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Qualitative cost-conscious control of combined energy sources in a residential building

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Nowadays, heating power for buildings is often produced by on-site renewable energy sources. However, such sources typically cover only part of the energy demand of the building. Thus, electricity supply from the grid is necessary although it is usually the only necessary external energy source. Cost-effective utilization of electricity requires not only reduction in the share of electricity from the grid but also comprehensive control of all on-site energy systems. In this paper, such a control method is presented. The control procedure takes into consideration fluctuations in the price of electricity, environmental conditions, the thermal mass of the building, and energy storage. The study aims to reduce energy costs by flattening the electricity load's profile and switching the energy systems on and off at predetermined times according to a qualitative control procedure. Thermal and electricity loads are either forwarded or delayed in response to variations in the electricity price but maintain a comfortable indoor temperature. The control method is verified in a simulated residential building using weather data from Helsinki, Finland. The building includes a geothermal heat pump, a solar collector, and an electric heater as energy sources and a hot water tank for thermal storage. The main thermal loads consist of space heating and domestic hot water. The results of a full-year simulation are compared with those of a conventional method with no price-responsive features. The results indicate that load shifting is successful, especially during the cold season. The control method adapts correctly to large and abrupt scheduled loads. Although this method reduces electricity consumption by only 2%, the yearly cost of electricity is decreased by 11.6%. *Published by AIP Publishing.*
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I. INTRODUCTION

Due to new energy regulations, the number of renewable energy systems in buildings is increasing. Thus, one building may contain several systems, combining renewable energy sources with existing external energy sources. However, renewable energy sources are, in a way, stochastic energy generators due to changes in weather conditions. Therefore, it is difficult to use renewable energy sources to cover all energy needs of a building. External energy sources such as the electricity supply are essential as they guarantee uninterrupted energy supply to the building. Furthermore, some renewable energy sources themselves consume a considerable amount of electricity. Therefore, intelligent control of such systems is necessary in order to efficiently use produced energy and minimize operating costs. Up to now, a number of studies have attempted to minimize the operating costs of hybrid energy systems by studying the effects of different parameters, such as optimum sizing of energy generation/storage components and load shifting.[1–6] Farmani-Parvizimosaed[3–5] presented a Smart energy management system (SEMS) for application in a residential Micro-Grid (MG) with the objective of minimizing the building's energy operation costs.

Ongoing developments in the power sector, such as rapid deployment of fluctuating renewable energy sources (RESs), power market liberalization, and widespread deployment of smart meters, show that electricity utilities and end consumers are facing significant changes. Together, smart metering in combination with dynamic electricity tariffs may profoundly change how electricity is consumed and billed.[7] Power plants usually set higher prices for electrical energy, which is used during times of high demand. Typically, the price of electricity follows an hourly changing curve based on the estimated power demand of the following day. Thus, the customer is informed of the next day's energy prices (Nord Pool day-ahead trading system). In principle, the customer is able to control energy costs by using less power during peak times.

It has been shown that additional information in the form of dynamic electricity tariffs, as a strong economic incentive, can be used in building control for shaping the demand profiles of retail end consumer groups. Previous research aiming to control buildings' electricity demand has focused on demonstrating utilization of thermal or electricity storage. Batteries provide flexibility and enable consumers to utilize less energy during electricity tariff peaks, leading, on average, to lower costs for electricity demand from the grid.[7–9]

A shift in consumption profiles due to dynamic tariffs also influences electricity markets since demand becomes increasingly price-responsive. Larger demand elasticity is expected to lead to different bidding strategies at spot markets and, long term, lower wholesale electricity prices.[7–10]

The fundamental idea of allowing small-scale generation, load, and storage to respond to instantaneous electricity prices has been investigated since the 1980s.[11] The main idea is allowing retail prices to reflect fluctuating wholesale prices so that end users pay what electricity is worth at different times of the day. Encouraging users to shift high loads to off-peak hours not only reduces the cost of their electricity but also helps to reduce the peak-to-average ratio (PAR) of load demand.[12] Small-scale generation, storage, and demand—so-called "demand side resources"—serve as an indirect control with the ability to alter electricity consumption patterns.[13]

Recent studies show that users' lack of knowledge about how to respond to time-varying prices and the lack of effective building automation systems are two major barriers to full utilization of the potential benefits of real-time pricing tariffs. Implementation of any residential load control strategy in real-time electricity pricing environments requires price forecast tools if utility companies provide price information only one or two hours in advance. Together, the proposed energy consumption scheduling design and price predictor filter lead to a significant reduction not only in users' electricity payments but also in the resulting *peak-to-average ratio* of load demand in various load scenarios. Therefore, such a combination is beneficial for both end users and utility companies and is an incentive for large-scale deployment of the designed energy schedules in residential smart meters.[12,14]

The control-by-price concept is appropriate for controlling small-scale units according to laboratory tests with electric space heating thermostat controls and a small combined heat and power (CHP) unit. The results of such tests show that a price-responsive controller reduces the end user's electricity cost or increases his income by about 7%. In addition, the price-responsive controller provides an interface for the transmission system operator to utilize distributed energy resources and flexible demand as a regulating resource. Nyeng[15] proposed infrastructure for controlling distributed energy resources and flexible demand and verified the applicability of the concept by his results.[15]

The possibility of using a heat pump applying the control-by-price concept in order to avoid overload in a distribution system has been investigated. It was shown that electric services could be provided with flexible units for peak shaving in order to minimize the necessary oversizing of power system components.[16]

