Predicting Future Fukushimas: A Response to Dr. Walden's Criticism

Spencer Wheatley, Benjamin K. Sovacool, and Didier Sornette

On 15-05-2015 Dr. Patrick L. Walden posted a criticism (http://www.triumf.info/wiki/pwalden/index.php/On_the_Probability_of_Predicting_Future_Fukushimas) of a manuscript that the authors of this document posted on arXiv (http://arxiv.org/abs/1504.02380). The response to this criticism is provided here, as of 22-09-2015.

Scholars generally post preprints or non-reviewed manuscripts to public archives such as arXiv so that they can solicit independent feedback from colleagues and researchers at large. The idea is to enhance the peer review process by receiving comments from a broader pool of experts, especially those in the public domain. The way it is supposed to work is that commentators will write to those scholars and engage in a frank but respectful discussion about how the paper, project, or experiment can be improved. A productive and collegial dialogue ensues.

In that regard, we are thankful to Dr. Patrick L. Walden's commentary for it has identified a few typos within our appendices and equations that needed corrected: Equation 1 should be a sum of N_t divided by a sum of v_t. This was a typo. The typo on page 9 regarding the aggregate distribution indeed needs to have a 1- in front of the exponential term. Also in equation 10 indeed a 1- was missing. Since a probability level of 0.5 was used and 1-0.5=0.5, this does not affect the calculated return times.

These minor mistakes, however, is largely where the scholastic and academic contribution of his critique ends. Rather than write to us directly, Dr. Walden chose instead to publicly attack the work without informing us. Further, instead of focusing on the manuscript posted on arXiv, Dr. Walden chose to instead personally attack one of the co-authors, Professor Sovacool, and extend his attacks into completely unrelated topics. He also spends much of the article espousing a vision of a nuclear utopian future instead of carefully staying on point with our article.

Due to the importance of this topic as well as the apparently biased and often erroneous criticism of Dr. Walden, we elected to offer a point-by-point response. This is provided in Appendix I. Here, we focus on the five most important responses: (1) Dr. Walden consistently conflates media reports of our article with the article itself; (2) Dr. Walden repeatedly tries to attack the credibility of the authors (namely Sovacool) rather than the article itself; (3) Dr. Walden often mistakes our sources of data and wrongly argues they are outlying with regards to alternative sources; (4) Dr. Walden does not accept the use of cost as a measure of accident severity / consequences, despite it being an often utilized and valued metric for measuring a range of losses including loss of life; (5) Dr. Walden criticizes our history-based statistical analysis, which in his view does not take sufficient account of the possible future nuclear technology that could improve safety features, but ignores the fact that conventional reactors will continue to operate for some time.

First, Dr. Walden's criticism shifts between our own analysis and a story published in the MIT Review interpreting it. The criticism of our work even opens with a criticism of the MIT Review piece. This is misattribution and un-scientific agglomeration typical of bad journalism. In fact, we were not even notified by them that they were going to review the manuscript.

Second, Professor Sovacool is not the lead author of the article, and the credentials and impartiality of his coauthors remain unchallenged. Moreover, in terms of his academic career and credibility, Professor Sovacool is the author of more than 330 refereed articles, book chapters, and reports, including solely authored pieces in *Nature* and *Science*, and the author, coauthor, editor, or coeditor of 18 books on energy and climate change topics. These include books with MIT Press, Oxford University Press, Cambridge University Press, Nature Publishing Group/Palgrave, and Johns Hopkins University Press. Professor Sovacool is also the recipient of more than 20 competitive international grants and has received 20 national and international awards and honors, including the 2015 "Dedication to Justice Award" given by the American Bar Association and a 2014 "Distinguished Visiting Energy Professorship" at the Environmental Law Center at Vermont Law School. These attributes do not reflect a researcher known for only choosing outliers or producing poor research.

Third, in various places, Dr. Walden frames our dataset as relying on outliers. Central to this claim is a $166 billion damage estimate for the Fukushima accident, which Dr. Walden presumes the authors got from *Russia Today*. This is false. When you de-adjust for inflation and deduct our monetization of loss of life, the damage amount drops to about $150 billion. That range was widely reported by both the local and international media including Yomiuri Shimbun, Asahi Daily, Reuters, Al Jazeera, and Grist, with references to official government projections, *not* Russia Today. This means the estimate was triangulated, that is, reported and confirmed by multiple sources. This estimate was also not an outlier—other estimates of damage, though less reliable, reach into the *trillions* of dollars.

Fourth, Dr. Walden claims that using $-cost is not scientific and that 6M$ per life is not respectful to life and the environment. This is the typical narrow engineering view point, which misses the need to encompass the holistic nature of the costs in all their dimensions. This is only possible by developing a common metric, the $-costs, a standard approach to develop evidence-based policies. Cost is a valid measure because it is cost and value that control all decisions that impact the life (and health and death) of billions of people.

