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**A cost-optimal solar thermal system for apartment buildings with
district heating in a cold climate**

Vahid Arabzadeh, Juha Jokisalo and Risto Kosonen

*HVAC Technology, Department of Mechanical Engineering, School of Engineering,
Aalto University, P.O. Box 14400, FI-00076 Aalto, Finland*

Corresponding author: Vahid Arabzadeh, vahid.arabzadeh@aalto.fi

Dr, Juha Jokisalo, juha.jokisalo@aalto.fi

Professor Risto Kosonen, risto.kosonen@aalto.fi

A cost-optimal solar thermal system for apartment buildings with district heating in a cold climate

Finding the global optimal combination of the main components for a solar thermal energy system is an important topic in utilizing solar radiation in a cost-effective way. However, selecting an optimal solar thermal system in a cold climate condition is a challenging task due to the dependency on the heat demand and the limited availability of solar radiation. This research presents several sets of optimum combinations of a solar thermal collector and a hot water storage tank regarding energy efficiency and the life cycle cost for a typical Finnish apartment building. Since domestic hot water consumption forms the significant part of the heat demand in new energy efficient apartment buildings, the applied consumption information were extracted precisely according to measured data. A multi-objective optimization algorithm as NSGAI was implemented to search for global optimal values for selected decision variables. The decision variables were considered as the hot water storage tank volume, the solar thermal collector area and the tilt angle. Based on the results, by using the measured domestic hot water consumption data and through various economic scenarios, the cost-optimal ratio of the solar thermal collector area and storage tank volume was achieved as 16 m²/m³ to 21 m²/m³. The solar thermal system with cost-optimal component sizes was able to save district heat energy consumption up 24% to 34% and made 4 €/m² to 23 €/m² in financial profit in the studied apartment building.

Keywords: Solar thermal collector; Hot water storage tank; Optimization, Life cycle cost; Energy efficiency; Apartment building.

1 Introduction

The European Council in 2012 planned to reduce greenhouse gas emissions about 80% to 95% and to increase the share of renewable energy at least 55% in gross final energy consumption by 2050 (Oettinger 2012). Since integrating renewable energy sources with apartment buildings provides opportunities to enhance energy efficiency and decrease CO₂ emissions, applying the solar thermal energy system is becoming important. Implementing solar energy is a challenging task because of the difficulties in optimal matching heat energy demand with the restricted on-site energy generation. An important part of the optimal utilization of the solar thermal energy is to define the proper size of the system components. For this purpose, an analysis of the solar thermal energy system with realistic input data and implementing global optimization methods is inevitable.

Energy analysis and optimization of solar thermal systems have been extensively concentrated on in the literature. The performance and evaluation of the utilization of solar thermal systems have been investigated in several studies. The performance of the solar heating system using two different storage strategies has been compared by experimental and simulation results (Abdul Jabbar 2010). The results showed the superiority of the presented storage system for the solar collector. The solar thermal collector has been simulated for domestic hot water consumption (HWC) (Dongellinia 2015). Optimization of the parabolic collector has been conducted through applying experimental data (Venkataramaiah 2013). The collector parameters were absorber materials, positions of the absorber tube and angle of the absorber tube. The maximum heat gain from the solar collector has been calculated based on the optimal slope angle under the climate condition in Iran (Abdolahzadeh 2011). The effect of different

parameters such as the consumption profile, the tank volume and the collector area have been analysed. An advanced control strategy has been developed for a heating energy system, including a solar domestic hot water system and an auxiliary heater (Homme 2001). Optimal collector parameters have been determined by implementing experimental data (Ghoneim 2016). The parameters have been considered as the collector tube length and diameter, the mass flow rate and the collector tilt angle. The control algorithm increased the potential of using onsite energy generation; however, this depended on the quality of the building and environmental information. Energy performance has been studied for two domestic solar water heaters with drain water heat recovery units (Tanha 2015). The simulation and experimental results showed that the proposed system could support an annual heat recovery of 789 kWh with 50% overall effectiveness. The application of a solar heating system has been studied for supporting the domestic hot water and space heating in Sweden (Lundh 2009). Performance of a solar heating system has been optimised for hot climate conditions (Hasan 2007). The decision variables have been set as the tank volume, the tilt angle, and the collector location.

In these studies, the solar thermal system has been studied for both detached houses and apartment buildings in terms of energy efficiency, control strategies and modelling. The studies have shown that the performance of the solar thermal system depends on the building type, the climate condition and the level of heat demand. The main outcome of these studies have emphasized that the operation and configuration of a solar thermal system should be investigated for different building types. In a cold climate condition, the application of a solar thermal system would be more challenging due to limited access

