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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 under most 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 buildings are due to heating and/or cooling, depending on local climatic conditions and type of building. 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 is presented. A model of the same hotel has been investigated under various climatic conditions in order to study the impact of sizing of key components on the overall performance. In addition an analysis of economic performance is presented for the example of the location Malta in Mediterranean Sea.

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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

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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 application of solar energy has 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 presented. The two main technologies discussed are

(1) photovoltaic systems which are used to operate a reversible heat pump which is used for heating, hot water production and cooling and

(2) solar thermal collector systems used for heating and hot water production and for cooling in combination with a thermally driven chiller system.

For the solar thermal solution a detailed analysis of the achievable solar fractions for the example of a hotel building is investigated for various climatic conditions. For the example of Malta also an analysis of primary energy saving has been carried out and a detailed cost balance is presented.

2. Solar active systems for heating and cooling of buildings - general solutions

Solar energy can be converted 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, not for heating and domestic hot water. Excess electricity which exceeds the actual electric load of the building might be fed into the electricity grid depending on local regulations. A control in the switchboard can be adjusted such that the local use of locally produced electricity within the building is maximized.

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.

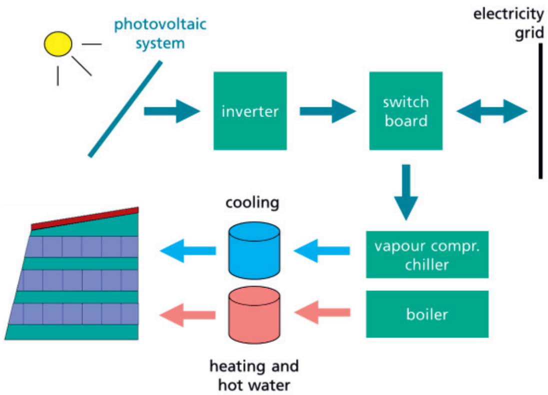


Fig. 1. Solar assisted heating and cooling system using photovoltaics for cooling and a conventional boiler for heating and hot water production

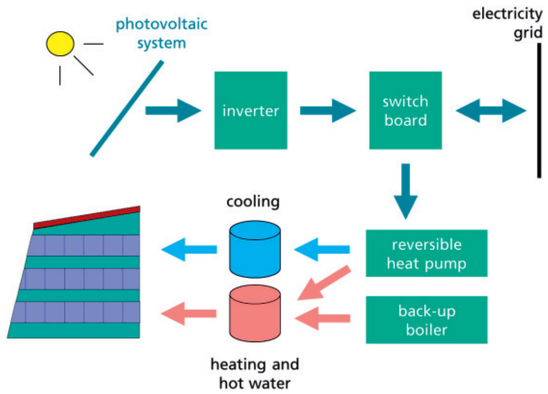


Fig. 2. Solar assisted heating and cooling system using photovoltaics for heating and cooling with a reversible heat pump; a boiler is used to cover heating loads and hot water loads that cannot be covered by the reversible heat pump driven with PV electricity

The reversible heat pump might also be used to completely cover the heat demand of the building. When not enough electricity from the photovoltaic generator is available 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.

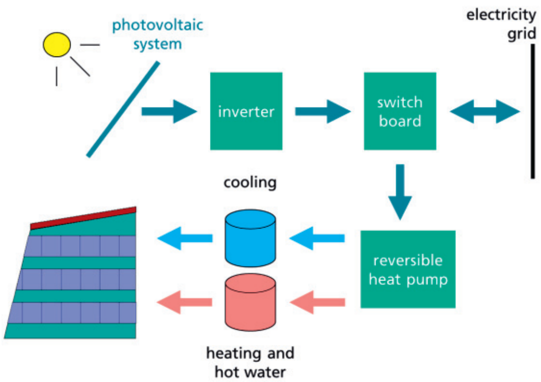


Fig. 3. Solar assisted heating and cooling system using photovoltaics for heating and cooling with a reversible heat pump

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 electricity fed into the grid led to strongly growing markets for PV installations [2]. Almost all these systems are simply connected to the grid and do not at all interact with the building energy system. However, this situation is going to change 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 of locally produced electricity from the point of view of a building owner. 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. A mix of a battery storage and heat storage (or cold storage in case of cooling) will lead to a maximized use of locally produced electricity at minimized cost.

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 in 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 800-2000 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 when not enough solar heat is 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 conversion efficiency of the back-up vapour compression chiller 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 at a significantly smaller capacity since it has not to cover peak cooling loads.

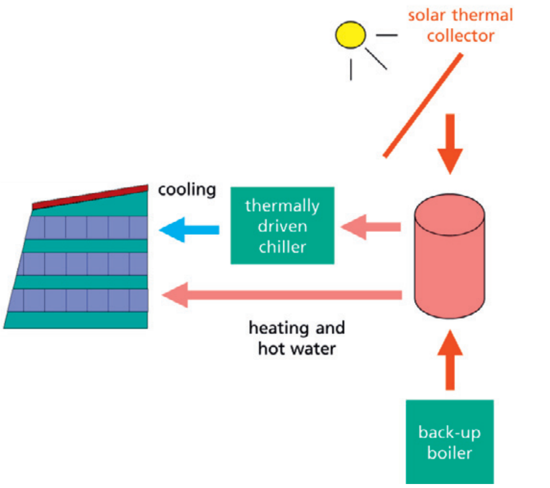


Fig. 4. Solar assisted heating and cooling system using a solar thermal collector for heating and cooling with a thermally driven chiller

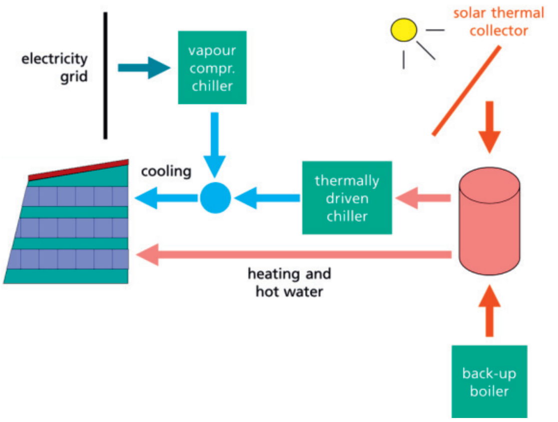


Fig. 5. Solar assisted heating and cooling system using a solar thermal collector for heating and cooling with a thermally driven chiller; a conventional vapour compression chiller is used as back-up for cooling

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.

