

Smart Home Electricity Management in the Context of Local Power Resources and Smart Grid

Weiliang Zhao, Lan Ding, Paul Cooper, and Pascal Perez

Abstract—This work proposes a smart home electricity management approach that can predict and schedule electricity demand and supply by considering: the ‘state’ of the smart grid, local power generation capacity, and electrical consumption of household appliances. The prediction of weather conditions and the immediate and longer-term plans of the residential home occupants are crucial parameters in the smart home decision-making system that acts on behalf of the occupants. This paper provides a motivation example and associated scenarios, electrical energy supply/demand models, formalization of the cost optimization problem, and scheduling schemes for a smart home electricity management system in the context of a smart grid, smart appliances, and local renewable energy resources. A case study is provided to illustrate how the proposed approach works.

Index Terms—Smart grid, renewable energy, smart home, demand side energy management.

I. INTRODUCTION

Global renewable energy generation capacity has been rising at a rapid rate in recent years. Renewables are on track to contribute significantly to electric power systems, for example, renewables accounted for almost half of the estimated 208 GW of new electric capacity installed globally in 2011 [1]. In particular, non-hydro renewables have registered a 24% capacity increase over 2010 and have exceeded 390 GW in total. Globally, wind and solar PV accounted for almost 40% and 30% of new renewable capacity, respectively.

There is an emerging trend for residential homes on smart grids to have local electric power generation as a portion of electricity supply. Home power local generation usually comes from photovoltaic systems, micro combined heat and power (microCHP) systems, wind turbines, etc. With the incorporation of distributed renewable energy generators, the present power system will be transformed into a large-scale distributed generation system [2], [3]. In the classical centralized power network, electric power flows from power plants to the customer premises in a one-way supply mode. Distributed renewable energy resources bring new situations of local electricity production and two-way electricity flows which dramatically increases the control requirements on the grid. However, advances in information and communication technologies provide the opportunity for efficient data

collection and exchange. Emerging smart grid technologies can potentially change the power network into a digitally enabled electrical grid that collects, analyzes, and acts on information according to the dynamic status of both suppliers and consumers of energy. A smart grid can improve the efficiency and reliability of electricity services and smart grids support varying electricity tariffs according to the dynamic status of power demand and generation and have become a promising means of managing renewable energy generation and use in the context of soaring energy prices [4].

Emerging smart appliance techniques enable residential or commercial electrical appliances to potentially take the advantage of a “smart grid”. The smart appliances have the capability to adjust their operation according to the dynamic electricity tariff of a smart grid. The cost of electricity consumption can be reduced through peak load management. Smart appliances also bring the benefit of reliability improvement of utility grids by their load management feature at the granularity level of individual appliances.

In recent years, there have been extensive efforts and research initiatives which target smart homes for residential buildings with “ambient intelligence” in terms of energy management for efficiency, services for comfort and convenience, provision of home-based healthcare etc. [5], [6]. In particular, smart home systems focusing on energy efficiency have been discussed in multiple articles [7], [8]. Most of this literature focuses on cost reduction by load management through dynamic electricity tariffs in smart grids. As an extension of this previous work, the present paper proposes a new approach for smart home energy management as a comprehensive solution, which takes account of the local renewable energy generation, smart grids, smart electronic appliances, and environmental factors. The approach aims to minimize the overall daily electricity cost of household appliances. The minimization needs to take into account both weather and electricity tariff forecasts, predictable home activities, and the flexibility of electricity use. It is clear that it is unlikely that a traditional optimization algorithm will be of benefit in solving this problem. Scenarios, energy models for smart grids, local power generation, individual household appliances, formalization of the research problem, scheduling schemes for electricity consumption in residential homes are presented in this paper.

The content of the remainder of the present paper is organized as follows. Section II provides a motivation example of a smart home electricity management system. Section III describes the energy models and profiles that a smart energy management system for a residential home could be built on. Section IV proposes a power price model and formalizes the scheduling of electricity consumption and local generation at residential homes as an optimization

Manuscript received March 15, 2013; revised May 27, 2013.

Weiliang Zhao, Lan Ding, and Paul Cooper are with the Sustainable Building Research Centre, Faculty of Engineering, University of Wollongong, NSW, 2522, Australia (e-mail: {wzhao, ld, pcooper}@uow.edu.au).

Pascal Perez is with the SMART Infrastructure Facility, University of Wollongong, NSW, 2522, Australia (e-mail: pascal@uow.edu.au).

problem. Section V proposes the scheduling scheme for electricity consumption and generation at residential homes. Section VI presents the analysis of the motivation example and scenarios using the proposed scheduling scheme. Section VII discusses related work and Section VIII provides some concluding remarks.

II. A MOTIVATION EXAMPLE OF SMART HOME ELECTRICITY MANAGEMENT

This section describes the scope of smart energy management in residential homes by highlighting the situations of local renewable power resources and household electrical appliances in the context of a smart grid. The following assumptions are made in relation to the smart home electricity management system.

