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Electricity Market Design for the Incorporation of Various Demand-Side Resources in the Jeju Smart Grid Test-bed

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Abstract – Many countries are increasing their investments in smart grid technology to enhance energy efficiency, address climate change, and trigger a green energy revolution. In addition to these goals, Korea also seeks to promote national competitiveness, prepare for the growth of the renewable energy industry, and export industrialization through its strategic promotion of the smart grid. Given its inherent representativeness for Korean implementation of the smart grid and its growth potential, Jeju Island was selected by the Korean government as the site for smart grid testing in June 2009. This paper presents a new design for the electricity market and an operational scheme for testing Smart Electricity Services in the Jeju smart grid demonstration project. The Jeju smart grid test-bed electricity market is constructed on the basis of day-ahead and real-time markets to provide two-way electricity transaction environments. The experience of the test-bed market operation shows that the competitive electricity market can facilitate the smart grid deployment in Korea by allowing various demand side resources to be active market players.

Keywords: Smart grid, Jeju smart grid test-bed, Smart electricity services, New electricity market design, Demand-side resources

1. Introduction

The "smart grid" refers to the next-generation power network that integrates information and communication technology (ICT) into the existing power grid to optimize energy efficiency through a two-way exchange of electricity information between suppliers and consumers in real time [1]. A number of countries have begun to increase their investment in smart grid technology to enhance energy efficiency, address climate change, and trigger a green energy revolution [2]. In addition to the environmental effects associated with their implementation, smart grid technologies are also expected to cultivate a fast-growing market [3]. As a result, many countries are attempting to secure a large portion of the market through the implementation of various smart grid demonstration projects and pilot tests.

Although the concept of smart grid technology is commonly understood around the world, policies related to smart grid development and implementation differ across nations. The United States, for example, is developing smart grid policy primarily to replace obsolete facilities and improve the country's electrical power system [4]. Within the U.S., the development of smart grid technologies is generally performed by the private sector (with financial support from the government). Research related to smart grid development has traditionally been conducted by the Electric Power Research Institute (EPRI) and the Department of Energy (DOE) through IntelliGrid, Advanced Distribution Automation (ADA), and GridWise. Research related to transmission and distribution (T&D) systems and distributed energy resources (DERs) have informed various technology developments such as the IntelliGrid architecture design, real-time system analysis, microgrid operation technology, and distribution system enhancement [5, 6].

In 2007, the U.S. Congress passed "The Energy Independence and Security Act" to promote research and development on the smart grid and allow pilot studies to become national projects from 2008 to 2020 [7]. For the successful development of the advanced national T&D system and the promotion of efficient energy use, the U.S. plans to optimize its power system operation and resources, integrate DERs and demand responses (DRs) into the conventional power system, and develop an Advanced Metering Infrastructure (AMI) and chargeable electric vehicle (EV) system by 2020.

In contrast to the U.S., the smart grid policy in the European Union (EU) is primarily designed to address the issues raised at the Climate Change Convention that specifically relate to the active utilization of renewable energy resources. Therefore, in the European Union, smart grid technologies focus on the spread of DERs on the basis of renewable energy, cross-border electricity transaction,

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and the improvement of energy efficiency [8]. Through the Smart Grids project, European Commission (EC) leads the EU's research efforts [9]. In particular, the European Smart Grids Technology Platform, which was launched in 2006, established the "20-20-20 target." This goal includes a 20% cut in emissions, a 20% improvement in energy efficiency, and a 20% increase in renewable resources by the year 2020 [10, 11]. Meeting these goals is expected to make T&D systems across Europe more efficient, boost cross-border electricity transactions, unify EU power grids, and integrate DERs into conventional grids.

Japan's smart grid is primarily geared towards the innovation of energy use and the expansion of renewable resources. To achieve these objectives, Japan plans to develop a smart grid system by 2030 to address energy and environmental issues and reinforce its industrial competitiveness [12]. In addition, Japan is currently promoting the commercialization of smart grid technologies through the development and demonstration of a new electric power network system that is based on the concept of the microgrid. This system is expected to accommodate nationwide renewable energy resources. Similar to the concept of the smart grid, the Triple I Power Systems (TIPS) project leverages IT technology to monitor new power systems and assess the reliability of the overall power system [13]. Through the TIPS project, Japan promotes the growth of related industries (e.g., EVs, batteries) and strengthens its industrial competitiveness.

Korea has dense power system networks compared to its limited land space, such as 31,622 c-km transmission lines, 271,247 MVA transformation capacities and 442,641c-km distribution lines as of 2012 [14]. With simplified transmission voltage levels, consisted of 765kV, 345kV, 154kV, 66kV and 22.9kV, and developing 765kV ultra-high voltage transmission line, Korea achieved very low rates of transmission and distribution losses. In addition, the power system reliability is quite strong with multi-loop networks of 154 kV and 345kV. Maximizing capacities of transmission lines and installing a variety of FACTS facility and low-loss equipments also reduced the losses.

However, Korea recently suffered the pretty low installed reserve margin due to slow installation of power plants compared to steep demand increases. Furthermore, high fuel prices has increased the electricity rates in Korea, importing most of fossil fuels and the pressure to reduce green-house gases would also increase the portion of environmental costs on a electricity rates in the near future. Due to these social costs increase in electricity supply, Korea tries to change the electricity policy direction in balancing the supply and demand, from supply side options to demand side options. Deployment of smart-grid in Korea is a key part in addressing the challenges and developing new energy policy. Specifically, Korea is strategically promoting smart grid technologies to secure national competitiveness, prepare for the expansion of renewable energy resources, and export industrialization. Korea has established a comprehensive plan for Power IT (Intelligent Grid Technology) from 2004 [15]. As a result, the National Smart Grid Roadmap was announced in 2010. The roadmap indicates that Korea will deploy the world's first nationwide smart grid by the year 2030 [16]. To successfully deploy the smart grid, the Korean government plans on establishing public-private partnerships by investing $25 billion (US) in the grid development projects implemented by private firms. The primary goals of the roadmap include:

- Developing five smart grid domains: Smart Power Grid, Smart Place, Smart Transportation, Smart Renewable Resources, and Smart Electricity Service,
- Installing a large number of EV charging stations, and Introducing tax credits and electricity tariffs to respectively promote smart grid technology development and support smart electricity services.

