Optimizing Energy Consumption of Hot Water System in Buildings with Solar Thermal Systems

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Abstract: This paper investigates the operation of a solar thermal system in a building, and seeks to craft a solution that would reduce the cost of electricity to the building manager, while concurrently ensuring that the water demand and the temperature of water are conform to the requirement of the building occupants. In particular, two energy management mechanisms are studies for controlling the multiple heat pumps that are connected to the solar thermal system for providing the system with heat when there is not enough solar energy. In this context, two control strategies are proposed, on-demanding control (ODC) and optimal day-ahead scheduling (ODS) with different degrees of information such as the water demand, weather, and so on. Moreover, three different types of scenarios are considered based on solar energy generation pattern and hot water demand of a commercial facility, and optimal number and operation schedules of heat pumps are identified for each of the scenario. It is shown that the ODS approach is more effective in saving energy and related costs in comparison with the systems ODC approach if the information of the weather conditions and hot demands are available for next 24 hours, and the performance improvement is corroborated numerically.

1 INTRODUCTION

Buildings account for around 40% of the worldwide energy usage (Kolokotsa, 2016), and therefore, the building sector has become the focus of many governmental and institutional energy reduction initiatives and research to achieve more sustainable and energy efficient buildings (Azar and Menassa, 2012). In this context and due to the fact that solar energy is one of the most encouraging ecological solution to combat catastrophic climate change. Solar energy can be captured and transferred to electricity power though photovoltaic (PV) panel, and therefore photovoltaic panels have been widely installed in buildings such as commercial buildings and EV charging stations for energy management schemes (Tushar et al., 2015; Tushar et al., 2016a; Tushar et al., 2016a; Tushar et al., 2016b). Alternative use of solar energy sources such as solar thermal has also been very popular to use in both commercial and residential buildings for the past few years (Buker and Riffat, 2015). The studies on solar thermal technology and its related application for building can be divided in two general categories. The first category mainly studies the design and optimization of solar thermal collectors with a view to increase their efficiency. For instance, in (Chauhan et al., 2016), the authors present the effect of flow and geometric parameters in the performance of solar thermal collector provided with impinging air jets. Based on multiple life cycle impact assessment methodologies, a comprehensive evaluation of the environmental profile of a building-integrated solar thermal collector is conducted in (Lamnatou et al., 2015). A comparative study on the suitability of different type of solar thermal collectors for use in a combined heat and power system at the UK market is demonstrated in (Freeman et al., 2015). Other studies in this category also include (Visa et al., 2015; Tanaka, 2015).

On the other hand, the second category of studies deal with different aspects of control strategies of solar thermal assisted power generation units. For instance, an energy scheduling problem for a household equipped with a solar assisted heating, ventilation, and air conditioning, and water heating system is studied in (Nguyen et al., 2015) to minimize the electricity cost while maintaining user's thermal comfort requirements. In (Li et al., 2015), the authors develop a dynamic model to maximize the solar energy harness ability of a variable speed dish stirling solar thermal system. The dynamics of solar thermal plants-the first model covering all processes between market de-

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mand through power output at millisecond resolution-for the purpose of control design is modelled in (Luo et al., 2016), and the authors in (Cirocco et al., 2015) demonstrate the use of linear programming and Pontryagin's principle to determine how storage should be operated in a solar thermal power plant to maximise the revenue.

As such, most of these existing studies have put moderate (or, very low) focus on the scheduling aspect of the solar thermal system. Although efficient solar thermal collector can considerably improve the generation of solar energy, the efficient use of these energy within the building necessitates the practice of effective energy scheduling process. Hence, such scheduling is particularly requires for solar thermal systems with heat pumps (for heating the water when solar energy is not enough).

This is due to the fact that the heat pumps are generally driven by the electricity from the main grid. Hence, if the fossil fuel driven heat pumps are run inefficiently to heat the water, the impact on the environment will be detrimental, and thus against the main purpose of using solar thermal system. In this context, there are needs for effective scheduling mechanism of heat pumps to heat the water within a solar thermal system such that, on the one hand, the water and heat demand of the building is fulfilled. On the other hand, the use of electricity for running the heat pumps is minimized. As such, this paper has made the following contributions to address this issue.

