i-Energy: Smart Demand-Side Energy Management

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Abstract Much of the discussion concerning smart grids focuses on the potential benefits of technological advances to power suppliers. However, there are many possible advantages that may benefit consumers as electricity grids exploit more of the opportunities provided by the cyber network society and emerge as a form of supporting social infrastructure. A critical element in the development of advanced consumer-friendly grids is the notion of an integrated system for energy management from the consumer's viewpoint. Here, we present such a concept—*i*-Energy—for smart demand-side energy management. The concept embodies four main elements: Smart Tap Network, Energy on Demand Protocol, Power Flow Coloring, and Smart Community. The key features of each are explained, and the characteristics and effectiveness of the required supporting technologies as demonstrated by ongoing research are presented. The importance of bringing together key stakeholders to achieve effective collaboration to implement the *i*-Energy concept is also emphasized.

1 Introduction

This chapter first introduces the concept of *Cyber-Physical Integration Systems* to develop social infrastructures in the twenty-first century such as smart electric power network systems. Then, we propose the concept of *i*-Energy for smart demand-side energy management. This differs from *the Smart Grid*. The former aims at energy management from the consumer's viewpoint while the latter from the supplier's viewpoint. The latter half of the chapter presents four steps in the realization of the *i*-Energy concept: (1) *Smart Tap Network* for monitoring detailed

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power consumption patterns of individual appliances and dynamic activities of people in homes, offices, and factories; (2) *Energy on Demand Protocol* to realize the priority-based best effort power supply mechanism as well as the automatic ceiling mechanism of power consumption in both watts (W) and watt hours (Wh); (3) *Power Flow Coloring* to allow versatile power flow controls depending on types and costs of power sources; and (4) *Smart Community* for bidirectional energy trading among households, offices, and factories in a local community. The technologies to embody each of these four ideas are presented with research achievements so far obtained.

2 Integrating the Physical Real World and the Cyber Network Society

Until the twentieth century, our society was structured in such a way that most social and personal activities took place in what we could call the physical real world. For example, appliances, furniture, housing space designs, building architectures, traffic systems, and even sporting environments are designed based on physical laws. The last decade of the twentieth century saw the cyber network society emerge, thanks to the advancement of information and communication technologies (ICT). And now, our social and personal activities are conducted in both the physical real world and the cyber network society.

To design twenty-first-century social infrastructures, therefore, it is crucial to study how we can integrate seamlessly the physical real world and the cyber network society (Fig. 1). One idea to realize this cyber-physical integration is to link and merge dynamical flows in the physical real world and the cyber network society; the former are characterized by the flows of goods, people, and energy and the latter by the flow of information.

We believe that the cyber-physical integration will be significant, not only for creating infrastructures for twenty-first-century society, but also in a more academic sense as well. In other words, the discovery of natural laws in the physical real world and the creation of basic theories which have allowed us to harness those laws for technologies have been extremely successful. Such theories include physical models represented by differential equations like the Newton and Maxwell equations. On the other hand, the foundations supporting the cyber network society can be seen in the computational theory of the Turing machine and Shannon's communication theory, on the basis of which many different kinds of ICT systems have been developed and are supporting our everyday activities. So the question is: What is the relationship between physical models on the one hand and computational and information models on the other? Is a theoretical model which could unify them possible? We believe that only after such a unified theoretical foundation has been established, will the way forward toward the cyber-physical integration be shown, leading to the creation of a sound twenty-first-century society. (Our research group is currently

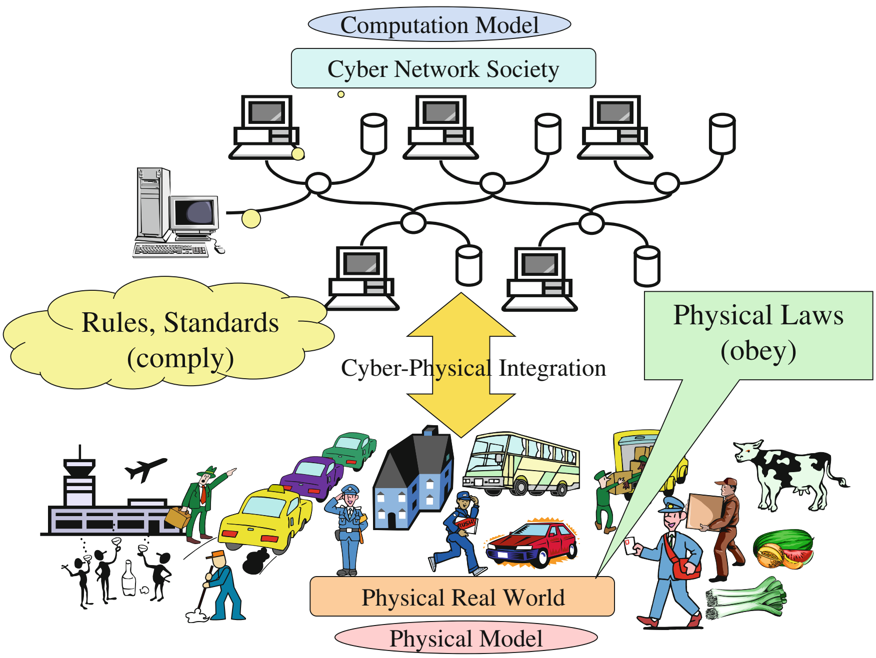


Fig. 1 Cyber-physical integration

involved in research on a hybrid dynamical system [1] as one attempt to set out a unified theory.)

Today, our social and personal activities are being supported by cyber-physical integration systems. The most striking example is *e-money*: the digitization of currency and securities. Value flows in the physical real world in the form of physical things such as precious metals, currencies, and securities, but in the cyber network society, value flows in the form of digital numbers and characters whose values are guaranteed by personal authentication and information security; these functions are critical mechanisms giving economical meaning to the flow of information in the cyber network society.

The second example is the realization of so-called *ubiquitous society*. By attaching bar codes, IC tags, and RF tags as well as microprocessors to objects in the physical real world and recording and managing the positions, types, and processing histories of these objects as information in the cyber network society, it becomes possible to associate flows of goods, traffic, and people with flows of digital data. These ID-ing methods together with location-sensing methods based on GPS and other localization/recognition devices (e.g., car license plate readers) have realized food product tracing systems, electronic highway toll collection systems, car navigation systems, cell phones, and the like. More recently, this trend has spread from objects to people as well, with experiments being performed to monitor the health and behavior of individuals with wristwatch-like devices that record biological states and physical activities.

Thus, the cyber-physical integration has created various infrastructures for the twenty-first-century society. In other words, while many people may be satisfied with currently available ICT services such as smartphones that make things more convenient and amusing, we should continue to develop new ICT to create a new social infrastructure through the cyber-physical integration. So then, we must ask "What is the next stage of the cyber-physical integration?"

3 Integrating Information and Electric Power Networks

Early computer and telecommunication systems were organized as star-shaped networks, with a single large computer or line switching machine in the center and terminals radiating outward from it. With the emergence of workstations and personal computers, however, information networks became more distributed, bidirectional, and personalized, resulting in the creation of the Internet. We should notice that this revolutionary change has been realized not only by advances in ICT (in the physical real world) but also by changes and reforms of societal rules such as the privatization of national telephone departments and the deregulation of telecommunication services (in the cyber network society).

