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Smart Building Heating, Cooling and Power Generation with Solar Geothermal Combined Heat Pump System

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Abstract

All electric Fuzzy Logic(FL) based smart building integrated Photovoltaic-Thermal(PVT) tri-generation (heating, cooling and Power) technology meets one of Korea government's new research and development policies about the national future economy growth engines field – hybrid renewable energy. The main objectives of this hybrid renewable systems are to model, simulate and analyze the performance of FL based PVT integrated GSHP system for typical residential buildings. In this study two systems: GSHP system and GSHP-PVT system are designed to apply the FL control strategy. TRNSYS software is used for the system modeling and simulations and the MATLAB Fuzzy Logic Toolbox is used for the FL controller implementation with annual weather data of Incheon and Ottawa. For the GSHP system, the advanced FL control results in approximately 9.5% primary energy saving in the heating period, 12.7% in the shoulder heating period and 18.3% in the cooling period, 17.4% in the cooling shoulder period and 12% annually compared to the On-Off control strategy.

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Keywords: FL(Fuzzy Logic), PVT(Photovoltaic Thermal), GSHP(Ground Source Heat Pump), TRNSYS, MATLAB, Primary Energy Savings

1. Introduction

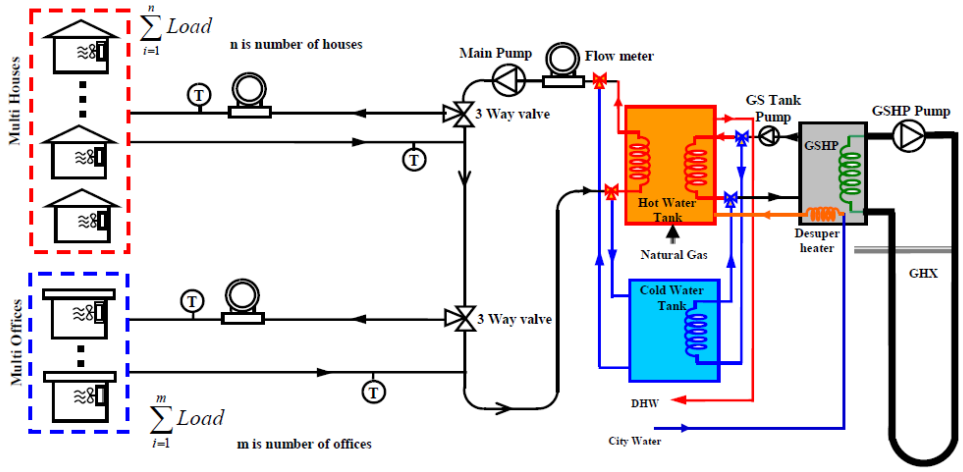
The control and management of microgeneration systems is a very important for their optimal operation. Simple On-Off control strategy is often used, but its major disadvantage is not being able to allow part load operation of devices. The efficient operation of the microgeneration systems, especially for single dwellings, has the following attributes: nonlinear behaviour; uncertainties of electrical and thermal demands; and vagueness of the performance of the microgeneration system [1]. Due to these attributes inherent in the operation of the microgeneration system, an intelligent approach is required. Some researchers have proposed advanced methods based on artificial neural networks (ANN) [2-4]. For such an approach to operate optimally, a large number of accurate historical data must be provided for the training of the neural network. PID control has also been proposed but can operate effectively in energy systems only if it uses a fuzzy self-tuning controller for adjusting the PID's gains in real time [5-6]. A fuzzy logic approach, which aims to imitate the aspects of human cognition or approximate reasoning, can deal with the complexities of the microgeneration systems [1]. The FL approach has

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been investigated for hybrid electric vehicles [7-9]. It has also been applied for real time operation of a micro CHP system [1], for management of polygeneration microgrids [9] and commercial buildings [10], for capacity control of photovoltaic systems [11-12] and a heat pump system [13]. The FL approach has several advantages such as the ability to be executed in a relatively short time when compared to optimization techniques; no need for offline training when compared to ANN; flexibility to change [14]; and the ability to deal with multiple inputs. It is well suited to dealing with complex systems where vagueness and imprecision exist, and where expert knowledge is more suitable than the use of mathematical condition statements. For these reasons, the advanced FL approach is chosen in the present comparative study to investigate the possible energy and cost savings in comparison to the conventional On-Off control strategy.

