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Experimental Demonstration of Smart Charging and Vehicle-to-Home Technologies for Plugin Electric Vehicles Coordinated with Home Energy Management Systems for Automated Demand Response

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ABSTRACT

In this paper, we consider smart charging and vehicle-to-home (V2H) technologies for plugin electric vehicles coordinated with home energy management systems (HEMS) for automated demand response. In this system, plugin electric vehicles automatically react to demand response events with or without HEMS's coordination, while vehicles are charged and discharged (i.e., V2H) in appropriate time slots by taking into account demand response events, time-ofuse rate information, and users' vehicle usage plan. We introduce three approaches on home energy management: centralized energy control, distributed energy control, and coordinated energy control. We implemented smart charging and V2H systems by employing two sets of standardized communication protocols: one using OpenADR 2.0b, SEP 2.0, and SAE standards and the other using OpenADR 2.0b, ECHONET Lite, and ISO/IEC 15118. We show that the both communication protocol sets enable the same energy management by adding some properties and class into ECHONET Lite that are equivalent to existing function sets in SEP 2.0 such as demand response, pricing, energy flow reservation. We evaluated developed systems in a demonstration platform, called the Energy Management System (EMS) Shinjuku Demonstration Center established by Waseda University upon the initiative by the Ministry of Economy, Trade and Industry (METI) in Japan. We show that developed systems enable automated demand response and peak shift by automatically reacting to demand response events without users' inconvenience. We also show that smart charging and V2H system with HEMS's coordination provides more peak demand reduction than one without HEMS's coordination and one without V2H capability.

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INTRODUCTION

Smart grid concept has drawn much attention as it significantly improves the energy efficiency, reliability, security, and cost of electricity grids, by using two-way digital communication and distributed computing technologies for remote and automated control. Smart grid technologies enable demand-side management [1] such as demand response (DR), which is considered as a promising technology to efficiently reduce the peak of power electricity demand. DR is a mechanism to realize that objective by encouraging consumers to reduce their power consumption or shift the demand from peak to off-peak hours (i.e., peak demand cut/shift) in response to DR events called by utility companies or DR aggregators. DR events comprise price-based programs (e.g., critical peak pricing and dynamic pricing) and incentive-based programs (e.g., peak time rebate and direct load control). DR is cost effective because utility companies can save the cost of building additional power generation to meet peak power demand, and also consumers can save the electricity cost and/or receive payments for peak demand cut and shift. DR events can be categorized into two types: price-based DR events and incentive-based DR events. In price-based DR events, a utility offers customers a time-varying tariff based on wholesale electricity costs. This type of events includes time-of-use (TOU) pricing, critical peak pricing (CPP), and real time pricing (RTP). In incentive-based programs, a utility pays incentives to consumers if the consumers reduce their power consumption as per the utility's requests. This type of events includes load control (LC) and peak time rebate (PTR).

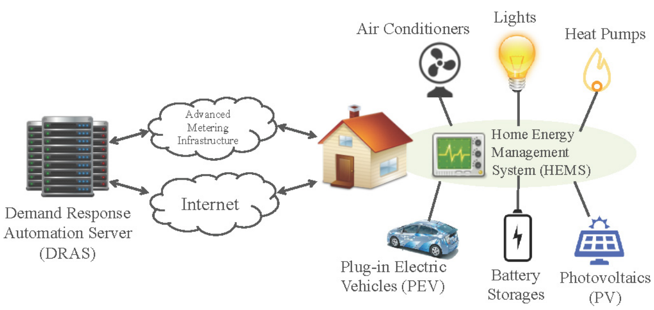


Figure 1. System architecture of home energy management systems (HEMS).

Automated demand response (ADR) is a key component of smart grids, which realizes DR in an automated manner by using two-way digital communication between utilities and consumers' equipment (see Figure 1). In ADR concept, consumers' devices automatically react to DR events and reduce or shift the power consumption by using smart home appliances [2] and/or relying on home automation systems such as home energy management systems (HEMS) [3]. HEMS technologies play an important role in smart grids and ADR to optimize the energy use of home appliances in smart homes by utilizing standardized two-way communication in home area networks (HAN). HEMS provide three main capabilities (or some of them): 1) visualizing how much energy is consumed in a home, 2) controlling home appliances automatically or manually based on users' preferences, and 3) controlling home appliances based on pricing information and/or DR events, provided by utility servers and/or demand response automation servers (DRAS), for reducing the energy cost and reducing peak demand with the least impact on users' lifestyle.

