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Fukushima and thereafter: Reassessment of risks of nuclear power

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HIGHLIGHTS

- ► Public perception associates reactor accidents with nuclear weapon explosions.
- ► Future siting of nuclear plants should avoid coasts prone to flooding and tsunamis.
- ► Nuclear regulators have to independent from political and industry pressures.
- ► Building new nuclear power plants will not be feasible without state subsidies.
- ► Social cost benefit analysis of nuclear power is essential to gain public acceptance.

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ABSTRACT

The Fukushima nuclear accident on March 11, 2011 in Japan has severely dented the prospects of growth of civilian nuclear power in many countries. Although Japan's worst nuclear accident was triggered by an unprecedented earthquake and tsunami, inadequate safety countermeasures and collusive ties between the plant operators, regulators, and government officials left the Fukushima Daiichi nuclear plant beyond redemption. A critical examination of the accident reveals that the accumulation of various technical and institutional lapses only compounded the nuclear disaster. Besides technical fixes such as enhanced engineering safety features and better siting choices, the critical ingredient for safe operation of nuclear reactors lie in the quality of human training and transparency of the nuclear regulatory process that keeps public interest—not utility interest—at the forefront. The need for a credible and transparent analysis of the social benefits and risks of nuclear power is emphasized in the context of energy portfolio choice.

1. Introduction

Nuclear power production grew significantly since 1990, rising from 1909 billion kW h in 1990 to 2620 billion kW h in 2010, while its share of total electricity generation declined from 16.8% to 13.5% during the period (USEIA, 2012). There are 436 commercial nuclear power reactors operating in 30 countries, with 370,000 MWe of total installed capacity, and 61 reactors with a total capacity 58,000 MWe under construction in 13 countries (IAEA, 2012). Although three fourths of the operating reactors are in developed countries, most of the reactors under construction are in developing countries. China and India alone have plans to build around 100 reactors over the next 25 years. Additionally, 45 new countries have plans to build nuclear power plants within the next two decades (WNA, 2012). A number of factors, largely relating to anticipated global primary energy resource scarcities and rising real prices and environmental concerns, have driven this growth. Improvements and investment cost reductions in the technology of nuclear power also contributed to growth prospects, raising hopes for revival of nuclear power.

However, the March 2011 Fukushima nuclear accident in Japan has raised afresh with wider and more intensive awareness the concern that expansion of nuclear energy portfolio may be socially too risky relative to its benefits compared to alternatives. The issue of risk benefit trade-off with respect to nuclear power is not a new issue, but the trade-off margins that were socially acceptable prior to Fukushima no longer seem so. This has led to a re-evaluation of the role of nuclear power in their future energy plans in many countries. Public protests against nuclear power have widened and become more intense. This global reaction to the Fukushima accident confirms the prescient remark of nuclear reactor pioneer Alvin Weinberg after the 1986 Chernobyl nuclear accident that a "nuclear accident anywhere is a nuclear accident everywhere" (Weinberg, 1986).

It is essential therefore to examine what Fukushima revealed on various prior assumptions underlying nuclear risk assessment and the risk-benefit trade-offs in public policy decisions. Public fear about nuclear power plants is not new and has surfaced

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periodically after every major and minor nuclear accident. The Windscale accident in 1957, the Three Mile Island accident in 1979, and Chernobyl disaster in 1986 also generated widespread fear and public protests forcing some European countries to abandon nuclear power. But, the Fukushima disaster is the first major nuclear accident in the era of 24-h global television news coverage and unprecedented access to information from the internet and social media networks. Under these changed circumstances, success in assuaging public fear about nuclear energy requires a credible examination of Fukushima accident based on what is reliably known both about the accident itself and of the system of regulation, transparency of communication by the plant operators and the government. The paper is organized as follows:

In Section 1, we summarize the elements of nuclear risks and place them in context relative to other risks. In Section 2, we narrate the sequence of events that triggered the Fukushima accident and led to a partial meltdown and the preliminary assessments made by the Japanese authorities and other independent agencies. Whether this accident revealed anything that was not known, or was known but overlooked earlier, about probabilities of occurrence of earthquakes and tsunamis and their implications for nuclear reactor safety is critically reviewed. In Section 3, we discuss the immediate impact of Fukushima on mature and emerging civilian nuclear programs. In Section 4, we revisit some of the traditional challenges to nuclear power development—nuclear waste management, environmental impact, regulatory independence, economics, and proliferation concerns—in light of the lessons learnt from Fukushima. Finally, in Section 5, the efficacy and likely role of nuclear power in energy generation portfolios that also take into consideration global carbon emissions and the resulting social damages are assessed.

2. Elements of nuclear risk

Almost all human activities involve some form of risk, many of which are taken voluntarily with adequate information and knowledge or involuntarily, and various means have been developed to cope with them. In terms of carcinogenic and mortality risks, nuclear power plants and fuel cycle facilities are claimed less dangerous than many occupational hazards and lifestyle choices (Fischhoff, Lichtenstein et al., 1981). However, comparison of riskiness of alternative sources is extremely complex. Nuclear risk, however, evokes strong negative feelings and the gap between claims of actual risk and perceived risk of nuclear hazards continues to be a major factor in public policy decisions. This can be attributed to the fact that over time people have internalized conflicting images about nuclear energy. At one time and one extreme, nuclear power was viewed as a source of cheap and unlimited energy to create a world of material abundance and economic prosperity. This was a dominant theme of energy future studies done in the 1950s and 1960s when energy use in the industrialized world grew rapidly amidst concerns of resource depletion (Putnam, 1954). Even strong supporters of nuclear power no longer subscribe to this view. At the other extreme was conflation of non-military use of nuclear energy with the destructive power of nuclear weapons that can kill people in hundreds of millions and wipe out large cities and industrial infrastructure as captured by H.G. Wells in *The World Set Free*, and later exemplified by the nuclear arms race during the Cold War. The build-up of tens of thousands of nuclear weapons through the 1980s with explosive yields far greater than the Hiroshima and Nagasaki weapons, and their continuing presence in the arsenals of the United States and Russia even after the end of Cold War has only reinforced the apocalyptic image of nuclear energy. Since these two different and persistent images are located in close proximity in public consciousness, this problem cannot be wished away and is relevant to issues concerning public perception of nuclear energy. Hence, it is essential and useful to attempt a clear distinction between the risks and effects of nuclear weapons and nuclear power reactors, although the dual-use nature of the technologies makes this a difficult task.

The risk from nuclear weapons to the society arise from possible unintended use, threat of nuclear war, their diversion of scarce economic resources, social hysteria, etc., which are in principle manageable politically. Proper maintenance of arsenals considerably reduces the risk of accidental launch and failure of command and control systems. Societal risks from technical failure of nuclear weapon systems are likely to be very small. However, intentional use of nuclear weapons can inflict far greater damage to the society than even the worst conceivable nuclear reactor accident. This is because a nuclear weapon detonation, say with an yield of 1 MT (megaton), over a large populated area will kill millions of people, destroy most of the physical structures, and contaminate a large area with radioactive fallout through blast waves, thermal radiation, and radioactive fallout, of which the blast waves account for 50% of the energy release, thermal radiation 35%, and radioactive fallout 15% (Glasstone and Dolan, 1977).