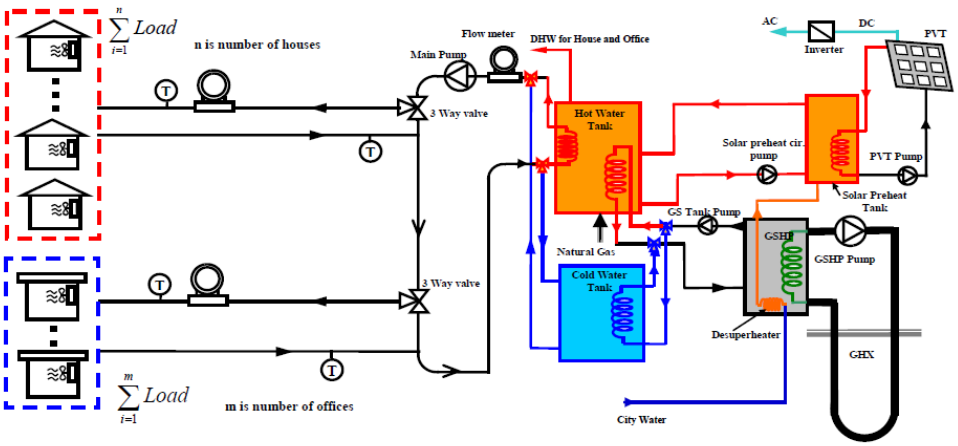
2. Systems for Study

Two systems, a GSHP system and a GSHP-PVT system, are designed to apply the fuzzy logic control strategy. The system configurations are the same as shown in Fig. 1 and Fig. 2. The systems are able to meet a residential house's space heating and cooling loads and part of the electrical loads in the case of the GSHP-PVT system.



#	1	2	3	4	5	6	7	8	9
Main component	House/ Office	Fan coil unit	Main pump	GSHP	GSHP pump	GS-Tank pump	Hot water tank	Cold water tank	Flow meter/ sensor/ valves
Quantity	1-n/1-m	n+m	1	1	1	1	1	1	N/A

Fig. 1. Case 5 - Load sharing (houses & offices) using GSHP system with fan coil units.



#	1	2	3	4	5	6	7	8	9	10
Main component	House/ Office	Fan coil unit	Main pump	GSHP	GSHP pump	GS-Tank pump	PVT pump	Solar-tank pump	Hot water tank	Cold water tank
Quantity	n/m	n+m	1	1	1	1	1	1	1	1

Fig. 2. Case 6 - Load sharing (houses & offices) using hybrid microgeneration system (GSHPPV/T)

3. Control Strategies

3.1. Fuzzy Logic Control Strategy

The operation of the GSHP and PVT panels is controlled by a fuzzy logic controller respectively. The control strategies is described and discussed in the following.

The operation of the heat pump is controlled by two input variables: the storage tank temperature and the temperature difference between the actual room temperature and the thermostat set-point. It should be noted that, the water temperature near the hot water storage tank top (T2 in layer 2) is used in the heating season while the water temperature at the cold water storage tank bottom(T9 in layer 9) is used in the cooling season. These two input variables are considered the most influential ones through studying and understanding the fundamental behaviour of the GSHP system. The output of the fuzzy logic controller is the fractional state of operation of the ground source heat pump with a number ranging from 0 to 1 with 0 turning the device OFF and 1 representing full load operation. The process of formulating the mapping from a given input to an output using FL is called fuzzy inference process. This process includes the membership function, FL operators and the fuzzy rules. The inputs and output are is linguistically described as shown in Table 1. The membership functions of the fuzzy logic system are presented in Fig. 3. The membership function is a curve which defines how to map each point in the input or output value to a membership value between 0 and 1. It should be noted that membership function can overlap as shown in Fig. 3, which makes the possibility for a certain temperature for example to be a member of two sets at the same time. This shows one of the ways in which the fuzzy inference system deals with uncertainty.

Table 1. Linguistic description of fuzzy logic system inputs and output for GSHP system.

