Fair Energy Resource Allocation by Minority Game Algorithm for Smart Buildings

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Abstract—**Real-time and decentralized energy resource allocation has become the main feature to develop for the next generation energy management system (EMS). In this paper, a minority game (MG)-based EMS (MG-EMS) is proposed for smart buildings with hybrid energy sources: main energy resource from electrical power-grid and renewable energy resource from solar photovoltaic (PV) cells. Compared to the traditional static and centralized EMS (SC-EMS), and the recent multi-agent-based EMS (MA-EMS) based on price-demand competition, our proposed MG-EMS can achieve up to 51x and 147x utilization rate improvements respectively regarding to the fairness of solar energy resource allocation. In addition, the proposed MG-EMS can also reduce peak energy demand for main power-grid by 30.6%. As such, one can significantly reduce the cost and improve the stability of micro-grid of smart buildings with a high utilization rate of solar energy.**

I. INTRODUCTION

The automatic building control has recently regained the attention due to the need of energy efficiency improvement. All buildings have automatic controllers with a computer as the central processor, called energy management system (EMS). The building facility managers have the need of computer-aided-design (CAD) technique for energy resource scheduling by assessing existing electricity from external power-grid, commissioning new renewable solar energy, evaluating service contract options, and optimizing EMS operations [8]. Although it has been successfully employed for a long time, the traditional EMS algorithms [4-8] have major limitations from two folds. Firstly, the traditional EMS follows the centralized control architecture with static energy allocation strategy. However, energy generators and consumers in modern urban era are constantly varying with time, and hence exhibit vastly different characteristics of both energy supply and load profiles (i.e., the amount of energy generated by suppliers and energy demand of customers, respectively). As such, the traditional static and centralized EMS (SC-EMS) algorithm may lead to problems of scalability, reliability and extensibility. Secondly, the traditional EMS has poor control over renewable energy such as solar energy due to the problem of hard-to-predict intermittent generation. Note that the utilization rate of renewable energy resources is actually one critical feature for future smart building development. For example, a significant portion of 21,000 Mega-watt solar photovoltaic (PV) has been installed globally in 2010 [2][3]. Thus, there is an emerging need to develop the EMS for smart buildings with hybrid energy sources, which includes main energy resource from electrical power-grid (called main power-grid in the rest of this paper) together with renewable energy resource from solar PV cells.

To achieve high utilization rate for a micro-power-grid composed of hybrid energy sources, a modern EMS actually requires an energy resource allocation deployed in a real-time and decentralized fashion. The primary reason of low utilization rate for the traditional EMS algorithms [4-8] is the ignorance of mismatched energy profiles between energy generators and consumers because buildings can exhibit variant real-time physical infrastructures and with different human behaviours. Recently, multi-agent-based EMSs (MA-EMSs) have been proposed in [9-11] to achieve supply-load equilibrium. However, although these techniques are deployed in a distributed manner which is the key in agent-based algorithm, they need to alter customer energy demand. For example, customers need to reduce their energy demand at peak time (i.e., highest energy demand point) which may bring inconvenience for people in the buildings. More importantly, in their model, a small proportion of selfish customers can dominate the energy allocation and hence may receive all the benefits from renewable energy. As such, they cannot address the objective for a fair energy resource allocation.

In this paper, we propose a novel minority game (MG)-based EMS, called MG-EMS. The MG-EMS is deployed in smart buildings with hybrid energy sources including electrical power-grid and renewable solar PV cells, where each room in the building competes for the limited amount of relatively cheaper solar energy to save energy cost. The primary advantage of MG algorithm is to provide balanced solution for complex dynamic systems where several selfish entities compete for resources while the system dynamics continuously change during the runtime [12]. As such, our MG-EMS can achieve a much fair resource allocation than the MA-EMS developed in [9-11]. Note that the proposed MG-EMS is scalable and flexible to be implemented on the existing buildings as well as to be pre-installed to the new buildings through power-line communication.

