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Simulated Evaluation of Combined Use of Building Thermal Mass and Thermal Storage in Solar Hybrid Heat Pump System for Demand Response

Kyoung-ho Lee[1], Jae-hyeok Heo[1], Soon-myoung Lee[1], Moon-chang Joo[1]

[1] Solar Thermal Laboratory, New and Renewable Energy Research Division,
Korea Institute of Energy Research

Abstract

In this study, TRNSYS simulations were employed to evaluate simple strategies for controlling energy demand response by utilizing building thermal mass and daily and weekly solar thermal storage. All control setpoints (i.e., for the building indoor space temperature, for heat pump on/off controls, and for pump and valve control for the weekly storage tank) were adjusted before and during the demand response period. Simulation results showed that a significant reduction in electric energy consumption could be achieved through combined use of thermal storage.

Keywords: *Demand response, Thermal storage, Solar heating, Heat pump, Weekly thermal storage, Setpoint adjustment*

1. Introduction

Demand response (DR) is an effective tool to reduce peak electric consumption of a national power grid when power supply is lower than demand. Energy storage systems can be utilized effectively to mitigate peak electric consumption during on-peak periods. In the case of electric heating systems combined with thermal energy storage, thermal energy storage systems are directly coupled with electric energy systems. Effective and intelligent use of thermal storage can therefore contribute to mitigating the electricity burden on the power grid. There has been significant research into DR technologies to reduce electric energy consumption during on-peak periods using thermal storage (Arteconi et al., 2016). However, most studies have focused on the summer period, when electric consumption due to space cooling is significant. Peak electric demand could also occur during winter time if electric heating systems (such as electric heaters or electric heat pumps) are widely used. During the heating season, solar thermal energy (through thermal storage) could be used for DR (Lee et al, 2015). In this study, we consider a solar hybrid electric heat pump system in an office building, with additional weekly thermal storage to use stored solar thermal energy, in order to reduce electric consumption related to heat pump operation for space heating. We consider combined use of thermal storage (such as building thermal mass, thermal storage connected to heat pumps, and weekly solar storage) for various control strategies.

2. Description of system and control strategy

Thermal storage systems could potentially contribute to managing response to electric load demand. They are activated by a control signal from electric utilities. The purpose of this control is to reduce peak demand on the power grid system. In this study, electric load shifting was evaluated by using a solar heating system with a ground-source heat pump and additional weekly thermal storage (ST_W); this is shown in Fig. 1.

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Weekly solar thermal storage can be feasible in office buildings because, during there is generally nearly no heating demand during weekends and surplus solar heat energy can be stored in the weekly storage tank on Sundays. A daily thermal storage tank(ST_D), used for heating domestic water and supplying energy for space heating, was connected with solar collectors and the heat pump. During weekends, the surplus solar yield was stored in the weekly storage tank. This stored thermal energy, together with building thermal mass control, could then be utilized for DR control during the following week. In this study, TRNSYS system simulation was used to evaluate the control strategy for load shifting to meet DR control. For DR with the weekly solar storage tank, the hot water in the ST_W tank was set to flow through the ST_D, so that the fluid temperature at the location controlled by the heat pump in the tank was maintained as high as possible during the DR period. In addition, the setpoint of the heat pump was set higher and lower than normal prior to and during the DR period, respectively. In this study, this control strategy was termed Solar DR (Demand Response). Simultaneously, the building indoor setpoint temperature can be set higher than conventionally the case before the DR period, to an upper limit temperature within the thermal comfort range; afterwards, the setpoint is reduced to a lower temperature within the thermal comfort range during the DR period. In this way, the building thermal mass and daily and weekly solar storage tanks could be utilized in combination to reduce the duration of heat pump operation as much as possible during the DR period. In this study, this control strategy was termed BC (Building Control). In addition, prior to the DR period, the storage setpoint temperature monitored by the heat pump can be set to an upper temperature higher than conventionally the case; subsequently, the setpoint is lowered to an allowable lower temperature suitable for space heating. This control strategy was termed HPC (Heat Pump Control). The three different control strategies can be employed either separately or simultaneously for combined use of thermal energy storage to maximize reduction of peak electric consumption.