to solar radiation. Several studies have discussed integrating the solar thermal energy system with the heat pump or the photovoltaic system to improve the energy efficiency of buildings. A comparison has been performed between a photovoltaic, a thermal collector and a photovoltaic-thermal collector (Good 2015). The results showed that using a high efficiency photovoltaic system is more beneficial. The integration of a heat pump and a solar collector has been investigated for a heating energy system (Banjac 2015). The studied system also included the underground tank; its burial depth, tank size and the initial water temperature have also been analysed. The performance of the solar heating system has been checked in combination with a heat pump for heating buildings (Eicher 2012). The simulation results have been validated with a series of practical tests. A novel configuration has been presented for a heat pump and photovoltaic/thermal collectors (Calise 2016). The new system has been depended on the performance of the applied solar system, and it could be profitable with a capital investment subsidy of 50%. The application of a solar heating system has been tested with the heat pump system for residential heating (Bakirci 2013). It has been found that the system was compatible with a cold region in Turkey. A different combination of a solar heating system has been investigated with a heat pump (Lerch 2015). Parallel and serial solar HP systems for heating purposes in buildings have been evaluated through simulations. Based on the results, the parallel system showed a significant reduction in electricity consumption. In the mentioned studies, integration of solar thermal energy system with the other onsite energy generation sources has also improved the problems due to the time difference between solar energy generation peak and the energy demand for space heating or domestic hot water (DHW) consumption. In all of the mentioned studies, the definition of the heat demand for the studied buildings has been one of the main parts of study. Since

a significant part of the heating load in new apartment buildings has been devoted to heating the DHW, applying realistic and relevant data for DHW consumption can have significant effect on the performance of a solar thermal system. Based on (Ahmed 2015), the average DHW consumption in Nordic countries is 36 L/person/day in apartment buildings, while in Finland this value stands at 46 L/person/day. However, (Ahmed 2015) has also discussed that when referring to measurement data due to a variety in the number and behaviour of occupants, different values could be achieved for the level of DHW consumption. For example, in the same study, the estimated annual Finnish DHW consumption based on measured data of 182 Finnish apartments with 379 occupants is 43 L/person/day. Multiple studies have also estimated and defined the DHW consumption in different locations and different buildings.

Domestic hot water consumption has been measured for Canadian houses by monitoring the hot water flow rate, occupancy and temperature data in 119 homes at a time-step of 1 minute (George 2015). Historical data for hot water consumption has been used for predicting demand (Lomet 2015). In addition, to study the trend of hot water consumption, an ARMA model has been applied to forecast daily hot water consumption demand. Hot water consumption has been investigated in an apartment building in Estonia (Koiv 2001). Data of 113 buildings have been measured to define the rate of hot water consumption per occupant. The level of consumption has been described as 55 litres/day, with a 95% confidence interval of ± 18 litres/day. Daily hot water consumption has been analysed to provide reliable estimation (Parker 2015). Several parameters such as the occupant number, the age and the environmental condition have been considered

for explaining the rate of consumption. Nevertheless, a few of the studies have considered the measured data in the optimization of the system.

For optimizing a solar thermal system by the measured DHW consumption data, a parametric analysis has been carried out regarding energy efficiency and CO₂ emission (Hidalgo 2012). In addition, the size of main components for solar thermal system has been investigated by a parametric analysis to define the optimal energy efficient system for residential and service buildings (Li 2015, Yan 2015). The ratio of tank volume to collector area has been defined as being between 50 and 70 L/m² by applying the experimental data (Çomaklı 2012). A parametric analysis has been applied to define the optimal operation of a solar thermal system according to the life cycle cost and the energy performance of the system (Ibrahim 2014, - Testi 2016). For defining the optimal solar thermal system under a cold climate condition, a part of the literature has concentrated on the efficiency of the system or the optimal energy storing strategy (Omu 2016, Hugo 2012). An optimal integration of a solar thermal system has been investigated with other onsite energy generation systems such as a heat pump or a photovoltaic system (Tamayo 2014, Lindenberg 2000). The main fact learned from the studies is the assumption about the energy demand and the building application having a possibly significant effect on the results. Moreover, where LCC has been used as a measure to define the optimal energy system, considering different scenarios with different interest rate values becomes important (Eisenberger 1977).

Reviewing the literature shows that the available studies of a solar thermal collector application do not properly cover global optimization of a solar thermal system in cold

climate conditions. First, in most of the studies, optimization has not been carried out by realistic DHW consumption data or global searching methods. The methodology of defining the optimal system in the literature was mainly according to a parametric analysis that is not able to find a globally optimal solution. Secondly, defining the optimal solar thermal system for apartment buildings in cold climate conditions has not been addressed in the literature. The novelty of the current study is the application of the multi-objective optimization procedure to define an optimal solar thermal system for an apartment building in cold climate conditions by implementing the measured DHW consumption.

Since the non-dominated sorting genetic algorithm (NSGAI) searches for a globally optimal set, this study has used it to define the global cost-optimal solution for solar thermal system specifications under cold climate conditions. A Finnish apartment building with a district heating system is simulated with IDA-ICE dynamic simulation (Björnsell 1999) regarding the measured hot water consumption profile. The present study has considered the combination of a solar thermal system and the district heating as one of the suitable candidate heating systems for Finnish apartment buildings. A multi-objective optimization procedure has been implemented to find the pareto front between energy performance and life cycle cost (LCC). The optimization has been carried out by using three decision variables: the solar area, the panel's tilt angle, and the tank volume.

2 Building description

2.1 Studied building

The studied building describes a typical Finnish apartment building according to Saari et al. (Saari 2017). The studied apartment building is located in Helsinki, and the heated net floor area of the building is 1594 m², and it has 4 floors. The main geometry of building was shown in Fig. 1. The U-value for the external walls is 0.17 W/(m² K), for the base floor 0.16 W/(m² K) and for the roof 0.09 W/(m² K). Moreover, the total U-value of the windows is 1.0 W/(m² K).