Our proposed MG-EMS improves the energy resource allocation and hence further utilization rate in rooms from two folds. Firstly, rooms (or customers) with different energy load profiles can benefit uniformly from solar energy. Moreover, the peak energy demand for main power-grid can be also reduced. While the traditional SC-EMS statically allocates the solar energy to rooms in proportion to customer energy demand under the centralized processor, real-time energy supply and load profiles are considered in our MG-EMS, which can allocate energy resource to large number of consumers under decentralized fashion. Furthermore, our MG-EMS ensures that more solar energy is allocated during busy hours and hence can reduce the peak energy demand for main power-grid. By employing the realistic energy supply and load profiles obtained from field testbed [13][14], experiment results show that our MG-EMS can achieve up to 51x and 147x improvements in term of fair solar energy allocation when compared to the traditional SC-EMS and MA-EMS [10]. Moreover, our MG-EMS can also reduce the peak energy demand for main power-grid by up to 30.6%.

The rest of this paper is organized as follows. The system overview and problem formulation are introduced in Section II. In Section III. the MG-EMS algorithm is elaborated in details. Then in Section IV. experiment results are presented to validate our MG-EMS and to further demonstrate its advantages. Finally, the paper is concluded in Section V.

II. SYSTEM DESCRIPTION

2.1 *Physical Architecture*

The physical architecture for smart buildings is similar to the one deployed in Newington Solar Village [1] and testbed in UCSD campus [19]. Figure 1 illustrates the overall physical architecture for smart buildings supplied with hybrid energies. The EMS infrastructures are installed on top of the building and inside each room respectively. For the smart building, the following components are needed:

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- *Solar PV panel* [1] to harvest solar energy with dependence between the amount of solar energy and the area of PV panel.
- *Main electrical power-grid* to ensure building electricity power supply in addition to renewable energy from solar PV cells.
- *Energy storage system (ESS)* [15] such as battery packs to keep remaining solar energies. In order to reduce the peak energy demand for main power-grid, solar energies generated at non-busy hours are better to be kept for later use during busy times. Each ESS has a monitor to indicate the *state-of-charge* (SoC) information of ESS [16].
- *Power converters* to convert DC solar energy to AC power-supply when AC supplies are assumed for energy customers in building; or convert AC electricity to DC supply when DC supplies are assumed for energy customers in building[17][18].

Different from the centralized control approach, the energy management responsibilities are distributed into rooms within the building. Specifically, each room contains the following infrastructures to carry out the EMS functionality:

- *Smart-power-meter* [8] to provide real-time sensing, recording and communication of numerous data such as current power demand and energy utilization history. It also contains a *switch* to physically select the supplied energy source.
- *Room agent* to decide either to use the solar energy or the electricity from main electrical power-grid at runtime. It is based on real-time sensed data with a controller to implement the proposed minority game (MG)-based allocation algorithm. Power line communication [16] is utilized for the communication between the agents.

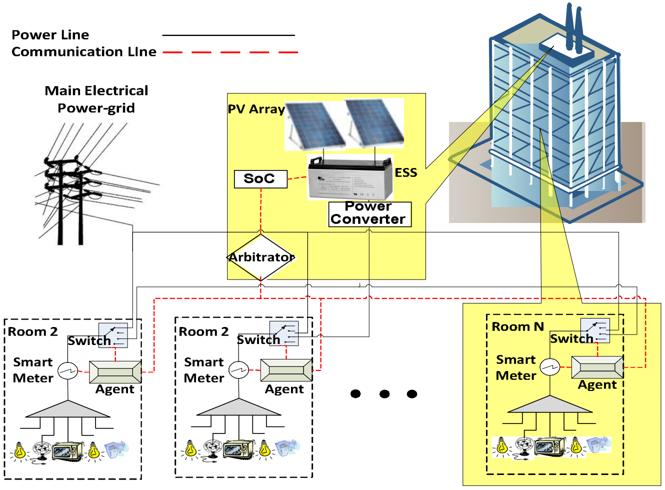

Figure 1: Overall system architecture for energy management system including: hybrid energy sources, energy storage system, power converters, smart power meter and room agent

Different from SC-EMS where a large and complex centralized controller is installed, in the proposed MG-EMS only a simple *game arbitrator* is needed with easy tasks as to decide the winning side of minority game, and to broadcast the game results back to all rooms. The primary characteristic of such physical architecture is the decentralization with real-time monitoring, which can bring various advantages in scalability, reliability and extensibility. For example, adding or removing a room does not involve the overall architecture modifications. Moreover, the breakdown of one single room will not affect the others. At the same time, the controller allows real-time dynamic control over different types of rooms.