Hot water temperature in HW storage tank	L (low)	M (medium)	H(high)	VH (very high)	
Cold water temperature in CW storage tank	VL (very low)	L (low)	M (medium)	H(high)	
Room temperature difference between its actual value and set-point	Large Negative	Small Negative	None	Small Positive	Large Positive
GSHP operation state	Off	L (low)	M (medium)	H(high)	

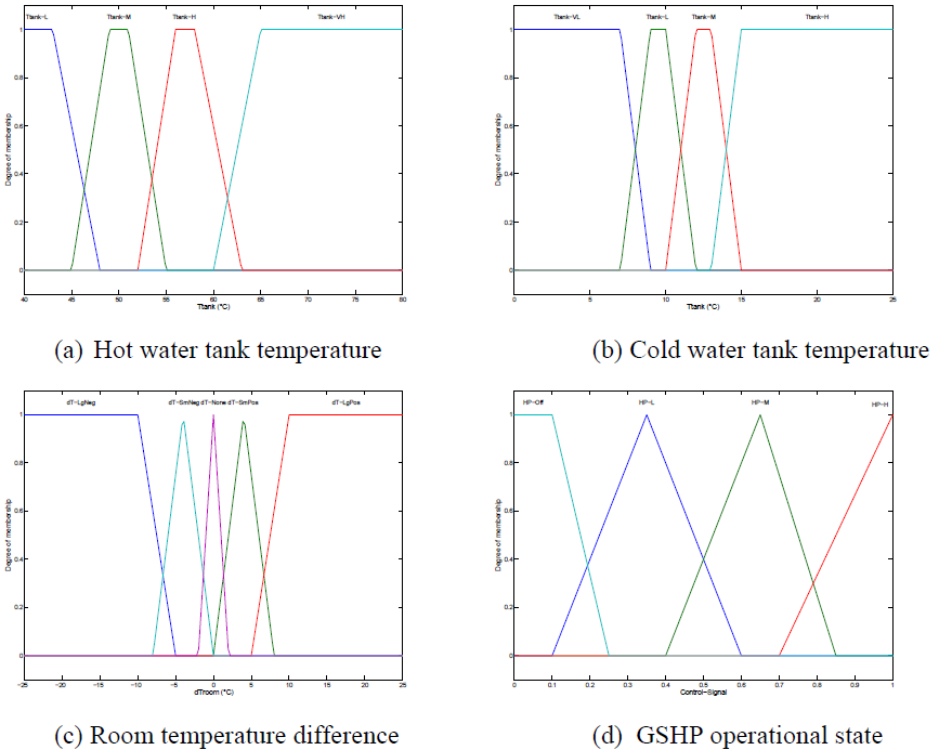


Fig. 3. Membership functions of storage tank water temperature, room temperature difference and GSHP operational state.

Mamdani type fuzzy inference system (FIS) is selected. The FIS operators that translate input values into an output value is shown in Table 2 and the fuzzy logic if-then rules for GSHP control signal are presented in Table 3 for heating and cooling period respectively. The rules are chosen intuitively based on the research team's experiences. For example, in the heating period, the GSHP will be running on high capacity when the hot water storage tank temperature is low and room temperature difference between its actual value and set-point is small negative (Sm Neg.) or large negative (Lg Neg.). Conversely, the GSHP will be turned off when the hot water tank temperature is very high and room temperature is higher than the thermostat set-point. In the cooling period, depending on the cold water tank temperature and room temperature, the GSHP will be operated based on the linguistic rules that are opposite to those applied in the heating season as shown in Table 3.

Table 2. fuzzy inference system operator used in the study

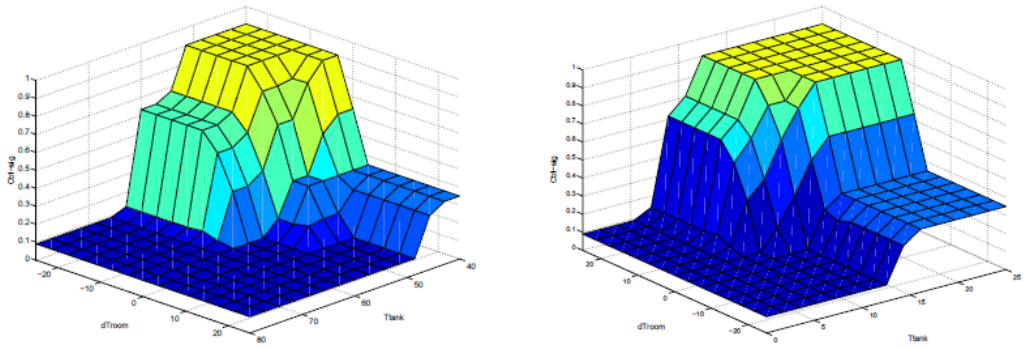
Stage	Operator selected
AND method	Min
Implication	Prod
Aggregation	Max
Defuzzification	Centroid