Given its inherent connectivity to nationwide deployment and potential for growth, the Korean government selected Jeju Island as a site for smart grid testing in June of 2009 [18]. Currently, the Jeju smart grid demonstration project is in the process of testing smart grid technologies in the five project domains outlined above to create new business models for these domains and promote Korean exports of smart grid technologies. The Smart Electricity Service domain seeks to incorporate a number of incentives such as consumer self-regulated power trade systems and dynamic pricing models to increase the power grid's efficiency and induce the emergence of industries for DRs and smart power exchange. However, the current electricity market structure in Korea does not allow for two-way bidding

Table 1. Comparison of power system status by county [17]

	Unit	Korea	US	Japan	China	France	UK
Gen. capacity	MW	77,693	1,135,040	282,315	966,410	123,783	90,208
Generation	GWh	452,447	4,120,028	1,156,921	4,227,800	550,222	381,128
Reserve margin	%	9.1(2009)	26.2(2009)	-	-	-	29.0(2009)
T&D loss	%	4.1	6.1	5.2(2009)	6.5	7.2	7.7
Load factor	%	74.1	59.7	66.7(2009)	72.3(2009)	60.6	64.7
Capacity factor	%	67.8	43.6	-	53.1	50.7	46.1
System efficiency	%	40.6	34.1(2007)	41.8(2009)	36.9	42.7(2003)	36.1

Note: These data are as of 2010. In case there were no data as of 2010, the earliest data available were noted with their years.

based on consumer participation [19]. Because the consumer has no mechanism through which he/she can communicate their intentions to the electricity market, the current market structure limits the extent to which AMI can be exploited. Therefore, the electricity market must be re-structured such that various demand-side resources, including DR, virtual power plants (VPP), energy storage systems (ESS), DERs, and EVs can play an active role in the smart grid system. For this reason, the Smart Electricity Service at the Jeju smart grid test-bed is delineated into the day-ahead market and the real-time market. The day-ahead market allows consumers to influence the price of electricity to hedge the risk of price spikes. The real-time market ensures that consumers effectively utilize demand side resources by responding to a real-time price that accounts for the current state of the power system [20].

This paper presents a new electricity market design and operational scheme designed to test the Smart Electricity Service that has been developed and implemented on Jeju Island.

2. Jeju Smart Grid Demonstration Project

In January 2010, Korea announced the "National Smart Grid Roadmap" with the goal of establishing a smart grid platform that minimizes society's carbon footprint [16].

As shown in Fig. 1, the roadmap is divided into three different phases that incorporate five separate domains: the Smart Power Grid, the Smart Place, Smart Transportation, Smart Renewable Resources, and the Smart Electricity Service. These domains served as key project areas for Korea's Jeju smart grid test-bed.

In June 2009, the Korean government selected Jeju Island as the site for testing developments in the smart grid [18]. At the time of the announcement, the government anticipated that the project would become the world's largest smart grid testing site. In addition to serving as a location for testing smart grid innovations, Jeju Island allows for the development of new business models associated with the five aforementioned domains. The test-bed will also serve as the central location from which Korean smart grid technologies will be commercialized and exported.

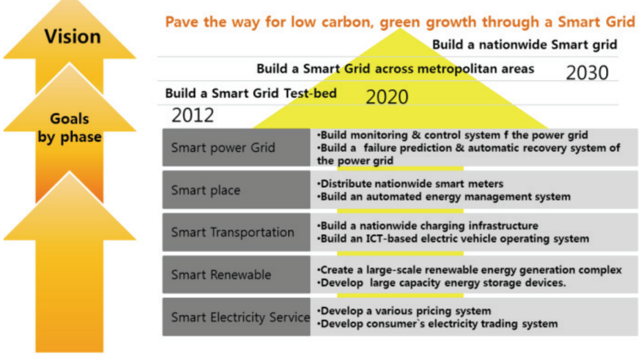

Fig. 1. Korean national smart grid roadmap

In total, USD 239.5 million have been invested in the project; the Korean government has invested USD 69.5 million, and the private sector has supplied USD 170 million. A total of 168 companies and 12 consortia are participating in the project. All participating companies were selected through an open-bid process, and the consortia members were chosen by the Korean government.

Consortia members participate in one or more of the five project domains, the objectives of which are as follows:

- ***Smart Renewables***: Renewable energy will play a key role in the smart grid and is essential for reducing greenhouse gas emissions. In this regard, the National Smart Grid Roadmap announced that the primary objectives for the development of smart renewable resources are to create large-scale renewable power plants and construct energy-independent buildings. Some key technological developments related to smart renewable resources include the implementation of a system to help cope with the intermittency problem induced by renewable sources and an energy storage system for bulk energy generation from renewable sources. The Korean government plans to produce and sell renewable energy and export innovations that contribute to its generation (e.g., energy storage system). By 2030, Korea also plans to increase the use of renewable energy by 11% and the number of zero-net-energy buildings by 30%. Three consortia participate in this domain in the Jeju smart grid testing project.
- ***Smart Transportation***: The primary objective for the smart transportation domain is to establish a nationwide EV charging infrastructure. This infrastructure is to be designed to allow consumers to charge their vehicles during times of low demand and provide customers the opportunity to re-sell stored energy. Through the Smart Transportation project, Korea plans to develop EV parts and materials by year 2012 and develop a vehicle-to-grid system by 2020. As a result of developments within the smart transportation domain, business models for EV and battery rental services and EV operating management services are expected to emerge. By 2030, Korea plans to deploy roughly 2,456,000 EVs and install 2,714 EV charging stations.
- ***Smart Place***: The smart place domain is designed to increase energy efficiency and reduce energy use through an AMI system. This will provide a mechanism through which energy consumers and suppliers can communicate with each other. Korea plans to develop an AMI and develop standards on AMI by 2012, which will reduce energy use by up to 10% by the year 2030. In addition, the Korean government plans to implement smart meters nationally by 2020.

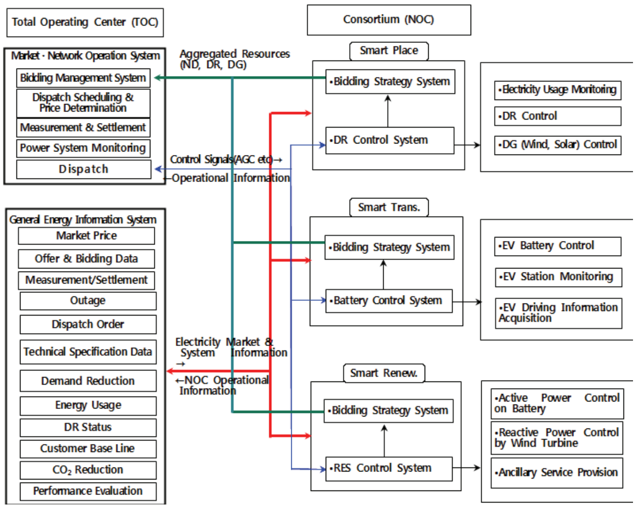

Fig. 2. Interoperation structure between TOC and NOCs

- ***Smart Power Grid***: The smart power grid domain will test distribution and transmission systems and create a self-automated recovery system. Two business models are expected to emerge from this domain: a certification system for smart grid technologies and the exportation of key smart grid technologies.
- ***Smart Electricity Service***: The key objective for the smart electricity service domain is to encourage consumer participation by implementing dynamic pricing rates and promoting an on-line system for power exchange and derivatives. The Smart Electricity Service project has provided a diversity of empirical analyses for the operation of real-time pricing strategies and the organized demand resource market. Based on these experiences, Korea plans to develop an on-line power exchange system by 2020. In the Jeju Island smart grid test-bed, smart electricity services are operated through the Total Operation Center (TOC) and are based on the information exchange with Network Operation Centers (NOCs) for each consortium. Fig. 2 shows the interoperation structure between the TOC and the NOCs for smart electricity services in the Jeju smart grid demonstration project.