When we envision the future of electric power networks (a major social infrastructure system in the physical real world) from this point of view, their current star-shaped networks, in which energy flows from centralized power plants to factories, offices, and households, can be expected to rapidly undergo the same process of becoming distributed, bidirectional, and personalized, thanks to physical-real-world technological advances in distributed power sources such as wind power plants, photovoltaics, fuel cells, and storage batteries, as well as complementary cyber network society policies designed to stop global warming and incubate new energy services.

Then, the critical question is how we can embody such revolutionary changes in the electric power network. A naïve idea would be to integrate the information and electric power networks by employing ICT to monitor and control electric power flows (Fig. 2). Such a slogan, however, is not enough to develop a new social energy infrastructure. Instead, we should learn from history: As is well known, packet data transmission and the IP protocol are the essential driving forces to implement the Internet. Hence, we should develop innovative technologies to implement distributed, bidirectional, and personalized electric power networks.

Accordingly, for about ten years, we have put forward the idea of *i*-Energy to devise innovative technologies, which will be described later in this chapter, and we believe they will grow as driving forces to implement the integration of the information and electric power networks like the packet data transmission and the IP protocol in the Internet.

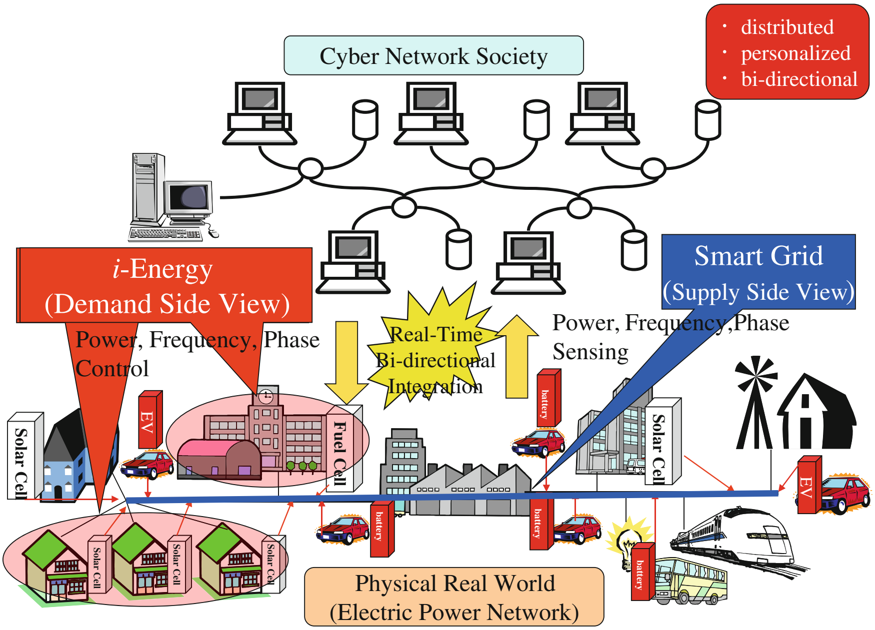


Fig. 2 Integration of information and electric power networks

3.1 i-*Energy Versus Smart Grid*

The idea of using ICT to improve electric power network management is similar to *the Smart Grid*. However, our idea of *i*-Energy differs largely from the smart grid; the former is for the demand (i.e., consumer)-side energy management while the latter for the supplier (i.e., producer)-side one (Fig. 2).

Figure 3 illustrates the scheme of demand response and dynamic pricing, which are the major functionalities supported by current smart grid systems. One of the most important roles of power suppliers is to balance the power generation with the power consumption. If the power generation capability were much larger than the expected maximum power consumption, the balance control would not be so difficult. In reality, however, the power generation capability is limited due to the cost of having excessive power plants, the reduction of greenhouse gas emissions, and the political policy to stop and/or limit nuclear power plants. The aim of smart grid systems is to make the balance even with the limited power generation capability, that is, to suppress the power consumption by asking consumers to reduce their power consumption according to power supplier's requests. In short, the scheme of current smart grid systems is designed from the power supplier's viewpoint: A supplier asks consumers to help the power balancing control by the supplier.

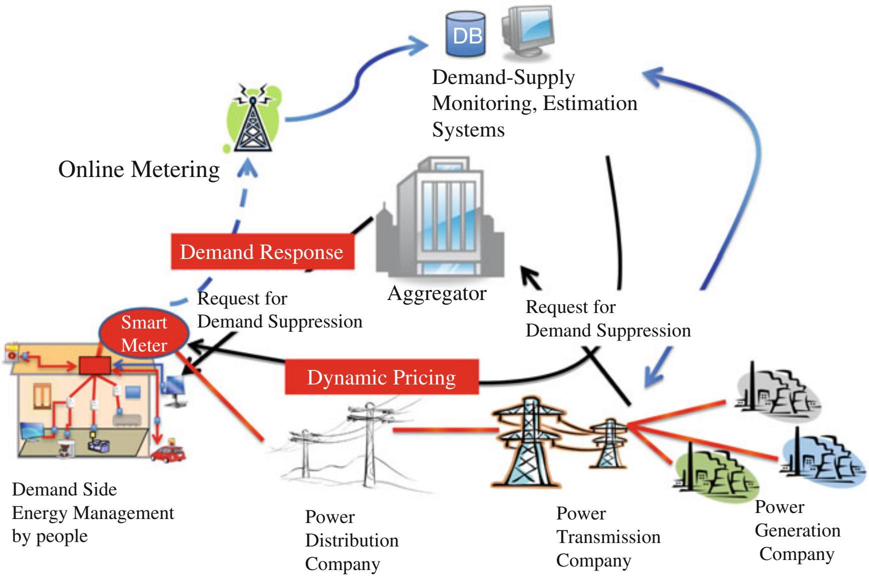


Fig. 3 Scheme of the demand response and the dynamic pricing

i-Energy systems, on the other hand, manage appliances and distributed power generation/storage devices in consumer's living spaces: households, offices, factories, and local communities. Thus, consumers manage all power consumption, generation, and storage by themselves to realize the power balance control as well as the reduction in the energy costs and the greenhouse gas emissions. That is, *i*-Energy systems enable consumers to become *prosumers*, i.e., live as both consumers and producers. Note that the population of prosumers has been rapidly growing in this century; supported by feed-in tariff systems, a large number of households have introduced photovoltaics to produce and sell electric power as well as to consume it.

The reasons why we focus on the demand-side energy management are as follows:

1. R&D balancing between power supply and demand-sides: Since electric power networks function well only when the power generation and consumption are balanced, supplier-oriented smart grid systems are not enough and consumer-oriented systems should be developed at the same time.
2. Cooperation with existing social infrastructures: Since modern countries, cities, and towns have accumulated large-scale complicated electric power networks and huge social and personal activities are conducted everyday on such infrastructures, it would not be reasonable to propose their drastic change whatever merits innovative technologies could bring. In other words, we will be able to implement innovative technologies rather easily into households, offices, factories, and communities if we can prove their merits.

