Energy Management by Controlling Air Conditioning Systems in Residential Settings

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***Abstract*—This paper demonstrates some results from an on-going experiment on energy management in a residential testbed in Singapore by controlling the air-conditioning (AC) system. The testbed is set up at the faculty housing of Singapore University of Technology and Design (SUTD) in which the ACs installed within each unit can be controlled from a remote server. The control can be conducted both in terms of switching on/off and changing the temperature set-point of the ACs. The main objectives are to reduce the consumption of energy at a residential setting by controlling the ACs' temperature set-points and investigating the feasibility of having residential ACs as interruptible loads for demand response and thus enabling residential users to participate in the energy market. The control methodology is briefly discussed and the users' inputs on the experience of such experiments are also explained. Some preliminary results from the experiments are discussed and some insights are provided into how much load can be controlled through the set-point temperature of ACs such that the users do not feel any discomfort.**

I. Introduction

Air-conditioning (AC) systems are one of the major consumers of energy and have significant influence on the overall energy usage of homes and buildings. For instance, it is shown in [1] that buildings account for 70% of electricity consumption in the United States and 40% of the building energy is due to ACs. Thus, controlling the energy consumption of ACs can lead to a significant energy savings for an entire electricity system. As a result, understanding the huge impact of ACs on the overall energy consumption of buildings, studying their energy consumption behavior and developing means for effective control without compromising users' comfort have become a central focal point of energy management research [2].

In this context, there has been a significant push towards developing models for controlling electricity consumption of ACs for both commercial and domestic sectors for the past few years. For instance, in [3], the authors propose an automatic thermostat control system based on the mobility prediction of users in an indoor environment by using contextual information (historical pattern and route classification) through mobile phones. A combination of stochastic dynamic programming and rollout techniques is developed in [4] for controlling ACs and lighting systems of buildings in order to minimize the total daily electricity cost. The authors in [5] demonstrate a novel methodology for determining the proper chilled piping pressure set point through which ACs used in high-tech industries can reduce electricity consumption. In [6], a mixed integer multi-scale stochastic optimization problem is formulated and a model predictive control based heuristic is proposed for scheduling loads with different characteristics including ACs for a home management system. A statistical process control technique and a Kalman filtering method are integrated in [7] for system level fault detection in AC. A neural network based fault detection method is proposed in [8] that improves the energy efficiency and thermal comfort by removing various faults in the system. Various other energy management techniques, including AC management techniques that consider the user's comfort and benefits, can be found in [2], [9]–[18] and [19].

Most of the existing studies on AC energy management are, however, based on theoretically developed phenomena and lack experimental detail. This is mainly due to the fact that the most ACs available on the market do not have application program interfaces (APIs) available for public use, and as a consequence, controlling ACs from a remote server is not easy to implement. Furthermore, due to privacy concerns, it is difficult to recruit participants who may volunteer to let a third party to control their ACs at home. Therefore, there is neither any guarantee that the existing AC management schemes can be implemented in a real building nor any real indication on whether or not the users will experience any discomfort owing to such control.

In this context, we propose and verify an energy management algorithm in this paper that considers both the energy consumption of ACs in individual homes as well as the thermal comfort levels that are experienced by the occupants. The

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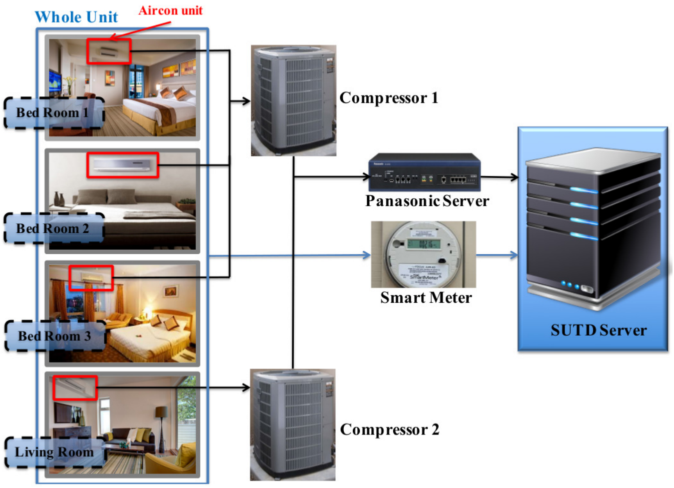