Although public perception generally associates reactor accidents with nuclear weapon explosions, blast and thermal effects are not relevant in the context of reactor failures including worst-case containment breach accidents like Chernobyl and Fukushima. The physical impact of a reactor blow-down does not extend beyond the immediate vicinity of the plant. The main risk from nuclear power reactors arise almost entirely from the enormous store of radioactivity inside the fuel. A typical large nuclear reactor with an electrical output of 1200 MWe contains about 5.6 billion curies of radioactivity, including 3.8 billion curies from the radioactivity of fission products (Lee and McCormick, 2011). The potential public health consequences from the release of even a small fraction of this radioactivity into the environment pose a unique safety concern. Fission products account for about 6–7% of the reactor's total power output, and this must be dissipated even after the main chain reaction is terminated. These two features of nuclear reactors provide distinctly different risk and safety concerns from a coal plant or any other energy facility. Hence almost all safety concerns of plant designers, reactor operators, and regulators revolve around these two sources of risk.

Nuclear reactors produce hundreds of fission products and transuranic elements during the course of operation and are tightly held within the fuel matrix. These elements are all radioactive with different levels of chemical activity, volatility, and have decay half lives ranging from seconds, hours, days, and years. Most of fission product radioactivity dissipates rapidly, on the order of seconds to hours, but a significant amount of radioactivity persists for many years. There is one group of fission products that is of special concern from the standpoint of reactor safety. Volatile species comprising halogens (iodine and bromine) and alkali metals (cesium and rubidium) pose public health risk due to their relatively short decay half-life and easy dispersion into the environment. Krypton, xenon, and iodine are among the first to be released in a reactor accident. Since krypton and xenon are chemically inert, their biological effect is relatively mild. The iodine isotopes are chemically active and affect the thyroid gland when ingested or inhaled. One particular isotope of iodine (I-131) delivers radiation dose for several weeks. Although the release of radioactive iodine from a nuclear power plant can be controlled by various chemical and physical means, the potential biological hazards associated with even a small fraction of the radioactive inventory are significant. For instance, radiation exposure rate at one meter from an unshielded 1 Ci Cobalt 60 source is approximately 1 rem/hr or 10 mSv/hr (Lee and McCormick, 2011). There are a few other sources of radioactivity in a nuclear reactor like activation products and transuranics, however, the principal risk from reactor accidents arises from volatile fission products that are chemically active.

The major objective of nuclear plant design and operation is to keep the fission products confined at all times, both during normal operation and during accident conditions, and prevent them from coming into contact with plant personnel and surrounding public. As discussed earlier, most of the radioactivity is produced inside the fuel and remains tightly contained within the fuel matrix under normal conditions. Thus the major area of safety concern and risk are events that seriously overheat or melt the fuel that releases the trapped radioactivity. Although concern over such events is common in all operating reactors and those under construction and the planned ones, the probability of events occurring could be different depending on the specifics of the plant. Overheating and eventual meltdown of fuel in reactors can happen if heat production was in excess of cooling capacity or if cooling system was not removing the heat at the rate it was designed (Rasmussen, 1981). The former is less frequent than failures resulting from loss of cooling mechanism because of the fundamental design feature of most operating reactors. Certain conditions could lead to a runaway chain reaction in excess to normal power, but those chances are rather unlikely.

Nuclear risk analysis is thus reduced to identifying and determining the probability of those chains of events that cause serious fuel heating. The risk of radioactive release can happen in one of the two ways: the loss of coolant accident (LOCA) that results in loss of primary coolant itself which can come about by ruptures in the primary system or by malfunctioning safety valves; and the failure in the heat removal system in which the coolant is present but various functions to remove heat to its ultimate sink fail. Both events are unlikely to occur with adequate availability of electric power to operate equipments, and systems of emergency core cooling (ECCS), the fission product removal and the adequacy of containment itself. In Fukushima, these failed as a result of total blackout and unavailability of backup power systems to operate all these critical systems.

Finally, nuclear risk management follows a philosophy of “defense in depth”. Although potential risks of release of large amount of radioactivity from an accident are large, most of the radioactivity is produced in the fuel matrix inside the reactor core shielded by multiple physical barriers to prevent the escape of radioactivity into the environment. Modern nuclear plants are designed with seven barriers between the fission products inside the fuel and the outside environment and cover fuel pellet, fuel rods, closed cooling loops, pressure vessel (6–8 in. thick), containment structure, siting, and evacuation (Lamarsh, 1981). The closed loop cooling system and the containment structure were quite effective in containing the radioactivity as demonstrated during the Three Mile Island accident. In this accident a total of only between 13 and 17 Ci of radioactive iodine were released from the plant during the course of the accident. About 7.5 million curies were retained within the cooling system and 10.6 million curies were held within the containment building of the TMI reactor. The absence of containment in Chernobyl, a flawed reactor design, and operating personnel violating clearly laid out rules resulted in extensive damage. For comparison, a total of 0.062 peta Becquerel of radioactivity was released in the TMI accident against 5200 peta Becquerel in Chernobyl and 770 peta Becquerel in Fukushima (Patel, 2011). Several studies have reached the conclusion that TMI’s main impact was financial and led to a virtual moratorium on new reactor builds in the US for nearly thirty years. TMI’s public health impact was negligible. The Chernobyl accident, however, resulted in significant public health impact with reports of cumulative cancer fatalities in the affected region ranging from 4000 to 25,000 until 2011. The 6000 cases of thyroid cancer in children in the immediate aftermath of the accident resulted in only 9 fatalities and most of them were saved after a simple clinical procedure. The estimates of cumulative cancer mortalities in the affected region are still contested and subject to significant uncertainties.

Although the contamination following Chernobyl was widespread, various studies sponsored under the aegis of the United Nations have suggested that the long-term environmental impact is considerably lower than the short-term impact. The total amount of radioactivity ten years after the accident (1996) had decayed to about 80 peta Becquerel (about 1.5% of the initial release) of long-lived radionuclides, principally cesium-137 and strontium-90 (Dreicer and Alexakhin, 1996). The highest doses from Chernobyl immediately after the accident were received by plants and animals within a radius of 30 km from the reactor. Contamination levels typically reached several tens of mega Becquerel per square meter. Within six months, the dose rate at the soil surface dropped by a factor of 100 of the initial value. Some of the food from contaminated areas, especially game animals, berries and mushrooms, continue to show elevated cesium-137 levels than nationally enforced limits in parts of Belarus, Ukraine, Russia, Nordic countries, and the United Kingdom.

Past nuclear accidents resulted in major improvements in technical nuclear safety and risk management, and Fukushima could potentially contribute to safety improvements if credible and convincing reassessment is undertaken of various assumptions in risk assessment. Human and institutional failures, to be discussed later, contributed in some measure in all nuclear accidents. However, the principal issue of risk from nuclear reactors, namely, from the billions of curies of radioactivity inside the reactor has not changed and had been recognized by the pioneers of reactor development. The prototypes of the current commercial nuclear reactors were conceived, designed, and built not for generating electricity, but to make plutonium for nuclear weapons program and submarine reactors for naval propulsion. Public safety was of lower order of priority during the early stages of reactor development. Since new reactor design and development takes many years, only incremental safety improvements are possible in the current and planned reactors. Thus the inherent risk from radioactivity inside the reactors remains and dominates all safety concerns.

