Joint MIT-Japan White Paper: Compatibility of Nuclear and Renewables with Grid Stability, Economics and Deregulation

1. Introduction

Policy objectives for electricity markets around the world include ensuring affordable and reliable supplies, achieving environmental goals including reductions in greenhouse gas [GHG] emissions, and reducing the risk of supply disruptions. In Japan two major changes are underway in support of these broad goals: liberalization of electricity markets and large-scale introduction of renewable energy systems (RES), especially solar and wind, to help reduce GHG emissions and meet other policy goals. Similar changes have been underway in the United States for somewhat longer. Pursuing both programs simultaneously is challenging. Even as governments are seeking to rely more heavily on decentralized market mechanisms to set electricity prices and allocate resources, they are actively promoting the transition to low-carbon electric power systems. A key question in both Japan and the United States is how to improve or redesign the power system and market regulation to reach these goals efficiently. What technological and institutional innovations will be necessary to meet these goals?

In recent decades state-owned or heavily-regulated infrastructure sectors such as rail and air transportation, telecommunications, and energy have experienced deregulation and privatization in many advanced economies. Governments have sought to rely more heavily on market mechanisms to set prices and allocate resources. In Japan, electricity market deregulation began in 1995, even as the government was adopting goals to limit greenhouse gas (GHG) emissions, and in 2012 the government initiated Feed-in-Tariffs (FIT) that provide guaranteed payments to solar and wind electricity generators. Full competition in generation and retail electricity markets has been implemented in the European Union. In the United States, where regulatory policies are in large part determined at the state level, about two-thirds of the states have implemented wholesale market mechanisms while almost 20 states have introduced competition in retail electricity markets. In both the U.S. and the EU many different subsidies designed to encourage renewable energy systems (RES) have been introduced. Governments are now modifying these policies in an effort to promote RES deployment at lower cost to taxpayers and electricity customers.

Both nuclear power and renewable electricity will need to play a key role in the transition to low carbon system. But the operation of the existing nuclear fleet and the outlook for new nuclear investment are both affected by the changes in wholesale and retail electricity markets that are underway, as well as by the growth of intermittent renewable generating capacity. The implications of these developments for the future role of nuclear energy as a source of low-carbon electricity are of interest in many countries around the world, including the United States and Japan.

The purpose of this white paper is to explore the key questions that must be addressed in order to gain a better understanding of the outlook for nuclear and renewable technologies and the interactions between them in the low-carbon power grids of the future. The particular focus of the paper is to explore these questions in the context of the Japanese electric power sector. In Japan, where as already noted major changes in the regulation of the electric power industry are underway, the outlook for nuclear has also been profoundly affected by the accident at Fukushima. This paper augments ongoing discussion of the future of Japan's nuclear fleet by considering the challenges of designing power grids in which nuclear and renewables combine to achieve deep reductions in carbon emissions while also providing affordable, reliable electricity supplies. The purpose of the paper is to frame the key questions posed by such scenarios. Additional work will be needed to answer them.

The paper is organized as follows: Section 2 introduces the set of constraints that seem likely to bound the range of future scenarios for nuclear and renewable energy in Japan. Section 3 presents a brief general discussion of the issues facing regulators in today's electric power markets. Section 4 introduces a range of new technologies that may facilitate the full utilization of low-carbon generation sources, especially nuclear, solar, and wind, in the electricity markets of the future. Section 5 summarizes the observations in the preceding sections and discusses possible pathways towards low-carbon electric power systems in Japan.

2. The development of nuclear and renewable energy in Japan: constraints and Implications

a. Technical issues raised by deregulation and increased share of intermittent renewables

The combination of market liberalization and the integration of intermittent renewables poses a number of challenges for the operation of electric power grids. Appropriate market mechanisms (rules) must be designed in order to balance supply and demand in both the short and long term, while also achieving key public policy goals, including grid stability against disturbances, security of supply and reduced GHG emissions, as well as other environmental goals. An increase in the share of intermittent renewables in total power output creates challenges for power system operation in terms of demand and supply balancing, transmission line overload and stability, and power quality (including voltage and frequency control). Existing thermal power plants have constraints on the rate at which output can be ramped up or down, as well as the minimum output level at which they can operate, in response to fluctuations in the output of wind and solar systems. These challenges may be addressed by new kinds of energy storage technologies in the longer run, but may also require the introduction of new grid controls and operating systems including smart grid technologies.