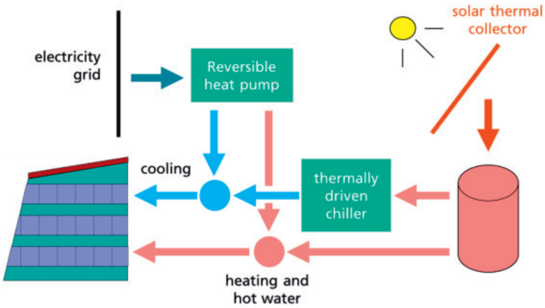


Fig. 6. Solar assisted heating and cooling system using a solar thermal collector for heating and cooling with a thermally driven chiller; a reversible heat pump is used as back-up for cooling and heating

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 source or sink, which is an important component for any type of heat pump or chiller, 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) and turned out as a significant contributor to the overall electricity consumption of solar thermally driven cooling systems [8].

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 (see sections 4.2 and 4.3). 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, 4 and 5) are more complex since more components are involved. However, they open a higher flexibility and may be more economic regarding operation cost. Therefore 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 simpler 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 only one heat storage is needed that can be used as buffer in heating as well as in cooling operation and solar gains that exceed the actual building loads can be saved to a later point of time in a single heat buffer. By this, mismatches between available solar gains and buildings loads can be balanced without the use of backup energy. 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. This results in a lower energy storage capacity per volume of the storage container.

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, these conditions will certainly change in future – even in countries which today have a high feed-in tariff. Reasons are on the one hand the significant cost reduction for PV modules and on the other hand the increasing grid capacity and operation management problems in grids with a high and increasing amount of fluctuating electricity generation from renewable sources such as solar and wind energy.

3. Case study – a solar heating and cooling system for a hotel building

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]. These systems cover a wide range of used technologies, implemented system designs, sizes and applications. For a systematic analysis of the potentials and limits for the application of solar heating and cooling systems in the following results of a computer study are presented. Energy performance and cost issues of a solar heating and cooling system have been assessed for a virtual hotel building. The performance of a solar thermal heating and cooling system for this hotel building has been studied for various climatic conditions and more in depth for one selected site (Malta). This study focuses only on solar heating and cooling systems using solar thermal collectors. PV based solutions are still scarce and no general trends on their design and operation strategy are existing. The design as well as the operation strategy will strongly depend on the price policies of utilities for selling and purchasing electricity. For instance electricity tariffs with diurnal profiles may influence which types and sizes of storages are installed. Therefore future work will certainly include design studies for PV based systems.

3.1. Modelling approach

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

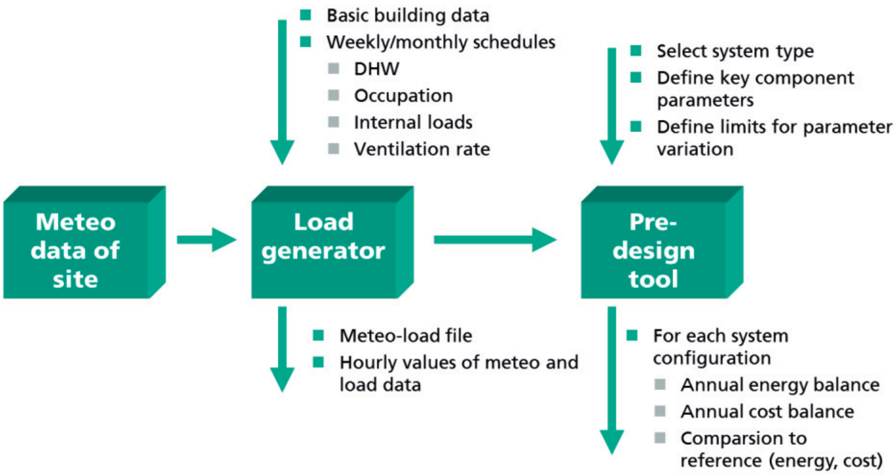


Fig. 7. Modelling approach

Meteorological data of different locations were generated with the software Meteonorm 6.1 [9]. An overview on the used locations is given in Table 1.

Table 1. locations used in the simulation study

Site	Load for hotel example (see section 3.2)		Energy demand for conditioning of ventilation air per 1000 m³/h			Solar irradiation on collector
	Heating	Cooling	Heating	Cooling, sensible	Cooling, latent	
	kWh/(m²a)	kWh/(m²a)	MJ/a	MJ/a	MJ/a	kWh/(m²a)
Beijing (CN)	139.5	45.0	24.5	5.2	10.6	1748.2
Denver (US)	148.4	15.7	27.8	3.0	1.0	1943.5
Freiburg (D)	141.0	8.2	26.6	1.4	3.2	1228.9
Malta (MT)	24.1	57.4	8.7	5.5	13.1	2162.9
Melbourne (AU)	67.1	9.9	18.9	2.0	3.1	1687.7
Minneapolis (US)	206.7	17.5	34.2	2.4	5.1	1696.7
Perth (AU)	16.4	27.9	9.4	4.6	4.9	2037.5
Phoenix (US)	16.9	147.4	6.7	17.2	2.7	2308.7
Portland (US)	113.5	6.6	23.8	1.3	1.7	1452.9
Sapporo (JP)	201.1	9.0	34.1	0.9	4.6	1388.7
Shanghai (CN)	70.9	75.0	6.9	6.9	20.9	1296.2
Tampa (US)	6.2	121.2	4.0	11.2	31.2	2016.2
Tokio (JP)	65.1	49.9	14.2	5.5	14.2	1292.1

