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The Fukushima nuclear accident and its effect on global energy security

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HIGHLIGHTS

- ► Japan's demands for fossil fuels raised the price of LNG and low-sulfur crudes.
- ► The accident affected the global price of uranium and producer share prices.
- ► The accident accelerated foreign-direct investment in LNG projects worldwide.
- ► The change in public perception toward nuclear power was relatively limited.
- ► A radical shift in global nuclear policy seems to be unrealistic after Fukushima.

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ABSTRACT

The March 2011 nuclear accident at the Fukushima Daiichi nuclear power station affected both short- and long-term energy-security in Japan, resulting in crisis-driven, ad hoc energy policy and, because of the decision to shutter all nuclear reactors, increased the country's demand for fossil fuels, primarily natural gas. However, the effects of the accident on energy security were not restricted to Japan; for example, the worldwide availability and affordability of liquefied natural gas were affected by Japan's increased demand; while the accident itself resulted in the loss of public acceptability of nuclear power and led countries, such as Germany and Italy, to immediately shut down some of the nuclear reactors or abandon plans to build new ones.

This paper examines some of the short-term effects on global energy security following the accident at Fukushima, focusing on the main replacement fuel, liquefied natural gas. It shows, amongst other things, that the accident increased investment in liquefied natural gas projects around the world. The paper shows that despite Fukushima contributing to nuclear power's loss of acceptability in most developed countries, it is still seen as an essential way of improving energy security in many countries and, despite what its critics may say, will probably continue to be used as a significant source of low-carbon electricity.

1. Introduction

The accident at the Fukushima Daiichi nuclear power station that resulted from the devastating earthquake and tsunami of March 2011 was both a catastrophic disaster and a serious event in terms of Japanese and global energy security (a companion paper (Hayashi and Hughes, 2012), describes the crisis-driven changes to policy and regulations in the aftermath of the accident and the effect on Japanese energy security). The shutdown of the Fukushima reactors and the subsequent closures of all other nuclear reactors across the country meant that the supply of electricity from nuclear power in Japan dropped from 31.2% in February 2011 to zero in May 2012 (ANRE, 2012).

Since the accident, the Japanese population has responded to the loss of electricity with significant levels of personal energy reduction, while electric-power companies have replaced part of the supply of electricity by increasing the use of thermal generation, primarily from natural gas and various petroleum products (Hayashi and Hughes, 2012). Given Japan's almost total lack of natural resources (in 2010, Japan imported 99.6%, 96.3%, and 100% of its petroleum, natural gas, and coal, respectively (METI, 2011b)), its increased demand for these energy sources could further tighten regional and potentially global supply, while also affecting the market price of various types of energy. With current global energy supply intricately interconnected and most countries importing at least some of their energy supply, changing

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energy consumption patterns in one country can have a significant influence on the energy security of other countries (Bahgat, 2006; Varrastro and Ladislaw, 2007). Hence it is reasonable to assume that given its state of development, the disruption to the Japanese energy system in March 2011 affected both domestic and international energy security.

In addition to its effect on short-term energy security in Japan, the accident was a critical event that could have short-to-medium-term energy security implications for many countries, regardless of whether they currently use or are planning to use nuclear power. It was a coincidence that the accident at Fukushima occurred amid an increasing global momentum for the peaceful use of nuclear energy, with some predicting a "nuclear renaissance" (World Nuclear Association, 2011). Globally, there was an rising trend in favor of nuclear power as compared to the decades following the accidents at Three Mile Island in 1979 and Chernobyl in 1986; in 2010, a total of 16 projects had commenced construction worldwide, the most since 1980 (IEA, 2011b). The International Energy Agency (IEA) also projected that the global nuclear capacity would jump to 1200 GW by 2050 from 370 GW at the end of 2009 (IEA, 2010b). However, the accident at Fukushima might affect the global impetus for nuclear power in much the same way as the two previous major accidents did, after which the number of nuclear reactors under construction decreased significantly worldwide (IAEA, 2008).

There are a number of factors that were triggered by the accident at Fukushima which could affect both the use of nuclear power and global long-term energy security. For example, as nuclear power is dependent on public acceptance to a larger degree than other electricity sources (WEC, 2007), any significant change in public opinion worldwide could affect global energy security. In addition to public perception, the rising costs associated with building nuclear power stations due to longer construction periods caused by increasingly rigorous safety regulations are expected to dampen enthusiasm for it. If nuclear power is not considered a secure energy source, it is imperative to identify those sources which will replace it as a source of electricity in a world where carbon constraint is becoming increasingly critical.

The remainder of the paper is organized as follows. In the next section, the definition of energy security and the methods used in this paper to analyze the impact on global energy security are introduced. This is followed by a brief description of the Fukushima accident and its impact on Japanese energy security. In the analysis section, the impact of the accident on global energy security is examined in light of the three indicators of energy security: availability, affordability, and acceptability. A discussion follows on the possible implications for global energy security. The paper concludes with a summary of the findings.

2. Energy security

All jurisdictions have an energy system intended to meet the tertiary energy demands of its energy services with supplies of primary or in some cases, secondary energy. Internally, the system has one or more energy chains, each consisting of processes responsible for converting primary energy into secondary energy and then distributing it to processes that convert the secondary energy into tertiary energy. The loss of a primary energy source or the failure of a process within a chain can result in a deterioration of energy security for an individual service or the entire system (Hughes, 2012).