- We consider a real solar thermal system, which is currently being operated within a commercial facility in Singapore. Then based on the real data of the specification of the system, heat water demand of the facility, and weather, we model the system, and show that significant energy savings is possible by scheduling the heat pumps without compromising the water and heat demand of the occupants.
- To do so, we propose two scheduling strategies based on on-demanding control (ODC) and optimal day-ahead scheduling (ODS). We show that although the system can effectively be controlled based on ODC scheme, the ODS performs better in terms of increasing energy efficiency and reducing cost if the future information on the weather condition and customers hot water demand is available prior 24 hours.

To this end, now we describe the considered system for this study and the related problem formulation in the subsequent sections.

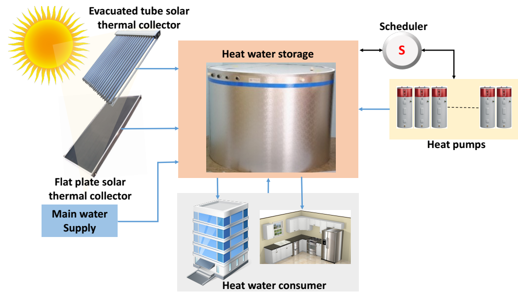

Figure 1: Demonstration of the solar thermal system considered in this work.

2 SYSTEM MODEL

Consider a solar thermal system of a building, as shown in Figure 1, that consists of a hot water storage, Z heat pumps, K circulator pumps, and both flat-plate and evacuated tube solar thermal collector (STC) arrays. The sets of heat pumps and circulator pumps are $\mathcal{Z}$ and $\mathcal{K}$ respectively. The hot water storage is connected to the main water supply of the public utility board (PUB), and is responsible for supplying hot water to each unit $n \in \mathcal{N}$ of the building, where $\mathcal{N}$ is the set of all units within the building. The hot water storage mainly uses the heat extracted by circulating water through the STCs via circulator pumps. Then the extracted heat is transferred to the water inside the hot water storage through heat exchangers. However, if the heat from the STCs is not enough to heat the water to the desired temperature, the deficient heat is supplied by the connected heat pumps of the system.

In this context, let us assume that at any time slot $h \in \{1, 2, \ldots, H\}$ of a day, where H is the total number of time slots, the heat water demand of each unit $n \in \mathcal{N}$ is $W_{n,h}$ with a required temperature $T_{n,h}$. Hence, the necessary thermal energy $q_{n,h}$ to heat the water from PUB supply to the desired temperature is

$$q_{n,h} = \sigma W_{n,h}(T_{n,h} - T_{\text{pub},h}), \quad (1)$$

where σ is the specific heat of water, and $T_{\text{pub},h}$ is the temperature of the water from PUB. Therefore, the total amount of required heat energy to meet the demand of all units within the building can be expressed as

$$Q_h^d = \sum_{n=1}^{N} q_{n,h}. \quad (2)$$

Now, if the power of the solar irradiance is I_h W/m^2 at h and the panel area of the flat-plate and evacuated tube STC array are A_f and A_e respectively, the total effective power generation from the two STCs is

$$Q_h^\theta = I_h A_f \eta_f M_f + I_h A_e \eta_e M_e. \quad (3)$$

In (3), η_f and η_e are the thermal efficiency[1] of the flat-plate and evacuated tube STCs respectively, M_f and M_e are the respective number of flat-plat and evacuated plat solar thermal panels. Now, depending on the total heat Q_h^θ produced by the solar thermal system and the total heat demand of the building, the number of circulator pumps $K_{on,h} \leq K$ that needs to be turned on is determined.

