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Demonstrating a Qualitative Control of a Hybrid Energy System in Reducing Energy Costs of a Residential Building

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Abstract

Today, many buildings are equipped with several renewable energy sources. The problem is how to take full advantage of their energy production. This includes decreasing the share and costs of external energy - usually electrical energy delivered from the grid. The following pages present a qualitative control designed to solve the problem. The approach is demonstrated using a simulated residential building equipped with a hybrid energy system: an energy storage combined with an electrical heater, a geothermal heat pump and a solar thermal collector. Consequently, the share of renewable energy was increased, and conversely, costs and share of the external energy from grid decreased. Still, the indoor conditions could be kept at a comfortable level. The method serves as one approach in developing a generic control strategy for multi-energy buildings.

Introduction

The number of hybrid renewable energy systems in buildings is growing fast. Available combinations of equipment and systems are many depending on energy sources, heating and cooling options, usage, number and type of energy storages, and control strategies (Zhai et al, 2011). Renewable energy sources act like stochastic energy generators depending on weather conditions. How to control such a combination of energy systems in order to take full advantage of the renewable energy and at the same time, decrease the share and costs of the external energy, typically the electrical power from the grid.

Dynamic electricity tariffs make the problem even more demanding. Typically, the price of electricity follows an hourly changing curve based on the estimated need of power of the following day. Thus, the customer is able to control energy costs by using less power during daily peak times, i.e. by load shifting of the power.

A number of studies have attempted to minimize the operating costs of a hybrid energy system. Some of the methods are: load shifting (Arteconi et al, 2013), optimum energy system sizing (Eltamaly et al, 2016, Parvizimosaed et al, 2103), smart control and building automation (Oldewurtel et al, 2010), price-responsive heating system (Corradi et al, 2013), usage of energy storages (Kaplani et al, 2015, Oldewurtel et al, 2011).

The following pages introduce a qualitative control method applied in a building equipped with a hybrid energy system: an energy storage combined with an electrical heater, a geothermal heat pump and a solar thermal collector. The focus is on reducing the costs of external electrical energy supplied from the grid.

The simulated building and systems

The residential building, its environmental conditions, structures, HVAC and energy systems including their operation and inner loads were created in TRNSYS simulation environment [11]. The total floor area of the building is 96 m^2 and the volume 408 m^3, consisting of three zones in two storeys. The structures were designed according to The National Building Code of Finland part D2 (Kalliomäki, 2012).

The air change rate for each zone is 0.5 1/h throughout the year, and without heat recovery. The internal heat loads were scheduled according to the assumed usage of a detached house. The building is assumed to be in Southern Finland. Therefore, weather data of the Typical Meteorological Year (TMY) from the city of Helsinki was used. As a result, the total heating energy demand for the space heating and for the domestic hot water was is 9160 kWh per year with the maximum power of 7.2 kW. The simulation was performed for the entire building, but the space heating system was built only for one zone on the ground floor. Thus, the presented energy demand and the maximum power concern only the zone. The simulation starts in the beginning of the year. The time step is one minute.

The energy systems and their connections are illustrated in Fig. 1. The solar circuit consists of three 2.5 m^2 solar collector, 27 W circulating pump, and 30 m piping. The circulating liquid is a water-glycol mixture, which is separated from the tank water with a heat exchanger. The maximum heating power of the solar collector is 5 kW.

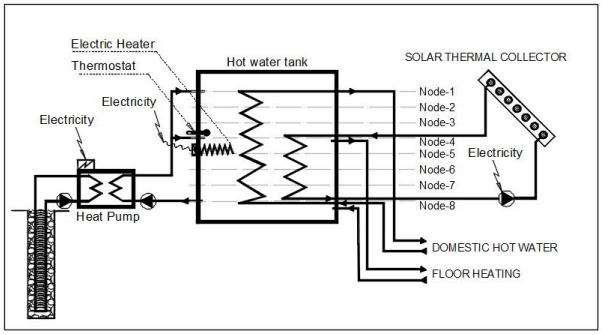

Figure 1. The schematic of the combined energy systems of the building.

The geo-thermal heat pump (5.9 kW) consists of a water-to-water heat pump, load and source side circulating pumps, and a vertical U-tube heat exchanger in the ground operating as a heat source. The borehole is 175 meters deep, where 35 % ethanol-water mixture liquid is circulated in a PEM pipe. The borehole and the building are connected to horizontal pipes (20 m). The properties of the pipes are the same as those in the borehole.