Description of the values in the columns of Table 1:

- Column 2: annual heating demand for the hotel example (see section 3.2)
- Column 3: annual cooling demand for the hotel example (see section 3.2)
- Column 4: theoretical energy demand for sensible heating of ventilation air for an assumed constant ventilation air flow of 1000 m³/h calculated according to

$$Q_{heat,sens} = \sum_{h=1}^{8760} \dot{V} \cdot \rho \cdot (c_{p,air} + x_{amb} \cdot c_{p,vap}) \cdot (T_{vent,set} - T_{amb})^{+}$$

with $\dot{V}$ = constant air volume flow (1000 m³/h)
ρ = air density
$c_{p,air}$ = specific heat capacity of dry air
x_{amb} = humidity ratio of ambient air
$c_{p,vap}$ = specific heat capacity of water vapour
$T_{vent,set}$ = set temperature of supply air (20°C)
T_{amb} = ambient air dry bulb temperature

The $^{+}$ indicates that the bracket is only taken for positive values and is set 0 for negative values.

- Column 5: theoretical energy demand for sensible cooling of ventilation air for an assumed constant ventilation air flow of 1000 m³/h calculated according to

$$Q_{cool,sens} = \sum_{h=1}^{8760} \dot{V} \cdot \rho \cdot (c_{p,air} + x_{amb} \cdot c_{p,vap}) \cdot (T_{amb} - T_{vent,set})^{+}$$

- Column 6: theoretical energy demand for latent cooling of ventilation air for an assumed constant ventilation air flow of 1000 m³/h calculated according to

$$Q_{cool,lat} = \sum_{h=1}^{8760} \dot{V} \cdot \rho \cdot r_0 \cdot (x_{amb} - x_{vent,set})^{+}$$

with r_0 = evaporation enthalpy of water vapour
$x_{vent,set}$ = set point of humidity ratio of supply air (8.5 g per kg of dry air)

- Column 7: irradiation on collector pane (assumed tilt angle 45°C)

The used locations cover a broad range of climatic conditions from strongly heating dominated climates to strongly cooling dominated climates. Among the cooling dominated climates some are characterized by large latent loads, such as Tampa, Shanghai and Malta. Figure 8 shows a comparison of the sites regarding meteorological conditions calculated according to the equations above.

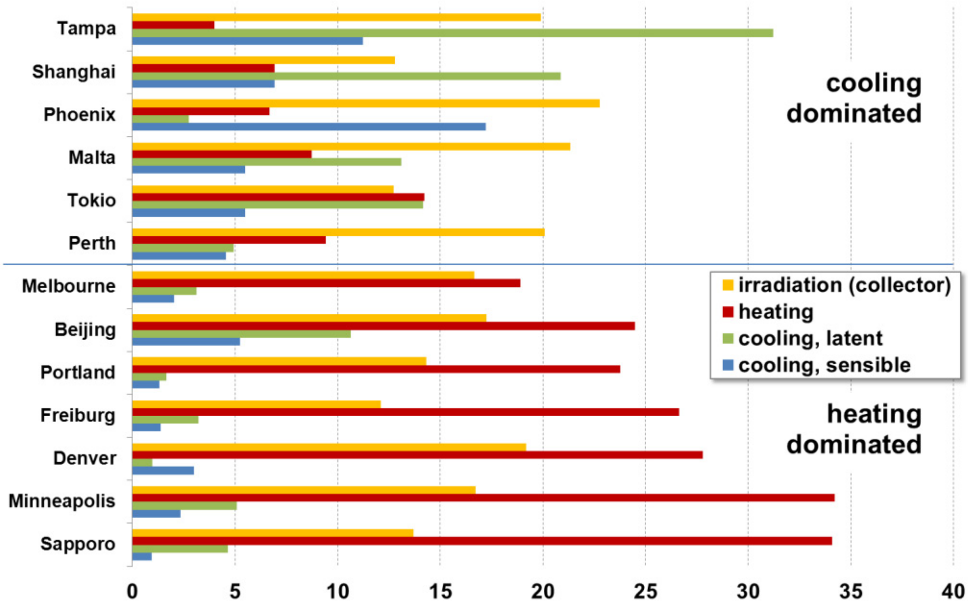


Fig. 8. comparison of the investigated locations; the red, green and blue bars correspond to columns 4, 5 and 6 of Table 1

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 each of the selected locations. For this purpose the 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 9 and described e.g. in [10]. 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 modelling of the respective technical system.

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 also 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 is simulated by a single node, 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 [11]. In addition for an economic analyses 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 may be computed.