Plug-in electric vehicles (PEV) are gaining in popularity because of their fuel efficiency and economic benefit and also because they reduce the dependency on fossil fuel, greenhouse gas emission, and air pollution, which make a society more environmental and sustainable. However, increasing market penetration of PEV will lead to a considerable increase of peak demand [4] and thus require more electricity generation and transmission capacity, which results in additional costs for utilities and consumers. Therefore, it is crucial to consider solutions for reducing the increased peak demand. A favorable aspect of PEV for ADR is that PEV can be considered as flexible loads, i.e., loads that users can reduce charging power and defer charging start time when the grid is stressed. Therefore, we can optimize charging schedules so that we can reduce peak demand and take into account DR events without impairing users' convenience [5]. In addition, PEV has the capability to provide its energy to home loads (V2H: vehicle-to-home) and/or to grids (V2G: vehicle-to-grid) [6, 7]. Particularly, V2H is useful for customers by using PEV as an emergency backup power when power outage occurs and also it is beneficial for peak shift by charging PEV in off-peak periods and discharging it in peak periods. One of the challenges in V2H is that PEV needs to coordinate with HEMS in order to optimize the schedules of PEV's charging and V2H.

For ADR, home energy management, and smart PEV charging/discharging, various standard communication protocols have been developed. For sending DR signals, OpenADR [12] is often used as an application layer protocol between DRAS and the home. SEP 2.0 [8] and ECHONET Lite [10] are application layer protocols for use in smart home energy management. SAE J2836/J2847/J2931 [9] and ISO/IEC 15118 [11] are suites of standards of two-way digital communication between PEV and electric vehicle supply equipment (EVSE) for smart charging and discharging control.

In this paper, we consider systems for smart PEV charging and V2H, coordinated with HEMS for ADR. In this system, PEV automatically react to demand response events with or without HEMS's coordination, while vehicles are charged and discharged (i.e., V2H) in appropriate time slots by taking into account DR events, time-ofuse rate information, and users' vehicle usage plan. For realizing different levels of HEMS's coordination, we introduce three approaches on home energy management: centralized energy control, distributed energy control, and coordinated energy control. Also, we implemented smart charging and V2H systems by employing two sets of standardized communication protocols: one using OpenADR 2.0b, SEP 2.0, and SAE standards and the other using OpenADR 2.0b, ECHONET Lite, and ISO/IEC 15118. We evaluate developed systems in a demonstration platform, called the Energy Management System (EMS) Shinjuku Demonstration Center established by Waseda University upon the initiative by the Ministry of Economy, Trade and Industry (METI) in Japan. Through demonstration experiments, we show the feasibility of smart PEV charging and V2H for ADR by employing standard communication protocols.

HOME ENERGY MANAGEMENT APPROACHES FOR AUTOMATED DEMAND RESPONSE

In this section, we introduce three approaches of home energy management for ADR, depending on who and how to manage and control home appliances, as shown in Figure 2: 1) centralized energy control, 2) distributed energy control, and 3) coordinated energy control.

Home appliances can be divided into two categories from energy management perspective:

- Passive home appliances: appliances that can be passively controlled by HEMS (e.g., TV displays, heating ventilation, air conditioners, thermostats, lights)
- Active home appliances: appliances that have inherently some intelligence on energy management for ADR by themselves (PEV, home battery storage, heat pumps)

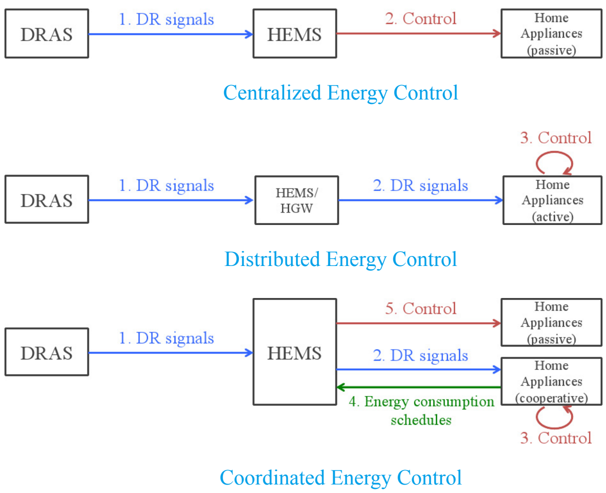


Figure 2. Different levels of home energy management.

Centralized Energy Control

In the centralized energy control approach, HEMS receives DR signals from DRAS and controls home appliances based on the received DR signals in a centralized manner. This approach is suitable for a specific type of home appliances that can be controlled by simply setting operation parameters (e.g., ON/OFF state, temperature, and illumination level) such as TV displays, air conditioners, thermostats, and lights. This approach allows us to efficiently control multiple home appliances because of its centralized architecture, by aggregating the power consumption of each home appliance and taking into account user's preferences and prioritization for home appliances. However, this approach has some limitations on control of home appliances when we use a standardized communication protocol for controlling multi-vendor appliances. Since HEMS is able to use only limited types of messages defined by a standardized communication protocol, the functionality of HEMS for controlling passive alliances is also limited.