Fifth, much of Dr. Walden's criticism rests on the fact that we (admittedly) refrain from making projections about the future of nuclear power and thus possible future nuclear technology that could have improved safety features. This was intentional—the future of the industry is highly uncertain, and due to improvements in capacity factors and current plans for multiple license extensions, coupled with the difficulty of siting new reactors in places like the United States, the existing fleet will continue to operate for some time. Unless new reactors substitute and phase out old ones—not necessarily the case—new technology won't reduce the risks of the old. Put another way, the bulk of our analysis is historical – though it does draw from this history to suggest a possible future, we by no means treat the future as predetermined. We would also argue, as Supreme Court Justice Oliver Wendell Holmes once stated, that a page of history is worth a volume of logic.

In sum, Dr. Walden's criticism was not only overly combative, but also biased and erroneous.

Appendix I: Authors' Detailed Response

A cutaway view of an AP1000 nuclear power plant. This is a GEN III+ power plant, which is about a 100 times safer to operate than the current fleet of GEN II reactors. This is the future of nuclear power but it bears no role in the consideration of the probability of future nuclear accidents as stated in this paper. The paper is thus deficient in this regard.

Authors reply: This is a statistical analysis that makes no claims about the safety level of new technologies. On the other hand, the claim that GEN III+ is 100 times safer is based on PSA – not experience. It is well known that PSA has consistently underestimated risk [1]. Further, it is possible that it will be a long time before the current fleet of GEN II reactors will be decommissioned. It remains for the next decades by far the dominant contribution to the fleet of nuclear plants in operation.

On April 7, 2015 a paper was submitted to the Cornell University Preprint Library, which purports to give probabilities on future Fukushima and Chernobyl disasters. It is a preprint and has not yet been refereed. The journal for which it is intended for publication has not been designated. One of the authors, Sovacool, has produced results in the past regarding nuclear power that are outliers with respect to the results of his colleagues and other researchers. His outliers always trend to place nuclear power in an unfavourable light.

Authors reply: Professor Sovacool's work on nuclear power is almost entirely peer-reviewed, and it is more rigorous and balanced than many existing pieces that advocate either way in favor of or against nuclear power. Moreover, personally attacking one of the authors (an ad hominum *attack) does not mean their results are wrong—it's a cheap shot. See above for more on Sovacool's qualifications and credibility. He was also not lead author.*

In this present paper, discussed below, a new measure is presented to quantify the scale of a nuclear disaster. It is the momentary cost of nuclear accidents expressed in 2013 USD. This measure neither quantifies the scale of the disaster nor is sufficiently robust enough to qualify as a measure.

Authors reply: Financial loss is a very common measure used in the quantification of risks, for instance in the insurance industry. In many ways, it is superior to other measures as it provides a common metric for comparability of events that caused different kinds of damage. The use of financial loss should be uncontroversial and is clearly a quantification of the scale of a disaster. On the other hand, it is not perfect. Our stance is that a full assessment of the severity of an accident requires several complementary measures, which together allow one to grasp the full consequences of the accident.

The figures Sovacool et al. use for the damage in 2013 USD are shown to be outliers with respect to other references.

Authors reply: Firstly, no other references have used such a comprehensive dataset and thus cannot be directly compared. Despite this, other papers using an older and smaller version of the data provide a similar extreme characterization of the risk level [2][3]. The paper [3] was co-authored by a professor *of nuclear energy and safety engineering (http://www.lsa.ethz.ch/people/prof/wkroeger/).*

With difficulties like this and other problems it is not apparent that the authors' prediction of a 50% chance of another future accident like Chernobyl by 2042 bears any real meaning. What can be shown is that by using Sovacool et al. figures as the worst possible case, modern nuclear technology would make nuclear accidents like Chernobyl and Fukushima become a thing of the past.

Authors reply: The logic that the past risk level of nuclear accidents has been high somehow implies that the future risk level will be low is false. You can argue that new technologies will radically reduce the risk, which is possible. However, this is not contained within the scope of our study. That said, within our study, we did find that previous industry responses to past accidents were not entirely effective.

The catastrophic disasters at Chernobyl and Fukushima are among the worst humankind has had to deal with. Both were the result of the inability of scientists and engineers to foresee how seemingly small problems can snowball into disasters of almost unimaginable scale.

This is a statement of hyperbolic proportions written by the author of the Review. Although the authors of the research paper did not use such hype, it sets the tone in which these accidents are still viewed by the public, and in which any future prediction of a repeat accident is viewed with dire foreboding. Consequently the predictions from this paper will be viewed with such dire foreboding, this foreboding which casts such a pale over the future use of nuclear power. Hence it is important that when any learned study portends to make such predictions that it be properly vetted because poorly done studies benefiting from the notoriety of the subject are of no use use to anyone.