b. Economic constraints and implications

The availability of adequate supplies of reliable, moderately priced electricity is essential for the competitiveness of Japanese industry and for sustainable economic growth. The most recent estimates (May 2015) prepared by the Power Generation Cost Verification Working Group of the Japanese government indicate that the levelized cost of electricity (LCOE) in Japan is lowest for nuclear (10.1 JPY/kWh), followed by coal (12.3 JPY/kWh), gas (13.7 JPY/kWh), oil (30.6~43.4 JPY/kWh), solar (29.4 JPY/kWh) and wind (21.6 JPY/kWh), with significant uncertainties in the longer-term price trajectories for fossil fuels, solar and wind. According to the Working Group's estimates, by 2030 the levelized cost of solar PV and on-shore wind are projected to decline to 12.5-16.4 JPY/kWh and 13.6-21.5 JPY/kWh respectively. Other estimates of the costs of these technologies by analysts in Japan and elsewhere are significantly lower.

Levelized cost is just one of several factors affecting the economic outlook for electricity supply. Other factors include the following:

a) *Changes in the overall power generation mix resulting from the goal of reducing the share of nuclear in total electricity output*. This is likely to result in added coal capacity (the next cheapest option in Japan) unless constraints on GHG emissions are also imposed.

b) *Additional costs associated with the need for backup generation or grid storage capacity to compensate for the intermittent nature of solar/wind electricity* (see Section 2a above)

c) *Increased cost burdens associated with FITs for solar and wind.* The Power Generation Cost Verification Working Group estimated annual FIT costs of JPY 300 billion, 470 billion and 700 billion associated with the share of intermittent renewables at 6%, 9% and 12% respectively, which would be roughly equivalent to additional costs of 4-5 JPY/kWh. According to estimates by IEEJ, the cumulative cost burden associated with FIT programs over a 20-year period will amount to 55 trillion yen (~0.5 trillion US$) if all of the 88GWe of approved renewable plants start operation.

d) *Impact of large-scale use of renewables on electricity markets in Japan.* One possibility is price collapse, a phenomenon that is already occurring in Europe and parts of the U.S. A recent MIT study on *The Future of Solar Energy* analyzed the impact on electricity prices of different solar market shares (Fig. 1).

Price collapse is already occurring in Europe and parts of the U. S..

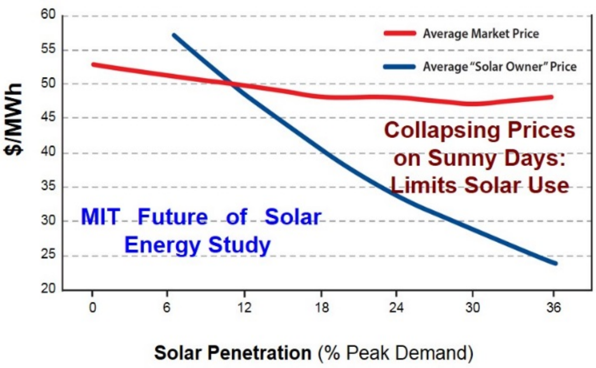

Fig. 1 Solar price collapse as production approaches electricity demand

In a deregulated market, as solar is added it drives electricity prices down on sunny days (blue line) resulting in less revenue for each solar plant owner as more solar is added to the electricity grid. If large quantities of solar are added, total generation may exceed demand at times of high solar output. At times of low solar output, other electricity generators must provide electricity; however, if they are only called on to operate for a few hours per year, these new plants will not be built unless the price of electricity rises dramatically during these hours. The same phenomenon is likely to occur with large additions of wind. Although the average market price of electricity does not change significantly as RES capacity increases, price volatility may increase substantially.