Distributed Energy Control

In the distributed energy control approach, home appliances receive DR signals from DRAS via HEMS or home gateways (HGW) and control their operation by themselves based on the received DR signals in a distributed manner. This approach is suitable for home appliances storing energy (e.g., PEV, home battery storage, and heat pumps) that inherently have some intelligence for energy management. The major advantage of this approach is that it is easy to deploy the system because we can easily add on additional smart home appliances into existing home energy management systems due to its distributed architecture. Another advantage is that since active home appliances control themselves, this approach does not necessarily require HEMS and thus this approach is cost effective.

However, in this approach, it is difficult to optimize the whole house energy use and energy management schedules due to the lack of coordination among active and passive home appliances.

Coordinated Energy Control

The coordinated energy control approach is a combination of centralized energy control and distributed energy control by utilizing coordination between HEMS and active home appliances. In this approach, HEMS, passive home appliances, and active home appliances coexist. The major advantage is that we can optimize the whole house energy usage for both passive and active home appliances by virtue of the coordination between HEMS, passive appliances, and active appliances. One of the technical challenges is that since both HEMS and active home appliances have intelligence for energy management, they need to coordinate with each other to avoid the conflict of energy management. In the following sections, we propose a solution to realize the coordination between HEMS and active home appliances and thus avoid energy management conflict.

We propose one-way energy scheduling for the coordination between HEMS and active home appliances. Here is an example:

1. HEMS allocates available energy resources (e.g., maximum available power and/or energy) for each time slot to each active home appliance (e.g. by imposing direct load control events defined in SEP 2.0)
2. Active appliances determine energy management schedules for themselves based on the allocated energy resources and users' preferences for their operation and ADR
3. Active appliances send the determined schedule information to HEMS (e.g., by using the Flow Reservation Function Set defined in SEP 2.0)
4. HEMS determines energy management schedules for passive home appliances based on the energy management schedule of active appliances and user's preference for their operation and ADR
5. Based on the determined schedules, active home appliances control themselves and HEMS control passive home appliances

Communication Protocols for Home Energy Management

In this section, we consider two communication protocols for smart home management from the viewpoint of the three energy control approaches stated above. In our experiments, we used SEP 2.0 [8] and ECHONET Lite [10] as application layer protocols for use in smart home energy management. Table 1 shows the comparison of SEP 2.0 and ECHONET Lite. In SEP 2.0, each device manages its own energy control based on DR signals. Also, HEMS can control devices by sending a control event that includes the start time, duration, and control information. In addition, SEP 2.0 supports Flow Reservation Function Set, which enables information exchange of energy management schedules between devices. Therefore, SEP2.0 is suitable for realizing the three energy control approaches. In ECHONET Lite, HEMS manages each device by aggregating the status of every device and controlling each device in a real-time manner based on their status and DR signals. Therefore, it is suitable for the centralized energy control. However, ECHONET Lite does not support some functions defined in SEP 2.0 such as Pricing Function Set and Direct Load Control. Due to this fact, it limits the realization of the distributed energy control. Also, if we want to implement the coordinated energy control approach, some additional functions such as Flow Reservation Function Set in SEP 2.0 is required for coordination between HEMS and active home appliance to avoid the conflict of energy management. In order to realize the distributed energy control and coordinated energy control using ECHONET Lite, we add some classes and properties to ECHONET Lite as explained in the later section.

Table 1. Comparison of SEP 2.0 and ECHONET Lite.

Item	SEP 2.0	ECHONET Lite
Concept	Each device manages its own energy management by using multiple function sets	HEMS controls devices by using device objects defined for each device type
Control	Control by events (time, command)	Realtime control (command)
OSI Layers	Layers 5-7	
Command	GET, PUT, POST, DELETE	GET, SET, ANNOUNCE
Format	Binary	XML/EXI
Organization	ZigBee Alliance, HomePlug Alliance	ECHONET Consortium
Recommendation	Adopted by NIST in USA for smart grid applications	Recommended by METI in Japan for smart home applications

SMART CHARGING SYSTEMS USING OPENADR 2.0, SEP 2.0, AND SAE STANDARDS

System Architecture

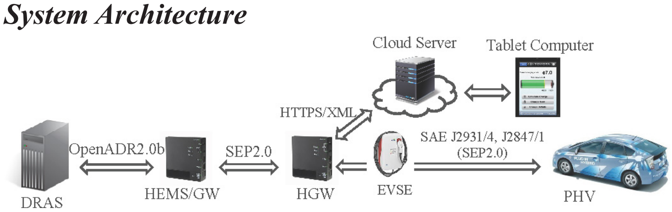


Figure 3. Developed smart charging system using OpenADR 2.0, SEP 2.0, and SAE standards.