A cylindrical, insulated steel tank of 500 litres, installed in vertical position serves as energy storage. The tank contains input and output connections and inner heat exchangers for domestic hot water and the solar collector. In addition, the tank is equipped with an electrical heater element (5 kW). Due to the stratified water temperature, connections are designed vertically in different locations (Fig. 1). The horizontal lines of the figure illustrate how the tank is divided into eight equal sized sections, starting from the uppermost section (1). For instance, the domestic hot water output is connected to section 1, where the water temperature is kept at 55 °C.

The floor heating consists of a pump driven circuit supplying water of 40 °C. The maximum power of the space heating is 4 kW. The structure and sizing of the energy systems are pragmatic and come directly from common design practices.

Thermostat controls

The room temperature is controlled by two thermostats, based on indoor and floor temperatures. Their setpoint temperatures are 21.5 °C and 29 °C. If both temperatures go below the setpoint, the circulating pump of the floor heating will be started. The heating control is not dependent on the controls of the solar collector, heat pump or electrical heater.

The heat pump and the electrical heater are connected to a two-stage thermostat installed on node 4 (Fig. 1). If node 4 temperature drops below the setpoint, the heat pump starts. Later, if the node temperature still drops also the electrical heater turns on. If the temperature of node 1 exceeds the upper limit temperature the heat pump turns off.

The solar collector control (not shown in Fig. 1) acts like a thermostat. The circulating pump turns on if the outlet temperature of the solar collector is greater than the inlet temperature and at the same time higher than the node 4 temperature. The above operation based only on thermostats is later referred as conventional control.

The qualitative control strategy

The qualitative control strategy is to take full advantage of renewable energy sources, if possible, and at the same time to produce domestic hot water and maintain comfort indoor conditions. The focus is in reducing the costs of external electrical energy supplied from the grid. This is done by periodically estimating the future need of heating power and by cost-effectively producing it. In practice, this means shifting the load of electrical power when the tariff is high by using heat energy of the tank and producing and storing heat into the tank when tariff is low. This is possible by means of a qualitative procedure, which controls operation of the energy systems. The following approach assumes that electricity pricing is time-varying, changing dynamically once in hour. Price information of the next 24 hours is provided to the user in advance by power supplying company.

Observe that the qualitative control takes advantage of the conventional control implemented by the thermostats. Both control methods are based on the same set points and parameters. The role of the qualitative control is to override the basic control implemented by thermostats. Figure 2. outlines the qualitative control system, which, when combined with the energy systems of Fig. 1, performs the designed operations. The left side of the figure illustrates the input signals of the system, consisting of temperatures inside the tank, room and solar collector output, the upper side shows time and environmental inputs. The outputs turn on and off the energy systems. This is done by turning on and off the circulating pumps of the solar collector and the heat pump including the compressor. The electrical heater control depends on the heat pump as described earlier.

The geothermal heat pump has a special role in the strategy. The heat pump consumes most of electrical power supplied from the grid. Therefore, by delaying its operation load shifting becomes effective. The starting time and length of the load shifting period depends on several variables. They are evaluated in a computer program, which determines the time and length of the period and operates parallel to the control logic (Fig. 2).

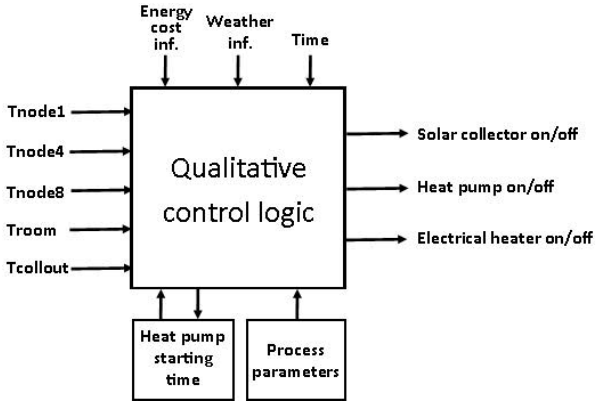

Figure 2. The proposed qualitative control of the energy systems.

The qualitative control logic

The qualitative control logic consists of states and transitions from one state to another. Each state is subject to one or more conditions, which are modified into inequalities and equalities. The conditions are created using time, former states, current and history values of inputs (Fig. 2). The conditions are discussed in the next chapter.

In practice, the control logic is a collection of IF-THEN-ELSE commands, where conditions are combined with Boolean functions. Once in a minute, the computer

program goes through all of them. If a condition comes true, the program turns an energy system on or off and/or determines the transition to the next state (Fig. 3).