The main internal heat gains of the building come from the lighting, the equipment and the occupants. The characteristics for the internal heat gain were presented in Table 1. These values were defined based on the standardized usage of the apartment buildings defined by the Finnish building code D3 (D3 2012). The number of occupants of the studied building was 57, based on the occupancy density defined by the Finnish building code D3.

2.2 Heating and ventilation system

The solar thermal system was implemented in the studied building for producing heat to the DHW, the spaces and the ventilation with the district heating system. The focus of the current study was on the dimensioning of the hot water storage tank and the solar thermal collector. In the studied system for auxiliary heating, the district heating system was considered to compensate for the heating energy when the solar radiation was not enough.

The schematic of the simulated heating system is shown in Fig. 2. The control for connecting the solar thermal collector to the storage tank includes two main parts, the PI controller and the thermostat. The mentioned control principle was shown in section A of Fig. 2. The strategy of the control is to maximize the solar thermal heat utilization. The set point for the PI controller was defined as 5 °C, which deals with the temperature difference between the inlet and the outlet of the solar thermal collector. The thermostat set point was set as 95 °C, which guarantees the tank is never overheated more than its assigned upper limit. A flat type of solar thermal collector was implemented in this study. The efficiency of the solar thermal collector was assigned as 0.92, based on the solar radiation conversion factor of a commercial product (Niemelä 2014). The longitudinal and tangential incident angle modifiers were 0.95 (at 50°C) for modelling the biaxial behaviour of the collector.

In this system, the fluid in the solar circuit was applied for a solar heat exchanger tagged as HXstc in Fig. 2; and in this way, it was separated from the water of the tank. The conductance of the heat exchanger connected to the solar thermal collector varied as a function of the solar thermal collector area as follows:

$$K = a(A_{sc}) \quad (1)$$

where a is the heat transfer coefficient 184 (W/m² K) and A_{sc} is the area of solar collector (m²). For the tank, the PI controller, located in section B, was connected to the auxiliary heating and the tank to keep the temperature of the upper layer of the tank between 60 and 70 °C depending on the temperature level of water needed in the building. The PI

controller receives temperature data measured from the top layer of the tank and the variable set point temperature of the tank. Section C of Fig. 2 shows the connection of the storage tank with the DHW system, air handling unit and space heating system. For the DHW, the separated heat exchanger, tagged as HXdhw, was used inside the tank to prevent the mixing of DHW with the water inside the tank and providing the water at 55 °C. The heat loss for the circulation of DHW was taken into account according to the guidelines of D5 as $0.43 \text{ W}/(\text{m}^2_{\text{floor}})$ (D5 2007). For the space heating, the inlet water temperature was controlled according to the control curve shown in Fig. 3, and the dimensioning temperatures of the radiators are 70/40 °C. The set point for space heating is 21.0 °C. For the inlet water temperature of a reheat coil of the air handling unit, the constant temperature set point at 60 °C was implemented.

The building includes a mechanical supply and exhaust ventilation system with heat recovery. The air handling unit operates in a constant air volume (CAV) mode, and the temperature efficiency of the heat recovery unit was defined as 75%. Moreover, the constant supply and exhaust airflow rates of the building were defined as $0.5 \text{ dm}^3/(\text{s}, \text{m}^2)$.

2.3 DHW consumption

In this section, two main features for modelling the DHW consumption were defined as the level of consumption and the consumption profile. The applied levels of consumption for the optimization part were assigned based on the Finnish building code D3 (D3 2012) and measurement data. The measured data were gathered from 16 buildings studied by Koivumäki (Koivuniemi 2005), where the number of apartments was changing from 28 to 220 and the number of occupants varying from 38 to 343. The

average daily hot water consumption is 67 L/occupant/day based on measured data, while it is 47 L/occupant/day according to the Finnish building code. The heat energy demand of DHW with the above-mentioned consumption levels are 50 and 35 kWh/(m²,a) if the temperature difference between the hot and cold water is 50 °C. In this article, both DHW consumption levels were used in the optimization of the system described in section 2.2. Two different periods, winter and summer, were defined for the analysis of the DHW data. The summer period covers June, July and August, and the winter period includes the other nine months. The daily average of DHW consumption of the studied apartment buildings during the summer and winter periods was demonstrated in Fig. 4.

The levels of hot water consumption discussed were applied in the study by means of the extracted consumption profile from the measured data. Fig. 5 explains the process of defining the DHW consumption profile.

The measured data in (Koivuniemi 2005) were recorded based on a 5-second time interval. In the first step, the data was scaled up to one-hour time resolution by calculating the average of the relevant samples values. Then for recognizing the general profile of DHW consumption, a 24-hour framework was applied to detect and eliminate unusual cases. For all apartment buildings, available data were grouped as days of the week, and then they were categorized according to two new groups: weekdays and weekends including Saturday and Sunday. The weekdays and weekends were again divided into two periods: summer and winter. In the final stage, to find out the profile of DHW consumption, the outlier data should be removed. To filter the measured data, one

standard way is defining and displaying the first quartile, median and third quartile from the distribution of the data. To achieve the distribution of the data, the sample days of all the buildings were plotted at the same time for all the mentioned groups. In Fig. 7, the distribution of the DHW consumption data was shown in addition to the mentioned limitations. The interquartile range (Seltman 2012) as IQR could be defined based on the difference of the first and the third quartiles as

$$\text{IQR} = \text{qu}_3 - \text{qu}_1 \quad (2)$$

where qu_3 is the third quartile (L/h/Occupant) and qu_1 is the first quartile (L/h/Occupant).