Figure 3 shows the system architecture of smart charging systems that we implemented. In this system, DRAS sends tariff information, i.e. electricity price information, and DR events to HEMS. HEMS forwards that information to the vehicle via EVSE. The cloud server gathers the vehicle information and DR information via HGW, in which the vehicle information includes the vehicle ID, the current state of charge (SoC) of the battery, the battery capacity, and the charging rate. Then, the cloud server calculates the charging schedule based on the vehicle and DR information. The charging schedule is sent to the vehicle and the vehicle is charged according to this schedule. Note that although the cloud server manages the charging schedule of the vehicle in this system, it is also technically possible that the vehicle has the capability of the cloud server. Using a mobile app of a tablet computer, the user can check the charging schedule and the charging status and also set the charging preference (i.e., charging completion time and the amount of energy to be charged). We retrofitted a Prius Plug-in Hybrid vehicle (PHV) with 4.4 kWh batteries and EVSE so that they can communicate with each other by using power line communications over the AC charging cable. In charging PHV, the nominal voltage is 200 V and the nominal current is 10 A.

We implemented the system by using some standardized communication protocols, including OpenADR 2.0b [12] between DRAS and HEMS, SEP 2.0 [8] between HEMS and HGW, SAE standards (J2931/4 [13] and J2847/1 [14]) between EVSE and PHV. SAE J2931/4 adopts HomePlug GreenPHY (HP-GP) [15] for the communication of the physical layer between PHV and EVSE over the control pilot (CPLT) of the AC charging cable. Also, SAE J2847/1 adopts SAE2.0 for the application layer protocol, which is designed for smart grid applications and thus it supports various types of DR events and pricing structures. By using SAE J2931/4 and J2847/1, PHV and EVSE can exchange the information of DR events and pricing information provided by DRAS.

Energy Management Policies

In this system, we assume that DR events are direct control events. For that purpose, we use SIMPLE events defined in OpenADR 2.0b, which are converted by HGW to End Device Control events, defined in the DRLC function set of SEP 2.0. With the mobile app, the user can set the DR preference from two modes:

- DR priority mode:
  The charging power is reduced during DR events to comply with the DR events.
- Charging priority mode:

  The vehicle can be charged even in DR events.

Based on the selected preference, the cloud server calculates the optimal charging schedule that minimizes the charging cost by following energy management policies.

The energy management policy in the DR priority mode:

1. Comply with DR events if the user selects the DR priority mode
2. Under 1), satisfy the target SoC by the departure time set by the user
3. Under 1) and 2), select the cheapest time slots for charging
4. Under 1)-3), select earlier time slots for charging as long as the charging cost is the cheapest

The energy management policy in the charging priority mode:

1. Satisfy the target SoC by the departure time set by the user
2. Under 1), select the cheapest time slots for charging
3. Under 1) and 2), select earlier time slots for charging as long as the charging cost is the cheapest

SMART CHARGING AND VEHICLE-TO-HOME SYSTEMS USING OPENADR 2.0, ECHONET LITE, AND ISO/IEC 1511815118

System Architecture

Figure 4 shows the system architecture of smart charging and V2H systems that we implemented. In this system, the functionality of each equipment is almost the same as the previous system. The differences from the previous system are two things. One is that we retrofitted a Prius Plug-in Hybrid vehicle and EVSE so that they can support a V2H capability (the maximum discharging power of 1kW). The other is that the cloud server calculates the schedule of charging and V2H based on the information of the vehicle and DR events.

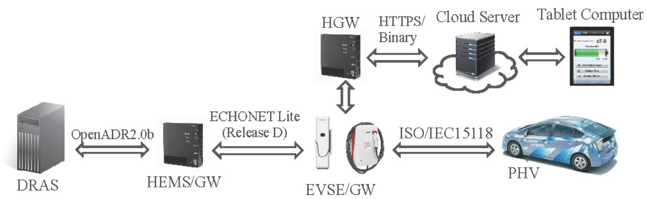


Figure 4. Developed smart charging and V2H system using OpenADR 2.0, ECHONET Lite, and ISO/IEC 15118.

We implemented the system by using some standardized communication protocols, including OpenADR 2.0b between DRAS and HEMS, ECHONET Lite (Release D) [10] between HEMS and EVSE, ISO/IEC 15118 [11] between EVSE and PHV. ISO/IEC 15118 is designed for smart grid applications and thus it supports some DR messages and pricing messages. Also, ISO/IEC 15118 adopts HP-GP over CPLT for the communication of the physical layer between EVSE and PHV. By using ISO/IEC 15118, PHV and EVSE can exchange the information of DR events and pricing information provided by DRAS. Figure 5 shows pictures of the developed equipment.

Figure 5. Pictures of developed equipment.