For simplification, we assume that each circulator pump $k \in \mathcal{K}$, while circulates water at its maximum capacity, can extract $Q_h^{\text{cp}} = Q_h^\theta / K$ heat from the STCs, which it transfers to the water within the hot water storage. Therefore, if the building manager want to extract the amount of heat energy Q_h^w, ($Q_h^w \leq Q_h^\theta$, $\forall h$), form STCs at each time slot h, the total number of circulator pumps $K_{on,h}$ that needs to be in operation at each time slot h can be calculated as

$$K_{\text{on},h} = \left\lceil \frac{Q_h^w}{Q_h^{\text{cp}}} \right\rceil, \tag{4}$$

which can be translated to a total electricity consumption of circulator pumps as

$$E_{\text{total},h}^{\text{cp}} = E_k^{\text{cp}} \times K_{\text{on},h}. \tag{5}$$

Here, E_k^{cp} is the power that each circulator pump $k \in \mathcal{K}$ consumes when it runs at its rated capacity, and $\lceil \cdot \rceil$ refers to the *next closest integer* operation.

Indeed, if the total demand of heat water is higher than the amount that can be produced with Q_h^θ, the excess amount of heat $Q_h^d - Q_h^\theta$ needs to be supplemented by the heat pumps connected to the solar thermal system. For this case, we assume that all the heat pumps in $\mathcal{Z}$ have only on and off control and equal heating capacity, and are run at their maximum heating capacity Q_z^{hp} while they are turned on. In this regard, the number of heat pumps that needs to be turned on to produce the deficient heat energy at h can be expressed as

$$Z_{\text{on},h} = \left\lceil \frac{Q_h^d - Q_h^\theta}{Q_z^{\text{hp}}} \right\rceil. \tag{6}$$

Now, if the rated electricity consumption by each pump z is E_z^{hp} Watt-hour, the total electricity consumption by the heat circulator pump at h is

$$E_{\text{total,h}}^{\text{hp}} = E_z^{\text{hp}} \times Z_{\text{on},h}. \tag{7}$$

Accordingly, the total cost J_{Total} of total electricity consumed by the heat pumps and the circulator pumps for the whole day (i.e., H time slots) is

$$J_{\text{Total}} = \sum_{h=1}^{H} \left(E_{\text{total},h}^{\text{hp}} + E_{\text{total},h}^{\text{cp}} \right) C_h, \tag{8}$$

where C_h is the price per unit of electricity from the grid at h.

Based on (6), (7), and (8), the total amount of electricity consumed by the heat pumps contingent on three factors including 1) the generation of solar heat by the STCs, 2) the amount of heat water demand by each unit of the building, and 3) the number of pumps running in each time slot h to meet the excess demand. In particular, we study the optimal control strategies of the heat pumps that can be driven by suitably controlling the on-off time of the heat and circulator pumps so that minimum number of heat and circulator pumps are in operation at any time slot h, and thus reduce the overall consumption of electricity. Such control strategy will explain in the next section.

3 CONTROL STRATEGIES OF HEAT PUMPS

The objective of this work is to devise strategies, in which the building manager would be able to pursue its own economic objective of reducing total cost J_{Total} of electricity usage, while maintaining all the relevant system constraints to meet the hot water demand of the consumers within the building. In this context, we propose two different approaches to control the operation of heat pumps within the considered system:

1. On-demanding control (ODC) approach, which does not require any future information of the weather condition and water demand. Thus, this control approach is practical and implementable in real time.
2. Optimal day-ahead scheduling (ODS) approach with the assumption that the future 24-hours information of weather and water demands are known. The solution of this approach can be used as a lower bound for the cost of the considered system.

3.1 ODC Approach

ODC approach aims to estimate the optimal number of heat pumps and circulator pumps that needs to be turned on with minimal electricity consumption at each time slot h so as to reduce total electricity cost J_{Total}. The functional flowchart of ODC approach is shown in Figure 2.

First, the ODC approach estimates the hot water demand $W_{n,h}$ of each unit and the power of solar irradiance I_h at time slot h. Then it calculates the heat energy Q_h^d necessary to heat the water from PUB

[1] That is how much heat energy is produced per unit of incidence I_h on the surface.

