Energy Policy 52 (2013) 726–736

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# Fukushima and thereafter: Reassessment of risks of nuclear power

T.N. Srinivasan, T.S. Gopi Rethinaraj *

*Lee Kuan Yew School of Public Policy, National University of Singapore, 469C Bukit Timah Road, Singapore 259772, Singapore*

## 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.

ARTICLE INFO

*Article history:*
Received 31 July 2012
Accepted 12 October 2012
Available online 3 November 2012

*Keywords:*
Nuclear power and regulation
Reactor safety
Fukushima nuclear accident

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

* Corresponding author. Tel.: +65 65168250.
*E-mail address:* spptsgr@nus.edu.sg (T.S. Gopi Rethinaraj).

0301-4215/$ - see front matter 
http://dx.doi.org/10.1016/j.enpol.2012.10.036

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