Fig. 1: Demonstration of one of the testbeds in a three bedroom faculty housing unit at SUTD. The ACs in the three bedrooms are connected to one compressor whereas the living room's AC is connected to another. The data from each compressor is stored in the Panasonic server which is then buffered to the local server at SUTD. Whereas the energy consumption of each AC can be directly obtained from the AC itself, the overall energy consumption data of a unit is obtained through a smart meter connected to the unit.

main objectives are to reduce the consumption and related cost of electricity without compromising any thermal comfort experienced by the users and to determine the feasibility of such ACs to participate as interruptible loads in the electricity market. To this end, first we set up testbeds at 20 units of the faculty housing apartment building of the Singapore University of Technology and Design (SUTD), in which we can control the temperature set-point of each AC unit as well as the switching of the devices. Then, we designed a control algorithm that enabled us to remotely control the energy consumption of the compressors of the ACs of some of the units.

The control was conducted in such a way that residents could not feel any changes in the indoor climate condition of their homes. In this regard, a heuristic algorithm was designed that could control the ACs of the testbed without significantly affecting the temperature experienced in the rooms. To verify the potential of the designed algorithm, we recruited selected residents from the 20 apartments to take part in the energy management scheme. Essentially, we controlled the temperature set-point of the participants' ACs during the entire duration of the experimental period such that the participants could not feel the differences in the indoor temperature within their homes. Finally, we conducted short surveys periodically to learn users' experiences on their comfort levels during the experiment period to obtain insights into the amount of load that can potentially be curtailed by altering the ACs' temperature set-point.

II. Brief Discussion of Testbed and Algorithm

The testbed is set up at 20 housing units of the SUTD's faculty service apartment building. Each of the housing units is either a three bedroom or a two bedroom apartment. In each unit, the ACs in the bedrooms are connected to one compressor whereas the AC in the living room is connected to a different compressor.

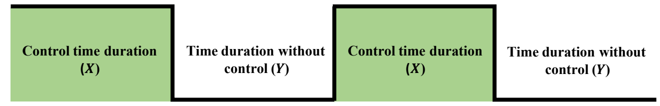


Fig. 2: This figure shows the control period of ACs in the faculty housing.

Note 1. *The ACs are designed and specially customized by Panasonic*[1] *for setting up the testbed and running experiments. The customized design allows the thermostat inside each AC to be controlled (both on/off and temperature set-point control) remotely from a centralized server at SUTD. The energy measuring unit inside each compressor is able to measure the energy consumption of the respective compressor and then send the data to the SUTD server (via buffering through the Panasonic server). We received data on the room temperature, AC set-point and power consumption in every* 30 *second period. Further, we can control and override the temperature set-point of ACs from the Panasonic server.*

Each apartment unit is also equipped with a smart meter that measures the overall energy consumption of the unit at a sampling rate of about 100 per second. The data is stored and can continuously be monitored from the server at SUTD. An overview of the testbed that has been set up in a three bedroom apartment is shown in Fig. 1.

A. Algorithm

We design an adaptive control algorithm without the need of detailed modelling of the AC power consumption. This is due to the fact that we could not find a suitable power consumption model relevant to ACs[2]. Further, building a power consumption model is time consuming as we need to collect more data before building a realistic model[3]. The algorithm is centralized and executed from the SUTD server to control the ACs' temperature set-points in the apartment units. The objectives are three-fold: 1) to reduce the consumption of electricity by the ACs within the apartment units; 2) to investigate the feasibility of having such ACs participating in the demand response as interruptible loads; and 3) to control the ACs in such as way that the residents of the units cannot feel any change in their thermal comfort level.

