i-Energy

~ Informationization of e-Power Flows by Integrating Information and e-Power Networks ~

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1. Integrating the Physical Real World and the Cyber Network Society

1. 1 Background and Objective

Until the 20th-century, our society was structured in such a way that most social activities took place in what you could call the "physical real world." After the last decade of the 20th-century, a "cyber network society" began to emerge thanks to the advancement of information and communication technologies (Fig. 1). While the physical real world is governed by physical and chemical laws such as gravity and human biological characteristics, activities in the cyber network society are designed based on “artificial” standards, regulations, laws, and so on.

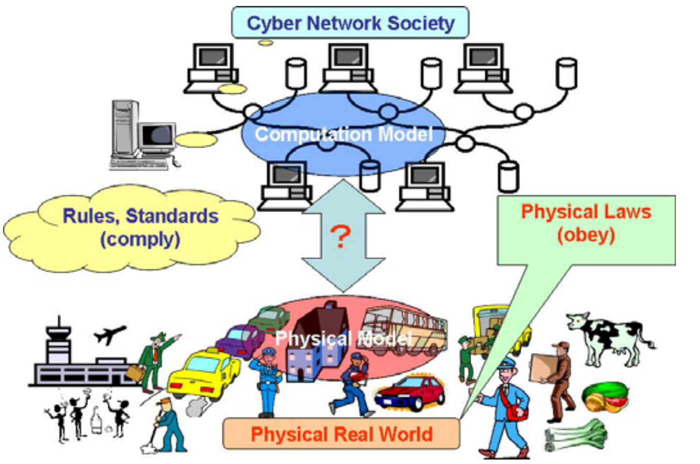


Figure 1: Physical Real World and Cyber Network Society

To design 21st-century social infrastructures, therefore, it is crucial to study how we can integrate the physical real world and the cyber network society. One idea to realize this cyber-real integration is to link and merge dynamical flows in the physical real world and the cyber network society; the former is characterized by the flows of goods, people, and energy and the latter by the flow of information.

We believe that the cyber-real integration will be significant, not only for creating infrastructures for 21st 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, such as 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 theories of the Turing machine and Shannon's communication theory, on the basis of which many different kinds of information systems have been developed and are being used today.

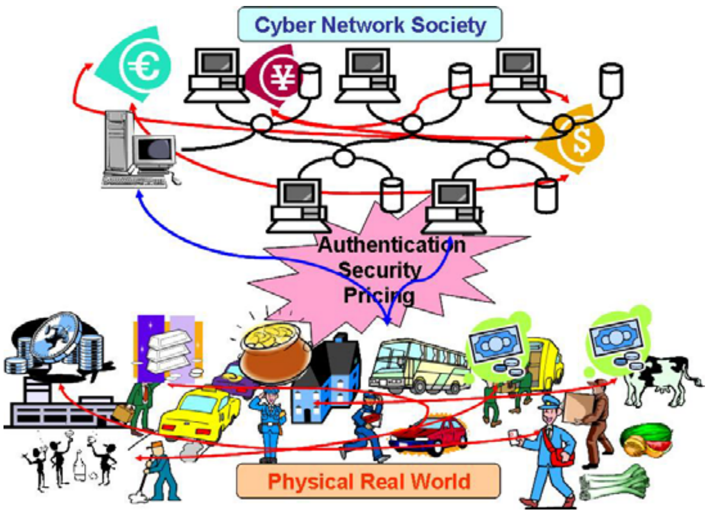


Figure 2: Informationization of Currency and Securities

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 theoretical foundation has been established, the way forward toward the cyber-real integration will be shown, leading to the creation of a sound 21st -century society. (Our research group is currently involved in research on a Hybrid Dynamical System [1] as one attempt to set out a unified theory, but that will be discussed elsewhere.)

1.2 Examples of the Cyber-Real Integration

It turns out that the physical real world and the cyber network society have already begun to merge. The most striking example of this is the digitization of currency and securities. Value flows in the physical real world in the form of physical things like precious metal, currency, and securities, but in the cyber network society value flows in the form of digitalized numbers and characters whose values are guaranteed by personal authentication and information security, which are critical rules giving meaning to the flow of information in the cyber network society (Fig. 2).