We found out that ECHONET Lite lacks some message sets required to realize distribution energy control and coordinated energy control such as charging/discharging schedule notification, direct load control, price information. Therefore, we added and extended some properties and class into ECHONET Lite as shown in Table 2 by reference to corresponding function sets already defined in SEP 2.0.

Table 2. The added and extended classes in ECHONET Lite and corresponding function set in SEP 2.0.

Function	Added/Extended Class in ECHONET Lite	Corresponding Function Set in SEP 2.0
Charging/Discharging Schedule Notification	Energy Schedule Property in Electric Vehicle Charger/Discharger Class	Energy Flow Reservation Function Set
Direct Load Control	Energy Limit Set Property in Electric Vehicle Charger/Discharger Class	DRLC Function Set
Price Information	Electricity Price Class	Pricing Function Set

Energy Management Policies

In this system, we assume that DR events are CPP, PTR, and LC events, defined in the DR object of ECHONET Lite. With the mobile app, the user can set the DR preference from three modes:

- DR priority (with V2H) mode:
  The vehicle performs V2H as much as possible during DR events. If V2H is not possible due to the lack of battery, charging and V2H are not performed in the DR events.
- DR priority (without V2H) mode:
  The charging power is reduced during DR events to comply with the DR events.
- Charging priority mode:
  The vehicle can be charged even in DR events.

Based on the selected preference, the cloud server calculates the optimal schedule of charging and V2H that minimizes the charging cost by following energy management policies.

The energy management policy in the DR priority (with V2H) mode:

1. Comply with DR events if the user selects the DR priority mode
2. Under 1), satisfy the target SoC by the departure time set by the user
3. Under 1) and 2), perform V2H during the DR events as much as possible
4. Under 1)-3), select the cheapest time slots for charging
5. Under 1)-4), select earlier time slots for charging as long as the charging cost is the cheapest

The energy management policies of the DR priority (without V2H) mode and the charging priority mode are the same as the previous system.

EXPERIMENTAL PLATFORM AND RESULTS

Experimental Platform

We evaluated developed systems in a demonstration platform, called the Energy Management System (EMS) Shinjuku Demonstration Center. This platform was established by Waseda University in November 2012, upon the initiative of the Ministry of Economy, Trade and Industry (METI) in Japan, for the purpose of establishing DR technology frameworks using standardized communication protocols and facilitating the industrialization of ADR technologies in Japan. 26 industry-wide companies joined this project, including utility companies, telecommunication operators, housing manufactures, home appliance manufactures, and automotive companies, for testing and evaluating ADR technologies and verifying interoperability among different manufactures' equipment.

The system model of the EMS Shinjuku Demonstration Center is depicted in Figure 6. This system consists of a power distribution control simulator (ANSWER: Active Network Systems With Energy Resources), DRAS, smart meters, HEMS, and smart home appliances. This system supports standardized communication protocols, including OpenADR 2.0b, SEP 2.0, and ECHONET Lite.

More specifically, DRAS communicates with smart meters and HEMS with OpenADR 2.0b for sending DR events and HEMS communicate with smart home appliances communicate using SEP 2.0 or ECHONET Lite for sending DR events and control signals.

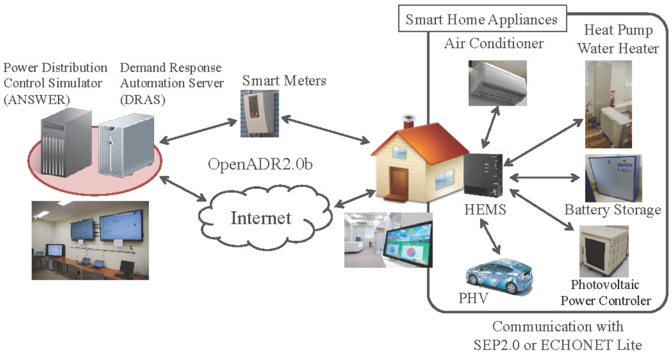


Figure 6. System architecture of EMS Shinjuku Demonstration Center.

Demand Response Events and Test Cases

In this experiment, we assumed 4 types of DR events: TOU pricing, CPP, PTR, and LC. Also, by considering some combinations of the timing of DR events and the number of events per day, we tested total 6 DR events as shown in Table 3.

Table 3. The list of test cases.