Energy security, from the perspective of an energy consumer, is defined by the IEA as, "the uninterrupted physical availability at a price which is affordable, while respecting environment concerns" (IEA, 2010a). This definition can be parsed into three indicators (or dimensions) of energy security: availability ("the uninterrupted physical availability"), affordability ("a price which is affordable"), and acceptability ("respecting environment concerns") (Hughes, 2012). These indicators can be employed to measure changes to the flows of energy between processes, within a chain, or within the system. A change can result in the improvement or deterioration of the system's energy security.

A jurisdiction can attempt to improve its energy security by targeting processes with policies to reduce energy consumption, replace insecure energy sources or processes with ones that are secure, and restrict demand to sources and processes that are secure (Hughes, 2009). The success of an energy security policy can be measured with the aforementioned indicators (Hughes, 2012).

In this paper, the three indicators, availability, affordability, and acceptability, are employed to examine the changes to global energy security in light of the March 2011 nuclear accident at Fukushima.

3. The Fukushima accident and Japanese energy security

3.1. The accident at the Fukushima Daiichi nuclear power station

On 11 March 2011, a magnitude 9.0 earthquake (Richter scale) occurred off the east coast of Japan's Honshu Island, triggering a tsunami that subsequently engulfed the Fukushima Daiichi nuclear power station and its reactors (NERH, 2011; JMA, 2011). Despite the automatic shutdown of the operating reactors, the loss of access to off-site power and a flooded emergency diesel-generator system caused the station to lose its ability to cool the reactor core and spent fuel ponds. The overheating of the reactors caused three of the six reactors to experience full meltdown resulting in the release of large amounts of radioactive materials (METI, 2011a). The Japanese Nuclear Safety Agency rated the events as level seven as a provisional appraisal on the accident scale of the International Atomic Energy Agency (IAEA), which is the same level as the 1986 Chernobyl accident (METI, 2011c).

In December 2011, the Japanese government announced that the reactors had been brought to a state of cold-shutdown (Prime Minister of Japan and His Cabinet, 2011). However, Tokyo Electric Power Company (TEPCO), operator of the plant, and the government assume that it will take up to 40 years to complete the entire decommissioning process (TEPCO and METI, 2011).

3.2. The impact on electricity capacity in Japan

The earthquake and tsunami resulted in the simultaneous loss of about 30,600 MW, primarily in the northeast part of Japan (8800 MW of nuclear, 15,800 MW of thermal, and 6000 MW of hydroelectricity) or 13.4% of the country's total electricity capacity (Hayashi and Hughes, 2012).

In addition to the immediate loss of nuclear capacity, a more significant decline in nuclear generation followed as a result of the government's decision to demand the immediate shutdown of reactors located in areas of high earthquake and tsunami risk and to call for the implementation of stress tests for all existing nuclear reactors across the country. As a result, by May 2012, all of the country's 54 nuclear reactors, with a total capacity of 48,960 MW were offline.

The loss of electricity from nuclear power was dealt with by both demand- and supply-side measures. A nationwide demand-reduction campaign saw the 2011 summer-peak demand in TEPCO's operating area (which includes metropolitan Tokyo) reduced by 18% from the previous year. The principal supply-

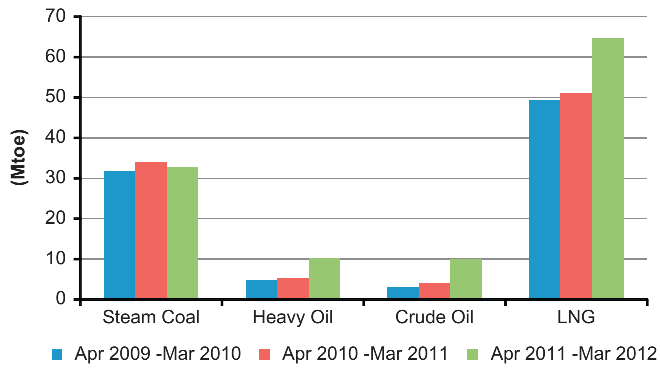

Fig. 1. Japan's fuel consumption for electricity generation (from (FECJ, 2012)).

side measure was to increase the availability of electricity from thermal sources, notably natural gas and oil, as well as electricity interchange amongst electricity suppliers and the use of self-generation and decentralized generation plants. As a result, in August 2011 (the Japanese summer peak), thermal generation met 77.8% of demand, up from 63.4% in February 2011 (ANRE, 2012). With the exception of steam coal, there was corresponding increase in fossil-fuel consumption and concomitant imports rose dramatically. Fig. 1 shows fuel consumption for electricity generation by Japan's ten electric-power companies before and after the accident. The fuel consumption of heavy oil, crude oil, and liquefied natural gas (LNG) a year after the accident (April 2011–March 2012) had increased by 87.7%, 143.1%, and 26.7%, respectively, compared to the same period prior to the accident.

4. The impact on short- and medium-term global energy security

4.1. Availability

4.1.1. Liquefied natural gas

Prior to the accident, Japan was the world's largest LNG importer, with annual imports accounting for 69.2 million tonnes or about one-third of the global LNG supply (BP, 2011). Because of the accident, by March 2012, Japan's annual LNG imports rose to about 81.8 million tonnes—an increase of 17.9% (MOF, 2012).

Although LNG traded under spot or short-term contracts accounts for about 18.9% of global LNG trade and correspond to more than 40 million tonnes of LNG a year (GIIGNL, 2011; BP, 2011), Japan's additional demand, coupled with growing LNG demand in emerging countries, affected not only major importers in the Asian region, such as South Korea and Taiwan, but others in the European region as well, including the United Kingdom (Chazan, 2012a).