The second example is the realization of so called ubiquitous society. By attaching barcodes, IC tags, and RF tags to physical objects in the physical real world and recording and managing the positions and types 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 IDing methods together with location sensing methods based on GPS and GIS have realized food product tracing systems, electronic highway toll collection systems, car navigation systems, cell phones, and the like (Fig. 3). More recently this trend has spread from objects to people as well, with experiments being performed to monitor the health and activity of individuals with wristwatch-like devices that record biological states and physical activities.

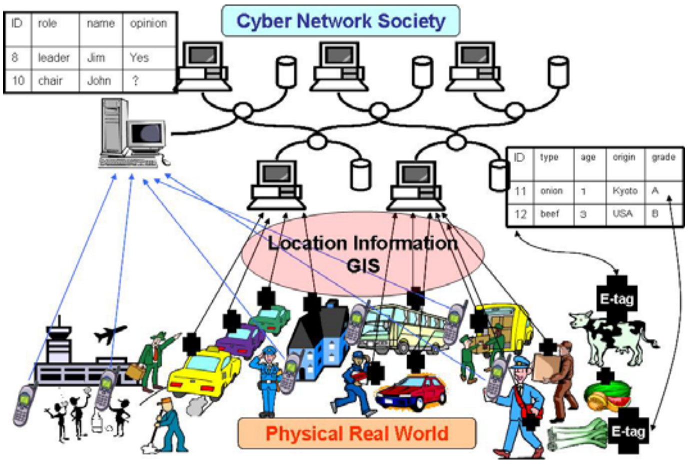


Figure 3: Informationization of Flows of Goods, Traffic and People (Realization of Ubiquitous society)

Thus, the cyber-real integration has created various infrastructures for 21st-century society. In other words, while many people may be satisfied with information and communication technologies (ICTs) that make things more convenient and comfortable, we should continue to develop new ICTs to create a new social infrastructure through the cyber-real integration.

So then we must ask, what is the next stage of the cyber-real integration?

2. Integrating Information and e-Power Networks

Early computer and telecommunication systems were star-shaped networks, with a single large computer or switching machine in the center and terminals radiating outward from it. With the emergence of workstations and personal computers, however, the exchange of information became more distributed, bi-directional, and personal, resulting in the creation of today's super-distributed network (a.k.a. the Internet). We should notice that this revolutionary change has been realized not only by advances in information communication technologies (in the physical real world) but also by changes and reforms of societal rules such as the privatization of Nippon Telegraph and Telephone Public Corporation, a Japanese public telephone company, and the deregulation of telecommunication services (in the cyber network society).

When you envision the future of electrical 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, bi-directional, and personal thanks to physical real world technological advances in wind power plants, solar cells, fuel cells, and storage batteries, as well as complementary cyber network society policies designed to stop global warming. Accordingly, for the past several years we have put forward the idea of "i-Energy: Informationization of e-Power Flows by Integrating Information and e-Power Networks" with the goal of creating a new social energy infrastructure, and have directed our R&D activities toward this end (Fig. 4). We believe this is the next stage of the cyber-real integration for developing 21st-century social infrastructure.

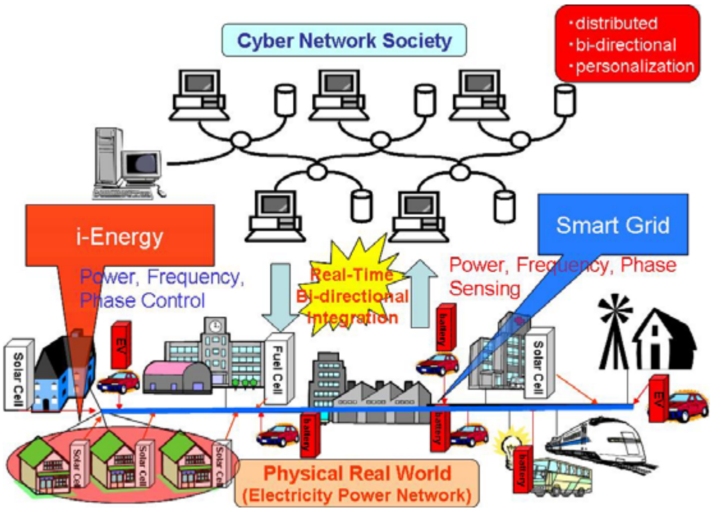


Figure 4: Integration of Information and Electricity Networks

Using information communication technologies to improve e-power network management is similar to the "Smart Grid" idea which has received a lot of attention thanks to the Green New Deal proposed by the Obama Administration last year. However, our idea of i-Energy differs in several important respects from the Smart Grid.

