Administrative Committee ...................................................i
Officers and Committee Chairs ...........................................ii
Special Section on Innovations in Digital Games .........................iii
Message from the Editor ....................................................iv

INTERNATIONAL GAMES INNOVATION CONFERENCE 2011
The iTron Family of Geocast Games .....................................................Robert J. Hall 171
Foodie: Play with Your Food Promote Interaction and Fun with Edible Interface ....................Jun Wei and Adrian David Cheok 178
Game Interface Using Digital Textile Sensors, Accelerometer and Gyroscope ....................Narisa N. Y. Chu, Ching-Ming Yang and Chih-Chung Wu 184
The Ghost Club Storyscape: Designing for Transmedia Storytelling .....................................Hank Blumenthal and Yan Xu 190
Adaptive Virtual Environments for Neuropsychological Assessment in Serious Games ................Thomas D. Parsons and James Reinebold 197

CAMERA/DISPAY/TRANSUCER SYSTEMS
Flash Shadow Detection and Removal in Stereo Photography ..................................................Sang Jae Nam and Nasser Kehtarnavaz 205
Total Harmonic Distortion Improvement for Elliptical Miniature Loudspeakers Based on Suspension Stiffness Nonlinearity ..........................................................S. J. Pawar, Soar Weng and Jin H. Huang 221
A Filter-Switching Auto-Focus Framework for Consumer Camera Imaging Systems ................Mark Gamadia and Nasser Kehtarnavaz 228
Optical Image Stabilizing System Using Fuzzy Sliding-Mode Controller for Digital Cameras ...................................................................................................................Tsau-Hsing S. Li, Ching-Chang Chen and Yu-Te Su 237
Visual Discomfort Visualizer using Stereo Vision and Time-of-Flight Depth Cameras ................Yong Ju Jung, Hoseik Sohn and Yong Man Ro 246
Employing a RGB-D Sensor for Real-Time Tracking of Humans across Multiple Re-Entries in a Smart Environment ...................................................................................Junggon Han, Eric J. Paiews, Paul M. de Zeeuw and Peter H. N. de With 255
A Highly Power-Efficient LED Backlight Driving System for LCD TVs ...........................................Ki-Soo Nam and Oh-Kyong Kwon 264

COMMUNICATIONS
Cell Interleaving Against Impulsive Noise in OFDM .................................................................Pablo Torio and Manuel Garcia Sanchez 269
Experimental Outage Capacity Analysis for Off-body Wireless Body Area Network Channel with Transmit Diversity .........................................................................................Chunsu Ahn, Byoungik Ahn, Sunwoo Kim and Jaehoon Choi 274
Performance Analysis on Demodulation of the Base Layer in the AT-DMB System ..................Wan-In Kim and Hyoung-Nam Kim 278
Cooperative Wireless Sensor Environments Supporting Body Area Networks ......................Stepan Iyvanov, Dmitri Botvich and Sastibharan Balasubramaniam 284
Efficient Signal Detection Technique for Interactive Digital Broadcasting System with Multiple Antennas .......................................................................................................................Hyun-Jin Park, Myung-Sun Baek and Hyoung-Kyu Song 293
A Cognitive Radio Indoor HDTV Multi-Vision System in the TV White Spaces ....................Mauro Fadda, Maurizio Murroni and Vlad Popescu 302
Digital Tuner Implementation Using FM Tuner for DRM Plus Receivers ...Seong-Jun Kim, Kyung-Won Park, Kyung-Taek Lee and Hyung-Jin Choi 311

CONTROL SYSTEMS
Real-time Household Load Priority Scheduling Algorithm based on Prediction of Renewable Source Availability ........................................................................................................Xin Liu, Liviu Ivanescu, Rui Kang and Martin Maier 318
An Adaptive Technique to Improve Wireless Power Transfer for Consumer Electronics ...........................................................................................................Huy Hoang, Seunggyu Lee, Youngsu Kim, Yunho Choi and Franklin Bien 327
Enhancing Online Power Estimation Accuracy for Smartphones .................................................Minyoung Kim, Joonho Kong and Sung-Woo Chung 333
Design and Implementation of Intelligent Energy Distribution Management with Photovoltaic System .................................................................................................Insung Hong, Byeongkwan Kang and Sehyun Park 340