If renewable energy system (RES) subsidies are keyed to electricity output, electricity prices are likely to become negative when solar and wind output approaches total electricity demand, because RES producers, in order to receive these subsidies, will supply electricity to the grid that can be generated at zero marginal cost. This type of market behavior does not occur in systems where the share of RES is low and arrangements to curtail RES are in place to protect the grid. In those markets, if the price of electricity falls below the cost of fossil fuels, the fossil plants will be curtailed or shut down, but nuclear plants would continue to operate at rated power. Price collapse occurs as a consequence of transitioning from electricity generation by low-capital-cost and high-operating-cost (fossil) technologies to high-capital-cost low-operating-cost (nuclear, wind, and solar) technologies. The benefits of large-scale RES only exist if there is productive use of excess electricity at times of high solar or wind input.

There are many possible technical solutions to reduce the risk of price collapse, such as pumped-storage hydro and batteries that buy low-price electricity, store the electricity, and sell it at times of higher prices—as well as shutting down renewables when production exceeds demand. Section 4 discusses those options. However, the fundamental problem is that the addition of RES in many parts of the world has been so rapid that there has not been time to develop cost-effective solutions to productively use excess electricity at times of high solar or wind output. This is a one-time transition from a fossil-based power system to a low GHG system.

This issue has large impacts for RES as well as nuclear. If renewables are not subsidized, price collapse at times of high solar and wind output will limit the use of renewables due to revenue collapse.

c. Climate implications

In July 2015 the Japanese government announced the goal of mitigating greenhouse gas emissions by 26 percent in 2030 relative to the 2013 level. This target was submitted to the United Nations Framework Convention on Climate Change (UNFCCC) for discussion in COP 21 in Paris in December 2015. The mitigation target was established on the basis of the official long-term energy outlook to 2030 developed by the Ministry of Economy, Trade and Industry (METI) in July 2015. This energy outlook provides a pathway for simultaneously achieving the "3E+S" goals, i.e. energy security, economic efficiency, environmental protection and safety, and postulates reduced dependence on fossil fuels. According to this outlook, Japan's CO_2 emissions will decrease from 1.24 billion tonnes in 2013 to 0.93 billion tonnes in 2030. The Federation of Electric Power Companies (FEPC), a trade group of 10 power companies, has set a voluntary target of reducing CO_2 emissions to 0.37 kg per kwh by 2030, a 35% reduction from the 2013 level. The prospects for achieving these targets in the event that nuclear is phased out over this period as a result of no new build (as discussed in section 2.f below) and restrictions on the operating life of existing nuclear plants (section 2.g) need to be carefully analyzed.

A high priority in the long-term energy outlook is to increase the use of carbon-free sources of energy, as well as improvements in energy efficiency. The policy and technical measures needed to comply with the carbon target must be harmonized with the other two E's in the "3E+S" goals, i.e. energy security and economic efficiency.

d. Societal

The shift to a low-carbon energy portfolio in Japan will face two major societal challenges: public distrust of nuclear energy, and limited tolerance for the economic burdens associated with a low-carbon economy. The Fukushima-Daiichi accident was a failure of risk management in a country prone to natural hazards. Actions are being taken by industry and regulators to establish stronger risk governance by addressing technological, human, and organizational issues; nevertheless, the loss of trust in the aftermath of the accident has resulted in a shift in public opinion in favor of more renewables, more energy saving, and less nuclear.

An increase in the share of renewables is being promoted by FIT subsidies. The adoption of these subsidies reflects favorable public opinion towards renewable technologies. The cost of these subsidies is projected to increase significantly (and may offset the savings that would be brought about by the restart of Japan's idle nuclear plants and the resulting reduction in fossil fuel use.) In parts of the U.S. as well as in some other countries, the increasing costs of subsidies for renewables have led to decisions to scale back the subsidies. The willingness of Japan's industrial and household consumers to pay for further electricity tariff increases stemming from such subsidies in is unclear.

e. Security

Historically, Japanese electricity supplies have been vulnerable to fluctuations in the price of fossil fuels…which motivated Japan to increase its reliance on nuclear energy

As a resource-poor country, Japan has been affected by the threat of supply interruptions and fluctuations in the price of fossil fuels in world markets. This vulnerability prompted Japan to increase the role of nuclear energy, a quasi-domestic power source, in the aftermath of the Arab oil embargo in the 1970s. If the share of nuclear in the power generation mix in 2030 is 22%, and that for renewables is 22-24% (goals envisaged in the long-term energy supply-demand outlook released by the Japanese government in July 2015), Japan's energy self-sufficiency would increase from the current level of 6% to about 25% -- higher than the pre-Fukushima level of 20%. Without nuclear, the self-sufficiency rate is about 15%.