3. Market Design for Jeju Smart Grid Test-bed

Smart electricity services in the Jeju smart grid test-bed are designed to increase the Korean power grid's efficiency and induce the emergence of industries for DR and smart power exchange. However, the current electricity market in Korea, dubbed a Cost Based Pool (CBP) system, cannot support some features of the smart grid [19]. CBP was designed to operate only temporarily and was subject to fulfillment of the two-way bidding pool (TWBP) by vertically integrated electricity markets held by Korea Electric Power Corporations (KEPCO). However, as a result of the delay in reforming the Korean electricity industry, the CBP system is still in effect. In the CBP system, generators have to bid their available capacity solely on the basis of their cost data. The demand side has no influence over the price of electricity.

In many foreign markets, the demand and supply of electricity determines its price. However, the CBP system cannot adopt a bi-directional pricing mechanism due to its incomplete structure. Most significantly, the CBP system is unable to reflect the advantages of an AMI, because the consumer has no way to communicate their intentions to the electricity market.

Therefore, a redesign of the electricity market is essential for leveraging a variety of resources (e.g., DR, VPP, energy storage, renewable resources, and electric vehicles) for the development of the V2G, which in turn supports the development of a new business model for participants of this demonstration project. In this section, we describe the market design concept in the Jeju smart grid test-bed electricity market in terms of demand-side resource participation.

3.1 Principles of market design

In the Jeju smart grid test-bed electricity market, customers can indirectly participate in the price-determination process by contracting with a consortium. Each consortium aggregates their customers' resources and develops a bidding strategy that is submitted to the electricity market. Due to the development of demand-side bidding mechanisms and the resulting prices, customers are expected to use their electricity more efficiently. In addition, virtual power plants (VPP) aggregate various demand-side resources through communication networks. Because the Jeju smart grid test-bed project is designed to verify the potential for Korean technologies and business models to be exported, the test-bed electricity market was formed to reflect the characteristics of advanced overseas markets. This electricity market features a two-settlement system, including a day-ahead market and a real-time market. As the day-ahead market is a kind of the forward market to hedge the price volatility caused by the uncertainty in the real-time power system operation, it is a pure financial market without actual commodity trades. Therefore, market participants have no supply obligation on the day-ahead schedule hourly transactions. On the other hand, market participants have supply obligation in the real-time market that settles the actual hourly quantity deviations from day-ahead schedule hourly quantities priced at real-time market clearing prices.

Price determination in this test-bed electricity market is based on the bids of market participants given real power system operating conditions. This design is intended to facilitate the analysis of the overall influence of demand-side resource applications in preparation for smart grid implementation. This market allows two-way bidding from the supply and demand sides. Demand-

Table 2. Types of demand side bidding

Bidding	Description
Normal demand (ND)	Purchase energy at prices for consumption
Dispatchable demand reduction (DDR)	Demand reduction being able to respond with dispatch orders
Non-dispatchable demand reduction (NDDR)	Demand reduction without dispatch orders
Dispatchable demand side generation (DG)	Generation being able to respond with dispatch orders
Non-dispatchable demand side generation (NDG)	Self-scheduled generation

Table 3. Example of demand side resources

Bidding	demand side resource
Normal demand (ND)	Electricity consumption of customers Charging of storage system
Dispatchable demand reduction (DDR)	Demand reduction smart appliance device Demand reduction of charging into battery Demand reduction of normal demand plus battery
Non-dispatchable demand reduction (NDDR)	Demand reduction of normal demand
Dispatchable demand side generation (DG)	Single mode renewable generator
Non-dispatchable demand side generation (NDG)	Renewable generator plus battery Vehicle to grid

side bidding includes three types of resources: normal-demand bidding, demand-reduction bidding, and demand-side generation bidding. Demand-reduction bidding and demand-side generation bidding also have two subtypes of bidding according to their dispatchability. Table 2 shows five types of demand-side bidding in the test-bed electricity market.

In realizing smart grid, energy storage systems are important in that they can enable non-dispatchable resources such as renewable or demand reduction resources to be dispatchable resources. This means that a system operator can monitor and control the combined renewable resources. Furthermore, by eliminating output uncertainty in a single-mode renewable resource, it becomes possible to extend the capacity for renewable energy generation and decrease the standby reserve. Table 3 summarizes multiple types of demand-side resources.

3.2 Scaling up demand side resources to national level

In the Jeju test-bed, there is a relatively low number of participant households (2,000), but demand-side bidding within the test-bed should be reflected in the procedure by which the market price is determined. To determine a stable market price, we performed a modification procedure. We scaled demand-side resources to expand demand-side bids such that they were representative of national-level bids. It is noted that the test-bed electricity market was designed to simulate the national electricity market operation assuming the full completion of smart grid deployment in Korea. For this reason, the demonstrated loads in Jeju smart grid test-bed was aggregated reflecting

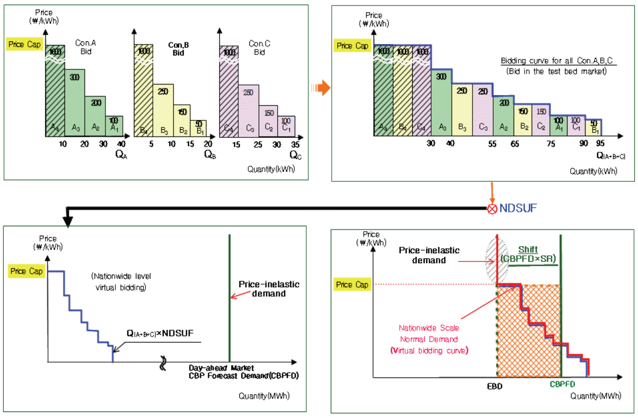

Fig. 3. Scaling-up scheme for normal demand bids

the national load characteristics so that demand side bids in the test-bed could be expanded to the national-level. About 15% of forecasted normal demands in the CBP market are assumed, as the price-sensitive load varies according to normal demand bids in the test-bed electricity market. The scaling factor for demand-reduction resources was the total capacity of respective resources in the Jeju smart grid test-bed (expanded to load management target amounts). Load management target in the 6th basic plan for long-term electricity supply and demand of Korea is 10~15% of yearly peak demand during the planning period [21]. If demand side resources are allowed to bid the price in the organized wholesale market, it is expected that more aggressive load management strategies can be implemented than in the present CBP environment. Based on this assumption, 15% of forecasted normal demands in CBP market is chosen as the level of price-sensitive load in the test-bed electricity market design.

We note that price-responsive normal demand is supposed to be roughly 15% of the total nationwide demand. Therefore, ND bidding in this test-bed ranges from -7.5% to +7.5 % of CBP demand forecasts. On the basis of the shift of CBP forecasted demand with transmission loss (*CBPFDTLti*), expected base demand (*EBDti*) is calculated using the following two equations:

$$EBDt = CBPFDTLt - SRt \times CBPFDTLt,$$

where, CBPFDTLt = [1/(1+TLRt)] × CBPFDt. SRti and TLRt represent the propotion of the price-responsive demand in CBPFDTLt and the transmission loss rate, respectively.