2.2 *Energy Profiles*

After the determination of physical architecture, we further present the energy supply and load profiles, which can show the real-time varying characteristics of source energy generation and customer energy demand respectively. To build the realistic EMS, the real-world energy profiles obtained from existing field tests in [13][14] are adopted.

2.2.1 Customer-side Energy Load Profiles

The customer-side *energy load profiles* characterize the time-varying energy *demand* of end users (i.e., rooms). Due to various room settings (e.g., air-conditioner) and human behaviours (e.g., life-style), the rooms inside the same building can have vastly different energy load profiles. For example, Figure 2 illustrates the energy load profiles of different types of rooms from field test in New Hampshire Electric Co-op building [13]. From this figure, two key characteristics can be observed:

1. The energy demand is non-uniform with regard to times. In other words, there exist daily peak and valley points of energy demand. For example, two peaks during 7-9am and 6-9pm are observed for residential rooms in Figure 2(a), when people are more active in their homes.
2. Different types of room exhibit different energy load profile characteristics. For example, the peak period of commercial rooms is on the opposite as the valley period of residential rooms, when most people are out of their homes. In addition, commercial rooms demand almost two times more energy than residential rooms do on average.

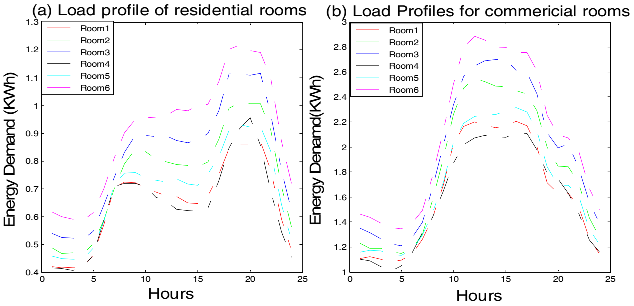

Figure 2: Average energy load profiles during summer (i.e., August), for: (a) residential rooms; (b) commercial rooms

As such, one can conclude with following design considerations for EMS. Since the cost of the traditional main power-grid is proportional to the peak energy demand to be matched, it is most beneficial when solar energy is utilized to compensate the mismatched peak during peak period [20]. Formal definition of peak periods will be introduced in the next section.

2.2.2 Supplier-side Energy Supply Profiles

The supplier-side *energy supply profiles* describe the time varying amount of energy generated by energy suppliers. Specifically in our MG-EMS, we consider the energy profile of solar PV cells. Figure 3(a) shows one typical example of such profiles obtained from the cooperative effort between National Renewable Energy Laboratory (NREL) and other agencies at selected locations in USA [14].

With leveraged analysis between Figure 2 and Figure 3(a), it is clear that solar energy alone cannot supply the daily energy demand of the entire building. As a result, the electricity from main power-grid is still required to supply such energy gap. As the solar energy is relatively cheaper compared to electricity from main power-grid, rooms would always prefer to use the solar energy. Given the limited amount of solar energy available, our proposed MG-EMS is targeted to fairly allocate the solar energy among different types of rooms with real-time varying energy load profiles. Moreover, as shown in Figure 3(b), the main electrical power-grid supplier usually sets different electricity prices to discourage/encourage the energy use at busy/non-busy times. Thus, instead of allocating the same amount of solar energy to different rooms, our proposed MG-EMS is targeted to balance the total amount of money saved from using solar energy for each room.

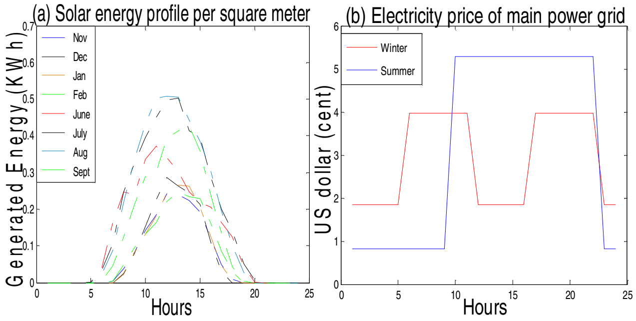

Figure 3: (a) Solar energy supply profile (per square meter of PV area); (b) Price fluctuations of electricity from main electrical power-grid

2.3 Problem Formulation

The problem of proposed EMS is formulated as follows. Denote each room as r_k ,$1 \le k \le N_r$, where N_r is the total number of rooms inside the building. In addition, each room is associated with a specific energy load profile $l_k(d,h), d \ge 0, 0 \le h \le 23$ where d and h represents *day* and *hour* respectively.