Corradi[17] proposes a model to estimate the average consumer's response to price changes and shows how these dynamics can be used to control electricity consumption. He studied a price-responsive heating system based on real data, showing that peak heating consumption is reduced by 5% and that 11% of the mean daily heat consumption is shifted after implementation of the system.[17]

Electric heating systems allow modification of their electrical load pattern without affecting the thermal energy service they deliver due to thermal inertia in the system, making them suitable for active demand response. However, these systems are hard to describe with traditional demand-side models since their performance depends on boundary conditions such as occupants' behavior and weather conditions. An integrated system approach takes into account the dynamics and constraints of both the electricity supply and the heating system, which makes it suitable for simultaneous consideration of all the technical and comfort-related constraints in the system.[18]

Some earlier studies investigated the use of a ground-source heat pump (GSHP) and a solar collector to create a so-called solar-assisted ground-source heat pump in order to study the heating performance, energy distribution, and approaches to integrated control of such a combined system.[19–22]

Further studies have explored load matching of combined renewable systems in order to reduce the mismatch between the amount of electricity produced by renewable sources and the building's electricity demand. The use of different types of storage, including batteries for electricity storage and a domestic hot water (DHW) tank as thermal storage, and suitable recharging strategies have also been studied.[23] Arteconi showed that combining a heat pump and thermal energy storage is beneficial for demand-side energy management and that it is possible to achieve good control of indoor temperature, even if the heat pump is turned off for three hours, and reduce the electricity bill if "time of use" is adopted as a tariff structure.[24]

This article introduces a qualitative control method appropriate for controlling energy in a building equipped with combined energy sources, and it aims to establish and develop a control method that reduces the total energy cost for the building. This is done by controlling the operation of energy sources in response to fluctuations in the cost of electricity (i.e., by storing energy during lower price periods and using the stored energy when the price is high). Throughout the process, the building is maintained at a comfortable indoor temperature. The control logic is based on a thermal model of the building as well as current and day-ahead hourly electricity prices. The method is demonstrated in a simulation environment consisting of a residential building equipped with an energy storage system and three energy systems: a solar collector, geothermal heat pump, and electric heater.

II. THE ENERGY SYSTEMS

A. Energy sources and thermal storage

Energy supplied to the residential building was produced and processed using a system (Fig. 1) involving renewable energy sources (a geo-thermal heat pump and a solar thermal collector) and an external energy source (an electric heater). The system also includes a 500-l hot water tank for thermal storage and an underfloor heating system equipped with a fixed speed pump supplying a constant flow of hot water to the building.

Most of the building's energy is supplied by a water-to-water geothermal heat pump based on the MW022S heat pump model produced by Geo-Furnace Manufacturing. R410 was used as a refrigerant. A vertical U-tube heat exchanger made of PEM (Polyethylene-medium) was used as a heat source, and the cylindrical heat storage system in which the U-tube was located consisted of rock. Outside the borehole, there was a five-meter layer of clay near the surface, a two-meter layer of moraine below the clay, and a 200-m layer of rock below the moraine. The depth of the borehole was calculated based on the building's heating power demand. In Southern Finland, a borehole can produce approximately 42 W of heating power per meter. Thus, based on the energy needs of the building examined in this study, a depth of 175 m was chosen. The material of the heat exchanger pipe was PEM. The heat transfer liquid was a 35% ethanol-water mixture. The properties of the ethanol-water mixture are given at a temperature of $-15\,^{\circ}$C. It was assumed that the borehole was filled with water, which was at the ground temperature.

The 15-m-long horizontal pipes connecting the borehole and the building had the same properties as the pipes inside the borehole. They were insulated with a 14-mm thick foam layer

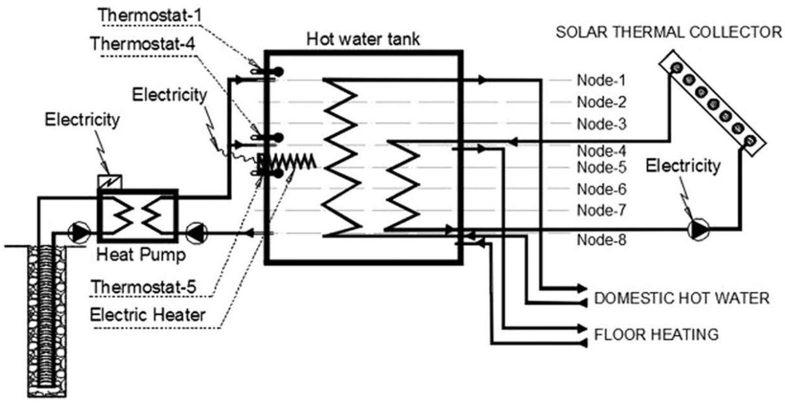

FIG. 1. Energy sources, hot water tank, inlets and outlets, and other details of the system.

and buried in the ground a meter below the surface. A heat loss coefficient based on the area of the pipe's inner envelope was calculated using the sum of thermal resistances. The calculated coefficient was 2.83 W/m^2 K.

The second renewable energy source used in this study is a one-row solar thermal collector system with an overall panel area of 5 m^2. It faced the south at a tilt angle of 45°, with a flow rate of 40 kg/hm^2. The outlet fluid from the solar collector is connected to the tank's heat exchanger, which is located within nodes 4 and 8 of the hot water tank. Solar radiation is limited, particularly in the cold season. Therefore, the solar thermal collector has the highest priority in the control method when solar radiation is available.

