling"); the heat demand to cover heating and cooling demand if the cooling would be completely covered by a thermally driven chiller with a constant thermal COP-value of 0.68 (denoted "heat + cool"); and the overall heat demand for heating, cooling (thermally driven chiller with constant thermal COP 0.68) and domestic hot water demand (denoted "heat + cool + DHW"). Based on the curve for the cooling load it can for instance be concluded that with a cooling capacity of 50 kW of the thermally driven chiller far more than 50 % of the annual cooling can be covered.

Table 1: Summary of load data (peak values and annual totals) for the hotel (total of 4 zones)

	Peak demand		**Annual Demand**		**h per year**
Unit	kW	W/m²	kWh/a	kWh/m²a	
Domestic hot water	89.5	29.34	129418	42.4	1446.1
Heating	105.1	34.46	73541	24.1	699.7
Cooling	147.0	48.21	174924	57.4	1189.8
Heat for cooling (assumed constant COP value)	233.4	76.52	277658	91.0	1189.8
Heat for heating and cooling	233.4	76.52	351199	115.1	1504.9
Heat for heating, cooling and domestic hot water	288.1	94.47	480617	157.6	1668.1

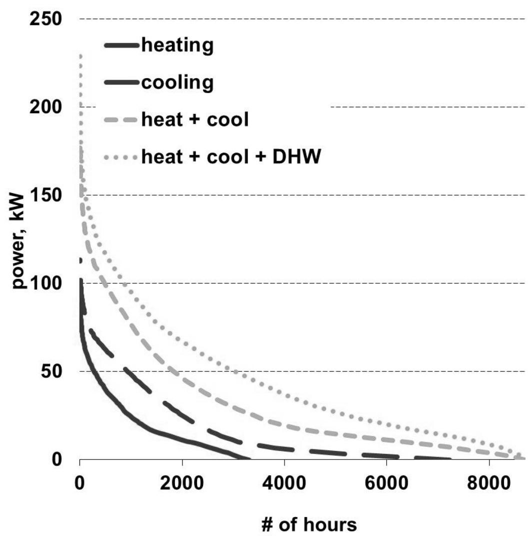

Figure 9: Annual load duration curve for the hotel building

Cost curves of key components used in the calculations are shown in Figures 10 and 11. These data are based on a Delphi survey that has been carried out among many experts working in the field of solar cooling [11].

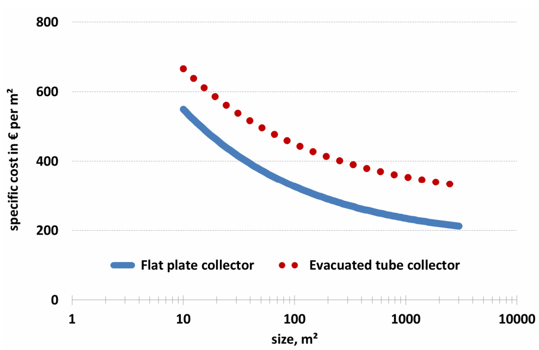

Figure 10: Cost figures of solar thermal collectors (without installation cost)

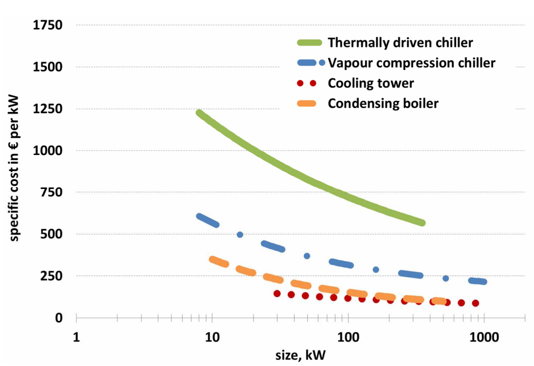

Figure 11: Cost figures for other components used in the simulation study

Other major cost and conversion efficiency values used are summarized in Table 2.

Table 2: Values of parameters used in the simulation study

Kind of parameter	Parameter	Unit	Value
Energy cost	Electricity	€/kWh	0.18
	Peak electricity cost	€/kW	50
	Fuel	€/kWh	0.06
	Increase rate electricity cost	% p.a.	4.0%
	Increase rate fuel cost	% p.a.	4.0%
Other cost items	Planning HVAC + solar thermal	% of invest	20.0 %
	Installation HVAC + solar thermal	% of invest	30.0 %
	Maintenance	% of invest p.a.	1.5%
	Lifetime	a	20
	Interest rate	%	5.0%
Primary energy conversion values	PE factor electricity	kWh_{PE}/ kWh_{el}	2.7
	PE factor fuel	kWh_{PE}/ kWh_{fuel}	1.1
	Value of saved PE	€/kWH_{PE}	0.05

4 RESULTS

The results which are presented in the following always compare the performance of the particular solar heating and cooling system with a conventional system which exactly covers the same building loads. In the following this system is called reference system; a sketch is drawn in Figure 12.