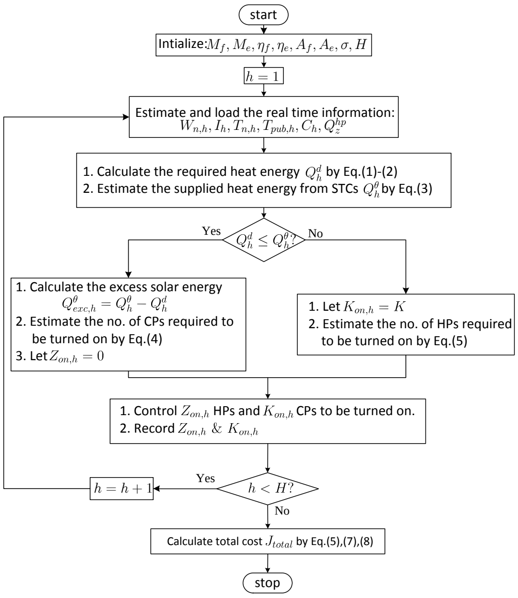

Figure 2: Demonstration of the functional flowchart of ODC approach.

(with the initial temperature $T_{\text{pub},h}$) to the desired temperature $T_{n,h}$ and the heat energy Q_h^θ it can extract from the STCs. The ODC prefer to meet the required heat energy Q_h^d by the solar energy Q_h^θ as much as possible because the electricity consumption of circulator pumps is generally smaller than that of heat pumps. Therefore, if $Q_h^d \leq Q_h^\theta$, no further heat energy is required from the heat pump (i.e., $Z_{\text{on},h} = 0$). However, the excess solar power $Q_{\text{exc},h}^\theta$, if there is any, will be wasted because ODC purposes to minimize the total electricity consumption at each time slot h .

On the other hand, the heat pumps will be turned on if $Q_h^d > Q_h^\theta$, and the number of the required heat pumps $Z_{\text{on},h}$ will be estimated via (6). Finally, the rated electricity consumption $E_{\text{total},h}^{\text{cp}}$ and $E_{\text{total},h}^{\text{hp}}$ at each time slot h can be calculated as well as the cost J_{total}. This simple real-time algorithm provides a simple solution, and serves as an upper bound on the worst case performance of a system.

3.2 ODS Approach

Although ODC can rapidly respond via controlling the heat pumps to meet the hot water demand in real time, it cannot effectively exploit the property of hot water storage such as a buffer thermal storage. Specifically, for ODC approach, the hot water storage is just considered a medium that facilitates to transfer heat from STCs and heat pumps to demand side. It is due to that fact that ODC approach lacks the future information such as the weather condition and hot water demand. Indeed, if we can exactly forecast future information of the weather condition and water demand, we can efficiently schedule the operations of heat pumps and circulator pumps of STCs. In that case, for instance, the building manager can have the flexibility to turn on more heat pumps to produce excess heat to store into hot water storage beforehand in order to meet the coming peak demand. Also, the building manager can turn on more circulator pumps to store the excess solar energy considered by ODC into hot water storage so as to supply toward hot water demand.

In this context, we briefly explain some key constraints and assumptions that are needed to be satisfied with the characteristics of hot water storage as follows:

- At any time slot h, $\bar{T}_{\text{tank},h}$ needs to be at least more than a lower temperature threshold

$$\bar{T}_{\text{tank},h} \geq T_{\min}. \tag{9}$$

This constraint is necessary to establish the fact that the requirement of energy to heat the water to a desired level would never be significantly high.

- Similarly, at any time slot h, $\bar{T}_{\text{tank},h}$ always needs to be lower than a maximum temperature threshold

$$\bar{T}_{\text{tank},h} \leq T_{\max}, \tag{10}$$

based on the type of the design and material of the hot water storage tank. Otherwise, it would compromise the lifetime and operational efficiency of the storage.

- At any time slot h, the average temperature of the storage tank is influenced by
  - Coefficient of heat loss G of the storage.
  - Volume capacity V of the hot water storage.
  - Average temperature of the tank in previous time slot $h-1$, i.e., $\bar{T}_{\text{tank},h-1}$.
  - The hot water demand $W_{n,h}$ of each unit $n \in \mathcal{N}\ \forall n$ at h.
  - The temperature difference $\Delta T_{n,h}$ between $T_{n,h}$ and $T_{\text{pub},h}$, i.e., $\Delta T_{n,h} = T_{n,h} - T_{\text{pub},h}$.
  - Heat energy Q_h^{cp} extracted by each circulator pump $k \in \mathcal{K}$ from STCs at h.
  - Heat energy $Q_{z,h}^{\text{hp}}$ generated by each heat pump $z \in \mathcal{Z}$ at h.