Japan's additional demand for LNG was met mainly by using the Upward Quantity Tolerance option (an option right to increase the import volume between 5% and 10% based on the long-term contracts between the electricity suppliers and LNG exporters) and procurement on the spot market (IEEJ, 2011). Qatar in particular contributed greatly to meeting this demand because of its expanded LNG production capacity (from 30 million tonnes at the end of 2008 to 77 million tonnes at the end of 2010, four months prior to the earthquake (Qatargas, 2011)), allowing Japanese LNG imports from Qatar in 2011 to increase by 55.4% year-over-year (MOF, 2012). About 20 million tonnes of this LNG have been shipped from Qatar to the United States (US); however, demand for LNG in the US has declined because of the significant expansion of unconventional natural gas production in recent years (Reuters, 2012).

On the other hand, given their robust economic growth, Chinese and Indian LNG demand increased in the first half of 2011 by 27% and 26%, respectively, compared to the same period in the previous year (Sethuraman, 2011); while demand from South Korea and Taiwan in the first 10 months of 2011 increased by 16% and 10%, respectively (Sakamoto, 2011). This, combined with Japan's additional demand, made the Asian LNG market tighter and resulted in a surge in the market price for LNG (discussed in Section 4.2). This price surge in the Asian market also influenced the European LNG market. In fact, the UK's imports of LNG between August 2011 and April 2012 plummeted by about 30% compared to the same period in the previous year (Chazan, 2012a); this resulted in many shipments originally destined for European countries being diverted to Japan instead, enticed by higher prices in the Asian market.

The accident and the availability of project financing in the aftermath of global economic downturn meant that the expectation of increasing LNG demand in Japan and some European countries, coupled with already rising demand in emerging countries in Asia, Latin America, and the Middle East, accelerated financial-investment decisions for new global LNG projects; for example, the total production capacity of LNG projects for which financial-investment decisions have been declared is expected to reach 34.6 million tonnes—four times larger than that of the previous year (Sakamoto, 2011). In addition to the traditional LNG consumers such as Japan and South Korea, emerging market economies and European countries aggressively strived to secure future LNG supply following the accident (Radowitz and Hromadko, 2012). This expanded demand in part due to the accident, increased the likelihood of new LNG exporting projects mainly in Oceania, North America, and Africa (Radowitz and Hromadko, 2012; Chazan, 2012b; Nikkei Inc., 2012a; Smith and Iwata, 2012; Fowler and González, 2012).

In Australia, significant investments on coal-seam gas LNG projects were seen after the nuclear accident at Fukushima (Sakamoto, 2011). In North America, the first shale gas-based LNG sale and purchase agreement between a South Korean gas utility (Kogas) and an LNG developer in the US was made in January 2012 (Cheniere Energy Partners, 2012). Japanese companies also aggressively started the negotiation with both Canadian and US companies to import shale-gas LNG.

4.2. Affordability

4.2.1. Plant cost of nuclear power

The construction costs associated with nuclear power plants increased worldwide after the Fukushima accident, driven by the public's demand for additional safety measures, although they were already trending upward before the accident in countries such as the US and France (Cooper, 2010; Davis, 2011). The accident also saw stricter regulations of nuclear power plants being introduced around the world and are expected to cause longer construction times and increased interest-burden (IEA, 2011b). Furthermore, the exposed risk is expected to raise the interest rates on loans for nuclear projects, potentially discouraging investors and lenders.

However, the extent of the impact on the actual costs of nuclear is uncertain and also depends on where the plant is constructed. Some argue that the short-term impact on construction costs is expected to be limited in the US, where a review of the country's existing 104 nuclear reactors by the Nuclear Regulatory Commission (NRC) concluded that they do not pose an imminent threat to safety (Platts, 2011a). The South Texas project (in which TEPCO was involved) in the US was canceled after the accident because of the loss of funding and already high construction costs (Platts, 2011a). However, the less-thanenthusiastic attitude of investors towards nuclear power and the ongoing trend of increasing construction costs were already evident prior to the accident (Kyodo News, 2011).

Nevertheless, it is likely that further increases in project costs of nuclear power could result in its loss of competitiveness as well as discouraging new investment. In fact, in the US, it is estimated that the electricity cost of natural gas combined-cycle gas turbines entering into service in 2016 will be cheaper than that of nuclear power because of the recent expansion of shale-gas production (US Energy Information Administration, 2010).

4.2.2. Liquefied natural gas prices

The LNG spot-price in the Asian market experienced a marked increase following the earthquake and accident. Fig. 2 shows the LNG spot-prices for Japan and South Korea (Platts' LNG Japan Korea Marker or JKM), increasing from $9.7/MMBtu in February 2011 to $11.5/MMBtu in the three weeks immediately following the earthquake and to $18.34/MMBtu in May 2012 (Platts, 2011b; Nikkei Inc., 2012b).

Fig. 3 compares LNG and natural gas spot-prices in Asia, Europe (the UK National Balancing Point), and the US (Henry Hub). In the aftermath of the Fukushima accident, LNG prices increased in the Asian market and had limited impact on European markets; the Henry Hub price was not affected as the US market is, for the moment, independent of the higher prices seen elsewhere for natural gas and is likely to remain so until it becomes an LNG exporter. In an effort to improve regional energy security in light of the Asian-market price increases, the governments of major LNG importers, such as South Korea and Japan, commenced talks on the possibility of increased cooperation regarding the procurement of LNG through joint purchases or the sharing of ships in an effort to lower import prices (Platts, 2011c).