- 1) The residential home is connected to a smart grid that provides electric power with a dynamic tariff.
- 2) The residential home has renewable energy resources with the capability to generate electric power locally.
- 3) The residential home has a set of electrical appliances that consume the electrical energy supplied by local renewable power resources and from the smart grid.
- 4) Some electrical appliances may be able to perform their functions in a flexible time frame.
- 5) The local weather forecast is accessible and can be used for prediction purposes to assess future:
 - Local renewable energy generation; and
 - Energy consumption by some electrical appliances.
- 6) The occupants of the home provide control requests to electrical appliances in the form of schedules and/or real-time manual requests.

Based on the above assumptions, a typical residential home in Australia is now described as a motivation example for smart home electricity management. The electric power supply, local renewable resources, electrical appliances in a typical residential home in Australia could be as follows:

- 1) A smart grid supplies the residential home with electric power at a varying tariff.
- 2) A solar photovoltaic system with 3kW peak output has been installed at the residential home.
- 3) A swimming pool pump is used for pool maintenance with 1.1 kW power. The swimming pool pump will run 4 hours each day. The starting time is flexible.
- 4) An automatic washing machine consumes 500W and a clothes dryer runs at 3kW. The washing time is half an hour. The dryer running time is 1 hour. The clothes washing and drying should be consecutive activities and can have a flexible starting time.
- 5) There is a central air conditioning system with a maximum power draw of 3kW. The air conditioning system runs according to climatic conditions and occupant requirements.
- 6) There is an electronic oven with a demand of 800W.
- 7) There is a lighting system, TVs, computers, etc. The electrical appliances run according to the occupants' home activities
- 8) There is an electrical refrigerator/freezer using 400W. Usually this electrical energy consumption is not affected by the target management approach.

The electricity energy management solution for residential

homes must be context-aware. The content of the context in a smart residential home will be composed of weather forecast and home occupants' scheduled activities. We have the following typical scenarios for weather forecasts and occupants' activity plans. The weather forecast is based on the weather data of Parramatta, New South Wales, Australia.

Weather and home activities Scenario A:

- 1) Weather forecast for tomorrow gives: Maximum Temperature 39°C, Minimum Temperature 19°C, Sunny, Related Humidity 40%, Sunrise: 06:45, Sunset: 19:31.
- 2) Tomorrow is a week day. The occupants of the residential home will go to work or school at daytime. The activities at the residential home follow the typical routine of a working day.

Weather and home activities Scenario B:

- 1) Weather forecast for tomorrow gives: Maximum Temperature 28°C, Minimum Temperature 18°C, Partly Sunny, Related Humidity 60%, Sunrise: 06:45, Sunset: 19:31.
- 2) Tomorrow is a weekday. The occupants of the residential home will go to work or school during the day. The activities at the residential home follow a typical routine of a working day.

Weather and home activities Scenario C:

- 1) Weather forecast is the same as that in scenario A.
- 2) Tomorrow is a weekend day. The occupants of the residential home will stay at home.

Weather and home activities Scenario D:

- 1) Weather forecast is the same as that in scenario A.
- 2) The occupants of the residential home will have holidays and they are not at home for the whole day.

Scenarios A, C, D have the same weather forecast data but have different occupant activities. These scenarios illustrate the context of electrical energy management at residential homes with smart grid power supply, local renewable resources, and electrical appliances described previously.

III. ENERGY MODELS AND PROFILES

High level description of energy consumption information has been discussed in [9]. The proposed approach is still lacking the capability to express the electricity consumption details in the context of weather conditions and occupant activities. This section describes our energy models for the smart grid, local power resources, and individual household appliances, which will provide a foundation for electrical energy information to be collected, organized, searched, and utilized in target smart management approach. The categories of smart home electric power are shown in Fig. 1.

The smart home electrical energy management system deals with categories as the smart grid, local power resources, and household appliances.

The smart grid energy model includes the electricity tariff and grid voltage at condition tuple (time point, day_type, month, temperature, wind, sunshine). The sample rate could be at intervals of 15 minutes. The day_type has values of "week_days", "week_ends", or "public_holidays". The month is value of month in the year calendar. Temperature has is a whole number. Wind has the value as its grade. The sunshine has the value as "sunny", "mostly_sunny", "cloudy", or "raining".

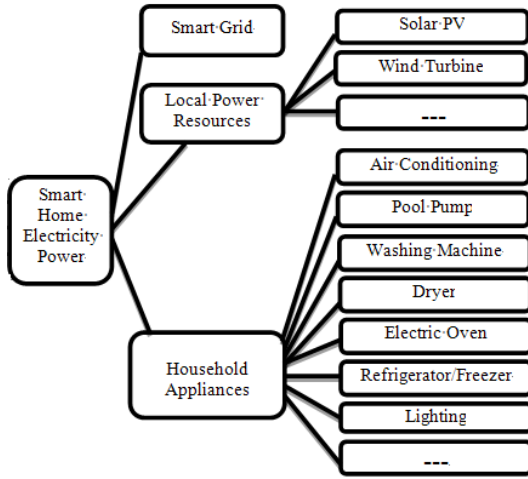


Fig. 1. Smart home electric power categories

The local power resources may include solar PV, wind turbine, etc. Here we assume that only a solar PV system is installed. The solar PV energy model is power capability at condition tuple (time point, month, temperature, sunshine). The time point could be in the interval of 15 minutes. The month is value of month in the year calendar. The temperature has the value as a whole number. The wind has the value as its grade. The sunshine has the value as “sunny”, “mostly_sunny”, “cloudy”, or “raining”.