DR Events	Notification Time	Time (0–23)
TOU (Peak Shift Plan)		0–7: 12.16 JPY/kWh; 7–13: 28.99 JPY/kWh; 13–16: 54.68 JPY/kWh; 16–23: 28.99 JPY/kWh
CPP-1 (Afternoon Peak)	12PM (1-day ahead)	0–13: Non CPP Period; 13–15: Rate x 3; 15–18: Rate x 6; 18–24: Non CPP Period
CPP-2 (Morning Peak)	12PM (1-day ahead)	0–9: Non CPP Period; 9–12: Rate x 3; 12–24: Non CPP Period
PTR-1 (Afternoon PTR)	12PM (1-day ahead)	0–13: Non PTR Period; 13–16: PTR Period; 16–24: Non PTR Period
PTR-2 (Dual PTR)	12PM (1-day ahead)	0–9: Non PTR Period; 9–12: PTR Period; 12–18: Non PTR Period; 18–21: PTR Period; 21–24
LC	12PM (1-day ahead)	0–9: Non LC Period; 9–21: LC Period; 21–24: Non LC Period

In the systems, we employ multiple communication protocols for exchanging DR events and thus we need to define how to convert a DR event information from a communication protocol to another protocol. Table 4 shows the mapping of DR event information between OpenADR 2.0b, SEP2.0, and ECHONET Lite. Due to lack of a class in ECHONET Lite corresponding to Pricing Function Set in SEP2.0 used for TOU event information, we added and implemented Electricity Price Class into ECHONET Lite solely for this experiment. This class allows us to convert TOU event messages from OpenADR 2.0b to ECHONET Lite.

Table 4. The mapping of DR event information between different protocols.

DR Event	OpenADR2.0b	SEP 2.0	ECHONET Lite
TOU	ELECTRICITY_PRICE (marketContext: TOU)	Pricing Function Set	Electricity Price Class (added for the experiment)
CPP	ELECTRICITY_PRICE (marketContext: CPP)	Pricing Function Set	CPP in DR Object
PTR	ELECTRICITY_PRICE (marketContext: PTR)	N/A	PTR in DR Object
LC	SIMPLE (marketContext: LC)	DRLC Function Set	LC in DR Object

The lists of test cases for our evaluation are shown in Table 5. We evaluated the developed systems for various test cases by considering various combinations of communication protocols (SEP 2.0 or ECHONET Lite), types of energy control (distributed control or coordinated control), DR events, users' preferences for DR events, and user's behavior on PEV charging (the time when PHV is plugged-in and the expected time when charging is completed).

Table 5. The list of test cases.

a. Test cases for SEP 2.0-based distributed energy control system

Exam ID	DR Events	OpenADR2.0b Signal	SEP2.0 Signal	DR Preference	Time of PHV Cable Connected	Expected Charging Completion Time
SEP-A1	TOU	TOU(Peak Shift)	Price	DR	10:00	19:00
SEP-A2	TOU	TOU(Peak Shift)	Price	DR	12:00	19:00
SEP-A3	CPP-1	TOU(Flat) + CPP	Price	DR	10:00	19:00
SEP-A4	CPP-1	TOU(Flat) + CPP	Price	DR	12:00	19:00
SEP-A5	CPP-2	TOU(Flat) + CPP	Price	DR	10:00	19:00
SEP-A6	CPP-2	TOU(Flat) + CPP	Price	Charging	10:00	13:00
SEP-A7	LC	TOU (Peak Shift) + Simple (Level:1)	Price + DRLC (Offset:50)	DR	10:00	19:00
SEP-A8	LC	TOU (Peak Shift) + Simple (Level:2)	Price + DRLC (Offset:100)	DR	10:00	19:00

b. Test cases for SEP 2.0-based coordinated energy control system

Exam ID	DR Events	OpenADR2.0b Signal	SEP2.0 Signal	DR Preference	Time of PHV Cable Connected	Expected Charging Completion Time
SEP-B1	TOU	TOU (Peak Shift)	Price	DR	10:00	19:00
SEP-B2	TOU	TOU (Peak Shift)	Price	DR	12:00	19:00
SEP-B3	CPP-1	TOU (Flat) + CPP	Price	DR	10:00	19:00
SEP-B4	CPP-1	TOU (Flat) + CPP	Price + DRLC (12:00-14:00)	DR	11:00	19:00
SEP-B5	CPP-2	TOU (Flat) + CPP	Price	DR	10:00	19:00
SEP-B6	LC	TOU (Peak Shift) + Simple-Level	Price + DRLC	DR	10:00	17:00

