Improving the Operation of Solar Water Heating Systems in Green Buildings via Optimized Control Strategies

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***Abstract*—Solar water heating (SWH) systems are well known and effective structures that transfer solar energy into thermal energy with hot water as the storage. The efficiency of an SWH system is mainly based on well-designed solar collectors and proper operation mechanisms. Although the most existing literature has focused on the efficiency enhancement of solar collectors, limited studies are devoted to improve the operating mechanism. As such, this paper studies the control mechanisms of the SWH system with a purpose so as to help the building manager to achieve targeted energy management goals. In particular, three control approaches are presented for improving the operational efficiency of the SWH system by controlling auxiliary heaters, such as heat pumps, electric heaters, and circulation pumps. The proposed approaches are developed based on different requirements of information such as the hot water demand, weather, and electricity price. Moreover, three various energy management objectives are studied with considering different scenarios in terms of real weather pattern and hot water demand of a commercial building. The results validate that the proposed approaches can improve the operation of the SWH system according to various operation objectives.**

***Index Terms*—Heat pump (HP), hot water storage, optimal control, optimization, solar thermal, solar water heating (SWH) system.**

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I. Introduction

With increasing global warming and its effect on recent climate change, adopting environmentally friendly technologies for energy sector has been recognized as a key potential solution to this problem [1]–[6]. Consequently, buildings, which account for around 40% of total global energy consumption [7], have become the focal point of many institutional energy reduction initiatives and research to make them more sustainable and energy efficient, e.g., see [1], [8]–[11]. In this context, and due to the fact that solar energy is one of the most promising ecological solutions to combat catastrophic climate change, photovoltaic (PV) panels have been widely installed in both commercial and residential buildings and facilities for using solar as an alternative source of energy [12]–[14].

One important solar energy resource for buildings, which is also the topic of this study, is the solar thermal system. Essentially, a solar thermal system uses the sun's energy to generate low-cost and environmentally friendly thermal energy. This energy is used to heat the water or other fluids, e.g., to power solar cooling systems, and has been very popular for use in commercial and residential buildings for past few years [15]. Recently, low heat generation capacity of solar thermal collectors (STCs) has been a key concern for the efficient use of such system. As such, designing and optimizing solar thermal panels for achieving higher efficiency are discussed in [16]–[20]. In [16], Chauhan *et al.* present the effect of flow and geometric parameters on the performance of STC provided with impinging air jets. Based on multiple life cycle impact assessment methodologies, a comprehensive evaluation of the environmental profile of a building-integrated STC is conducted in [17]. A comparative study on the suitability of different type of STCs for use in a combined heat and power system at the UK market is demonstrated in [18]. Other studies in this category can be found in [19] and [20].

While the emphasis on improving the efficiency of solar collectors is of great importance as efficient STCs can considerably improve the generation of solar energy, the efficient use of this energy within the building requires the practice of effective energy scheduling process. As such, an energy scheduling problem for a household equipped with a solar-assisted heating, ventilation, and air conditioning, and water heating system is studied in [21] to minimize the electricity cost while maintaining user's thermal comfort requirements. In [22], Li *et al.* 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, covering all processes between market demand through power output at millisecond resolution, for the purpose of control design is modeled in [23], and Cirocco *et al.* [24] 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.

However, a reliable solar thermal system not only takes the efficiency of solar collectors into account but also the operation of auxiliary heaters, such as heat pumps (HPs) and electric heaters (EHs), that produce heat energy in the absence of solar energy. Hence, we note that one critical question that is needed to answer in existing studies: *what is the efficient way of scheduling these auxiliary heaters within a solar thermal system that are used for heating the water/fluid when the generated and/or stored solar energy is not enough to meet the demand*? This is particularly important as the auxiliary heaters are generally driven by the electricity from the main grid. Hence, if the auxiliary heaters are run inefficiently to heat the water, the impact of the building on the environment would still be detrimental, and thus go against the main purpose of using the solar thermal system. Furthermore, the operation schedule of auxiliary heaters is also critical. If auxiliary heaters are run at the periods of peak hour or high electricity price, high penalty cost may be charged by the utilities. In this context, there are needs for effective scheduling mechanism of heaters to heat the water within a solar thermal system such that the electricity cost for running the auxiliary heaters is minimized while fulfilling the heat demand of the building.

As such, we study optimized control strategies for the operation of a solar thermal system in this paper. In particular, we consider a real solar water heating (SWH) system, which is currently being operated within a commercial facility in Singapore. Based on the system specification, actual data on the hot water demand of the facility, and weather condition, we model the system and show that significant energy and cost savings are possible by scheduling the auxiliary heaters without compromising the hot water demand by the occupants. An initial version of this study has been published in [25], and we have extended our previous work that the main contributions of this study are threefold.

1) We develop a mathematical model of the SWH system considering the general hot water demand of the entire building and a specific hot water demand with a higher temperature requirement. This is a practical scenario of the considered commercial facility, where the general hot water (60 °C) demand could be for the showering purposes and the specific hot water (70 °C) is necessary for the cooking purposes in the kitchen. Such two-tier demand adds a new dimension to the optimization framework due to not only the fact that the temperature requirement is higher, but also because it has a different demand profile and is equipped with separate auxiliary heaters (EHs) to heat the water to the required temperature. Furthermore, the EHs are also run by electricity from the grid, which contributes to increased cost.

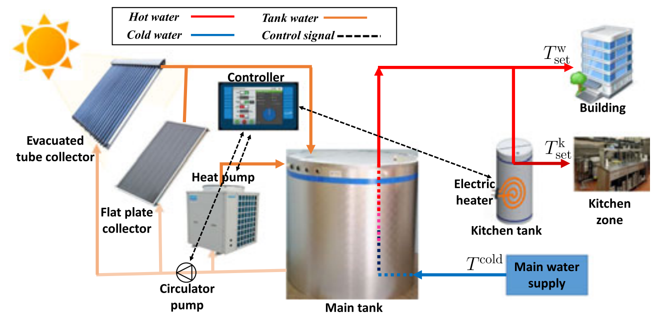

Fig. 1. Demonstration of the SWH system considered in this work.

2) We propose three different control scheduling techniques in this paper. First, we study the real-time control of HPs, EHs, and circulation pumps based on the hot water demand of the buildings. This study provides us with insights on the upper bound of the control performance. Then, we propose an optimization technique to find the optimal schedule of HPs and EHs that are required to be turned ON at any time of the day to meet the hot water demand with necessary temperature. This provides the lower bound of the control performance. Finally, we propose a perdition based scheduling method to determine a solution that lies between the lower bound and the upper bound. The perdition based method is designed using a two timescale scheduling technique.