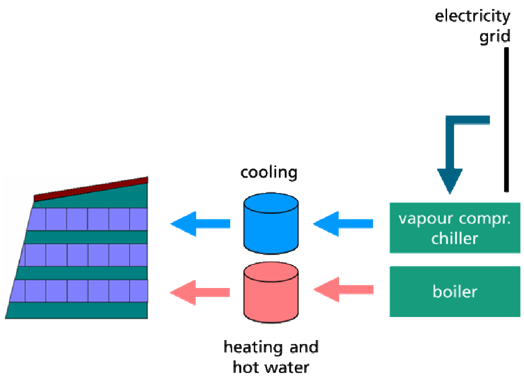

Figure 12: Conventional reference system

The following control strategy for the solar heating and cooling system has been implemented: first priority for discharge of heat from the buffer storage is given to the heating system, since heating requires the lowest temperature when compared to domestic hot water and driving of the thermally driven cooling. Second priority is given to domestic hot water and third priority is given to drive the thermally driven cooling.

4.1 Primary energy saving

In order to be able to compare different systems which use both electricity and fuel all energy values have been converted into their corresponding primary energy values; the values of the conversion values are shown in third and second last line of Table 2.

Figures 13 and 14 show the system boundary for the primary energy balance for the reference system (Figure 13) and the solar thermal solution (Figure 14).

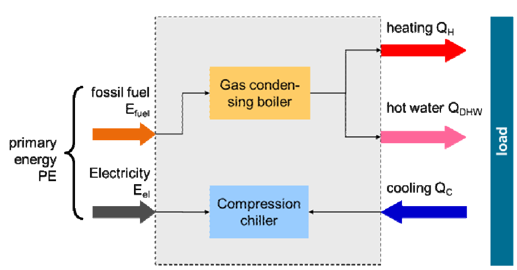

Figure 13: System boundary for the reference solution

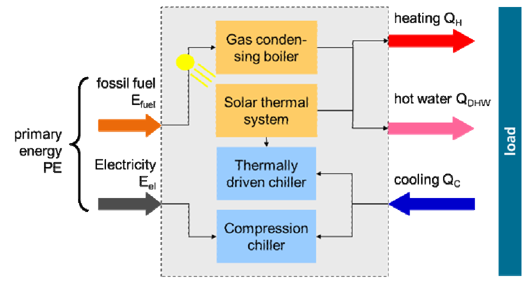

Figure 14: System boundary for the solar thermal solution

The saved primary energy of the solar system in comparison to the conventional reference system is given by

$$PE_{saved} = PE_{ref} - PE_{sol} \quad ,$$

whereby the index 'ref' refers to the reference system and the index 'sol' refers to the solar system. PE denotes primary energy.

The fractional primary energy saving can then be defined by

$$f_{PE,saved} = 1 - \frac{PE_{sol}}{PE_{ref}} = \frac{PE_{saved}}{PE_{ref}} \quad .$$

The results of a broad parametric study lead to the results shown in Figure 15. The solar collector size was varied in a range from 150 m² up to 750 m² in steps of 150 m², the volume of the buffer storage was varied in a range from 30 litres per m² of collector up to 80 litres per m² of collector (steps of 12.5 litres per m²) and the size of the thermally driven chiller was varied in a range from 0 kW up to 60 kW (steps of 15 kW). Thus, overall 125 simulation runs were performed. It turned out that a buffer storage size of 55 litres per m² is a good compromise between energy saving and cost; therefore this value is used for all further presentations of results.

The results indicate that without using any thermally driven cooling machine the primary energy saving is in the range of 38 % saving compared to the reference system for the smallest collector area. A further increase of the collector size above approximately 450 m² does not lead to a significant further reduction in the primary energy consumption, i.e. the behavior shows a typical saturation. The installation of a thermally driven cooling machine leads to a significant increase of primary energy saving up to a total saving close to 80 % for the design with largest investigated collector field (750 m²) and the largest size of the thermally driven chiller (60 kW). The larger the installed capacity of the thermally driven chiller the larger is the spread between two subsequent curves for different solar collector sizes. This indicates that an increase of the solar collector area is more justified in cases of a thermally driven chiller, which is able to make use of the solar collector system.