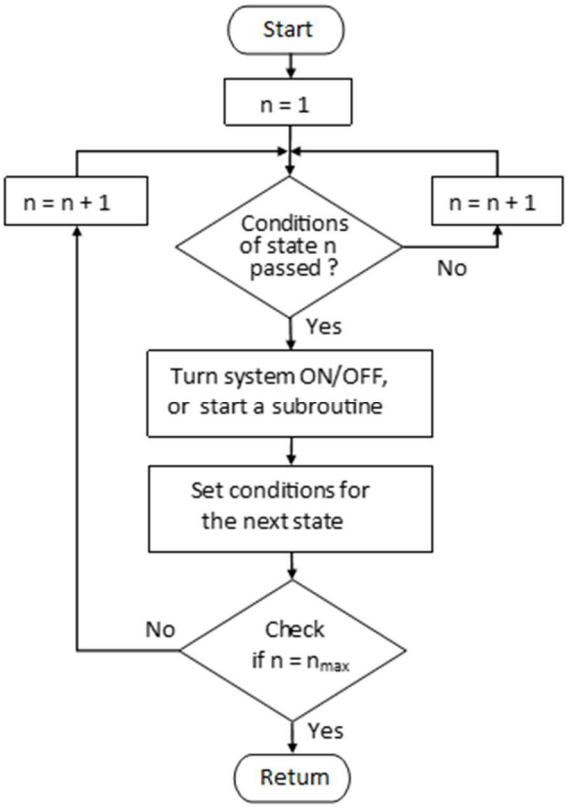

Figure 3. The control logic of the state n.

Prioritizing energy systems

All three energy systems operate with the aid of electrical energy. A natural way to reduce external energy costs is to prefer energy sources, where ratio between consumed electrical power and produced total power is small. Therefore, the strategy prioritizes the use of the solar collector, which needs electrical power only for the circulating pump. In principle, the solar collector feeds the tank all the time, when the collector output temperature is greater than the bottom temperature of the tank, i.e. $T_{CollOut} > T_{Node8}$ & $T_{CollOut} > T_{Node4}$. A necessity is that at the same time water temperature on the top is not too high: ($T_{Node1} < 95$ °C). If the collector output temperature is high ($T_{CollOut} > 95$ °C) and the middle node temperature rises over the limit ($T_{Node4} > 55$ °C), then the tank is full loaded. Similar decision is made if the water temperature on the top of the tank is high enough ($T_{Node1} > 95$ °C).

The geothermal heat pump provides major amount of the heat for the building but also consumes electrical energy. Therefore, the heat pump has a central role in reducing energy costs; it is useful in load shifting. The operation of the geothermal heat pump depends on several conditions. First, in the beginning of the six hours period the control program calls a subroutine, which checks if the tank must be charged and determines a cost-effective period for it. This is explained in the next chapter. The same subroutine is also called if the room temperature decreases under the prescribed limit, i.e. $T_{Room} < 21$ °C and at the same time $T_{Node4} < 54$ °C. After starting, the heat pump operates until $T_{Node4} > 55$ °C. If the solar collector output temperature exceeds the bottom temperature of the tank $T_{CollOut} > T_{Node8}$ & $T_{CollOut} > T_{Node4}$, both energy systems may operate at the same time.

The electrical heater only consumes electrical power. That is why, it has a minor role in heat production. Still, the electrical heater may have effect on energy cost reduction, if it is used when the energy price is low. Its main function is to operate as back up energy system, i.e. to support the solar collector and the heat pump in producing domestic hot water and in keeping indoor conditions comfortable. Control actions of the electrical heater are taken care by the thermostat and they are based on water temperatures of T_{Node4}.

Checking the need of energy

Estimating the need of energy for the whole building is made periodically once in six hours. Six hours is roughly the period the storage tank can provide the whole building energy demand in most outdoor conditions during winter.

The first step is to check the current amount of heat Q of the hot water tank.

$$Q = cm(T_a - T_{ma}), \quad (1)$$

where *c* refers to heat capacity and, *m* to the mass of water. T_a represents average water temperature of the tank, measured from Node 4, and T_{ma} means the minimum allowable water temperature of the same node. T_{ma} is one of the parameters (Fig. 2) given as an initial value of the procedure.