As such, the average temperature $\bar{T}_{\text{tank},h}$ of the hot water storage is determined via following relationship:

$$\bar{T}_{\text{tank},h} = (1-G)\bar{T}_{\text{tank},h-1} - \frac{\sum_n W_{n,h}\Delta T_{n,h}}{V} + \frac{s}{V\sigma}\left(\sum_z Q_z^{\text{hp}} u_{z,h} + \sum_k Q_h^{\text{cp}} v_{k,h}\right), \quad h = 1,2,\ldots,H. \tag{11}$$

where $u_{z,h}, v_{k,h} \in \{0,\ 1\}$ are boolean variables that refer to the on/off status of each heat pump $z \in \mathcal{Z}$ and circulator pump $k \in \mathcal{K}$ respectively at h. In addition, s is the duration of time slot.

Since the control of both type of pumps is only possible through on/off control, searching for the optimal choice of tuples $(u_{z,h}, v_{k,h})$ from set $\{0,\ 1\}\ \forall h$ is the ultimate target of this study. In this context, the objective of optimal day-ahead scheduling (ODS) problem can be expressed as

$$\min_{u_{z,h}, v_{k,h}} \sum_h C_h \left(\sum_z u_{z,h} E_z^{\text{hp}} + \sum_k v_{k,h} E_k^{\text{cp}}\right), \tag{12}$$

Note that (12) is a modified version of (8) with the explicit mention of possible on/off switching operation of each pump at h. Nonetheless, while minimizing J_{Total} as explained in (12), the building manager also needs to meet the system constraints (9)–(11) for the effective operation of hot water storage. As such, ODS (12) is formulated as an integer programming problem, and we employ built-in tool of MATLAB to solve this problem.

4 CASE STUDY

In this section, the simulation results of the proposed approaches are presented. To do so, we consider a commercial facility in Singapore, which has a real solar thermal system. We captured the historical data of hot water demand used in this facility, and some specifications of the solar thermal system. The initial specifications and parameters setting are detailed in Table 1.

4.1 Considered Data for Simulation

To demonstrate the effectiveness of the proposed approaches, we run simulations for three particular days with different weather conditions including a rainy day (RD - 26/07/2015), a sunny day (SD - 05/07/2015), and a day with no solar (NS - worst case). The RD and SD have been chosen based on the Singapore weather data in the month of July 2015. Furthermore, we conduct simulations for one month

Table 1: Initial specifications and parameters setting.

Initial temperature of water from PUB	$T_{\text{pub},h},\ \forall h$	25°C
The required temperature of hot water	$T_{n,h},\ \forall n,h$	65°C
The maximum temperature of hot water storage	$T_{\max}$	75°C
The minimum temperature of hot water storage	$T_{\min}$	65°C
The heat loss coefficient of the storage during	G	$0.1\%/hr$
The number of flat-plate panels	M_f	27
The number of evacuated-tube panels	M_e	70
The number of circulator pump	K	4
The absorber area of flat-plate panels	A_f	$2.8m^2$
The absorber area of evacuated-tube panels	A_e	$2.8m^2$
The thermal efficiency of flat-plate panels	η_f	0.5
The thermal efficiency of evacuated-tube panels	η_e	0.7
The heating capacity of heat pump	$Q_z^{hp}\ \forall z$	40 kW
The electricity consumption of heat pump	$E_z^{hp}\ \forall z$	12.85 kWh
The electricity consumption of circulator pump	$E_k^{cp}\ \forall k$	1.375 kWh
Electricity price (Singapore dollar (SGD))	$C_h\ \forall h$	0.22 $/kWh
The duration of time slots	s	15 mins
The total number of time slots	H	96

with the real daily data of solar irradiance and hot water demand, and show the energy consumption by the heat pumps, the number of required heat pumps, the energy consumption by the circulator pumps, and the total cost of electricity consumption for whole month of July 2015. In Figure 3 and Table 2, we show