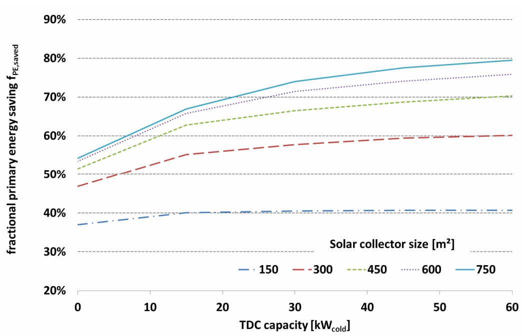

Figure 15: Fractional primary energy saving of the solar heating and cooling system for the example of the hotel in Malta

4.2 Economics

Installation of a solar heating and cooling system leads to much higher investments compared to a conventional solution mainly due to the solar thermal collector field but also due to the more components which are needed, i.e. the thermally driven chiller in addition to the conventional chiller and the larger cooling tower. Figure 16 compares first cost for the complete system including planning and installation cost (100 % states the value of the conventional reference).

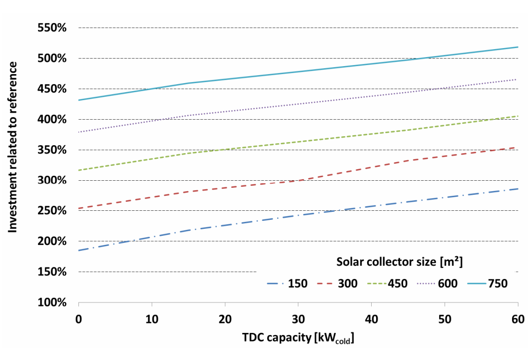

Figure 16: Investment for solar heating and cooling solutions compared to the reference (reference investment = 100 %).

Due to the lower operation cost of the solar heating and cooling system an adequate cost comparison has to compare full life cycle cost (LCC) of the two systems. LCC includes all cost items over the whole system life time, i.e. investment, capital cost (depreciation over lifetime), energy cost and maintenance cost. The LCC of the investigated systems is shown in Figure 17. It is interesting to note that for the smallest studied collector area (150 m²) no reduction of the LCC appears with increasing capacity of the thermally driven chiller. The reason is that almost all heat produced by the solar collector is used for either domestic hot water production or heating and thus only little use is made of the thermally driven chiller to cover part of the cooling load. This can also be seen by the very slight increase of the primary energy saving for a collector area of 150 m² in Figure 13. For all other collector sizes there exist certain values of the thermally driven chiller that leads to a minimum of the LCC. For instance a system with a solar collector area of 300 m² and a capacity of the thermally driven chiller of 30 kW leads to a LCC which is about 5.7 % below that of the conventional reference; the corresponding primary energy saving lies in the range of about 58 %. The largest investigated system (collector area 750 m²; TDC capacity 60 kW) leads to a slight increase of 3.4 % in the life cycle cost compared to the conventional solution and the corresponding primary energy saving is 79.5

%.

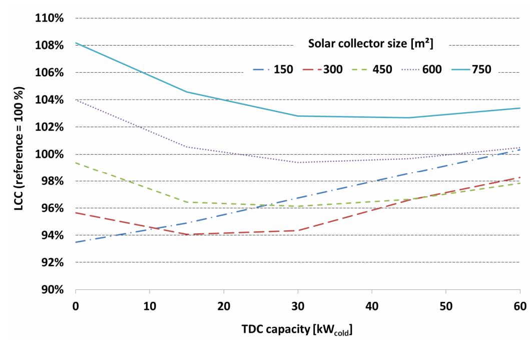

Figure 17: Life cycle cost of solar heating and cooling solutions, normalized to the life cycle cost of the reference system (100 %)

4.3 Combined energy-cost performance

Neither the energy analysis nor the cost analysis (LCC) allow s the selection of a “best” solution. The larger the solar collector field the larger is also the related investment and – as Figure 17 shows – the larger is also the life cycle cost. Thus it is desirable to define a combined performance-cost figure of merit, which makes systems in terms of both energy performance and cost comparable.