Namely, the Smart Grid idea is conceived in terms of the nationwide public e-power transmission networks that are operated and run by e-power companies, which are therefore subject to public laws, making it impossible for individuals or businesses to freely manage their own energy unfettered by such laws.

On the other hand, the i-Energy manages privately-owned lines within households, institutions, and communities which would be operated and run by individuals and businesses, making a completely unprecedented and very advanced type of energy management system possible. Also, looking at yearly changes in CO2 emissions in Japan, , it is obvious that there is only limited room for reductions in industries so attention is naturally turned to reducing emissions in households and offices. You could say that the i-Energy concept is designed to solve this problem.

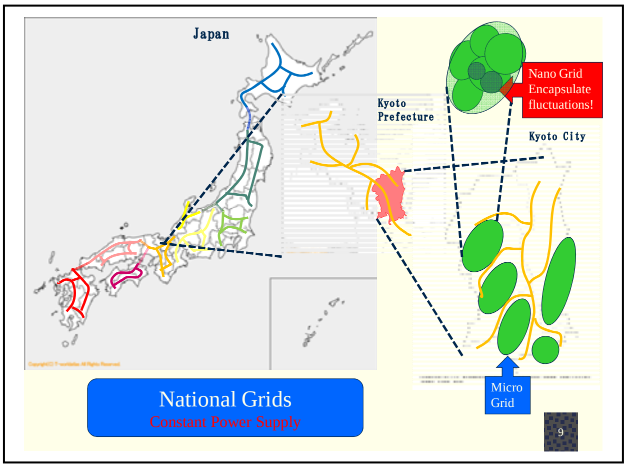


Figure 5: Two Layered Grid Architecture: National and Nano Grids

Another reason why we focus on privately-owned e-power lines is as follows. Since in Japan national grids managed by e-power companies are very well maintained and stable, we should keep them as is while encapsulating fluctuations of renewable energy sources and variations of power consumption due to human activities by utilizing i-Energy technologies implemented in households, institutions, and communities, which we call “Nano Grids.” This two layered grid architecture would be an optimal social energy infrastructure to guarantee stability as well as efficiency (Fig. 5).

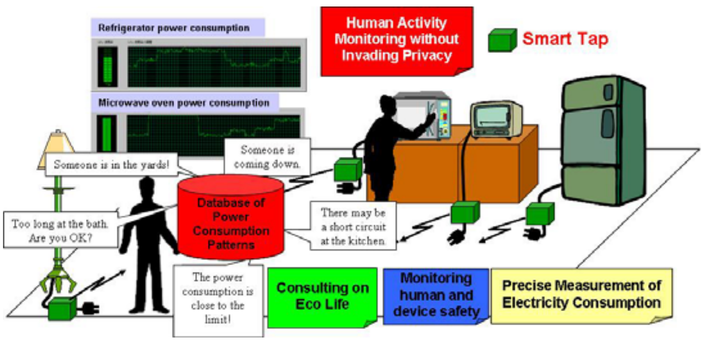


Figure 6: Household Electric Power Sensing Network with Smart Taps

3. Research Plans and Attainments of the i-Energy Project

We are currently studying, developing, and testing ways of creating a new living environment and social infrastructure by applying the i-Energy concept in practice in the four steps described below.

3.1 Visualization of Energy Consumption Patterns Using Power Sensor Networks and Learning and Monitoring of Human Behavior

The first step in the i-Energy project is to attach "Smart Taps," which consist of a power sensor and a communication module, to all electrical devices inside houses and offices to create a sensor network that monitors power consumption patterns in minute detail. (Fig. 6) By making it possible to measure, analyze, and display power consumption by appliances in a household in real time (Fig. 7), not only is energy savings awareness raised, but it is also possible to study and monitor behavior patterns of residents without intruding into their privacy. This is also useful for early detection of problems with devices, thereby contributing to safe and secure life.