Table 3. If-Then rules for GSHP operational state

Hot Water Storage Tank Temp.	dT=Troom-Tset				
	Lg Neg.	Sm Neg.	None	Sm Pos.	Lg Pos.
L	H	H	M	L	L
M	H	M	L	Off	Off
H	M	L	Off	Off	Off
VH	Off	Off	Off	Off	Off

Cold Water Storage Tank Temp.	dT=Troom-Tset				
	Lg Neg.	Sm Neg.	None	Sm Pos.	Lg Pos.
VL	Off	Off	Off	Off	Off
L	Off	Off	Off	L	M
M	Off	Off	L	M	H
H	L	L	M	H	H

Finally the fuzzy logic control surfaces of the ground source heat pump are illustrated in Fig. 4 for heating and cooling operation modes respectively.



(a) Heating mode. (b) Cooling mode.

Fig. 4. FL control surface for ground source heat pump operational state in heating and cooling modes.

Although recent advances in variable-speed compressor to produce the target capacity opened up new possibilities in improving heat pump performance and energy efficiency, fully modulated ground heat source pumps are not yet commercially available at the moment. In the present study, a two-stage GSHP is chosen. The GSHP is operated at its low capacity when the FL control signal is less than or equal to 0.5, at its high capacity when the FL control signal is greater than 0.5.

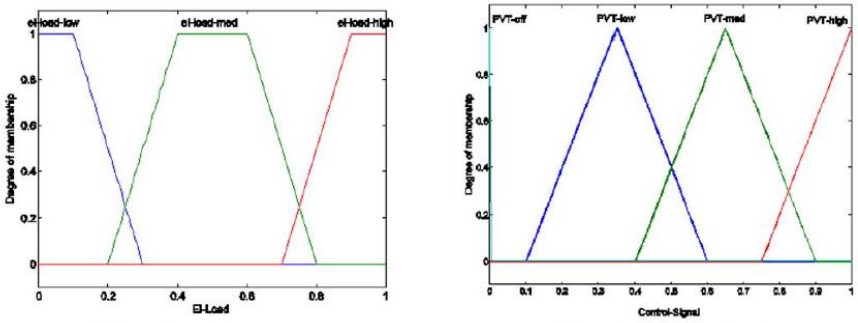
Photovoltaic and thermal panels provide both electricity and heat to the house. However, the electrical and thermal energy generations are intermittent depending on the solar radiation. PVT's electrical and thermal efficiencies both decrease when the panel temperature increases. Based on the characteristics of the PVT panel, two control strategies are proposed in the study as shown in Table 4. The GSHP is operated with fuzzy logic control in both strategies. On the other hand, the PVT system is operated either with FL control, FL (A), or with On-Off control, FL (B).

Table 4. Fuzzy logic control strategies for GSHP-PVT system

Strategy A FL (A)		Strategy B FL (B)	
GSHP	PVT	GSHP	PVT
FL	FL	FL	On-Off

In the first control strategy, FL (A), the PVT circulation pump operational state is determined by two input variables in the heating season: the house electrical demand and the temperature difference between the panel surface and the pre-heat tank bottom. Only part of the PVT panels are in operation (circulated with the glycol fluid) to provide thermal energy to the house. For panels not circulated with fluid, they act like PV panels generating electricity only. As there is no heating load in the cooling season, the PVT circulation pump is not in the operation. The membership functions for the two input variables are shown in Fig. 5 (a) for the electricity demand and (b) for the temperature difference. Table 5 presented the fuzzy logic if-then rules for determining the fraction of PVT

panels in operation (circulating with glycol fluid) to provide thermal energy to the house. Fig. 6 presents the fuzzy logic control surfaces of the PVT circulation pump in heating season. The FL control signal for the PVT system is between 0 and 1: 0 represents no PVT panels having fluid circulation, 1 represents all PVT panels having circulation fluid, and a control value between 0 and 1 means a fraction of total installed PVT panels having fluid circulation fluid to provide thermal energy to the house.