GAMES TECHNOLOGIES
Real-Time Eye Gaze Tracking for Gaming Design and Consumer Electronics Systems ..........Peter M. Corcoran, Florin Nana, Stefan Petrescu and Petronel Bigoi 347

NETWORKS
Efficient GF(256) Raptor Code Decoding for Multimedia Broadcast/Multicast Services and Consumer Terminals ........................................................................................................Todor Mladenov, Saeid Nooshabadi and Kiseon Kim 356
Verity: An Ambient Assisted Living Platform ....................................................................................J. Winkley, P. Jiang and W. Jiang 364
A Network-Aware Quality Adaptation Scheme for Device Collaboration Service in Home Networks ............................................Dongchil Kim and Kwangseung Chang 374
A Popularity-Aware Prefetching Scheme to Support Interactive P2P Streaming ........................Choonhwa Lee, Euiyoung Hwang and Dohooy Pyeon 382
Resource and Service Management Architecture of a Low Capacity Network for Smart Spaces .......................................................................................................................Sachin Bhardwaj, Tanir Ozelebi, Johan Lakkien and Cagri Uysal 389

(Continued on back cover)
Real-time Household Load Priority Scheduling Algorithm based on Prediction of Renewable Source Availability

Xin Liu, Liviu Ivanescu, Rui Kang, and Martin Maier, Senior Member, IEEE

Abstract — We propose a real-time household load priority scheduling algorithm based on renewable source availability prediction to maximize the benefits of renewable sources and minimize the total cost of energy consumption with consumers’ comfort constraints. Home appliances are assigned dynamic priority according to their different energy consumption modes and their corresponding status. Hour-by-hour weather forecast is considered to predict the availability of the renewable sources. Based on the allocated priority, home appliances are scheduled according to the predicted output of renewable sources and the forecast electricity market price. In addition, to effectively schedule appliances according to the real-time output of renewable sources and the electricity market price changes, which generally deviate from the corresponding forecasting, an algorithm for real-time household load scheduling is proposed and its benefits on cost and energy efficiency are discussed as well.

Index Terms — Smart home, renewable sources, energy management, dynamic priority scheduling.

I. INTRODUCTION

Due to the continuous increase of residential electricity demand, energy consumption and management in households have received more attention in recent years. To achieve the energy efficiency of smart homes [1], [2], which use technology to make all electronic devices in a house act "smart" or more automated, issues on both communication technologies and energy management methods in the home domain need to be addressed.

On one hand, with millions of smart meters [3], sensors, and automatic control devices to be deployed in electric power distribution grids close to residential and commercial buildings, Machine to Machine (M2M) communications [4], which is characterized by involving a large number of intelligent machines sharing information and making collaborative decisions without direct human intervention, have emerged as a cutting-edge technology for home energy management systems [5]. Issues on energy efficiency, reliability, and security of M2M communications were discussed in [4] and comparisons of communication technologies and network architectures for M2M communications in home area networks were investigated in [5] and [6], respectively. Results showed that ZigBee is the most reliable technology to facilitate M2M communications in the home domain and the optimal traffic concentration for network design can minimize the total cost of the home energy management system.

On the other hand, since the consumer is neither an economist nor an experienced grid operator, it is impractical to request him to create an optimal household load schedule to save energy, reduce cost, and help grid operation (e.g., by reducing the contribution of the consumer to the peak load). To solve this problem, automatic load scheduling methods should be provided, which can collect status and power consumption demand from home appliances and schedule them in an energy- and cost-efficient way by simultaneously considering comfort as well. Pedrasa et al. described algorithmic enhancements to a decision-support tool to help consumers optimize their acquisition of electrical energy services in [7]. The decision-support tool can optimize energy service provisioning by enabling end users to first assign values to desired energy services and then schedule their available distributed energy resources (DER) to maximize net benefits. A solar photovoltaic (PV) system was considered as an example of renewable energy sources in [7] but the solar insolation was roughly described as sunny or cloudy in days, which is not accurate enough for scheduling household load in hours. Du et al. presented an appliance commitment algorithm to schedule thermostatically controlled household loads in order to meet an optimization objective such as minimum payment or maximum comfort in [8]. Both price and consumption forecasts and users’ comfort settings were considered in the algorithm but the utilization of renewable energy sources was missing, which will play an important role in the future residential energy supply system [9].