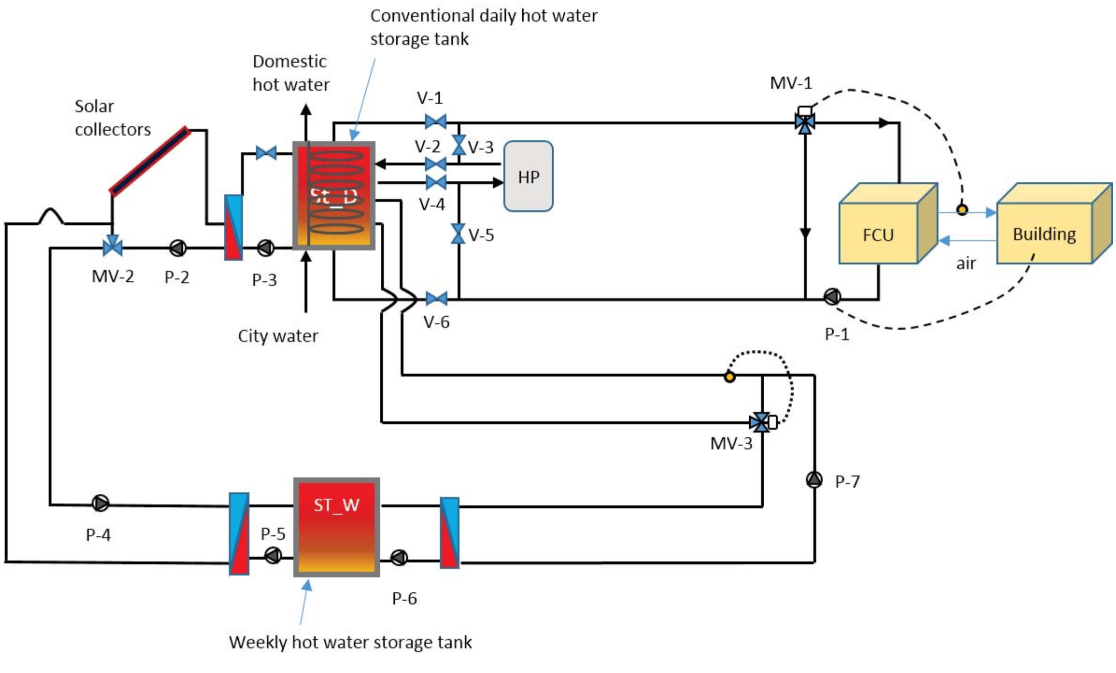

Fig. 1: Schematic diagram of solar hybrid heat pump system with daily and weekly storage tanks.

3. Simulation method and results

3.1. Simulation method

TRNSYS (SEL, 2013) simulation software was used to model the heating system. A simple capacitance and resistance model was employed for the building thermal load. A small office building was modeled for this study with total floor area of 150 m^2. Type 88 module in TRNSYS was used for the building model with 150,000kJ/K of thermal capacitance and thermal loss coefficient of 2.2kJ/hr-m^2-K. The building model parameters were calibrated using measured load data from an actual office building. Fig. 2 compares simulated TRNSYS model and actual measured data for space heating load and domestic hot water on a monthly basis. In this study, demand response was requested from 10 am to 12 pm and from 5 pm to 7 pm, for four hours. For simulation convenience, the Thursday of every week from December to February was selected for employment of the control strategy. The ratio of the solar collector area to the total building area was 0.04 m^2/m^3, the ratio of the volume of the daily solar storage tank to the area of the solar collector area was 83 L/m^2, and the ratio of the volume of the weekly solar storage tank to the solar collector area was 25 L/m^2. The weekly storage tank is designed to be smaller than the daily storage tank, taking into consideration the fact that the weekly storage tank is used for one day (Sunday) per week, while the daily storage tank is used on Saturdays.

3.2. Simulation results

The annual solar fraction was estimated at approximately 10%. Figs. 3 and 4 show simulation results resulting from the application of diverse control strategies. For the purpose of the simulated evaluation, it was assumed that a DR signal is called on Thursday each week from December to February. The resultant values are averaged on a monthly basis for comparison. ‘Nonsolar’ indicates use of only the heat pump heating system, without solar collectors and weekly storage. ‘CC’ refers to conventional control. The control strategy using the weekly solar storage tank is termed DR_Solar, while HPC and BC indicate heat pump setpoint control and building thermal mass control, respectively. It was found that electric energy consumption of the solar heating system, with DR control, was reduced on average by 45.3%, 84.2%, 82.7%, and 99.4% for Solar DR control, DR_Solar+HPC, DR_Solar+BC, and DR_Solar+BC+HPC, respectively, over the three-month period. In addition, it was found that solar irradiation conditions over weekends contributed significantly to performance of solar DR control. Figs. 5 and 6 represent the performance over a day with the highest electric energy consumption due to space heating over the year. The results are similar to yearly average performance, with significant reduction of electric energy consumption during DR periods through combined use of thermal storage. However, it should be also noted that electric energy consumption over whole days could be increased by employing thermal storage control, due to the efficiency of thermal storage between thermal charge and discharge periods. This increase in energy consumption on a whole daily basis could be compensated by different hourly electric rate structures. In general, the electric charge rate during the DR period is much higher than during other periods. Fig. 7 compares the variation of heat pump electric consumption for ‘Nonsolar’, ‘Solar(CC)’, and ‘DR_Solar+BC+HPC’ according to time of day with highest electric consumption. It should be noted that heat pump almost does not operate during on-peak periods for the control strategy using combined thermal storage, including weekly solar thermal storage, daily thermal storage, and building thermal mass.