(a) Electricity demand (b) PVT system operational state

Fig. 5. Membership functions of electric power demand and PVT system operational state.

Table 5 . If-Then rules for determining the fraction of PVT panels in operation to provide thermal energy.

Electrical Demand	$dT_{tank}=T_{panel} - T_{btm}$			
	VLow	Low	Medium	High
L	Off	L	L	M
M	Off	L	M	H
H	Off	L	M	H

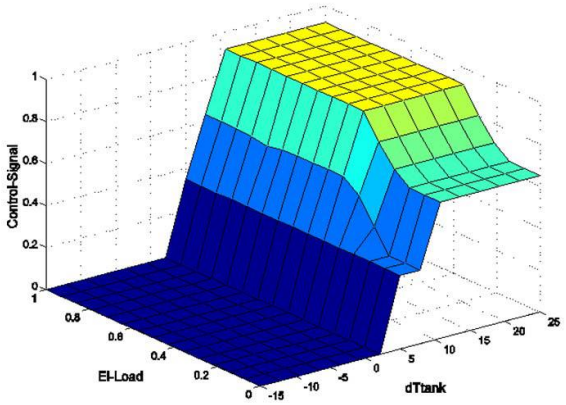


Fig. 6. FL control surface for PVT system operational state in heating season.

Pre-modelling analyses found that by applying the FL control for the PVT system, it restricts the electricity generation and consequently increase the electricity import from the grid and primary energy consumption. For this reason, the second control strategy, FL (B), is proposed. In this control strategy, the PVT panels' thermal energy generation is controlled by On-Off strategy based on the temperature difference between panel and solar preheat tank bottom. With this control strategy, the control signal is either 0 or 1, which means either none or all PVT panels are in operation to provide thermal energy to the house. The algorithm of the On-Off control is discussed in the following section. It should be noted that the hot water storage tank has a gas burner at the bottom to provide supplementary heat in conditions where the GSHP and PVTs cannot provide sufficient heat. The

operation of this auxiliary burner is based on on-off strategy as it is rarely used. The room thermostat is set at 21 °C in heating season and at 25 °C in cooling season with a dead-band of 1 °C.

3.2. On-Off Control Strategy

With the On-Off strategy, the ground source heat pump is controlled by an aquastat in the hot water tank and cold water tank in the heating season and cooling season respectively as shown in Table 6. It should be noted that the hot and cold storage tanks are modelled with 10 isothermal temperature layers to better represent the stratification in the tank. The top layer is 1 and the bottom layer is 10. T2, T8 and T9 in Table 6 indicate the temperature sensor locations in the tank layers. The gas fired auxiliary heater located at the bottom of the hot water storage tank is controlled by the same two separated temperature sensors (T2 and T8) as for the GSHP heating mode operation.

Table 6. On-Off control strategy for GSHP and auxiliary heater operation

GSHP		Aux. heater	
ON	OFF	ON	OFF
$T2^a(HT^b) \leq 50$ °C $T9^a(CT^b) \geq 12$ °C	$T8^a$ $(HT^b) \geq 55$ °C $T9^a$ $(CT^b) \leq 8$ °C	$T2^a(HT^b) \leq 45$ °C	$T8^a(HT^b) \geq 55$ °C

[a] T2, T8, T9 are the temperature sensors in storage tank node 2, 8 and 9 respectively. Each storage tank is divided into 10 isothermal nodes, 1 at the tank top and 10 at the tank bottom.
[b] HT: hot water storage tank; CT: cold water storage tank (when GSHP in cooling mode operation).

The circulation pumps in the PVT system are operated based on the algorithm shown in Table 7. The operation of the PVT circulation pump is dependent on the temperature difference between the PVT panels and the solar preheat tank bottom. The pump will be on and start to circulate glycol fluid to all PVT panels when the panel temperature is at least 10°C higher than that of the solar preheat tank bottom. It will be stopped until the temperature difference is less than 3°C. The solar preheat-tank circulation pump circulates water between the solar tank and the hot water storage tank. It is controlled by the temperature difference between the solar tank top and the hot water storage tank bottom. The pump starts when the temperature difference greater than 7°C and stops until the difference is smaller than 2°C.