Authors reply: We are not responsible for what MIT Technology Review chooses to write about a preliminary unpublished manuscript. See above.

The probabilities of future nuclear incidents given in the paper assumed no improvement in nuclear technology. The probabilities are projections from a comprehensive accident database that has been compiled by the authors for all nuclear accidents from 1950 to the present, 2014. While this database maybe noteworthy, the assumption of the authors is not, because this assumption is even contradicted by the data set itself …

Authors reply: Partially repeating a previous response: This is a statistical analysis, which makes no claims about the safety level of new technologies. It is only based on observed technologies. Next, we found that the rate of events has roughly stabilized. We then use this current rate to "predict". However we state this prediction is totally conditional on assuming that the future fleet is the same as the current one. There is nothing wrong with providing this status quo scenario prediction. Other scenarios may be considered in future works. On the other hand, the status quo scenario may be quite useful: Generation II is certainly not a model T given that the majority of the current fleet is Generation II and this is expected to be the case for many years. Further, the claim that GEN III+ is 100 times safer is based on PSA – not experience. It is well known that PSA has consistently underestimated risk of consequences [1]. Further the frequency and severity of accidents were modeled as functions of time, accommodating improvements in nuclear technology, and significant changes identified and discussed.

Sovacool et al. would not only have us believe nuclear technology would stand still but also have us believe in the existence of Dragon King events, runaway nuclear disasters whose damage is so great they belong to their own regime. They make it quite clear that their maximum costly event, Fukushima at 166 billion dollars, would be nothing in comparison to future accidents, and in the end they quote average damage costs that could be over 20.5 billion dollars a year to pay for such accidents. This is somewhat scary stuff and would make you think twice before replacing a fossil fuel energy driven economy with one driven by nuclear power.

Authors reply: Given that there are many plants in highly developed and populated areas, one cannot exclude the possibility of a damage/loss event in excess of Fukushima. The probability is quite small, but across a large fleet of reactors it is a real threat.

Wait! What's this? TMI has a NAMS score almost equal to Chernobyl? That's right. ….

Authors reply: The value of 7.9 for TMI was taken from the paper of the originator of the scale, available at (http://www.davidsmythe.org/nuclear/accidents.htm). Next, removing TMI from the data altogether has little effect. The remaining NAMS outliers are still outlying, and TMI was never a damage/loss outlier and thus has no effect there.

A plot for the probability to have a higher value than the point in question. The lowest value would have a probability of 1, the highest zero. These are the points from the database for the INES above 2, shifted to the left by 1, the NAMS scores above 2, and the natural logarithm of all damage after 1980 exceeding a value of 27 million dollars in units of millions of dollars shifted right by 2. The dots with the black X's are the Dragon King events. The red lines and dots with the red X's are my corrected values. From fig. 5 of the paper

Thus with errors like this, what is the evidence for the authors' Dragon King events?

Authors reply: To be clear, the red X's are different damage values provided by Dr. Walden. We are not sure where they came from. As we mentioned before, removing TMI from the dataset does not have a large qualitative impact (nor quantitative on the significance of the remaining outliers).

However the authors pin their real hopes on the damage caused by the Dragon King events.

Authors reply: This is false. We opt to include a DK regime in the extreme tail as a feature of the risk model. It is an important feature, but is defensible. The DK regime is justified based on the available data. Further, even without the DK regime, the risk is still very high. Further, we use a conservative estimate of the frequency of events – made even more conservative due to the fact that our dataset is probably incomplete. Thus our model is not out of order, and the main point of the paper – that the risk is high, and certainly higher than advertised – remains intact.

In the new revised version now available on the arXiv, we have included multiple estimates for return periods based on both optimistic and conservative parameter estimates. This can be seen in the new Table 4, and is discussed in Sec. 6.1. This exposition is useful to show that the inclusion of the DK regime (conservative in severity) does not inordinately amplify the risk. It also addresses the important criticism that the uncertainty of the return periods had not been provided. We have modified the abstract of our paper as follows: "In terms of dollar losses, providing conservative and optimistic estimates together, under current conditions there is a 50% chance that (i) a Fukushima event (or larger) occurs in the next 60-150 years, (ii) a Chernobyl event (or larger) occurs in the next 30-60 years and (iii) a TMI event (or larger) occurs in the next 10-20 years."