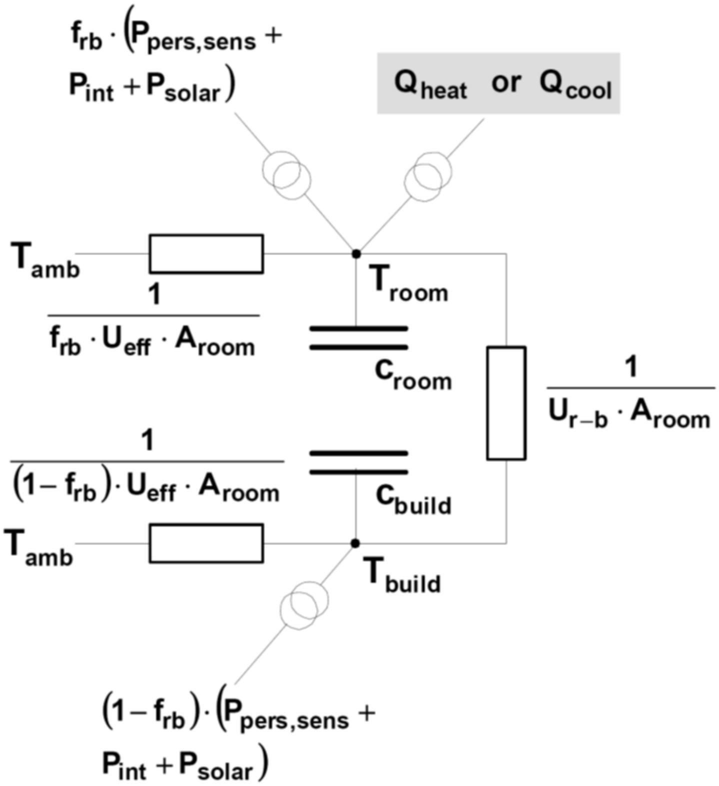


Fig. 9. 2C-3R-model for a building zone used in the Load Generator

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 calculations are displayed in columns 1 and 2 of Table 1 for all investigated locations; these values comprise the annual total heating and cooling load of all four zones. More details are shown for the location Malta in Table 2 and the annual load duration curves which result under the climatic conditions in Malta are shown in Figure 10. The shown values and curves correspond to the following loads: the heating demand (denoted “heating” in Figure 10); 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 2. Summary of load data (peak values and annual totals) for the hotel (total of 4 zones) in Malta

	Peak demand		Annual Demand		Full load hours 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

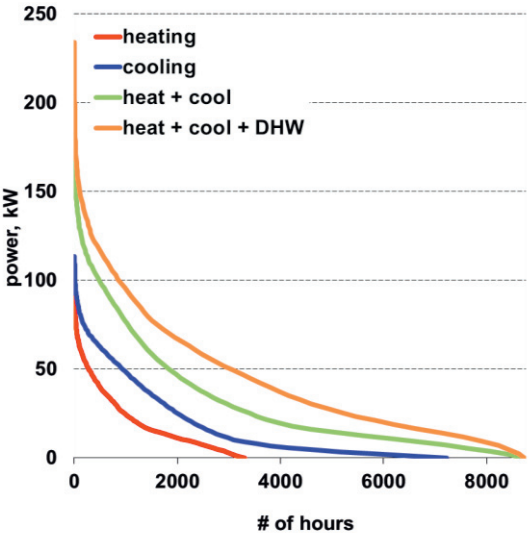


Fig. 10. Annual load duration curve for the hotel building in Malta

3.3. Basic assumptions

The assumptions used for all technical specifications and cost values are summarized here. A flat plate collector was assumed with the following collector parameters: c_0=0.81, c_1=3.0 W/m²K and c_2=0.006 W/m²K². A thermally driven chiller with an average thermal COP of 0.68 was assumed. The back-up electric vapour compression chiller was assumed to have an average COP value of 3.0 and the boiler an average efficiency of 0.9, related to the upper heating value of the fuel. For the cooling tower was assumed that in average 40 Wh of electric energy are used per kWh of heat rejected to the environmental air; this value refers to well designed and operated wet cooling towers.

3.4. Assumptions used for the detailed cost analysis for the example of the hotel in Malta

Cost curves of key components used in the calculations are shown in Figures 11 and 12. These data are based on a Delphi survey that has been carried out among many experts working in the field of solar cooling [8].

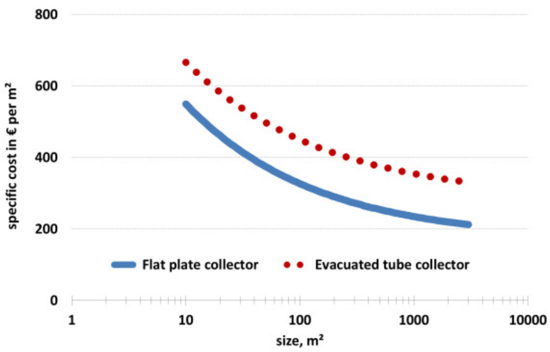


Fig. 11. Cost figures of solar thermal collectors (without installation cost)

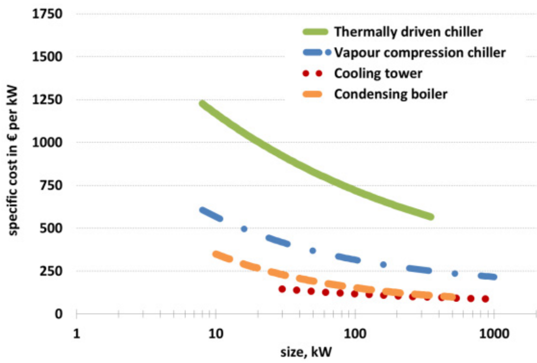


Fig. 12. Cost figures for other components used in the simulation study

Other major cost and conversion efficiency values used are summarized in Table 3.

Table 3. Values of parameters used in the economic analysis

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

4. Results

In the following results of extensive simulation studies are presented. First the energy performance of the solar heating and cooling system design for a hotel building is investigated under various climatic conditions. Then a more detailed analysis is carried out for one single site (Malta). Here the primary energy saving and cost is compared to a conventional system using fossil fuels for heating and domestic hot water production and a conventional vapour compression machine for cooling.

The following control strategy for the solar heating and cooling system has been implemented in all simulations: first priority for discharge of heat from the buffer storage is given to the heating system, since heating requires the lowest temperature (40°C) when compared to domestic hot water (55°C) and driving of the thermally driven cooling (80°C). Second priority is given to domestic hot water and third priority is given to drive the thermally driven cooling.

4.1. Solar fraction and specific final energy saving

In this section solar fractions for heating, cooling, domestic hot water and total solar fraction are compared for the hotel building at the different locations outlined in section. Therefore simulation for different collector sizes (150…750 m², varied in steps of 150 m²), storage sizes (30…80 litre per m² of collector, varied in steps of 12.5 litre per m²) and sizes of the thermally driven chiller (0…60 kW cooling capacity, varied in steps of 15 kW) were carried out.