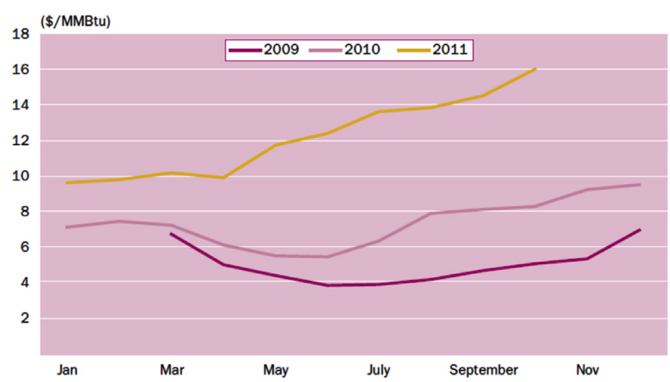

Fig. 2. Monthly average LNG spot-prices for Japan and South Korea (Platts, 2011b).

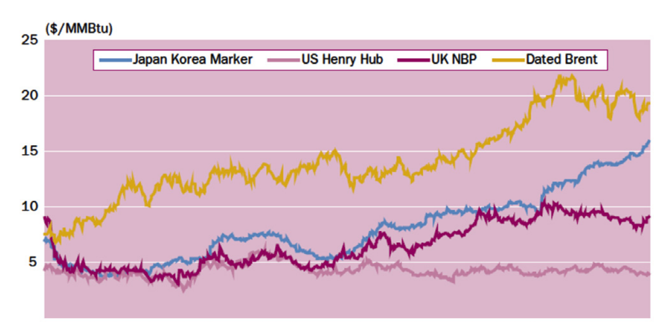

Fig. 3. LNG and natural gas spot-prices in Asia, Europe, and the U.S. ($/MMBtu) (Platts, 2011b).

The aggressive moves by Asian and European LNG importers in pursuit of LNG from shale-gas in the US were motivated by its low production cost and the high price of LNG. Currently, the price of LNG imported into Asia and Europe (and also the price of natural gas supplied by Russia to Europe) is essentially linked to the price of crude oil (IEEJ, 2010). Of course, growing demand in the US for domestic shale-gas and its eventual export as LNG could tighten supply and result in a surge in prices there; an analysis from Shell suggests that the price of natural gas in the US could double by 2015 if this occurs (Chazan, 2012c). However, the export of LNG from US could also affect the other LNG exporters which might make it possible to change the current oil-linked pricing mechanism by giving buyers new bargaining power. This is already evident in the European market (more so than in Asia) where Russia's Gazprom and Norway's Statoil, which meet 40% of European gas demand, have started to revise their traditional oil-indexed natural gas contracts (including take-or-pay clauses) with European buyers, primary due to lower gas prices given the global gas glut as the result of the global economic recession since 2008 and the US shale gas revolution (The Economist, 2012).

4.2.3. Uranium prices

In 2008, Japanese demand for uranium accounted for 11.7% of world production (OECD et al., 2009). Despite the number of offline reactors in Japan, the volume of natural and concentrated uranium imported by Japan after the earthquake had not declined significantly (MOF, 2012). However, due to the uncertainty over the future of nuclear power in the aftermath of the Fukushima accident, both uranium prices and the share prices of companies involved in the uranium industry (including exploration, production, and processing) fell and continued to fall as other countries such as Germany and Italy announced plans to accelerate the timing to abolish nuclear power or abandoned plans to construct new ones.

Fig. 4 shows weekly uranium oxide (U_3O_8) prices and stock prices of Areva and Cameco, two of the world's major uranium producers. Uranium oxide prices fell from $68.24/lb in March 2011 to $49.99/lb immediately after the earthquake and were still around $50/lb in May 2012 (Bloomberg, 2012b), even though the price had increased by 80% in the eight months prior to the earthquake (The Wall Street Journal, 2011). Nevertheless, uranium prices remained higher than their 2010 levels.

Cameco's share prices decreased by 24% immediately following the earthquake and continued to decline for the next eight months; at the end of 2011, the price had fallen by 57% (Bloomberg, 2012c). Areva also saw its share prices fall by the end of 2011, it was almost half the level prior to the earthquake (Bloomberg, 2012a); subsequently, it was decided to temporarily shut down two uranium conversion plants due to the sharp

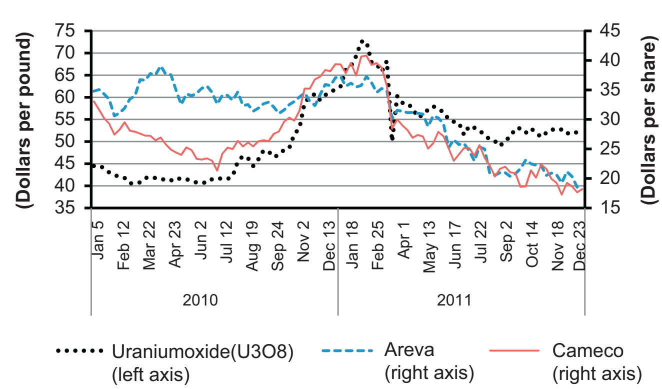

Fig. 4. Weekly uranium oxide prices and stock prices of Areva and Cameco (from Bloomberg (2012a, 2012b, 2012c)).

decline in the demand for uranium (Maitre, 2011). A mining project in the Central African Republic was also suspended by Areva due to the low uranium-prices in November 2011 (The Globe and Mail, 2011); while in February 2012, the company announced that its 2011 operating losses were €1.9 billion (Areva, 2012b). Notwithstanding the decline in both uranium and stock prices, the world's existing 425 reactors, along with those under construction, will require about 180 million pounds of uranium in 2011, compared to the 145 million pounds in the previous year (Saefong, 2011). Considering this demand, the impact of the accident on the uranium and stock prices might be a short-lived.