Plotted to the right of NAMS are the natural logarithm of the damages of accidents since 1980. And again, the Dragon King events pop up as the crossed black dots to the right of the dashed extrapolation line. Except now they are different! We have lost Kyshtym and TMI. They happened before 1980, and besides they were not expensive enough anyway. To shore up the Dragon King event numbers comes Tsuruga, an event that nobody has ever heard of, but is expensive enough to qualify. So now we have, in order of cost, Tsuruga, Chernobyl, and the largest, Fukushima.[19] Yes Fukushima in this analysis is the largest most catastrophic nuclear accident because it will cost more even though it emitted 5 times less radiation than Chernobyl. Does this make sense? This is a measure that an economist would choose, not a scientist. To say Fukushima was the worst nuclear accident of all time based on how much it is projected to cost is ludicrous. Chernobyl by all accounts emitted 5 times the radiation of Fukushima and killed 50 people whereas Fukushima killed no one. By radiation alone Chernobyl was more deadly to the environment and those 50 deaths, which Sovacool et al. argued were only worth 6 million dollars a shot, only totalled 300 million dollars, a mere drop in the bucket compared to the author’s statement that Fukushima will cost 166 billion dollars.[20] That is a measure not very respectful of human life or the environment.

Authors reply: The shortage of NAMS data limits its analysis and its comparison with financial damage. However, large radiation releases do not need to correspond to large financial damage, and vise versa. Clearly there are cases when this is true, and others when it is not true. Next, the value of 6 MM per human life is on the order of magnitude of the statistical value of life used in many studies. Dr. Walden claims that using $-cost is not scientific and that 6M$ per life is not respectful to life and the environment. This is the typical narrow engineering view point, which misses the need to encompass the holistic nature of the costs in all their dimensions. This is only possible by developing a common metric, the $-costs, a standard approach to develop evidence-based policies. Cost is a valid measure because it is cost and value that control all decisions that impact the life (and health and death) of billions of people. Further, we would encourage Dr. Walden to reconsider how damaging – as measured in dollars – the Fukushima accident has been. Such losses have broad impacts that harm many people. Loss of life is only a binary measure of damage to life quality.

Let's examine this 166 billion dollar cost figure. How robust is it? The official cost is pegged at 55 billion dollars, but a recent report has doubled that cost to 105 billion dollars.[21] This is a report from RT (Russia Today) news which is claimed to be a propaganda wing of the Russian government.[22] Thus this report is not exactly considered to be a source of impartial information, and the $105 billion figure could be viewed as an inflated figure. Even if the cost of plant decontamination is added, which the report said had not been added to the costs, we get to only 140 to 153 billion dollars. Sovacool et al.'s estimate at 166 billion dollars is still beyond that. Thus the $166 billion cost Sovacool et al. place on Fukushima appears to be an exaggerated outlier. They do not say how they got their figure or any other figures in their data base. Indeed they do not even make their database available for examination. Thus the cost of the Fukushima accident is not robust but wildly varying,[23] and as such it is a poor measure of the severity of the accident. All these cost estimates make the cost of the Fukushima accident a rather murky affair including the authors' exaggerated figure of $166 billion, and the most reasonable course to consider, under these circumstances, is the official cost, $55 billion.

Authors reply: Here is where you should have simply emailed us to ask, instead of deducing (wrongly) that our source was Russia Today. The estimate is partially our own since we adjusted it for inflation and also monetized loss of life, mainly the 573 deaths from the evacuation of Fukushima. When you de-adjust for inflation and deduct those numbers, the damage amount drops to about $150 billion. That range was widely reported by both the local and international media including Yomiuri Shimbun, Asahi Daily, Reuters, Al Jazeera, and Grist, with references to official government projections. See here for a *few (of many) stories:*

http://in.reuters.com/article/2011/07/16/idINIndia-58291120110716.

A draft of Japan's post-quake reconstruction plan expects the recovery effort to cost up to $152 billion over five years, but does not address tax rises seen as necessary to pay for the project

http://grist.org/list/2011-04-18-what-if-the-152-billion-to-clean-up-fukushima-were-spent-on-geot/

The projected cost for the management of the Fukushima crisis is $152 billion.

http://www.reuters.com/article/2013/10/25/us-fukushima-workers-specialreport-idUSBRE99O04320131025

Hayashi's hard times are not unusual in the estimated $150-billion effort to dismantle the Fukushima reactors and clean up the neighboring areas, a Reuters examination found.

http://america.aljazeera.com/watch/shows/america-tonight/america-tonight-blog/2014/1/7/fukushima-cleanupworkerssubcontractors.html

There's plenty of money to be made in the estimated $150-billion cleanup effort

Moreover, this ~$150 billion estimate is not an outlier. The Telegraph reported that the crisis resulted in $1 trillion in economic losses if you include impacts to financial markets and some blogs (which we could not confirm as accurate) quote $500 billion to $1 to $10 trillion in losses:

https://randrewohge.wordpress.com/2015/08/01/fukushima-no-its-not-over-not-by-a-long-shot-just-follow-the-money-video/
http://agreenroad.blogspot.dk/2012/06/fukushima-crisis-total-cost-up-to-10.html