Because the earliest reactors were built in remote and sparsely populated sites, even without containment they allayed most safety concerns. But interest of power utilities to build nuclear plants close to load centers near populated areas elevated the inherent risk. Building them far away from population and transmitting power to demand centers was very costly. Given these challenges for site isolation and the large size of the planned reactors located near population centers, elaborate engineering features were incorporated to contain the billion curies of radioactivity in the reactor itself and not release it to the environment.

The Three Mile Island accident vindicated the importance of containment philosophy, which originated in the United States in the early 1950s. A minor accident in a military production reactor in Idaho in 1961 killed three operators and it had no containment. Because of its isolation, its public health impact was negligible. Another accident in 1966, in the experimental breeder located near Detroit, resulted in partial meltdown but the primary coolant and containment contained the radioactivity within the reactor. The 1975 fire accident in the Browns Ferry nuclear plant in Alabama disabled the cooling systems, but enough coolant and power remained to prevent core meltdown.

The 1957 accident in Britain’s plutonium production reactor in Windscale had no containment and resulted in the release of about 20,000 Ci of iodine into the environment. The Chernobyl disaster highlighted the danger of not having containment in a large power reactor. But, as Fukushima highlighted, containment structures can help minimize the impact of accidents only if reactors are built in locations that are not vulnerable to large earthquakes and tsunami waves. Engineering innovation helps insure, ex-ante, against risks from natural events through better safety designs. But ex-ante insurance is inadequate because the events of low probability that were excluded could still occur. Hence ex-post response adequacy is also needed, as in the case of Japan, to plan for worst-case scenarios (rare natural disasters) that can completely overwhelm even the best reactor design.

The last and final response to an accident is to shield the public from released radioactivity, in case it occurs, is evacuation. Thus if all built-in engineering safety features and barriers fail, dangerous amounts of radioactivity will inevitably be released and will threaten the population living nearby and the only remaining option is to evacuate people to safer distances. In the case of TMI, around 140,000 people were evacuated from within 8 km zone. In Chernobyl, a 30 km evacuation radius was followed and 116,000 people were evacuated in 1986 followed by another 230,000 people over later years. In the case of Fukushima, the government evacuated around 80,000 people within 20 km radius and their return remains uncertain. Although evacuation is not uncommon in industrial accidents and natural disasters, nuclear-related evacuation poses a far greater challenge because uncertain meteorological conditions determine the immediate impact for evacuation and post-accident planning.

Reactor meltdown accidents essentially involve radiation exposure and resulting cancer risks. Humans are constantly exposed to radiation from various natural sources and lifestyle choices, with the nuclear power industry arguably contributing only a slight increase to the total exposure. For instance, a single dental x-ray exposes an individual to 10 mrem and the average annual exposure, excluding medical and occupational exposures, is around 300 mrem (Princeton University, 2012). Such an accounting measure does not convey much about public health risks because exposure per se is a poor indicator of cancer risk. Although exposure to dose levels above 500 rems (LD 50% or a dose having 50% probability of death) can be lethal, the effects of exposure from small doses (a few rems) over a long period are contested due to significant uncertainty.

3. Fukushima nuclear accident

The massive earthquake and resulting tsunami that hit Japan on March 11, 2011 plunged the country into one of the worst crisis since it emerged from the Second World War. The magnitude 9 earthquake occurred at a depth of around 24 km in the Pacific Ocean floor with epicenter at 130 km east of Sendai, 373 km northeast of Tokyo, and 70 km northeast of the Fukushima Daiichi nuclear complex housing six reactors (USGS, 2011). This earthquake was Japan's largest and world's fourth largest recorded in data spanning 130 years. The Fukushima Daiichi nuclear power station operated by the Tokyo Electric Power Company (TEPCO) was severely affected by the natural disaster and continues to draw international attention. Hundreds of thousands of people lost their homes following the tsunami and earthquake. The number of confirmed deaths and missing people, estimated as of March 10, 2012 was around 19,000 and most (around 95%) of the deaths were tsunami related (Vervaeck and Daniell, 2012). The median estimate, subject to unavoidable errors of measurement and possible biases, of direct economic loss due to the earthquake and tsunami is around US$275 billion in addition to US$65 billion damage as a result of the Fukushima nuclear accident.

The Japanese government has established the Fukushima Office for Environmental Restoration to clean up and restore the environment in Fukushima and surrounding prefectures contaminated by the nuclear accident (MOE, 2011). Estimating precisely the time and cost required for this major effort is virtually impossible. However, initial and necessarily imprecise estimate of the cost of cleanup alone is around US$14 billion over 30 years (Adelman, 2011). If compensation to victims and resettlement cost were included, the total cost could be as high as US$250 billion (Reuters, 2011).

The situation at Fukushima Daiichi is claimed to be under control given that TEPCO officials announced in December 2011 that the plant had been brought to a safe state of cold shutdown, and no radiation deaths have been reported so far. The temperature of the reactor pressure vessel in the affected units are below well below 100 °C, and radioactive releases from the plant have been reduced to "acceptable" levels (not to exceed 1 mSv/year at the site boundary as a target for public exposure) deemed by regulatory authorities (Yasui, 2012). Yet significant uncertainties remain about the extent of damage inside the reactor and the long-term public health consequences of the accident. Complete recovery of the site and affected areas will take many years and require substantial human and financial resources.

3.1. Sequence of events leading to the accident

It is useful and helpful for a discussion of lessons from Fukushima to review the features of the Fukushima Daiichi Nuclear Power Station and summarize the sequence of events that resulted in the accident. The following account is based on the information provided by TEPCO officials and Japanese authorities (with all its potential biases) and our correspondence with various Japanese experts since the accident.

The power station (see Table 1) housed a boiling water reactor of the 1960s vintage (BWR-3 Mark 1), four BWR-4 Mark 1, and one BWR-5 Mark 2 with a combined electric generation capacity of around 4700 MWe (IAEA, 2012). At the time of the accident only three reactors were in operation, and the remaining three shutdown for planned maintenance. The earthquake automatically triggered a shutdown as designed and halted fission reaction, the main source of energy production, in the three operating reactors. However, the residual heat from the core would remain significant for a long enough time to melt the fuel unless removed

Table 1
Fukushima Daiichi nuclear power station.

Reactor unit	Reactor type	Gross (MWe)	First grid connection (status)
Fukushima Daiichi-1	BWR3, Mark 1	460	November 1970 (Permanent Shutdown)
Fukushima Daiichi-2	BWR4, Mark 1	784	December 1973 (Permanent Shutdown)
Fukushima Daiichi-3	BWR4, Mark 1	784	October 1974 (Permanent Shutdown)
Fukushima Daiichi-4	BWR4, Mark 1	784	February 1978 (Permanent Shutdown)
Fukushima Daiichi-5	BWR4, Mark 1	784	September 1977(Uncertain)
Fukushima Daiichi-6	BWR5, Mark 2	1100	May 1997(Uncertain)

continuously by the main cooling system, and if unavailable, by an emergency core cooling system, both of which require electric power either from the plant or grid or batteries or diesel generators.

At Fukushima, after the plant shutdown, the only source of electric power was external power supply from the grid. Although TEPCO claimed that reactor buildings were largely intact despite ground acceleration exceeding design values, all of the six external power lines connecting the site to the off-site transmission grid were damaged severely during the earthquake and resulted in total loss of all offsite power. However, the independent committee appointed by the Japanese Diet speculates that the earthquake might have damaged the reactors even before it was hit by the tsunami (National Diet of Japan, 2012).