The ability of renewables to enhance energy security depends partly on the power source that is used as backup at times of low wind and solar input. If, as is the case in the U.S. and Europe thus far, backup is provided by fossil fuels, the energy security benefits of renewables will be reduced. As discussed in more detail in Section 5, the need to rely on fossil fuels as backup for renewables arises partly because economic low-carbon technologies have not yet been developed that could substitute for fossil fuels as a source of variable dispatchable electricity.

f. Implications of deregulation for investments in nuclear plant life extension

Increased competition may force premature shutdown of old plants

Because nuclear power is capital-intensive, while fuel and variable operating and maintenance costs are low, extending reactor lifetimes can provide very low-cost electricity. Japanese law sets a limit of 40 years for nuclear power plant life, with an allowance for life extension contingent on meeting regulatory requirements. In the U.S., about 80% of operating reactors have been granted permission by the regulatory authorities to extend their operating licenses to 60 years, and regulators have now defined the pathway for license extensions out to 80 years. Life extension activities are underway in many other countries as well.

Electricity market deregulation, combined with a growing share of renewables, can impact nuclear plant lifetimes. Increased wholesale market competition may force the premature shutdown of some old plants, since the investment required to extend operating lifetimes may exceed the economic benefit in these markets. Low or even negative wholesale electricity prices caused by the growth of renewable capacity and the effect of market subsidies for renewables has recently forced the premature shutdown of some older nuclear plants in the U.S., and may be responsible for the shutdown of several more plants in the coming years.

g. Implications of deregulation for investment in nuclear new build

No new nuclear build in deregulates states in the U.S.

New build of capital-intensive generating technologies is difficult in deregulated electricity markets because of the longer time periods required for cost recovery and because of the greater uncertainties in the electricity markets, which in turn are partly the result of regulatory changes, renewable additions, and the expectation of a transition to a low GHG electricity system. Only a few nuclear plants are currently under construction in the United States, and all such projects are located in states where traditional economic regulation of the power industry has been maintained. New nuclear plant construction in Europe is only occurring where there are other incentives. Proposals to reduce the economic and financial risks of nuclear new builds have included:

- FIT or equivalent for all low-carbon electricity supplies (i.e., not just renewables)
- Capacity markets with payments for assured dispatchable electricity
- Long-term power off-take arrangements
- Portfolio standards for all carbon-free electricity, not just renewables.
- Small modular reactors intended to enable incremental capacity investments that are matched to the growth in demand.

Although not itself a result of deregulation and RES, various studies have pointed to the possibility that electricity consumption will increase in the longer run as a consequence of efforts to mitigate carbon emissions, since one of the most likely pathways to a low-carbon energy system involves, along with more aggressive energy efficiency measures, continued electrification, including the use of electricity in the transportation sector.

3. Regulatory options and issues for deregulated markets

a. Objectives of deregulation and limitations of markets

The goal of market liberalization (deregulation) is to increase the efficiency in the operation and expansion and planning of power systems, on the basis of a proper allocation of risks between producers and consumers. Utility planning errors committed in regulated environments are paid for by customer tariffs; thus, utilities have only weak incentives to make efficient decisions. In contrast, the idea behind the implementation of a competitive market is to allocate investment and operation decisions to agents, who benefit from making correct choices and bear the costs of their mistakes. The expectation is that these incentives will lead market agents towards better-informed decisions, and as a result, towards the maximization of the net social benefit.

The limitation of leaving decisions (particularly long-term planning) to the market is that decisions are innately short-sighted. Without additional regulatory intervention, the market is likely to look exclusively to minimize the energy supply cost in the short to medium term and ignore other higher order objectives such as GHG emissions reductions or renewables deployment. The experience in the United States and Europe has shown that developing the market rules for deregulation is challenging. This has resulted in continued evolution of market rules in the U.S. and Europe as regulators learn what does and does not work.