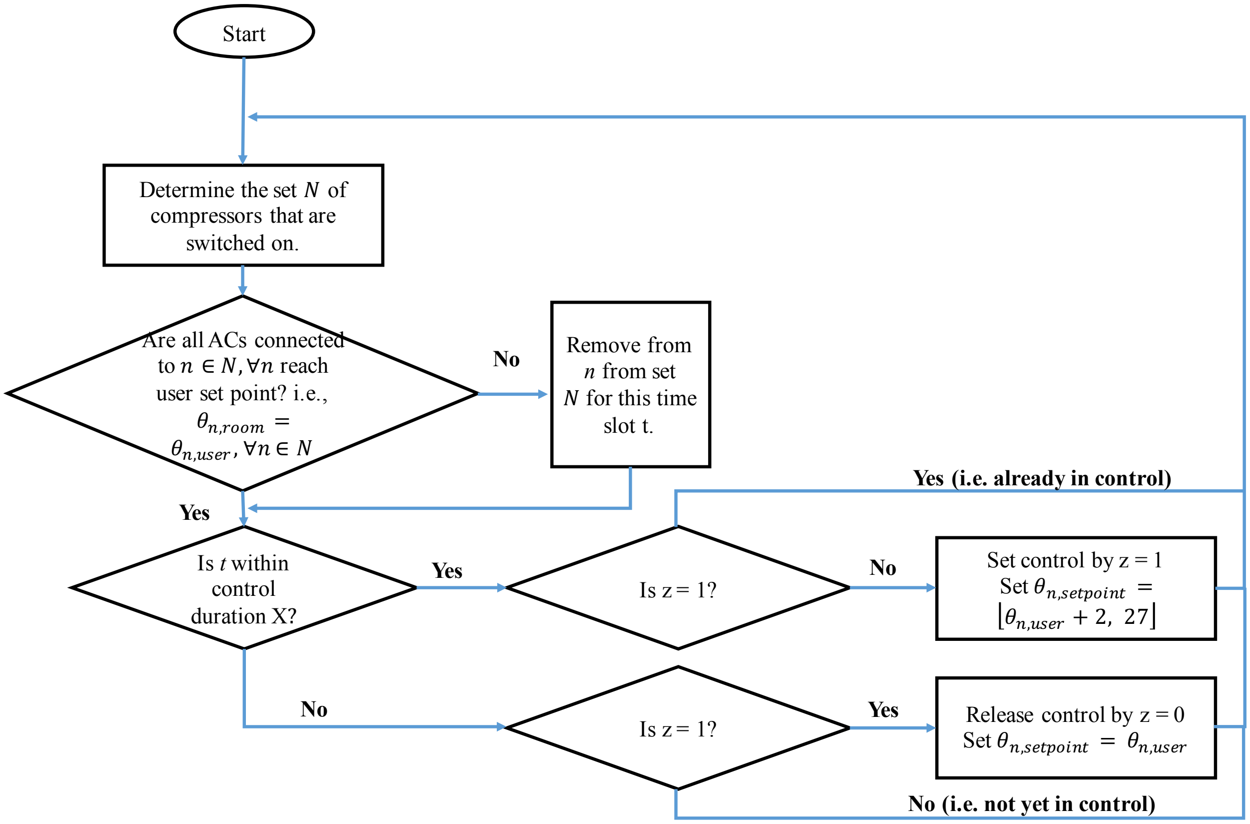
To do so, we first determined the compressors that are switched on and then all the connected ACs that were in their stable states. We say that a compressor is in its stable state when the room temperature $\theta_{n,\text{room}}$ of each of the ACs connected to the compressor reaches its user defined set-point temperature $\theta_{n,\text{user}}$. Please note that we only controlled the ACs of the compressors that reached the stable state. This is due to the fact that, as we have noticed in our experiments, the change of temperature set-point, i.e., increasing the set-point, could be detrimental in terms of increasing energy consumption and cost if the compressor has yet to reach the stable state.