Figure 7: Visualization of Energy Consumptions by Appliances

Fig. 8 shows a smart tap developed in cooperation with the National Institute of Information and Communications Technology (NICT), and Fig. 9 shows power consumption patterns for a hair drier. Since people use appliances in different ways, analyzing power consumption patterns makes it possible to guess the user. Given a map of spatial arrangement of appliances at home or office, moreover, we can estimate locations and motions of people by analyzing ON/OFF timings of the appliances.

The smart tap we developed is designed to measure the voltage and current at a 20KHz sampling rate, which enables us to identify types of appliances by analyzing the current waveform over one AC cycle. We developed a novel method of appliance identification, by which 16 different types of home appliances can be identified with 99% accuracy. This means that an appliance can be identified simply by plugging it into a socket [2].

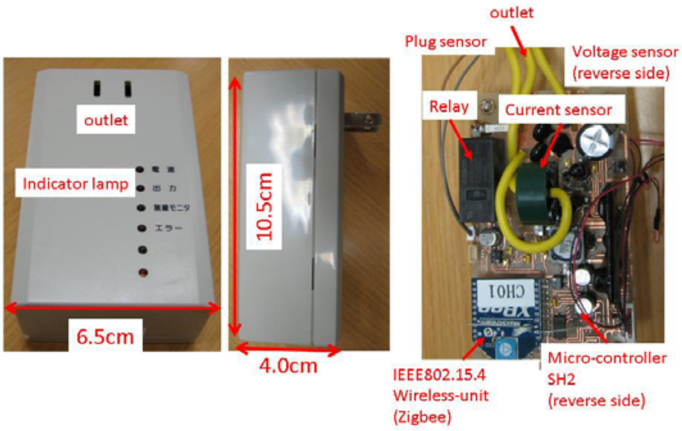


Figure 8: Smart Tap (co-developed with NICT)

3.2 Energy On-Demand (EoD) Protocol for Advanced Power Management

While raising awareness about energy savings by making power consumption patterns more visible does lead to a reduction in wasted energy, the effects are nevertheless limited. Accordingly, the second step of the i-Energy project involves managing household power consumption intelligently by developing a novel power management system.

We are proposing what we call an "Energy on Demand (EoD)" protocol for this intelligent power management system. Its hardware architecture is realized just by adding a power control function to the smart taps (the smart tap in Fig. 8 includes an on/off relay and a newer version features a continuous power controller) and using storage batteries as energy buffers (Fig. 10). As regards storage batteries, by using an electric car as shown in the figure, electric power energy management for activities inside the house, as well as transportation outside the house, can be managed in a unified manner.

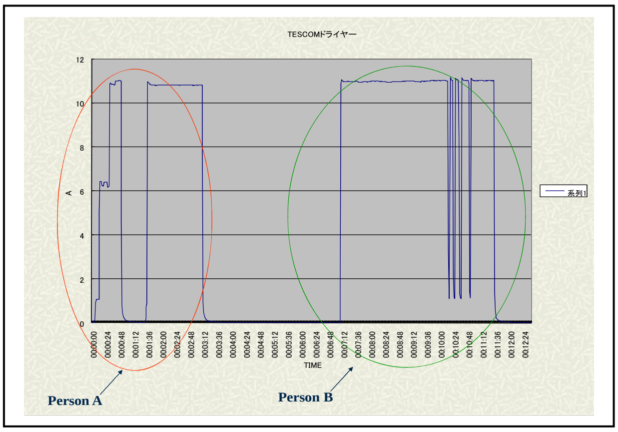


Figure 9: Hair Drier Energy Consumption Pattern (co-studied with NICT)

The software architecture, on the other hand, is completely different from current power management systems. The following describes the EoD protocol.

1. When the power switch on an electrical appliance is turned ON, a data packet describing the power requirements and characteristics of the device, which we call "QoEn" (Quality of Energy), is sent to a power manager. (Note that the electrical appliance is not actually turned on as soon as the switch is flipped.)