The goal of deregulation is to increase competition in generation and retail and reduce electricity tariffs. However, experience in the United States and Europe has shown the challenges of developing market rules for deregulation and the net price changes that have occurred have depended as much on external factors such as natural gas prices as on the new market rules.

b. Market-pull instruments for security and sustainability

How to improve or redesign power system and market regulation to enable environment- and security-oriented policies to achieve their objectives efficiently?

In the current policy context, the goals of security and sustainability have at least as high a priority as competitiveness. Thus, it is necessary to create a market with some kind of long-term vision, such that, while minimizing interference with market allocation mechanisms, market agents also receive signals steering them in the right direction. The question is how to improve or redesign the power system and market regulation to enable sustainability and security-oriented policy goals to be achieved efficiently.

According to basic economic principles, the most straightforward way to design this regulatory support is through so-called "market pull" instruments –i.e., creating market conditions where these still-uncompetitive clean technologies can have a chance in the marketplace with some help. Examples include a carbon tax or a mandated emissions quota. These kinds of mechanisms solve one of the problems related to the market myopia, by allowing the introduction of environmental considerations into the decision-making process of market agents. Unfortunately they do not fully address the problems related to the lack of long-term view of market agents. Carbon taxes or tradable emissions quotas (or standards) are theoretically the most efficient complement to market mechanisms to fulfill emission reduction objectives, and they are likely to lead to the deployment of the cheapest clean technological solution at hand in the short term, However they do not fully compensate for the inability of markets to develop alternatives that could bring benefits in the long run, and they are often not acceptable from the political and social perspective, as they increase consumer prices more than technology-oriented subsidies.

Technology policies can be used to promote all types of technologies in need of support (e.g., wind, solar, carbon capture and sequestration). Until recently, the most popular way of supporting the deployment of these technologies has been through the implementation of *feed-in tariffs* (FITs): the regulator establishes the payment deemed necessary to attain the required output from renewable sources (by guaranteeing an acceptable rate of return for the investment) and then allows the market to operate freely. FITs are being replaced or at least redesigned worldwide in two orthogonal dimensions: first, to keep up with technological improvements, additional rules and/or mechanisms (such as auctions) are being designed to constantly update the value of the subsidy; second, the remuneration mechanisms are being defined to find an efficient trade-off between optimal investment incentives and market compatibility.

The idea that renewables should be insulated from the risks and competitive pressure of the wholesale market is increasingly tenuous, especially in light of the inefficiencies introduced by special treatment. This has led to a growing consensus that renewables should participate in wholesale markets with the same responsibilities and risks as conventional generators, and any associated support policies should be fully market compatible.

RES support mechanisms (e.g., FITs) are being redesigned to update the volume of subsidies with the evolution of learning curves and to provide RES with incentives to contribute to the reliability and efficiency of system operation, increasing their market compatibility, with the ultimate objective of reducing the costs of promoting them.

c. Difficulty of investment under uncertainties and capacity remuneration mechanisms

The electricity industry is a cornerstone of national economies and it has always been subject to certain degree of political control. This increases uncertainties for investors beyond those that are typical of all markets (price volatility, uncertainty about competitors' strategies, etc.), since agents also have to face the risk of possible regulatory changes, an element commonly referred to as regulatory risk. There is a second concern. Demand (the customer) has at least to date been somehow "unconcerned" about the risk of power shortages, because it is commonly assumed that the government will take actions to avoid these conditions (and of course the corresponding very high prices). This gap in risk perception results in electric generators under-investing in high-capital-cost low-operating-cost generating technologies with the consequent threat to security of supply.

> *Many countries are introducing capacity remuneration mechanisms, which remunerate the contribution of power resources such as nuclear energy to the reliability of the system*

When considering long-term capital investments where it takes many years to recover the investment, such as in nuclear plants, power sector deregulation obviously increases the uncertainty and the risk for market agents. The expansion of the system is no longer centrally planned, but rather it depends on individual decisions of several investors. Furthermore, the constant threat of regulatory interventions, which could change market rules in order to pursue a strategic objective, represents a further uncontrollable risk. In order to avoid decommissioning and to guarantee the security of supply, many countries are introducing capacity remuneration mechanisms (CRMs), which remunerate the contribution of power resources such as nuclear energy to the reliability of the system.