One often used combined performance-cost figure of merit is the so called cost of saved primary energy, $C_{PE,saved}$. It quantifies the additional costs per unit of primary energy savings with respect to a conventional reference system, and is defined by

$$C_{PE,saved} = \frac{\Delta LCC}{\Delta PE \times t_{life}} \quad \left[\frac{€}{kWh_{PE}}\right],$$

where ΔLCC denotes the difference in life cycle cost between solar solution and reference system,

$$\Delta LCC = LCC_{sol} - LCC_{ref}$$

and ΔPE denotes the saved primary energy per year,

$\Delta PE = PE_{ref} - PE_{sol}$ and

t_{life} the lifetime of either system (assumed similar for both, solar and reference; see Table 2).

However, this parameter leads only to reasonable results if the overall annual cost of the solar-assisted system is higher than that of the reference system. Otherwise the fraction does not make sense since not a cost per benefit is calculated but a relation between two benefits (cost saving and energy saving, respectively) is computed.

Therefore we propose an alternative combined cost-performance figure, namely the summation of the differences in cost and primary energy of the solar assisted system and the reference. However, in order to be able to do this summation both figures have to be converted to the same unit. This can for instance be done by multiplying each unit of saved primary energy with a corresponding cost value, named value of saved primary energy, $f_{C,PE}$ [€/kWh$_{PE}$]. Using this value of saved primary energy the resulting overall cost-performance indicator, $F_{PE,cost}$, is leads to

$$f_{PE,cost} = f_{C,PE} * \Delta PE * t_{life} - \Delta LCC.$$

The advantage of this cost-performance indicator, $F_{PE,cost}$, is that is can be applied for any system, regardsless of whether it leads to higher or lower life cycle cost compared to the reference. The disadvantage is that a value for the saving of primary energy has to be defined. This value has somehow to reflect the benefit of avoided primary energy consumption for the society and can be interpreted as avoided external cost; however, it is very difficult to calculate it in practice.

The result for the comparison of the investigated solar heating and cooling system dimensions is shown in Figure 18; these results are based on an assumed value of saved primary energy, $f_{C,PE}$, of 5 €-cent per kWh of primary energy (last line in Table 2).

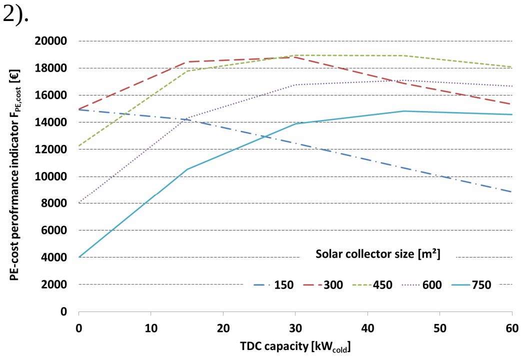

Figure 17: PE-cost performance indicator $F_{PE,cost}$ for solar heating and cooling solutions

A system with a collector area of 450 m² and a thermally driven chiller with a capacity 30 kW leads to an optimum when using this combined PE-cost performance indicator. Such system leads to a primary energy saving of 66.5 % compared to the reference and the lifecycle cost lies about 3.9 % below that of the reference.

5 SUMMARY

Solar heating and cooling systems using solar thermal collectors and thermally driven cooling equipment are an interesting option under many boundary conditions and should always be considered as an alternative in the planning phase of a building project. As was shown in this study the life cycle cost (LCC) of a solar heating and cooling system has not to be higher than that of a conventional solution; at the same time primary energy savings up to 80 % can be realized. Overall, most favourable conditions for a successful market implementation of solar heating and cooling systems are:

- Applications with a high need for heating and cooling (and sanitary hot water); in those cases a year-around use of the solar collector system is possible.
- Places with a high solar energy potential, i.e. high solar radiation.
- Conditions characterized by a high coincidence of loads and solar gains since this reduces the need for storage.
- Economics will be most favourable in places with high cost of conventional energy.

A major obstacle often is no or very little experience with solar energy use exists among the professionals in the heating and cooling sector. Therefore training and education will be important in order to assure long term quality and durability of such installations. Companies that offer overall solutions and which have the capability to provide maintenance services (e.g., using remote control approaches) will be able to exploit best this market opportunity.

Overall, renewable energies will play an increasingly important role in future buildings due to the strong need to limit CO_2 emissions originating from conventional energy sources. Solar heating and cooling technologies are one of the most important solutions applicable on the demand side. This technology provides a market opportunity for many involved stakeholders including building owners, planners, manufacturers, and installation companies. Today mainly solutions using solar thermal collectors are realized but in future also solutions making use of photovoltaic modules in combination with electrically driven heat pumps will gain increasing attention.

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