The outlier data are those points that are beyond the quartiles by one-and-a-half IQRs. After filtering the data by the discussed limits, the DHW consumption profile could be recognized. The box plot technique (Seltman 2012) uses the defined logics about quartiles, and it is able to identify the outlier data through the distribution of the data. The analysed profiles used in the simulations are shown in Fig. 7.

3 Methodology

3.1 IDA ICE simulation tool

The simulations of the studied building and the systems were carried out with the IDA-ICE dynamic simulation tool. This software allows the modelling of multi-zone buildings, HVAC and solar systems, internal and solar loads and outdoor climate; and the software

provides a dynamic simulation of heat transfer, air flows, thermal comfort, indoor air quality, infiltration and energy consumption in complex buildings. IDA-ICE was originally developed by the division of Building Services Engineering, Royal Institute of Technology (KTH), and the Swedish Institute of Applied Mathematics, ITM (Sahlin 1996, Sahlin 2004), but today the software is a commercial tool. The performance of this software has been validated in several studies, for example in (Travesi 2001, Loutzenhiser 2007).

3.2 Hot water storage tank

The non-ideal one-dimensional stratified storage tank modelling approach was used in this study with the IDA-ICE simulation software. The tank consists of 8 identical layers, the height of each layer being defined according the height of the tank. The dimensions of the tank and level of connections are shown in Fig. 8. The locations of the connections of the tank were adjusted according to the commercial storage tanks (Akvaterm Co. 2015).

To model the temperature stratification of the storage tank by the IDA-ICE simulation software, the appropriate mixing factor value was needed to model the heat transfer between the adjacent layers. The value of the mixing factor (12 W/mK) used in the study has been defined by means of experimental data in (Alimohammadisagvand 2016). The heat transfer between the adjacent layers of the storage tank model is

$$Q_i = A_t M_f (\Delta T_i / H_i) \quad \forall i \in [1, 2 \dots 8] \quad (3)$$

where A_t is a cross section area of the tank (m^2), M_f is the mixing factor (W/Mk), ΔT_i is the temperature difference between adjacent layers (K), and H_i is the height of each layer of the tank (m). The heat transfer between the bottom and the top of the tank is the aggregated heat transfer between the adjacent layers:

$$Q_t = \sum_{i=1}^n Q_i \quad \forall i \in [1, 2 \dots 8] \quad (4)$$

where n is the number of the layers. Since in this research the height of the tank was kept constant, the tank radius was changed according to defined variable boundaries to define different volumes.

3.3 Weather data

Finland belongs to the cold climate zone (D) according to the Köpper-Geiger climate classification (Peel 2007). Finland has also been divided into four climate zones (I–IV) according to the Finnish building code for the energy performance calculation of buildings (D5 2007). According to this country-specific classification, Helsinki is located in zone I, which is the southern-most climate zone in Finland. The hourly test reference year (TRY) which was applied in this study describes the current climatic conditions of climate zone I according to Kalamees et al. (2012). This test reference year was measured at the weather station of Helsinki-Vantaa airport by the Finnish Meteorological Institute. The annual average temperature of the applied weather data is $+5.4\text{ }^{\circ}\text{C}$, and the average degree-day number is 3952 Kd at indoor temperature of $17.0\text{ }^{\circ}\text{C}$.

3.4 Financial calculation

The LCC was set as the sum of the present value of investment and operating costs, including those related to maintenance and energy for heating over a specified life span. The utilized solar energy in the building was considered as profit in the LCC analysis. The life cycle cost for 20 years is determined as:

$$LCC_{20a} = \sum I_{0,tot} + \sum M_{tot} - \sum E_{tot} \quad (5)$$

where $\sum I_{0,tot}$ is the total investment cost of the studied systems (€), $\sum M_{tot}$ is the total maintenance cost of the studied systems (€), and $\sum E_{tot}$ is the financial value of saved purchased energy (€). In these terms, the consumed electrical energy for the pumping system of the solar thermal collector is also considered. The residual value of the studied systems after the 20-year discount period was not taken into account in the study. The maintenance cost can be explained as:

$$\sum M_{tot} = \frac{1-(1+r)^{-n}}{r} \times M_a \quad (6)$$

where r is the real interest rate, n is the discount period of the LCC calculation, and M_a is the annual maintenance cost (€). The profit from the utilized solar energy explains the cost saving due to replacing the district heating energy with the utilized solar thermal energy. This value can be calculated as:

$$\sum E_{tot} = \frac{1-(1+r_e)^{-n}}{r_e} \times E_a \quad (7)$$

where r_e is the escalated real interest and E_a is the annual financial value of saved purchased energy. The escalated interest rate was explained as:

$$r_e = \frac{(r-e)}{1+e} \quad (8)$$

where r is real interest rate and e is the escalation. The required parameters for the life cycle cost analysis were presented in Table 2. For the sensitivity analysis of LCC parameters, the applied values were also presented in Table 2.

3.5 Optimization method

The applied optimization method of this study was set as the non-dominated sorted genetic algorithm version II, which was used for defining the optimal set solution for multi-objective cases. The basic idea of the NSGAI is similar to the genetic algorithm in generating the population and searching the search space. The NSGAI is able to handle the multi-objective problems with two concepts as a non-dominated ranking and a crowding distance (Deb 2002). The optimization in this article was done by connecting the IDA-ICE simulation software with the MOBO (Multi-Objective Building Optimization) optimizer program. MOBO has been developed at Aalto University and the VTT technical research centre of Finland as the optimization software that could be connected to different simulation software (Palonen 2013).

