

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-of-use 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).

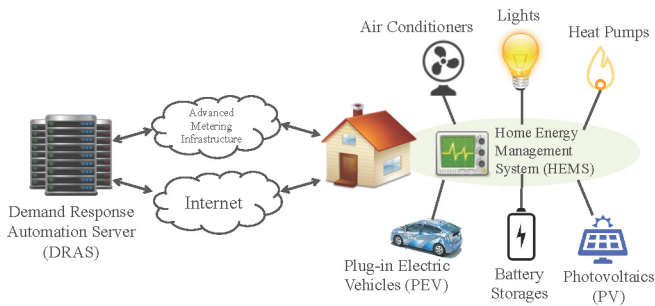


Figure 1. System architecture of home energy management systems (HEMS).

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-of-use 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)

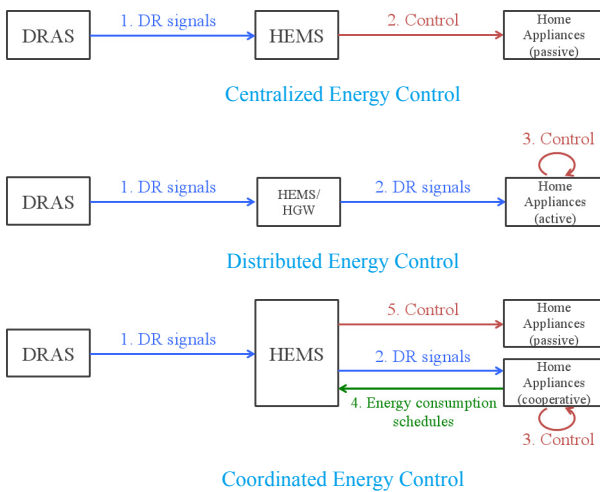


Figure 2. Different levels of home energy management.

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 appliances 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, in order to implement the coordinated energy control approach, some additional