Solar fractions for heating, cooling and domestic hot water (DHW) are defined as follows:

$$f_{solar,i} = \frac{(Q_i - Q_{i,back-up})}{Q_i} = 1 - \frac{Q_{i,back-up}}{Q_i}$$

i stands for heating, cooling or DHW, respectively; Q_i is the annual energy demand for heating, cooling or DHW, respectively, and $Q_{i,back-up}$ is the heating, cooling or DHW demand which is covered by the back-up source, respectively.

The total solar fraction, $f_{solar,tot}$, is calculated according to

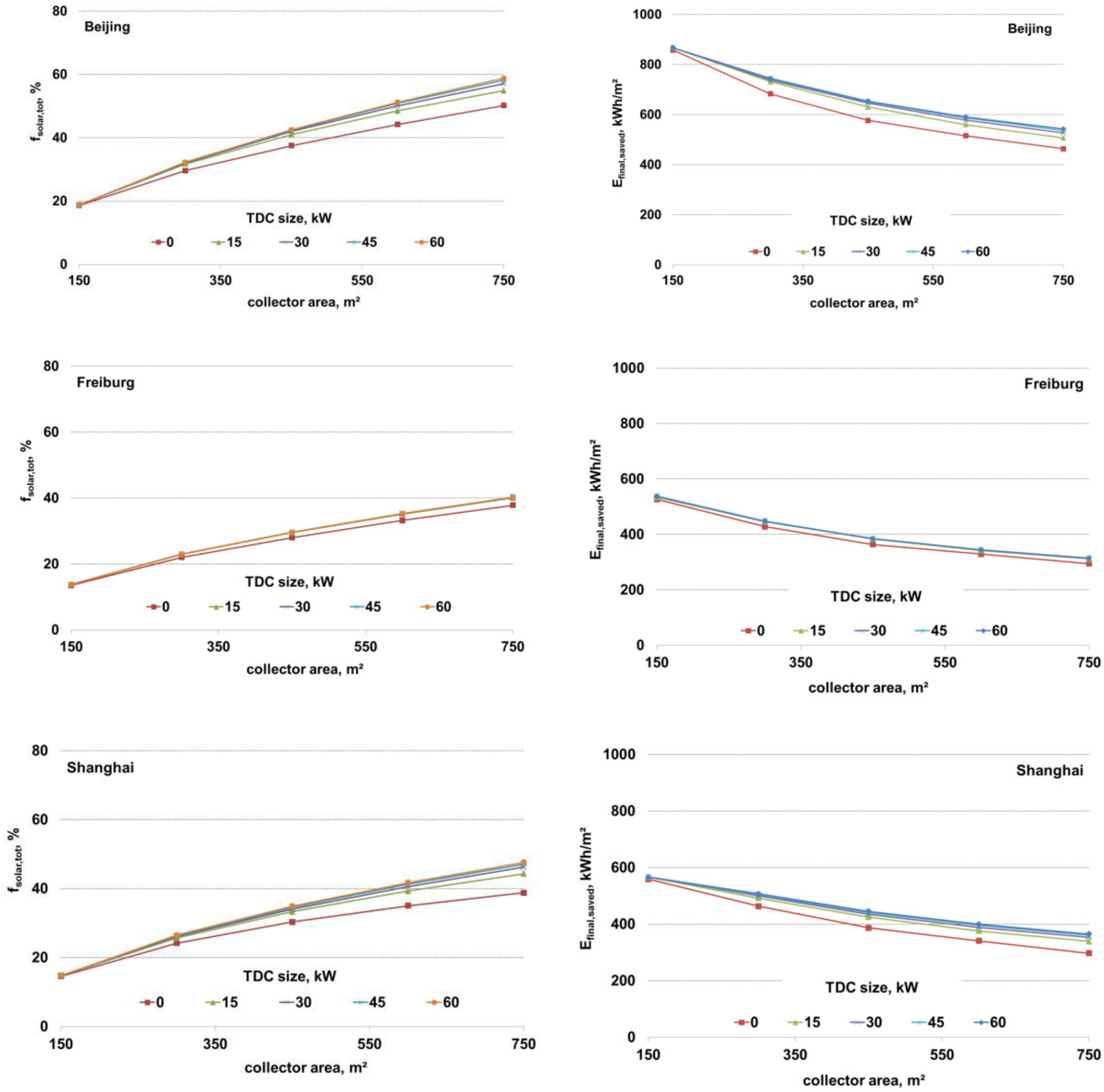
$$f_{solar,tot} = \frac{(Q_h + Q_c + Q_{DHW}) - (Q_{h,back-up} + Q_{c,back-up} + Q_{DHW,back-up})}{(Q_h + Q_c + Q_{DHW})}$$

It expresses the fraction of the total heating, cooling and domestic hot water load covered by the solar thermal system.

A second important parameter to assess system performance is the specific final energy saving, defined as the annual final energy saved per unit of collector area:

$$E_{final,saved} = \frac{((Q_h + Q_c + Q_{DHW}) - (Q_{h,back-up} + Q_{c,back-up} + Q_{DHW,back-up}))}{A_{coll}}$$

Figure 13 shows the total solar fraction, $f_{solar,tot}$, and the specific final energy saving, $E_{final,saved}$, for six selected locations from both, heating and cooling dominated climates.