The majority of countries have introduced, or are in the process of introducing, CRMs. The goal is to reinforce the economic signal provided by short-term electricity markets with an additional financial hedge to attract investment and ensure system adequacy in liberalized power sectors. The key challenge now is to find the most adequate way to design these mechanisms to maximize their effectiveness and economic efficiency.

d. Other issues

Many of the existing loose ends and regulatory imperfections will be amplified by the emerging new factors. For instance: intermittent renewable penetration will test market design and the rules of price formation; the extended geographical scope of regional markets significantly increases the complexity of transmission network capacity expansion planning; the need for flexibility will require levels of activation of demand response that have not been explored yet; the pressure on energy efficiency and conservation will reveal the conflicts of interest of distributors and retailers and will require innovative regulatory measures; and the standard approaches to remuneration of distribution networks will have to be modified with the expansion of distributed generation.

4. Technology: Matching Electricity Production with Demand

Throughout the world major efforts are underway to increase the efficiency and reduce the cost of renewable energy technologies. Efforts are also underway to develop next-generation nuclear technologies, with goals including greater reliance on passive safety mechanisms, lower construction costs, reduced requirements for waste management and disposal, and support for non-proliferation goals. In this section we focus on technological innovations that are specifically intended to address operational and economic challenges in electric power grids that rely very little on fossil fuels.

Fossil-fuel power plants have low capital costs and high operating cost; thus, it is economical to operate these plants at part load to match electricity production with demand. Nuclear, wind and solar have high capital costs and low operating costs. Operating these technologies at part load is very expensive. Furthermore, the electricity output of these facilities at full capacity does not match electricity demand over time scales ranging from seconds to seasons. New technologies are required to economically integrate nuclear and renewables into a low-carbon system so that demand is always met and capital-intensive low-operating-cost nuclear, wind and solar plants can operate at full capacity to minimize costs. Six classes of such technologies are discussed below. In some of these categories new technologies are already being commercialized. In other cases technologies are under active development. But some technologies are still only under preliminary consideration and much additional work is needed to determine feasibility.

a) *Demand Shift.* Electricity demand can be shifted over time intervals of seconds to hours by methods such as changing operating schedules of some industrial facilities and real-time price signaling to residential customers to encourage the use of grid-supplied electricity at times when it can be delivered at low cost. 'New' demand created by new applications such as external charging of electric car batteries can also be used to shape demand for grid services and thus match supply with demand more closely.

b) *Electric storage.* Electricity (work) at times of low prices can be stored (hydro pumped storage, batteries, etc.) to provide electricity at times of high prices. These technologies store electricity for hours, but not for weeks or seasons. Electricity storage is expensive; thus, storage capacity is limited with the risk in a low-carbon system that external conditions (multiday heat wave, cloudy weather, low wind, etc.) will deplete storage with resultant power outages.

c) *Hybrid Systems.* Hybrid systems use heat from nuclear or solar thermal plants operated at full capacity to produce electricity and a second energy-intensive product in variable proportions. At times of low electricity prices and demand, less electricity is produced and more of the second product is produced. From a long-term perspective, hydrogen may be the primary non-electrical secondary product because (1) there is an existing industrial market (metals production, chemicals, and refineries), (2) it can be stored until needed, and (3) it can potentially be used for transportation and peak electricity production.

In addition, several new classes of technologies are being developed to enable an economic low-carbon nuclear-renewable grid:

d) *Convert Electricity to Stored Heat for Industrial and Other Applications.* With large-scale deployment of wind and solar there will be periods when the supply of electricity exceeds demand. During these periods, the excess electricity can be converted to and stored as high-temperature heat, which will be an economically competitive heat source for industry if the combined cost of the excess electricity and heat storage falls below the market price of fossil fuels that would otherwise be used for industrial heating. One example of a low-cost heat storage technology (~$5/kWh, more than a factor of 10 less than batteries) is Firebrick Resistance Heated Energy Storage (FIRES). In a FIRES-based system, whenever the electricity price is less than the price of the competing fossil fuel, the electricity is used to heat bricks to high temperatures. Air is blown through the hot bricks to provide hot air when needed to partly replace the use of natural gas in industrial furnaces and kilns. FIRES in effect sets a minimum price for electricity about equal to (slightly below) that of natural gas, with excess electricity at times of high wind or solar output transferred to industry to partly offset the use of fossil fuels and thereby reduce GHG emissions.