3.3 Market participation

As described above, we classified demand-side resources into five bidding types. Among these, dispatchable bidding types (DDR, DG) are eligible to participate in price determination practices (DAMCP, RTMCP) and can revise their initial bidding strategies in the real-time market. Dispatchable resources can procure payment for capacity,

Table 4. Market participation according to bidding type

Classification	ND	NDDR	DDR	NDG	DG
Price Determination (DA)	○	○	○	○	○
Price Determination (RT)	X	X	○	X	○
Revised bidding	X	X	○	X	○
Dispatch	Pre-scheduled (DA)	Pre-scheduled (DA)	Real-time (5min.)	Pre-scheduled (DA)	Real-time (5min.)
Metering	Consumption	Reduction	Reduction	Generation	Generation
Capacity Payment	X	X	○	X	○
Energy Payment	DA/RT	DA	DA/RT	DA	DA/RT
Regulation Payment	X	X	○	X	○
Reserve Payment	X	○	○	X	○

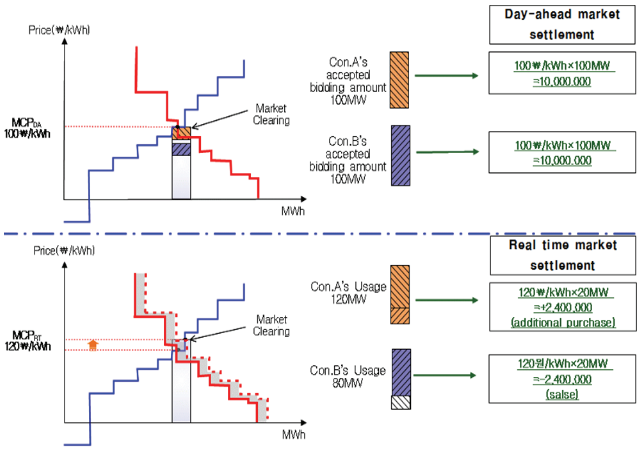

Fig. 4. Example of two-settlement system for normal demand

energy, regulation and reserve services, and non-dispatchable resources can get payment for energy and reserves. To acquire the metering data in real-time, smart meters are paramount. Table 4 provides a summary of bidding types and the types of behaviors in which market participants can engage.

3.4 Settlement for demand side resources

The Jeju smart grid test-bed electricity market settles for energy, demand reduction, capacity, standby reserve, and regulation. With respect to the energy market, it adopts a two-settlement system that delineates settlements performed for the day-ahead market and the real-time market. Day-ahead market settlement is financially binding for scheduled hourly quantities and day-ahead hourly market price. Real-time market settlement is based on hourly estimates of deviation from the day-ahead schedule valued at real-time market price. Demand reductions are settled for their negative kW provisions. Standby reserve settlement is based on scheduled quantities and standby reserve prices (which is determined by co-optimization for energy and reserve in the day-ahead market). Contrarily, regulation service settlement is based on real-time dispatch scheduling. Fig. 4 depicts the two-settlement system in the Jeju test-bed market.

4. Price Determination Algorithm Design

The electricity market in the Jeju smart grid test-bed implements an interactive process in determining price. Market participants can influence the price of electricity by submitting their bids to the electricity market. The resulting price not only reflects the nature of those bids but also promotes the efficient use of electricity on the part of market participants. In addition, the market division (i.e., the separation of the day-ahead and real-time markets) can provide new business opportunities by compensating market participants for their demand responses and demand-side resources. As such, the two-settlement system can enhance business stability and hedge financial risk.

The day-ahead market determines day-ahead market clearing prices (DAMCP) and quantities at thirty-minute intervals by using a dispatch schedule optimization scheme based on generation offers and demand bids. Therefore, transactions in the day-ahead market can provide market participants with opportunities to hedge risk of real-time price volatility. In contrast, the real-time market is a physical market that provides information related to real-time price volatilities according to variation in system operating conditions. The real-time market determines market clearing prices (RTMCP) at five-minute intervals and dispatches targets through the economic dispatch. Table 5 summarizes the characteristics of the two electricity markets.

Table 5. Characteristics of the day-ahead and the real-time electricity markets in the Jeju smart grid test-bed

Market	Day-ahead	Real-time
Objectives	dispatch schedule + price determination	dispatch target + price determination
Optimization model	UC+ED(MIP)	ED(LP)
Scheduling interval	30 minutes	5 minutes
Ancillary services	Regulation+Standby (10-minute)	Regulation
Demand	CBP load forecast + demand bids	MOS 5-minute load forecast

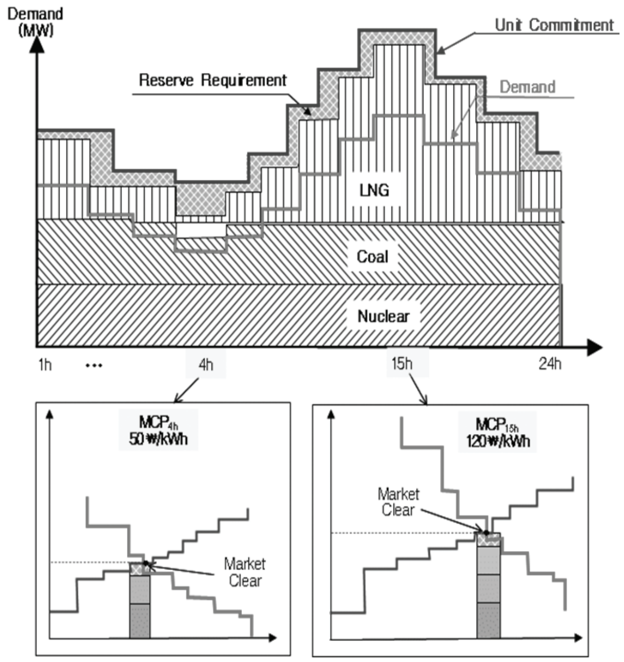

Fig. 5. Day-ahead market clearing concept

4.1 Day-ahead market

The day-ahead market price for electricity in the Jeju smart grid test-bed is determined on the basis of unit commitment (UC). In turn, UC is based on market participants' generation offers and demand bids for the following day. Specifically, the UC in the day-ahead electricity market is calculated as a mixed integer programming (MIP) problem that co-optimizes energy / reserve dispatch and price with various system and technical constraints. Fig. 5 illustrates how the market price is determined by the day-ahead UC.

The day-ahead UC can be modeled as an optimization problem to maximize social welfare. The general form of the objective function is formulated as:

$$minimize \sum_t \sum_i B_{j,t}(de_{j,t}) + \sum_t \sum_i C_{i,t}(ge_{i,t}) + \sum_t \sum_v P_{v,t}(s_{v,t}) \quad (1)$$

As a result of some constraints, it may be impossible to solve the optimization problem. To avoid this issue, slack variables are applied to those constraints that render the problem unsolvable. Thus, slack variables multiplied by high penalty prices are added in the objective function.