[1]http://www.panasonic.com/sg/

[2]Although studies like [20] have discussed some models, we have not found them useful for applications in a real-testbed scenario.

[3]This is part of our planned future work.

Algorithm 1: Algorithm to control the temperature set-points of ACs at SUTD faculty housing. The parameter z is used to indicate whether or not the ACs belonging to a compressor are under control or not.



By setting a higher AC set-point than the user set-point, we observe that it takes more than 20 minutes for the room temperature to increase, and for the residents to feel any change in the room temperature[4]. We exploited this observation to control the set-point so as to keep the residents unaware of the change of temperature in their homes. In this respect, we divided the total control period into multiple time slots as shown in Fig. 2, where we kept controlling the ACs within time slot X and released the control for the rest of the period, which is shown as Y in the figure. We tried various values of X and Y from 20 to 30 minutes. Note that we claim no optimal setting of X and Y values, and they can be different for different cases based on weather, room type, sensitivity of users and time of experiments. The control was done by setting the AC set-point temperature $\theta_{n,\text{user}}$ to $\theta_{n,\text{setpoint}} = \lfloor \theta_{n,\text{user}} + 2,\ 27 \rfloor$, where $\lfloor \cdot \rfloor$ represents the lower integer floor. The cap of 27 degrees Celsius was chosen due to the Institutional Review Board (IRB) limitation on the maximum temperature set-point in order for not disrupting the user's comfort level. After each control period of X, we released the control and set the AC set-point temperature $\theta_{n,\text{setpoint}}$ back to $\theta_{n,\text{user}}$. The detail of the algorithm is shown in Algorithm 1.

We recorded the consumption of electricity by the compressor in time slots X and Y, and demonstrated a significant savings in energy, which we will explain in the next section.

[4] We gained this insight by observing the room temperature and by collecting feedback from the participants in every one month period.

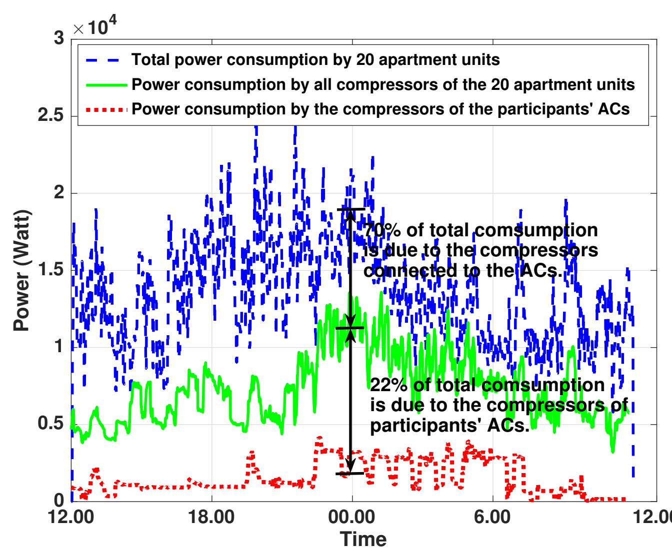


Fig. 3: Demonstration of the electricity consumption by the AC systems at SUTD faculty housing on November 6, 2015. The figure clearly shows the significant impact of the ACs on the overall consumption. The figure shows the opportunity of energy savings by intelligently controlling the temperature set-point of the ACs.

III. Experimental Results

We ran the experiment at the SUTD faculty housing testbed, which has 20 units with 68 Panasonic ACs that are

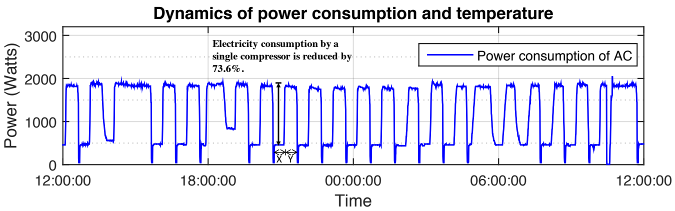


Fig. 4: This figure shows the potential savings from a single compressor by controlling the temperature set-point of the AC connected to it. The experiment was performed at the SUTD testbed for a whole day on 21st of December 2015.