e) *Thermal Energy Storage for Electricity.* Nuclear and solar thermal systems produce heat that can either be directly converted to electricity or stored and later converted to electricity. When the price of electricity is low, heat is sent to storage. When the price of electricity is high, the nuclear and solar thermal systems produce electricity and the stored heat is converted to added peak electricity production. In principle the heat can be stored for periods from minutes to seasons, depending on the technology, but until now only technologies enabling storage times up to hours have been developed. Some solar thermal electric plants today store heat when there is excess electricity supply, producing electricity later when it is needed. The same technologies apply to nuclear.

f) *Nuclear with 'topping' cycle.* This is an advanced reactor and power cycle option where base-load nuclear reactors with gas-turbine power cycles operate in two modes: (1) base-load on nuclear heat, and (2) added variable peak electricity production using natural gas (near term), stored heat, biofuels, and/or hydrogen. The topping-cycle incremental heat-to-electricity efficiency is significantly greater than stand-alone natural gas plants and other technologies; thus, the potential the most efficient method to convert additional heat into variable electricity. A nuclear topping cycle coupled to a fluoride-salt-cooled high-temperature reactor is shown in Figure 2 with the differences in heat to electricity efficiency between base-load electricity and peak electricity. This power cycle can't be coupled to light water reactors because their operating temperatures are too low but can be coupled to a variety of higher-temperature reactors.

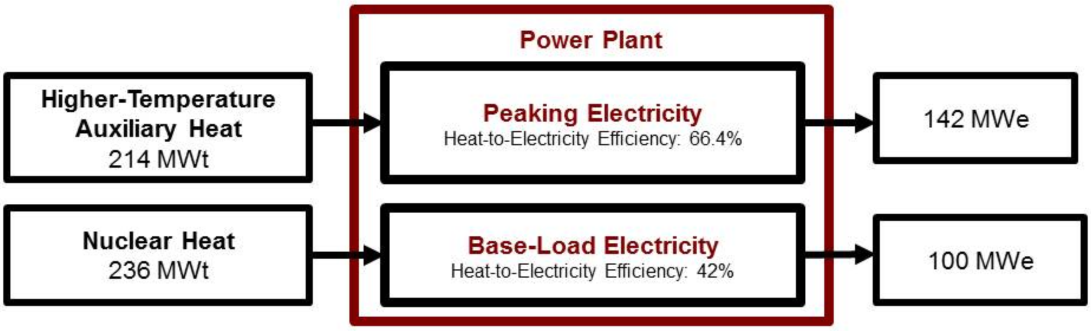

Fig. 2. High-temperature Reactor with High-Efficiency Topping Cycle Using Natural Gas, Hydrogen or Stored Heat

These 6 categories are not mutually exclusive in their application. The role of each technology will depend upon: (1) the pace of technological advance in each case, (2) the relative quantities of nuclear, wind and solar generating capacity, and (3) the electricity demand profile over time. The preferred technology for storing energy for an hour will be different from the preferred technology for storing energy for a day or for a month. Solar output has a daily cycle whereas wind has multiday cycles. Both have seasonal variations. The scale of deployment of these technologies will also depend upon the relative quantities of nuclear, wind, and solar capacity. Because of large seasonal variations in solar and wind output, grids with large amounts of wind and solar and little nuclear will require larger storage capacity over longer times than systems where significant nuclear is deployed with its year-round operation.

Finally, nuclear reactors produce heat that is converted into electricity, whereas wind and solar photovoltaic produce electricity directly—an important difference. The lowest-cost energy storage technologies store heat rather than electricity (work). This is because of the fundamental physical difference between work and heat. That difference may make nuclear energy the enabling technology for larger-scale use of renewables because it can provide, through low-cost heat storage (as in options c, d, e, and f above), the variable electricity output that will enable nuclear + wind + solar systems to match supply with demand.