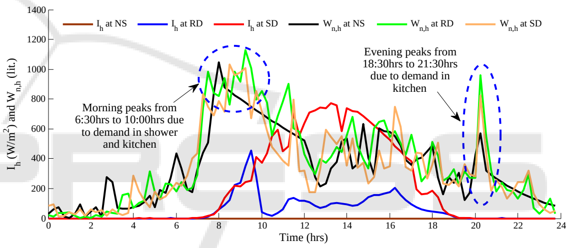

Figure 3: Illustration of solar irradiance I_h (W/m^2) and hot water demand $\sum_n W_{n,h}$ (lit.) of the building at each time slot h on a rainy day (RD), sunny day (SD) and on a day with no solar (NS).

the solar irradiance I_h and the total amount of hot water demand (i.e., $\sum_n W_{n,h}$) on RD, SD, and NS at each time slot h (of days with three considered weather conditions) respectively. In Figure 3, the peaks in the morning from 6:30 hrs to 10:00 hrs are due to shower and kitchen demand, and the peaks in the evening from 18:30 hrs to 21:30 hrs due to kitchen demand of the considered building. As can be seen from the figure and Table 2, the maximum hot water demand for NS is 1048 liters, RD is 1128 liters, and SD is 1030 liters. Similarly, the solar irradiance is 455.7 W/m^2 and 770.0 W/m^2 for RD and SD respectively.

In Figure 4, we show the total hot water demand and solar generation per day for the month of July 2015. The summary of the total and average hot water demand, and average solar irradiance per day for the same month is, however, shown in Table 2.

Table 2: Information of the selected days and July 2015.

Description	No solar	Rainy day	Sunny day	Description	July 2015
Total hot water demand $\sum_{h,n} W_{n,h}$ (liter)	33046	36364	32692	Total hot water demand (liter)	978,163.0
Maximum hot water demand $max_h \sum_n W_{n,h}$ (liter)	1048	1128	1030	Average daily hot water demand (liter)	31,553.6
Average hot water demand $\bar{W}_h$ (liter)	344.2	378.8	340.5	Average hot water demand at each time slot $\bar{W}_h$ (liter)	328.7
Maximum solar irradiance I_h (W/m^2)	0	455.7	770.0	Average daily solar irradiance (kWh/m^2)	3.39
Average solar irradiance $\bar{I}_h$ (W/m^2)	0	55.2	209.1	Average solar irradiance at each time slot $\bar{I}_h$ (W/m^2)	140

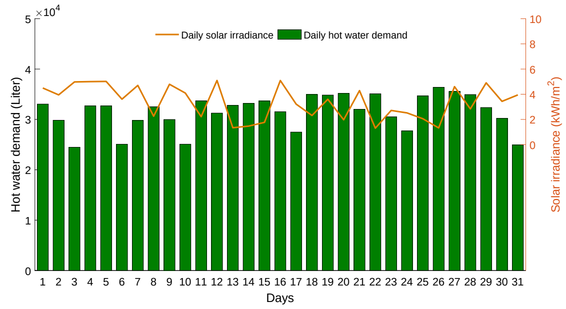

Figure 4: Demonstration of hot water demand (liter) and solar irradiance (kWh) in each day of July 2015.

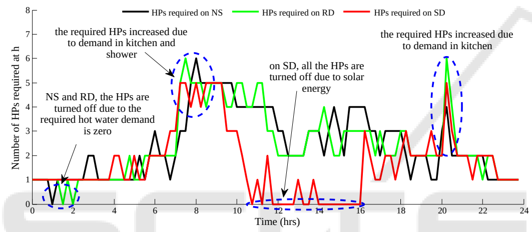

Figure 5: Demonstration of the number of heat pumps (used as HP in the figure) required on the selected days performed upon ODC.

4.2 Results for ODC

In Figure 5, ODC is performed to meet the demand of hot water of the building, it shows the number of heat pumps to be turned on at each time slot on selected RD, SD, and NS separately. It is observed that the maximum two heat pumps are necessary to maintain the required hot water demand after 21:00 and before 06:00 hours for all the considered weather conditions.