These energy load profiles can be regarded as the real-time prediction of user energy demand. In practice, it can be calculated at runtime by specific software/hardware module attached to the smart meter based on methods like [21]. As such prediction is out of the scope of this paper, the energy load profiles from [13][14] as are taken as inputs to our EMS. However, please note the proposed MG-EMS is not bounded to any specific energy load profiles.

At any specific time (d,h), the energy demand of room k for the next hour is[1]

$$E_k^{d,h} = l_k(d,h) \tag{1}$$

Note for real-time control, at any specific time $(\mathrm{d}',\mathrm{h}')$, the EMS is only aware of the past and current energy demand $\mathrm{E}_\mathrm{k}^{\mathrm{d,h}}, 0 \le d \le d', 0 \le h \le h'$.

Similarly, we denote the solar energy supply profile as $s(d,h), d \ge 0, 0 \le t \le 23$. Thus, the amount of solar energy generated for the next hour from time (d,h) will be

$$G^{d,h} = s(d,h) \tag{2}$$

To quantitatively measure the peak period, we define the peak threshold E_{th}^d of day d as the average hourly energy demand of the entire building over one day.

$$E_{th}^d = \frac{\sum_{h=0}^{23}\sum_{k=1}^{N_r} E_k^{d-1,h}}{24 * N_r} \tag{3}$$

As we cannot get the future energy demand in one day advance, E_{th} is actually calculated based on the energy demand of the previous day[2]. The peak period is then defined as those times when the entire building's energy demand exceeds that threshold. During peak periods, the proposed MG-EMS is deployed to allocate more solar energy if available to reduce the energy demand to main power-grid.

The energy source in our EMS is composed of both solar PV cells and main power-grid. At each control time (d,h), the EMS selects one of the two energy sources to be used in the next hour for each room. Mathematically, we define the Boolean variable $s_k^{d,h}$ to represent the selection of energy source for each room r_k

$$s_k^{d,h} = \begin{cases} 1, & E_k^{d,h} \text{ supplied by solar energy} \\ 0, & E_k^{d,h} \text{ supplied by main power grid} \end{cases} \tag{4}$$

In addition, as the price of main power-grid electricity varies by time, we define its price value at time (d,h) as $p_m^{d,h}, d \ge 0, 0 \le t \le 23$. On the other hand, solar energy has a constant price p_s. As solar energy is cheaper than energy from main power-grid, the *energy cost savings* room r_k receives due to the use of solar energy is defined as the amount of money saved up to the current moment

$$b_k^{d,h} = \sum_{d=0}^{d}\sum_{t=0}^{t-1} E_k^{d,h} \cdot s_k^{d,h} \cdot (p_m^{d,h} - p_s) \tag{5}$$

Finally, we can describe the two objectives to optimize of our proposed MG-EMS:

Objective 1: Balance the energy cost savings received from the utilization of solar energy for each room. Mathematically, it equals to minimize the standard deviation of $b_k^{d,h}$

$$\min \sqrt{\frac{\sum_{k=1}^{N_r}(\overline{b_k^{d,h}} - b_k^{d,h})^2}{N_r}} \tag{6}$$

Objective 2: Reduce the peak energy demand to main power-grid, i.e., to maximize solar energy utilization when the energy demand exceeds peak threshold E_{th}^d

$$\max \sum_{k=1}^{N_r} E_k^{d,h} \cdot s_k^{d,h}, when\ \frac{\sum_{k=1}^{N_r} E_k^{d,h}}{N_r} > E_{th}^d \tag{7}$$

In addition, the constraint here is that there must be enough solar energy to be allocated at each control step:

$$\sum_{k=1}^{N_r} E_k^{d,h} \cdot s_k^{d,h} \le C_s^{d,h}, for\ d \ge 0, 0 \le h \le 23 \tag{8}$$

where $C_s^{d,h}$ is the available solar energy to be allocated at time (d,h), which will be introduced in detail in the next section.