A built-in electric heater with a maximum heating rate of 5 kW was installed on node 5 of the hot water storage tank. The heater is designed to add heat to the flow stream at a designated limited rate ($Q_{max} = 5$ kW) whenever the heater outlet temperature is less than a specified maximum set point temperature. It finally delivers the flow stream at a constant temperature with a limited heating rate, which is specified. It operates at COP = 1, whereas the geothermal heat pump operated at $COP_{HEATING} = 3.5$ and the solar thermal collector operated at $COP \geq 10$. Although the solar thermal collector has the highest priority in the control method, however, the availability of solar radiation particularly in the cold season is its drawback.

A vertical cylindrical storage tank enables stratification of water temperature as it is divided into eight equally sized sections. As shown in Fig. 1, the tank contains several inputs and outputs. One input and one output are connected to the floor heating circuit, and two inputs and one output are connected to the heat pump. In addition, tanks' heat exchangers for the DHW and solar thermal collector are connected to the tank with one input and one output each (Fig. 1). The tank's envelope is made of steel, and the tank is insulated with polyurethane and covered by a second layer of steel.

III. THE COST-CONSCIOUS CONTROL METHOD

A. Principle of the method

Typically, operation of an energy system is controlled by one or more thermostats. Usually, the system is turned on or off if the temperature sensed by the thermostat is under or over the set point temperature, which is a fixed value. The proposed control strategy relies on continual adjustment of the set point temperatures according to the price of electricity.

The heat pump is controlled by two thermostats. Their control actions are based on temperature measurements taken at the 1st and 4th nodes of the hot water tank. The thermostats will cause the nodes to reach a new temperature by turning the heat pump on and off. The electric heater is controlled by one thermostat. Its temperature is measured at the 5th node. By adjusting the set points, energy is charged or discharged to the tank depending on the price of electricity. The solar collector, however, will generate heat whenever enough solar energy is available.

Therefore, the operation of the solar collector is only indirectly controlled by the control strategy, and the heat generated by the solar collector is utilized if the tank can thermally absorb the energy. The space heating system controlled by the room thermostat is also included in the control strategy. The strategy utilizes the thermal mass of the building as the thermal capacitance for charge or discharge energy to shift the load. In practice, this is achieved by slightly increasing or decreasing the set point for indoor temperature in response to electricity price variations.

The control method prioritizes energy sources based on its electricity consumption and costs per kW of heat. Among the energy systems, the solar collector has the highest COP and, consequently, the highest priority. The solar collector operates as soon as solar energy is available (i.e. when the water temperature circulating in the collector exceeds the temperature of tank node 4). The electric heater has the lowest COP and thus least priority. The electric heater can operate only in cases of insufficient energy production from other sources or very low electricity prices. As the price of electricity fluctuates, the set point temperatures will also vary, as shown in Fig. 2. To better illustrate how the method works, one of the periods with more radical price variations is selected to represent in Fig. 2. Roughly speaking, set point temperature is inversely proportional to electricity price. The principle of the control process is shown in Fig. 3.

B. Adjusting the set point temperatures

The set point temperature is a sum of fixed and varying values. The fixed value is a set point temperature that guarantees fundamental but successful operation of the energy system in all conditions, while the varying part of the set point temperature, which can either be negative or positive, may change periodically over time. Its value can be described by means of a piecewise constant function, and it reflects electricity price fluctuations. The control procedure is comparable to the three energy systems and the space heating system under study.

The heat pump is controlled by two thermostats located at nodes 1 and 4 with set point temperatures T_{Node1} and T_{Node4}. The set points change according to the following equations:

$$T_{Node1} = 70.0 + T_P + T_S, \tag{1}$$

$$T_{Node4} = 65.0 + T_P + T_S, \tag{2}$$

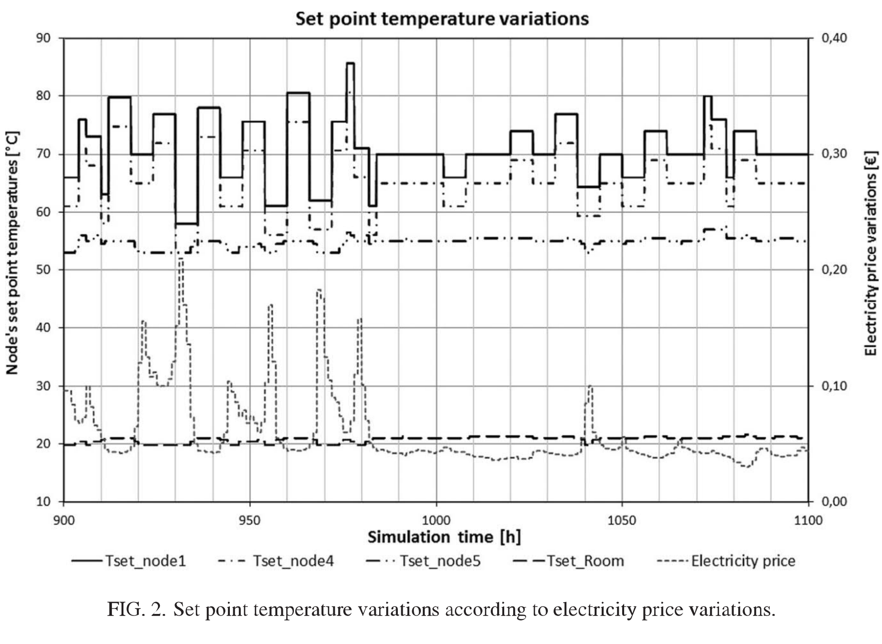

FIG. 2. Set point temperature variations according to electricity price variations.