Then, the stored amount of heat *Q* will be compared to the heating energy demand of the building. The comparison gives a period of hours the storage tank can provide heat to the floor heating and domestic water. In practice, the heating energy demand of the building will be estimated by means of a static thermal model of the building and a weather forecast.

The static thermal model is created by collecting data of a twelve-month simulation of the building. The data was further processed to a simple linear regression model, which presents the heating energy demand $\hat{O}$ of the building per one hour as a function of outdoor temperature *T*.

$$\hat{O} = \hat{O}(T). \quad (2)$$

It is assumed that indoor temperature is kept stable. Thus, variable *T* could also represent the difference between indoor and outdoor temperatures.

The next step is to check how long period the storage tank can discharge heat to the floor heating and domestic water and at the same time maintain the indoor conditions at comfortable level. This is done by testing what is the largest value *M* of index $i, (1 \le i \le 6)$, where the following equation holds

$$Q > \sum_{i=1}^{M} \hat{O}(T_i), \quad (3)$$

where T_i means the predicted hourly outdoor temperature, i hours forward from the current time instant. The predicted outdoor temperature is directly read from the TMY data file. In a real building, the weather forecast data will be periodically picked up from an Internet server of a weather service provider.

If $M = 6$, there is energy enough for the whole period and the next checking will be done again after six hours. If $M < 6$, heat amount of the storage tank must be increased within the next M hours. This is done by starting the geothermal heat pump. A necessity is that at the same time the cost of electrical energy is low enough. If the heat pump operates two hours, it is enough to charge the tank for the next six hours.

Therefore, the control procedure tries to find a two hours period within the next M hours, where the cost of electrical energy is lower than in average. The idea is to avoid peak load times and find the maximum cost difference C_D between average energy costs during continuous pair of hours i, and $i + 1$, i.e. $(C_i + C_{i+1})/2$ and the average energy costs C_a. Thus, C_D can be written as

$$C_D = max\left[\frac{(C_i+C_{i+1})}{2} - C_a\right], \quad (4)$$

where

$$C_a = \frac{1}{M}\sum_1^M C_i. \quad (5)$$

The continuous pair of hours means the hours $(i, i+1) \in \{(1,2),(2,3),\dots,(M-2,M-1)\}$. If such a pair $(i, i+1)$ is found, the program starts the geothermal heat pump in the beginning of the hour i. If no such period is found, the heat pump will be started within the next hour despite of the energy costs. The whole procedure is repeated after six hours.

Discussion and result analysis

The qualitative control is compared with a conventional control method. The latter is put into operation simply by disconnecting the qualitative control logic. Then, the energy systems operate independently, by means of the thermostats (Fig. 1). Set points and parameter values need not be changed after disconnection. In both cases a 24-hour day-ahead hourly tariff scheme is applied in calculating the costs.

The test runs consisted simulations of twelve months, starting in the beginning of January. The sampling time was one minute. The conventional method and the qualitative method were simulated separately using the same weather data, inner loads, and operation of the building.

The total electrical power supplied from the grid consists of the electricity delivered to the heat pump $E_{HP}(h)$, solar thermal collector $E_{SC}(h)$ and the electrical heater $E_{AH}(h)$. Thus, the total yearly electricity costs of the systems are summed over 8760 hours:

$$C_A = \sum_{h=1}^{8760}\{E_{HP}(h) + E_{SC}(h) + E_{AH}(h)\} \times T(h) \quad (6)$$

Where $T(h)$ is the electricity tariff at the hour h. The tariff is a 24-hours-ahead hourly electricity price. The yearly electricity consumptions are: 10059 kWh (the conventional method) and 9531 kWh (the qualitative method). The share of each energy system is illustrated in Fig. 4. As shown the difference between energy consumptions is 5.2 %.