3.6 Simulation-based optimization process

In simulation based multi-objective optimization, at least one of the fitness functions was evaluated with simulation software. Here the performance of the solar thermal system was checked using the IDA-ICE simulation software. Then the resultant cost function beside the cost function for the LCC forms the multi-objective optimization structure. Fig. 9 shows the whole procedure of the used simulation-based optimization.

4 Optimization of the solar thermal system

4.1 Optimization problem

The main aim of this article is to carry out a series of multi-objective optimizations that lead to optimal solutions regarding the performance of the solar thermal system and the LCC. The optimization case could be defined as

$$\text{Minimize } f(x) = \{f_1(x_1, x_2, x_3), f_2(x_1, x_2, x_3)\} \quad (9)$$

subject to $x \in S$

where f_1 is the cost function for the LCC (€), f_2 is the purchased district heating energy (MWh), S is a feasible set of decision vectors including the constraint functions, x_1 is the area of the thermal solar collector (m^2), x_2 is the tilt angle of the thermal solar collector, and x_3 is the volume of the hot water storage tank (m^3). Two functions were defined to search for optimal possible solutions for the solar thermal system. These two cost functions consider the optimal utilization of the solar thermal system regarding the LCC

during the life span. The first cost function deals with LCC, which was defined in section 3.3.

4.2 Optimized decision variables and cost data

Decision variables were considered as three parameters related to performance of the solar thermal system. The collector area, the tilt angle and the tank volume are decision variables that were used to search for the assigned design space. Each decision variable has a reasonable upper and lower limit. These limits are shown in Table 3.

The upper limits for the solar thermal collector area and storage tank volume were selected based on the limitation of available roof area and the available space in the technical room. The applied prices for the LCC calculation were extracted from available products and an inquiry of Finnish companies. For the thermal solar collector, the investment cost was divided into a constant and varying sections. The constant cost which covers the installation, piping, control system, pump and expansion chamber for the studied building is 26660 €. The varying cost changes with the area of the solar collector, which is 248 €/m²_{collector}. The investment cost of the hot water storage tank varies with the volume of the tank, as shown in Fig 10. This cost data is updated information available in Niemelä et. al. (2016). The average Finnish district heat price (69.3 €/MWh) was used in this study. The presented component and the energy prices include the Finnish value added tax (V.A.T.) of 24% (Finnish Energy Association). The price of electricity for the pumping system was considered to be 188 €/MWh, after adding the 24 % tax (V.A.T.).

5 Results

5.1 Operation of auxiliary heating system

Fig. 11 shows the operation of auxiliary heating system during one example day. The selected day is 2nd of April, when generated heat by the solar thermal system is not adequate to fully respond to the building's heat demand. Therefore the auxiliary heating system is needed to cover a part of the building heat demand as well. The size of the collector was set at 84 m², and the tank volume is 4 m³. The upper section in Fig. 11 shows the heat demand components as the AHU, space heating and domestic hot water. In the lower section, the heat transferred to the hot water storage tank from the solar thermal and auxiliary heating systems are compared to the building's total heat demand. The tank's top layer temperature has also been shown in the lower section.

In the beginning of the day, there is no solar generation but there is heat demand in the building. Tank top layer temperature is decreasing and because of that the control system increases the auxiliary heating power. Later, because the solar heat generation starts to heat the tank, the auxiliary heating power decreases.

5.2 Studied scenarios

Four scenarios were used to define the optimal solutions of the solar thermal system in the studied apartment building. The logic behind defining these scenarios was checking the effect of the main economic parameters on the optimal size of components and the corresponding profitability. The assigned scenarios were set as follows:

Scenario 1: In this stage, the solar thermal system was optimized with two different levels of domestic hot water consumption based on values explained in section 2.3. The values for the real interest rate and the escalation were defined as 3% and 1%, while the investment cost was set based on the cost of the components defined in section 4.2. The optimization of the system was conducted with the measured domestic hot water data. The basic values defined in Table 2 were used in the reference optimization case.

Scenario 2: In this part, the setting of optimization was similar to Scenario 1, but the real interest rate was varied from 3% to 5% and 7%.

Scenario 3: The arrangement of the parameters was defined based on Scenario 1, but the investment cost was changed by $\pm 15\%$ of the components cost, defined in section 4.2.

Scenario 4: The setting of optimization in this part was similar to Scenario 1, but the escalation was changed from 1% to 3% and 5%.

5.3 Breakdown of heat demand

The breakdown of the building heat demand with the defined DHW consumption levels is shown in Fig 12. The figure shows the heat demand for DHW, space heating and ventilation.

Based on Fig. 12, more than half of the total building heat demand was devoted to DHW consumption in both of the cases.

5.4 Scenario 1: Effect of the domestic hot water consumption level

The multi-objective optimization was carried out over the solar thermal energy system to define the optimal values for the hot water storage tank volume, the solar collector area and the tilt angle by using two different domestic hot water consumption levels, which were defined in section 2.3. The total annual district heating energy consumption without the solar thermal system was $69 \text{ kWh}/(\text{m}^2, \text{a})$ in the D3-based case and $84.3 \text{ kWh}/(\text{m}^2, \text{a})$ for the measured DHW level.