4.3. Acceptability

The accident at Fukushima changed the public acceptability of nuclear power globally. Since 2000, public acceptance of nuclear power was increasing in countries with domestic nuclear power plants such as the US, UK, Sweden, and Finland (IEA, 2008). Table 1 shows the changes in public opinion in favor of nuclear power in some countries as revealed by a survey of 47 countries by WIN-Gallup International (2011). Worldwide, public acceptance of nuclear power fell from 57% to 49% in the aftermath of the accident at Fukushima.

Following the accident, some countries reviewed their nuclear-energy policies, driven in part by public opinion (Newsweek, 2011). Germany, which relies on nuclear power for 23% of its electricity needs, immediately shutdown seven of its older reactors and reaffirmed that it would abandon all nuclear power plants by 2022 (Strahan, 2011), while Switzerland also decided to abandon nuclear power by 2034 (Copley, 2011). In Italy, a referendum turned down a government plan to construct new nuclear power plants (BBC News, 2011).

In some respects, none of these actions were surprising, as most of these countries already had sizeable anti-nuclear lobbies and the accident at Fukushima was seen as the last straw by these groups (Mukarami, 2011). In fact, in 2002, Germany had already decided to phase-out nuclear power completely by 2022; however, in 2010, the Merkel government changed the policy, extending lifetimes until 2030, but not the phase-out itself. Also, other factors affected the change in policy; for example, the transition of German nuclear policy is largely attributable to political reasons such as the forthcoming federal elections (Jahn and Korolczuk, 2012). Merkel's government intended to reach a consensus with the opposition parties by accelerating nuclear-exit policy, given the immense public pressure in the wake of the Fukushima accident (Radowitz and Hromadko, 2011). As Table 1 shows, positive opinion toward nuclear power in some European countries (including Germany) was already low when compared with other countries. However, public acceptance of nuclear power in France, South Korea and emerging economies, such as China and Russia, is still relatively positive even after the accident.

Table 1
Percent changes in positive opinion toward nuclear power pre- and post-Fukushima (from WIN-Gallup International (2011)).

Country		Pre-Fukushima	Post-Fukushima
OECD Countries	Canada	51	43
	U.S.	53	47
	Austria	13	9
	France	66	58
	Germany	34	26
	Italy	28	24
	Switzerland	40	34
	Japan	62	39
	South Korea	65	64
Non-OECD Countries	China	83	70
	India	58	49
	Russia	63	52
Global Average		57	49

5. The impact on long-term global energy security

5.1. Availability

It is too early to determine the impact of Fukushima on the long-term availability of nuclear power, although the number of reactors operating and under construction worldwide after the accident did not change significantly. However, if electricity production is restricted to non-nuclear sources, it is reasonable to assume that at least for the foreseeable future, generation will come from fossil sources rather than renewables. In fact, in the decision to phase out nuclear power in Germany by 2022, renewable energy is considered a long-term answer; despite this target (or perhaps because of it), Germany plans to construct 20 GW of thermal generation using coal and other fossil fuels to complement the loss of nuclear power over the next decade (Strahan, 2011). It is reasonable to assume that if more countries change their nuclear policies and increase the use of fossil fuels for electrical generation, demand and supply of fossil fuels can be expected to tighten. In view of this, the accident at Fukushima could be another impetus to intensify international competition for acquiring natural resources, coupled with an already rising global demand driven by factors such as rapidly growing economies in emerging countries.

Japan's increasing demand for LNG is perhaps the most critical factor which could affect global energy security; the total demand will depend upon the post-Fukushima energy policies and the number of reactors reactivated. Nationwide discussions on Japan's future energy policies suggest that by 2030, nuclear will supply between 0% and 25% of the country's electricity.

Table 2 shows Japan's current and potential post-Fukushima energy policies with their projected nuclear generation and LNG consumption (for electrical generation) in 2030. For example, if the 15% nuclear-power scenario is adopted, 33 million tonnes of LNG will be required to meet 26% of the total electricity supply; this is 9 million tonnes less than the level in 2010 and is attributed to the expected reduction in Japan's electricity demand. If the 0% nuclear-power scenario is adopted, 41 million tonnes of LNG will be required, which is almost the same volume as in 2010. In this context, Japan's additional LNG demand is small compared to the rapid growth in natural gas demand in emerging countries; as an example, the IEA expects that by 2035, LNG demand in China and India will be 436 and 148 million tonnes, respectively (IEA, 2012a).

Table 2
Japan's pre- and post-Fukushima energy policies and LNG consumption for electrical generation in 2030.

Policy	Post-Fukushima policies			Pre-Fukushima policies
Dependency on nuclear power in 2030	0%	15%	20–25%	53%
Dependency on LNG-fired power and co-generation using natural gas in 2030	32%	26%	23%	20%
LNG consumption for the power sector (million tonnes per year)	41	33	29	25

Table 3
Global electricity scenarios for 2035 (all units TWh).