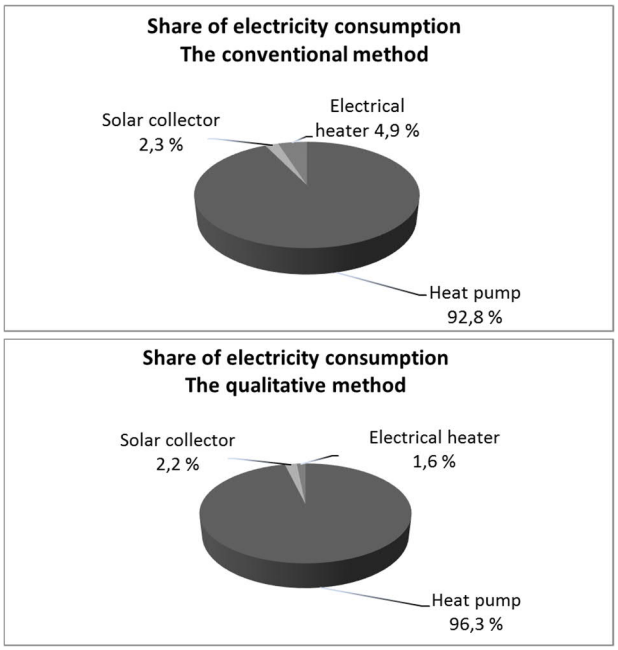

Figure 4. Electricity consumption of the three energy systems using the conventional and the new method.

The electricity costs are compared in Table 1. The percentage cost reduction between the methods is 5.7%. The cost reduction is close to the results published by Corradi et. al. (2013) or Nyeng, P. and Østergaard (2011). Observe that the cost reduction is based on common sizing of the energy systems. Test runs show that larger cost reductions will be achieved by increasing the water tank size.

Table 1. Comparison of electricity consumption between the conventional and the new method.

Month	Electricity Costs [€]		Percentage cost reduction
	Conventional method	New method	
January	66,2	59,5	10,2
February	69,0	62,7	9,0
March	34,8	32,6	6,2
April	18,9	18,7	1,1
May	13,7	13,7	-0,4
June	12,9	11,2	13,4
July	5,2	5,4	-3,7
August	16,1	15,8	2,0
September	22,4	21,7	3,3
October	28,0	26,3	6,2
November	50,4	49,1	2,6
December	50,8	49,5	2,5
Total	**388,4**	**366,2**	**5,7 %**

The Figure 5 illustrates variation of the indoor and outdoor temperatures during the heating season. The period is limited to the heating season because the simulated building does not contain any cooling system. Therefore, during summer time the indoor temperature cannot be kept stable. As seen in the figure the range of the indoor temperature variation is limited to ± 2 degrees around the set-point temperature.

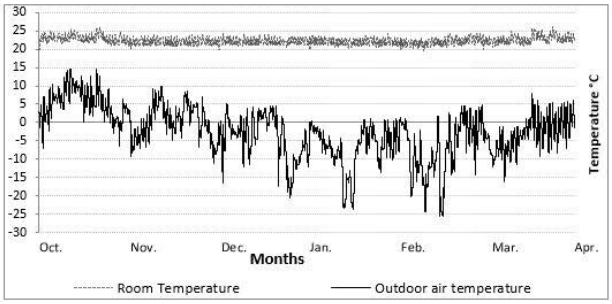

Figure 5. Indoor and outdoor temperatures during the heating season.

One concern of the control strategy are inaccuracies in weather forecast and linear regression thermal model of the building. If outdoor temperature becomes lower than predicted by the weather forecast, the heat stored in the tank may not cover all heating energy demands. The same is true if the thermal model of the building proposes too low energy consumption for the next few hours. In both cases the shortage of heating energy could be later seen in dropping of the indoor temperature. However, the control logic starts the heat pump immediately, if the indoor temperature drops below 21 ℃ and at the same time $T_{Node4} < 54$ ℃. In this way the indoor conditions can be kept at a comfortable level.

In case the outdoor temperature is higher than predicted or the energy demand presented by the thermal model is too high, the system may operate inefficiently; cost reduction may be lower than the potential. In real building the weather forecast is provided by a weather service company. Thus, one possibility to address the problem is to focus on developing a more comprehensive thermal model of the building.

One option to develop the method is to apply a varying discharge period for the tank. In the above method the maximum discharge period was fixed, set to six hours. Six hours is roughly the period the storage tank can provide the whole building energy demand in most outdoor conditions during winter. When conditions are milder, maximum discharge period could be longer. This gives more opportunities to find low tariff periods for starting the heat pump and more cost reductions of the electricity. As shown, a larger storage tank would produce similar benefits, even using a fixed discharge period.

Conclusion

A qualitative control method was presented, which decreases costs of electrical energy in a simulated residential building, equipped with a hybrid energy system: an energy storage combined with an electrical heater, a geothermal heat pump and a solar thermal collector. The achieved energy cost reduction was 5.7 %. At the same time domestic hot water was produced and indoor conditions were maintained comfortable.

The results are based on common sizing of the energy systems. Larger cost reductions could be achieved by increasing the water tank size. The demonstrated method serves as a first stage approach in developing a generic control strategy for multi-energy buildings.

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