G Model
ERSS-270; No. of Pages 5
ARTICLE IN PRESS
Energy Research & Social Science xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Energy Research & Social Science
journal homepage: www.elsevier.com/locate/erss

Short communication

Reassessing the safety of nuclear power[☆]

Spencer Wheatley[a], Benjamin K. Sovacool[b,c,*], Didier Sornette[a]

[a] ETH Zurich, Department of Management, Technology and Economics, Switzerland
[b] Department of Business and Technology, Aarhus University, Birk Centerpark 15, DK-7400 Herning, Denmark
[c] Science Policy Research Unit, University of Sussex, United Kingdom

ARTICLE INFO

Article history:
Available online xxx

Keywords:
Nuclear energy
Nuclear power
Nuclear safety
Nuclear accidents

ABSTRACT

We summarize the results of a recent statistical analysis of 216 nuclear energy accidents and incidents (events). The dataset is twice as large as the previous best available. We employ cost in US dollars as a severity measure to facilitate the comparison of different types and sizes of events, a method more complete and consistent that the industry-standard approach. Despite significant reforms following past disasters, we estimate that, with 388 reactors in operation, there is a 50% chance that a Fukushima event (or more costly) occurs every 60–150 years. We also find that the average cost of events per year is around the cost of the construction of a new plant. This dire outlook necessitates post-Fukushima reforms that will truly minimize extreme nuclear power risks. Nuclear power accidents are decreasing in frequency, but increasing in severity.

1. Introduction

It has been more than four years since an earthquake and tsunami caused an accident at the Fukushima Daiichi nuclear power plant in Japan resulting in repeated fires and three reported core meltdowns. At the latest count, the accident had caused $166 billion in damages[1] [1] and at least 573 immediate deaths from the evacuation, along with hundreds of future deaths related to cancer anticipated to occur [2]. Somewhat sweeping industry reforms were called for, and public acceptance of the technology plummeted [3]. Supporters of nuclear power were quick to point out that a complete phase out would complicate efforts at mitigating greenhouse gas emissions from the electricity sector [4] and could lead to cumulative global losses in global gross domestic product [5].

The March 2011 Fukushima nuclear accident is a poignant reminder that disasters of enormous consequences can occur in the nuclear industry. But how often and with what severity? These two questions constitute the core of sound risk management, which requires identifying and quantifying such potential losses and their frequencies. For most natural and human-made catastrophes such as earthquakes, meteorites, avalanches, mountain collapses, forest fires, hurricanes, epidemics, health care costs, war sizes, terrorist intensities, cyber risks, dam failures, industrial disasters, and so on, plentiful historical data has allowed scientists and engineers to determine the distributions of losses.

The admittedly favorable situation of a paucity of nuclear accidents, combined with scantly available public historical data, has prevented any such statistical analysis. Nuclear engineers have thus resorted to the classification of hypothetical accident scenarios deemed credible and of their potential consequences. The common industry approach to assessing nuclear accident risk depends on a technique known as probabilistic safety analysis (PSA), which assigns probabilities and damage values to particular failure scenarios. Nonetheless, such techniques are known to poorly predict events and to under-appreciate incidents that cascade into failures [6–11,12].

Similarly, the IAEA (International Atomic Energy Agency) provides the INES (International Nuclear Event Scale) to communicate the severity of nuclear accidents on a progressive discrete scale of 1 (anomaly) to 7 (major accident), meant to correspond to the amount of radiation released by order of magnitude. Yet its approach has been critiqued for offering relatively crude scores, for reporting only a fraction of known events, for not being transparent in its methodology, and for being more of a public relations tool (propaganda) than a meaningful metric [9,13]. For instance, there are about 12,000 events reported by French operators every year, of which 600–800 are classified annually as “significant for nuclear safety,” yet little to none of these show up on the INES database, and such unreported events occur at just 15% of the currently operating world nuclear fleet [14].

☆ One of the authors of this paper is an editor for Energy Research & Social Science. They were not involved in managing the peer review process for this article.
* Corresponding author. Fax +45 3032 4303.
E-mail address: sovacool@vt.edu (B.K. Sovacool).
[1] Updated to US$2013 and adjusted to monetize human fatalities. Originally reported as $150 billion in $2010 damages.

http://dx.doi.org/10.1016/j.erss.2015.12.026

Please cite this article in press as: S. Wheatley, et al., Reassessing the safety of nuclear power, Energy Res Soc Sci (2016), http://dx.doi.org/10.1016/j.erss.2015.12.026

In this study, we summarize the results of a statistical analysis of a dataset of 216 events (incidents and accidents) occurring in nuclear energy systems [15], a dataset that is twice as large as any of the previous best ones available in the scientific literature [8,16], but we refrain from using the INES data directly. Instead, we use the estimated cost in USD (US dollars) as the common metric that allows one to compare often very different types of events across the nuclear fuel cycle. This dataset has more than three times the number of accidents compared with studies using solely the INES data, providing a much better basis for statistical analysis and inference, and a better comparative tool for reassessing the safety of nuclear power. Following Chernobyl, several authors proposed utilizing a monetary value of damage severity to make events comparable, and use a rate measure normalized by the number of reactor operating years to consider frequency [17–19]. This is what we have done here, but extending the range of analysis well beyond 1986 to include Fukushima and other nuclear events leading up until the end of 2014. The dataset has been published online[2], where the public is encouraged to review and recommend additions and modifications with the intention of continually expanding and improving the quality of the data.