3. Bottom-up creation of clean-slate social infrastructures: In developing countries, on the other hand, many people, perhaps more than half of the human population, live without stable or sufficient electric power network services. Even if their sizes are small, compact demand-side energy management systems can support such people and improve their lives at a reasonable cost, which would be far less expensive than implementing national-wide electric networks as in developed countries.

4 Technologies to Implement the *i*-Energy Concept

We have been developing technologies to implement the *i*-Energy concept and conducting real-life experiments to evaluate their utility for 10 years. The following are the four steps in our R&D road map:

- Step (1) *Smart Tap Network* for visualizing power consumption patterns of individual appliances and monitoring human activities based on observed data
- Step (2) *Energy on Demand Protocol* to realize the priority-based best effort power supply mechanism and the automatic ceiling mechanism of power consumption in both watts (W) and watt hours (Wh)
- Step (3) *Power Flow Coloring* to allow versatile power flow controls depending on types and costs of power sources
- Step (4) *Smart Community* for bidirectional energy trading among households, offices, and factories in a local community.

In what follows, overviews of our technologies and experimental results are presented. As for technical details, please refer to the references and the demo videos on the Web.

4.1 Smart Tap Network

The first step to implement the *i*-Energy concept is to develop a smart tap network: attach *Smart Taps*, which consist of voltage and current sensors, a power controller, a wireless (i.e., Zigbee) communication module, and a microprocessor to individual electric devices inside households, offices, and factories to create a sensor network that monitors detailed power consumption patterns of individual devices (Fig. 4).

We developed the following application systems by implementing smart tap networks in an ordinary apartment room, an independent house, an office room in our university, and an actual small factory, respectively:

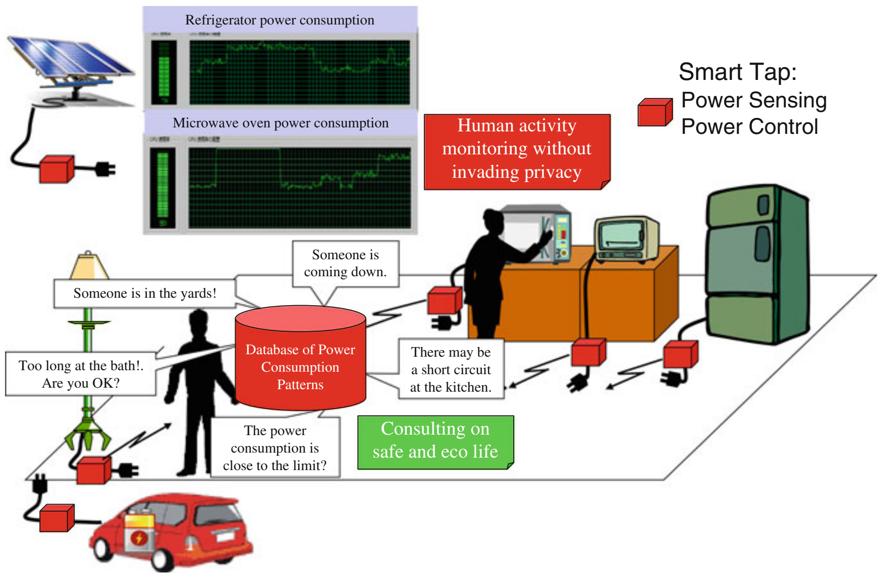


Fig. 4 Smart tap network

1. Real-Time Visualization of Power Consumption Patterns: Fig. 5 illustrates a TV screen displaying power consumptions of all appliances in the apartment room. Since the data are renewed every 0.5 s, we can monitor which appliances are operating in which modes. With this function, energy-saving awareness can be raised to switch off and/or reduce power of useless appliances. Such power control can be conducted just by clicking appliance icons on the screen by a TV game machine or a smartphone; power control commands are issued to the smart taps attached to the selected appliances. Real-life experiments at the smart apartment room showed that at best, about 20 % power reduction in Wh a day can be attained with this real-time visualization and control system.
2. The smart tap we developed is designed to measure the voltage and current at 20 kHz sampling rate, which enables us to identify types of appliances by analyzing the current waveform over one AC cycle (see Fig. 6). We developed a novel method of appliance identification, by which 16 different types of home appliances can be identified with 99 % accuracy [2]. This means that an appliance can be identified simply by plugging it into a socket. Our recent study showed that aging phenomena and malfunctions of appliances can be detected by analyzing current waveforms, which is useful for early detection of problems with devices, thereby contributing to a safe and secure life.
3. The power control of some appliances is done manually by a person, while for others, it is done automatically. If we can recognize which power control events are by a person, we can estimate his/her location since the location of each smart tap is known a priori. In fact, the newest version of the smart tap is implemented

Fig. 5 Real-time visualization of individual appliance power consumption: Every 0.5 s, the consumed power is displayed on *top* of each appliance icon. By clicking an appliance icon, we can monitor its power consumption profile as well as control its supplied power. The overall power consumption pattern in the apartment room can be monitored to analyze which appliances consume how many watts

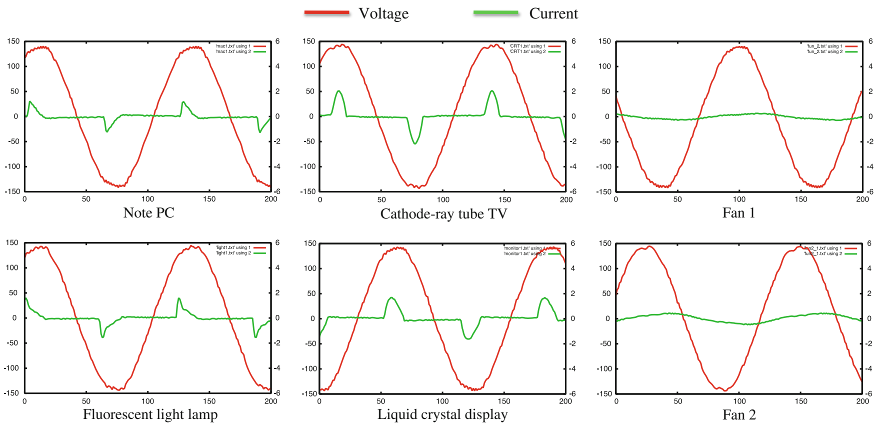


Fig. 6 Voltage and current waveforms of appliances. While the former is maintained constant, the latter varies a lot from appliance to appliance

in a wall socket. We developed a human activity monitoring system in the smart apartment room, which estimates the motion trajectory of a person based on manual power control events. The system can be used, for example, for children living away to monitor the degree of activities of their old parents without directly intruding into their privacy. Moreover, patterns of manual operations of