2. The power manager assigns power usage and time available to that device based on current and future expected power demands as well as activity patterns in the house, which have been learned using the sensor network described above. (Since the manager provides "best effort" power supply, not all demands are met 100%. In other words, 80 W might only be supplied in response to a 100 W request.)

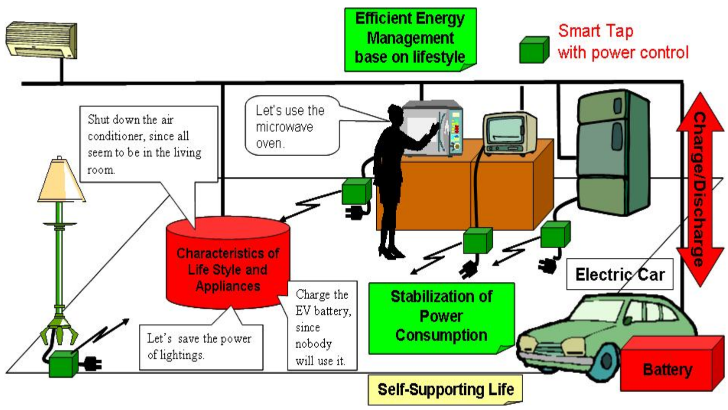


Figure 10: Energy on Demand Power Network

3. Power is supplied to the electrical device only after a packet giving permission to begin supplying power is received. The smart tap only supplies as much power to the electrical device as has been permitted.

4. The manager performs online real time control of power supply based on usage of other electrical appliances as well as the importance of the demand. (Since the control is performed using a "cap system" whereby power is supplied at no more than a limited value, vis-à-vis the total power usage amount set in advance by the user, it is possible that supply of power to electrical devices could be reduced or interrupted if a more important power request arises.)

By introducing systems which are inconceivable under current power transmission network control, such as best effort or cap systems, EoD systems can deliver dramatic power savings without fail. With an EoD system it is possible to cut power consumption 100% (i.e., ignore all requests for power), but that would adversely affect QoL (quality of life). In other words, the key question is how much power consumption can be reduced while maintaining quality of life, and in order to answer this question it is vital to accurately study lifestyle patterns and develop power control systems based on them.

3.3 Power Routing Using Household Nano Grid

As part of the third step, power generators and storage batteries that are installed in each house are connected in a network to create a total power management system for each house. In other words, current household power networks are organized in the shape of a tree, but it is possible to expand this into a looped graph shape by introducing multiple power sources and storage batteries, thereby creating a "Nano Grid" that has a flexible power routing functionality. Fig. 11 shows a group of smart taps for creating a household nano grid. In addition to the smart taps attached to individual electrical devices as described above, a new functionality is needed which can be provided by “Smart Breakers” (Fig. 11) or “Power Routers” (Fig. 12) that perform grid control.

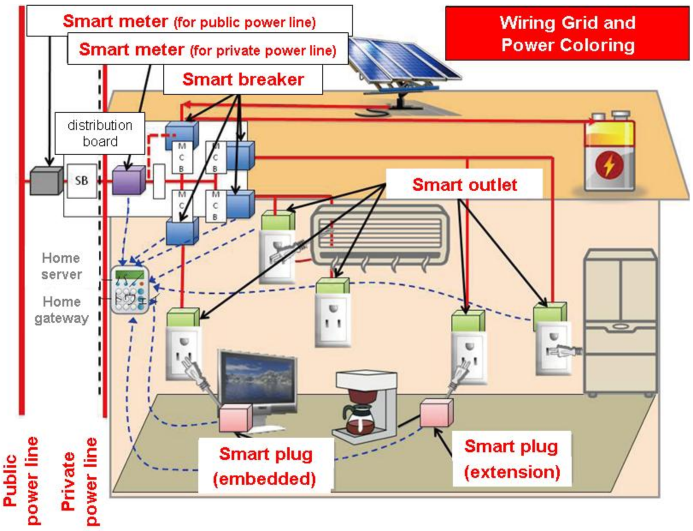
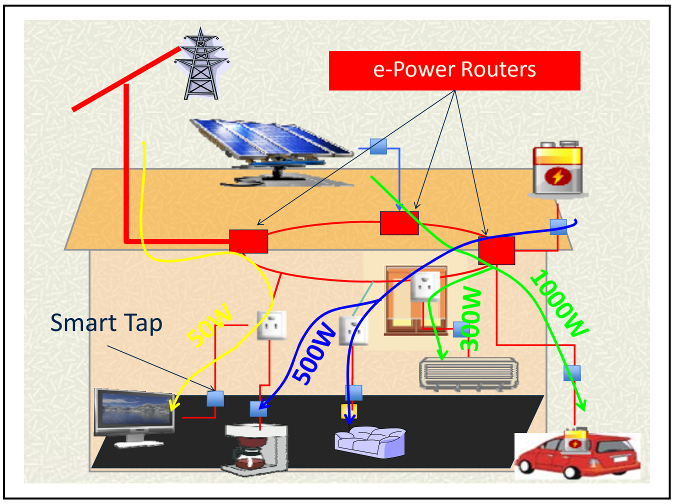