Very recently, a wireless sensor network-based in-home energy management application was proposed in [10], which can decrease energy expenses, reduce the contribution of the consumers to the peak load, and reduce the carbon emissions.
of the household. Both performance of the energy management application and the wireless sensor network were evaluated and the presence of local energy generation capability and fixed-priority based scheduling was considered in [10]. However, the local energy generation capability was still roughly described as three PV panels that are able to generate 350 W per day considering a climate with several hours of sun light.

Contrary to traditional fossil fuel power plants, energy production of wind, PV, and other renewable sources is generally fluctuating and the continuously growing amount of those renewable sources starts compromising the stability of the electrical grid [11]. One solution could be the integration of storage systems in the home area power grid but there is a tradeoff between cost and efficiency in the battery system. In this paper, we propose a real-time household load priority scheduling algorithm based on renewable sources availability prediction. Home appliances are assigned dynamic priorities according to their different energy consumption modes and their corresponding status. Hour-by-hour weather forecast is considered to predict the availability of the renewable sources. Based on the allocated priority, home appliances are scheduled according to the predicted output of renewable sources and the electricity market price forecasting [12]. Our goal is to maximize the benefits of renewable sources and minimize the total cost of consumption of grid import energy for given consumers’ comfort constraints. To effectively schedule appliances according to the real-time output of renewable sources and the electricity market price changes, which generally deviate from the corresponding forecasting, an algorithm for real-time household load scheduling is proposed and its benefits on cost and energy efficiency are studied.

The remainder of the paper is structured as follows. In Section II, we use smart meters in a ZigBee-based wireless sensor network testbed established in our lab to trace the energy consumption of some typical home appliances, including microwave oven, refrigerator, and printer. Based on the observation of different energy consumption modes, we classify home appliances into three categories and discuss their respective features. Then, we propose our real-time household load priority scheduling algorithm based on the renewable source availability prediction and electricity market price forecasting in Section III. We study the benefits of our proposed scheme on cost and energy efficiency in Section IV. Finally, we conclude the paper in Section V.

II. ENERGY CONSUMPTION MODES OF HOME APPLIANCES

Energy consumption modes of home appliances vary from one to another and have a strong relationship with consumers’ behavior. However, recent studies only analyzed the customer behavior in using electrical energy without considering individual appliances [13] or analyzed the power dissipation patterns of typical home appliances without considering the impact of consumers’ behavior and habits [14]. It appears therefore to be a lack of analysis of the real-world energy consumption of individual appliances, driven by real-world customer behavior. Actually, it is essential to know exactly the individual appliance’s energy consumption modes by considering consumers’ behavior and habits to design an effective scheduling scheme.

Toward this end, we recorded, for a few weeks, energy traces for three types of appliances (a shared printer, two microwaves and two refrigerators), covering two of the three classes of appliances with different energy consumption modes studied in the following subsections. They are regularly used in one of the INRS University buildings, home of our lab, by the students and the personnel (about 100 persons). The experimental energy trace network using a ZigBee-based energy monitoring system is shown in Fig. 1. The energy consumption of the appliances was monitored by three sensors and to record energy traces at high temporal resolution, instead of using typical hourly or half-hourly time intervals, the data of the energy consumed in each 5 minutes were uploaded to the server via a relay routing node (the router in Fig. 1) and a base node.

![Fig. 1. ZigBee-based wireless sensor network for energy traces of different appliances in our lab.](image)

Based on the observations of the energy trace results, we classify home appliances into three categories, namely, appliances with real-time energy consumption mode, appliances with periodic nonreal-time energy consumption mode, and appliances with nonperiodic nonreal-time energy consumption mode, as explained in greater detail in the following.

A. Home appliances with real-time energy consumption mode

The energy consumption of this type of home appliance is directly related to consumer behavior, which means that after the consumer turns on this type of home appliance, energy will be consumed instantaneously and continuously until the appliance is shut down. When real-time electricity market price is adopted, the cost of energy consumption of this type of home appliance is directly related to the time when the consumer turns it on and the duration of its usage.

The microwave ovens and printer, whose energy traces are shown in Fig. 2, belong to this category. From Fig. 2 we observe that the energy consumption of the printer is mainly...
during working hours and the energy consumption of the microwave oven approximately starts at 12:00 and ends at 16:00, when students may print documents or heat their lunch, respectively. It should be pointed out here that different from the microwave ovens, which only consume energy when they are in use, the printer also consumes energy during the nonworking hours, i.e., standby energy consumption.