Source	2009	2035	Nuclear replaced by natural gas	Coal reduced to 25%, restrict to…		
				Natural gas alone	Nuclear alone	Both equally
Coal	8118	12,035	12035	2973	2973	2973
Natural gas	4229	7923	12,581	16,986	–	12,454
Nuclear	2697	4658	0	-	13,721	9189

If the post-Fukushima policies currently under review in Japan are applied globally, the potential impacts are significant. Under the IEA's World Energy Outlook 2011 New Policies Scenario, by 2035, the world demand for electricity is projected to rise by 80% from 2009 levels (20,043–36,250 TWh), a third of which will come from coal (12,035 TWh) and roughly another third from natural gas and nuclear, at 7923 TWh and 4658 TWh, respectively (see Table 3).

As Table 3 shows, by 2035, phasing-out nuclear and restricting its replacement to natural gas would increase electricity production from natural gas to 12,581 TWh or over 57%, along with a concomitant rise in CO_2e emissions. If serious efforts were made to reduce greenhouse gas emissions and electricity from coal generation was reduced to 25% of its expected 2035 levels and its replacement was restricted to natural gas, electricity produced from natural gas would increase by 114%; restricting to nuclear alone would result in an increase of almost 200%. Restricting increases in generation to natural gas and nuclear equally is less onerous; however, the increase is still almost 60% and 100%, respectively. In all cases, considerable increases in the production of natural gas or uranium, or both, would be required.

While renewables, energy reduction policies, and economic factors could reduce these requirements, demand for electricity will be such that nuclear will probably still be needed, if for no other reason than limits to the availability of natural gas.

5.2. *Affordability*

The accident at Fukushima will result in stricter regulation of nuclear power plants globally (IEA, 2011a), because the essential problem was not the tsunami but the station's loss of all measures to cool the reactor and the spent fuel (Nikkei Inc., 2011). In the US, a NRC task-force established following the disaster at Fukushima proposed a series of actions to strengthen the ability of nuclear plants to withstand severe events, including a recommendation that all plants have backup battery capacity; however, the industry is reluctant to follow any new requirement which could result in cost increases (Power and Smith, 2011). The member countries of the E.U. also conducted stress tests and there are plans to develop new regulations, which could lead to a 10% of increase in the cost of electricity in Western Europe (Amiel and Colchester, 2011).

The Japanese government has projected that the additional cost of safety measures would be about ¥20 billion ($256 million) each, excluding the extreme case of the Hamaoka reactors where the construction of a coastal tsunami levee is also required (NPU, 2011). To meet these new safety measures, one study predicts that the construction cost of new nuclear power plants will triple by 2020 (Japan Center for Economic Research, 2011).

The problem of storing spent fuel will also contribute to the increasing cost of nuclear power. For example, in the US, with its 104 nuclear reactors, the construction of the Yucca Mountain waste repository was to have solved this problem; however, the contract was recently canceled although the project has spent about $9 billion to date (U.S. DOE, 2012).

Furthermore, the adoption of more advanced technology will further increase the capital costs of nuclear power. Moreover, prolonged construction periods caused by increased safety measures and the use of advanced technology could increase the interest burden and hence the cost of nuclear power (IEA, 2011b). The higher construction costs associated with new nuclear facilities might not be alleviated as the technology improves; for example, despite technical advances, the cost of constructing nuclear power plants in the US and France has been constantly increasing since the 1970s (Grubler, 2010; Davis, 2011).

The resulting increase in the cost of nuclear electricity suggests that nuclear will lose its competitiveness. However, restricting electricity production to non-nuclear sources will also affect the cost of electricity globally. In the case of Japan, as a result of restricting electricity supply to non-nuclear sources, corporate electricity prices in TEPCO's service area were raised by 17% on average in April 2012 (Mainichi, 2012). TEPCO also increased residential electricity rates by about 8% on average in September 2012 (Jiji Press, 2012). The price increases have been reflected in the costs of petroleum-based thermal generation (i.e., low construction costs and expensive fuel costs); however, if more countries opt for non-nuclear thermal generation, both demand for, and price of natural gas for electrical generation can be expected to increase still further over the long-term.

Nuclear is not the only energy source facing cost issues; a transition to renewables is also expected to result in increased electricity costs. DENA, a state-owned research institution in Germany, expects electricity prices in Germany, which are already higher than in other European countries due to its aggressive renewable policy, will increase by 20% by 2020 because of the nuclear-exit policy involving renewables, efficient-fossil fuels, and expansion of power lines (Nicola, 2011).

5.3. *Acceptability*

Since nuclear power is more dependent on public acceptance than most other electricity sources (WEC, 2007), potential changes in public attitude could greatly affect global energy policy. The accident at Chernobyl in 1986 illustrates this: the average number of new construction projects following the accident declined to seven per year in the 1980s and 1990s, compared with 26 per year prior to the accident (IEA, 2011b).

Not surprisingly, the situation differs from country to country. Japan and South Korea did not stop the construction of new nuclear power plants after the accident at Three Mile Island (IEA, 2011b); in fact, Japan began the construction of 21 nuclear reactors and started commercial operation of 16 in the 1980s (Aldrich, 2012). Ukraine currently relies on nuclear power for 48% of its electricity generation despite the negative public perceptions surrounding the accident at Chernobyl (due in part to an ongoing natural gas supply dispute with Russia (World Nuclear Association, 2012b)). Also, as previously shown in Table 1, the public's attitude toward nuclear power in countries such as China, Russia, and South Korea, where an increase of nuclear power is expected, is still higher than the global average even after the accident at Fukushima. In this context, although it is too early to determine the long-term impact on the acceptability of nuclear power, the change in public perception will differ from country to country and will change with time.