The electrical consumption of each appliance at per state of operation with a specific condition is modeled by its energy model. The energy model of air conditioning system is the power load at condition tuple (mode, temperature_setpoint, weather_temperature, weather_humidity). Typical mode values could be “automatic”, “dry”, “cooling”, “heating”, “fan”. The precision of a continuous variable will be determined based on calculation concerns of energy efficiency management at smart homes. The temperature_setpoint and weather_temperature could be the temperature value at whole number. The weather_humidity could be rounded to 5 intervals. The electrical consumption of pool pump, washing machine, dryer, electronic oven are modeled as the power loads at their different modes. The electrical consumption of lighting is modeled as the power load at different time point and different occupants’ activity modes. The time point could be in the interval of 15 minutes. The occupants’ activity modes include “week_days”, “week_ends”, and “holidays”.

Each electrical facility has its energy profile with energy data which are in compliance with its energy model. These energy models of individual electrical entities are implemented using specific data structures in databases or profile documents. These energy profiles are the foundation of the energy analysis and decision support systems in smart electrical energy management systems in residential homes. Some of such data can be obtained from facility providers. If these data profiles are put on web for sharing with communities, metadata of individual entities should be attached to describe the provider, model, device specifications, and configuration details. These data can also be obtained and updated with the help of smart meters, home sensors, weather reports etc. In this paper, we simply assume they are available and will not provide details of how to establish and update them.

IV. POWER PRICE MODEL AND PROBLEM FORMALIZATION

There have been some studies [8], [10] on smart home energy management in the context of smart grid which focus on smart scheduling of household appliances by load-shifting to reduce energy cost according to variable electricity tariff. The variable electricity tariff of smart grid is used as the only driving force in the load-shifting (different constraints maybe considered). When a residential home has its local renewable electrical resources, the cost of electrical consumption becomes more complicated. The dynamic relationships among local power generation, power supply of the smart grid, and consumption demand must be taken into account when deciding on the cost rate in the cost evaluation at residential homes. In this section, a practical power price model will be proposed at first. Based on the power price model in the context of smart grids, we will formalize the schedule of electrical consumption and local generation at a residential home as an optimization problem for minimizing the total cost of electrical power while satisfying power requirements.

At residential homes, the supply of electrical power is composed of two parts which will be referred to as local-power and grid-power. The voltage of a smart grid at time t is denoted as $V_{grid}(t)$. It is assumed that electrical power cannot be sent to the smart grid if $V_{grid}(t)$ is equal to or higher than a threshold value, $V_{threshold}$. In the following part of the paper, the variable $V_{gap}(t) = V_{threshold} - V_{grid}(t)$ will be used for judging the real time situation. From the point of view of smart grid customers, one of the major features of a smart grid is its time-variable pricing. The local power generation at residential homes must integrate with the smart grid. The power price model is critical in the successful business operation of a smart grid. Considering the characteristics of smart grids, the following price model is adopted in this paper:

- 1) The grid-power has a variable tariff $T_{grid}(t)$ which is determined by the smart grid.
- 2) If $V_{gap}(t) > 0$, the selling price of a local power to the smart grid is $T_{local}(t) = T_{grid}(t) - \Delta$. The Δ is a constant value.
- 3) If $V_{gap}(t) \leq 0$, a local power cannot be sold to the smart grid.

There are n household appliances with power consumption rate U_1, U_2, \dots, U_n (unit kW/h) and m local power resources with power generation rate R_1, R_2, \dots, R_m (unit kW/h). The U_i ($i=0, \dots, n$) has flexibility variables denoted by a vector \mathbf{x}_i . The R_i ($i=0, \dots, m$) has flexibility variables denoted by a vector \mathbf{y}_i . An example of flexibility variable is the starting time of an electric facility. Referred to energy models and profiles for individual electrical entities described in last section, $U_i(\mathbf{x}_i, t)$ ($i = 1, \dots, n$) and $R_i(\mathbf{y}_i, t)$ ($i = 1, \dots, m$) are built up based on weather forecast and occupant activities plan. With \mathbf{X} to represent $[\mathbf{x}_i (i = 1, \dots, n)]$ and \mathbf{Y} to represent $[\mathbf{y}_i (i = 1, \dots, m)]$, the net electrical consumption rate at a specific time point t is:

$$P(\mathbf{X}, \mathbf{Y}, t) = \sum_{i=1}^n U_i(\mathbf{x}_i, t) - \sum_{i=1}^m R_i(\mathbf{y}_i, t)$$