Generally, the usage of this type of appliance can not be delayed. In other words, the energy consumption of this type of appliance can not be scheduled and they must run immediately to satisfy the consumer’s requirements. Other appliances such as desktop computers without battery availability prediction and day-ahead electricity market price

During the usage of the appliance.

This type of home appliance can be scheduled by aggressively maintaining the temperature inside the refrigerators, i.e., consuming energy to decrease the temperature before it gets higher than the upper bound or stopping to consume energy before the temperature reaches the lower bound. Other thermostatically controlled appliances, such as water and space heater, air conditioner, and so on, are also included in this category. In addition, it should be pointed out that appliances with embedded battery, such as laptop computers, can also be considered this type of home appliance since the battery can be charged and discharged periodically during the usage of the appliance.

C. Home appliances with nonperiodic nonreal-time energy consumption mode

This type of home appliance consumes energy nonperiodically and does not have any running time limit. However, they may have a deadline to run, i.e., they must provide service before some certain conditions (time, capacity, throughput, etc.) apply.

The pool pump and the plug-in hybrid electric vehicle (PHEV) discussed in [7] belong to this category. Specifically, the PHEV should be fully charged before the residents go to work in the morning while the residents do not care about the state of charge at any other hour. The pool pumps should not run after midnight due to noise considerations, but they have to run for 6 hours each day. Other appliances such as dishwashers and laundry machines also belong to this category. They can run at any time but only once before the next serving time. This type of appliances can be scheduled since they do not have strict time restrictions to run.

We summarize the features of the three different types of home appliance in Table I. Since appliances with real-time energy consumption mode can not be scheduled, we only focus on the other two types of appliance in the following sections.

III. HOUSEHOLD LOAD SCHEDULING

The objective of household load scheduling is to improve its energy and cost efficiency subject to given consumers’ comfort constraints. Towards this end, renewable source availability prediction and day-ahead electricity market price

![Fig. 2. Energy traces of the two microwave ovens and the printer.](image)

![Fig. 3. Energy traces of the two refrigerators.](image)
forecasting are considered and dynamic priority allocation and scheduling for appliances with consumers' comfort constraints is proposed in this section. In addition, to effectively schedule appliances according to real-time weather and electricity market price changes, an algorithm for real-time household load scheduling is also proposed in this section.

A. Renewable source availability prediction

The main advantages of using renewable energy sources are the inexhaustible resources of the primary energy and the elimination of harmful emissions. However, unlike traditional fossil fuel power plants, energy production from wind, PV, and other renewable sources is generally fluctuating and the continuously growing amount of renewable sources starts compromising the stability of the electrical grid [11]. Based on the information provided by the hour-by-hour weather forecast, which can be easily obtained from a weather forecast website, we can predict the output of the renewable energy sources since it is directly related to the weather. For example, we can obtain a steady output from a wind turbine system if the forecast of the wind speed in the next several hours is higher than its rated speed, which is the minimum wind speed at which the wind turbine can generate its designated rated power, and we can obtain less output from a solar PV system if there are few showers in the same period. Based on the historical statistical data, more practical data of the energy output from renewable sources can be obtained and considered in the household load scheduling.

B. Day-ahead electricity market price forecasting

Electricity has been turned into a traded commodity nowadays, which is sold and bought at market prices. Therefore, electricity market price forecasting is essential for market participants in both daily operation and long-term planning analyses, such as designing bidding strategies and making investment decisions [14]. Especially, in the short term, consumers need electricity price forecasts to optimally schedule their household loads.

In recent years, several techniques have been applied to short-term electricity market price forecasting and forecast accuracy improvement (e.g., [11] and [15]). Also, the economic impact of price forecast inaccuracies on forecast users has been analyzed in [16]. The price forecast and the actual price on a typical day are shown in Fig. 4 [8]. Based on the price forecast, home appliances can be scheduled in a cost-efficient way.

C. Dynamic priority allocation and scheduling

In our proposed scheme, priority is dynamically allocated according to the corresponding status of appliances that can be scheduled, i.e., appliances with periodic nonreal-time energy consumption mode and appliances with nonperiodic nonreal-time energy consumption mode. Appliances with real-time energy consumption mode, since they can not be scheduled and must run immediately, do not need priority allocation.