The resulted pareto fronts for multi-objective optimization are presented in Fig. 13. From the results, it can be seen that the solutions with a higher level of domestic hot water consumption formed the profitable part of the pareto. The global cost-optimal solution, marked with $\text{GOS}_{\text{measured}}$, belongs to the pareto with the higher domestic hot water consumption level ($67 \text{ L}/\text{occ.}/\text{day}$). The size of the tank and the solar collector area for this point were achieved as 4 m^3 and 84 m^2 . For the pareto front with the lower level of hot water consumption ($47 \text{ L}/\text{occ.}/\text{day}$), the cost-optimal solution was marked as, GOS_{D3} . For GOS_{D3} , the size of the tank and the solar collector area were obtained as 3 m^3 and 55 m^2 . According to Fig. 13, the cost-optimal solar thermal system decreases the annual district heat energy consumption by 24% for the GOS_{D3} and 33% for the GOS -measured cases compared to the case without a solar thermal system.

The ratio of the solar collector area per tank volume for the $\text{GOS}_{\text{measured}}$ is $21 \text{ m}^2/\text{m}^3$ and for the GOS_{D3} it is $18 \text{ m}^2/\text{m}^3$. Two other points as numbers 2 and 3 were also marked in Fig. 13 over the pareto that belongs to the higher level of the domestic hot water consumption. For number 2, without significant changes in the LCC, it is possible to save

more district heating energy by increasing the size of the tank and the collector area. Number 3 lay down on the profitability boundary, which shows the extreme feasible solution for the studied apartment building.

From Fig. 13, it can be seen that the profitable range for the solar thermal collector area varied between 84 m^2 and 130 m^2 , while the tank size changed from 4 m^3 to 6 m^3 . The ratio of the solar collector area per tank volume varied from $21 \text{ m}^2/\text{m}^3$ to $22 \text{ m}^2/\text{m}^3$ in the profitable range. It means that any ratio out of this range was not economically optimal. Increasing the size of the tank more than 6 m^3 was not able to form any profitable combination with the assumed range of the solar collector area and the studied consumption levels. This is evident by the constant tank volumes for the solar collector area larger than 90 m^2 .

The ratio of district heating energy saving per LCC was investigated from the results. The mentioned ratio variation from point number 1 to point number 3 was $1.8 \text{ kWh}/\text{€}$, while the same ratio variation from point number 3 to point number 5 was $0.2 \text{ kWh}/\text{€}$. The part of the pareto which was laid down between points 1 and 3 was able to save more energy in a more reasonable economic way. The tilt angle was not found to be an effective decision variable in the optimization. Solutions that were tagged with the numbers 5 and 6 produced the most solar energy. Four of the mentioned points were not economically feasible. These solutions, which touched the defined maximum boundaries of decision variables, could not compensate for their investment cost by utilizing the solar energy during the assigned life span.

Fig. 14 shows the breakdown of the heating energy demand and the utilized solar energy for the two points 1 and 5 shown in Fig 14. Between April and September, collected solar

energy was a significant source of heat energy, while there was no collected solar energy in January, November and December. The heating energy demand between April and September was 22 kWh/m². The solar energy utilized with system number 1 was 21 kWh/m² and 25 kWh/m² by system number 5. Therefore, both systems were able to cover most of the heating energy demand from April to September. The percentage ratio of annual utilized solar energy per annual total heating energy demand was 41% for point 5 and 30% for point 1. The percentage ratios of annual utilized solar energy per annual heat energy demand of DHW of the preceding points was 69% for point 5 and 50% for point 1.

Fig. 15 shows the effect of the collector area and the tank volume on the district heating energy consumption. Fig. 15 also explains the distribution of the cost optimal tank sizes against the solar collector area as a curve with a thicker line. In Fig. 15, the points between point numbers 1 and 3 referred to those economic profitable points on pareto with a higher level of domestic hot water consumption (see Fig. 13).

5.5 Scenario 2: Effect of real interest rate

The real interest rate was changed from 3% to 5% and 7% to check its effect on the optimization results. This analysis shows the consequences of the LCC setting on the economic profitability of optimal solutions. For the studied apartment building and the described solar energy system, increasing the real interest rate as shown in Fig. 16 made the optimal solutions unprofitable. The global cost-optimal solutions, which were tagged by GOS_{3%}, GOS_{5%} and GOS_{7%} in Fig. 16 was affected mainly by the solar collector area. The area of the collector had a reduction of 8 m² in the GOS_{5%} and 15 m² in the GOS_{7%}. When the real interest rate was increased from 3% to 7%, the optimal tank size decreased

from 4 m³ to 3 m³. The ratio of the solar collector area per the tank volume changed from 17.5 m²/m³ in the GOS_{3%} to 15.5 m²/m³ in the GOS_{5%} and 18.3 m²/m³ in the GOS_{7%}. The utilized solar energy showed a reduction of 1 and 2 kWh/m² after increasing the real interest rate for the marked points as GOS_{5%} and GOS_{7%} because of the reduction of the solar collector area. About the LCC, the increment could be detected in the GOS_{5%} as 6 €/m² and for the GOS_{7%} as 10 €/m² compared with the LCC value in point GOS_{3%}. These amounts of imposed additional cost and reduction in applying the solar energy made the mentioned optimal solutions to remain out of the profitable region. According to Fig. 16, the cost-optimal solar thermal system decreased the annual district heat energy consumption by 28%, 28% and 31% in the GOS_{7%}, GOS_{5%} and GOS_{3%}, respectively, compared to the case without a solar thermal system.