With external power loss, the plants depended totally on onsite emergency diesel generators to run the cooling systems and other safety equipment. Forty minutes after the earthquake the Fukushima complex was struck by the first in a series of massive tsunami waves and triggered a serious plant emergency situation. The first of the tsunamis had reached a height of around 4 m, less than the designed 5.7 m seawall protection and was contained. The second tsunami's height is unknown, but resulted in the failure of the tidal gauge. The remaining five tsunami waves, of which one reached a height of 14–15 m and turned deadly and resulted in the inundation of Units 1, 2, 3, and 4. The inundation in Unit 5 and 6 was less because of their higher elevation. The waves triggered by the largest of the tsunamis reached around 15 m high was above the designed seawall of 5.7 m, and flooded the entire complex with seawater and rendered all of the onsite diesel power generators except one in Unit 6 unusable. Four units were extensively inundated by around 5 m of water and the plant lost its ability to perform main safety functions. Since the seawater pumps and the diesel generators were located at a lower elevation than the reactor buildings at Fukushima, they were submerged and destroyed by the tsunami and the residual heat removal systems and the auxiliary cooling systems lost their functions. Hence, even if power had been available there were no auxiliary cooling systems to operate and dissipate the heat. The backup diesel generators also failed, and the battery power of just 8-hour capacity proved to be insufficient.

Initially, TEPCO operators tried to restore power and save the reactors rather than flooding them with seawater and reduce the risk of releasing large amounts of radioactivity into the environment. With the plant getting out of control, operators alternatively injected fresh and seawater by using fire engines and pumps. But this operation was not smooth in the prevailing adverse weather conditions and water injection was not effective. When adequate water did not reach reactor pressure vessel, the fuel in reactor core was exposed and resulted in partial or substantial meltdown that produced high temperature steam. Violent chemical reactions between high temperature steam and the fuel cladding tubes made of zirconium alloy generated hydrogen and radioactivity from melted fuel escaped into the primary containment structure and resulted in subsequent explosions that tore off the secondary containment structure in Units 1, 3 and 4. Had difficulties in accessing the control systems of Unit 1, due to the faulty location decision relating to seawater pumps and diesel generators within the plant susceptible to flooding, not occurred and operators had been able to control it, the sequence of events would have been very different and possibly less catastrophic (Strickland, 2011).

The location of the pressure suppression pool (an additional safety to minimize the impact of an accident) at the bottom of the reactor core in the BWR design only delayed the onset of the accident. Efforts to restore the plant were further complicated by the presence of large amounts of spent fuel in the storage pool located on an upper floor of the defueled Unit 4 reactor building. Without power supply to operate the cooling system in the spent fuel pool in each unit, the water level continued to drop as water evaporated from the heat of the spent fuel. Although Unit 4 was not in operation, according to TEPCO problems arose in it due to hydrogen leaks from Unit 3. Initial assessments showed that spent fuel stored in Units 4–6 were fully covered with water throughout the accident and never presented a risk. However, the crisis in the first three units and each explosion made efforts to control the plant more difficult.

In addition to worst affected Fukushima Daiichi, the earthquake and tsunami also affected four reactors at Fukushima Daini, three reactors at Onagawa, and one reactor in Tokai Daini. These reactors automatically shut down after the quake and were brought under control, since they did not face the flooding problem as Fukushima Daiichi because of the faulty location decision mentioned earlier. The four reactors in Fukushima withstood the earthquake but suffered badly because of partial meltdown of fuel and hydrogen explosions, which blew off the secondary containment structures.

Further with the station blacked out and unavailability of all safety and non-safety systems created the conditions for the worst nuclear accident to occur. Operators had to rely solely on torch lights in the absence of full lighting in the reactor and turbine buildings. Only hotline and landline phones were available between the Emergency Response Room and each control room. Due to lack of power sources, initial recovery activities had to be conducted in complete darkness, without any instrumentation, and without most communications facilities.

Technical difficulties in the reactor complex were compounded by haphazard institutional response and signs of growing distrust between among various Japanese stakeholders were evident. TEPCO had long been under watch and repeatedly warned of its safety lapses and other omissions. It was, at least initially, reluctant in sharing information in a transparent manner. The fact that TEPCO had been warned by official regulators and still the safety lapses apparently continued suggests regulatory failure and possible collusion between TEPCO and regulators. On March 11, the government ordered evacuation of residents within 3 km and proper shelter for residents within 10 km. By March 15 residents within 30 km were evacuated. The U.S. NRC during the time advised 80 km evacuation zone for its citizens living in Japan. Nearly 25 years after the Chernobyl disaster rated the highest at 7 on the International Nuclear Event Scale (INES), the Fukushima nuclear disaster became the second accident to be rated 7 on INES scale. The Three Mile Island was rated 5 on INES scale and the radiation effect was limited to the site and public health impact was absent. In its June 2011 report to the IAEA explaining the accident, the Japanese government estimated that the quantity of radiation released into the atmosphere by the accident was about 15 percent of the radiation released from Chernobyl (Government of Japan, 2011). Although Fukushima and Chernobyl received the same INES ratings, it is too early to estimate the full public health and ecological damage of Fukushima and to assess whether they warranted Fukushima being rated the same as Chernobyl by INES. Even after 25 years, estimates of excess cancer death due to radiation leakages from Chernobyl range from 4000 (IAEA and UN Chernobyl Forum) to 25,000 (Union of Concerned Scientists).

4. Lessons from Fukushima

The Fukushima nuclear disaster exemplifies human fallibility and cupidity and inherent dangers of complex technological systems. It is evident now that the Japanese authorities deliberately withheld damaging information sometimes in the press briefings to enable smooth evacuation. Although mutual distrust among the former prime minister's aides, TEPCO officials, and bureaucrats complicated decision making remarkably, the overall evacuation was efficient. A former chief nuclear regulator from India told one of the authors that very few countries would have done better than the Japanese under those circumstances (Gopalakrishnan, 2011).

The available narratives from TEPCO and officials of the accident sequence and causes suggest that the Fukushima nuclear accident could not have been forestalled even by the best engineered system. Clearly, given their source, these narratives could be self-serving. Still, there is no denying that the Fukushima disaster was triggered by the joint event of a massive earthquake and tsunami rarely seen in Japanese history and that the plant workers made every effort under adverse and severe constraints to mitigate the situation. Emergency response when a natural disaster had completely destroyed critical infrastructure (power supply, communication and transportation systems) could at best somewhat mitigate but could not prevent the disaster. However, a high-level parliamentary inquiry by the Fukushima Nuclear Accident Independent Investigation Commission completed in July 2012 presents a totally different picture than presented from all official accounts so far (National Diet of Japan, 2012). The report was scathing in its criticism of all the players both before and during the nuclear crisis, and speculates that the plant may have suffered significant damage from the quake itself and affected the cooling systems even before the tsunami hit the plant. Confirming this will take some years due to the difficulties in accessing the interior of the plant. Describing the nuclear crisis as "man-made", the commission blamed the government, TEPCO, and the regulators for ignoring sufficient early warnings and for failing to implement various safety measures against events that can lead to total loss of power and put the nuclear plants at risk. Kiyoshi Kurakawa, the chairman of the inquiry commission, said that the nuclear disaster was preventable although triggered by a natural disaster, and said that the fundamental causes of the accident are result of the "ingrained conventions of Japanese culture: our reflexive obedience; our reluctance to question authority; our devotion to 'sticking with the program'; our groupism; and our insularity" (National Diet of Japan, 2012). This assertion is questionable for at least two reasons: first, Japanese culture is by no means unique in having all these characteristics and second, casual attribution to culture for events or consequences that could have been contributed by many non-cultural factors is a confession of ignorance and failure of analysis.