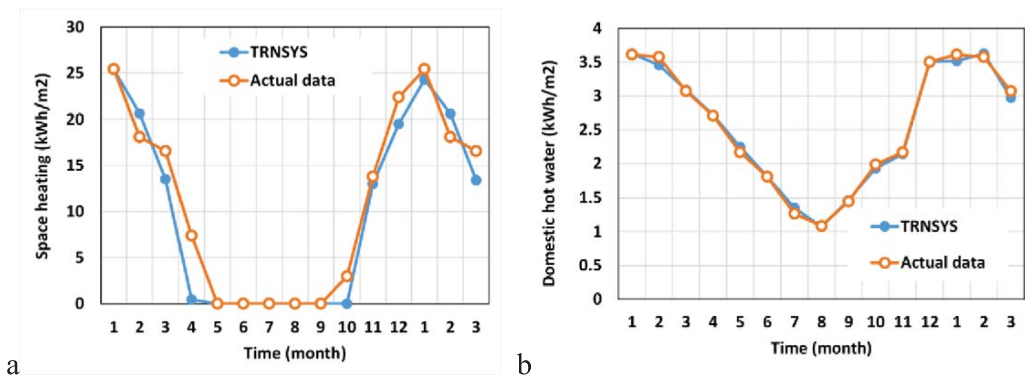

Fig. 2: Comparison of calibrated TRNSYS simulation results with measured data for monthly load of space heating and domestic hot water

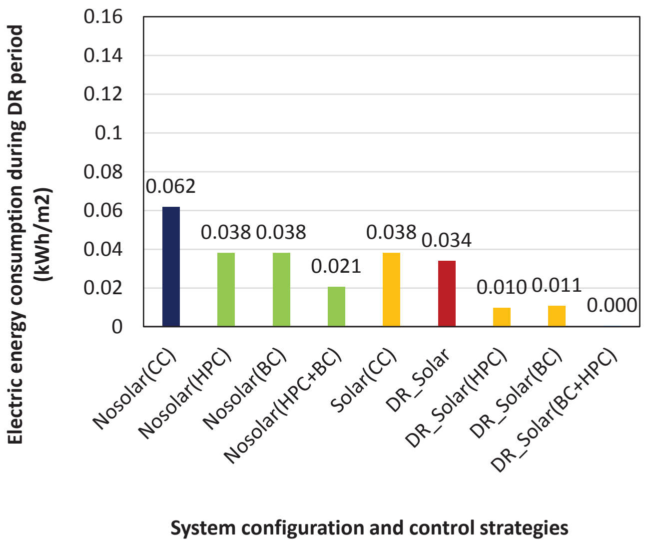

Fig. 3: Average electric energy consumption of solar hybrid heat pump system during the demand response period

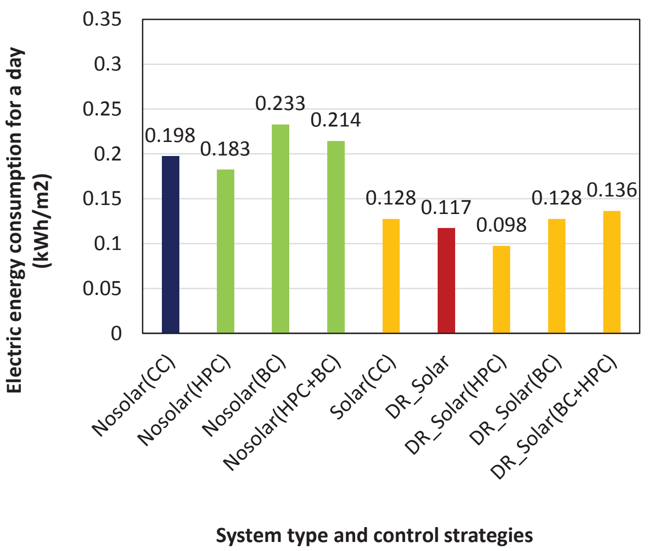

Fig. 4: Average electric energy consumption of solar hybrid heat pump system for whole day of demand response control implementation