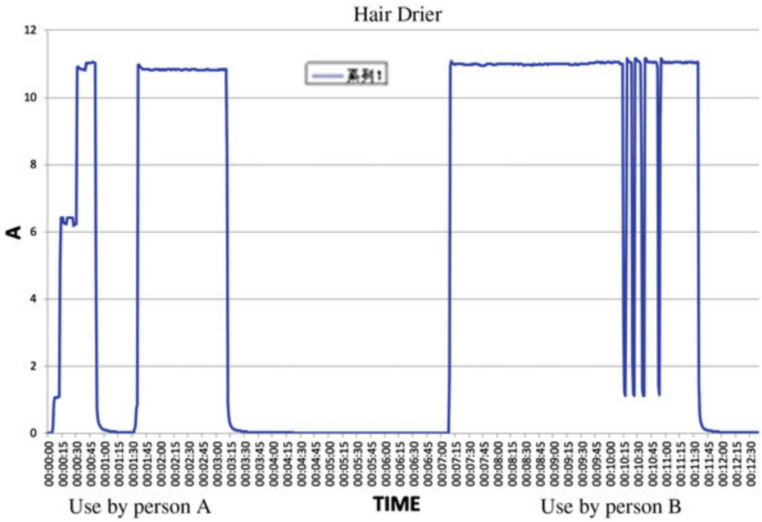


Fig. 7 Usage patterns of a hair drier

appliances vary a lot person by person. Figure 7 shows power consumption patterns of a hair drier by different persons. By learning such appliance usage patterns, it is possible to estimate who is using an appliance.

The demo video showing fundamental functions of the smart tap and the real-time power consumption monitoring system with the appliance recognition and the malfunction detection is available at http://www.youtube.com/watch?v=QRQ72xtzDHE.

4.2 Energy on Demand Protocol for Intelligent Power Management

While raising awareness about energy saving by visualization systems like the one described above does lead to a reduction in wasted energy, the effectiveness of such manual power control methods is nevertheless limited and moreover hard to maintain for a long time; people are busy and prone to get lazy. Accordingly, the second step of the *i*-Energy concept explores an automatic power control mechanism.

The *i*-Energy concept is best characterized by a novel automatic power control method named *Energy on Demand* (EoD) that supplies electric power based on power demand messages issued from appliances [3]. Its basic protocol is as follows (Fig. 8):

1. When an appliance is switched on or changes its operation modes, a power demand message describing the required power and its priority, which we call *Quality of Energy* (QoEn), is issued from the appliance to the power manager.

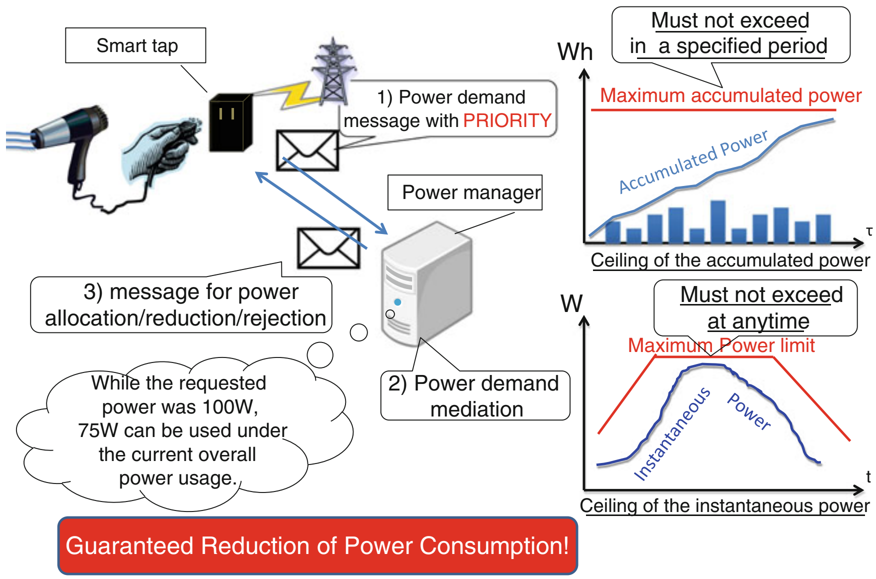


Fig. 8 Scheme of the energy on demand

Note that for simple appliances such as heaters and fans, smart taps attached to them detect switching events and issue messages, while so-called smart appliances, which can directly communicate with the power manager via a network, can issue messages by themselves as well as monitor and control consuming power according to requests from the power manager. Note also that the power manager may be installed inside a house or a cloud energy service provider may support its functions.

2. The manager mediates such power demands from appliances taking into account available energy sources and appliance priorities as well as human activity patterns, which have been learned using the sensor network described above. This mediation is conducted based on *the best effort policy*; some demands with low priorities may not be satisfied. For example, garden lamps might not be supplied power or 75 W might only be supplied in response to a 100 W demand.
3. Power is supplied to the appliance only after a power supply permission message is received by the smart tap attached, which in turn controls the power as specified in the permission message.

To attain substantial power savings by the priority-based best effort power supply mechanism described above, ceiling values in both W and Wh for the power demand mediation are specified by a human power manager. The red lines in the right graphs in Fig. 8 illustrate such ceiling value profiles. At the power demand mediation process in the second point of the basic protocol given above, the power manager supplies power only when the ceiling constraints are satisfied. That is, if the acceptance of a new power demand leads to the violation of the

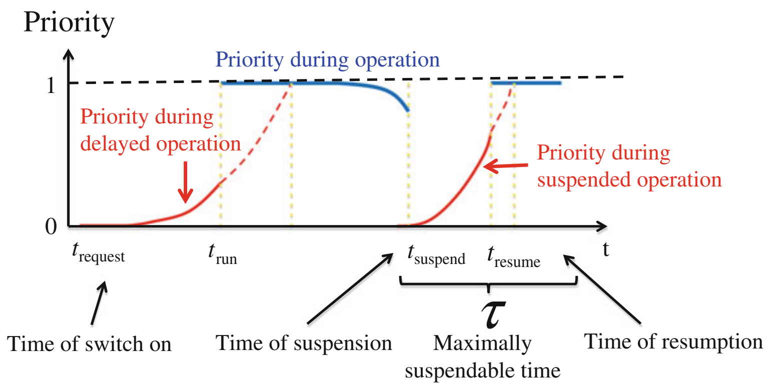


Fig. 9 Dynamic property of the priority of an air conditioner

ceiling constraints, the manager selects the appliance with the least priority and asks it to reduce or cut off the power so that appliances with higher priorities can be supplied power. In other words, appliance operations with low priorities may be interrupted when a new demand with a higher priority is issued. Consequently, the EoD system can guarantee the user-specified reduction rate of power consumption in both W and Wh.

As described above, the power saving rate is specified by a user and its attainment is 100 % guaranteed by the EoD system. So the power saving rate is not a goal to achieve or a performance evaluation measure of the EoD system. Instead, the performance of the EoD system should be measured by how well the user's quality of life (QoL) is maintained. To this end, the priority specification of each appliance is crucial.

In the EoD system, the priority changes dynamically depending on appliance characteristics and human activity patterns in individual households, offices, and factories. For example, Fig. 9 illustrates the dynamic priority profile of an air conditioner. Even if switched ON, its operation can be delayed (time-shiftable characteristic). Moreover, the amount of power supply can be changed (power controllability) and the power supply can be suspended during its operation (temporary interruptible characteristic). The priority increases during delay and suspension periods to start/resume operation when the priority becomes high enough. On the other hand, the priority decreases after sufficient operation, because the air temperature is maintained for a while even if an air conditioner stops. This dynamic priority modification mechanism allows the EoD system to make full use of appliance utility even under the power ceiling control. Currently, we are studying modeling and learning methods of human activity patterns from power consumption data measured by the smart tap network, which will enable the EoD system to adjust the appliance priority based on human activities.