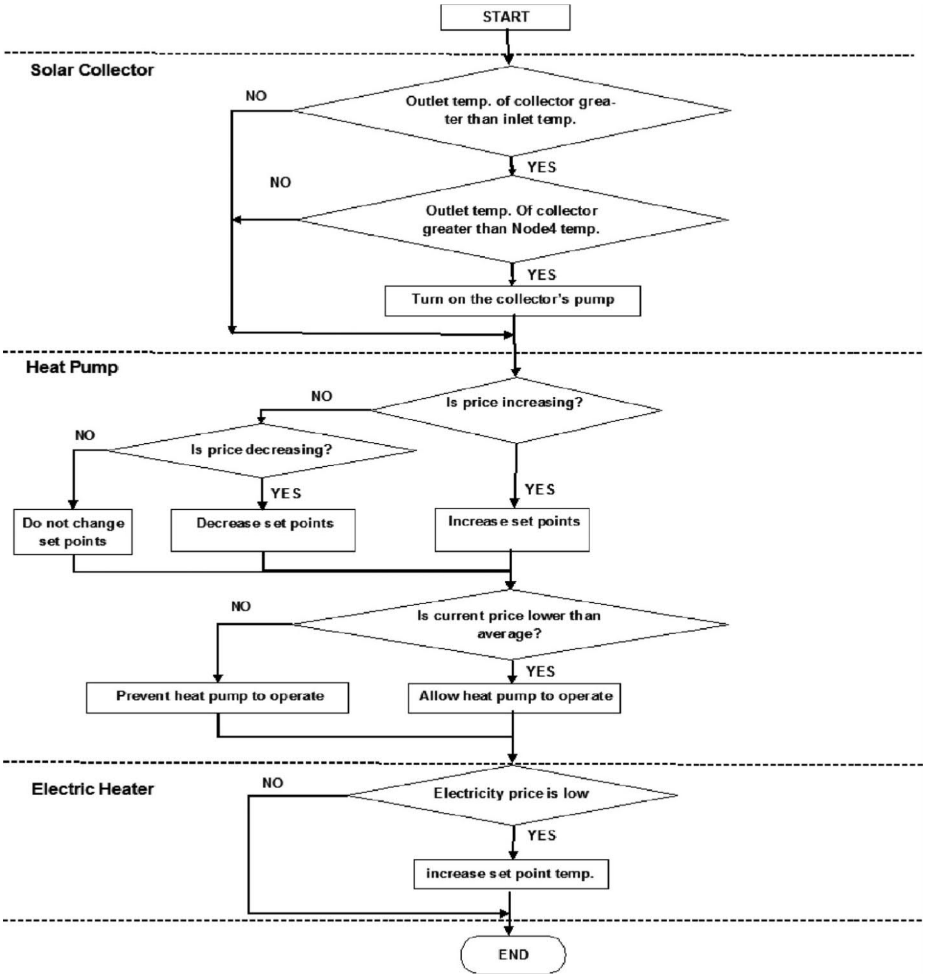

FIG. 3. Principle of the cost-conscious method.

where numerical values of 70.0 and 65.0 represent the fixed and T_P and T_S variable parts of set point temperatures, respectively. T_P denotes the effect of a positive or negative trend caused by changes in the electricity price. The trend value is calculated based on the weighted average price of the current and subsequent 6-h period. In practice, numerical T_P values are restricted to the following range: $[-7.0 \leq T_P \leq 7.0]$. T_S, on the other hand, is a variable that reacts to scheduled abrupt DHW loads such as bathing. The value of T_S is empirically determined using the measured consumption of DHW. T_S is one of only two values: $[T_S = 0.0]$ or $[T_S = 10.0]$. A value of 10.0 is applied when the scheduled large load starts, and the value returns to zero when the scheduled large load is over. In addition to Eqs. (1) and (2), the heat pump is also logically controlled by electricity price information; if the current price is higher than the average price of the period, then the control logic prevents operation of the heat pump.

The electric heater is the lowest-priority energy source. Therefore, it is associated with the lowest set point temperature values as well as the lowest set-point increase. Similar to the heat pump, the set point temperature reflects the current electricity price. The equation defining the set point temperature of the electric heater is as follows:

$$T_{Node5} = 55.0 + T_A, \tag{3}$$

where 55.0 is the fixed value and T_A is the effect of electricity price trends on the electric heater. T_A may vary from $[-4.0 \leq T_A \leq 4.0]$. When the electricity price is getting lower, then the discrepancy with other set points becomes unnoticeable and operation of the electric heater does not have a considerable effect on the total cost of electricity.

The set point temperature and control of indoor air are also included in the control strategy. Like tank water, heat is charged or discharged through the building's structures, depending on the sign of the trend variable

$$T_{Room} = 21.0 + T_R, \tag{4}$$

where 21.0 is the suggested fixed room temperature[25,26] and T_R is the effect of electricity price trends on indoor temperature. In order to maintain comfortable indoor conditions, the range of T_R is restricted to $[-1.5 \leq T_R \leq 1.5]$.