Let us examine the other Dragon King events. For Chernobyl, the authors quote $32 billion while other sources quote less,[24] $15 billion. For the unknown Dragon King event, Tsuruga, this turns out to be an extended construction SNAFU rather than an accident. This is about startup problems with the Monju nuclear power plant[25] within the Tsuruga complex. It is a sodium cooled reactor which started up in 1994 and had major fire damage from a sodium leak in 1995. It was closed until it started up again in 2010. It shut down a month or two later when a transfer machine was dropped onto the reactor vessel. Its future status is unknown, but it is presently shutdown. The reactor has cost to date (2014) 9.8 billion dollars including the accidents. Sovacool et al. list 15.5 billion. The authors report "an unknown radiation release value" for this event. But we can do better than that. There has been no radiation release or very little radiation release. Can this be called a Dragon King event? I mean being as there has been effectively zero radiation release, it hardly qualifies as a nuclear accident. That is why you never heard about it.

Authors reply: Tsuruga was not an explosion that cost human life. However it was highly expensive, and this is important.

Thus we have the Fukushima cost reduced from $166 billion to $55 billion, Chernobyl reduced from $32 billion to $15 billion, and Tsuruga reduced from $15.5 billion to $9.8 billion. Do you notice a pattern here? The authors' costs seem to have been estimated on the high side. If these costs are plotted in the figure (they are as the red dots and crosses on the natural logarithm plot of the damage) the Dragon King regime disappears just as it did for the NAMS plot. The statistical evidence for a Dragon King regime occurring at "a threshold[26] above which runaway disasters occur" seems spurious at best.

Authors reply: It appears that the values above are those used by Dr. Walden in modifying the figures.

Thus the "Dragon King" regime appears to have an artificially manufactured element about them. Juggling different events between the NAMS and the natural logarithm of damage scales, NAMS typos, and over estimates of damage costs make the existence of this regime somewhat dubious. Nevertheless scaling back the costs and doing away with the Dragon King regime will do nothing to change the authors' calculation for the probability of future events. All it will do is to lower those scary estimates of average annual future damage costs. Their estimates for the probabilities of future TMI's, Chernobyl's, and Fukushima's will remain the same, and even with lower estimated annual damage costs, nobody wants to see a future TMI, Chernobyl, or Fukushima. However there is a problem with their probabilities. They appear to have been somewhat manufactured as well.

A plot of accident rate per power plant per year, \widehat{\lambda_t}. It is claimed that there is a sudden change in this parameter in and around 1980, but that is difficult to see if you concentrate on the data points (the black dots with the vertical error bars) and ignore the coloured bands (fits) guiding the eye. Indeed in the previous figure of \widehat{\lambda_t}(above), it is difficult to discern such a break. From fig. 3 of the paper

Authors reply: This change-point can be made abundantly clear by estimating the rate of events running backwards in time from 1979, and forwards in time from 1980. If one does this one finds a drop from a level of 0.11 to 0.04, which remains relatively stable until the most current point of the data (2014). A figure illustrating this will be provided in a future publication.

The problem is with their empirical CCDF's. Due to the way they are defined (see a preceding footnote) their resolution is limited to 1/(number in event sample). For the natural logarithm of the damage scale, the event sample was 59 making the resolution around 1.7%. Thus because Fukushima was in that event sample, we ended up with a probability of 1.5% of having a Fukushima type accident for any given nuclear accident, which for the present world nuclear plant inventory averages to about 0.9 per year. Hence we end up with a 50:50 chance of another Fukushima in the next 50 years. No error was attached to this probability. Why was there only an event sample of 59? The authors' database had 174 events in it. Well, the authors made cuts. Events that had damages less than $20 million were said to be underrepresented, and were thus eliminated from consideration. Events which occurred before 1980 were said to obey a different probability distribution and thus were also eliminated. Hence we ended up with a sample of 59. While this change of probability distribution after 1980 may have some justification,[27] it is nevertheless somewhat statistically anemic.

Authors reply: This change-point in the damage/loss distribution occurring at the TMI event is highly significant, and also the only identifiable change-point in the dataset. The figure (Fig. 4 in the version of the manuscript reviewed by Dr. Walden) shows this. However this figure has not been included in this review.

Looking at the figure to the left, if the coloured bands were removed, the break would hard to see just as it is hard to see in the previous \widehat{\lambda_t} plot above.

Authors reply: Fig. 3 could have been clearer on this point and will be improved in future publication.