Please notify that the above net electrical consumption rate $P(t)$ could be both positive and negative. The negative value

means that the residential home generates more electrical power than what it is consuming at time t . The residential home may buy from or sell to the smart grid electrical power. The net cost rate of the residential home is:

$$\begin{aligned} \text{If } P(\mathbf{X}, \mathbf{Y}, t) &= 0, & C(\mathbf{X}, \mathbf{Y}, t) &= 0; \\ \text{if } P(\mathbf{X}, \mathbf{Y}, t) &> 0, & C(\mathbf{X}, \mathbf{Y}, t) &= P(\mathbf{X}, \mathbf{Y}, t) \times T_{\text{grid}}(t); \\ \text{if } P(\mathbf{X}, \mathbf{Y}, t) &< 0 \\ \text{if } V_{\text{gap}}(t) &\leq 0, & C(\mathbf{X}, \mathbf{Y}, t) &= 0 \\ \text{if } V_{\text{gap}}(t) &> 0, & C(\mathbf{X}, \mathbf{Y}, t) &= P(\mathbf{X}, \mathbf{Y}, t) \times T_{\text{local}}(t) \end{aligned}$$

In the proposed approach for electrical energy management, a specific time period T is considered in the prediction, recommendation, and schedule of electrical consumption and local generation. A practical period could be a whole day as 24 hours from 8:00 AM to the following day's 8:00 AM. The specific time period T is divided into N time intervals. An individual time interval is $\Delta T = T/N$. The total cost of the residential home in time period T is:

$$C_{\text{total}}(\mathbf{X}, \mathbf{Y}) = \sum_{t=0}^N C(\mathbf{X}, \mathbf{Y}, t) \times \Delta T$$

The schedules of electrical consumption and local generation at a residential home becomes the optimization problem for minimizing the total cost of electrical power while satisfying power requirements at a residential home.

V. SCHEDULING SCHEME

The section above set out how to formalize the scheduling of electrical consumption by household appliances and power generation by local resources. The weather forecast and occupant activities plan play a crucial role in $U_i(x_i, t)$ ($i = 1, \dots, n$) and $R_i(y_i, t)$ ($i = 1, \dots, m$). The dynamic status of the smart grid including the variable electricity tariff and the capability of buying electrical power from residential homes, the predictable local electrical generation, and electrical consumption of household appliances are considered in the optimization problem.

The optimization problem has the following characteristics: i) it is a nonlinear problem that conditional judgments based on dynamic variables are embedded in the calculation process of $C_{\text{total}}(\mathbf{X}, \mathbf{Y})$; ii) there are multiple variables (such as starting times of facility running) to be optimized for power consumption and power generation; iii) the time, weather, occupant activities are considered to be discrete rather than continuous; iv) there is no analytical formula for optimal variables to be included in the optimization problem, these variables are inputs to get time-dependent power distributions of individual entities in their specific context of weather and occupant activities; v) profiles of individual electrical entities may have a fairly big volume of data to be processed in the optimization.

A complete mathematical solution of this optimization problem would require very significant computing resources due to the characteristics described above. In this paper, we propose a solution based on first principles to make a schedule and achieve the approximate minimum total electricity cost. The following section overviews the high-level design of the proposed approach.

The whole solution includes two parts as the building up

database for profiles of individual electrical entities and scheduling of household appliances and power resources to achieve the approximate minimum total electricity cost at a residential home. The energy models for profiles of individual electrical entities have been described in Section III. Microsoft Access database is selected as the database system. Database schema will be developed to implement the proposed energy models. Profile data are collected and/or simulated and stored in the database. The part of scheduling of household appliances and power resources as the solution of the optimization problem specified in last section has the following kernel steps:

- 1) Collect weather data from weather forecast
- 2) Collect occupant activities data
- 3) Get the date for prediction
- 4) Get the prediction of smart grid including the variable electrical tariff $T_{\text{grid}}(t)$ and electrical voltage of smart grid $V_{\text{grid}}(t)$ using data of weather forecast and the date for prediction
- 5) Get local power generation capability based on data of weather forecast. By considering $V_{\text{grid}}(t)$ obtained at last step, the local power generation capability are divided into the following two parts:
 - Time-dependent power generation capability $P_{\text{not-sold}}(t)$ which cannot be sold to the smart grid.
 - Time-dependent power generation capability $P_{\text{can-sold}}(t)$ which can be sold to the smart grid.
- 6) For each household appliance ($i = 1, \dots, p$) without running flexibility, gets the predictable electrical consumption time-dependent distribution $P_{\text{inflex-con}}(i, t)$ using data of weather forecast and occupant activities as input.
- 7) Calculate $P_{\text{inflex-con}}(t) = \sum_{i=1}^p P_{\text{inflex-con}}(i, t)$
- 8) Calculate $P_{\text{diff}}(t) = P_{\text{not-sold}}(t) - P_{\text{inflex-con}}(t)$
- 9) Update $P_{\text{not-sold}}(t)$ by keeping positive values in $P_{\text{diff}}(t)$ unchanged and setting other values to zero.
- 10) Update $P_{\text{inflex-con}}(t)$ by taking the absolute value of negative values in $P_{\text{diff}}(t)$ and setting other values to zero.
- 11) Update $P_{\text{can-sold}}(t)$ by keeping positive values in $P_{\text{can-sold}}(t) - P_{\text{inflex-con}}(t)$ and setting other values to zero.