Figure 11: Smart Taps creating in-House Nano Grid

Fig. 12 illustrates the architecture of a Nano Grid at home, where smart taps and power routers form a cooperative distributed power network. When multiple power sources are installed in a house, novel power management methods may be realized if we can “color” power flows depending on their sources and apply different controls based on the colors. For example, give higher priority to renewable natural energy sources to reduce CO2 emission and do not supply electricity (i.e. neglect EoD demands) unless enough renewable natural energy is available. When the price of renewable natural energy is set higher, do not consume the power in the house but sell it to the power supply company. This IDing of e-power will change our lifestyles as well as open exploration into new energy services and businesses which drastically reduce CO2 emission in our society.



While e-power coloring is physically impossible, it could be achieved if we estimate power energy flows over a nano grid with smart taps and manage them with real time synchronized cooperative controls of smart taps and power routers. Currently we are studying such a cooperative distributed control method.

Figure 12: e-Power coloring over in-House Nano Grid with power routers and smart taps

3.4 Creating an Energy Trading Market over a Community Nano Grid

While the CO2 reduction effect by a single household might not be that great, greater reductions are possible if the in-house nano grid is expanded to a local community. This is the fourth step of the i-Energy project. When a community nano grid is developed by linking a group of in-house nano grids into a network, a new energy trading market will be created, where colored e-powers will be exchanged among individual households (Fig. 13). In other words, community nano grids are not just physical power networks

Figure 13: Creating Energy Trading Market over a Community Nano Grid

that deliver and receive energy, but also cyber economic networks that allow participants to trade energy, thereby making it possible to offer each household large incentives to save power and cut CO2 emissions. For example, a household may largely lower the energy cap setting of its in-house EoD system, even if that introduces the reduction of quality of life (e.g. cold in winter or hot in summer) to get the economic benefit of selling leftover energy in return. Such economical incentives will make large energy savings and CO2 reduction possible to a technically difficult level. It is exactly the goal of our i-Energy project, in that it will create a new foundation for society and a new way of living.

As shown in Fig. 5, another crucial function of in-house and community nano grids is to stabilize instabilities of renewable energy sources and variations of power consumptions due to versatile human activities. EoD systems at homes and in local communities should be designed to make e-power generation and consumption stable as well as to realize efficient e-power management. As a result, national grids become stable, supplying constant e-power to each nano grid.

4. Future Steps

Several years have passed since the i-Energy idea was proposed, and many R&D projects have sprung up in the Ministry of Internal Affairs and Communications (MIC) and the Ministry of Economy, Trade, and Industry (METI), partly riding the Smart Grid wave from the previous year. However, in order to make the i-Energy vision a reality, a unified theory has to be created that merges academic and research fields that operate based on different paradigms. Namely, these include the field of information communications which is based on computation and information models, and the field of power management, which is based on physical models.

Additionally, systematic efforts must be made to bring together activities in many fields, including industrial fields such as home appliances, storage batteries, electric cars, and housing, as well as the creation of an online auction-type energy trading market in which anyone can take part. 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. WG welcomes any parties who can share interests with us.

Japan has a particularly large number of strong companies that have the technologies required for integrating electric power and information networks, including makers of solar power generators, storage batteries, electric cars, and household appliances. i-Energy WG is working hard to consolidate the R&D activities of universities and companies which would otherwise be working separately, to create new academic fields and industries.

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