Figures 10 and 11 show the experimental results of one-day real-life activities by a university student at the smart apartment room, where the EoD system with

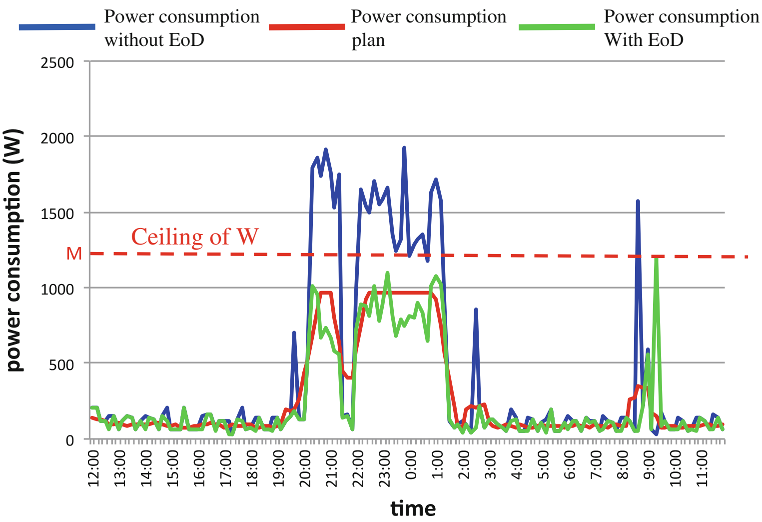


Fig. 10 Instantaneous power consumption profiles of one-day real-life experiment at the smart apartment room (see text)

smart taps and smart appliances is implemented. Figure 10 illustrates the instantaneous power consumption profile and Fig. 11 the accumulated one. The blue lines in the figures indicate the power consumption data without the EoD system, the red the power consumption plans to comply with the ceilings (30 % reduction of the one-day accumulated power and 1,200 W as the maximum instantaneous power), and the green the actual power consumption data with the EoD system. Note that while the constant value, i.e., 1,200 W, was specified as the instantaneous power consumption ceiling in Fig. 10, an arbitrary shaped ceiling profile can be set by a user taking into account daily activities and dynamic pricing data. We conducted a series of weekly real-life experiments at the smart apartment room to evaluate QoL by setting the ceiling of W as 1500 W and the accumulated power reduction rate a day as 10, 30 and 50 %, respectively. The subjective evaluation proved that QoL was not damaged significantly even with 50 % power saving. Currently, we are developing a quantitative QoL evaluation measure, whose validity will be tested with a variety of lifestyles as well as living environments.

In most smart grid projects, demand response and/or dynamic pricing mechanisms have been introduced to reduce the peak power demand. As is well known, however, the actual power reduction is uncertain and fluctuates from time to time. Moreover, the power reduction cannot be attained in real time. With the EoD system, on the other hand, the instantaneous power consumption can be automatically reduced in real time by setting the ceiling value for W. That is, when utility companies are allowed to set and modify ceiling values based on contracts with consumers, EoD systems work as real-time automatic demand response systems.

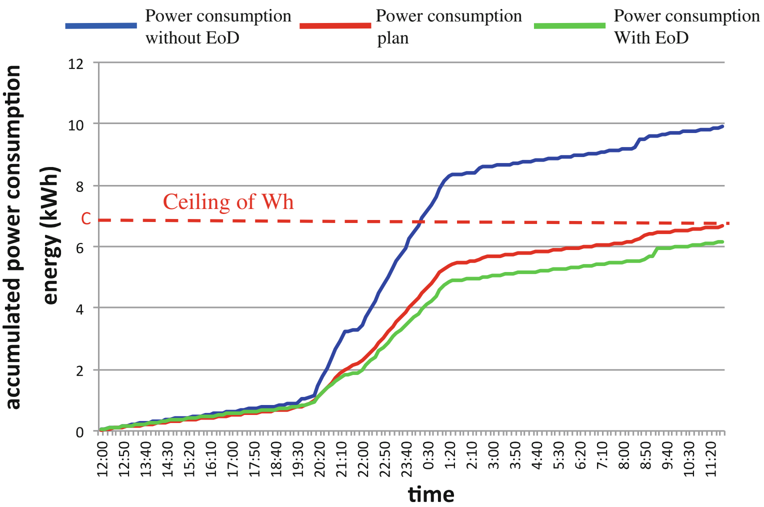


Fig. 11 Accumulated power consumption profiles of one-day real-life experiment at the smart apartment room (see text)

The demo video of the EoD system at the smart apartment room is available at http://youtube/rTgxpD7mAwU. We believe that the EoD can be a driving force to introduce revolutionary changes in our energy infrastructures just as the packet data transmission and the IP protocol have done in communication infrastructures.

4.3 EoD-based Battery Design and Management and Power Flow Coloring

The third step of the *i*-Energy concept realization is the management of multiple power sources: power generators and storage batteries. Toward this end, we first developed the EoD-based battery design and management system [4]. The system consists of two processes: One is the battery design and management plan generation and the other the real-time battery management (i.e., charge/discharge control).

4.3.1 Battery Design and Management Plan Generation

Figure 12 illustrates the basic idea of our EoD-based battery design and management plan generation. Given an expected power consumption profile without the EoD system ($D(t)$, the dotted line in the upper graph of Fig. 12) as well as the ceiling specifications in W and Wh, the EoD system first makes a power usage plan satisfying the ceilings, which is denoted as $PD^{PLAN}(t)$ and illustrated by the solid line in the upper graph of Fig. 12 (see also the blue and red lines in Fig. 10).

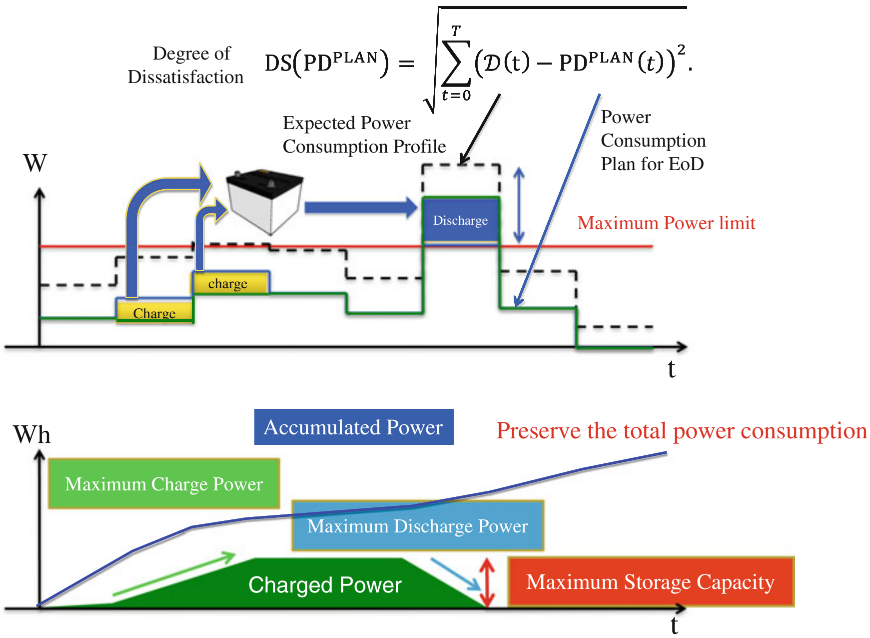


Fig. 12 Optimal charge/discharge planning and battery design to minimize the degree of dissatisfaction

The gap between these profiles, $DS(t) = D(t) - PD^{PLAN}(t)$, implies the degree of user's dissatisfaction; while a user wants to use appliances, some of such demands are not satisfied due to the power ceilings.