3) To show the effectiveness of the proposed scheduling techniques, we study three cases with three different objectives including operational cost reduction, consumption of peak power alleviation, and multiobjective of joint cost-peak mitigation. The results demonstrate that the proposed approaches can effectively and efficiently improve the operation of the SWH system.

The rest of the paper is organized as follows. The system model considered in this study is described in Section II followed by the problem formulation and proposed control strategies in Section III. The cases with various situations are studied in Section IV, where we also explain the related results. Finally, the paper is concluded in Section V.

II. System Model

A. Description of the SWH System

The schematic of a SWH system in a building is illustrated in Fig. 1 that consists of two different sizes of hot water storages called main tank and kitchen tank, HPs, EHs, and both flat-plate and evacuated tube STC arrays with circulator pumps (CPs). The number of HPs and EHs is N and K, respectively. The main tank, which is connected to the cold water supply, HPs, and STCs with CPs, is responsible for supplying hot water to the whole building. The main tank stores the heat extracted from the STCs by circulating water via CPs. When the heat from the STCs is not enough to heat the water to the desired temperature, the deficient heat is supplied by the connected HPs.

For kitchen's demand, the hot water from main tank is flowing in the kitchen tank, and the water inside the kitchen tank is further heated up to the higher specific temperature by EHs before supplying to kitchen zone.

B. Thermal Energy Model

In this section, the mathematical model of SWH system is presented according to the above-mentioned description.

1) Required Thermal Energy: Let the amount of hot water demand of the whole building be denoted as D_h^w (liter) at any time slot $h \in \{1, 2, \ldots, H\}$ of a day, where H is the total number of time slots. Then, referring to [26], the necessary thermal energy Q_h^w (kW·h) required for heating the water from cold water source to the desired temperature is calculated as

$$Q_h^w = \mathcal{C} D_h^w \left(T_{\text{set}}^{\text{w}} - T_h^{\text{cold}}\right) \tag{1}$$

where $\mathcal{C} = 0.0012$ [kW·h/(L°C)] is the specific heat capacity (or thermal capacity) of water. $T_{\text{set}}^{\text{w}}$ represents the required temperature of hot water set by the building manager (e.g., $T_{\text{set}}^{\text{w}} = 60\,°\text{C}$), and T_h^{cold} is the temperature of the cold water that is assumed as same as ambient temperature. Note that the thermal energy Q_h^w is extracted from the main tank.

For kitchen zone, the hot water with temperature $T_{\text{set}}^{\text{w}}$ is further heated up to the higher temperature. Then, the required thermal energy extracted from kitchen tank is expressed as

$$Q_h^k = \mathcal{C} D_h^k (T_{\text{set}}^{\text{k}} - T_{\text{set}}^{\text{w}}) \tag{2}$$

where D_h^k represents the amount of kitchen's demand, and $T_{\text{set}}^{\text{k}}$ is the required temperature of hot water for cooking purposes, e.g., $T_{\text{set}}^{\text{k}} = 70\,°\text{C}$. Note that the amount of kitchen's demand must be less than or equal to the amount of hot water demand of the whole building (i.e., $D_h^k \leq D_h^w, \forall h$).

2) Solar Energy: Considering the panel area of the flat-plate and evacuated tube STC array are A_f and A_e respectively. Also, M_f and M_e are the respective number of flat-plat and evacuated plat solar thermal panels. Let the solar irradiance be dented as I_h (kW/m^2) at time slot h, then the total effective thermal energy collected from the two STCs is expressed as

$$q_h^{\mathsf{s}} = I_h \left(\eta_f A_f M_f + \eta_e A_e M_e\right). \tag{3}$$

In (3), η_f and η_e are the thermal efficiency[1] of the flat-plate and evacuated tube STCs, respectively. Hence, the solar energy extracted by CPs is determined as

$$Q_h^{\mathsf{s}} = q_h^{\mathsf{s}} \Delta h \times u_h \tag{4}$$

where Δh (hour) is the interval of time slot and u_h represents the status of CPs that are only switched ON or OFF. Note that the all CPs are synchronously operated due to the setting of system. As a result, $u_h \in \{0, 1\}$ is a binary variable.

3) Heat Energy From Auxiliary Heaters: In this study, ON/OFF controlled air-to-water HPs and electric immersion heaters are considered as auxiliary heaters. Assuming one HP consumes electricity power P^{hp} (kW) while HP in service. Then, the heat production of HP is determined as

$$q^{\mathsf{hp}} = \mathsf{COP}_{\mathsf{hp}} \times P^{\mathsf{hp}}. \tag{5}$$

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

Here, $\mathsf{COP}_{\mathsf{hp}}$ represents the *coefficient of performance* of HP, that is, an indicator of the relationship between the produced heat and consumed electricity by the HP. If the required heat demand of water is more than the amount that can be produced with Q_h^{s}, the deficient amount of heat needs to be supplemented by the HPs. For this case, we assume that all HPs have equal heating capacity, and are running at their maximum heating capacity (i.e., q^{hp}) while they are turned ON. Hence, the heat energy produced by HPs can be expressed as

$$Q_h^{\mathsf{hp}} = q^{\mathsf{hp}} \Delta h \times n_h \tag{6}$$

where n_h is the number of HPs that need to be turned ON to produce the heat to fill the deficient amount of heat energy at time slot h. Similar to HP, the produced heat of EH is expressed as

$$q^{\mathsf{eh}} = \mathsf{COP}_{\mathsf{eh}} \times P^{\mathsf{eh}}. \tag{7}$$

where $\mathsf{COP}_{\mathsf{eh}}$ is the *coefficient of performance* of EH and P^{eh} is the power consumption of EH. Then, the total heat energy produced by EHs at time slot h is obtained as

$$Q_h^{\mathsf{eh}} = q^{\mathsf{eh}} \Delta h \times k_h. \tag{8}$$

where k_h is the number of EHs that are switched ON at time slot h.