c. Test cases for ECHONET-Lite-based distributed energy control system

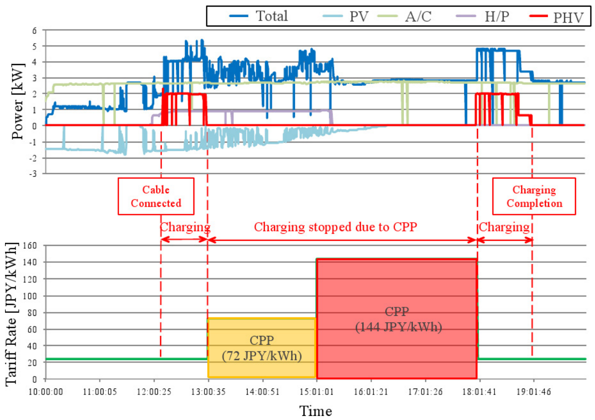
Exam ID	DR Events	OpenADR2.0b Signal	ECHONET Lite Signal	DR Preference	Time of PHV Cable Connected	Expected Charging Completion Time
EL-A1	TOU	TOU(Peak Shift)	Price	DR (w/o V2H)	10:00	19:00
EL-A2	TOU	TOU(Peak Shift)	Price	DR (w/o V2H)	12:00	19:00
EL-A3	CPP-1	TOU(Flat) + CPP	Price + DR-CPP	DR (w/o V2H)	10:00	19:00
EL-A4	CPP-1	TOU(Flat) + CPP	Price + DR-CPP	DR (w/o V2H)	12:00	19:00
EL-A5	CPP-2	TOU(Flat) + CPP	Price + DR-CPP	DR (w/o V2H)	10:00	19:00
EL-A6	CPP-2	TOU(Flat) + CPP	Price + DR-CPP	Charging	10:00	13:00
EL-A7	PTR-1	TOU(Peak Shift) + PTR	Price + DR-PTR	Charging	12:00	13:00
EL-A8	PTR-2	TOU(Peak Shift) + PTR	Price + DR-PTR	DR (w/o V2H)	10:00	13:00
EL-A9	LC	TOU(Peak Shift) + Simple-Level	Price + DR-LC	DR (w/o V2H)	10:00	19:00

d. Test cases for ECHONET-Lite-based coordinated energy control system

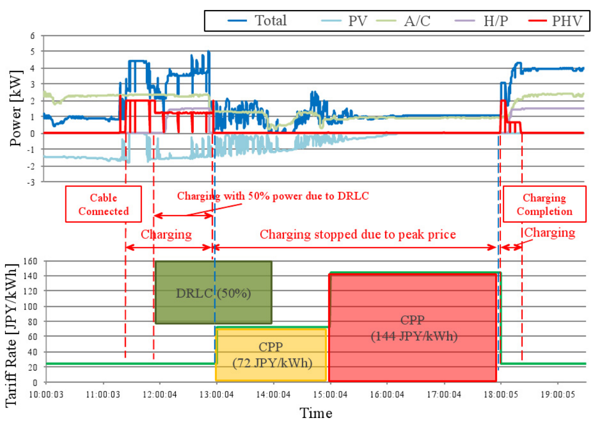
Exam ID	DR Events	OpenADR2.0b Signal	ECHONET Lite Signal	DR Preference	Time of PHV Cable Connected	Expected Charging Completion Time
EL-B1	TOU	TOU(Peak Shift)	Price	DR (w/o V2H)	10:00	19:00
EL-B2	TOU	TOU(Peak Shift)	Price	DR (w/o V2H)	12:00	19:00
EL-B3	TOU	TOU(Peak Shift)	Price	DR (w/ V2H)	12:00	19:00
EL-B4	CPP-1	TOU(Flat) + CPP	Price + DR-CPP	DR (w/o V2H)	10:00	19:00
EL-B5	CPP-1	TOU(Flat) + CPP	Price + DR-CPP + DLC (12:00-14:00)	Charging	11:00	19:00
EL-B6	CPP-2	TOU(Flat) + CPP	Price + DR-CPP	DR (w/o V2H)	10:00	19:00
EL-B7	CPP-2	TOU(Flat) + CPP	Price + DR-CPP + DLC (12:00-14:00)	DR (w/ V2H)	10:00	19:00
EL-B8	PTR-1	TOU(Peak Shift) + PTR	Price + DR-PTR	Charging	12:00	13:00
EL-B9	PTR-2	TOU(Peak Shift) + PTR	Price + DR-CPP + DLC (12:00-16:00)	DR (w/o V2H)	10:00	17:00
EL-B10	PTR-2	TOU(Peak Shift) + PTR	Price + DR-CPP + DLC (12:00-15:00)	DR (w/ V2H)	10:00	17:00
EL-B11	LC	TOU(Peak Shift) + Simple-Level	Price + DR-LC	DR (w/o V2H)	10:00	17:00
EL-B12	LC	TOU(Peak Shift) + Simple-Level	Price + DR-LC	DR (w/ V2H)	10:00	17:00

Experimental Results

Figure 7 shows experimental results of smart charging systems using OpenADR 2.0b, SEP 2.0, and SAE standards. Due to space limitation, we only show the results of the test cases SEP-A4 and SEP B-4. In this figure, we show the total power consumption (Total), the power generated by the photovoltaic (PV), the powers consumed by the air conditioner (A/C), the heat pump water heater (H/P), and PHV, respectively. From the figure, we can see that PHV complied with the DR events and thus the charging power was successfully reduced in an automated manner during the DR events. Also, PHV was charged during the cheapest TOU periods and charging was completed by the expected charging completion time.