Table 7. On-Off control strategy for PVT and solar tank circulation pumps operation

PVT circulation pump		Solar preheat tank circulation pump	
ON	OFF	ON	OFF
$\Delta T^a \geq 10$°C	$\Delta T^a \leq 3$°C	$\Delta T^b \geq 7$°C	$\Delta T^b \leq 2$°C

[a] ΔT is the temperature difference between the PVT panel and solar preheat tank bottom.
[b] ΔT is the temperature difference between the solar preheat tank top and hot water storage tank bottom.

4. Result and Discussion

The Ottawa annual weather data is used in the simulations. The results are presented and discussed. Fig. 7 shows the electricity and natural gas energy consumption intensities in the heating and cooling periods and whole year for the GSHP system with On-Off and fuzzy logic control strategies respectively. The energy consumption intensity results for the GSHP-PVT system with On-Off and two FL control strategies are presented in Fig. 8, Fig. 9 in a similar format.

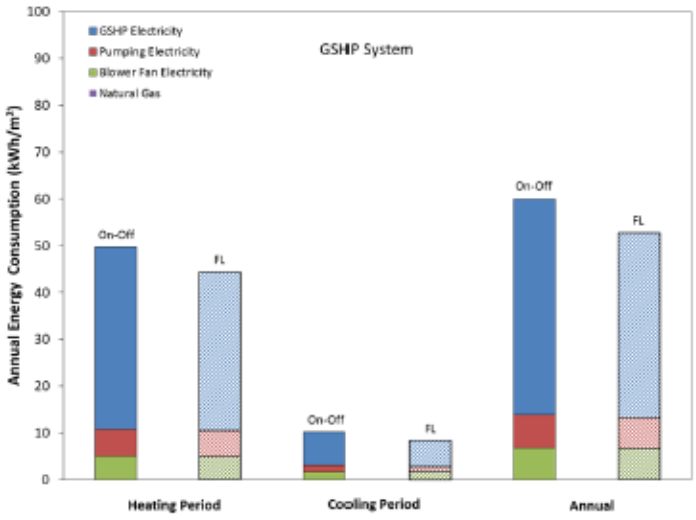


Fig. 7. Comparison of energy consumption intensities of GSHP system with On-Off and FL control strategies.

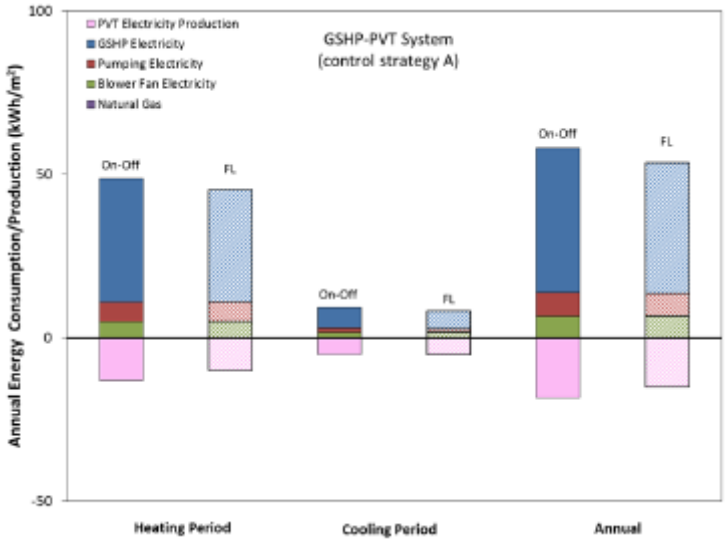


Fig. 8. Control strategy A: GSHP and PVT system with FL control

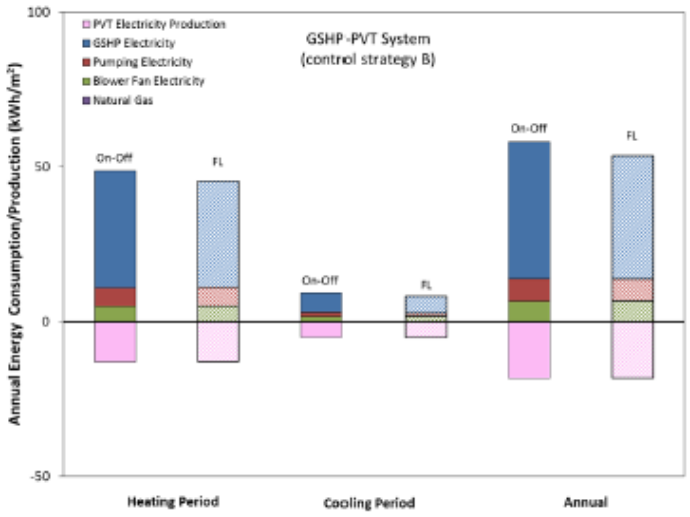


Fig. 9. Control strategy B: GSHP with FL control and PVT system with On-Off control.