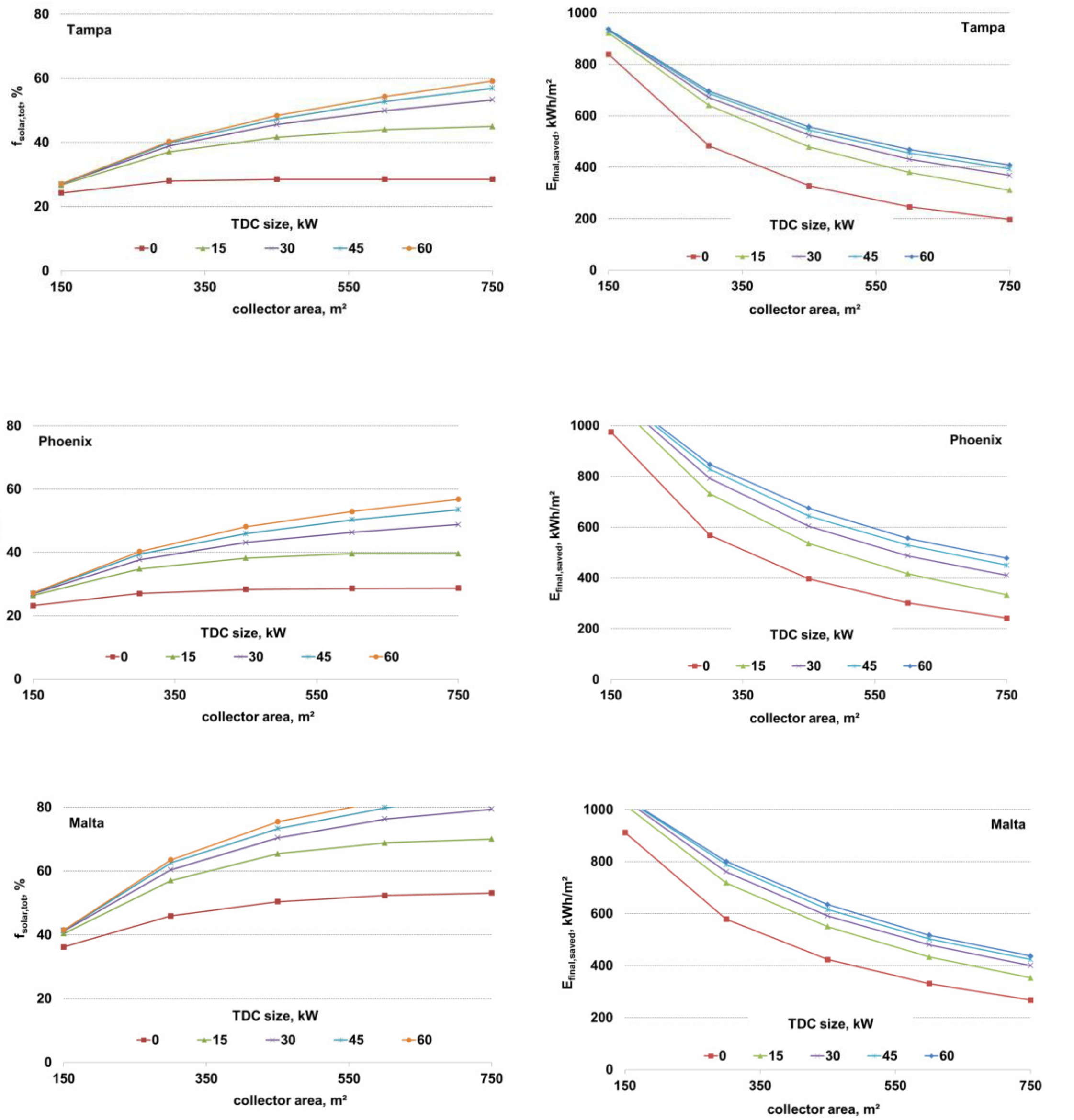


Fig. 13. Solar fraction (left) and specific final energy saving (right) for 6 selected locations; all results correspond to the load profile of the hotel example. In all presented results a storage size of 55 litre per m² of collector has been chosen

Main conclusions that can be drawn from Figure 13 are:

(1) For all climates the design of a solar heating and cooling system has to compromise between a high solar fraction and high (final) energy saving per unit of solar collector.

(2) Significant differences exist between the locations. For instance in Malta a high total solar fraction of more than 80 % can be achieved with the investigated system sizes while in Freiburg it turns out difficult to achieve a solar fraction much higher than 40 %.

(3) Mainly in the cooling dominated climates such as Malta, Tampa and Phoenix adding a thermally driven chiller to a solar thermal collector system leads to a significant increase of the total solar fraction. For instance in the case of Malta the total solar fraction increases from 50.4 % (without thermally driven chiller) to 65.4 % for a collector area of 450 m² if a small thermally driven chiller of 15 kW is added and increases up to 75.5 % if a thermally driven chiller of 60 kW is used.

Figure 14 shows for each location the required collector area that is needed to achieve a total solar fraction of 60 %; for these simulations again a storage size of 55 litre per m² of collector was used. The size of the thermally driven chiller was set as 25 % of the maximum cooling load of each location and year. Large differences occur for the different locations and in some places (e.g. Freiburg, Sapporo) very large areas are needed to achieve this value. Figure 15 shows the saved final energy per collector unit for the same design, i.e. a system layout which leads to a total solar fraction of 60 %.