4) Energy Balance in Hot Water Storage: We regard hot water storage as a pool that all relevant thermal energy steam must flow into or out of this pool. That is, if the amount of the sum of the produced energy is more than required energy, then the excess energy will be stored in the pool. On the other hand, the energy stored in the pool can also be discharged to support the deficient amount of heat energy. Hence, a simple energy balance model can be expressed as

$$Q_h^{\mathsf{M}} = Q_{h-1}^{\mathsf{M}} + Q_h^{\mathsf{s}} + Q_h^{\mathsf{hp}} - Q_h^w - Q_h^l \tag{9}$$

where Q_h^{M} is the total thermal energy stored inside main tank at time slot h. Q_h^l represents the overall energy loss due to heat exchange, demand delivery, and insulation materials of the storage tank. Furthermore, the energy balance model can be transferred as dynamic variation of temperature in the hot water storage. In this context, let T_h^{M} denote as the water temperature in the main tank at time slot h that can be calculated as [26]

$$T_h^{\mathsf{M}} = T_{h-1}^{\mathsf{M}} + \frac{\Delta Q_h^{\mathsf{M}}}{\mathcal{C} V^{\mathsf{M}}} \tag{10}$$

where $\Delta Q_h^{\mathsf{M}} = Q_h^{\mathsf{M}} - Q_{h-1}^{\mathsf{M}}$ and V^{M} is volume capacity of the main tank. For simplification, we assume that the overall energy loss relies on the temperature of tank at pervious time slot, that is, $Q_h^l/(\mathcal{C}V^{\mathsf{M}}) \equiv \eta^{\mathsf{M}} T_{h-1}^{\mathsf{M}}$, where η^{M} represents the heat loss coefficient of the main tank that indicates the influence of energy loss. By substituting (1) into (10), the dynamic temperature model of the main tank is determined as

$$\begin{aligned} T_h^{\mathsf{M}} = {} & \left(1 - \eta^{\mathsf{M}}\right) T_{h-1}^{\mathsf{M}} + \frac{1}{\mathcal{C} V^{\mathsf{M}}} \left(Q_h^{\mathsf{s}} + Q_h^{\mathsf{hp}}\right) \\ & - \frac{\Delta T_h^w}{V^{\mathsf{M}}} D_h^w, \; h = 1, 2, \ldots, H \end{aligned} \tag{11}$$

where $\Delta T_h^w = T_{\text{set}}^{\text{w}} - T_h^{\text{cold}}$.

Similarly, for the kitchen tank, the energy balance model is expressed as

$$Q_h^{\mathsf{K}} = Q_{h-1}^{\mathsf{K}} + Q_h^{\mathsf{eh}} - Q_h^k - Q_h^{lk} \tag{12}$$

where Q_h^{K} is the total thermal energy stored in the kitchen tank at time slot h and Q_h^{lk} is the overall energy loss corresponding to the kitchen tank. Then the dynamic temperature model of the kitchen tank is given as

$$T_h^{\mathsf{K}} = \left(1-\eta^{\mathsf{K}}\right) T_{h-1}^{\mathsf{K}} + \frac{1}{\mathcal{C}V^{\mathsf{K}}}\left(Q_h^{\mathsf{eh}}\right) - \frac{\Delta T^k}{V^{\mathsf{K}}} D_h^k,\ h = 1, 2, \ldots, H. \tag{13}$$

η^{K} and V^{K} are the heat loss coefficient and volume capacity of the kitchen tank, respectively, and $\Delta T^k = T_{\text{set}}^{\text{k}} - T_{\text{set}}^{\text{w}}$.

In addition, there are some key constraints and assumptions that are needed to be satisfied with the characteristics of storage tanks as follows.

1) At the beginning of a day, we assume the temperature of the both tanks should have individual initial value as

$$T_0^{\mathsf{M}} = T_{\text{ini}}^{\mathsf{M}} \tag{14a}$$

$$T_0^{\mathsf{K}} = T_{\text{ini}}^{\mathsf{K}}. \tag{14b}$$

Also, the temperature should be maintained above certain threshold at the end of control period H

$$T_H^{\mathsf{M}} \geq T_{\text{ini}}^{\mathsf{M}} \tag{15a}$$

$$T_H^{\mathsf{K}} \geq T_{\text{ini}}^{\mathsf{K}}. \tag{15b}$$

2) At any time slot h, the temperature inside tanks needs to be more than a lower temperature threshold

$$T_h^{\mathsf{M}} \geq T_{\text{min}}^{\mathsf{M}} \tag{16a}$$

$$T_h^{\mathsf{K}} \geq T_{\text{min}}^{\mathsf{K}}. \tag{16b}$$

The lower temperature threshold must be great or equal to the desired temperature of hot water based on the law of thermal equilibrium, i.e., $T_{\text{min}}^{\mathsf{M}} \geq T_{\text{set}}^{\text{w}}$, $T_{\text{min}}^{\mathsf{K}} \geq T_{\text{set}}^{\text{k}}$.

3) Similarly, at any time slot h, the temperature always needs to be lower than a maximum temperature threshold

$$T_h^{\mathsf{M}} \leq T_{\text{max}}^{\mathsf{M}} \tag{17a}$$

$$T_h^{\mathsf{K}} \leq T_{\text{max}}^{\mathsf{K}} \tag{17b}$$

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 tank.

C. Electricity Consumption

Now, most of electricity consumption of SHW system is consumed by HPs, EHs, and CPs. Then, the total electricity consumption (kW·h) of HPs at time slot h is calculated by

$$E_h^{\mathsf{hp}} = P^{\mathsf{hp}} \Delta h \times n_h. \tag{18}$$

Similarly, the electricity consumption by EHs is

$$E_h^{\mathsf{eh}} = P^{\mathsf{eh}} \Delta h \times k_h. \tag{19}$$

Furthermore, the electricity consumption by CPs at h is

$$E_h^{\mathsf{cp}} = P^{\mathsf{cp}} \Delta h \times u_h \tag{20}$$

where the rated power of all CPs is P^{cp}.

Accordingly, the total cost J_{cost} of total electricity consumption for the whole day (i.e., H time slots) is determined as

$$J_{\text{cost}} = \sum_{h=1}^{H} \mathbb{C}_h \left(E_h^{\mathsf{hp}} + E_h^{\mathsf{eh}} + E_h^{\mathsf{cp}}\right) \tag{21}$$

where $\mathbb{C}_h$ is the price per unit of electricity at h.

III. Energy Management Schemes

The aim of this work is to devise control approaches to improve efficiency of the SWH system. It indicates that the building manager would be able to pursue its own efficiency objectives such as

1) Minimizing the total electricity cost

$$J_{\text{cost}} = \sum_{h=1}^{H} \mathbb{C}_h \left(E_h^{\mathsf{hp}} + E_h^{\mathsf{eh}} + E_h^{\mathsf{cp}}\right)$$

2) Minimizing the peak power consumption

$$J_{\text{peak}} = \max_h \{P^{\mathsf{hp}} n_h + P^{\mathsf{eh}} k_h + P^{\mathsf{cp}} u_h\}.$$

At same time, all the relevant system constraints need to be maintained so as to meet the hot water demand of the consumers within the building. Based on (18)–(21), it can be clearly observed that these objectives are related to the operation of HPs, EHs, and CPs. Hence, in this section, we propose three energy management strategies for the operation of HPs and EHs as well as CPs in terms of different objectives and knowledge of future information.