Although many technical lapses have been identified earlier (Government of Japan, 2011), the risk of the joint occurrence of very strong earthquakes and unusually high tsunamis and the need to strengthen measures to protect nuclear power plants against them were not adequately appreciated in Japan. When the Fukushima plant was being built the logarithmic Richter scale for measuring intensity of earthquakes was in wide use. Seismologists had also been using other scales to judge it better and the moment magnitude scales currently in use are improvisations of the surface wave magnitude scale developed by Charles Richter and calibrated using a particular type of seismograph (Wood-Anderson seismograph). In the 1970s seismologists realized that the Richter scale was effective in judging only small and intermediate size earthquakes observed and studied in California until then, but significantly underestimated the energy of larger earthquakes. To overcome this limitation, a new magnitude scale that quantifies more accurately the total amount of seismic wave energy released in an earthquake was developed (Kanamori, 1977). Moment magnitude scale is preferred by professional seismologists for earthquakes larger than 6.5 on the original Richter scale, although to simplify responses to queries of media and non-seismologists researchers often refer any magnitude scale as Richter scale even though it applies only to local magnitude. A magnitude 9 earthquake releases 30 times more energy than a magnitude 8 event. Hence it is plausible that the Japanese authorities could have underestimated some of the earlier events using the unmodified Richter scale. The magnitude of Sumatra and Tohoku earthquakes in 2004 and 2011, measuring 9.3 and 9 in the new moment magnitude scale, would have been estimated as 8.6 and 8.2 using the old surface wave magnitude scale (Noggerath et al., 2011). Before the use of new scale, the 2004 and 2011 earthquakes would have been grossly underestimated. Also, the earthquake hazard maps prepared by government agencies were mainly based on events occurring with a predictable frequency (around magnitude 8 or less) in Japan over a long period of time. Nuclear power plants in Japan were built just to withstand earthquakes up to magnitude 8. Although knowledge about magnitude 9 events as a separate class was available for at least 30 years since the completion of the Fukushima reactor complex, Japanese nuclear regulators had totally ignored the four magnitude 9 events that occurred around the world during the past 60 years.

The frequency and height of the tsunamis were also underestimated. When the Fukushima Daiichi station was built, there was no record of large tsunamis in that particular section of the coast. However, there was evidence of large tsunamis that struck other areas of the Tohoku region which included the Sanriku earthquakes in 1896 and 1933 generating tsunamis that reached a maximum height of 38 m and 27 m respectively (Noggerath et al., 2011). This should have alerted the regulators to demand TEPCO to install appropriate countermeasures. The chairman of Japan's Nuclear Safety Research Association told one of the authors that this was a serious lapse and that Japanese utilities do an independent and systematic evaluation of only earthquake hazards and take tsunami related information from other agencies without further verification (Matsuura, 2012). Japanese utilities rely on information provided by Japan Society of Civil Engineers (JSCE) on tsunami risks and take them without further evaluation. Although earthquake risks were considered and addressed systematically in design, design against tsunamis has been performed based on folklore and failed to attract the same systematic study. In fact, the license approval for the Fukushima Daiichi reactors were based on the assumption that the maximum design basis tsunami height expected was 3.1 m, which originally came from JSCE. JSCE's 2002 assessment "Tsunami Assessment Method for Nuclear Power Plants in Japan" revised their maximum water level to 5.7 m. TEPCO raised the height of seawater pump installation for Unit 6 in response to that assessment and built protection to reflect updated information on tsunami risk. However, tsunami waves reached a maximum height of around 15 m in Fukushima Daiichi and overwhelmed all the cooling systems inoperable. The inadequate power supply and lack of diversification of power sources to reduce the chances of equipment failing to withstand floods illustrates the need for having secure power supply for a long enough time to restore power. Revisiting the reactor's safety systems to ensure resilience in the face of adverse plant conditions similar to Fukushima natural disaster has also been identified as an important lesson.

The three lessons above are about the risks of potential accidents and about the design features to be built in that would insure against accidents covered. But no reactor design can ever insure against all contingencies ex-ante, since some could be new and unknown before. For this reason, ex-post insurance in the form of adequate emergency response, were an accident to occur that was beyond the designed capacity, of the plant to cope is essential. Even for a country with long experience in dealing with natural disasters such as Japan, emergency planning for the accident at Fukushima was a major challenge.

An assessment published by MIT's nuclear engineering department in July 2011 highlighted the main engineering lessons learnt from Fukushima (Buongiorno and Ballinger et al., 2011). The difficulties in managing hydrogen accumulation and its threat to containment integrity emphasize the need for all boiling-water reactors with (BWRs) with Mark I or II to have containment structures with venting systems that prevent or mitigate core damage in the event of a serious accident. Lack of sufficient ventilation led to hydrogen build-up and subsequent explosion in Units 1 and 3 at Fukushima. In new plant designs currently built by the French and Swedish vendors, passive containment and catalytic recombiners that automatically activate during power loss are incorporated. Early containment venting is estimated to reduce radioactivity releases by two orders of magnitude. Because of lack of power at Fukushima, operators had to open the valves manually and thus venting of containment to prevent over pressurization was delayed. It is suggested that, in the long run, avoiding use of materials that generate hydrogen when coming into contact with steam could greatly reduce this risk. Fukushima also highlighted the risk of locating spent fuel pools within the reactor building which exposed them to hydrogen explosions as in Units 1, 3, and 4. The MIT report concluded that all plants with spent fuel storage facilities onsite should be retrofitted with passive cooling that can withstand external shocks. Since many of the failures at Fukushima originated from disruption of power supply, it is also clear that emergency backup generators should be installed in sufficiently high elevations or in watertight chambers if flooding is a serious risk.

Finally, the most important engineering lesson concerns plant layout and siting of nuclear plants. At Fukushima a single external event of flooding disabled all the diesel generators at the station simultaneously. Although there is merit in the site's compact layout, problems such as the hydrogen explosion at Unit 3 disabled some fire pumps used for seawater injection at Unit 2. The explosion at Unit 4 was most likely caused by leakage of hydrogen released from Unit 3 through shared duct-work with Unit 4. Units 5 and 6, which are located far from Units 1–4, were not affected by the explosions at Units 1 and 3. Japan because of its land constraints has generally opted cluster siting unlike land-unconstrained US where most reactor complexes do not have more than two units. Hence the obvious siting approach for future plants should be to locate them inland, provided it is feasible to do so, and away from highly seismic areas and coasts, to greatly reduce (and perhaps eliminate) the possibility of damage due to massive earthquakes, tsunamis and floods. But in many countries mostly coastal sites have been chosen for cooling and logistic convenience.