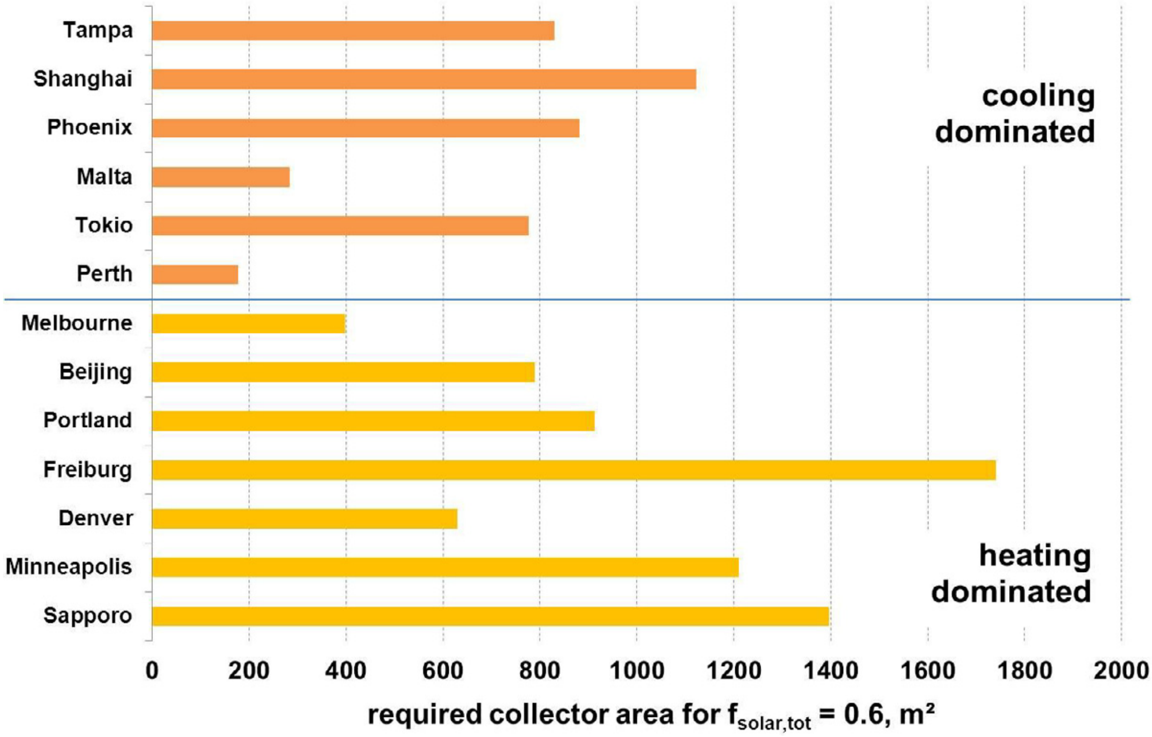


Fig. 14. required collector area to achieve a total solar fraction of 60 %

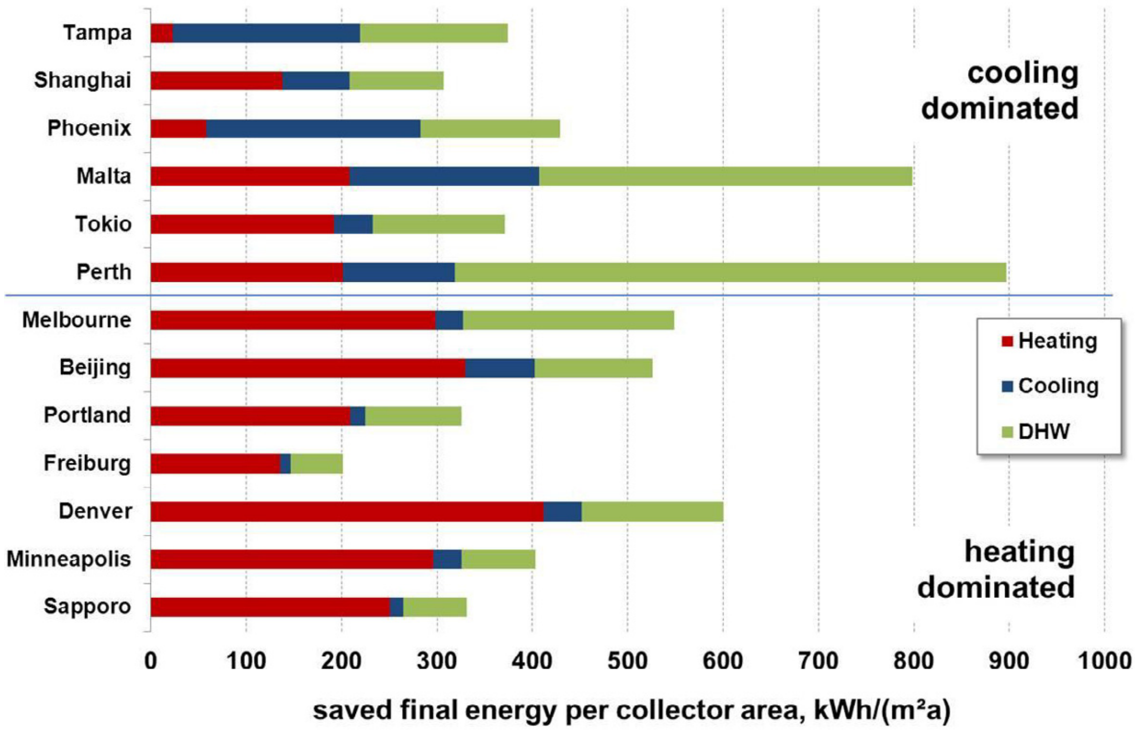


Fig. 15. specific saved final energy at all sites for a design that leads to a total solar fraction of 60 %

The above analysis shows clearly that it is not sufficient to assess the achievable solar fractions and saved final energy per collector area in order to obtain a clear result about the "best" size of key components. For this purpose a more comprehensive approach is needed which includes a more in-depth analysis of the overall energy balance including electricity consumption of all auxiliary components and which includes the analysis of corresponding life cycle cost of the overall system. Therefore a primary energy analysis and life cycle cost analysis is carried out for one location (Malta) in order to demonstrate the approach and provide detailed results for this example.

4.2. Primary energy saving

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 16. In order to be able to compare different systems which use both forms of energy, electricity and fuel, all energy values have been converted into their corresponding primary energy values; the values of the conversion factors are shown in the last two lines of Table 3.

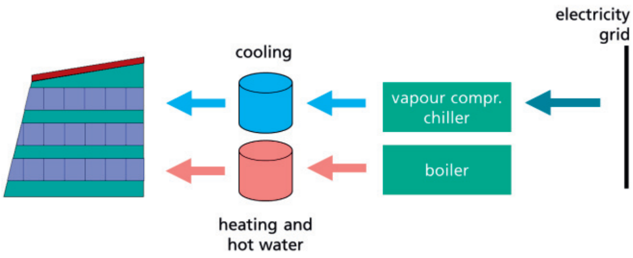


Fig. 16. Conventional reference system

Figures 17 and 18 show the system boundary for the primary energy balance for the reference system (Figure 17) and the solar thermal solution (Figure 18).