After step 11, we only need to consider $P_{\text{not-sold}}(t)$, $P_{\text{can-sold}}(t)$, $P_{\text{flex-con}}(x_i, t)$ for each household appliance ($i=1, \dots, q$) with a flexible starting time x_i , and $T_{\text{grid}}(t)$.

- 1) For each associated task of household appliances ($i=1, \dots, q$) with a flexible starting time, evaluate the total energy to be consumed, rank them from the most energy consuming to least energy consuming and make the appliance list as (A_1, \dots, A_q) .
- 2) Find the best starting time T_1 for A_1 , update $P_{\text{not-sold}}(t)$ keeping positive values in $P_{\text{not-sold}}(t) - P_{\text{flex-con}}(T_1, t)$ and setting other values to zero; update $P_{\text{can-sold}}(t)$ by keeping positive values in $P_{\text{can-sold}}(t) - P_{\text{flex-con}}(T_1, t)$ and setting other values to zero, remove A_1 from the appliance list.
Note: the statement "find the best starting time T_1 for A_1 " can be achieved by calculating the electricity cost of

appliance A_1 for all possible starting time with a specific time interval and select the best one for the minimum cost. If there are multiple best values, the earliest one will be selected as the best starting time.

- 3) Repeat the step 13 until the appliance list is empty. Each appliance ($i=1, \dots, q$) with a flexible starting time has a best starting time T_i .

The above algorithm provides an approximate solution for the optimization problem formalized in last section. This approach is efficient and has a clear physical meaning at each step. It is quite straightforward to implement with a suitable programming language.

VI. CASE STUDY

This section sets out a case study for the proposed approach. The motivation example and scenarios described in Section II are used as the inputs for the case study. The scheduling period is the whole 24-hour day from 4:00 AM of next day to 4:00 AM of the day after next day. Fig. 2 shows the electrical power output of the installed Solar PV system on a sunny day for scenarios A, C, and D.

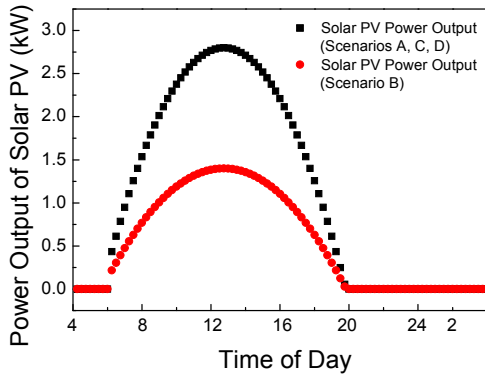


Fig. 2. Power output of solar PV

Here we assume that the smart grid has $V_{grid}(t) > V_{threshold}$ between 10:45 AM to 2:45 PM in scenarios A, C, and D. $P_{not-sold}(t)$ and $P_{can-sold}(t)$ can be obtained for these scenarios. Δ is the price gap between buying and selling power from the smart grid and is set to be 10 cents/kWh. In sScenario B, the total power output of the solar PV system equals $P_{can-sold}(t)$ which can be sold to the smart grid at any time.

Our proposed approach can process any form of varying tariff. In this case study, the tariff scheme in the ‘‘Power Smart Home’’ plan of Energy Australia is used (see Table I).

TABLE I: ELECTRICAL ENERGY TARIFF

Time of Use	Tariff (cents/kWh)
Peak: 2pm – 8pm on working weekdays	52.5470
Shoulder: 7am – 2pm and 8pm – 10pm working weekdays and 7am – 10pm on weekends and public holidays	21.3400
Off Peak: all other times	13.0900

For scenarios described in Section II, the power consumption profiles of the household appliances without running flexibility are obtained by querying the profile database in their specific context of weather and occupants’

activities. The overall inflexible time-dependent power consumption distributions $P_{inflex-con}(t)$ at scenarios A, B, C, and D are shown in Fig. 3. Horizontal axis is the time. Vertical axis is the power with unit kW.