The status of appliances with periodic nonreal-time energy consumption mode can be indicated by the corresponding temperature in case of thermostatically controlled appliances or the battery power status in case of appliances with battery. Fig. 5 shows the relationship between dynamic priority and temperature or battery power status of appliances with periodic nonreal-time energy consumption mode. For appliances with a heating system, such as water and space heaters, as shown in Fig. 5(a), when their temperature is between the thermostat setpoint and the upper limit, they have low priority to consume energy. When the temperature is lower than the thermostat setpoint, they have middle priority to consume energy. If their temperature reaches the lower limit or even lower, the appliances will have high priority to consume energy. On the contrary, for appliances with a cooling system, such as refrigerators and air conditioners, as shown in Fig. 5(b), they have low/middle/high priorities when their temperature is lower/higher than the thermostat setpoint, or reaches the upper limit or even higher, respectively. For appliances with battery installation, as shown in Fig. 5(c), they have low/middle/high priorities when their battery power is higher or lower than 50\%, or lower than 3\%, respectively.

---

**TABLE I**

**HOME APPLIANCE CATEGORIES**

<table>
<thead>
<tr>
<th>Category</th>
<th>Energy Consumption</th>
<th>Eligible for Scheduling</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appliances with real-time energy consumption mode</td>
<td>Instantaneous and continuous</td>
<td>No</td>
<td>Microwave ovens, desktop computers without battery, printers, lights, TV sets, DVD players</td>
</tr>
<tr>
<td>Appliances with periodic nonreal-time energy consumption mode</td>
<td>Periodic and flexible</td>
<td>Yes</td>
<td>Refrigerators, water and space heaters, air conditioners, laptop computers and other appliances with battery</td>
</tr>
<tr>
<td>Appliances with nonperiodic nonreal-time energy consumption mode</td>
<td>Nonperiodic and flexible</td>
<td>Yes</td>
<td>Pool pumps, plug-in hybrid electric vehicles, laundry machines, dishwashers</td>
</tr>
</tbody>
</table>

![Fig. 4. Day-ahead electricity market forecasting price and actual price on a typical day [8].](image-url)
Appliances with nonperiodic nonreal-time energy consumption mode generally have low priority since they do not have strict time restrictions to run. However, appliances, which have a serving deadline, such as the pool pump and the PHEV discussed before, will be assigned high priority at the end of the whole period. As shown in Fig. 6, those appliances only have high priority before the deadline. The serving time in Fig. 6 is the net running time of the appliances.

Based on the above allocation method, home appliances have different priorities to consume energy under different conditions. Generally, according to given consumers’ comfort constraints, the energy consumption of appliances with low priority can be delayed for a relatively long period while the energy consumption of appliances with middle priority can be delayed only for a relatively short period. Different appliances have different time limits with different priority and the corresponding time limit can be predefined by consumers or manufacturers. Considering the energy consumption, appliances with high priority, since they are directly related to the consumer’s satisfaction, must be implemented immediately.

The proposed algorithm for scheduling appliances with different priorities based on the prediction of the renewable sources’ output and electricity market price forecasting is summarized as follows: If the appliance has high priority, it runs immediately in order to satisfy given consumers’ comfort constraints. Meanwhile, all the running appliances with middle and low priorities are rescheduled based on the renewable sources’ output prediction or the electricity market price forecasting. For the appliance with middle priority, which generally has a short time period to be scheduled (i.e., appliance with middle priority and time limit (short)), the scheduler checks the renewable sources’ output prediction within the time limit first and tries to schedule the appliance according to the predicted output. Note that the scheduler can assign the predicted output to the appliance with middle priority even though the output has already been assigned to other appliances with low priority before. In this case, appliances with low priority are rescheduled accordingly. However, if there is not enough output, the appliance with middle priority is scheduled according to the electricity market price forecasting and will be turned on during the lowest price period within the time limit. Finally, for the appliance with low priority and a relatively long time limit, the scheduler tries to schedule the appliance according to the predicted output of the renewable sources or the electricity market price forecasting (if the predicted output of renewable sources is not enough).