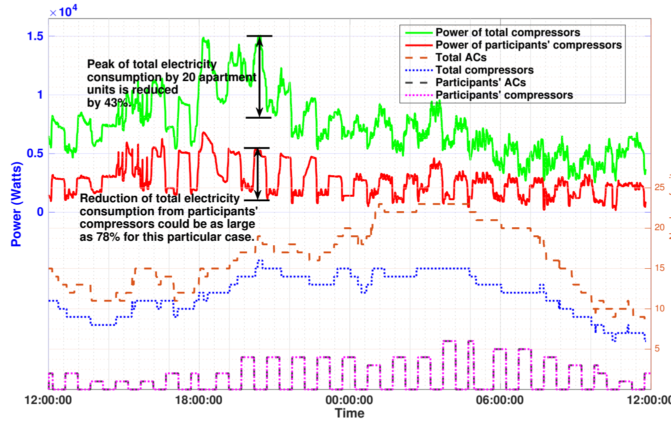


Fig. 5: This figure shows the potential total reduction of energy from controlling the ACs in the SUTD faculty housing on 21st of December 2015.

connected to 36 compressors. In our testbed, one compressor is connected to either two or three ACs based on the type of unit (i.e., two or three bedroom apartment) and to one AC if it is a living room. Considering the number of participants who voluntarily agreed to give us the control of their ACs, we could only control 8 compressors that are connected to 14 ACs of the testbed. However, even the control of only 8 compressors, we can demonstrate significant potential in electricity saving and having ACs as flexible loads for demand response due to the reason explained in Fig. 3.

In Fig. 3, we show the total electricity consumption by the 20 faculty housing units in comparison with the electricity consumption of their ACs. It is clearly portrayed that, e.g., from 11 pm to 2 am on November $6,\ 2015$, as highlighted in the figure, about 70% of the total consumption is due to the ACs. Furthermore, the energy consumption of the participating ACs is on average[5] 22% of the total AC consumption (this matches the statistic that $8/36 = 22.22\%$ are our participants). Note that the drop in the power consumption is due to the increase in set-points of the participating ACs. Therefore, we can control the temperature set-points of the participant ACs appropriately in order to reduce the energy consumption of the compressors of the ACs.

In this context, we show the energy saving for a single compressor in Fig. 4. The AC connected to this compressor was switched on for the whole day of December $21,\ 2015$. It is shown that the power consumption by the compressor is 1900 Watt (W) during the off-control period, whereas once the control is turned on, i.e., $\theta_{n,\text{user}}$ is changed to $\lfloor \theta_{n,\text{user}} + 2,\ 27 \rfloor$, the consumption of power is reduced by around 73%. By doing such control for the entire day (we kept both the values of X and Y to 30 minutes for this experiment), we essentially managed to save 35%, on average, of the total power consumption by the compressor of the particular AC.

Further, we control the temperature set-points of the ACs in our testbed with a view to participate as interruptible load and show the outcome in Fig. 5 based on the readings of December $21,\ 2015$. In the figure, we zoom in to the electricity consumed by all the ACs within the apartment building and the consumption by the participant ACs during both on-control (i.e., X) and off-control periods (i.e., Y). The total number of compressors within the apartment building is always greater than the participant compressors as not all residents agreed to participate in the experiment. However, even controlling a small number of compressors, we show that the potential flexible energy that can participate as interruptible load is noticeable. For example, around 9 pm to 10 pm, the peak consumption of electricity by all compressors across 20 units can be reduced by 43% by increasing the temperature set-point of the participating ACs, which is a direct result of the 78% reduction in electricity consumption by the four compressors connected to the participating ACs that are switched on during that period of time in this particular experiment. However, the power consumption again increases as soon as we release the control of the ACs. Note that, as we mentioned before, such release of control is necessary for the residents to not feel any discomfort due to such temperature variations. According to Fig. 5, 1) the total consumption of power by the compressors reduces significantly during the control period due to raising the temperature set-points of the respective ACs by two degrees Celsius; and 2) as the number of the participating compressors increases, the flexible load to participate as interruptible load in the energy market increases consequently. Thus, through such control it is possible for the controllers to provide the grid with loads that the grid can interrupt during peak hours so as to reduce its cost of spinning reserve. Further, by incorporating prediction of interruptible load, e.g., 30 minutes or 1 hour ahead prediction, the controller can offer these loads in the auxiliary energy market. Of course, the grid needs to provide the participants with incentives.