The day-ahead UC problem includes various technical constraints. We note that the reserve requirement incorporated in the day-ahead UC is represented by the spinning reserve. These are formulated as follows:

4.1.1 Energy and reserve requirements

1) Energy balance:

$$\sum_i ge_{i,t} + s_{ge1,t} - s_{ge2,t} = \sum_i ge_{i,t} + ND_t \quad (2)$$

2) Spinning reserve constraint:

$$\sum_i r_{i,t} + s_{ge3,t} \geq RR_t \quad (3)$$

4.1.2 Generating unit constraints

1) Maximum and minimum generation limit

$$ge_{i,t} + r_{i,t} \leq m_{i,t} \cdot GM_{i,t} \quad (4)$$

$$ge_{i,t} \geq m_{i,t} \cdot GN_{i,t} \quad (5)$$

2) maximum generation increase and decrease limit

$$ge_{i,t} \leq ge_{i,t-1} + RU_{i,t} \quad (6)$$

$$ge_{i,t} \geq ge_{i,t-1} - RD_{i,t} \quad (7)$$

c) Reserve constraint

$$0 \leq r_{i,t} \leq m_{i,t} \cdot RA_{i,t} \quad (8)$$

d) Minimum up and down time constraint

$$\sum_{t=k}^{k+MU_{i,t}-1} m_{i,t} \geq u_{i,t} \cdot MU_{i,t} \quad (9)$$

$$\sum_{t=k}^{k+MU_{i,t}-1} 1 - m_{i,t} \geq d_{i,t} \cdot MU_{i,t} \quad (10)$$

e) Generation state constraint

$$u_{i,t} - d_{i,t} = m_{i,t} - m_{i,t-1} \quad (11)$$

$$u_{i,t} + d_{i,t} \leq 1 \quad (12)$$

f) Slack constraint

$$0 \leq s_{v,t} \quad (13)$$

These mathematical representations can be adjusted in accordance with generation types, including demand-side resources.

4.2 Real-time market

To operate the rational real-time market, TOC engages in real-time dispatch scheduling across five-minute intervals. This process co-optimizes generation and regulation schedules on the basis of market participants' bidding. This real-time dispatch scheduling determines targets for energy production and regulation and the real-

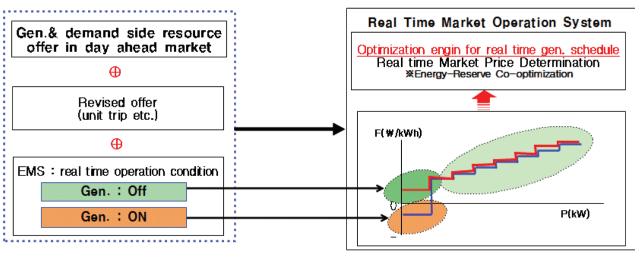

Fig. 6. Real-time market pricing procedure

time market price over a dispatch period. The real-time market price is defined as the price of an incremental change in demand at the end of a corresponding dispatch period, given various requirements and constraints.

Scheduling for a real-time dispatch period is optimized ten minutes prior to its implementation. It is based on offers from generators and demand-side resources, revised offers, and forecasted electricity demand during the corresponding dispatch period. As such, it aims to determine the amount of supply provided by generators and demand-side resources while minimizing the total operating cost during the dispatch period. This objective is formulated using the following optimization function:

$$minimize \sum_{on\ units} C_{i,t}(ge_{i,t}) + \sum_{on\ units} D_{i,t}(r_{i,t}) + \sum_{system\ constraints} P_{v,t}(s_{v,t}) \quad (14)$$

The optimization problem for real-time dispatch scheduling accounts for various technical constraints with the exception of those related to the transmission network. The UC schedules for generators and demand-side resources are provided by the day-ahead market clearing information. In addition, the initial values of generators and demand-side resources are established using their respective outputs from the previous dispatch period. We note that real-time dispatch scheduling accounts for only regulation service as the reserve requirement. The constraints of the real-time scheduling problem are as follows:

4.2.1 Energy and reserve requirements

1) Energy balance:

$$\sum_{on\ units} ge_{i,t} + s_{ge1,t} - s_{ge2,t} = L_t \quad (15)$$

2) Reserve constraint:

$$\sum_{on\ units} r_{i,t} + s_{ge3,t} \geq RR_t \quad (16)$$

b) Generating unit constraints (on-line units)

$$GNR_{i,t} \leq ge_{i,t} \leq GMR_{i,t} \quad (17)$$

where, $GNR_{i,t}$ and $GMR_{i,t}$ are determined as follows:

if $s_{i,t} \geq GM_{i,t}$,
$GNR_{i,t} = max(gs_{i,t} - RD_{i,t}, GN_{i,t})$ and
$GMR_{i,t} = max\{GNR_{i,t}, min(gs_{i,t} + RU_{i,t}, GM_{i,t})\}$ (18)

otherwise,
$GMR_{i,t} = min(gs_{i,t} + RU_{i,t}, GM_{i,t})$ and
$GNR_{i,t} = max\{GMR_{i,t}, max(gs_{i,t} - RD_{i,t}, GN_{i,t})$ (19)

4.2.2 Inflexible generation (on-line units)

When a generator claims that energy generation is inflexible, the maximum and minimum capacities of that generator are set as such.

$$GN_{i,t} = GM_{i,t} = GI_{i,t} \quad (20)$$

d) Reserve-generation constraint for on-line units

$$ge_{i,t} - r_{i,t} \geq GNR_{i,t} \quad (21)$$
$$r_{i,t} + ge_{i,t} \leq GMR_{i,t} \quad (22)$$

e) Generation constraint for off-line units

$$ge_{i,t} = 0 \quad (23)$$

f) Reserve constraint

$$0 \leq r_{i,t} \leq RA_{i,t} \quad (24)$$

g) Slack constraint

$$0 \leq s_{v,t} \quad (25)$$

5. Workings of Jeju Smart Grid Test-bed Electricity Market

5.1 Market participation of demand-side resources

As explained above, demand-side resources are allowed to participate in Jeju smart grid test-bed electricity market. Table 6 shows the state of aggregated demand-side resources participating in Jeju smart grid test-bed electricity market as of March 2012. For the market participation, each eligible resource should submit its standing bidding data to TOC. The standing bidding data includes a series of technical characteristics of a demand side resource such as default bidding amount of normal demand, available capacity, duration time for demand reduction, AGC responding range, ramp rate limit and minimum start-up/shut-down time.