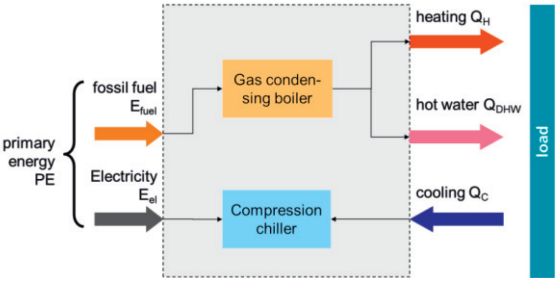


Fig. 17. System boundary for the reference solution

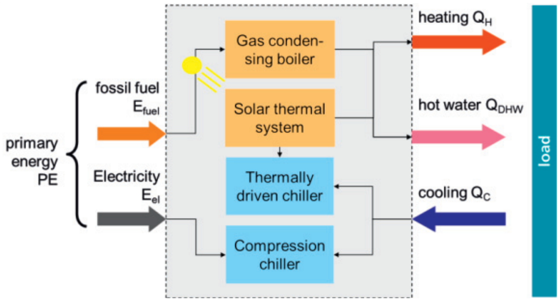


Fig. 18. System boundary for the solar thermal solution

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

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

where 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 as

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

The results of a broad parametric study lead to the results shown in Figure 19. The solar collector size was again varied in a range from 150 m² up to 750 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 and the size of the thermally driven chiller was varied in a range from 0 kW up to 60 kW. 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 (see Figure 19). A further increase of the collector size above approximately 450 m² does not lead to a significant further reduction of the primary energy consumption, i.e. a typical saturation behaviour occurs. 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.

The primary energy saving shown in Figure 19 does not achieve as high values as the total solar fraction shown for the same site (Malta) in Figure 13. The reason is that in the primary energy balance also the electricity demand of auxiliary components – in particular the cooling tower pump and fan – is taken into consideration.

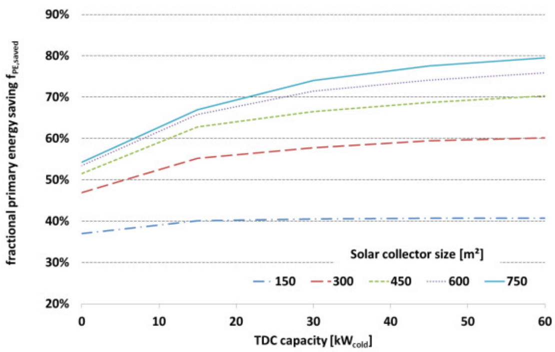


Fig. 19. Fractional primary energy saving of the solar heating and cooling system for the example of the hotel in Malta

4.3. Economic analysis

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 20 compares first cost for the complete system including planning and installation cost (100 % states the value of the conventional reference).

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 21. 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 17. For all other collector sizes there exist certain values of the thermally driven chiller that lead 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 %

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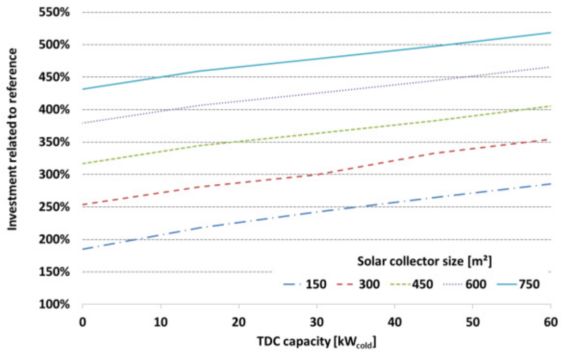

Fig. 20. Investment for solar heating and cooling solutions compared to the reference (reference investment = 100 %)

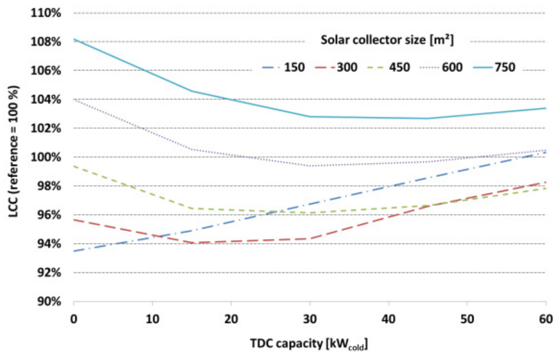

Fig. 21. Life cycle cost of solar heating and cooling solutions, normalized to the life cycle cost of the reference system (100 %)

This example shows that only a holistic analysis which includes an extensive energy balance including the electricity consumption of all auxiliary components and a cost analysis that takes the whole system lifetime into consideration allows the decision on sizes of key components such as the solar collector and the thermally driven chiller. In the example of Malta and for the load profile of the example hotel a reasonable design is for instance a system with a collector area of 450 m² and a thermally driven chiller with a capacity 30 kW. This design 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 and outlook

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, cooling and sanitary hot water; in these cases a year-around use of the solar collector system is possible. Therefore hotels seem to be a promising application sector for solar heating and cooling.
- 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. This is again particularly given in climates which need both heating and cooling.
- Economics will be most favourable in places with high cost of conventional energy.
- In most cases it turns out sensible to install a thermally driven chiller that is much smaller than peak cooling load. This thermally driven chiller mainly covers base load and thus achieves a large number of annual operation hours. Peak cooling loads should be covered by a conventional vapour compression machine.

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 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 and vapour compression chillers will gain increasing attention due to decreasing prices of PV modules on the one hand and increasing needs for maximizing electricity consumption of locally produced electricity in order to minimize negative grid impacts on the other hand.

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