It is important to note that the willingness to participate in such control mechanism by the residents is challenging, which is mainly due to the fear of having thermal discomfort and the possibility of violating privacy of the residents. We address these issues by conducting experiments through an IRB approved experimental policy that preserved the participants' privacy and also by continuously taking participants' inputs on their thermal comfort levels during the experiments, and revising the process of control accordingly. Based on the participants' responses to our questionnaire, we note that the participants could hardly feel that their ACs were controlled during the experiment, which increases the possibility of potential application of such third party control of flexible devices in the grid more generally.

[5] Assuming all compressors are switched on.

IV. Conclusion

This paper has presented some preliminary results on the control of ACs of residential users and discussed the algorithm behind the control. A testbed has been set up at SUTD faculty housing consisting of 20 apartment units and it has been shown that the electricity consumption of the compressors of the testbed can be reduced significantly without affecting the thermal comfort level of the residents. Further, we have shown that even with less than 25% participation rate, we could also reduce peak electricity consumption by the total 20 apartment units considerably, which can potentially participate as interruptible loads in the energy market. Based on the feedback from the participants, it has been realized that such control of flexible of devices has significant potential to deploy in real grid systems if the comfort level of the residents can be kept uninterrupted and their privacy can be maintained.

We are currently working on a number of extensions of this work. For instance, we are currently working on extending the proposed work for a large number of residential units of our testbed and focusing on predicting the load usage pattern of the users so that we can estimate an accurate reduction of load beforehand. Such a finding may assist the grid in determining the optimal and cost-effective spinning reserve it may require to supply its consumers during peak hours. We are also building a realistic energy consumption model for ACs in a residential settings based on the data from our testbed. Furthermore, we are investigating the effect of communication delay on the demand response and energy savings of this proposed method. The results from these experiments will be reported in future publications.

References

[1] Z. Wu, Q.-S. Jia, and X. Guan, "Optimal control of multiroom HVAC system: An event-based approach," *IEEE Transactions on Control Systems Technology*, vol. 24, no. 2, pp. 662–669, Mar. 2016.

[2] N. U. Hassan, Y. I. Khalid, C. Yuen, and W. Tushar, "Customer engagement plans for peak load reduction in residential smart grids," *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 3029–3041, Nov. 2015.

[3] S. Lee, Y. Chon, Y. Kim, R. Ha, and H. Cha, "Occupancy prediction algorithms for thermostat control systems using mobile devices," *IEEE Transactions on Smart Grid*, vol. 4, no. 3, pp. 1332–1340, Sep 2013.

[4] B. Sun, P. B. Luh, Q.-S. Jia, Z. Jiang, F. Wang, and C. Song, "Building energy management: Integrated control of active and passive heating, cooling, lighting, shading, and ventilation systems," *IEEE Transactions on Automation Science and Engineering*, vol. 10, no. 3, pp. 588–602, July 2013.

[5] C.-L. Su and K.-T. Yu, "Evaluation of differential pressure setpoint of chilled water pumps in clean room HVAC systems for energy savings in high-tech industries," *IEEE Transactions on Industry Applications*, vol. 49, no. 3, pp. 1015–1022, June 2013.

[6] Z. Yu, L. Jia, M. C. Murphy-Hoye, A. Pratt, and L. Tong, "Modeling and stochastic control for home energy management," *IEEE Transactions on Smart Grid*, vol. 4, no. 4, pp. 2244–2255, Dec 2013.