The nature of the accident could also influence changes in public perception toward nuclear power. The IAEA stated that the accident at Fukushima was caused by the combination of existing design weakness regarding the defense against natural hazards, a lack of regulatory oversight, accident mismanagement, and poor emergency response handling; given the several safety measures conducted in the wake of the accident, the global use of nuclear power is even safer than when the accident occurred (IAEA, 2012b). Also, unresolved issues surrounding nuclear power such as disposal of spent fuel will affect public perception. Interestingly, the spent fuel which was temporarily stored inside the Fukushima plant exacerbated the damage of the accident. It is too early to predict whether the enhanced safety measures will alleviate the public distrust; however, these are some of the important factors in improving public perception over the long-term.

6. Discussion

The implications of the Fukushima accident on future global energy policies are now considered given the constraints imposed by both energy security and environmental concerns.

6.1. Developed countries

In the companion paper on the Fukushima accident and its effect on Japanese energy policy (Hayashi and Hughes, 2012), it was concluded that nuclear power, as well as fossil fuels, will continue to be used in Japan while the country makes the utmost efforts to reduce energy consumption and develop renewable-energy technologies. Although there are circumstances specific to Japan necessitating the use of nuclear technology, such as its overwhelming reliance on imported energy and the expectation of export revenue from the development of nuclear technology, a radical shift in nuclear policy in other developed countries appears unrealistic when taking energy security and environmental constraints into account.

The accident at Fukushima has affected the affordability of nuclear power: additional safety measures, higher interest rates, and the burden of interest during a longer construction period due to more stringent regulations are expected to result in increasing capital costs. The exposed high risk of nuclear power projects will further discourage investors and lenders from participating in the construction of new nuclear power projects. Although the cost of nuclear power was increasing prior to the accident, these additional costs can be expected to affect the construction of new nuclear reactors in countries such as the US where affordable fossil fuels are readily available; for example, since 2009, the growth in shale-gas production in the US has resulted in a 9.5% increase in gas-fired electrical generation (U.S. Energy Information Administration, 2012), while an additional 258 gas-fired power plants are expected to be built between 2011 and 2017 (Areddy and Spegele, 2012).

This does not mean that the US has abandoned nuclear energy. If shale-gas prices increase or stringent carbon constraints are introduced, the nuclear energy option could be reconsidered. In 2011, the Nuclear Regulatory Commission issued 20 year extensions to nine nuclear reactors with original 40-year licenses (Smith, 2011), while the Energy Information Administration predicts that nuclear power will play an important role in the country's electricity portfolio and is expected to generate about 21% of total electricity supply in 2030 (US Energy Information Administration, 2012). Although burning natural gas emits much less carbon than coal, it is still a carbon source, unlike zero-emission or near-zero-emission sources, such as nuclear or renewables (Myhrvold and Caldeira, 2012). Indeed, if the 13% of global electricity generation by nuclear power plants in 2010 was restricted to thermal generation from natural gas and coal, global CO_2 emissions would increase by 17% (IEA, 2011b).

In countries with limited access to secure supplies of fossil fuels, it is more difficult to abandon nuclear power, in part because of the current economic crisis and growing energy demand in emerging economies; even inexpensive natural gas prices in the US, which are amongst the lowest in the developed world, are not guaranteed for the long term (Chazan, 2012c). The ongoing threat of the closure of the Straits of Hormuz and Russia's overuse of energy as a tool to promote their foreign policy goals is a constant reminder to major importers of fossil energy, such as most E.U. member states, of the importance of diversification of energy sources, including nuclear.

Reactions to the Fukushima accident varied by country; perhaps the most notable was Germany, where the planned complete phase-out of domestic nuclear generation by 2022 was reaffirmed (Strahan, 2011). However, the long lead-time means that Germany could still reconsider the policy since the country does not have a concrete plan to bridge the gap left by the phase-out in an affordable and environmentally acceptable manner (Germany's carbon emissions targets, set before Fukushima, are for a 40% drop from 1990 level by 2020 and by 80% by 2050 (Jolis, 2012)). Although electricity prices are already amongst the highest in the E.U. due to aggressive renewable energy policies, polls have revealed that more than 60% of Germans appear willing to pay higher electricity prices for the supply of electricity from renewables (FOCUS, 2012). Any policies that result in higher electricity prices could mean the loss of competitiveness by German industry and result in the transfer of manufacturing industry abroad.

Having said that, a significant expansion of nuclear power is not expected in most developed countries either, because of a number of issues, including the severity of the accident and the disposal of radioactive waste; this means that use of nuclear power will not preclude the continued reliance on thermal generation from fossil sources. Depending upon its availability and affordability, some countries can be expected to restrict new electricity supply to high-efficiency thermal generation or simply replace coal in existing thermal generation stations with natural gas. The availability of affordable (for the short term at least) natural gas in the United States is resulting in a move to natural gas for the generation of electricity (at the expense of coal), whereas in Europe, the consumption of coal in Germany and most other E.U. member states has been increasing steadily since 2008 (Schaps, 2012; BP, 2011; IEA, 2012b).

As the need to address climate change caused by anthropogenic energy-use becomes more pressing, it will be a challenge for countries to implement effective measures to mitigate their greenhouse gas emissions affordably without using some combination of nuclear power coupled with significant advances in renewable energy, both technological and economic (Hayashi and Hughes, 2012). Notwithstanding the increased worldwide interest in renewables (global investment in renewable energy in 2011 increased by 17% over 2010, in a part driven by the accident at Fukushima (JMA, 2011)), the use of nuclear power can be expected to continue to play an important role in the global electricity portfolio.