1) On-Demand Control (ODC) approach, which requires no future information and is performed in real time. Thus, this control approach is more practical and implementable in real SWH systems.
2) Optimal day-ahead scheduling (ODS) approach that assumes the prior information is perfectly known for future 24-h. The solution of this approach is theoretical optimum based on exact future information, and thus can serve as a lower bound for different objectives.
3) Sliding time-scale window scheduling (STWS) approach, which is the modified ODS approach performing based on forecasted information. It can be expected the solution of STWS would be close to ODS's as the accuracy of forecasts increasing.

A. On-Demand Control

ODC approach aims at maximizing the utility of solar energy. That is, ODC approach gives priority to using solar energy to heat up water at each time slot h, and stores surplus solar energy into the main tank for future usage. The idea behind ODC is to minimize the number of HPs and EHs that need to be turned ON at each time slot h so as to reduce total electricity cost J_{cost}. By minimizing the number of HPs and EHs that are turned ON at

Algorithm 1: ODC approach.

initialize: Specifications and parameters of system: $\{M_f, M_e, \eta_f, \eta_e, A_f, A_e, \cdots\}$
input : Solar irradiance $\{I_h\}$, hot water demand: $\{D_h^w,\ D_h^k\}$
output : The number of HPs, EHs and CPs: $\{n_h,\ k_h,\ u_h\}$, and temperature of both tanks: $\{T_h^{\mathsf{M}}, T_h^{\mathsf{K}}\}$

```
begin
  for each h ∈ {1, ··· , H} do
    Main tank:
      Estimate the required heat energy by Eq. (1);
      Estimate the current solar energy by Eq. (3);
      if q_h^s > 0 then
        u_h = 1
      else
        u_h = 0
      Let Q_h^hp, n_h = 0 and calculate T_h^M by using Eq. (11);
      if Eq. (16a) (& Eq. (15a) if h=H) hold then
        Update the temperature of the main tank by Eq. (11);
      else
        Determine the necessary number of HPs, n_h, and calculating Q_h^hp by Eq. (6);
        Update the temperature of the main tank by Eq. (11);
    Kitchen tank:
      Estimate the required thermal energy by Eq. (2);
      Let Q_h^Eh, k_h = 0 and calculate T_h^K by using Eq. (13);
      if Eq. (16b) (& Eq. (15b) if h=H) hold then
        Update the temperature of the main tank by Eq. (13);
      else
        Determining the necessary number of EHs, k_h, and calculate Q_h^eh by Eq. (8);
        Update the temperature of the kitchen tank by Eq. (13);
  Return {n_h, k_h, u_h, T_h^M, T_h^K}, ∀h
```

each time slot h, it means that the objective of peak reduction is also considered within ODC approach. The basic functionality of ODC approach is shown in Algorithm 1. First, the ODC approach receives the estimated measurement of the main hot water demand D_h^w and the power of solar irradiance I_h at time slot h. Then, it calculates the necessary heat energy Q_h^w and the solar energy Q_h^{s} by using (1) and (3), respectively. After estimation, the ODC prefers to use the solar energy Q_h^{s} and the heat energy stored in the tank to meet the required heat energy Q_h^w as much as possible. This is due to the fact that the electricity consumption of CPs is generally less than that of HPs. Thus, heat energy is no required from HPs if enough heat energy form solar and the main tank. Furthermore, surplus solar energy will be stored into the main tank.

Otherwise, the necessary number of the HPs that need to be turned ON and the heat energy produced by HPs will be estimated. Finally, ODC updates the temperature of main tank for next time slot $h+1$. The procedure for kitchen part is similar to the above-mentioned explanation except of solar energy. In fact, ODC approach is a simple real-time algorithm that provides a simple and rough solution, and serves as an upper bound on the worst case performance of SWH system. As such, ODC serves as a reference control and benchmark for performances comparison afterward.

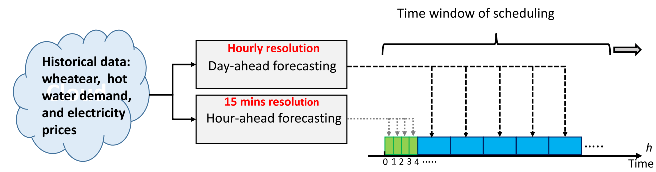

Fig. 2. Architecture of STWS approach.

B. Optimal Day-Ahead Scheduling

Although ODC is a practical and implementable approach via controlling the HPs, EHs, and CPs to meet the current hot water demand in real time, ODC may be confronted by some problems. For instance, if the upcoming hot water demand is lager than the available capacity of heat energy of all HPs and STCs, the desired temperature of hot water would not be achieved leading to user uncomfort. It is due to the fact that ODC approach lacks the future information, such as the weather condition and hot water demand. Therefore, if the exact forecasting for future information is available, we can efficiently schedule the operations of HPs, EHs, and CPs according to various aims. In this study, since the control of HPs, EHs, and CPs is only possible through ON/OFF control, searching for the optimal patterns of (n_h, k_h, u_h) from set $\{0,1\}\,\forall h$ is the ultimate target. In this context, the ODS problem can be expressed as

$$\begin{aligned} \min_{n_h, k_h, u_h} \quad & \mathcal{J} \\ \text{s.t.} \quad & (11), (13), (14)-(17) \\ & n_h, k_h, u_h \in \{0,1\}\ \ \forall h. \end{aligned} \tag{22}$$

Note that (22) is a general version of ODS, and $\mathcal{J}$ can be any objective as long as the system constraints (11), (13), (14)–(17) are satisfied. That is, if the building manager wants to schedule the HPs, EHs, and CPs via ODS so as to minimize the total electricity cost, J_{cost} would be substituted for $\mathcal{J}$ in (22). Similarity, substituting $\mathcal{J}$ by J_{peak} indicates minimizing the peak of power consumption via ODS approach. In addition, ODS (22) is formulated as an integer programming problem (MILP), and there are many popular solvers that can be applied to solve it. In this work, we employ built-in tool of MATLAB to solve this problem.

C. Sliding Timescale Window Scheduling

ODS gives the optimal solutions for the corresponding objectives, but it may not be suitable for practical implementation due to the requirement of extremely accurate forecasting for the future 24-h. Moreover, the computational time is exponential increasing as the scheduling period or control variables increasing. Hence, inspired by [27], we develop an online control approach, namely STWS. The scheme of STWS is based on ODS with some modification and relaxation that are detailed below.