III. MINORITY GAME-BASED EMS

3.1 Multi-Agent Systems for Decentralized Control

The centralized control is ineffective to obtain fair resource allocation for large-scale dynamic systems. Multi-agent (MA)-based algorithm [24] is currently the most effective approach to realize decentralized control. In MA-based decentralized control, each agent can independently make its own decision under certain negotiation scheme. With carefully designed negotiation strategy, the overall system equilibrium can be expected even under vastly different agent profiles for real time resource allocation. As discussed in section II. , the modern smart buildings involve multiple energy suppliers and consumers with time varying energy supply and load profiles such that a real-time and decentralized EMS is required for the energy resource allocation. MA-based EMS (MA-EMS) algorithms have been explored in [9-11]. However, in most previous studies, they do not well address the problem of fair energy resource allocation under real-time energy demand and hence a small proportion of selfish agents can dominate the energy allocation.

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[1] As the energy profiles from [13][14] are hourly based, we set the control step of our EMS as one hour..

[2] Based on data obtained from field tests in [13][14], it is reasonable to assume that there rarely exists abrupt change of energy load profiles between two successive days.

In this paper, we have developed a minority game (MG)-based EMS (MG-EMS) in order to achieve the fair allocation of renewable solar energy for all customers. The details are discussed in the following parts.

3.2 Minority Game Overview

Minority Game (MG) [12] is one of the classical problems in multi agent systems. In its original form, the El Farol Bar problem, *n* players make their decisions on whether to attend a bar each night. Going to a bar is only enjoyable only if it is not too crowded, otherwise people would rather stay at home. Intuitively, players adjust their behaviour based on their expectations on what other players are going to do next, and these expectations are generated by information of what other players have already done in the past.

The problem is later more generally formalized by Zhang et.al. [25]. In this form, several players participate the minority game. At each game round, each player decides his own action based on historical and preference factors. After all decisions made, the action associated with least number of players is declared as minority side and those players get the chance to win certain payoffs. The game result is also broadcast back to all players such that they can update their information and make necessary adjustments in future expectations. As each player makes his own decision independently, the game is carried out in a decentralized manner.

Recently, the MG-based method has been successfully adopted to solve various resource allocation problems in multi-agent systems [22][23]. As history resource allocation result is recorded and participates as a key factor in future resource scheduling, no single selfish agent is allowed to monopolize the limited resources. In this paper, the problem described in 2.3 is mapped to a modified MG problem for the sake of fair solar energy resource allocation. We introduce the detail realization of the proposed MG-EMS as follows.

3.3 Modified Minority Game for EMS

The overall working flow of the proposed MG-EMS is described in Figure 4.

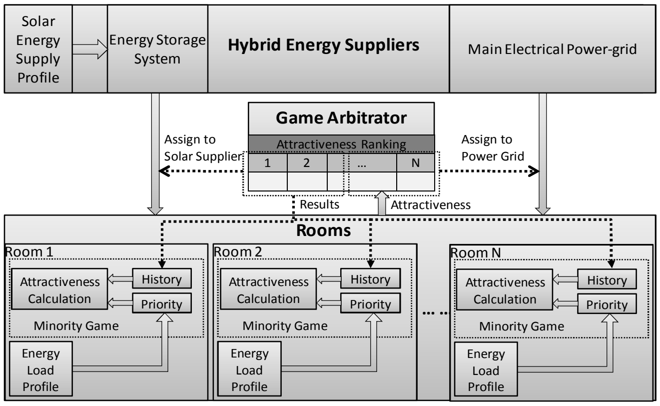

Figure 4: Working flow of the proposed MG-EMS

At every control time t, each room will play the modified minority game based on its real-time energy demand and past energy allocation results to calculate its attractiveness to use solar energy for the next Δt period of time. These attractiveness are then gathered to the game arbitrator which decides the winning side to be allocated with solar energy, and finishes one round of minority game. After that, the game result will be broadcast back to all rooms for updating their local history information. Another round of game will be played until there is not enough solar energy available for further allocation. In our system, we set $\Delta t = 1\, hour$ since the time-step of energy supply and load profiles obtained from [13][14] is hourly based. After all solar energy gets allocated, the system move to the next control step (i.e., next hour).

In order to elaborate our minority game strategies with more details, we first introduce two necessary definitions:

Definition 1: The *priority* is the factor to measure each room's preference to choose using the solar energy. Mathematically, it is defined as the percentage of energy that room r_k demands at time (d, h) over its previous day's total energy demand

$$p_k^{d,h} = \frac{E_k^{d,h}}{\sum_{h=0}^{23} E_k^{d-1,h}} \tag{9}$$

Intuitively, rooms tend to prefer using the solar energy at their higher energy demand periods such that the peak energy demand to main power-grid can be expected to be reduced. We set denominator in Equation (10) as previous day's total energy demand to achieve real-time control where only the current and historical status is known.