5. Summary and the way forward

1) Japan is initiating two changes in its electric power system: deregulation/liberalization of markets; and integration of intermittent renewables into the grid, implying a more distributed electricity system with many users who are also electricity generators. Worldwide there is much experience with deregulation of

electricity markets but less experience with the impact on markets of a significant share of renewables.

2) The combination of deregulation and integration of intermittent renewables into the grid will pose technical and economic challenges. Unbundling of power companies leads to a system that is no longer centrally planned. Increased share of intermittent renewables in the power system influences its stable operation, in terms of demand and supply balancing, transmission line overload and stability, and quality of electricity in distribution. This necessitates additional capacity and storage in the grid.
3) The shift to a low-carbon power grid, especially if it involves significant increases of RES and reduced fossil fuel use, may dramatically change electricity markets in several ways, including increases in the FIT burden and possible price collapse at times of high wind and solar output. Development of technologies to productively use excess low-price electricity at such times has not matched the rapid increase in RES.
4) Deregulation was supposed to increase competition in generation and retail and reduce electricity tariffs. However, experience in the United States and Europe has shown the challenges of developing market rules for deregulation and the net price changes that have occurred have depended as much on external factors such as natural gas prices as on the new market rules. Relying exclusively on market mechanisms may lead to short-sighted decisions. Policies for long-term sustainability and security are required, which could include such options as modified FIT or related methods for low carbon electricity, capacity markets, long-term power off-take arrangements, and portfolio standards applying to the share of carbon-free electricity that would be applicable to both nuclear and RES. All of these mechanisms reduce the financial risks of building high-capital-cost low-operating cost nuclear, solar, and wind.
5) The idea that renewables should be insulated from the risks and competitive pressure of the wholesale market is increasingly tenuous, especially in light of the inefficiencies introduced by special treatment.
6) The development of a low-carbon energy system will transform the electricity grid and much of industry. In such an economy, nuclear, wind, and solar will be the primary sources of electricity. The transition from fossil fuels to a low-carbon electricity system will require new technologies and new policies. New technologies are needed to integrate nuclear and renewables into a low-carbon system economically so that capital-intensive low-operating-cost nuclear, wind, and solar plants can operate at full capacity to minimize costs. Both nuclear power and renewables are capital-intensive Electricity from renewables is supply-contingent and is supported by FIT, while nuclear is not. This creates economic, technological, and policy challenges for nuclear. New technologies are needed to enable nuclear plants to provide peak variable electricity while the reactor itself operates economically at its rated power. Such technologies will improve nuclear power economics while also enabling larger-scale utilization of RES. Incentives are needed for research and development on such options as hybrid operation (for example, producing hydrogen while electricity demand is low), thermal storage coupled to reactors, and nuclear with topping cycles.
7) Decision-makers must: a) understand the challenges of simultaneously liberalizing electricity markets and integrating intermittent renewables on the grid while also carefully designing the system for sustainability and energy security goals; b) find methods to productively use excess electricity generated in low-carbon grids (the

excess is produced as a result of increases in supply-contingent renewable capacity while operating nuclear reactors at rated power economical); and c) consider which innovations will be most important in designing low-carbon power systems comprised primarily of renewables and nuclear. The symbiotic deployment of nuclear and renewables can provide the backbone of low-carbon power grids delivering affordable, reliable electricity service. To realize this potential, however, both technical and institutional innovations will be needed.

Authors in alphabetical order:
(U.S.)

FORSBERG, Charles W.	Professor, Massachusetts Institute of Technology
HARATYK, Geoffrey	Graduate student, Massachusetts Institute of Technology
LESTER, Richard	Professor, Massachusetts Institute of Technology
BATLLE LOPEZ, Carlos	Visiting Scholar, Massachusetts Institute of Technology

(Japan)

FUJII, Yasumasa	Professor, University of Tokyo
KOMIYAMA, Ryoichi	Associate Professor, University of Tokyo
KURIHARA, Ikuo	Chief Researcher, Central Research Institute for Electric Power
OMOTO, Akira	Professor, Tokyo Institute of Technology
MURAKAMI, Tomoko	Group Manager, Institute of Energy Economics of Japan
TANIGUICHI, Tomihiro	Professor, Tokyo Institute of Technology