The idea behind STWS is that forecasting the upcoming time is generally more accurate than forecasting future time. Hence, we focus on deciding the actual control with respect to the immediate and upcoming time slots, and only perform a rough plan for the future. For instance, as seen in Fig. 2, we consider two kinds of time slot with different time intervals; the time slots within the upcoming one hour have 15 min time interval, and otherwise the time interval is 60 min. On the basic of the forecast data from different time resolution, i.e., 15 min and hourly forecast, STWS schedules the control decisions for whole period as ODS does. Different from ODS, STWS relaxes the relevant variables and certain of constraints for future time slot. This is due to the fact that the control decisions of future time slot have highly uncertainty due to inaccurate forecasting. Hence, the general problem formulation of STWS can be express as

$$\begin{aligned} \min_{n_h, k_h, u_h, N_{h'}, K_{h'}, U_{h'}} \quad & \mathcal{J}(h, h') \\ \text{s.t.} \quad & (11), (13), (14)-(17) \\ & n_h \in \{0, N\}, k_h \in \{0, K\} \\ & u_h \in \{0, 1\} \;\; \forall h \in \mathcal{H} \\ & N_{h'} \in [0, N], K_{h'} \in [0, K] \\ & U_{h'} \in [0, 1] \;\; \forall h' \in \mathcal{H}'. \end{aligned} \tag{23}$$

Here, $\mathcal{J}(h, h')$ indicates that the representation of objective is adapted by different time resolution. Note that $N_{h'}$, $K_{h'}$, and $U_{h'}$ represent the variables for hourly time slot, and are relaxed form integer variable to real variable. $\mathcal{H}$ and $\mathcal{H}'$ are the sets of chosen time slot with the time interval of 15 min and 1 h, respectively. For a better understanding on the problem formulation of STWS, we provide an example to explain it. Assume that the objective of building manager is to minimize total electricity cost, and the index of current time slot is 1, i.e., $h = 1$. Then, the set $\mathcal{H}$ of chosen time slots is $\mathcal{H} = \{1, 2, 3, 4\}$, and the set of hourly time slots is $\mathcal{H}' = \{2, 3, \ldots, 24\}$. Given the forecasting values of 15 min and hourly resolution,[2] e.g., W_h^m, $W_{h'}^m$, the problem can be written as

$$\begin{aligned} \min \quad & \sum_{h=1}^{4} \mathbb{C}_h \left(E_h^{\text{hp}} + E_h^{\text{eh}} + E_h^{\text{cp}} \right) \\ & \quad + \sum_{h'=2}^{24} \mathbb{C}_{h'} \left(E_{h'}^{\text{hp}} + E_{h'}^{\text{eh}} + E_{h'}^{\text{cp}} \right) \\ \text{s.t.} \quad & (11), (13), (14)-(17) \\ & n_h \in \{0, N\}, k_h \in \{0, K\} \\ & u_h \in \{0, 1\}, h = 1, 2, 3, 4. \\ & N_{h'} \in [0, N], K_{h'} \in [0, K] \\ & U_{h'} \in [0, 1], h' = 2, 3, \ldots, 24. \end{aligned} \tag{24}$$

Here, $\mathbb{C}_{h'}$ is the electricity price for hourly time resolution. $E_{h'}^{\text{hp}}$ is based on (18), that is $E_{h'}^{\text{hp}} = P^{\text{hp}} \Delta h' \times N_h'$, where $\Delta h' = 4 \times \Delta h$. Similar to $E_{h'}^{\text{eh}}$ and $E_{h'}^{\text{cp}}$, they are based on (19) and (20), respectively.

However, the problem (23) is still possible to be infeasible because sometimes the certain constraints, e.g., (16a), could not be satisfied when performing STWS approach based on the forecasted information. Such situation will result in an infeasible solution. Fortunately, those unsatisfied constraints usually take place at future time intervals. Therefore, we adjust the limit of those unsatisfied constraints in order to overcome such problem, for example, we relax the constraint as $T_i^{\mathsf{M}} \geq (T_{\min}^{\mathsf{M}} - \delta)$, which δ is the tolerance, if (16a) cannot be satisfied at ith time slot.

After scheduling, only the control decisions for the current time slot are made, and then STWS will repeat for each time slot. Compared with ODS, STWS can be performed promptly without huge computational burden due to relaxing the relevant variables and constraints for far future.[3]

IV. Case Study

In this section, we conducted the simulation to examine the proposed approaches based on the real data of SWH system from a commercial building in Singapore. That is, we captured the historical data of hot water demand consumed in this building, and the specification of the SWH system. The initial specification and parameters setting are detailed in Table I. Furthermore, the real weather data [28] and electricity tariff [29] are also considered.

A. Considered Data for Simulation

To validate the effectiveness of the proposed approaches under various scenarios, we first consider different weather situations, such as sunny, rainy, cloudy, and even dark such the worst case. In particular, we select three practical days to run simulations, including a rainy day (RD—July/26/2016), a sunny day (SD—July/05/2016), and a semisynthetic day with no solar (NS—July/01/2016). The RD and SD have been chosen based on the real data including solar irradiance, ambient temperature, hot water demand, and electricity price in the month of July 2016, and also the NS has been chosen based on the real data except the whether data. Note that, only in the NS case, the solar irradiance and the ambient temperature are assumed to be zero and a constant value, 25 °C, respectively. Fig. 3 shows the real date on RD, SD, and NS at each time slot h. It is observed that, in Fig. 3, the peak of hot water demand arises from 6:00 to 10:00 h in the morning, and the peak in the evening is from 18:00 to 21:00 h for all selected days. Furthermore, the peaks of the electricity price and hot water demand profile are roughly coincident besides midnight. This indicates that the high electricity cost and power load, caused by auxiliary heaters, will have a high correlation during those periods without the optimized control.

To perform STWS, the forecasted information is necessary. Hence, we generate a series simulated forecast data, including solar irradiance, ambient temperature, hot water demand, and electricity price by incorporating the real data with Gaussian white noise, which is simulated as the forecasting errors. In this

[2] There have been many methods, e.g., ARMA, artificial neural network, Kalman filter, etc., that can applied to short term and long term forecasting. However, how to implement the forecasting methods is out of scope. Hence, in this study, we only simulate the forecasted value.

[3] Essentially, STWS approach is a variant of model predictive control (MPC) without the computation burden and complexity that typical MPC meets.