For the remaining hours, however, the number of the required heat pumps to fulfil the demand of hot water varies with respect to the solar irradiance and hot water demand. For instance, on the selected SD, the heat pumps are turned off for a number of time slots during the period from 11:00 to 16:00 due to the abundant solar energy. However, the number of turned on heat pumps varies from 4:00 to 10:00 in the morning and from 20:00 to 22:00 in the evening due to higher demand by the consumers. Similar variation in the number of required heat pumps is also found for the cases of NS and RD. For example, according to Figure 5, a maximum of 6 heat pumps are necessary to heat the water in the morning peak period on NS and RD, whereas the number of required heat pump is much less for other time slots of the respective days. In Figure 6, we demonstrate the results on the total number of required heat pumps and subsequent energy consumption per day of July 2015 based on the ODC approach. It is observed that the maximum number of heat pumps that is required to fulfil the demand of hot water varies from 3 to 8 based on the different amount of hot water demand and the variation of weather conditions.

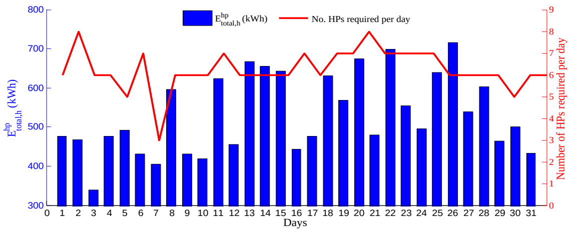

Figure 6: The daily electricity consumed by HPs and the maximum no. of HPs required per day in July 2015 upon ODC.

4.3 Results for ODS

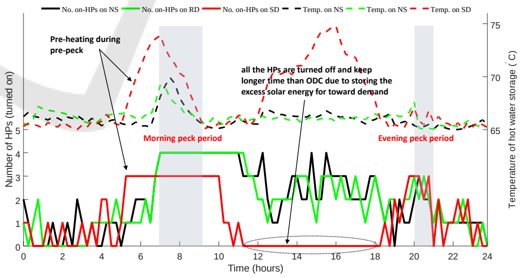

Figure 7: Number of heat pumps required on the selected days performed upon ODS.

As mentioned in Section 3.2, we assume that the weather and demand information are known for the next 24 hours for the proposed ODS approach. As such, the ODS is first performed for the selected days with individual weather conditions and the results are shown in Figure 7.

Observably, the most four heat pumps are operational on NS and RD, whereas three heat pumps are enough to meet the hot water demand on SD. Note that these required amounts are significantly lower than that in ODC approach as a result of the knowledge of future information and the usage of buffer thermal storage. It can be observed that more heat pumps starts to be turn on at 5:00, and then the temperature of hot water storage rises up significantly on SD. This is owing to the awareness of the morning peak that will be coming soon, and therefore, ODS approach schedules 2 heat pumps that are early turned on to produce more heat energy and store in the hot water storage.

Similar phenomenon is also observed before the evening peak period. Furthermore, ODS approach schedules more circulator pumps to be turned on so as to store more solar energy into hot water storage from 12:00 to 18:00 on SD. This is the reason why the total turned off time of all heat pumps is longer than that in ODC during the period of abundant solar energy on SD. Also, we study the ODS approach for

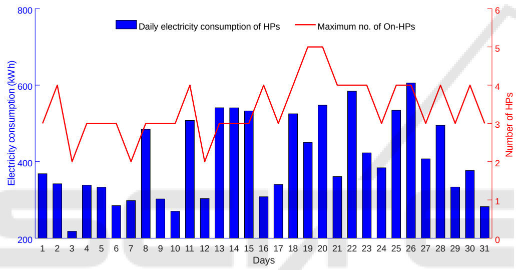

Figure 8: The daily electricity consumed by heat pumps and the maximum number of heat pumps required per day in July 2015 using ODS approach.

the whole month of July 2015 to determine the total energy consumption by the heat and circulator pumps as well as the overall cost as shown in Figure 8. It can be observed that 2 to 4 heat pumps are usually enough for most of the days whereas only two days need 5 heat pumps to supply demand.