2. Methods

There are many ways to quantify the risk of accidents in nuclear energy systems. The Farmer curve is one of the standard tools of nuclear risk assessment, with the risk defined as "probability × consequences" [20]. Typical Farmer plots display the annual frequency of fatalities or of property damage from human made sources of risk. Remarkably, the nuclear risks reported in Farmer plots are fundamentally different from all previously mentioned risks, in that the distributions for nuclear event losses are always thin-tailed and Gaussian-like, presenting a downward concave shape in the standard log–log representation.

The appearance of the Soviet Union's Chernobyl accident in 1986 and of Japan's Fukushima Daiichi nuclear power plant accident, after the tsunami on 11 March, 2011, seem at odds with the statistics implied by the Farmer curves. Actually, following the Chernobyl accident, Hsu [17] and Sengor [18,19] suggested a different approach, based on the reasoning that the number of fatalities is an incomplete, if not misleading, metric for measuring nuclear losses given the difficulties in assessing long term real mortality in addition to early morbidity and mortality. Indeed, this metric misses many other dimensions and also prevents quantitative comparisons. Hsu in particular made the point that the statistical analysis of earthquake risks, for instance, would have missed the fundamental Gutenberg–Richter magnitude–frequency law [21] if seismologists had focused on only the few large earthquakes. By considering a range of event sizes above which the data is known to be sufficiently complete, or at least representative, one can identify possible statistical regularities that are relevant to the largest events.

Here, we analyze the distribution of losses resulting from all possible types of nuclear events from 1952 to 2014. To be consistent with both the INES, as well as earlier peer-reviewed studies [8,9], we assessed events across the entire nuclear fuel cycle—that is, not only at nuclear reactors and power plants but also at uranium mills, fuel enrichment facilities, reprocessing stations, and nuclear waste repositories. In addition to maintaining consistency, this inclusion of non-reactor events is also necessary to trace the full impact of nuclear power technology on society as well as to account for the fact that many sites prone to accidents concentrate multiple elements of the fuel cycle in one location.[3] Searching historical archives, public utility commission filings, regulatory reports, and other sources explained in SM1, we created a unique dataset of 216 nuclear events, with 104 of these events having at least $20 million in inflation-adjusted cost.[4] In addition, whenever events had the same dependent cause, such as Fukushima, we treated them as a single occurrence. As it is important to evaluate the number of accidents relative to the number of reactors in operation, we have normalized our assessment to operational reactor data from the IAEA [22].

To be fair, a few caveats and limitations deserve mentioning. In this study, we focus only on damage and loss of life from nuclear accidents, and not other externalities such as lung cancer risks from coal mining or particulate pollution from petroleum-fuelled automobiles. Consequently, our study details the risks present from continuing to operate existing reactors, it does not assess the risks from not operating them (such as greater reliance on fossil fuels) [4]. Also, as is typically the case in data such as this, there is an event severity level below which events are less frequently reported, or even noticed—making our analysis conservative because of incomplete data. We base our analysis on the current reactor fleet, heavily tilted towards older light water reactors (often called "Generation II" technology), not state-of-the-art designs such as the European Pressurized Reactor or "paper" units at the conceptual stage such as small modular reactors, primarily because there is insufficient operating experience for their statistical analysis, but also since the adoption of these designs is uncertain. Our characterization of the current risk level, and its use for forecasting, presumes that 388 reactors remain in operation, and does not include any potential improvements in response to Fukushima. Any significant nuclear renaissance or massive build-out would alter our characterization, as would any massive phase-out. Lastly, we limit our assessment to nuclear generated electricity and its fuel cycle, and thus exclude risks posed by nuclear explosives and nuclear weapons, except for those facilities (such as reprocessing spent fuel) that are dual use.

3. Results and discussion

We quantify four identifiable dimensions of risk: (i) historical frequency of accidents, (ii) historical costs, (iii) the presence of so-called "dragon kings" and extreme events, and (iv) expected future costs.

In terms of frequency, panel (I) of Fig. 1 plots the number of events with at least $20 million in damage (and standard errors) per reactor per year, calculated on 5 year windows spanning 1960 to 2014. The main message here is that the rate of events has dropped substantially since the 1960s, and may have stabilized since the late 1980s. In panel (II) of Fig. 1 the rate of events is calculated running away from the Chernobyl accident in both directions. From here it is clear there was a significant decline in event frequency after the Chernobyl accident, and the rate of events since that drop has been roughly stable, indicating that Chernobyl was a catalyst for change that decreased the rate of events, but not necessarily the size of each event. Rate estimates for 2014 remain in a conservative range of 0.0025–0.0035, or 1–1.4 events per year over the entire nuclear fleet. The methodology used here is described in SM2.

[2] See https://tasmania.ethz.ch/index.php/Nuclear_events_database.

[3] Sellafield in the United Kingdom, for instance, is home to commercial reactors, research reactors, waste repositories, and reprocessing facilities and Fukushima Daichi in Japan was home to commercial reactors and waste repositories.

[4] The analysis here is focused on events with at least $20 million USD in damage. These events are more visible and thus the dataset is more likely to be complete above this threshold. Therefore statistics on this subset will be more reliable than when considering smaller events. Further, these large events are most relevant as they drive the total risk level. For instance, the ten most costly events contribute approximately 94% of total costs to date.