TABLE I

INITIAL SPECIFICATION AND PARAMETERS SETTING (THE DESCRIPTION OF THE PARAMETER WITH THE NOTATION (*) INDICATES THE CORRESPONDING VALUE IS ASSUMED)

Description	Parameter	Value	Description	Parameter	Value
The interval of time slot	Δh	15 min	The total number of time slots	H	96
The required temperature of hot water for whole building	$T^{\mathrm{w}}_{\mathrm{set}}$	60 °C	The absorber area of flat-plate panels	A_f	2.8 m^2
The required temperature of hot water for kitchen zone	$T^{\mathrm{k}}_{\mathrm{set}}$	70 °C	The absorber area of evacuated-tube panels	A_e	2.8 m^2
The maximum temperature of tank	$T^{\mathrm{M}}_{\mathrm{max}}$ and $T^{\mathrm{K}}_{\mathrm{max}}$	80 °C	The thermal efficiency of flat-plate panels (*)	η_f	0.5
The minimum temperature of main tank	$T^{\mathrm{M}}_{\mathrm{min}}$	60 °C	The thermal efficiency of evacuated-tube panels (*)	η_e	0.7
The minimum temperature of kitchen tank	$T^{\mathrm{K}}_{\mathrm{min}}$	70 °C	The capacity of tank	$V^{\mathrm{M}}/V^{\mathrm{K}}$	12/3 m^3
The heat loss coefficient of the storage (*)	$\eta^{\mathrm{M}}\&\eta^{\mathrm{K}}$	0.1%/h	The COP of HP	$\mathrm{COP}_{\mathrm{hp}}$	3.1
The number of flat-plate panels	M_f	27	The COP of EH	$\mathrm{COP}_{\mathrm{eh}}$	0.76
The number of evacuated-tube panels	M_e	70	The electricity consumption of HP	P^{hp}	12.85 kW
The number of heap pumps	N	5	The electricity consumption of EH	P^{eh}	18 kW
The number of EHs	K	6	The electricity consumption of CP	P^{cp}	2.75 kW

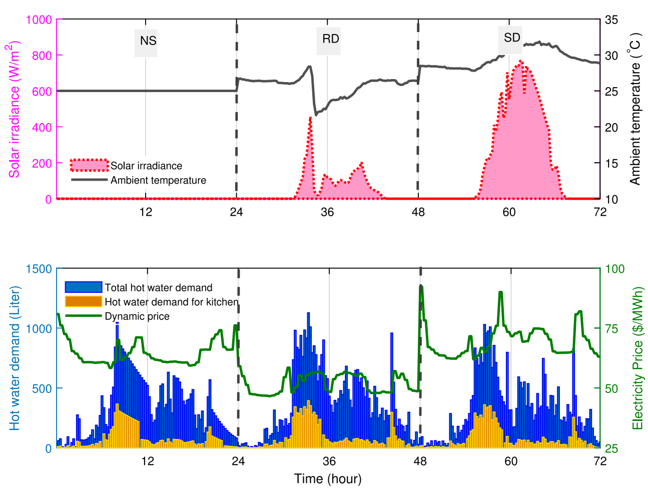

Fig. 3. Illustration of the considered data on a RD, SD and on a day with NS.

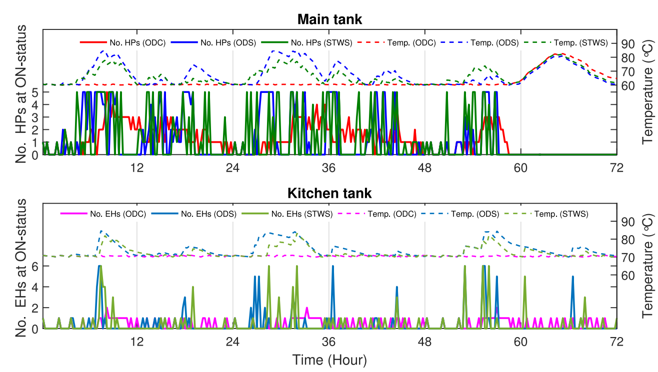

Fig. 4. Demonstration of number of HPs and EHs and temperature of main tank and kitchen tank on the selected days in Case 1.

work, we assume the any information within first hour to be perfectly forecasted at the sliding time window of STWS. For the remainder periods of time window, we assume that the mean of foretasting error is 0, and the standard deviation of foretasting error σ is the 20% of actual data value for hourly resolution. For example, the foretasted solar irradiance at time slot h' can be express as

$$\hat{I}_{h'} = I_{h'} + 0.2 I_{h'} \times \mathcal{N}(0,1) \tag{25}$$

where $I_{h'}$ is the exact value of solar irradiance, and $\mathcal{N}(0,1)$ represents Gaussian distribution with zero mean and unit variance.

B. Case1: Cost-Optimal

Now, this case study aims to minimize the electricity cost via the proposed approaches. Hence, we perform the the proposed approaches, and show the results of the temperature of main tank and kitchen tank and the status of HPs and EHs in the Fig. 4. For reference control, ODC approach, the number of the required HPs and EHs to fulfil the demand of hot water varies with the variation of solar irradiance and hot water demand, correspondingly. For ease of observation, the results of ODC, as shown in Table II, will serve as a reference benchmark for performances comparison with ODS and STWS. Note that the results of ODC are same through all case studies. For ODS approach, as expected, it can be observed that more HPs are turned ON early before the morning peak to preheat up water leading to rise the temperature of main tank up significantly. Moreover, more HPs and EHs are turned ON during the periods of lower price in order to reserve heat for future demand. Similar phenomenon is also observed from the results of STWS approach, that demonstrates the effectiveness for the forecasts of demand and price. Table III shows the results of ODS and STWS obtained in Case 1. According to Table III, the total electricity consumption of ODS and STW is sightly more than ODC for all selected days, except ODS's on SD. However, the

TABLE II

SUMMARY RESULTS OF ODC

	No solar	RD	SD	Average of three days
Total electricity consumption (kW·h)	618.8	626.1	330.6	525.2
Peak power consumption (kW)	100.3	72.2	77.3	83.2
Total electricity cost (SGD)	39.87	33.18	22.75	31.9

TABLE III
SUMMARY RESULTS OF ODS AND STWS COMPARED TO ODC IN CASE STUDY

	Approach	Case 1			Case 2			Case 3		
		NS	RD	SD	NS	RD	SD	NS	RD	SD
Total electricity consumption	ODS	0.52%	1.52%	−0.73%	14.22%	3.54%	1.81%	0.52%	0.04%	−1.73%
	STWS	0.52%	1.52%	1.78%	0.52%	3.25%	16.71%	0.52%	0.55%	0.25%
Peak power consumption	ODS	71.82%	142.55%	122.83%	**−61.55%**	**−46.57%**	**−60.09%**	**−61.55%**	**−53.43%**	**−60.09%**
	STWS	71.82%	138.74%	122.83%	**−61.55%**	**−46.57%**	**−56.53%**	**−35.91%**	**−28.76%**	**−43.47%**
Total electricity cost	ODS	**−5.04%**	**−7.32%**	**−6.42%**	14.67%	2.18%	2.24%	**−2.81%**	**−2.53%**	**−3.59%**
	STWS	**−3.21%**	**−4.92%**	**−3.00%**	0.76%	1.42%	17.83%	**−1.31%**	**−2.17%**	**−1.81%**
Remark		In case 1, ODS and STWS achieve lower electricity cost than ODC in all weather conditions, specially on RD.			In case 2, ODS and STWS achieve lower peak power consumption than ODC in all weather conditions, especially on NS and SD.			In case 3, ODS and STWS achieve both lower electricity cost and lower peak power consumption than ODC in all weather conditions.		