Definition 2: The *history* factor considers the past energy cost savings given in Equation (5) that each room has already received from solar energy utilization, defined as

$$h_k^{d,h} = C - \frac{b_k^{d,h}}{\sum_{k=1}^{Nr} b_k^{d,h}} \tag{10}$$

where *C* is a constant normalizer. The larger cost savings that room r_k has already received in past, the smaller the history factor will be and hence the smaller chance for that room to be allocated with solar energy in the future.

Based on both priority and history factors, each room independently calculates its *attractiveness* or *preferences* to select use solar energy in the next hour by

$$Attr_k^{d,h} = a_k * h_k^{d,h} + (1 - a_k) * p_k^{d,h} \tag{11}$$

where a_k is the *attitude* which adjusts the importance of the priority and history factor for each room. When the priority increases, the room has more chance to accept the solar energy. However, using solar energy will reduce the history parameter and hence leads to less opportunity for the room to obtain solar energy in the future. Such balanced strategy autonomously overcome the selfish nature of customers (i.e., rooms) and converges to a fair renewable solar energy allocation among rooms over a period of time.

Different from the original minority game, we define the *minority side* (or winning side) as the room with largest attractiveness value in Equation (11), and that room will be allocated with solar energy in that game round. In other words, only one room will finally win and obtain the solar energy in each game round

$$s_k^{d,h} = 1,\ for\ room\ r_k\ with\ largest\ Attr_k^{d,h} \tag{12}$$

Multiple rounds of minority game will be played until no solar energy is available to be allocated, which ends the allocation of the current control step.

3.4 Reducing Peak Energy Demand to Main Grid

To make the best utilization of solar energy and to reduce the peak energy demand for main power-grid, more solar energy shall be allocated during peak demand times of a day. To achieve this objective, we dynamically control the maximum amount of solar energy that can be allocated at each time (d, h) to be proportional to the percentage of the energy demand at (d, h) over the total energy demand in the previous day:

$$E_s = \beta * Es' * \frac{\sum_{k=1}^{Nr} E_k^{d,h}}{\sum_{h=0}^{23} \sum_{k=1}^{Nr} E_k^{d-1,h}} \tag{13}$$

where $Es' = \sum_{h=0}^{23} G^{d-1,h}$ is solar energy production amount from previous day and β is the adaptive parameter. Unallocated solar energy will be stored in ESS whose state-of-charge (i.e., amount of energy stored) is indicated as E_{soc}. As shown in Figure 2 and Figure 3(a), the peak time of energy demand and solar energy generation does not well match. Hence, the adaptive β is important to avoid keeping excessive amount of solar energy in ESS which will reduce solar energy utilization rate. At runtime, it dynamically adjusts its value based on the extent of mismatch

$$\beta = \beta + \frac{E_{soc} - E_s}{10 * E_{soc}} \tag{14}$$

Finally, the amount of solar energy available for allocation $C_s^{d,h}$ is calculated as the minimum of E_s and the physically stored amount of solar energy in ESS

$$C_s^{d,h} = \min\,(E_s, E_{soc}) \tag{15}$$

Through such solar energy scheduling scheme, the peak energy demand to main power-grid can be reduced without altering customer energy demand. To summarize, the pseudo-code and initial settings for attitude parameters in the proposed MG-EMS running one day is shown in Table 1. Initial parameters are set in line 1. Line 3-5 calculates the amount of solar energy to be allocated for one hour based on Equations (13)-(15). The while loop line 7-16 is the minority game played independently by each room based on Equations (9)-(12), Finally, E_{soc} is updated and move to the next control step.