5. Immediate impact of Fukushima

The Fukushima accident generated an immediate and widespread public opposition to nuclear power and encouraged policy shifts in some countries. However, in earlier accidents social resistance gradually dissipated over time, typically in 10–15 years, and resulted in policy reversals.

5.1. Public attitudes

An international survey commissioned by the BBC after the Fukushima accident suggests that public opinion in many countries is increasingly skeptical about nuclear power (BBC, 2011). This survey was conducted in 31 countries, including 12 countries that have a civilian nuclear program, and was compared with the results of a similar survey in 2005. The proportion of those opposing new constructions increased from 73% in 2005 to 90% in 2011 in Germany, 51% to 82% in Mexico, 76% to 84% in Japan, 66% to 83% in France, and 61% to 80% in Russia (BBC, 2011). Overall, around 39% of those who responded from countries with a nuclear power program are against further expansion and 30% are in favor of phasing out nuclear power altogether. The poll results also show some increased support for new constructions in UK and USA. Support for new constructions increased from 33% to 37% in UK, remains stable in the USA at around 40%, and remains at similar levels in China and Pakistan at 42% and 39% respectively. Among countries that plan to build nuclear power plants for the first time, support in Nigeria was 41%, Ghana 33%, and Egypt 31%. Whether support in the range of 30–40% should be deemed "strong" is a matter of judgment, given that there has also been a sharp increase in opposition to nuclear power in many countries. It is therefore understandable that the policy response to Fukushima across the world varies from complete phase out to delays in construction of new plants to moderation in growth. Comparisons of public opinion surveys are problematic as they generally suffer from significant sampling and non-sampling errors, and it is hard to tell whether the changes are statistically significant and whether the survey designs would enable statistical testing.

5.2. Public policy impact

After Fukushima accident global nuclear electricity production declined from 2010 to 2011 by 4.3% (IAEA, 2012), largely due to reactors being idled in Japan and Germany's decision to shutdown its older units permanently. Not surprisingly, Fukushima's greatest impact is in Japan which faces a host of challenges such as the nuclear clean-up operations and decisions on stopping or continuing with the civilian nuclear program. Prime Minister Naoto Kan proposed during the crisis a major shift in energy policy by reducing the nuclear share and increasing funding for renewable energy projects, energy conservation, and efficiency improvements. Mr. Kano is believed to have always been suspicious of the collusive ties between the bureaucracy, nuclear regulators, industry, and the utilities. Yoshihiko Noda, who took over after Kano resigned in August 2011, while ruling out new constructions and life extensions of old plants, indicated that nuclear plants in good condition will be restarted after extensive safety checks. Japan shutdown the last of the 50 reactors on May 5, 2012, for the scheduled stress tests and additional safety checks, rendering its electric grid nuclear free after more than four decades. Since then mayors of some towns where nuclear plants are located approved restarting them provided they successfully pass the safety checks (McCurry, 2012). This is largely due to the impact of power shortages on local economy and the fear that increased dependence on fossil fuels will increase electricity tariffs.

Nuclear power has been viewed as a "strategic necessity" by Japan since the 1973 oil crisis, which shaped its expansionary energy policy. Nuclear power plants generated around 30% of Japan's electricity prior to March 11, 2011. Before 1973, nearly two thirds of Japan's electricity generation was from oil-fired generators. Japan's poor endowment of primary energy resources makes it dependent on imports for around 85% of its primary energy needs. Hence nuclear power has always received government patronage for energy security and environmental reasons, especially in the context Japan's Kyoto Protocol commitment to reducing carbon emissions to tackle climate change. A 2002 government white paper on energy policy emphasized the role of nuclear power in meeting a major share of future energy needs and achieving emission reduction goals of the Kyoto Protocol.

A year before the Fukushima crisis, Japan's policymakers had been planning to raise the share of nuclear power in electricity generation to about 40% by 2020 and eventually to 50% for meeting an ambitious carbon emissions reduction target of 25% below its 1990 levels. Although a complete nuclear phase out is unlikely in Japan, post-Fukushima a major reorientation of Japan's nuclear energy policy is likely. The immediate and critical test for the role of nuclear energy in the future will be whether to let reactors that are deemed safe and pass transparent and credible stress tests to operate, and the degree of public support to do so.

Elsewhere, the impact of Fukushima on public policy decisions appears minimal. The World Energy Council (WEC) published a special report in March 2012 on the first anniversary of Fukushima accident summarizing the impact of Fukushima on nuclear energy policy decisions of various countries (WEC, 2012). Surprisingly, according to the report, Fukushima has hardly impacted nuclear energy policies except in Japan, Germany, Italy, and Switzerland. Although delays in planned projects, including those under construction, is anticipated, there is a strong official support for nuclear power in China, India, Vietnam, Middle East, Central Europe, United Kingdom, France and a few other countries.

In USA, Fukushima has resulted in more stringent regulation and delays in licensing, but the pre-Fukushima challenges for nuclear expansion still remain, such as storage of nuclear waste and problems with spent fuel pools. Availability of cheap shale gas will make nuclear power less competitive in some regions. Still a significant growth in nuclear capacity can be expected in the United States. Francois Hollande, the newly elected President of France, had promised to reduce the country's reliance on nuclear power during his election campaigns. However, history and institutional inertia are likely to leave intact its commitment to sustain current high levels of nuclear power. Germany had decided even before Fukushima to shutdown all existing nuclear reactors, however, Fukushima gave it the political cover for hastening the process. Britain appears unaffected by Fukushima and plans to replace old capacity besides adding new capacity.

China has the most ambitious nuclear expansion plan in the world and is expected to add 86 GWe of capacity by 2020. Fukushima resulted in a temporary slowdown in China, but expansion plans are still intact. In Southeast Asia, the Fukushima crisis has delayed new construction plans except in Vietnam. Vietnam signed agreement with Russia to build its first nuclear power reactor before 2020, and negotiations are ongoing with Japan to build its second unit. Although Indonesia had proposed to build nuclear power plants several years ago, anti-nuclear sentiments were strong there even before Fukushima and remain a major issue. Malaysia and Thailand have recently expressed interest to build nuclear plants soon after 2020. India announced a target of reaching 60 GWe of nuclear capacity by 2030 after the successful negotiation of the civilian nuclear deal with the United States in 2008 and its subsequent clearance by the Nuclear Suppliers Group (NSG). India's expansion plans temporarily suffered in the aftermath of Fukushima after a well-organized public protest movement delayed the commissioning of the near-complete Kudankulam nuclear power project in the state of Tamil Nadu. The state and central governments' use of repressive means to break the movement and threats to the people who led the protests has subdued public protests for now. But it can resurface in other sites where nuclear power projects are planned.

6. Post-Fukushima challenges

Nuclear power has traditionally faced several challenges on reactor safety, radioactive waste management, economics, public acceptance, and international security concerns arising from both credible and hypothetical scenarios of diversion of nuclear materials from electricity generation to production of nuclear weapons. Most of these challenges still remain, and the Fukushima accident has highlighted new vulnerabilities and also narrowed some of the earlier concerns. We shall summarize them in this section.