The solar collector has no set point limits to turn on or off; the controller turns on if solar energy is available and energy can be absorbed by the tank. To do so, the collector's outlet temperature must be higher than the inlet temperature. In addition, the outlet temperature of the collector must be higher than the temperature of node 4. Then, the controller turns on the circulating pump (Fig. 1) and transfers heat to the tank.

The control equations, set point temperatures, and operation ranges of the trend variables as well as thermostats and their parameter values must be carefully designed. Since several energy systems are operated simultaneously, there is risk of overlapping and malfunction. In such a case, the control procedure turns on or off several systems at the same time or turns on a system at the wrong time.

IV. THE SIMULATION ENVIRONMENT

A. The simulation tool and building model

The proposed control method was validated in a residential building using the TRNSYS 17 simulation tool. The simulation model consisted of the building and its structures, HVAC and energy systems, occupants and their behavior, and inner and outer loads. The simulated building is composed of three zones, two of which are on the first floor and the third of which is on the second floor. The total area of the building is 96 m^2, and the volume is 408 m^3. Windows are located on the southern façade. The building, its structures, and technical systems meet the D2 and D5 Finnish building codes.[25,26]

The indoor air conditions are defined based on the D2 National Building Code of Finland, and so, the designed room temperature in the occupied zone of the building during the cold season is 21 °C.[25,26] The acceptable deviation from the designed room temperature is ±1 °C.[25,26] During periods of occupancy, the temperature of the occupied zone should normally not be higher than 24 °C during the heating season.[25,26] The ventilation in dwellings is generally designed based on the extract airflow so that the air change coefficient is at least 0.5 l/h.

Regarding the simulated residential building, it is further assumed that the temperature of air supplied to the room is 18 °C, the supply air flow rate is defined based on D2 (0.5 l/h), the humidity of the air is 55%, and the infiltration rate is 0.08 l/h. Heat is assumed to be released by two humans in the room. The building is assumed to be located in a cold climate similar to the Helsinki area in southern Finland. DHW and space heating are the main heating loads. DHW has two different daily consumption schedules: one for ordinary days and the other for weekly bathing days. Space heating is accomplished using floor heating, which is delivered to the first and second zones on the first floor of the building. The third zone on the second floor is considered a cold attic with no heat supply.

V. SIMULATION RESULTS AND DISCUSSION

A. Comparison of the costs

The proposed control strategy was compared with a conventional method in which the set point temperatures are fixed and each energy system is controlled separately, without any coordinated control or reaction to electricity price changes (Table I). Comparison is performed using

TABLE I. Conditions of each control approach.

Electricity price scheme	Cases to compare	
Dynamic hourly tariff	Cost-conscious method	Conventional method
	24-h day-ahead hourly electricity price information is used in the control algorithm	Only the current electricity tariff is used for both the strategy and cost calculations (24-h day-ahead hourly electricity price information is not considered)
	Current outdoor temperature is used in both the control algorithm and the dynamic thermal modeling, but weather forecasts are not used	Current outdoor temperature is used in both the control algorithm and the dynamic thermal modeling, but weather forecasts are not used

the monthly and annual cost of electricity supplied by the grid. An hourly tariff scheme is used for both methods.

The total electrical power supplied by the grid includes hourly energy delivered to the heat pump $E_{HP}(h)$, solar thermal collector $E_{SC}(h)$, and electric heater $E_{AH}(h)$. Thus, the annual electrical energy costs of the three systems summed over 8760 h are calculated as follows:

$$C_A = \sum_{h=1}^{8760} \{E_{HP}(h) + E_{SC}(h) + E_{AH}(h)\} \times T(h), \tag{5}$$

where $T(h)$ is the electricity tariff at hour h. The tariff is based on the 24-h day-ahead hourly electricity price.

The monthly costs, overall yearly costs, and percentage of difference between the two methods are shown in Table II.

The simulation results show that the cost-conscious method reduces the yearly energy cost of the building by up to 11.6% compared to the conventional method. This is achieved by shifting the energy demands to time periods in which the electricity rate is lower and by utilizing combined control of energy sources. The monthly cost and percentage of reduction compared to the conventional method vary each month, as shown in Table II. The monthly costs of both the conventional and new methods are illustrated in Fig. 4.

TABLE II. Integrated monthly and yearly energy costs of the building using two different control methods and the percentage of discrepancy between them.

	Monthly cost of the conventional method	Monthly cost of the cost-conscious method	Percentage of cost reduction achieved by the cost-conscious method
January	63.5	54.3	14.5
February	69.1	53.1	23.2
March	31.2	29.1	6.5
April	20.3	19.6	3.1
May	14.6	15.2	−4.0
June	12.1	12.9	−6.6
July	4.9	6.1	−23.2
August	14.4	15.6	−8.5
September	20.3	19.8	2.5
October	28.2	22.9	18.6
November	50.6	41.3	18.5
December	48.2	43.7	9.4
Yearly cost	**377.5**	**333.7**	**11.6%**