5.6 Scenario 3: Effect of investment cost

The effects of the main component prices as the investment cost were also studied in the optimal solutions in Fig. 17. As explained before in section 5.2, the investment cost was set at $\pm 15\%$ of the reference investment cost, which was listed in section 4.2. The analysis revealed how changing the investment cost affected the financial profitability of optimal solutions. The ratio of the solar collector area per tank volume for GOS_{-15%} was 16 m²/m³ and for GOS_{+15%} it was 16 m²/m³. For GOS_{+15%}, increasing the investment cost by 15% did not change the optimal tank size, but it reduced the optimal collector area by 6 m². A reduction in investment cost by 15% in GOS_{-15%} made a small change in the system configuration compared with the reference case. This change is the increment of the size of the tank to 5m³ and the area of collector to 79 m² in comparison with the GOS_{reference}. The LCC value for the GOS_{-15%}, as the maximum profit in this scenario, was achieved

around 9 €/m²_{floor}. The LCC value for GOS_{+15%} had a 5 €/ m²_{floor} increment against the reference case. For GOS_{-15%} around 5 €/m²_{floor} reduction in LCC was calculated from the results to compare with the reference case. The utilized solar energy increased from 31 kWh/m² to 32 kWh/m² in GOS_{-15%} and decreased to 30 kWh/m² in GOS_{+15%}. According to Fig. 17, the cost-optimal solar thermal system decreased the annual district heating energy consumption by 30% and 32% in the GOS_{+15%} and GOS_{-15%}, respectively.

Reducing the investment cost made the range of optimal selections of components wider compared to Scenario 1. The ratio of the solar collector area per tank volume varied from 16 m²/m³ to 33 m²/m³ in the economic profitable solutions after applying 15% off in the investment cost.

5.7 Scenario 4: Effect of escalation

The two escalation rates of 3% and 5% were used to study the sensitivity of the optimal solution to the escalation rate. Increasing the escalation made more profitable solutions, which was evident by the presented results in Fig. 18. The effect of raising the escalation rate on cost-optimal solutions as points GOS_{es3%} and GOS_{es5%} was the increment in the sizes of the main components and extending the financial profit for optimal solutions. The area of the solar collector increased 26 m² from points as GOS_{es1%} to GOS_{es5%}, while the volume of the tank increased 2 m³. The ratio of the solar collector area per tank volume for GOS_{es3%} was 16.2 m²/m³, and for the GOS_{es5%} it was 16 m²/m³. The maximum financial profit increased from 4 €/m²_{floor} to 13 €/m²_{floor} and 24 €/m²_{floor} if the escalation rate increased from 1% to 3% and 5%. According to Fig. 18, the cost-optimal solar thermal system decreased the annual district heat energy consumption by 31%, 32% and

34% in the $GOS_{es1\%}$, $GOS_{es3\%}$ and $GOS_{es5\%}$, respectively, compared to the case without a solar thermal system.

6 Discussion

The economic profitability of a solar thermal system for buildings in cold climate conditions depends strongly on the level of heat demand for the building. DHW consumption typically forms the main part of heating energy demand in new apartment buildings. In the design stage, the level of hot water consumption is defined based on the relevant design guide or the national building code. However, the real DHW consumption could be different from the design stage assumption due to uncertainties in the occupant's behaviour. Therefore, it is recommended that different scenarios or similar building information are considered for the DHW consumption to evaluate the true potential of the solar thermal system.

The results showed that the bigger collector and tank could not necessarily make profitable solutions for any apartment buildings. This is because of the actual heat demand of the building. The results emphasized that the size of the system components should be adapted to the level of the heat demand. If they are not compatible, then mismatching between energy generation and energy demand will be increased, which means imposing an unnecessary investment cost. So a trade off in the energy saving ability of the system and corresponding LCC value is essential, especially in the cold climate condition.

Moreover, the results showed that the cost-optimal solar thermal system could cut the district heating energy consumption about 22% to 32% in the studied cases. This justified the application of the solar thermal system in the new apartment buildings under the cold climate condition. However, for investing in the solar thermal energy system, a different part of the resulting pareto fronts should be interpreted precisely. In the most cost-effective part of the pareto front, the change of the LCC against the energy usage is smaller. Therefore, investment in solutions in this part would be recommended for an energy-efficient and cost-feasible system. As shown in the results, those components that made the main portion of investment had the main effects on the optimization results. The size of the solar thermal collector as the main element in the investment cost had the highest correlation with the profitability of the system.

The assumptions for setting the LCC calculation are important and have a strong effect on the results. Among the studied economic issues, increasing the escalation rate had the most significant effect on the optimization results. The increment of the escalation to 5% made the highest financial profit (24 €/m²floor) among the studied cases. However, increasing the real interest rate from the basic value (3%) made the solar thermal system unprofitable in all the studied cases. Since the reference optimization that made profitable solutions was run with stricter values for the LCC parameters (see sections 3.4 and 4.2), applying the solar thermal system in apartment buildings under cold climate conditions could be an economically feasible option to reduce energy consumption. The total investment cost for an optimal solar thermal system in the studied apartment building was 46780 €. The unit price was about 29 €/m²floor, which showed that applying the solar thermal system in the studied apartment building was an economically feasible option.