6.1. Nuclear regulation

The Fukushima crisis has highlighted the problems of regulatory capture by the industry resulting in collusive ties between the regulators and the industry that can seriously compromise public health and safety, and lack of transparency in nuclear safety and regulatory functions. In Japan, three agencies (The Nuclear Safety Commission of Japan (NSC), Nuclear Industrial Safety Agency (NISA), and Nuclear Safety Division) share regulatory responsibilities. During the Fukushima crisis, coordination and consistency of responses among them was difficult to achieve. Creation of the new independent regulator is delayed in the political process, fueling further public skepticism of nuclear power.

These problems are not unique to Japan and can be found in some measure in almost all nuclear programs in the world largely because of earlier connection of nuclear energy with military programs. In the early days of the nuclear era, promotional and regulatory functions were carried out by the same organization. In the US, the Atomic Energy Act of 1946 established tight federal control over both military and the civilian uses of technology. The Atomic Energy Commission (Vervaeck and Daniell) was given the general responsibility for promoting nuclear power as well for licensing it to private producers, creating an obvious conflict of interest. Although the Congress had oversight powers, it left to the AEC to determine what constituted adequate protection of public health and safety. Earlier, the AEC did not publish any document about potential safety problems in a given application, nor did it make them public when the internal regulatory committee highlighted them. The current US Nuclear Regulatory Commission (NRC) was created only in 1975 after the earlier arrangement became untenable with the expansion of the civilian nuclear program.

Even before the Fukushima accident, cozy relations between the regulatory officials and the industry were a source of concern. In Japan and in other countries it is not uncommon to see retired nuclear industry professionals working as regulators. Even in countries where nuclear regulatory agencies are fairly independent, their frequent reliance on operators and vendors for technical expertise is problematic. Since independence of regulatory agency is not an end but only a means to an end, the challenge is to create a regulator with the necessary human and technical resources to identify threats and effectively discharge its regulatory responsibilities without fear or favor to safeguard public health and safety. In some countries where civilian nuclear programs are operated by government owned entities, safety lapses are often covered up by invoking secrecy and national security. The 1996 report by India's former nuclear regulatory chief listed several safety lapses and vulnerabilities in civilian nuclear facilities (Rethinaraj, 1999). This report has not been made public as of 2012, although media published selectively leaked contents. Following this a public interest litigation was filed in 1996 in the Bombay High Court by two civil society groups to make the report public and also to create a more independent regulator as had been promised by the government. When the court summoned the Department of Atomic Energy (DAE), which manages India's civilian and military nuclear programs, it invoked national security clause and avoided potential embarrassment the disclosure could have caused. Structural deficiencies in India's regulatory process have long been a cause for concern as it calls into question the independence of the regulatory process. Organizational restructuring for effective and transparent regulation has become even more urgent after the Fukushima crisis. The Indian government announced the setting up Nuclear Safety Regulatory Authority (NSRA), after Fukushima and have it separated from AEC. But questions about its capacity, dependence on the operator for resources remain.

The nuclear regulator has to be sufficiently independent from political and industry pressures, as well as perceived so by the public. The International Atomic Energy Agency's action plan on safety after the Fukushima nuclear accident emphasized the importance of having a nuclear regulator with sufficient independence and resources (IAEA, 2011). In response to Fukushima and IAEA's advisory, the European Commission plans to make regulatory independence legally binding on member states. Even in the US, where NRC is perceived to be far more independent than its counterparts in other countries, the independence of regulatory officials has been an area of concern due to features of the US political process.

6.2. Setting radiation standards

The Fukushima crisis has freshly highlighted the challenges in setting radiation protection standards to safeguard public health and safety. This issue still generates controversy due to the underlying scientific uncertainties and political sensitivities. Even after more than hundred years after the discovery of ionizing radiation, many questions remain unanswered about the risks associated with low-level exposure and the effectiveness of various national and international regulatory limitations on them. Since these issues involve difficult technical as well as social and political value judgments, what constitutes an acceptable level of exposure has been an emotionally divisive issue since the mid-1950s. Even as agencies began to adopt more stringent requirements for radiation releases from civilian nuclear facilities, lack of transparency over the health impact of nuclear weapons programs caused much public anxiety. In the US, for example, the 1957 radiation regulations did not apply to the testing fallout (Walker, 2000). The tightening of regulations for civilian nuclear power in the midst of the fallout controversy did not inspire much public confidence because the AEC was responsible for testing program as well as commercial nuclear regulation, and this undermined its credibility on all radiation safety standards it initiated. Although the target "as low as reasonably achievable" (ALARA) was not adopted until the 1970s, regulatory agencies set radiation protection standards by applying principles very conservatively. However, by the mid-1990s, existing radiation standards came under attack for being too strict and radiation professionals claimed that a reassessment of assumptions used in radiation protection was long overdue. They questioned the validity of the "linear no threshold" hypothesis as a basis for policy and cited the high costs it imposes on producers of nuclear energy. The Fukushima accident, however, now makes it more difficult to approach radiation standards without bias.

A major public-health study by Fukushima Medical University is underway with an estimated budget of around US$958-million over 30 years to monitor the health of around 2 million people from the region (Brumfiel and Fuyuno, 2012). According to recent estimates, people living in towns or villages close to the plant received less than 10 millisieverts (mSv) in accumulated effective dose in the first four months after the accident (Brumfiel and Fuyuno, 2012). The highest recorded dose was 23 mSv, which is considered well below the acute 100 mSv exposure levels linked to a slight increase in cancer risk after discounting the delayed effects which manifest after several years. After the Fukushima accident Japanese authorities relaxed (more than doubled) the exposure limits to enable emergency workers to control the situation, but returned to the previous threshold levels in December 2011. The current occupational exposure limit is 100 mSv over five years, with a maximum exposure limit of 50 mSv in any one year. Another disturbing revelation currently under investigation is falsification of radiation data by one of TEPCO's subcontractors who had asked workers to cover their dosimeters with lead plates to record lower levels of radiation exposure (Associated Press, 2012). Dosimeter readings are critical personal health records that help monitor the safety of workers in contaminated areas. Incidents of falsifying records like this have only resulted in more public apprehension and loss of credibility. The major clean-up operation underway is mainly an effort by the government to gain public trust that was severely affected after the accident. Japan hopes to bring down the background radiation level within the 20 km evacuation zone to 1 mSv, which is less than half their annual exposure from natural sources.

6.3. Nuclear contribution to slowing climate change

The Fukushima accident has rekindled the debate on energy portfolio choice and the pros and cons of relying on nuclear power to achieve carbon emissions target. In the case of Japan, taking the nuclear reactors (which accounted for 30% of Japan's electricity production) off the grid will certainly increase the country's emissions in the short term since much of the replacement will likely be with fossil fuels. For example, replacing all of Japan's nuclear capacity with coal plants will result in 260 million tons of carbon dioxide emissions annually. Oil or natural gas option will result in 200 million tons of carbon dioxide and 160 million tons of carbon dioxide respectively. These estimates of avoided emissions are based on standard power plant calculations (Rubin and Davidson, 2001).