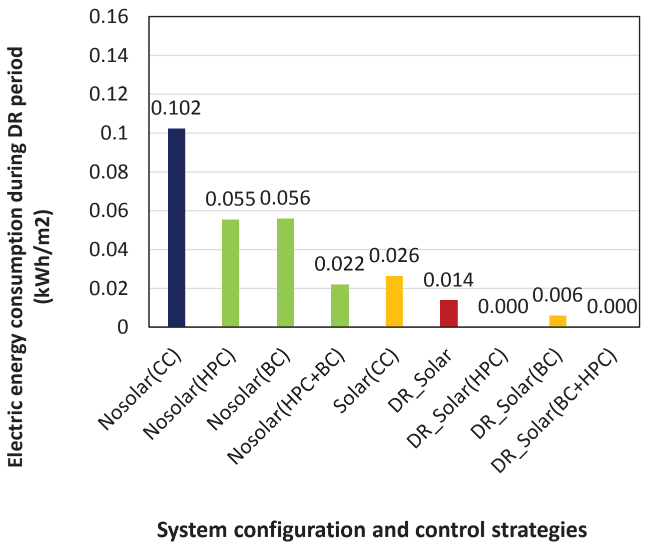

Fig. 5: Electric energy consumption of solar hybrid heat pump system during the demand response period on the day with highest electric energy consumption throughout the year

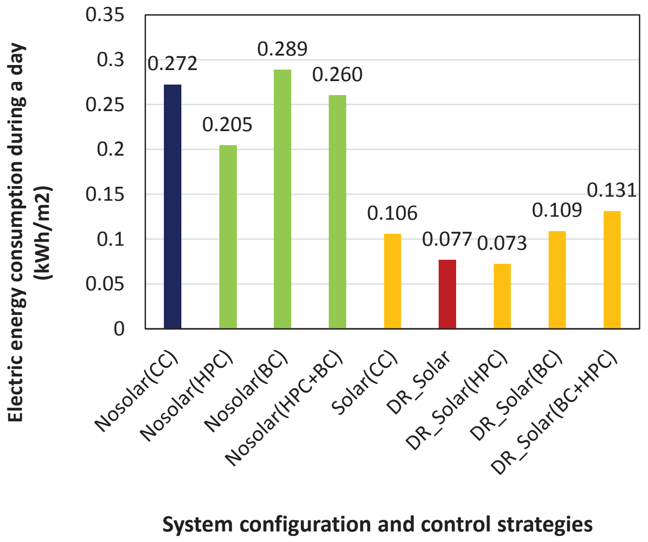

Fig. 6: Whole-day electric energy consumption of solar hybrid heat pump system on the day with highest electric energy consumption throughout the year

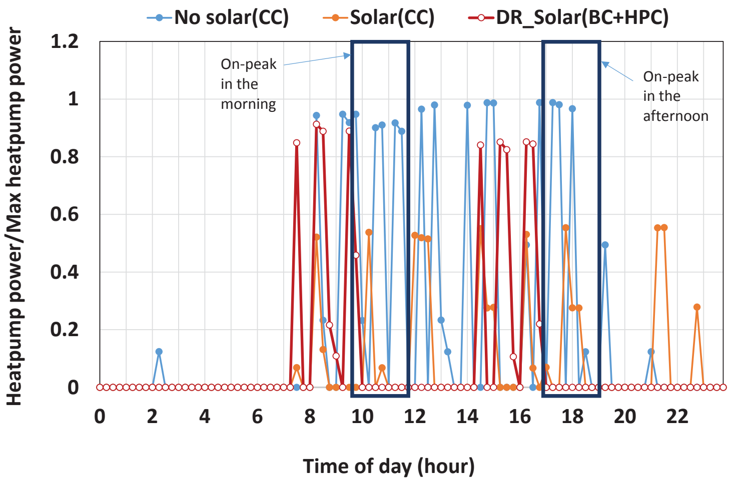

Fig. 7: Comparison of heat pump power according to time for control strategies during the day with highest electric energy consumption

4. Conclusion

The study evaluates the performance of a simple control strategy using a combination of building thermal mass and daily and weekly solar thermal storage. The TRNSYS simulations for the system indicated significant reduction in electric energy consumption of the heating system during the DR period. It was assumed that the control was called every Thursday from December to February from 10 am to 12 pm and 5 pm to 7 pm. On average, when using combined thermal storage, 99.4% of electric energy consumption during the DR control period could be shifted to the period before DR control. Based on simulation results, it can be concluded that weekly solar thermal energy storage can be used for electric demand management during space heating periods for electric heating systems installed in office buildings. The effect of demand management in solar hybrid heat pump systems can be enhanced by combined use of building thermal mass, conventional daily thermal storage, and weekly solar thermal storage.

5. References

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