The results shown in figures 7 and 8,9 clearly indicate that with the application of the advanced FL control strategy, the electricity consumption by the ground source heat pump is reduced significantly. This is because that the operation of the GSHP is modulated based on house's heating and cooling demands, which improves the devices' efficiency at partial loads. The pumping and blower fan energy consumption are reduced slightly both for the GSHP and GSHP-PVT systems. As discussed earlier, two control strategies are applied for the GSHP-PVT system based on the findings from the pre-modelling analyses. The results shown in Fig. 8, 9 indicate that the GSHP and blower fan electricity consumption are approximately the same and the pumping energy is slightly higher for the system with control strategy B. The main difference resulted from the two different control strategies is the PVT electricity production. Control strategy B with On-Off control for the PVT system results in higher electricity production, since all PVT panels are circulated with glycol fluid which reduces panel surface temperature and subsequently increases electric efficiency (production). Conversely, in the case of PVT system is controlled with FL strategy (strategy A), a fraction of total installed PVT panels is circulated with fluid to provide thermal energy depending on solar pre-heat tank temperature and electric demand. This causes the panel surface temperature increase for PVT panels without circulation fluid and consequently reduces electric efficiency and overall electricity production. The primary energy consumption intensities are illustrated in Fig. 10 and Fig. 11 for the GSHP and GSHP-PVT systems with On-Off and FL control strategies respectively. The savings shown in the figures are breakdown into five different periods: heating, shoulder heating, cooling, shoulder cooling and annual. The primary energy factor is assumed as 2.6 for the electricity and 1.1 for natural gas to consider 10% of overhead for delivery to the site. The results show that the systems with FL control strategy have low primary energy consumption. For the GSHP system, as shown in Fig. 10, the advanced FL control results in approximately 9.5% primary energy saving in the heating period, 12.7% in the shoulder heating period, 18.3% in the cooling period, 17.4% in the cooling shoulder period and 12.0% annually compared to the On-Off control strategy. The primary energy savings in the shoulder heating period is considerably higher than that of in the heating period. This means the system is benefited from the staged GSHP operation in the shoulder heating period. However, the difference in the primary energy savings (%) in the shoulder cooling period and cooling period is relatively low. This is mainly due to the characteristics of the Ottawa summer, either hot or cool, especially in the shoulder cooling period. Therefore, the energy savings from the staged GSHP operation are not that significant. For the GSHP-PVT system, as shown in Fig. 11, the annual primary energy saving is higher with the application of control strategy B, at 11.2% compared to 3.6% with control strategy A. The major impact of the primary energy saving is from the PVT electricity production. Control strategy A restricted the PVT electricity production and hence requires more electricity-import from the grid. This occurs mainly in time periods with medium or low heating load, i.e. in shoulder heating period. For this reason, primary energy consumption with FL (A) control strategy is higher than that of with On-Off control (also with FL(B) control) in this period.

It is noticeable that the percentage of primary energy saving trends in the shoulder heating/cooling period in comparison to the heating/cooling period, are opposite to that shown for the GSHP system. The results shown in

Fig. 11 indicate that the percentage of primary energy saving in the shoulder heating period, resulted from the application FL controls (A and B) is lower than that of in the heating period. In the shoulder period the heating loads are relatively low, thus the GSHP operation is much less required due to the use of thermal energy from the PVTs. Therefore, the energy savings resulted from the staged GSHP operation is reduced. Figure 34 also shows that the percentage of primary energy savings in the shoulder cooling period is considerably higher than that of in the cooling period. This is because the PVT electricity production can cover all most all of the HVAC electricity demand in the shoulder cooling period with the use of the FL controls (A and B).