Stabilization of atmospheric carbon dioxide concentrations, which is critical to avoid worse climate change scenarios, requires an eventual decline of global emissions. In this context, nuclear and renewable energy technologies have the potential to contribute to the growing demand for energy without emitting carbon dioxide. Given the enormous technical and economic hurdles for large capacity additions through renewable sources in the near term, nuclear power has a greater potential for reducing the share of fossil fuel in the global energy mix. However, though this has tremendous value in a climate constrained world, several-fold increases in nuclear capacity will be needed to make a significant impact in the global energy system. Such rapid large-scale deployment of nuclear reactors pose several challenges in the post-Fukushima era. A global nuclear energy system comprising 2,500–4,500 reactors by the end of the century (which is five–ten fold increase from current capacity level) is required to replace a significant share of fossil fuels (Kim and Edmonds, 2007). In such a scenario, the frontend fuel cycle requirements and backend waste management challenges are daunting. Fresh uranium requirements for such an expansion could be met if one inappropriately discounts the environmental impact of expanded mining operations. However, the direct and indirect economic costs of a large nuclear expansion program will be tremendous. Alternatively, a large nuclear program could be supported without the need for fresh uranium mining if and when commercially viable breeder reactors become available. But, prospects for this appear far distant that it seemed during the 1960s, leaving the current thermal spectrum reactors the mainstay of nuclear industry for the foreseeable future. With the once-through fuel cycle option for these types of reactors, 25–43 million metric tons of uranium will be required by the end of this century. This is several times the "reasonably assured" estimate of world's uranium resources (OECD/NEA, 2010). Assuming direct disposal of spent fuel, the 4.1 million tons of spent fuel that will be accumulated by the end of this century globally under such a scenario will require as many as 59 US Yucca Mountain repositories (at the legislated capacity of 70,000 t) by the end of the century (Kim and Edmonds, 2007). While increasing the share of nuclear power has the potential to mitigate climate change through emissions reduction, the difficulty of policy choice arises in evaluating the comparative risks of increased nuclear power generation vis-à-vis projected future climate change effects. Methods for comparing these two risks far into the future are problematic. In the case of anticipated future risks posed by a larger commercial nuclear reactor fleet, the challenge lies in precisely estimating low probability but high consequence events. On the other hand, uncertainties underlying future emissions and simplistic linear projections of current emissions forward (which builds the case for increased share of non-fossil energy use) renders comparing future climate risks with nuclear risks analytically difficult.

Arguments favoring increased nuclear share are mostly based on assumptions that carbon emissions will continue to rise and will be reflected in the cost of electricity production. In the absence of a global agreement to cap emissions and an effective market mechanism to internalize the costs of carbon emissions, there is additional difficulty in comparing the cost of nuclear electricity production with other competing sources. Historically, construction of nuclear power plants has been largely funded or subsidized by governments. This situation has not changed much worldwide. Nuclear plant construction cost has increased dramatically since 2001, when the reported costs of nuclear in OECD countries stood at US$ 2000 per kW of capacity (Economist, 2001). Recent figures suggest a three to four fold increase in construction costs (Economist, 2012). Although some annualized cost calculations over the lifetime of the plant show nuclear power to be competitive, they depend on assumptions about the price tag for carbon, and the additional risk premium charged for nuclear projects after the Fukushima accident. In addition to the economic cost, lack of certainty in the policy process adds an additional risk with its own added premium. This uncertainty and anticipated regulatory delays have a huge implication for financing costs of nuclear projects. In the post-Fukushima environment, building new nuclear power plants will not be feasible without state subsidies. As a consequence, already financially constrained governments will have the fiscal capacity to bear all or a major portion of the financing and associated risks to the benefit of the utility is an open question.

6.4. Factoring social costs and benefit

While economic and financing costs for nuclear utilities have been a subject of much discussion, the issue of social costs and benefits of nuclear power have not received adequate attention. Economic costs are those faced by the utility, including capital charges, operating expenses, and fuel cycle costs. Social costs for each plant and its associated fuel cycle include routine environmental impacts such as air pollution as well as risk to the public from reactor accidents or sabotage and subsidies to private utilities. Relative to nuclear power, coal has lower capital costs but substantially higher fuel costs and social costs; the social costs for coal are primarily from air pollution especially sulfur oxide emissions. Nuclear power also has the problem of dealing with events that have a low probability of occurrence but have large social costs were they to occur, a feature that is present in evaluating the risks of climate change about which public has poor understanding. Regardless of the difficulties associated with public perception about low probability but high consequence events, quantitative analyses of both economic and social costs in a rigorous analytical framework is needed for engaging the public in the decision making process. This not only helps bring transparency in the decisions relating to siting and waste disposal options; it also provides a better framework for improving communication with the concerned public about various risks and benefits associated with nuclear power, and involving them appropriately. There is a vast literature on the social cost benefit analysis relevant to this subject (Barrager and Judd et al., 1976).

For example, although economic costs of nuclear waste management are small compared to other costs of nuclear power, residual radioactivity that will persists for thousands of years if not carefully managed poses social costs across several generations. Hence society must confront these issues in a transparent manner to decide whether to expand the role of nuclear power from the current level. A similar dilemma also arises in the choice of fossil fuels, which have potential to cause large climatic impact. When a society's preferences are included in any analysis in a credible and transparent way, there is a better chance of accommodating public concerns. Such an approach provides an analytical framework for comparing the benefits of nuclear versus other alternatives (all of which involve varying degrees of risk) and making the basis of public policy decisions explicit and accessible for an independent review. Except in some countries there is little evidence that this is done systematically in the decision making process. In India, decision makers simply assert without analytical justification that the priorities of development overrides other concerns and summarily dismiss the use of social cost benefit analysis in decision making (Ahluwalia, 2012).

7. Conclusion

The Fukushima accident has highlighted the challenges in siting nuclear reactors. The earliest reactors in the US and other countries were built in remote places and didn't have containment. Expansion of civilian nuclear industry necessitated siting of reactors closer to load/population centers. Hence later emphasis was on engineered safety features and containment structures to minimize environmental impact of accidents. Most countries avoid building reactors close to active faults and coasts that are vulnerable to flooding. Due to its being in an earthquake zone and land constraints, Japan built many of them in vulnerable sites and tried compensating with enhanced engineered safety features. Since a large number of reactors (operational and planned) are located along coastal areas for cooling convenience, effective protection against flooding will be crucial. Although clustered siting of reactors has certain convenience, Fukushima has highlighted the risks of clustering reactors in sites and chances of simultaneous failures of more than one reactor. The need for a larger safety margin during accident conditions and extended station blackout scenarios will have to be incorporated into future reactor designs.

Finally, the need for deeper statistical analysis of probabilities of natural events that could trigger vastly damaging nuclear accidents is essential. Engineering safety, focusing on reducing the probability of a reactor event due to design failures to some acceptable global standards by itself is not adequate. Besides equipment failures, human failures of operators of equipment also could result in a reactor event. Except in the NRC of the US, human error analysis is virtually unknown elsewhere. In Fukushima, the plants performed as they were designed to perform. Had the tsunami and earthquake not eliminated access to external power to access the plant cooling systems, there would not have been a core meltdown or hydrogen explosion or any radiation leak would have been very unlikely. In the larger context of the role of nuclear power in energy portfolios for the future, it is essential to institutionalize social-cost benefit analysis taking its risk considerations explicitly into account. In particular, the assessment of accidents with very low probability of occurrence but with very high social costs, if they occur should not be ignored. In addition to ex-ante insurance through appropriate siting and plant design and other safety features, response plans in the event of accidents have to provide post ex-post insurance in nuclear power plants. Exclusive attention only to engineered safety ex-ante is dangerous.

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