Our aim of employing a storage battery is to reduce this degree of dissatisfaction. That is, the battery design and management plan generation process conducts the minimization of the totally accumulated degree of dissatisfaction by using a battery, which gives us a new power usage plan $PLAN^*$ with much less user dissatisfaction while complying with the ceilings, the optimal battery characteristics, and its optimal charge/discharge plan:

$$PLAN^* = \underset{PLAN}{\arg\min}\, DS(PLAN) = \sqrt{\sum_{t=0}^{T} (D(t) - PD^{PLAN}(t))^2}.$$

The basic idea to conduct the optimization to derive $PLAN^*$ is to charge when $DS(t)$ is small and discharge when $DS(t)$ is large while keeping the balance between charged and discharged powers as well as considering charge/discharge losses. Note that constraints on the battery capacity or charging/discharging capabilities need not be specified in this optimization process; they will be derived from the optimization process as described below. Note also that the ceiling of Wh, which was set for the EoD system, is preserved. That is, while the total consumed power is reduced to comply with the pre-specified ceiling of Wh, the degree of dissatisfaction can be reduced with the battery management. The bottom graph in Fig. 12 illustrates the profiles of the accumulated power to be supplied (consumed) from the utility line and the accumulated charged power in the battery.

This optimization process gives us

1. the optimal power usage plan, $PLAN^*$, with much less user dissatisfaction than that by the original EoD system and
2. the optimal charge/discharge plan of the battery (the bottom graph in Fig. 12), which then gives us the following design specifications of the battery:
   (a) the required battery capacity = the peak value of the accumulated charged power in the battery,
   (b) the required charging capability = the maximum positive gradient of the accumulated charged power in the battery, and
   (c) the required discharging capability = the maximum negative gradient of the accumulated charged power in the battery.

Figure 13 shows the experimental results using one-day real-life data at the smart apartment room, which demonstrate that a very small battery with only 420 Wh capacity is enough for the EoD system to attain a 30 % reduction in Wh and 1,000 W ceiling. Note that the total power consumption a day without the EoD system in this experiment is about 12 KWh, which is the standard in Japanese households. Figure 14 illustrates how $DS(PLAN^*)$ changes by reducing the ceiling of W, which proved that the degree of dissatisfaction stays constant even if the ceiling is reduced by more than 50 % from that without the EoD system. It should be noted that this significant peak-cut gives large energy cost savings for those consumers whose energy pricing plans include peak demand charging (W) as well as accumulated power consumption charging (Wh).

4.3.2 Real-Time Battery Management

To realize the real-time battery management, i.e., the dynamic charging and discharging control, the EoD system described above, which only mediates power consumption demands from appliances, should be augmented so that it can mediate power supplies from multiple power sources. We first introduced the *load factor profile* to characterize the availability of a power source (Fig. 15):

(a) The profile takes a monotonically increasing curve ranging from 0 to 1.
(b) The horizontal location of the profile is specified and dynamically shifted left and right depending on the planned power supply at t of the power source, which is depicted by the vertical blue dotted line in Fig. 15. In the case of a battery, when its planned power supply is charging, its profile is shifted left into the negative power supply area for the battery to operate like a power-consuming appliance, while in discharging, the profile is shifted right in the

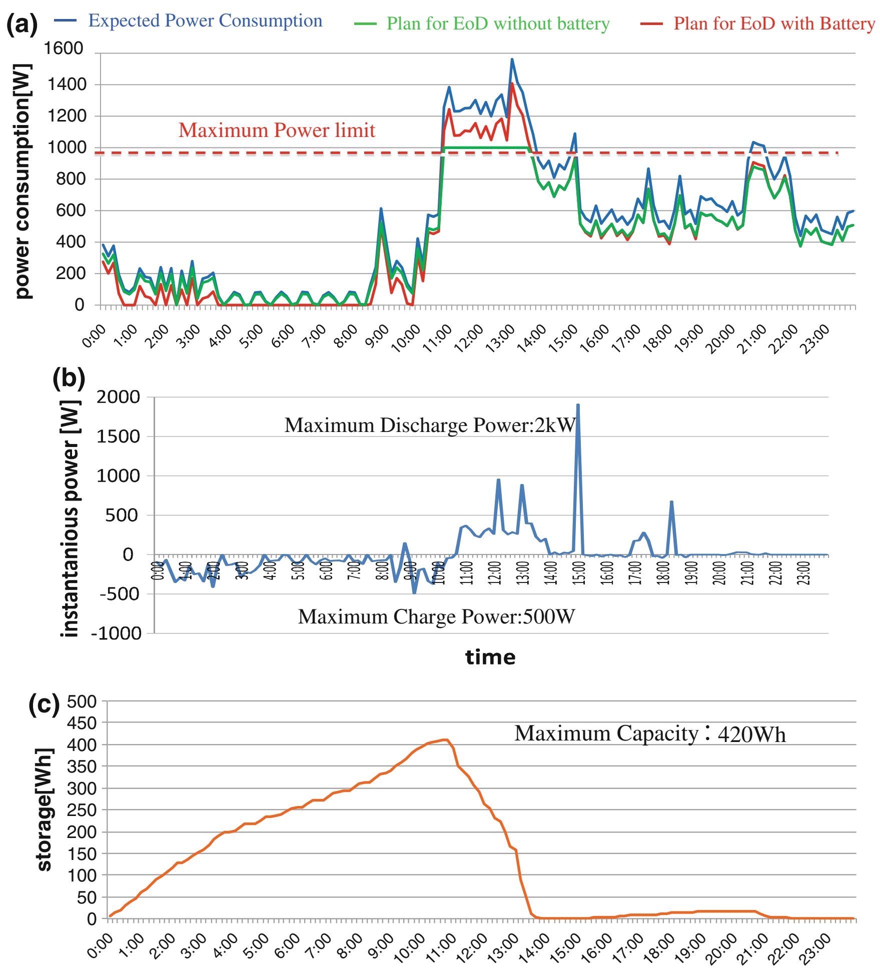


Fig. 13 Experimental results of the battery design and management using one-day real-life data at the smart apartment **a** power usage plans **b** charge (negative power usage) /discharge (positive power usage) plan for the battery **c** accumulated power profile in the battery

positive power supply area for the battery to work as an ordinary power supply.