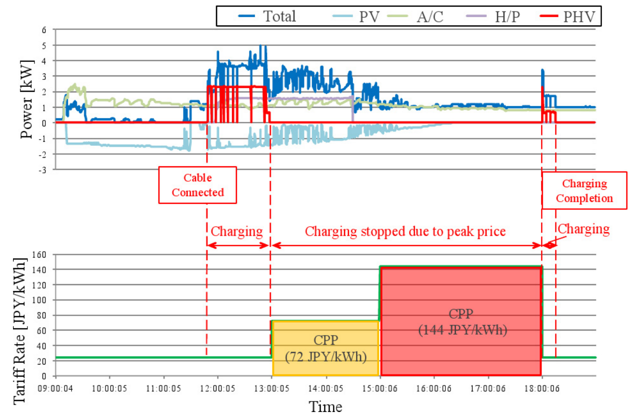


a. Result of Test Case SEP-A4 in SEP 2.0-based distributed energy control system

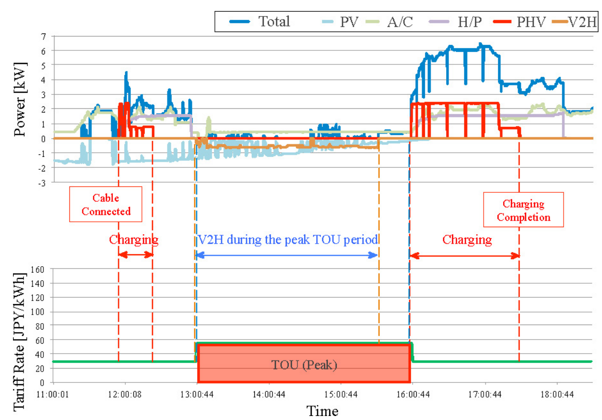


b. Result of Test Case SEP-B4 in SEP 2.0-based distributed energy control system

Figure 7. Experimental results of smart charging systems using OpenADR 2.0, SEP 2.0, and SAE standards.



a. Result of Test Case EL-A4 in ECHONET-Lite-based distributed energy control system



b. Result of Test Case EL-B3 in ECHONET-Lite-based distributed energy control system

Figure 8. Experimental results of smart charging and V2H systems using OpenADR 2.0, ECHONET Lite, and ISO/IEC 15118.

Figure 8 shows experimental results of smart charging systems using OpenADR 2.0b, ECHONET Lite, and ISO/IEC 15118. Due to space limitation, we only show the results of the test cases EL-A4 and EL B-3. In this figure, the power consumed by PHV for charging and the power discharged by PHV for V2H are shown as PHV and V2H, respectively. In Figure 8 (a), charging was successfully stopped in an automated manner during the CPP events as in Figure 7 (a). Therefore, we confirmed that the system based on ECHONET Lite and ISO/IEC 15118 can successfully perform ADR as the system based on SEP 2.0 and SAE standards can do in Figure 7. In Figure 8 (b), V2H was performed during the TOU peak period, while PHV was charged during the TOU off-peak periods and charging was completed by the expected charging completion time. In the TOU peak period, we can see that the total power consumption was significantly reduced by virtue of V2H and thus successful peak shift was achieved.

CONCLUSION

In this paper, we proposed smart PEV charging and V2H systems coordinated with HEMS that are able to support different levels of HEMS coordination and react to DR events in an automated manner. We implemented the proposed systems by employing two sets of standardized communication protocols: one using OpenADR 2.0b, SEP 2.0 and SAE standards and the other using OpenADR 2.0b, ECHONET Lite and ISO/IEC 15118. We demonstrated the feasibility of the proposed systems through experiments in the EMS Shinjuku Demonstration Center and showed that the developed systems enable ADR and peak shift by automatically reacting to DR events.

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DEFINITIONS/ABBREVIATIONS

A/C - Air Conditioner

ADR - Automated Demand Response

DR - Demand Response

DRLC - Demand Response and Load Control

DRAS - Demand Response Automation Server

CPP - Critical Peak Pricing

EMS - Energy Management System

EVSE - Electric Vehicle Supply Equipment

HEMS - Home Energy Management System

HGW - Home Gateway

H/P - Heat Pump

HP-GP - HomePlug GreenPHY

LC - Load Control

PEV - Plug-in Electric Vehicle

PHV - Plug-in Hybrid Vehicle

PTR - Peak Time Rebate

PV - Photovoltaic

SoC - State of Charge

TOU - Time-of-Use

V2G - Vehicle-to-Grid

V2H - Vehicle-to-Home