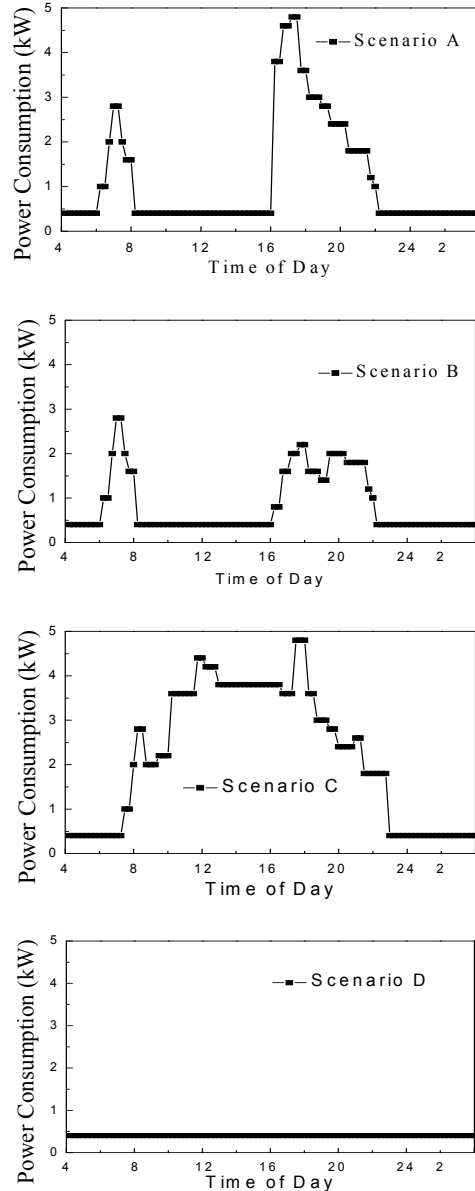


Fig. 3. Inflexible time-dependent power consumption

Using the scheduling scheme presented in Section V, the best starting times for swimming pool pump running and washing/drying in interested scenarios are showed in Table II.

TABLE II: SCHEDULED STARTING TIMES

	scheduled time of swimming pool pump	scheduled time of washing/drying
Scenario A	10:45 AM	11:30 AM
Scenario B	10:00 AM	10:00 PM
Scenario C	10:00 PM	10:00 PM
Scenario D	10:45 AM	11:30 AM

The study case above shows some simple situations for smart home electrical management in the context of local resources and smart grid. In reality, a residential home may have more electrical appliances such as electric vehicles,

storage battery, hot water system, etc. It is also possible to have alternative local electrical resources such as wind turbine. The scheduling of electrical consumption and generation can be very complicated and challenging.

VII. RELATED WORK

Smart grids employ modern information and communication technology to achieve computer-based remote control and automation of utility electrical networks. There has been extensive research, development, and deployment of smart grids [11], [12] across the world in recent years. Smart grids assist in more efficient use of existing power system assets through demand response, peak shaving, and service quality control. Smart grid technology changes the power system into a complex adaptive system [13].

Major suppliers of smart appliances include Samsung, LG, GE, and Whirlpool. Smart appliances normally have the capability to react to electricity price and demand response signals. They bring additional value with intelligent control, power management, and networking technologies for household appliances on the Smart Grid [14], [15].

Distributed generation by local renewable energy sources has gained worldwide attention [16], [17]. The introduction of large-scale renewable energy resources brings up the surplus-electricity production problem due to fluctuations of generation capability of sustainable energy resources [18].

Energy informatics has become a hot topic and is concerned with analyzing, designing, and implementing systems to increase the efficiency of energy demand and supply systems [19]. Smart home systems [20] incorporates ubiquitous [21] and context-aware [22] computing into a residential home. Smart home systems are widely referred to as "home automation", which has attracted more attention in recent years due to the development of control systems for entertainment, heating, broadband, lighting and security from one of many types of digital computer control devices, panels and mobile handsets [23]. An overview has been presented in [24] of the challenges of smart homes that information and communication technology will face in the residential home environment. The relationship between human and automated intelligence in green buildings is explored in [25]. A simulation system for validating contextual rules in smart homes is proposed in [26]. An agent-based smart home, referred to as MavHome, is proposed in [27] in which a home acts as an intelligent agent in an adaptive and automated environment. A rule-based framework is proposed in [28] based on an Event-Condition-Action pattern inherited from the field of expert systems for heterogeneous subsystems management in smart home environment.

The research on semantic representation of energy-related information in future smart homes is reported in [29]. This work focuses on the representation of individual homes' electrical entities and their energy demand or supply. The dynamic relationships among electrical entities, predictable environmental variables, and occupant involvement are not considered. Research is reported in [30] on monitoring and analysis of energy consumption at device level and at near real-time by designing a smart home system that can interconnect common devices available in private households

and integrate wireless power metering plugs to gain access to energy consumption data. A decision-support tool for coordinated scheduling of energy consumption at a residential home is presented in [10]. The electricity tariff is found to be the critical factor in the scheduling of energy consumption. Communication networks in smart homes have also been highlighted in [31].

VIII. CONCLUSION

This paper describes our research on smart home electrical energy management in the context of a smart grid. Energy models for individual electrical entities at residential homes and scheduling schemes for electrical energy management have been presented. A formalization of the research problem has been presented and a motivation example and case study have been provided. The proposed approach provides a practical solution which can take account of the local renewable energy generation, smart grids, smart electronic appliances, decisions/commands of home owners, and environmental factors. The proposed scheduling scheme has the following limitations: a) correlations among household appliances with flexible start running times have not been considered; b) total electrical energy consumption of individual appliances is used to judge the priority of the household appliances with a flexible starting time. If power distributions of different household appliances have totally different shapes, the priority assessment processes becomes weak. More extensive research by the present authors on this topic is ongoing.