(c) The gradient of the profile is changed depending on the available accumulated power to be consumed by the end of the planed period, e.g., a day or a week. That is, if more power than planned has been consumed by t, the gradient gets steeper, while if less power has been consumed, the gradient gets gentler.

We developed the real-time power mediation algorithm among both power sources and appliances using appliance priority values and power source load factors:

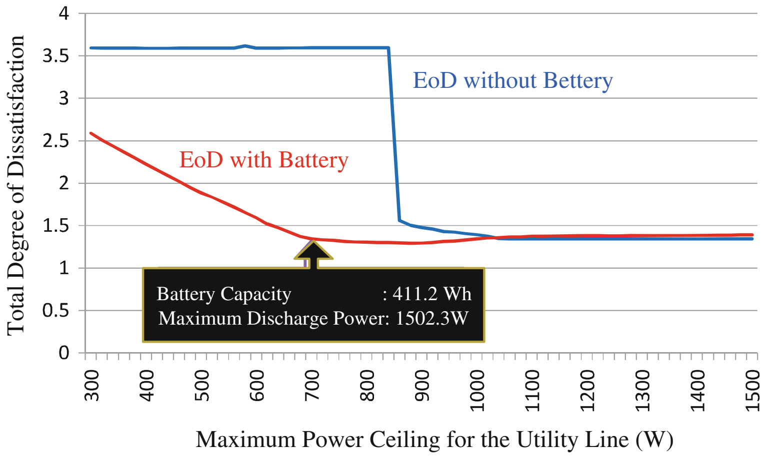


Fig. 14 Relation between the degree of dissatisfaction and the maximum power ceiling

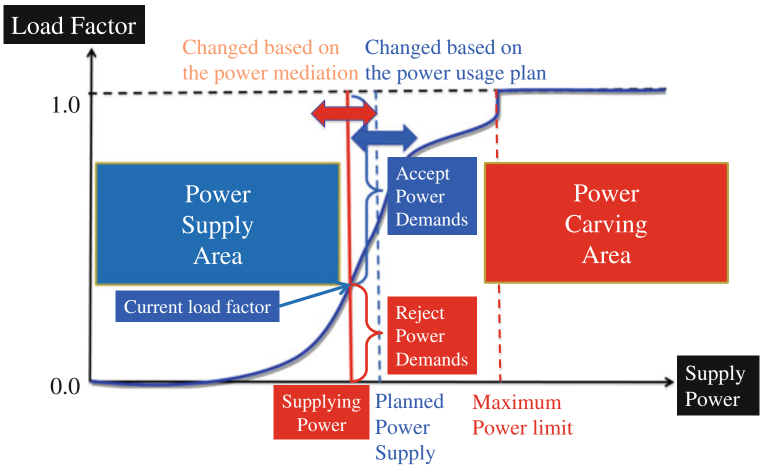


Fig. 15 Load factor profile (see text)

1. Given the currently supplying power denoted by the vertical red line in Fig. 15, the intersecting point with the load factor profile specifies the current load factor of the power source.
2. Intuitively, a power demand request from an appliance whose priority value is larger than the current load factor will be accepted for the power source to supply power, while that with a smaller priority value will be rejected.
3. When multiple power sources can supply power in response to a new power demand request from an appliance, the power source with the least current load factor is selected to supply power to that appliance.

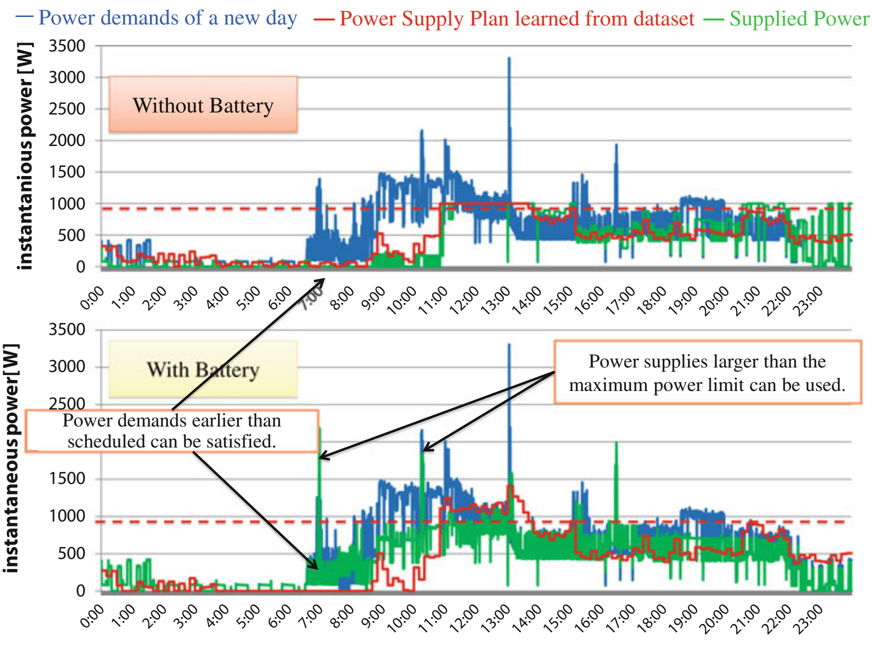


Fig. 16 Experimental results of the EoD systems with and without battery (see text)

As for technical details of the real-time battery management system implemented based on this power mediation algorithm, see [4].

Figure 16 shows the experimental results using one-day real-life data at the smart apartment room, where the power supply plans with and without a battery (the red lines in Fig. 16) were generated from the same daily power consumption dataset at that room and a power demand profile of a new different day (the blue lines in Fig. 16 representing the same data) was used to evaluate the performance. We can observe the effectiveness of the battery management system:

(a) In the power supply plan for the EoD system with a battery, more power than the ceiling, 1,000 W, can be supplied to reduce the degree of dissatisfaction.

(b) The green lines in Fig. 16 illustrate the real-time power supply profiles through the power mediations by the EoD systems with and without a battery. The real-time load factor- and priority-based battery management system can dynamically mediate power sources as well as power consumption demands to comply with the power demand (the blue lines in Fig. 16) as faithfully as possible reducing the degree of dissatisfaction:

1. With a battery, the system can supply enough power even if power demands are issued earlier than planned (e.g., get up earlier than usual).
2. With a battery, power demands larger than the plan as well as the ceiling of W can be satisfied (e.g., multiple appliances happen to be used simultaneously).