The bold values indicate the main metrics (objectives) considered in each case.

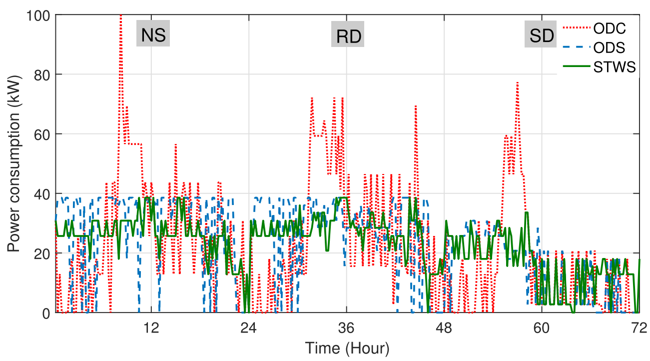

Fig. 5. Dynamic profile of electricity power consumption in Case 2.

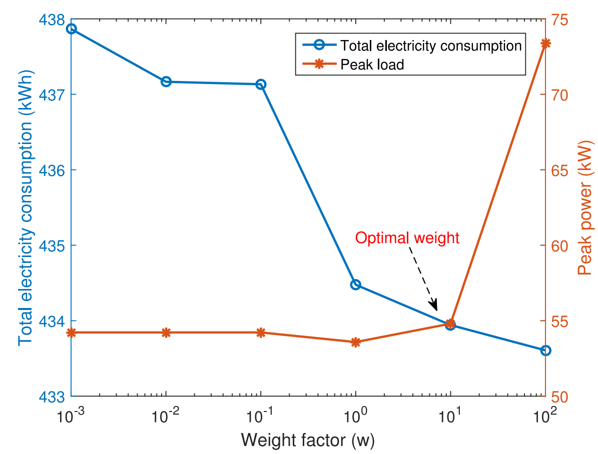

Fig. 6. Demonstration of the weight selection performed upon ODS.

total electricity cost of ODS and STWS is reduced, compared with ODC, for all selected days, and the cost saving of STWS is less than ODS due to the forecasting uncertainty. In addition, the peak power consumption of ODS and STW is significant increased. This is due to the fact that the more HPs and EHs, compared with ODC, are turned ON during the periods of lower price in order to achieve more cost saving.

C. Case2: Peak Reduction

In this case study, we aim to minimize the peak power consumption of the SWH system. Fig. 5 shows the electric power consumption of the proposed approaches. Observably, ODC approach results in many peak loads due to the peaks of hot water demand that indicate a large number of in-service HPs and EHs during those periods. On the contrary, as seen in Fig. 5, ODS and STWS have a much improvement, that is, almost flat power consumption profile. It is observed that, as shown in Table III, ODS and STWS have the almost equal performance in terms of the objective of peak reduction. However, it is noted that the higher electricity consumption and cost will be caused due to the influence of pursuing peak reduction. Hence, it is interesting that how to increase cost-saving while reducing the peak. Therefore, simultaneously considering the objectives of cost-optimal and peak reduction is studied in next section.

D. Case3: Dual Cost-Peak Objectives

Multiobjective of joint cost-peak is considered in this case study. For ease, let J_{dual} denote the multiobjective function that simultaneously considers the reduction of peak load and the total electricity cost. In general, the optimal solution of J_{dual} will be taken in the presence of tradeoff between peak load and total electricity cost. Therefore, we employ the weighted sum method to address this multiobjective optimization. Specifically, we sum peak load and total electricity cost with multiplying a weight factor as

$$J_{\text{dual}} = \omega \times J_{\text{cost}} + J_{\text{peak}} \tag{26}$$

where ω is weight factor. However, how to select weight factor so as to optimize peak load and total electricity consumption simultaneously is an important issue. To do so, we choose the SD day's condition to conduct ODS with various scale of weight factor. Fig. 6 shows that the curves of peak load and total electricity consumption relating to various scale of weight factor. It is note that the curves cross at ten. Hence, $\omega^\star = 10$ regards as the optimal weight factor in this case study. Note that all relevant results shown below are carried out with the optimal weight factor. The results of ODS and STWS with respect to three cases are shown in Table III. Observably, only considering the objective of cost-optimal or peak-reducing can only maximize their own objective but suffer in terms of peak or cost. That is, based on the objective of electricity cost reduction, ODS and STWS will increase the peak of power consumption. On the other hand, ODS and STWS based on the objective of peak reduction reduce the peaks of power consumption but significantly rise the total electricity cost due to load shifting to the periods with high price. However, ODS and STWS based on J_{dual} with optimal weight, gain both advantage of cost-saving and peak-reducing, and avoid those drawbacks. But the performance of ODS and STWS based on J_{dual} is less than that of considering individual objective. Moreover, the performance of STWS is approaching ODS, without the needs of having perfect information on weather, hot water demand and electricity price, as well as heavy computational burden.

V. Conclusion

In this paper, the optimal control mechanism for controlling HPs, EHs, and CPs within a SWH system has been studied with a view to improving the operation of the SWH system. Three control strategies including ODC, ODS, and STWS have been proposed based on different requirements of information on weather, hot water demand, and electricity price. Furthermore, we have studied three cases that consider the cost-optimal, peak-reducing, and dual cost-peak objectives, by using the real data of weather, price, and hot water demand of a commercial building in Singapore.

The effectiveness and efficiency of the proposed approaches have been validated via numerical case studies. The case results have shown that the proposed approaches can improve cost-efficiency as well as reduce the peak demand. Specifically, ODC, which is a simple and real-time control method, has been shown to have the potential for practical implementation. Hence, we have let the results of ODC serve as a reference benchmark for performances comparison, which has shown that ODS can obtain a maximum cost-savings of 7.32%, compared with ODC for the cost-optimal objective. Then, for peak reduction objective, ODS can archive a maximum of 61.55% peak-reduction compared with ODC. For the dual cost-peak objectives, the demonstrated cost-savings and peak-reduction of ODS are 3.59% and 61.55%, respectively, compared with ODC. However, the potentiality of ODS for practical implementation is limited due to the requirement of perfect future information and extensive computation time. Thus, ODS may not be implemented in reality. On the contrary, STWS has lower computation time and acceptable performance when compared to ODS.

The gap of performance between ODS and STWS is due to forecast uncertainty. Indeed, the performance of STWS depends on the accuracy of forecast, i.e., forecasting of solar irradiance, ambient temperature, and hot water demand. If the accuracy of forecast is near perfect, we can anticipate that the performance of STWS approach would archive ODS's. On the other hand, by considering the worst case, which means highly foretasting error is incorporated, the STWS approach will be degraded as ODC. As such, we can conclude that STWS is the most suitable and recommendable approach for scheduling the operation of the SWH system.