[7] B. Sun, P. B. Luh, Q.-S. Jia, Z. ÓNeill, and F. Song, "Building energy doctors: An spc and kalman filter-based method for system-level fault detection in HVAC systems," *IEEE Transactions on Automation Science and Engineering*, vol. 11, no. 1, pp. 215–229, Jan 2014.

[8] Z. Du, B. Fan, X. Jin, and J. Chi, "Fault detection and diagnosis for buildings and HVAC systems using combined neural networks and subtractive clustering analysis," *Elsevier Building and Environment*, vol. 73, pp. 1–11, Mar 2014.

[9] Y. Ma, J. Matuko, and F. Borrelli, "Stochastic model predictive control for building HVAC systems: Complexity and conservatism," *IEEE Transactions on Control Systems Technology*, vol. 23, no. 1, pp. 101–116, Jan 2015.

[10] W. Tushar, J. A. Zhang, D. B. Smith, H. V. Poor, and S. Thiébaux, "Prioritizing consumers in smart grid: A game theoretic approach," *IEEE Transactions on Smart Grid*, vol. 5, no. 3, pp. 1429–1438, May 2014.

[11] W. Tushar, C. Yuen, S. Huang, D. Smith, and H. V. Poor, "Cost minimization of charging stations with photovoltaics: An approach with EV classification," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 1, pp. 156–169, Jan. 2016.

[12] W. Tushar, C. Yuen, K. Li, K. L. Wood, Z. Wei, and L. Xiang, "Design of cloud-connected IoT system for smart buildings on energy management (Invited paper)," *EAI Endorsed Transactions on Industrial Networks and Intelligent Systems*, vol. 16, no. 6, pp. 1–9, Jan. 2016.

[13] W.-T. Li, C. Yuen, N. U. Hassan, W. Tushar, and C.-K. Wen, "Demand response management for residential smart grid: From theory to practice," *IEEE Access (Special issue on Smart Grids: A Hub of Interdisciplinary Research)*, vol. 3, pp. 2431–2440, Nov. 2015.

[14] A. Naeem, A. Shabbir, N. U. Hassan, C. Yuen, A. Ahmed, and W. Tushar, "Understanding customer behavior in multi-tier demand response management program," *IEEE Access (Special issue on Smart Grids: A Hub of Interdisciplinary Research)*, vol. 3, pp. 2613–2625, Nov. 2015.

[15] Y. Liu, C. Yuen, S. Huang, N. U. Hassan, X. Wang, and S. Xie, "Peak-to-average ratio constrained demand-side management with consumer's preference in residential smart grid," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 6, pp. 1084–1097, Jun 2014.

[16] W. Tushar, B. Chai, C. Yuen, D. B. Smith, K. L. Wood, Z. Yang, and H. V. Poor, "Three-party energy management with distributed energy resources in smart grid," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2487–2498, Apr. 2015.

[17] X. Wang, C. Yuen, X. Chen, N. U. Hassan, and Y. Ouyang, "Cost-aware demand scheduling for delay tolerant applications," *Journal of Network and Computer Applications*, vol. 53, pp. 173–182, July 2015.

[18] Y. Liu, C. Yuen, R. Yu, Y. Zhang, and S. Xie, "Queuing-based energy consumption management for heterogeneous residential demands in smart grid," *IEEE Transactions on Smart Grid*, pp. 1–10, 2015, pre-print (doi:10.1109/TSG.2015.2432571).

[19] Y. Liu, C. Yuen, N. U. Hassan, S. Huang, R. Yu, and S. Xie, "Electricity cost minimization for a microgrid with distributed energy resources under different information availability," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 4, pp. 2571–2583, Apr. 2015.

[20] Y. Li, M. Liu, and J. Lau, "Development of a variable speed compressor power model for single-stage packaged DX rooftop units," *Applied Thermal Engineering*, vol. 78, pp. 110–117, Mar. 2015.