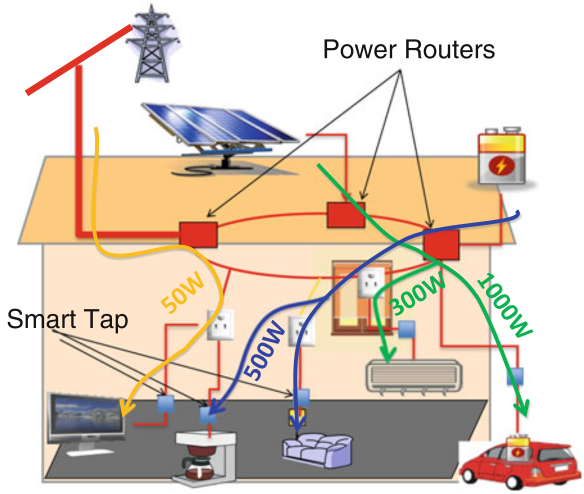
In short, even with a small-size battery, the augmented EoD system can improve QoL while complying with the ceiling constraints for power saving. Note that the real-time load factor- and priority-based battery management system can be used for managing a variety of power sources by designing their load factor profiles based on their power generation characteristics. Currently, we are implementing the EoD-based battery management system in an independent smart house to evaluate its effectiveness in the real lives of a variety of families as well as designing load factor profiles for photovoltaics and fuel cells.

4.3.3 Power Flow Coloring

Our idea to further augment the management of power generators and storage batteries described above is illustrated in Fig. 17, where what we call *power routers* are attached to individual power sources in addition to smart taps attached to appliances. Both types of power control devices are connected through wired and/or wireless networks to form a cooperative distributed power network. A novel power control mechanism named *the power flow coloring* enables us to design versatile power flow patterns between power sources and appliances. That is, we can "color" power flows depending on their sources and apply different controls based on the colors. For example, watch a TV with the utility supplying power, use an air conditioner with photovoltaic power, make coffee using power stored in a battery, and mix 60 % photovoltaic power and 40 % battery power to operate a heater. As the ubiquitous society described in Sect. 2 has done, this ID-ing of electric power will change our lifestyles as well as open exploration into new energy services and businesses which will drastically reduce energy costs and CO_2 emission in our society.

While power flow coloring is physically impossible, it can be realized by making full use of the concept of virtualization, which has been employed widely in computer systems and the Internet to enrich computational functionalities and communication services even with limited physical resources. Currently, we are developing power routers which can control powers cooperatively with each other as well as with smart taps. We believe that with power routers, the real-time load factor-based power source mediation method developed for the EoD-based battery management can be augmented to realize the cooperative control of multiple power sources. To realize the power flow coloring as illustrated in Fig. 17, a power demand message from an appliance should include the specification of the amounts of power to be supplied from individual power sources as well as the power demand priority. The power manager mediates such demands to determine how much power should be supplied from which power sources and issues power control messages to power routers and smart taps. The demo video of an early version of the power flow coloring with smart taps alone is available at http://www.youtube.com/watch?v=v41NZOmimQc.

Fig. 17 Power flow coloring



4.4 *Smart Community for Bidirectional Energy Trading Market*

While the CO_2 reduction effect by a single household might not be that significant, greater reductions are possible if the in-house EoD system described so far is expanded to a local community. This is the fourth step of the *i*-Energy concept realization. When a group of in-house EoD systems are linked with each other to form a *smart community* system, a new energy trading market will be created, where colored powers including positive powers from different power sources, negative powers (i.e., power saving), and available battery capacities (i.e., storable powers for later use) will be exchanged bidirectionally among individual households (Fig. 18). Note that whereas such bidirectional power exchanges over utility power lines are not allowed in many countries like Japan, we can implement them without any problems inside condominium buildings and local areas with private power lines.

A smart community is not a just physical power network that delivers and receives energy, but also a cyber economic network that allows participants to trade energy, thereby making it possible to offer each household large incentives to save power and cut CO_2 emissions. For example, a household may largely lower the energy ceiling setup of its in-house EoD system, even if that may introduce the degradation of QoL (e.g., slightly colder in winter or slightly hotter in summer) to get the economic benefit of selling leftover energy and/or megawatts (i.e., guaranteed power reduction can be regarded as an item with economic value to be traded). Such economic incentives will make large energy savings and CO_2 reduction possible to a technically difficult level. It is exactly the goal of our *i*-Energy project, in that it will create a new social infrastructure and a new way of living. Currently, we are developing a power trading system among in-house EoD

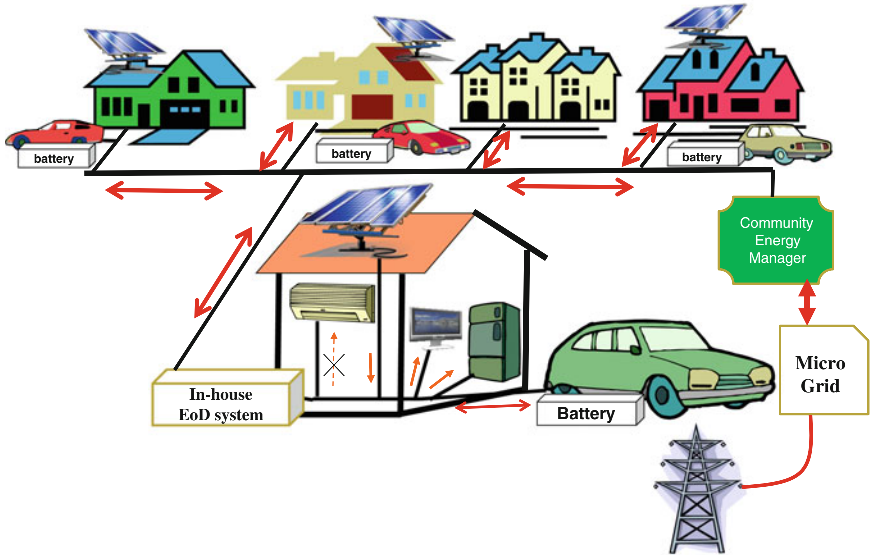


Fig. 18 Smart community for bidirectional energy trading

systems, where mechanisms to guarantee the stability of the physical power network as well as to allow us to implement versatile energy services are being studied.

5 Concluding Remarks

As noted at the beginning of this chapter, while cyber-physical integration plays a crucial role to design new social infrastructures in the twenty-first century, a unified theory has to be created to seamlessly bridge computation and information models and physical models. Moreover, to change social infrastructures dramatically, systematic efforts in business as well as in R&D must be made to bring together activities in many fields. To implement the *i*-Energy concept, for example, collaboration among a variety of industrial fields such as home appliances, storage batteries, electric cars, housing, ICT systems, and utilities should be established. To this end, we have set up the *i*-Energy Working Group (http://www.i-energy.jp) which coordinates activities among industry, academia, and government. The smart apartment room and smart house systems described in this chapter have been developed by collaboration among Working Group members, and we welcome any parties who can share their interest with us.

References

1. Kawashima H, Matsuyama T (2005) Multiphase learning for an interval-based hybrid dynamical system. IEIC Trans. Fundam E88-A(11):3022–3035
2. Kato T, Cho H, Lee D, Toyomura T, Yamazaki T (2009) Appliance recognition from electric current signals for information-energy integrated network in home environments. Int J Assistive Rob Syst 10(4):51–60
3. Kato T, Yuasa K, Matsuyama T (2011) Energy on demand: efficient and versatile energy control system for home energy management. Second IEEE international conference on smart grid communications, pp 410–415
4. Kato T, Tamura K, Matsuyama T (2012) Adaptive storage battery management based on the energy on demand protocol. Third IEEE international conference on smart grid communications, pp 43–48