D. Real-time household load scheduling

The real-time weather and electricity market prices usually deviate from the corresponding forecasting. To effectively schedule appliances according to the real-time output of renewable sources and the electricity market price changes, an algorithm for real-time household load scheduling is proposed in this subsection.

The household energy management network architecture is illustrated in Fig. 7. Different types of home appliances and renewable sources are connected to the energy management unit (EMU) via a home-area wireless sensor network. Sensor data and control commands are exchanged among them to realize the appliances’ priority and renewable sources’ real-time output update and to implement the energy scheduling and management. To obtain weather forecast information and real-time electricity market prices, the EMU also connects to the Internet and the grid operator, respectively.

The state transition diagram of the EMU is shown in Fig. 8. It periodically updates weather forecast information and
The process of the appliances’ energy management and scheduling in the EMU, i.e., the real-time household load scheduling algorithm, is summarized as follows: When the weather forecast information changes, the EMU reschedules appliances with middle and low priorities based on the new predicted output of the renewable sources. If the predicted output increases, the EMU reschedules appliances with middle or low priority based on the corresponding changes, whereas if the predicted output decreases, the EMU reschedules appliances with middle or low priority based on the forecast electricity market price. When the real-time electricity market prices change, the EMU controls (turns on, turns off, or reschedules) appliances accordingly. If the price increases, the EMU reschedules appliances with middle and low priorities based on the predicted output of renewable sources or price forecasting. Otherwise, if the price decreases, the EMU turns on the appliances that have been scheduled immediately. When the received sensor data indicate that an appliance’s priority status or the real-time output of the renewable sources is changed, the EMU reschedules the appliance according to the new priority status or controls appliances according to the changes of the renewable sources’ output.

### IV. Benefits and Feasibility Analysis

Residential energy consumption may vary depending on a number of factors such as the size of a house, the number of occupants, the location, and so on [10]. In addition, different consumers may have different comfort constraints and the weather and electricity market price forecasting varies from one day to another. Although simulation platforms such as [14] have been proposed to evaluate the energy management methods for smart homes, it is impractical to build explicit models to describe all the possibilities above in order to present a comprehensive evaluation of our proposed scheduling algorithm. Alternatively, we analyze the benefits and feasibility of our algorithm by considering all the possible transitions between weather, price, and priority states and presenting all the foreseeable results when some of those factors change and use a case study to illustrate the potential benefits of our proposed scheduling algorithm.

The key of a scheduling algorithm is to decide when to run an appliance and when to stop it. In the remainder of this section, to better demonstrate the benefits and feasibility of our proposed scheduling algorithm, we divide our proposed scheduling algorithm into two steps, the offline appliance scheduling, which is used to decide when to run an offline appliance, and the online appliance scheduling, which is used to decide when to stop an online appliance. An appliance is considered as an offline appliance when it stays in standby state and considered as an online appliance when it is running and consuming energy in full power state. As the two refrigerators shown in Fig. 3, they are considered as offline appliances and online appliances periodically due to their periodic nonreal-time energy consumption mode.

#### A. Benefits and feasibility analysis of the offline scheduling

Fig. 9 shows the benefits and feasibility analysis of the offline scheduling. For a given offline appliance, the proposed scheduling algorithm initially schedules the appliance according to its priority status and the current weather and price forecasting. Then, the appliance runs immediately in the case it has high priority or waits for a certain time period to run in the case it has middle or low priority. For the high-priority appliance, since it can not be scheduled, no energy and cost will be saved. For the middle- or low-priority appliances, if they run before their priorities change to high, energy and cost will be saved in the case they consume energy from renewable sources or only cost will be saved in the case they consume energy from the grid at the indicated time with the relatively low price.

However, due to the uncertainty of the weather and price forecasting, they may change when the appliance is waiting to run. If this happens, the scheduling algorithm reschedules the appliance according to the new forecasting and tries to save more energy and cost. In addition, because of consumers’ behavior, the appliances’ priority may also change during the waiting period. If this happens, the appliance will also be rescheduled according to its new priority. On all accounts, our
proposed algorithm can effectively schedule the offline appliances according to the changes of the weather and price forecasting as well as the appliances’ priority change caused by consumer behavior.