A log-log plot of the empirical CCDF vs. damage. 1-F=CCDF. The accident labels and red arrows are my addition. "?" indicates a point which does not appear to be in table 1 of the paper (the list of the top 15 most costly nuclear accidents). The figure is from the paper's fig. 7. Both the dashed and solid fits go through the Fukushima point according to the other part of the figure in the paper.

Authors reply: This plot has simply been removed since we instead opted to model severity for the post-TMI period separately from the pre-TMI period.

Doing an empirical CCDF distribution for both the pre-1980 and post-1980 sample of 100 events[28] combined together as it is done in appendix 1, the distribution appears to be continuous without any breaks [29] (see figure to the right), and the higher cost nuclear accident events appear to be on the same trajectory as the lower cost events over $800 million. No Dragon King regime is evident which makes the Dragon King regime of the 59 event plot above look like an artifact.

Authors reply: Here the data is combined which completely distorts the structure of the tail and thus does not allow for sound outlier detection. This plot should not be interpreted and is excluded from current versions of the publication.

Note that here the higher cost arm bends down to a faster fall off than it does in the 59 event plot in which it bends up to a slower fall off and the so-called Dragon King regime. With the higher probability resolution of the 100 event sample, which is 1/100 = 1%, the distribution now suggests that for every nuclear accident, the probability that it will be a Fukushima type accident or larger is now only 0.23%. That would mean that the 50:50 chance of another Fukushima accident or greater would occur would be extended to the next 342 years, which is almost a magnitude larger than the previous result of 50 years. This result cannot be ruled out with the statistics in the given data set. By the reasoning given by the authors, if I could rationally cherry pick the appropriate event sample size down to just 2 events, and one of them was Fukushima, then for every nuclear accident, the probability for a Fukushima type accident or larger would be ≈1/2=50%. This of course is ridiculous.

Authors reply: This criticism is ridiculous. The probability would be 50% GIVEN that the event was in excess of the 3rd largest event (and assuming a histogram estimator of the distribution). The probability of being in excess of the 3rd largest event is VERY low. Dr. Walden does not understand that, as we increase the lower truncation threshold, our estimate of the rate of events decreases. The rate of events in excess of the 3rd largest event would be extremely low. Thus, introducing a lower truncation threshold REDUCES the calculated risk! Further, statistically speaking there is a major difference between using only the 2 largest events and using >50 events.

Hence any such predictions of high cost nuclear accidents using this data set will be associated with large errors. The authors even stated as such "However, there is tremendous estimation uncertainty associated with these estimations." Thus the prediction of another Fukushima or worse will happen in 50 years before 2064 is 50:50 is just as likely to be 50:50 all the way up to the year 2356. In other words this analysis gives a prediction, but what that means to any degree of accuracy is anybody's guess. As such the prediction is not very useful, and as I stated previously, "it is important that when any learned study portends to make such predictions that it be properly vetted because poorly done studies benefiting from the notoriety of the subject are of no use use to anyone". The predictions of the probability of future nuclear accidents stated in this paper are of no use to anyone.

Authors reply: Indeed it is essential to provide a standard error. This is now provided in the updated manuscript, as presented above.

There was a remark in the review article to the effect that "their database is carefully researched and their statistical pedigree hard to match". The anti-nuclear crowd lionize credentialed academics who produce results that favour their view of shutting down nuclear power, justified or not, and it is no different with Sovacool et al. …

Authors reply: Dr. Walden will probably be surprised to learn that we are not simply "anti-nuclear", on the contrary as can be surmised from the call for a civil super-Apollo project to rejuvenate nuclear research and nuclear energy [4] by one of us, and published in the journal ERSS whose senior editor, the very Prof. Sovacool Dr. Walden criticizes, has been supportive of this piece. Our diagnostic is that the nuclear energy industry and its regulators have done a significant disservice to their development and to society in general by developing a culture of secrecy, with claims of safety levels that are blatantly in apparent contradiction with facts, at least in the eyes of the public. We believe that this is one of the main factors contributing to the distrust of the public. We propose that more transparent and honest reports of the real risks (as well as the benefits)of the processes that are put in place for improvement and of the merits of different metrics of reporting will help revive this industry, based on one of the most fantastic gifts of Nature.

As for the other attacks on Sovacool for greenhouse gas emissions and LCOE, Dr. Walden should reread those articles closely and consider methodological assumptions of all sources. (He should also keep on target – his critique is supposed to be about this article, not the others).