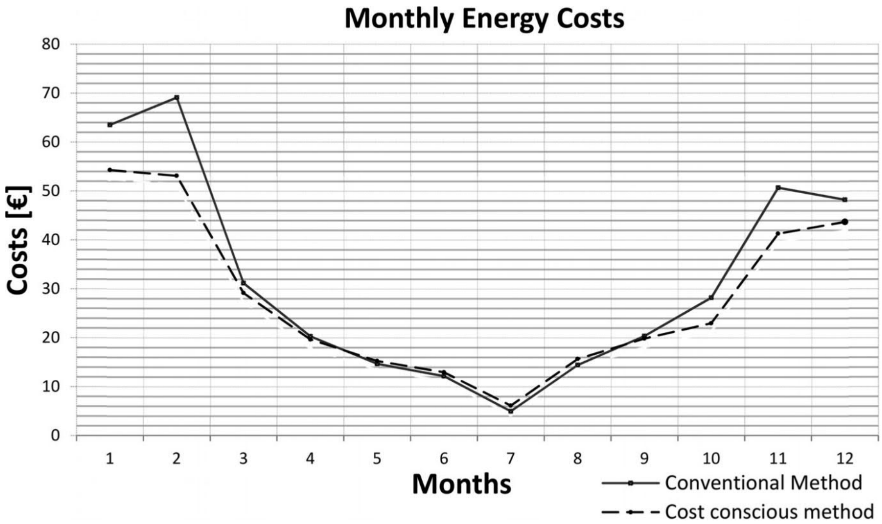

FIG. 4. Monthly costs of the cost-conscious method and the conventional method.

Figure 5 illustrates how the cost-conscious method operates when the electricity price varies. The figure shows operation of the heat pump and the electric heater as well as electricity price variations as a function of time. The control procedure generally avoids turning on the heat pump and the electric heater when the price of electricity is higher. In other words, the operation is mostly shifted to periods when the electricity price is relatively low. The example operation period shown in Fig. 5 is the operation during January, when the solar thermal collector is ineffective in Finnish climate. The simulation results depicted in Fig. 5 show that not even a single operation of the solar collector occurs in this period. Thus, the contribution of the solar collector, which is literally zero in that particular period, is not neglected.

The performance of the method may vary according to the inner and outer loads of the building. Large abrupt changes in the load expose the algorithm to undesirable fluctuations in performance. For example, a large negative factor affects the thermostats' set point values when the large abrupt load is imposed to the system. Having a large abrupt load may sometimes cause the heat pump to start operation too early, when the electricity price is high. However, the method is argued to be efficient via support of provided results in Table II, showing the overall yearly cost reduction.

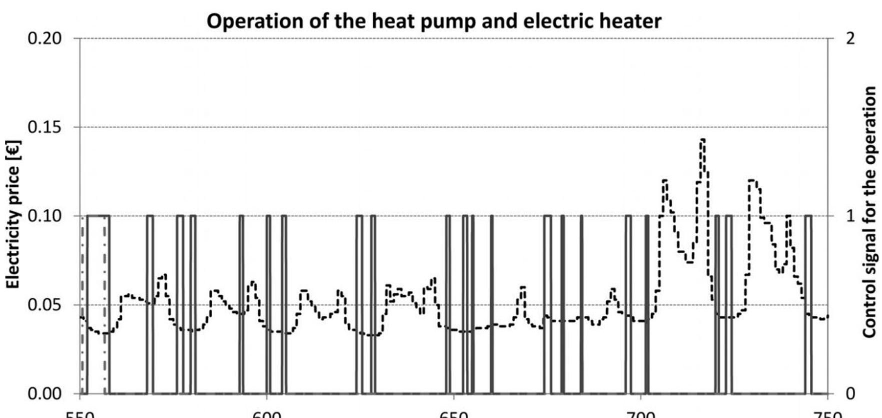

FIG. 5. Operations of the heat pump and the electric heater are avoided during peaks in the electricity price.

TABLE III. Electricity consumption results of the two methods.

	Electricity consumption (kWh)							
	Conventional method (kWh)				Cost-conscious method (kWh)			
	Total	Share of heat pump	Share of solar collector	Share of electric heater	Total	Share of heat pump	Share of solar collector	Share of electric heater
Yearly electricity consumption	9551.8	9190.7	253.4	108.2	9332.7	8898.6	239.3	194.6
Percentage of share compared to the total electricity consumption (%)		96.2	2.7	1.1		95.3	2.6	2.1

B. Comparison of electricity consumption

The electricity consumption results of each method are shown in Table III. The results confirm that the proposed cost-conscious method reduces overall electricity consumption by 2% and reduces electricity costs by nearly 12%. The detailed results of each system show that the overall electricity consumptions of the solar collector and the heat pump are reduced by 5.5% and 3.2% compared to the conventional method, while the electricity consumption of the electric heater is increased by 80.0%. Still, the total electricity consumption of the solar collector and the electric heater is very low; the heat pump consumes approximately 95% of the total electricity.

The role of the solar collector is similar in both methods, and their energy consumption is approximately equal, as shown in Fig. 6. Still, the cost conscious method results in considerable cost reduction due to load shifting. The share of electricity consumed by the electric heater is defined by the control strategy. Therefore, its contribution can be changed by changing the operating conditions of the electrical heater.

C. Seasonal effects

The cost-conscious method results in the most significant cost reduction during cold months (November–January). During this period, the price of electricity and consumption of heat and electricity are higher. Also, in winter, the contribution of the solar collector approaches zero and the heat pump dominates the energy supply. As shown in Fig. 5, the proposed method successfully avoids operating the heat pump during periods of higher electricity prices. The conventional method, on the other hand, allows the heat pump to operate during these periods.