B. Benefits and feasibility analysis of the online scheduling

Fig. 10 shows the benefits and feasibility analysis of the online scheduling. During the period when an appliance is running, weather and electricity price as well as the appliance’s priority may change and other appliances with higher priority may preempt the energy from renewable sources. If this happens, the scheduling will control the appliance accordingly. More precisely, when the weather changes, i.e., the output of renewable sources is changed, to save energy and cost, the scheduling algorithm will reschedule the appliance that consumes the energy from renewable sources if the output decreases or turn on new appliances that have been scheduled if the price decreases. In addition, when the priority of the appliance changes or the energy that it consumes is preempted by an appliance with higher priority, it will also be rescheduled. If the appliance can be rescheduled, energy and/or cost will be saved. Otherwise, the appliance will continue to run till the service ends. It should be pointed out that when an appliance is turned off and renewable sources’ output can be used, new appliances that have been scheduled will be turned on by the scheduling algorithm. On all accounts, our proposed algorithm can effectively schedule the online appliances according to the changes of the weather and price forecasting as well as the appliances’ priority change caused by consumer behavior.

C. Case study

Fig. 11 shows a case study of our proposed priority scheduling algorithm. The appliance used in this case is with periodic nonreal-time energy consumption mode. In both of the two scenarios (with or without priority scheduling), we use the priority changes of the appliance to represent its state transitions and energy requirements. Without priority scheduling, the appliance consumes energy periodically in despite of the availability of renewable sources’ output and the electricity price. As shown in Fig. 11, when the priority of the appliance changes to high at time $t_2$, it starts to consume energy and stops at time $t_4$ when its priority changes back to low. Since there is no energy output from
renewable sources during the time period between \( t_2 \) and \( t_4 \), the appliance has to consume the energy from the grid during that period. However, with the proposed priority scheduling, according to the given renewable source availability and electricity price, the appliance starts to consume energy from renewable sources at time \( t_1 \) when its priority changes to middle (using the offline scheduling) and stops at time \( t_2 \) when its priority changes back to low (using the online scheduling). Consequently, the appliance does not need to consume energy from the grid during the time period between \( t_2 \) and \( t_4 \) and energy and cost are saved. In addition, during the time period between \( t_1 \) and \( t_11 \), when there is no energy output from renewable sources, by using our proposed scheduling algorithm, the appliance only consumes energy from the grid when the price is low, thereby saving on the cost of energy consumption.

\[
\begin{array}{c}
\text{RS availability} \\
\text{Electricity price} \\
\text{Appliance priority} \\
\text{Energy consumed}
\end{array}
\]

\[
\begin{array}{c}
\text{Appliance priority} \\
\text{Energy consumed}
\end{array}
\]

\[
\begin{array}{c}
\text{w/o Priority scheduling} \\
\text{w/ Priority scheduling}
\end{array}
\]

\[
\begin{array}{c}
0 \quad t_1 \quad t_2 \quad t_3 \quad t_4 \quad t_5 \quad t_6 \quad t_7 \quad t_8 \quad t_9 \quad t_{10} \quad t_{11}
\end{array}
\]

\[
\begin{array}{c}
\text{From Grid} \\
\text{From RS}
\end{array}
\]

\[
\begin{array}{c}
\text{time} \\
\text{time}
\end{array}
\]

\[
\begin{array}{c}
\text{time} \\
\text{time}
\end{array}
\]

\[
\begin{array}{c}
\text{Fig. 11. Case study. (RS: renewable source.)}
\end{array}
\]

V. CONCLUSIONS

In this paper, a real-time household load priority scheduling algorithm based on prediction of renewable source availability was proposed to maximize the benefits of renewable sources and minimize the total cost of consumption of grid energy for given consumers’ comfort constraints. We classified home appliances into three categories and presented a dynamic priority allocation and scheduling algorithm based on their different energy consumption modes. In addition, to effectively schedule appliances according to the real-time output of renewable sources and the electricity market price changes, an algorithm for real-time household load scheduling was also proposed. We analyzed the benefits and feasibility of our algorithm by considering all the possible transitions between weather, price, and priority states and presenting all the foreseeable results when some of those factors change. We presented a case study to illustrate the potential benefits of our proposed priority scheduling algorithm. Results showed that by allocating different priorities to appliances according to their status and scheduling them according to the predicted output of renewable sources and the electricity market price forecasting, both energy and cost efficiency can be improved.

REFERENCES


BIOGRAPHIES

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