REFERENCES

- [1] RENEWABLES 2012 Global Status Report. [Online]. Available: <http://new.ren21.net/REN21Activities/GlobalStatusReport.aspx>.
- [2] I. Koutsopoulos and L. Tassiulas, "Challenges in demand load control for the smart grid," *IEEE Network*, vol. 25, no. 5, pp. 16–21, Sep.–Oct. 2011.
- [3] B. Ramachandran, S. K. Srivastava, C. S. Edrington, and D. A. Cartes, "An intelligent auction scheme for smart grid market using a hybrid immune algorithm," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4603–4612, Oct. 2011.
- [4] Smart Grid Australia. (2010). Submission to Prime Minister's Task Group on Energy Efficiency. [Online]. Available: www.smartgridaustralia.com.au.
- [5] D. J. Cook, "How smart is your home?" *Science*, vol. 335, no. 8–13, pp. 1579–1581, 2012.
- [6] S. Davidoff, M. Lee, C. Yiu, J. Zimmerman, and A. Dey, "Principles of smart home control," *Lecture Notes in Computer Science*, vol. 4206, pp. 19–34. Springer Berlin / Heidelberg, 2006.
- [7] M. J. Kofler, C. Reinisch, and W. Kastner, "A semantic representation of energy-related information in future smart homes," *Energy and Buildings*, vol. 47, pp. 169–179, 2012.
- [8] A. D. Giorgio and L. Pimpinella, "An event driven Smart Home Controller enabling consumer economic saving and automated Demand Side Management," *Applied Energy*, vol. 96, pp. 92–103, 2012.
- [9] D. Bonino, F. Corno, and F. Razzak, "Enabling machine understandable exchange of energy consumption information in intelligent domestic environments," *Energy and Buildings*, vol. 43, no. 6, pp. 1392–1402, 2011.
- [10] M. A. A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Coordinated scheduling of residential distributed energy resources to optimize smart home energy services," *IEEE Transactions on Smart Grid*, vol. 1, no. 2, pp. 134–143, 2010.
- [11] H. Farhangi, "The path of the smart grid," *Power and Energy Magazine*, IEEE, vol. 8, no. 1, pp. 18–28, January–February 2010.
- [12] J. A. Momoh, "Smart grid design for efficient and flexible power networks operation and control," in *Proc. IEEE Power Systems Conference and Exposition*, 15–18 March 2009, pp. 1–8.

- [13] S. Massoud Amin and B. F. Wollenberg, "Toward a smart grid: power delivery for the 21st century," *Power and Energy Magazine*, IEEE, vol. 3, no. 5, pp. 34–41, 2005.
- [14] T. Catania, "Appliances & the smart grid," *ASHRAE JOURNAL*, vol. 54, no. 2, pp. 72–74, 2012.
- [15] J. Stragier, L. Hautekeete, and L. D. Marez, "Introducing smart grids in residential contexts: Consumers' perception of smart household appliances," in *Proc. IEEE Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply*, 2010, pp. 135–142.
- [16] P. C. Loh, L. Zhang, and F. Gao, "Compact integrated energy systems for distributed generation," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1492–1502, 2013.
- [17] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galvan, R. C. P. Guisado, Ma A. M. Prats, J. I. Leon, and N. Moreno-Alfonso, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 4, pp. 1002–1016, 2006.
- [18] H. Lund and E. Mønster, "Management of surplus electricity-production from a fluctuating renewable-energy source," *Applied Energy*, vol. 76, no. 13, pp. 65–74, 2003.
- [19] R. T. Watson, M. Boudreau, and A. J. Chen, "Information systems and environmentally sustainable development: Energy informatics and new directions for the is community," *MIS Quarterly*, vol. 34, no. 1, pp. 23–38, 2010.
- [20] D. J. Cook, "How smart is your home?" *Science*, vol. 335, no. 8–13, pp. 1579–1581, 2012.
- [21] M. Weiser, "The computer for the 21st Century," *Scientific American*, vol. 265, no. 3, pp. 94–104, 1991.
- [22] A. Dey, G. Abowd, G., and D. Salber, "A conceptual framework and a toolkit for supporting the rapid prototyping of context-aware applications," *Human-Computer Interaction*, vol. 16, no. 2-4, pp. 97–166, 2001.
- [23] P. Pellegrino, D. Bonino, and F. Corno, "Domotic house gateway," in *Proc. the 2006 ACM symposium on Applied computing*, 2006, pp. 1915–1920.
- [24] D. Markovic, D. Cvetkovic, D. Zivkovic, and R. Popovic, "Challenges of information and communication technology in energy efficient smart homes," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 1210–1216, 2012.
- [25] R. J. Cole and Z. Brown, "Reconciling human and automated intelligence in the provision of occupant comfort," *Intelligent Buildings International*, vol. 1, no. 1, pp. 39–55, 2009.
- [26] P. Joonseok, M. Mikyeong, H. Seongjin, and Y. Keunhyuk, "Development of simulation system for validating contextual rule in smart home," in *Proc. International Conference on Advanced Communication Technology*, 2007, vol. 2, pp. 1143–1146.
- [27] D. J. Cook, M. Youngblood, III Heierman, E. O., K. Gopalratnam, S. Rao, A. Litvin, and F. Khawaja. Mavhome, "An agent-based smart home," in *Proc. IEEE International Conference on Pervasive Computing and Communications*, 2003, pp. 521–524.
- [28] C. Leong, A.R. Ramli, and T. Perumal, "A rule-based framework for heterogeneous subsystems management in smart home environment," *IEEE Transactions on Consumer Electronics*, vol. 55, no. 3, pp. 1208–1213, 2009.
- [29] M. J. Kofler, C. Reinisch, and W. Kastner, "A semantic representation of energy-related information in future smart homes," *Energy and Buildings*, vol. 47, pp. 169–179, 2012.
- [30] M. Jahn, M. Jentsch, C.R. Prause, F. Pramudianto, A. Al-Akkad, and R. Reiners, "The energy aware smart home," in *Proc. International Conference on Future Information Technology*, 2010, pp. 1–8.
- [31] D. M. Han and J. H. Lim, "Design and implementation of smart home energy management systems based on zigbee," *IEEE Transactions on Consumer Electronics*, vol. 56, no. 3, pp. 1417–1425, 2010.