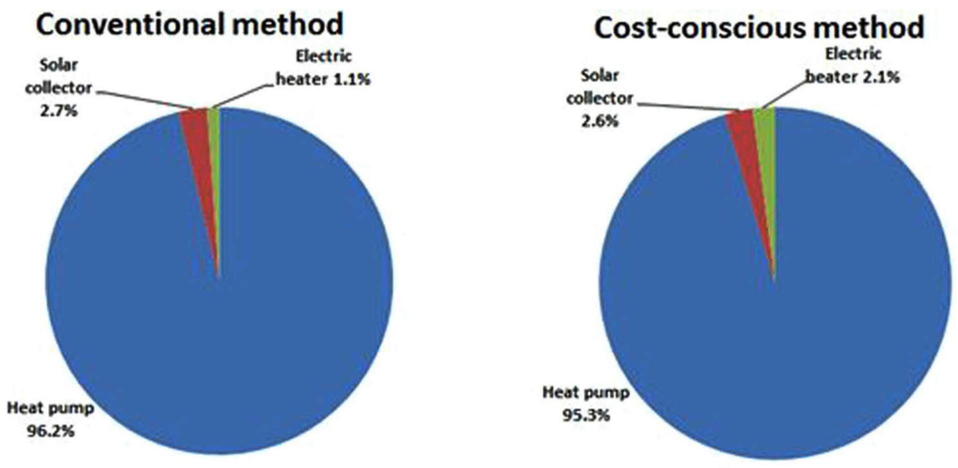

FIG. 6. Percentages of electricity consumption for each system in both methods.

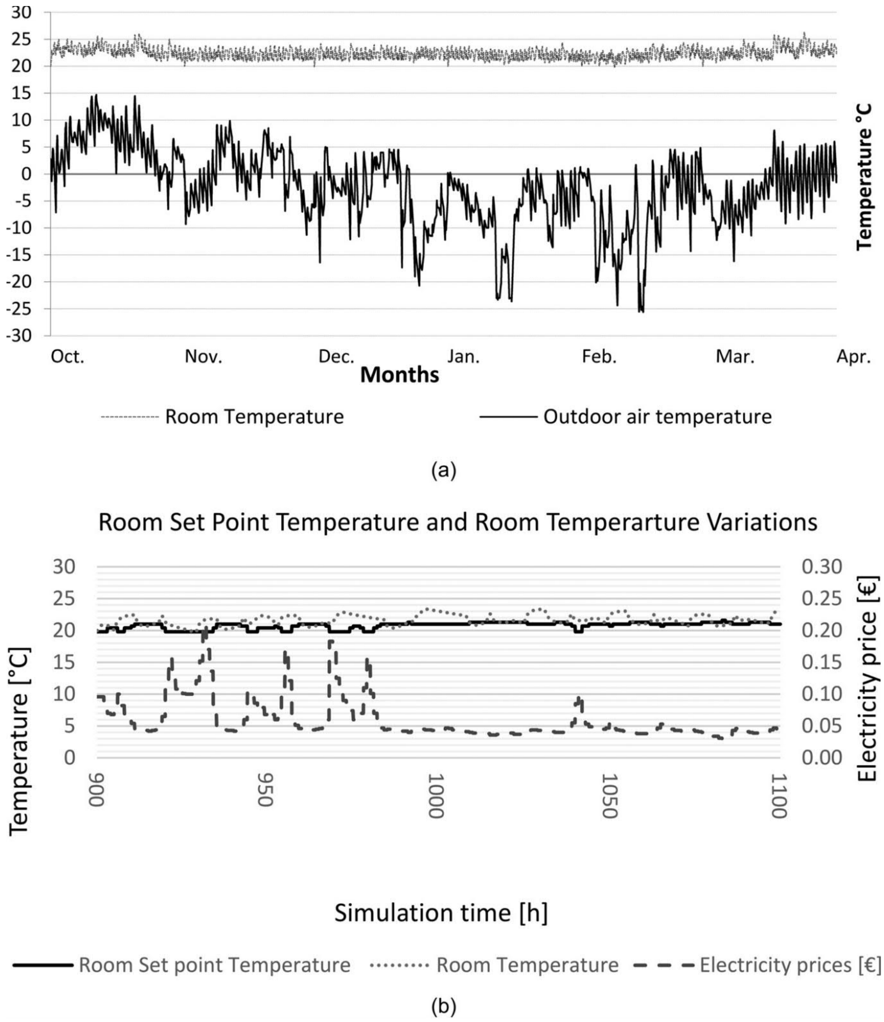

FIG. 7. (a) Room temperatures and outdoor temperatures during the cold season (October–March). (b) Variations in room temperatures and room set point temperatures compared to variations in the electricity price.

The cost-conscious method results in higher energy costs than the conventional method during warm months. As the outdoor temperature increases, the need for heat in the building decreases. In addition, the contribution of the solar collector to the total energy supply increases. Therefore, most of the energy demand is covered by the solar collector and benefits of the cost-conscious method approach those of the conventional method. Further, electricity rates during warm months are very low, with only a few peaks. The small difference in results during warm months (Fig. 4) is caused by large scheduled abrupt DHW loads. The cost-conscious method increases the set point temperature of the hot water tank prior to scheduled large load periods in order to supply DHW to the building with minimal temperature drops. This method results in DHW temperature drop from 55 °C to 50 °C, whereas the conventional method results in larger temperature drop to nearly 45 °C (Fig. 8.). Therefore, the cost conscious method requires a slight increase in heating power compared to the conventional method.