Table 1: Minority game-based EMS running for one day

```
Input: Energy supply and load profiles
Output: Solar energy allocation scheme
1    $a_k = 0.75; s_{k,0} = 0; C = 0.5; \beta = 1.0;$
2    For t=0 to 23  // For one day
3      Calculate $E_s$ based on Equation (13)
4      Update $\beta$ on based Equation (14);
5      $C_s^{d,h} = \min(E_s, E_{soc})$  // Solar energy for allocation
6      round = 0;
7      While($\sum_{k=1}^{N_r} E_k^{d,h} \cdot s_k^{d,h} < C_s^{d,h}$) // Enough energy
8        For k=0 to $N_r$     // Playing MG for each room
9          $p_k^{d,h} = E_k^{d,h} / \sum_{h=0}^{23} E_k^{d-1,h}$;
10         $h_k^{d,h} = C - b_k^{d,h} / \sum_{k=1}^{N_r} b_k^{d,h}$;
11         $Attr_k^{d,h} = a_k * h_k^{d,h} + (1 - a_k) * p_k^{d,h}$;
12       End For
13       r = findRoomWithMaxAttr(); // Game arbitration
14       $s_r^{d,h} = 1$;  // Allocate solar energy
15       round = round + 1;
16     End While
17     $E_{soc} = E_{soc} + G^{d,h} - \sum_{k=1}^{N_r} E_k^{d,h} \cdot s_k^{d,h}$; //Update ESS
18   End For
```

IV. SIMULATION RESULTS

4.1 Experimental Settings

To verify the effectiveness of the proposed minority game-based EMS (MG-EMS), we perform a few simulations based on energy supply and load profiles obtained from real testbed data [13][14]. For comparison, we also implement the following two baselines.

Baseline 1: The centralized EMS based on static energy demand (SC-EMS). In this method, the solar energy generated at each hour is allocated to each room directly in proportion to its energy demand.

Baseline 2: The multi-agent EMS (MA-EMS) similar to [10]. In this approach, each room competes for the solar energy based on the price-motivation function $m_{k,t}(p_s) = -\alpha * p_s + E_k^{d,h}$, which represents the quantified motivation of each room to choose solar energy at solar energy price p_s. Intuitively, as rooms with larger energy demand can obtain more energy cost savings by using solar energy, they have larger value of $m_{k,t}(p_s)$. At each round, those rooms with larger motivation will win the competition.

To illustrate the capability of the proposed MG-EMS under various energy supply and load profiles, we set up the smart buildings with hybrid types of rooms (i.e., six residential rooms with ID 1 to 6 and six commercial rooms with ID 7 to 12), and with different size (i.e., area) of PVs from $21m^2$ to $25m^2$. In addition, the simulation is carried out for a whole month in both summer (i.e., August) and winter (i.e., December) seasons to avoid result bias on a certain day or season. As for initial parameters used in MG, we set $C = 0.5$, $a_k = 0.75$ and $\beta = 1.0$. Nevertheless, these parameters can be adjusted by the system manager to obtain the desired EMS behaviour according to the real world experience.

4.2 Fair Solar Energy Allocation

Figure 5 compares the received energy cost savings defined in Equation (5) of each room using different EMS schemes with PV area of $25m^2$ over summer and winter, respectively. The horizontal axis represents different rooms, where the first six are residential rooms and the last six are commercial rooms. The vertical axis is the received energy cost savings counted as US dollars. We can observe that our MG-EMS leads to a fairly equal distribution of energy cost savings from solar energy utilization under any seasonal variation with different energy load profiles. On the contrary, in SC-EMS, the money each room saved is directly proportional to their total energy demand. Even worse, although the decentralized control manner is achieved, only commercial rooms can get allocated with solar energy in MA-EMS because commercial rooms have larger energy demand than residential rooms almost all the time. As the agent negotiation is in a greedy or selfish fashion, commercial rooms always have larger motivation to employ solar energy.

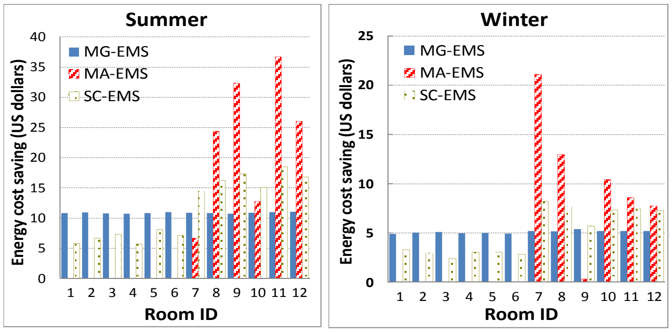

Figure 5: Comparison of energy cost savings obtained in different energy management system

To further demonstrate the capacity of MG-EMS under different energy supply profiles as well, we sweep the PV area from $21m^2$ to $25m^2$ in both summer and winter seasons, and the result is summarized in Table 2 and 3 where each column illustrates the standard-deviation of energy cost savings achieved among different rooms. Apparently, in MG-EMS, the energy cost savings almost keep constant as the PV area is increasing. Moreover, compared to SC-EMS and MA-EMS, our MG-EMS achieves on average 51x and 147x reductions in energy cost saving deviation in summer, and on average 16x and 48x reduction in energy cost saving deviation in winter. The smaller reduction ratio in Table 3 is due to the relatively less amount of solar energy generated in winter season.