There are various types of demand-side resources in Jeju smart grid test-bed electricity market. As of March 2012, 4 SP consortia mainly bid on normal demand (ND) and demand reduction (DR) through their demonstration households and 2 ST consortia only bid on ND to charge their EVs. On the other hand, all SR consortia bid on demand-side generation (DG) using their renewable generation technologies. Table 7 shows types of demand-

Table 6. State of demand-side resources participating in Jeju smart grid test-bed electricity market (March 2012)

Consortium		Normal Demand [kW]	Demand Reduction [kW]		Demand-side Generation [kW]	
			NDDR	DDR	NDG	DG
SP	A	460	-	-	600	300
	B	500	-	130	-	40
	C	150	-	50	-	50
	D	1,000	100	-	-	-
ST	E	101	-	-	-	150
	F	500	-	-	-	55
	G	248	-	-	5	55
SR	H	-	-	-	60	2,060
	I	-	-	-	1,500	1,500
	J	-	-	-	-	2,775
Total		2,959	100	180	2,165	9,195

Table 7. Type of demand-side resources in Jeju smart grid test-bed electricity market (March 2012)

Consortium	Type of demand-side resource				Max. bidding quantity [kWh]
	Demonstration household			EV & Generation	
	Foreign	Domestic	Total		
A	455	167	622	-	392
B	375	195	570	-	500
C	172	167	339	-	150
D	235	235	470	-	1,000
E	-			7 (EV)	101
F	-			34 (EV)	10
H	-			Wind/PV (with Battery)	2,060
				Small hydro	60
Total	1,237	764	2,001		-

Table 8. Monthly market operation results (June to December 2011)

Month / Market		Demand [MW]			MCP [₩/kWh]		
		Max.	Min.	Avg.	Max.	Min.	Avg.
June	DA	61,805	34,502	48,494	210.0	45.4	122.8
	RT	63,557	36,319	49,168	1,000.0	40.5	128.5
July	DA	67,003	40,745	53,850	278.0	45.1	138.4
	RT	68,398	40,246	52,731	400.0	44.0	122.5
August	DA	70,381	41,070	54,052	982.0	45.1	139.4
	RT	71,726	36,556	53,123	1,000.0	42.6	143.5
September	DA	68,956	34,021	50,458	1,000.0	44.5	148.3
	RT	70,233	34,564	49,122	1,000.0	45.0	155.4
October	DA	58,591	38,914	49,510	227.0	53.0	127.6
	RT	59,157	38,431	49,102	350.3	46.6	121.7
November	DA	63,124	40,873	52,169	258.0	53.0	146.8
	RT	64,116	39,640	51,320	235.9	50.2	132.0
December	DA	66,912	42,804	57,111	324.0	86.0	160.5
	RT	67,863	44,489	57,064	525.1	119.3	153.8
Average	DA	-	-	52,235	-	-	141.0
	RT	-	-	51,661	-	-	137.0

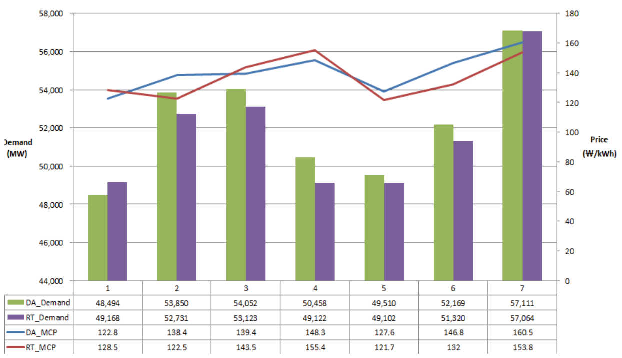

Fig. 7. Comparison of monthly market operation results (June to December 2011)

side resources participating in Jeju smart grid test-bed electricity market on March 2012.

5.2 Results of market operation

During June to December 2011, the average day-ahead (DA) market price is KRW 4/kWh higher than the average

Table 9. Level of market prices (June to December 2011)

Price level [₩/kWh]	Day-ahead market		Real-time market	
	Number of cleaing	Proportion [%]	Number of clearing	Proportion [%]
200 ~ 1,000	592	5.8	490	4.8
170 ~ 200	831	8.1	160	1.6
150 ~ 170	823	8.0	305	3.0
130 ~ 150	2,129	20.7	1,880	18.3
110 ~ 130	**4,486**	**43.7**	**5,816**	**56.6**
90 ~ 110	872	8.5	666	6.5
70 ~ 90	215	2.1	83	0.8
50 ~ 70	183	1.8	151	1.5
< 50	141	1.4	721	7.0

Note) For comparison, real-time market prices are converted to the demand-weighted average price in 30 minutes.

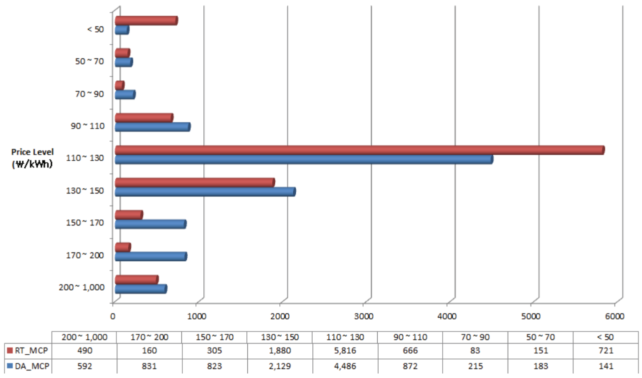

Fig. 8. Comparison of occurrence numbers by market price levels (June to December 2011)

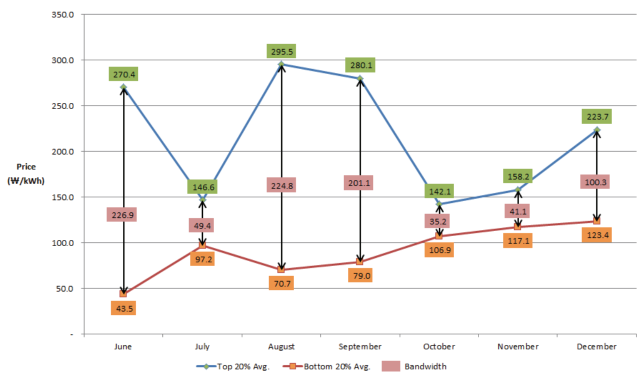

Fig. 9. Comparison of bandwidth in real-time market price (June to December 2011)

real-time (RT) market price since the day-ahead demand is mostly higher than the real-time demand. Table 8 shows these results in detail.

Examining the levels of market clearing price from June to December 2011, 44% of the overall day-ahead market price is cleared between KRW 110/kWh and KRW 130/kWh while 57% of the overall real-time market price is formed at this price level. Since the real-time demand is adjusted according to the level of the accepted demand in the day-ahead market, it has a limit that the real-time demand is lower than the actual demand when the accepted demand in the day-ahead market is relatively small at the corresponding period. It is considered as the reason that the relatively low price volatility is observed in Jeju smart grid test-bed electricity market.

As the price signal to facilitate demand response, the price volatility in the real-time market can be evaluated by i) the bandwidth between averages on the top 20% and the bottom 20% of the real-time prices, and ii) the occurrence number of scarcity prices. As the result, the bandwidth of the real-time market prices from June to December 2011 is derived at KRW 126/kWh. However, it is noted that this is the result when there is only normal demand bidding in the market. If the market participation of DR resources is facilitated in the future, it is expected that the bandwidth of the real-time market price would be reduced.