For the record, the sample of greenhouse gas footprint studies evaluated in [5] did include van Leeuwen data but this was counterbalanced with very, very low estimates that were also included [6-9]. Follow-up, peer-reviewed studies have also confirmed the legitimacy of Sovacool's original estimations. One found, looking not at the global mean but performance according to distinct clusters, that the best performing reactors had associated lifecycle emissions of 8 to 58 gCO_2/kWh but that other reactors emitted more than 110 gCO2/kWh [10]. Another study from Yale University harmonized global lifecycle data (something neither of the first two studies did) from 99 independent studies of light water reactors. It found that, depending on the type of plant and methodology utilized, median life cycle greenhouse gas emissions could be 9 to 110 g CO2-eq/kWh by 2050 (or a mean of 59.5, very close to the 66 number [11] presented in Sovacool). These additional studies were both peer-reviewed and written by impartial academics.

Also, the greenhouse gas emissions numbers from the IPCC report were low for nuclear power because they excluded land use change (across the entire fuel cycle, from uranium mines and mills to construction and decommissioning) and focused almost entirely on reactors in North America and Europe. The claim about uranium ore and higher emissions rates in the future did not come from Sovacool but these two sources, one of them peer-reviewed [12-13].

For the LCOE figure, it is so high because it took into account construction, operation and fuel, reprocessing, waste storage, and decommissioning. The EIA, Lazard, etc. do not, and thus their LCOE numbers are much lower.

Finally, and critically: Sovacool is not the only author of the article, and the statistical credentials of his coauthors are strong and their perspectives on nuclear technology unbiased.

So what have we learned from this current paper of Sovacool et al? There is this database which is not accessible, but which we know is not trustworthy. We know that because the radiation release that the database reportedly claimed that came from TMI was overstated by a factor of 64,000. This error remained undetected by the authors and was even discussed in the text as being true. Also the cost of nuclear accidents, which the authors claimed to be a good measure of the severity of the accident, was shown not to be robust as the cost of the Fukushima accident was shown to be all over the map, and the value chosen by Sovacool et al., 166 billion, was an exaggerated outlier. In fact all of the high cost "Dragon King" events were costed on the high side. Furthermore the cost of the accident was not correlated to the severity of the accident as Fukushima was tagged as the most severe accident in terms of cost, but in terms of radiation release, which is the real physical parameter by which to measure the impact of a nuclear accident on the environment, Fukushima emitted only a fifth of the radiation that Chernobyl emitted. Thus the database appears to be flawed. In terms of predicting the time span in which we could expect the next major nuclear accident, the paper cannot do this with any reasonable accuracy. The next Fukushima could have a 50:50 chance to occur in the next 50 years, in the next 342 years, or anywhere in between, take your pick. Thus the paper would appear not to be very useful. However maybe something could be made of the probability of a nuclear accident per year per nuclear plant. That number just depends on the number of incidents, the year, and the number of reactors, which are statistics that are difficult to get wrong.

Authors reply: The database is available (https://tasmania.ethz.ch/index.php/Nuclear_events_database) and we intend to improve the data over time. This is clearly an important task that we are committed to, and that nobody else has done. Here is the call to our students to be part of this exciting project put on the website of our group http://www.er.ethz.ch/about-us/open-positions/internships.html. Some of us are looking for a motivated student to participate in this well-defined and important project. This would preferably be a master thesis project, but could also be carried out as a research assistantship. Quite surprisingly official data about the severity/consequences of historical nuclear power accidents is not published by the industry, who wants to conceal risk. Studies based on an incomplete record of past events illustrate a level of risk which is certainly much higher than the industry claims [2,3,14-16]. To dramatically improve the quality of the study of this risk we must expand and re-enforce our novel and highly important database of accidents occurring at nuclear power plants. This requires the curation of data about past accidents, and the development of methodology for computing the total economic cost of accidents. For instance, for a single event there may be many estimates of cost with different scope and sources. These estimates must be reconciled and decomposed into relevant categories (e.g., property damage, fatalities, lost revenue, etc.) such that estimates are comparable across events. After the data is prepared, a statistical study of the risk will be completed. This project has received broad interest and media coverage (e.g., [17]) and has the potential to make an important statement about the risk of nuclear power.

Let us assume then, as stated by Sovacool et al., that the probability for another Fukushima[36] is 50:50 in the next 50 years is correct. We will take this as the worst possible case. Now let us consider the the impact of improved technology, something which Sovacool et al. failed to consider. As stated above the current technology is producing GEN III+ reactors which are a factor of 100 less accident prone than the current GEN II reactors which make up the bulk of the current nuclear reactor fleet. If all the current reactor fleet were replaced with GEN III+ reactors, the probability of a reactor accident per year per nuclear plant would shrink by a factor of 100. Therefore all else remaining the same, like the probability of a Fukushima-like accident or greater for any given a reactor event, the probability for another Fukushima or greater would be a 50:50 chance in the next 50×100 = 5000 years. Five thousand years encompasses the entire time span of recorded history from the ancient Sumerians of the Fertile

Crescent to Greece, Rome, the Middles Ages and onto the present. In practical terms that means forever. However just replacing the present nuclear fleet with with GEN III+ reactors will not be all that progressive. It will make us all feel safer about nuclear power, like hitting a fly with a sledgehammer, but it does nothing to alleviate the crises facing mankind and our planet. We are facing a possible 6th global mass extinction event due to global warming, and here we have an energy technology which does not emit green house gases (GHG), which turns out to be extremely safe, and it is not being used to end our dependence on fossil fuel energy. Why?