In the future work, we will investigate more general framework in terms of control strategies that could be adapted in various architectures of SWH system, e.g., only one tank is used to supply hot water with two different described temperature.

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References

[1] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Trans. Ind. Informat.*, vol. 7, no. 3, pp. 381–388, Aug. 2011.

[2] R. Deng, Z. Yang, M. Y. Chow, and J. Chen, "A survey on demand response in smart grids: Mathematical models and approaches," *IEEE Trans. Ind. Informat.*, vol. 11, no. 3, pp. 570–582, Jun. 2015.

[3] Z. Zhou, J. Gong, Y. He, and Y. Zhang, "Software defined machine-to-machine communication for smart energy management," *IEEE Commun. Mag.*, vol. 55, no. 10, pp. 52–60, Oct. 2017.

[4] Y. Zhang, R. Yu, S. Xie, W. Yao, Y. Xiao, and M. Guizani, "Home M2M networks: Architectures, standards, and QoS improvement," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 44–52, Apr. 2011.

[5] S. Maharjan, Q. Zhu, Y. Zhang, S. Gjessing, and T. Başar, "Dependable demand response management in the smart grid: A Stackelberg game approach," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 120–132, Mar. 2013.

[6] Y. Zhang, R. Yu, M. Nekovee, Y. Liu, S. Xie, and S. Gjessing, "Cognitive machine-to-machine communications: Visions and potentials for the smart grid," *IEEE Netw.*, vol. 26, no. 3, pp. 6–13, May 2012.

[7] D. Kolokotsa, "The role of smart grids in the building sector," *Energy Buildings*, vol. 116, pp. 703–708, Mar. 2016.

[8] S. N. Han, G. M. Lee, and N. Crespi, "Semantic context-aware service composition for building automation system," *IEEE Trans. Ind. Informat.*, vol. 10, no. 1, pp. 752–761, Feb. 2014.

[9] S. Fang *et al.*, "An integrated system for regional environmental monitoring and management based on internet of things," *IEEE Trans. Ind. Informat.*, vol. 10, no. 2, pp. 1596–1605, May 2014.

[10] A. Safdarian, M. Fotuhi-Firuzabad, and M. Lehtonen, "A distributed algorithm for managing residential demand response in smart grids," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2385–2393, Nov. 2014.

[11] F. Y. Xu and L. L. Lai, "Novel active time-based demand response for industrial consumers in smart grid," *IEEE Trans. Ind. Informat.*, vol. 11, no. 6, pp. 1564–1573, Dec. 2015.

[12] Q. Chen, N. Liu, C. Hu, L. Wang, and J. Zhang, "Autonomous energy management strategy for solid-state transformer to integrate pv-assisted EV charging station participating in ancillary service," *IEEE Trans. Ind. Informat.*, vol. 13, no. 1, pp. 258–269, Feb. 2017.

[13] W. Tushar, C. Yuen, S. Huang, D. B. Smith, and H. V. Poor, "Cost minimization of charging stations with photovoltaics: An approach with EV classification," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 1, pp. 156–169, Jan. 2016.

[14] O. Kilkki, A. Alahäivälä, and I. Seilonen, "Optimized control of price-based demand response with electric storage space heating," *IEEE Trans. Ind. Informat.*, vol. 11, no. 1, pp. 281–288, Feb. 2015.

[15] M. S. Buker and S. B. Riffat, "Building integrated solar thermal collectors – A review," *Renewable Sustain. Energy Rev.*, vol. 51, pp. 327–346, Nov. 2015.

[16] R. Chauhan, T. Singh, N. S. Thakur, and A. Patnaik, "Optimization of parameters in solar thermal collector provided with impinging air jets based upon preference selection index method," *Renewable Energy*, vol. 99, pp. 118–126, Dec. 2016.

[17] C. Lamnatou, G. Notton, D. Chemisana, and C. Cristofari, "The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment of methodologies," *Building Environ.*, vol. 87, pp. 45–58, May 2015.

[18] J. Freeman, K. Hellgardt, and C. N. Markides, “An assessment of solar-thermal collector designs for small-scale combined heating and power applications in the United Kingdom,” *Heat Transfer Eng.*, vol. 36, no. 14–15, pp. 45–58, 2015.
[19] I. Visa *et al.*, “Design and experimental optimization of a novel flat plate solar thermal collector with trapezoidal shape for facades integration,” *Appl. Thermal Eng.*, vol. 90, pp. 432–443, Nov. 2015.
[20] H. Tanaka, “Theoretical analysis of solar thermal collector and flat plate bottom reflector with a gap between them,” *Energy Rep.*, vol. 1, pp. 80–88, Nov. 2015.
[21] H. T. Nguyen, D. T. Nguyen, and L. B. Le, “Energy management for households with solar assisted thermal load considering renewable energy and price uncertainty,” *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 301–314, Jan. 2015.
[22] Y. Li, S. S. Choi, C. Yang, and F. Wei, “Design of variable-speed dish-stirling solar – Thermal power plant for maximum energy harness,” *IEEE Trans. Energy Convers.*, vol. 30, no. 1, pp. 394–403, Mar. 2015.
[23] Q. Luo, K. B. Ariyur, and A. K. Mathur, “Control-oriented concentrated solar power plant model,” *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 2, pp. 623–635, Mar. 2016.
[24] L. R. Cirocco, M. Belusko, F. Bruno, J. Boland, and P. Pudney, “Controlling stored energy in a concentrating solar thermal power plant to maximise revenue,” *IET Renewable Power Gener.*, vol. 9, no. 4, pp. 379–388, 2015.
[25] W.-T. Li, K. Thirugnanam, W. Tushar, C. Yuen, and K. Wood, “Optimizing energy consumption of hot water system in buildings with solar thermal systems,” in *Proc. Int. Conf. Smart Cities Green ICT Syst.*, Porto, Portugal, Apr. 2017, pp. 266–273.
[26] C. Yan, S. Wang, Z. Ma, and W. Shi, “A simplified method for optimal design of solar water heating systems based on life-cycle energy analysis,” *Renewable Energy*, vol. 74, pp. 271–278, 2015.
[27] J. Fink, R. P. Leeuwen, J. L. Hurink, and G. J. M. Smit, “Linear programming control of a group of heat pumps,” *Energy, Sustain. Soc.*, vol. 5, no. 1, p. 33, Nov. 2015.
[28] Department of Geography, NUS, “Geography Weather Station,” [Online]. Available: https://inetapps.nus.edu.sg/fas/geog/
[29] Energy Market Company of Singpore, “Price information,” [Online]. Available: https://www.emcsg.com/

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