Weiliang Zhao is a vice chancellor research fellow at the Sustainable Buildings Research Centre (SBRC) in the Faculty of Engineering, University of Wollongong. He holds a PhD in Computing from University of Western Sydney, a Master in Engineering from Chinese Academy of Science, and a Bachelor of Science from Peking University. Prior to joining the University of Wollongong, he had been a data analyst at

the Copyright Agency, software developer at ROAMZ, research fellow at Computing Department of Macquarie University, and software developer at ANZ Bank, and researcher at University of Western Sydney, Hong Kong University of Science and Technology, and Chinese Academy of Science. He has more than 40 refereed publications on energy efficiency systems and applications, business intelligence, service computing, information security and trust management, data analytics, and statistical modeling. His current research interests focus on models and simulation of the integration of smart energy systems, people, and buildings to increase energy efficiency and reduce carbon emissions.



Lan Ding is a senior lecturer with the Sustainable Buildings Research Centre (SBRC) in the Faculty of Engineering, University of Wollongong. She holds a bachelor in Architecture and a master in Knowledge-based Design Systems from Huazhong University of Science and Technology, and a PhD in Artificial Intelligence in Design from University of Sydney's Faculty of Architecture, Design and Planning. Prior to joining the University of Wollongong, she held the position of Senior Research Scientist at CSIRO. Her research interest is helping create more sustainable cities and buildings, including integration of smart grid with smart buildings and cities, complex systems science, agent-based modelling, 3D collaborative virtual environments, Building Information Modelling (BIM), human-computer interactions and collective intelligence for sustainability. She has numerous awards including national and state awards from the Australian Institute of Building.



Paul Cooper is the director of the University of Wollongong (UOW) Sustainable Buildings Research Centre (SBRC). Professor Cooper has been involved in research on a wide variety of topics in energy systems, energy efficiency and fluid mechanics over the past thirty years. He holds a bachelor in Electrical Engineering, a master in Science and Technology Studies and a PhD in heat transfer, all from Imperial College London. In the mid-1980's he was a research fellow in the Built Environment Research Group (BERG) and the Research in Building (RIB) group, at the University of Westminster prior to joining the Faculty of Engineering at the University of Wollongong in 1988. He was the Head of the UOW School of Mechanical, Materials and Mechatronic Engineering at the University of Wollongong up until July 2010, when he took up his present appointment as Director of RRSB.

His research interests have included modeling and measurement of energy and ventilation systems in buildings, dust and fume control systems, gas pipeline analysis, and research on renewable energy systems, including photovoltaic-thermal systems, small scale wind and ocean wave energy systems.



Pascal Perez is currently the research director of the SMART Infrastructure Facility, University of Wollongong. He is a specialist of Integrative Social Simulation, using Multi-Agent Systems technologies to explore complex infrastructure systems. He is a member of the Technical Committee of the Australian Urban Research Infrastructure Network (AURIN). He is also a member of the Modeling and Decision Support Division of Simulation Australia and of the Modeling and Simulation Society of Australia and New Zealand (MSSANZ). In 2002, he received an ARC-International Linkage Fellowship to develop social modeling research at the Australian National University.

Professor Perez has published 100 refereed papers and book chapters. In 2006, he co-edited with his colleague David Batten the book 'Complex Science for a Complex World' (ANU E Press).