Authors reply: It is counterfactual to state that "We are facing a possible 6th global mass extinction event due to global warming"; yes, there is mounting evidence that we are in the "Anthropocene" with massive control and change of the Planet by the human species with a 6th global biological extinction in the making, but global warming (or better "climate change") is not the major driver, as documented in many investigations (e.g., [18]). Humankind is now controlling over 60% of the total Earth surface and this is accelerating. There are many Nature *and* Science *publications on this. Climate change is just one, but not the most important driver of the systemic risks that we are facing.*

References for Response

[1] Kroger, W. and Sornette, D. Reflections on Limitations of Current PSA Methodology, ANS PSA 2013 International Topical Meeting on Probabilistic Safety Assessment and Analysis, Columbia, South Carolina, USA, September 22-26, 2013, on CD-ROM, American Nuclear Society, LaGrange Park, IL (2013), invited article for the Probabilistic Safety Analysis 2013 (PSA2013) (accepted 5 July 2013)

[2] Hofert, M. & Wuthrich, M.V (2013) Statistical Review of Nuclear Power Accidents. Asia-Pacific Journal of Risk and Insurance, 7(1):1–18

[3] Sornette, D., Maillart, T. \& Kroger, W. (2013) Exploring the limits of safety analysis in complex technological systems. International Journal of Disaster Risk Reduction, 6:59–66

[4] Sornette, D. "A civil super-Apollo project in nuclear research for a safer and prosperous world." Energy Research & Social Science 8 (2015): 60-65.

[5] Sovacool, BK. "Valuing the Greenhouse Gas Emissions from Nuclear Power: A Critical Survey," Energy Policy 36 (8) (August, 2008), pp. 2940-2953.

[6] Dones, Roberto, Christian Bauer, and Thomas Heck. 2003. LCA of Current Coal, Gas, and Nuclear Electricity Systems and Electricity Mix in the USA (Switzerland: Paul Scherrer Institute).

[7] Dones, R., X. Zhou, C. Tian. 2004. "Lifecycle Assessment of Chinese Energy Chains for Shandong Electricity Scenarios." International Journal of Global Energy Issues 22(2/3) (December), pp. 199-224.

[8] Dones, R., Thomas Heck, Mireille Faist Emmenegger, and Niels Jungbluth. 2005. "Lifecycle Inventories for the Nuclear and Natural Gas Energy Systems, and Examples of Uncertainty Analysis," International Journal of Lifecycle Assessment 10(1), pp. 10-23.

[9] ExternE. 1998. Power Generation and the Environment - a UK Perspective". ExternE-UK AEAT 3776. Volume 1, June 1998, http://externe.jrc.es/uk.pdf.

[10] Jef Beerten, Erik Laes, Gaston Meskens, William D'haeseleer, "Greenhouse gas emissions in the nuclear life cycle: A balanced appraisal," Energy Policy 37(12) (December, 2009), pp. 5056-5068.

[11] Ethan S. Warner and Garvin A. Heath, "Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation," Journal of Industrial Ecology, Volume 16, Number S1, S73-S92.

[12] Gavin M. Mudd & Mark Disendorf, Sustainability of Uranium Mining and Milling: Toward Quantifying Resources and Eco-Efficiency, 42 ENVTL. SCI. & TECH. 2624, 2626, 2629 (2008).

[13] Barnaby, Frank and James Kemp. 2007. Too Hot to Handle? The Future of Civil Nuclear Power (Oxford: Oxford Research Group, July, 2007).

[14] Smythe, D. (2011) An objective nuclear accident magnitude scale for quantification of severe and catastrophic events." Physics Today: Points of View.

[15] Escobar Rangel, L. & Leveque, F. (2014) How Fukushima Dai-ichi core meltdown changed the probability of nuclear accidents? Safety Science 64 90-98, 2014.

[16] Ha-Duong, M. & Journe, V. (2014) Calculating nuclear accident probabilities from empirical frequencies. Environment Systems and Decisions 34.2, 2014

[17] http://www.technologyreview.com/view/536886/the-chances-of-another-chernobyl-before-2050-50-say-safety-specialists/

[18] Barnosky, A.D. et al., Approaching a state shift in Earth's biosphere, Nature 486, 52-58 (2012)