4.4 Summary of ODC and ODS

Now, based on the results of the selected days and the whole month July 2015 with the both proposed approaches, we provide an overview of the related energy parameters for the considered selected days and month of July 2015. First, we provide a summary of comparison between the ODC and ODS approaches on different energy parameters for NS, RD, and SD in Table 3. Table 3 shows the related energy parameters including total turned on time of the heat pumps, total energy consumption by the heat pumps, total energy consumption by the circulator pumps, and the total electricity cost of energy consumption. According to this table, the electricity consumption of heat pumps are 749.2 kWh, 745.3 kWh and 514.0 kWh on NS, RD, and SD respectively for ODC approach. These values for ODS approach are, however, 623.3 kWh, 607.8 kWh and 334.1 kWh, which are 16.8%, 18.4% and 35% less than the ODC approach respectively on NS, RD, and SD. Furthermore, the total cost of the total electricity consumption on NS is 164.8 SGD, RD is 177.9 SGD, and SD is 128.2 SGD for ODC case and 137.1 SGD, 148.5 SGD, and 88.6 SGD for the same respective day for ODS approach. Clearly, the prior knowledge of weather condition and demand makes the overall electricity cost of ODS lower than the ODC approach.

Table 3: Summary of the proposed approaches on the selected days.

	No solar		Rainy day		Sunny day	
	ODC	ODS	ODC	ODS	ODC	ODS
$\max_h Z_{\text{on},h}$	6	4	5	4	6	3
Turned on time (hrs)	58.3	48.5	58.0	47.3	40.0	26.0
$\sum_h E^{\text{hp}}_{\text{total},h}$ (kWh)	749.2	623.3	745.3	607.8	514.0	334.1
$\sum_h E^{\text{cp}}_{\text{total},h}$ (kWh)	0.0	0.0	66.0	67.4	62.6	68.8
J_{total} (SGD)	164.8	137.1	178.5	148.5	126.8	88.6

Noticeably, sunny days are most cost-effective for the building manager. Interestingly, cost of energy on the selected rainy day is greater than the day with no solar. This is mainly due to the higher hot water demand by the consumers for this particular day (see Table 2). Nonetheless, for other days of the month, it can have different values based on the demands of the consumers.

Table 4: Summary of the proposed approaches for the month of July 2015.

Parameters	ODC	ODS
Maximum number of the required heat pumps	8	5
Total turned on time of heat pumps (hrs)	1340.8	982.5
Total electricity consumption of heat pumps (kWh)	16491.2	12625.1
Total excess solar energy (kWh)	1452.46	305.0
Total turned on time of circulator pumps (hrs)	1449.3	1508.4
Total electricity consumption of circulator pumps (kWh)	1992.8	2074.1
Total electricity cost (SGD)	4066.5	3233.8

Then, we provide an overview of the related energy parameters for the considered month of July 2015 in Table 4. According to Table 4, it is noted that there is excess solar energy that can not be effectively exploited by ODS as a results of the limited temperature of hot water storage. Indeed, we can set the higher temperature bound to store more solar energy, but that will reduce lift time of hot water storage. However, the amount of excess solar energy by ODS is still much less than that by ODC. As for the energy consumption of circulator pumps, it can be observed the electricity consumption of circulator pumps for ODS is slightly more than ODC because ODS keeps circulator pumps running in order to store more solar energy, which will be seen as excess by ODC, into hot water storage. To sum up, the overall electricity cost of ODS is reduced by 20% of ODC's in the one month of July 2015. Furthermore, the number of heat pumps required by ODS is less than that required by ODC, which means that the cost of installation and facilities will be significantly reduced if building manager adopts ODS approach.

5 CONCLUSION

In this paper, the operation of solar thermal system within a building has been studied with a view to reduce the cost of electricity to the building manager. Two control strategies including ODC and ODS approaches have been developed based on real data from a facility in Singapore. In designing the strategies, three different kinds of scenarios have been considered, and the necessary number of heat pumps that is needed to meet the demand of the building is identified. It has been shown that if the prior knowledge of the weather condition and are available, ODS technique is more effective compared to the ODC approach in terms of electricity cost reduction and increasing energy efficiency. However, if such knowledge is unavailable, ODC technique has been shown to be still suitable for running the considered real system and numerical solutions have been provided to support our claims.

In the future works, we will involve the prediction methods in order to capture the prior knowledge of the weather condition and demand, and consider various possible scenarios such as dynamic pricing and peak demand shifting.

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