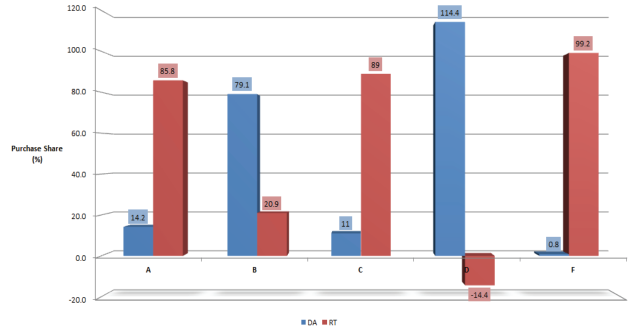

Fig. 11. Purchase share in day-ahead and real-time market (June to December 2011)

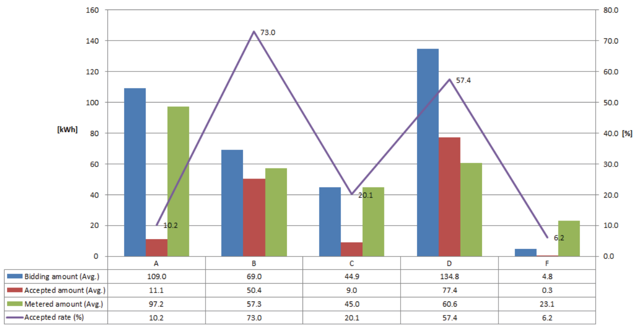

Fig. 10. Comparison of average bidding and accepted quantities for normal demand by consortia (June to December 2011)

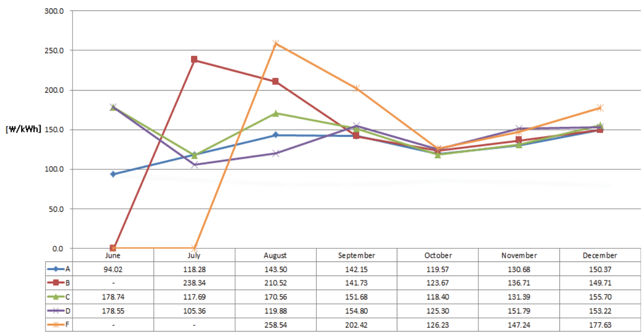

Fig. 12. Monthly purchase price by consortia (June to December 2011)

Table 10. Average bidding and accepted quantities for normal demand by consortia (June to December 2011)

		A	B	C	D	F
June	Bidding [kWh]	123.4	156.8	126.1	318.1	-
	Acceptance[kWh]	7.1	112.8	36.4	116.2	-
	Acceptance rate [%]	5.746	72.0	28.8	36.5	-
	Metering [kWh]	73.2	135.2	38.9	72.6	-
July	Bidding [kWh]	95.4	258.3	126.3	261.9	-
	Acceptance [kWh]	0.6	174.8	23.9	113.7	-
	Acceptance rate [%]	0.67	67.67	18.89	43.43	-
	Metering [kWh]	124.7	26.4	22.5	83.6	-
Aug.	Bidding [kWh]	75.8	22.3	4.1	61.4	5.5
	Acceptance [kWh]	57.1	16.0	1.7	47.2	0.6
	Acceptance rate [%]	75.4	72.0	41.1	76.9	10.1
	Metering [kWh]	125.5	23.8	8.7	50.6	40.1
Sep.	Bidding [kWh]	168.1	28.0	25.0	115.4	8.0
	Acceptance [kWh]	14.6	25.2	3.3	91.0	0.6
	Acceptance rate [%]	8.7	89.9	13.4	78.9	7.9
	Metering [kWh]	116.2	63.0	12.3	62.6	45.8
Oct.	Bidding [kWh]	136.3	29.0	25.9	94.3	8.4
	Acceptance [kWh]	1.0	28.3	5.2	78.2	0.9
	Acceptance rate [%]	0.7	97.7	19.9	82.9	10.5
	Metering [kWh]	112.2	63.3	11.0	76.7	47.8
Nov.	Bidding [kWh]	136.5	29.0	25.9	110.3	7.7
	Acceptance [kWh]	0.0	25.4	1.0	81.2	0.1
	Acceptance rate [%]	0.0	87.7	3.8	73.6	1.9
	Metering [kWh]	94.9	59.2	184.5	45.9	27.9
Dec.	Bidding [kWh]	136.3	29.0	25.9	117.0	8.7
	Acceptance [kWh]	8.7	20.5	0.9	91.4	0.2
	Acceptance rate [%]	6.4	70.6	3.4	78.2	1.8
	Metering [kWh]	131.3	87.8	82.3	93.2	22.9

The acceptance rate of the normal demand bidding is observed at 41% on average. This implies that consortia bid on normal demand timidly and the acceptance demand in the day-ahead market relatively low. It is noted that the real-time demand is adjusted according to the level of the accepted demand in the day-ahead market and the real-time demand is lower than the actual demand when the accepted demand in the day-ahead market is relatively small at the corresponding period.

During June to December 2011, the average purchasing cost of consortia is derived at KRW 141/kWh and the average payment is observed at KRW 215 million. In the beginning of Jeju smart grid test-bed electricity market (from June to August 2011), there were wide variances in purchasing costs by consortia. However, it is observed that these variances are gradually reduced as consortia have learned from accumulated experiences of market transaction. The purchasing cost of ST consortium F is higher than other consortia since its normal demand have been mostly purchased at peak hours for charging EVs.

6. Conclusion

The Jeju smart grid test-bed electricity market design is intended to determine the nationwide impact of smart grid implementation in Korea. In addition, it serves as a useful model for exploring the effects of (a) two-way (supply- and demand-side) bidding on the price of electricity and (b) the design and dual settlement of incremental electricity trading in one-day ahead and real-time markets.

To investigate these issues, the Jeju Island test-bed contains 2,000 households, over 200 electric vehicles, and five wind power plants and energy storage devices. Because these figures represent only 0.01% of the overall Korean population, we used a scale up factor for resource-specific bids (Normal Demand, Demand Reduction and Demand Side Generation), which led to empirical simulations of nationwide smart grid implementation. In addition, we explored the possibility of redesigning the current one-way CBP electricity market such that it is more interactive. Specifically, we investigated an approach whereby both the supply and demand of electricity determine its price, which in turn, affects electricity consumption patterns. Finally, we delineated the one-day ahead and real-time markets in the Jeju Demonstration Complex to provide an opportunity to hedge risks associated with real-time price fluctuations. In other words, we provided a mechanism for market participants to protect against the possibility of price variations and balance electricity supply and demand through unit commitment. To do this, we opened a five-minute real-time market that generates real-time prices that continuously reflect the status of electricity supply and demand. The purpose of opening the real-time market was to provide a synchronized pricing signal to general customers through the activation of DR. This was accomplished by converting the controlled operating system of CBP to voluntary price response systems.