Table 2: Energy cost saving deviation under different energy management system with varying PV area in summer (i.e., August)

Solar PV Area (m^2)	21	22	23	24	25
SC-EMS (US dollar)	4.36	4.55	4.77	4.97	5.17
MA-EMS (US dollar)	12.84	13.25	13.58	13.94	14.34
MG-EMS (US dollar)	0.07	0.08	0.09	0.13	0.11
SC-EMS/MG-EMS	60.1x	55.6x	53.5x	39.2x	47.9x
MA-EMS/MG-EMS	177.2x	161.9x	152.5x	109.9x	132.7x

Table 3: Energy cost saving deviation under different energy management system with varying PV area in winter (i.e., December)

Solar PV Area (m^2)	21	22	23	24	25
SC-EMS (US dollar)	1.98	2.07	2.16	2.25	2.34
MA-EMS (US dollar)	6.13	6.41	6.66	6.76	7.03
MG-EMS (US dollar)	0.11	0.14	0.15	0.14	0.14
SC-EMS/MG-EMS	17.3x	14.8x	14.6x	16.2x	16.3x
MA-EMS/MG-EMS	53.8x	46.0x	45.0x	48.6x	48.8x

4.3 Reducing the Peak Energy Demand for Main Power-Grid

Figure 6 further illustrates the average daily energy demand for main electrical power-grid under different EMS in both summer and winter times. The blue dash curve is the original energy demand without using solar energy, or called non-EMS. The peak period covers from 9am to 21pm of the day. Compared to the non-EMS case, the proposed MG-EMS reduces the peak demand for main power-grid from 20.05*KWh* to 13.91*KWh* in summer and from 22.67*KWh* to 20.07*KWh* in winter. In other words, a 30.62% and 11.47% reduction is achieved respectively. Compared to SC-EMS, the reduction ratio is 16.86% in summer and 10.60% in winter. Furthermore, MG-EMS achieves a lower peak-to-valley ratio (i.e., more flat) than SC-EMS, which further enhance the stability to access the main electrical power-grid when using the renewable solar energy under the MG-EMS control.

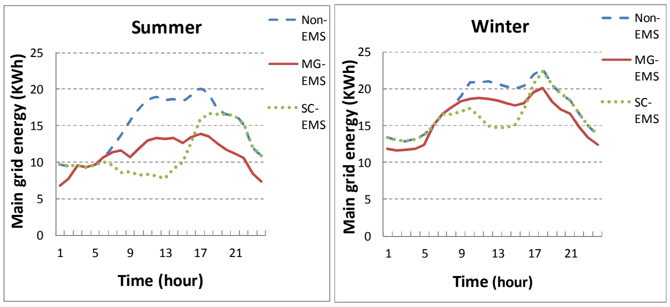

Figure 6: Energy demand reduction for main power-grid in summer and winter

V. CONCLUSION

The energy management system (EMS) of modern smart buildings needs to consider time-varying energy profiles from multiple suppliers and customers. It becomes a need to design a real-time and decentralized EMS based on multi-agent (MA), instead of the traditional centralized EMS with static energy allocation scheme. This paper introduces a minority game (MG)-based EMS (MG-EMS) for this sake, which avoids the negative impact of selfish agent in MA and hence can achieve a globally fair energy resource allocation. In addition, our developed MG-EMS can also reduce the peak energy demand for main power-grid without altering customer energy demand. Compared to the static and centralized EMS (SC-EMS) and one multi-agent-based EMS (MA-EMS), 51x and 147x improvements respectively in term of fair solar energy allocation are observed for our MG-EMS for rooms with various realistic energy supply and load profiles obtained from field testbed. In addition, our MG-EMS also reduces the peak energy demand for main power-grid by over 30.6%.

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