D. Room temperature and floor heating water temperature

Using both methods, room temperature remains in the range of 20–23 °C throughout the cold period [Figs. 7(a) and 7(b)]. In addition, both methods can maintain water heat near the set point temperature during all heating months. During February, when there are larger variations in the energy price, the room set point temperature may vary when using the cost-conscious method [Fig. 7(b)] because the structures of the building are used for thermal storage. This makes it possible to lower the energy demand of the building for a short time and maintain room temperature over 20 °C during the entire cold period. During the warm months, no energy is used for cooling. Therefore, room temperature may exceed the acceptable value. This is also partly true for warm days in transitional seasons.

E. Influence of abrupt large loads of DHW

The first simulations indicated that, regardless of the method used, the temperature of DHW drops drastically (from 55 °C to nearly 40 °C) due to abrupt large loads during weekly bathing times. Therefore, the set point temperatures calculated by Eqs. (1) and (2) will increase by adding a transitory increase T_S to the set point temperatures T_{Node1} and T_{Node4}. This additional value activates a few hours prior to the scheduled loads. Figure 8 shows the temperature drop of DHW only a few degrees, from 55 °C to 50 °C when using the proposed method, while the temperature drop would be under 45 °C using the conventional method.

F. Consistency with other results

The results of the current study are consistent with the findings of previous studies. For instance, Halgaard[27] employed a heat pump in a residential building for floor heating and studied the thermal capacity of the building to shift energy consumption to periods of low electricity prices. He introduced a predictive control method and used both weather and electricity price forecasts in his model, showing that optimized control saves 25%–35% in electricity costs compared to a traditional method.[27] This large reduction is probably due to the use of weather and price forecasts and the use of the constant electricity tariff for comparison. Oldewurtel[9] used a building automation system with a dynamic electricity tariff to reduce peak electricity demands. Electric storage (i.e., batteries) was utilized as an additional means to respond to electricity demand and shift loads. The study demonstrated a peak load reduction of 3.5% (with no battery) to 17.5% (with a large battery).[9] Sun[28] developed a demand-limiting control strategy in order to reduce monthly electricity costs. His strategy involved restraining daily peak demand by adjusting the indoor room temperature set points and was able to reduce monthly electricity bills by 8.5%.[28] The cost-optimal solutions defined by Behrang show that the demand response control algorithm based on the hourly electricity price can reduce energy costs by up to 12%

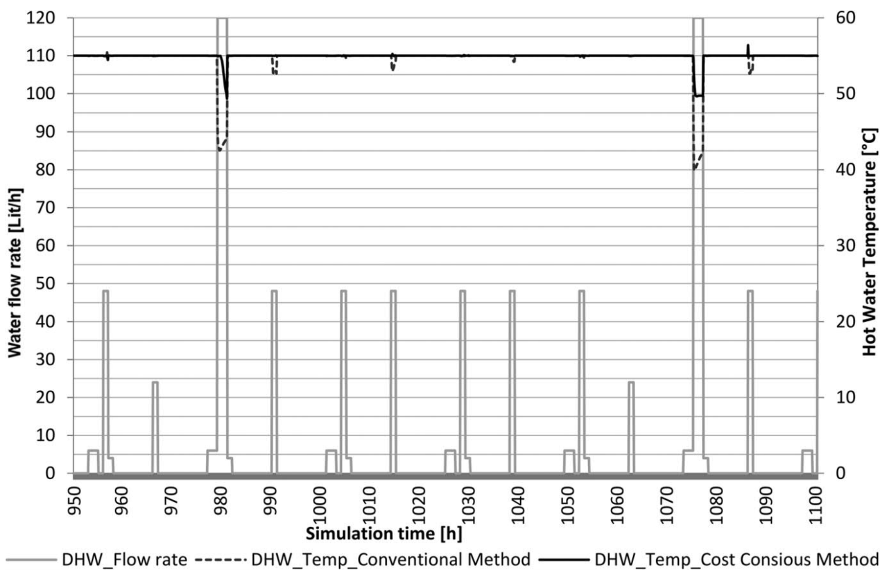

FIG. 8. The effect of large abrupt changes in the DHW demand on water temperature.

annually.[29] These examples show that moderate savings can be achieved by shifting demand and using thermal storage, similar to our study.

VI. CONCLUSIONS

This paper presented a qualitative control approach to reduce the electricity costs of a building equipped with several energy systems. This is done through combined control of the energy systems (i.e., by switching from one energy source to another in response to electricity costs, storing energy during lower price periods, and using the stored energy when the price is high). The control logic is based on a thermal model of the building as well as current and day-ahead hourly electricity prices. The method was demonstrated in a simulation environment consisting of a residential building equipped with a hot water tank for energy storage and three energy systems: a solar collector, a geothermal heat pump, and an electric heater.

The simulation results show that the cost-conscious method reduces the yearly cost of energy by 11.6% and total electricity consumption by only 2% compared to the conventional method. This means that the proposed load shifting procedure is successful; the cost is reduced considerably despite similar electricity consumption. Load shifting operates best when electricity prices are relatively high. Using this method, indoor conditions can be maintained at a comfortable level, even when large scheduled loads cause abrupt changes in the need for DHW.

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