The results of this study are applicable to apartment buildings with a similar level of DHW consumption under similar climate conditions. The simulation-based optimization methodology presented in this study could be used to study the cost-optimal dimensioning of different solar thermal systems in any building type, with other system configurations (for example, with heat pumps or dual storage tank systems), and the analyses can be performed in any kind of climate conditions.

7 Conclusion

In this study, the cost-optimal sizes of main components as collector area and storage tank volume were investigated for a solar thermal energy system in a Finnish apartment building. Different scenarios for studying the effect of investment cost, real interest rate, and escalation were applied to study the potential of financial profitability for optimal solutions.

The range of the cost-optimal solar thermal collector area and the storage tank volume varied from 52 m² to 82 m² and from 3 m³ to 6 m³ in the studied apartment building cases, depending on the DHW consumption level, the investment cost and the values of the parameters of the LCC calculation. The ratio of the cost-optimal collector area and the storage tank volume varied between 13 and 17 m²/m³ in the studied cases. The investment in the solar thermal system with the cost-optimal component sizes created a financial profit from 3 €/m²_{floor} to 24 €/m²_{floor} in the studied cases when the DHW consumption level was assigned as 67 L/occupant, day. Based on the results of this study, the following conclusions could be made:

- The effect of the DHW level is important in evaluating the performance of the solar thermal energy system and its financial feasibility.

- The installation of the optimized solar thermal system in the new apartment building is a true energy-saving measure, and the investment can be economically profitable, depending on the DHW consumption level, the investment cost and the realization of the assigned economic parameters. The solar collector area was found to be the main decision variable in the optimization.

- Selection of the component sizes for a solar thermal system needs good information about the energy consumption of the building and a sensitivity analysis of the optimal solutions through different economic scenarios.

- Based on the method of presenting the findings in the current study, the results could be generalized for other apartment buildings with a similar heating demand under cold climate conditions.

The presented results support decision-makers in meeting their commitments and expectations from investments in a solar energy system for apartment buildings.

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911 Table 1. The internal heat gain characteristics of the studied apartment building (D3
912 2012).

Internal heat gain	Specific power / Notifications
Persons	<i>3.0 W/m² average sensible gain, which equals 1 person per 28 m² with activity level of 1.2 met and clothing 0.75 ± 0.25 clo</i>
Lighting	<i>11.0 W/m² average heat gain, which equals 9.6 kWh/(m²,a) with an average usage rate of 0.1</i>
Household equipment	<i>4.0 W/m² average heat gain, which equals 21.0 kWh/(m²,a) with an average usage rate of 0.6</i>

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914 Table 2. The applied parameters in LCC analysis

Parameter	Basic values (scenarios 1 and 3)	Applied in real interest rate sensitivity analyses (scenario 2)	Applied in escalation rate sensitivity analyses (scenario 4)
Real interest rate	3.0 %	5%, 7%	3%
Escalation in energy prices	1.0 %	1%	3%, 5%
Holding period of investments	20 a	20 a	20 a
Running time period of annual maintenance costs	18 a	18 a	18 a
Present value factor of maintenance costs	13.70a	11.70a, 10a	13.70a
Present value factor of energy costs	16.32 a	13.62a, 11.52a	19.92a, 24.52a

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Table 3. List of optimization variables

Decision variables	Lower limit	Upper limit	Notifications
Collector area [m ²]	1	200	Continuous
Tank volume [m ³]	0.5	6	Continuous
Tilt angle [degree]	30	60	Continuous

Figure 1. 3D view of studied apartment building.

Figure 2. Schematic of the studied heating system (HXaux: the heat exchanger connected to auxiliary heating system; HXstc: the heat exchanger connected to solar thermal collector; HXdhw: the heat exchanger for DHW).

Figure 3. Inlet water temperature control according to the outdoor temperature with the district heating system.

Fig. 4. Average hot water consumption in studied buildings in winter and summer (B:Building)

Figure 5. Process of DHW consumption framework.

Figure 6. Measured data distribution for domestic hot water consumption on weekdays and weekends through the summer and winter periods (median=red line, first quartile=lower line of the box, and third quartile=upper line of the box) .

Figure 7. The hot water consumption profiles used in the simulations.

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942 Figure 8. Schematic of the simulated hot water storage tank.

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Figure 9. Simulation-based optimization process.

Figure 10. The price of hot water storage tank as function of volume.

Figure 11. Heat demand and heat transferred to the tank.

Figure 12. The breakdown of heat demand with applied DHW consumption levels.
 Right: According to measured data (A), Left: According to Finnish building code D3 (B).

Figure 13. The pareto front for optimization of solar thermal energy system
 (V = Tank volume, A_{sc} = Solar collector area, θ_{sc} = Solar collector tilt angle, Q_{sc} =
 utilized solar energy).

Figure 14. Monthly breakdown of the heating energy demand and utilized solar energy (Point 1 and point 5 from Fig. 13).

Figure 15. Sensitivity of solar collector area to tank volume (thicker line shows cost optimal tank sizes).

Figure 16. The effect of interest rate on optimal solutions.

Figure 17. The effect of the investment cost on optimal solutions.

Figure 18. District heating price effect on optimal solutions.