6.2. Emerging economies

Prior to the accident, it was generally assumed that an increased use of nuclear power was inevitable in emerging economies where electricity demand was being driven by expanding economies (IEA, 2010c). Despite the accident, these assumptions appear well-founded, at the end of May 2012, of the 62 nuclear reactors currently under construction worldwide, 52 are in non-OECD countries (26 of which are in China) (IAEA, 2012a). The impact of the accident on energy policy in emerging countries is expected to be limited because of the significant growth in demand for electricity. The IEA forecasts global electricity demand will grow at a rate of 2.4% annually by 2035 (IEA, 2011b); however, there is a significant difference between emerging economies and developed countries (IEA, 2011b). The anticipated growth rate in the E.U. and US is around 1%, while that of India and China is 5.4% and 4%, respectively (IEA, 2011b). It would be extremely difficult for these countries to cancel the deployment of nuclear power plants because of their need to supply electricity without affecting economic expansion and reducing the competitiveness of their industrial sectors under carbon constraints. Today's economic prosperity in developed nations was greatly supported by the availability of affordable supplies of energy (Berkley et al. 2010); many emerging countries argue that they also require the same type of energy for their development, and nuclear power is seen as indispensable given the high price of fossil fuels and carbon constraints. Further carbon constraints on the energy sector in emerging countries can be expected; China, the world's largest CO_2 emitter, showed an intention for the first time to accept a legally binding emission-reduction obligation in the conference of parties (COP) in Durban in December 2011 (The Chinese Central Government, 2011).

The accidents at Three Mile Island and Chernobyl, coupled with low fossil-fuel prices and investors' low-risk preferences in the developed world, resulted in setting back nuclear policy for about two decades (IEA, 2011b). However, the current situation is quite different: in addition to being driven by higher fuel prices, an increase in the use of nuclear power can be expected in emerging economies such as China where projects are funded mainly by governments that do not require a substantial amount of market equity or finance. Moreover, even if there is a decline in public acceptability towards nuclear, public opinion in countries such as China and Russia carry little weight (Butler, 2011).

Data from the IAEA suggests that some emerging economies have accelerated their nuclear energy programs since March 2011 (Dahl, 2012). Rosatom Nuclear Energy, a state-run nuclear power company in Russia, has stated that none of their international orders had been canceled in the wake of the Fukushima accident; instead, international orders jumped from 11 at the time of the accident to 21 as of end of 2011 (Dawson e al., 2012). Areva (2012a) also announced that the backlog in 2011 had increased by 3.1% compared with the previous year, because of the growing demand from emerging countries.

Unlike in some OECD countries, fundamental changes in nuclear policy have not been evident in emerging economies, although there have been some delays due to safety inspections and the suspension of the approval process (IEA, 2011b; Spegele, 2012). In China, expanding nuclear energy is a core strategy to address global warming as clearly stipulated in the 2011–2015 Five-Year Plan formally adopted by the National People's Congress soon after the accident (Areddy and Spegele, 2011). Although the government has suspended the approval process until after establishing a safety framework and inspecting all existing reactors, it has been reported that the government will resume its ambitious nuclear plan which intends to construct more than 102 nuclear reactors by 2030, an increase since the Fukushima accident (Sankei, 2011). In India, the government also postponed the approval of four nuclear projects post-Fukushima; however, it resumed the approval process in June 2012 (Chauhan, 2012). Russia intends to double its current nuclear capacity by 2020 (World Nuclear Association, 2012a), while Saudi Arabia announced plans to build 16 nuclear reactors by 2030 to meet rising electricity demand as well as reducing reliance on fossil fuel-fired power (Al Arabiya News, 2011). Other countries planning to develop nuclear programs include the United Arab Emirates, Turkey, Brazil, South Africa, and Vietnam, to name a few (JAIF, 2012).

7. Concluding remarks

Although it is still too early to appreciate the full extent of the Fukushima accident on both Japanese and global energy security, some indications of the impacts have now become apparent more than a year later.

The Fukushima accident has short- and long-term implications for both Japanese and global energy security. Japan's additional demand for fossil fuels, especially liquefied natural gas, in the aftermath of the accident affected global energy-security in the short-term by significantly raising the price of LNG, particularly in the Asian market, where consumption was already rising because of the increasing demand from emerging market economies and political unrest in the Middle East and North Africa. The accident also caused a significant decline in uranium prices while simultaneously affecting the global nuclear industry. Furthermore, the accident was an opportunity to accelerate global financial-investment decisions in new LNG projects, driven by the expected increase in LNG demand in the future, although Japan's long-term LNG demand may not be significant when compared with that of emerging countries. The accident has also contributed to the escalating capital costs associated with the construction of new nuclear reactors because of the additional safety measures required. It has also affected the acceptability of nuclear power in some countries in Europe.

Although the nuclear accidents in the 1970s and 1980s were decisive events that temporarily curtailed the global expansion of nuclear power, the current situation is significantly different because of concerns over anthropogenic greenhouse gas emissions and the potential for nuclear power to mitigate them. Today, it is difficult to ignore climate change when considering energy policy; therefore, when taking into account electricity costs from fossil fuels and the need to reduce greenhouse gas emissions, a radical shift either way in global civilian nuclear policy as a result of the accident appears unrealistic despite the severity of the Fukushima accident.

In this context, even though the cost of electricity from nuclear power is rising and Fukushima has resulted in a public backlash against nuclear, the accident has not changed the fundamental dynamics of global energy policy and the need to improve energy security: nuclear power, as well as fossil fuels, will continue to be used while jurisdictions continue to make efforts to improve and incorporate new renewable energy technologies.

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