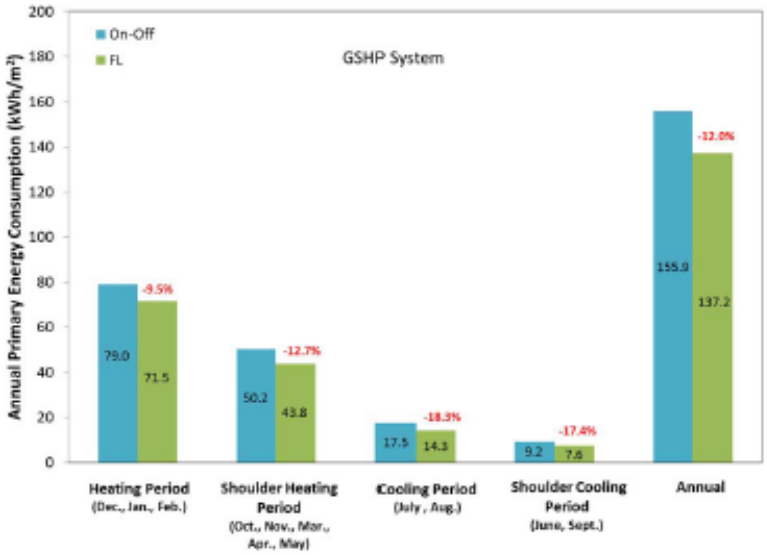


Fig. 10. Comparison of primary energy consumption intensities of GSHP system with On-Off and FL control strategies.

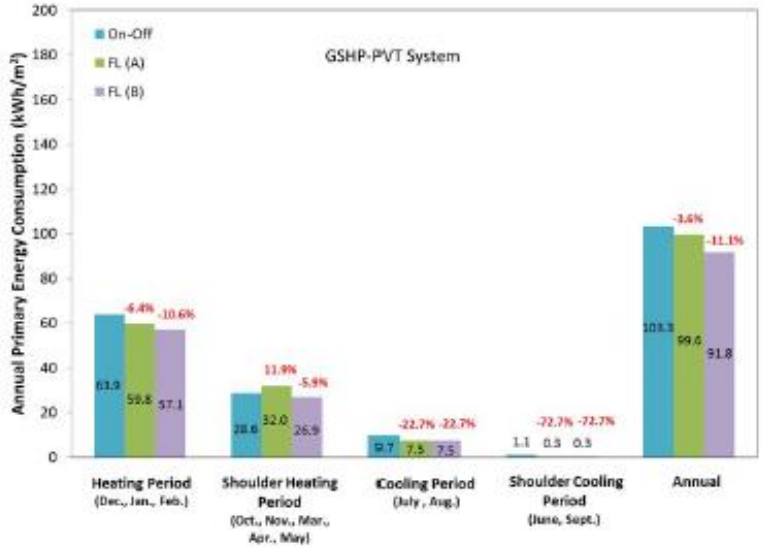


Fig. 11. Comparison of primary energy consumption intensities of GSHP-PVT system with On-Off and FL control strategies.

5. Conclusions

The results in the figures also shown that, in the heating season, the cost saving percentage resulting from FL control is higher in the shoulder heating period for the GSHP system, but lower for the GSHP-PVT system. In the cooling season, on the other hand, the higher cost saving percentage occurs in the cooling period rather than in the

shoulder cooling period. In summary, the comparative study clearly shows that, with the application of the FL control strategy instead of conventional On-Off control, the GSHP and GSHP-PVT systems are able to attain both primary energy and cost savings. The savings are primary resulting from the staged operation of the GSHP. Furthermore, the analysis results reveal that the characteristics of each controlled component should be considered before using the FL control strategy. For the cases studied, the GSHP certainly benefitted from the application of the FL control. On the other hand, the PVT system should be operated with On-Off control - that is when the control signal is ON, all (not fraction of) panels are circulated with fluid in order to reduce the panel surface temperature thereby to increase electricity efficiency/production. Further analysis found that the PVT electricity generation can be increased significantly if the surplus thermal energy can be used by other consumers or dumped in a heat sink (e.g. a cooling tower) to further lower the circulation fluid temperature return to the PVT panels. With this control strategy, although the pumping energy will increase in order to pump the panel circulation fluid to additional consumers or heat sinks, overall the system can achieve substantial primary energy and cost savings (>30%) in comparison to the one with On-Off control strategy. It is expected that with the application of advanced control strategies and system optimization, a microgeneration system will be able to achieve further energy and cost savings. Additionally, the FL control algorithms can be easily implemented in a microprocessor to integrate with a microgeneration system.

Acknowledgements

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