The Jeju smart grid test-bed provides a chance to demonstrate smart grid technology and the business opportunities that would derive from it. In addition, the experience of the test-bed market operation shows that the competitive electricity market can facilitate the smart grid deployment in Korea by allowing various demand side resources to be active market players. The result of smart grid maturity test including the two-way electricity market design shows the improvement in Korea's Smart Grid Maturity Model (SGMM) level from 0.8 to 2.8 [22]. This over-achieves 2.5 SGMM level set up by Korean government [23]. Given the benefits outlined in this paper, we hope for a paradigm shift within the electricity industry such that an emphasis on sustainable green growth becomes the norm.

7. Nomenclature

t dispatch/trading period index
i generator index
j load index
$u_{i,t}$ unit start up state at end of dispatch/trading period t
$d_{i,t}$ unit shut down state at end of dispatch/trading period t
$m_{i,t}$ unit on/off state at end of dispatch/trading period t
$de_{i,t}$ energy purchase at end of dispatch/trading period t
$ge_{i,t}$ energy dispatch target i.e. generation target at end of dispatch/trading period t; the (dispatchable) demand reduction is modeled as the positive generation.
$gs_{i,t}$ dispatch start point which is assumed (energy) generation at start of dispatch/trading period t
$r_{i,t}$ ancillary service dispatch target i.e. regulation or spinning reserve enabled at end of dispatch/ trading period
$GM_{i,t}$ maximum generation
$GN_{i,t}$ minimum generation
$GI_{i,t}$ inflexible generation level (where generator declared inflexible)
$GMR_{i,t}$ ramp-limited maximum generation
$GNR_{i,t}$ ramp-limited minimum generation
$RA_{i,t}$ reserve availability for regulation or spinning
$B_{i,t}$ energy purchase payment
$C_{i,t}$ generation (energy) dispatch cost (start-up cost is also included in day ahead UC)
$D_{i,t}$ ancillary service (regulation) dispatch cost (enabling-only equivalent)
$ND_{i,t}$ 92.5% of national demand
$RR_{i,t}$ reserve requirement
$L_{i,t}$ generation requirement i.e. forecasted load demand
$RU_{i,t}$ maximum generation increase ("run-up") in next 5 minutes starting from $gs_{i,t}$ given the offered ramp-rate set
$RD_{i,t}$ maximum generation decrease ("run-down") in next 5 minutes starting from $gs_{i,t}$ given the offered ramp-rate set
$MU_{i,t}$ minimum up time
$MD_{i,t}$ minimum down time
$s_{i,t}$ slack variable for system constraint v
$p_{i,t}$ penalty cost for system constraint v

References

[1] The Office of Electricity Delivery and Energy Reliability (DOE), *The Smart Grid: an Introduction,* U.S. Department of Energy, 2009.

[2] Energy Technology Policy Division (IEA), *Technology Roadmap: Smart Grids,* International Energy Agency, 2011.

[3] Peter Asmus and Clint Wheelock, *Virtual Power Plants: Smart Grid Platform for Aggregating Distributed Renewables, Demand Response, and Energy Storage Technologies*, Pike Research, 2011.

[4] National Science and Technology Council, *A Policy Framework for the 21st Century Grid: Enabling Our Secure Energy Future,* Executive Office of the President of the United State, June 2011.

[5] Consortium for Electric Infrastructure to Support a Digital Society (CEIDS) Website: About *IntelliGrid Architecture,* Via <http://www.intelligrid.info/ Intelli Grid_Architecture/Overview_Guidelines/index.htm>.

[6] GridWise Alliance Website: About *The Association Advocating for a Smarter Grid,* Via <http://www.gridwise.org/index.asp>.

[7] Fred Sissine, *Energy Independence and Security Act of 2007: A Summary of Major Provisions,* Congressional Research Service, CRS Order Code RL34294, December 2007.

[8] Mario Ragwitz, Anne Held, Eva Stricker, Anja Kerchting, Gustav Resch, and Christian Panzer, *Recent Experiences with Feed-in Tariff Systems in the EU - A Research Paper for the International Feed-in Cooperation*, Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (Germany), November 2010.

[9] Directorate-General for Research Information and Communication Unit (EC), *European Smart Grids Technology Platform: Vision and Strategy for Europe's Electricity Networks of the Future,* European Commission, 2006.

[10] Communication from the Commission to the European Council and the European Parliament, *An Energy Policy for Europe,* European Commission COM (2007) 1 Final, 2007.

[11] Directorate-General for Energy and Transport (EC), *EU Energy Security and Solidarity Action Plan: Second Strategic Energy Review,* European Commission, 2008.

[12] Shinsuke Ito and Koichi Ogawa, *Japan's Initiative on Smart Grid – A Proposal of "Nature Grid",* Ministry of Economy Trade and Industry (Japan), Paper presented at the seminar for Smart Grid – Current status and technical development: Comparative views from the EU and Japan, Brussels, Belgium, December 2009.

[13] Yoshizumi Serizawa, *CRIEPI's Research on Smart Grid: TIPS,* Central Research Institute of Electric Power Industry, Paper presented at EPRI Workshop, Nice, France, December 2008.

[14] Electric Power Statistics Information System (EPSIS) Website: About *Facility,* Via <http://www.kpx.or.kr/epsis>.

[15] Korea Smart Grid Institute (KSGI) Website: About *10 Power IT Projects,* Via <http://www.smartgrid.or.kr>.

[16] Korea Smart Grid Institute (KSGI), *Korea's Smart Grid Roadmap 2030: Laying the Foundation for Low Carbon, Green Growth by 2030,* Korea Smart Grid Institute and Ministry of Knowledge Economy (Korea), Via <http://www.smartgrid.or.kr/10eng4-3.php>.

[17] Electric Power Statistics Information System (EPSIS) Website: About *Overseas,* Via <http://www.kpx.or.kr/epsis>.

[18] Korea Smart Grid Institute (KSGI), *For the World's Green Growth: Jeju Smart Grid Test-bed in Korea,* Korea Smart Grid Institute and Ministry of Knowledge Economy (Korea), Via <http://www.smartgrid.or.kr/Ebook/JejuTestBed.pdf >.

[19] Korea Power eXchange (KPX), *KPX Knowledge power 2011,* June 2011.

[20] Jeju Smart Grid Test-bed Website: About *Five Areas of Jeju Smart Grid Test-bed*, Jeju Special Self-Governing Province, Jeju. Via <http://smartgrid.jeju.go.kr/eng>.

[21] Ministry of Knowledge Economy (Korea), *The 6th Basic Plan for Long-term Electricity Supply and Demand (2013~2027),* February 2013.

[22] Ministry of Trade, Industry & Energy (Korea), *MOTIE Press Releases (23 August 2013).* Via <http://www.motie.go.kr/motie/ne/rt/press/bbs/bbsView.do?bbs_seq_n=78222&bbs_cd_n=16>.

[23] Ministry of Knowledge Economy (Korea), *The 1st Basic Plan for Smart Grid (2012~2016),* July 2012.

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