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Review

Limitations of Nuclear Power as a Sustainable Energy Source

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Abstract: This paper provides a review and analysis of the challenges that nuclear power must overcome in order to be considered sustainable. The results make it clear that not only do innovative technical solutions need to be generated for the fundamental inherent environmental burdens of nuclear energy technology, but the nuclear industry must also address difficult issues of equity both in the present and for future generations. The results show that if the concept of *just sustainability* is applied to the nuclear energy sector a global large-scale *sustainable nuclear energy system* to replace fossil fuel combustion requires the following: (i) a radical improvement in greenhouse gas emissions intensity by improved technology and efficiency through the entire life cycle to prevent energy cannibalism during rapid growth; (ii) the elimination of nuclear insecurity to reduce the risks associated with nuclear power so that the free market can indemnify it without substantial public nuclear energy insurance subsidies; (iii) the elimination of radioactive waste at the end of life and minimization of environmental impact during mining and operations; and (iv) the nuclear industry must regain public trust or face obsolescence as a swarm of renewable energy technologies quickly improve both technical and economic performance.

Keywords: nuclear energy; nuclear power; life cycle analysis; green wash; sustainability; nuclear insecurity; future

1. Introduction

Global energy demand continues to climb [1] as the industrialized world's energy use rises, millions pull themselves out of poverty in developing countries, and the world population expands. Thus, the

debate over the energy supply of the future intensifies [2–7]. This debate is complicated by ongoing global climate destabilization as a result of green house gas (GHG) emissions produced largely from combustion of fossil fuels (coal, oil, and natural gas) for energy [8–11]. These scientific findings and economic threats have catalyzed commitments by many industrialized countries to curb GHG emissions, which in turn have created an enormous need for large-scale sources of energy alternatives to the polluting and potentially dwindling economic supplies of fossil fuels [5]. Nuclear technology is often proposed as a solution or as part of the solution for a sustainable energy supply [2,5,7]. In fact, the Intergovernmental Panel on Climate Change (IPCC) recommended nuclear power as a key mitigation technology that is currently commercially available [11]. The term sustainability, however, has numerous meanings that range from the *light (pale) green* definitions that normally refer to near-term financial sustainability to *dark green* long-term multi-faceted descriptions of sustainability [12]. Here the concept of *just sustainability*, which includes what has been called the *equity deficit* of environmental sustainability [13], will be used as if these requirements are met so will those of the other weaker definitions. Just sustainability generates a more nuanced definition of sustainable development as it is the need to ensure a better quality of life for all, now and into the future, in a just and equitable manner, whilst living within the limits of supporting ecosystems [13]. This conception of sustainable development focuses equally on four conditions: (i) improving our quality of life and well-being; (ii) on meeting the needs of both present and future generations (intra- and intergenerational equity); (iii) on justice and equity in terms of recognition [14], process, procedure and outcome; and (iv) on the need for us to live within ecosystem limits [13]. In this paper, nuclear power, as it is practiced within the U.S. considering only technologies that have been reduced to practice, is analyzed by just sustainability criteria. The barriers, which must be overcome for nuclear power to be included in the collection of sustainable energy sources is reviewed including: (i) the nuclear energy life cycle, GHG emissions and energy cannibalism; (ii) present and future externalities; and (iii) economic sustainability and insurability. These challenges are discussed and conclusions are drawn about the requirements for a just sustainable nuclear energy source in the future.

2. Barriers to Nuclear Sustainability

2.1. Nuclear Energy Life Cycle GHG Emissions and Energy Cannibalism

Common in the popular press, but even in peer reviewed literature is the repeated misperception that because nuclear energy does not produce carbon dioxide (CO₂) as a byproduct during electricity generation as do fossil fuels, it is an “emission free” source of energy and often is shown in tables comparing energy sources as “0 emissions” [15–17]. The Nuclear Energy Institute reports that there are 104 nuclear reactors in the U.S. that provide electricity “while emitting no carbon dioxide” [18]. Even the U.S. Department of Energy when issuing millions of dollars in grants hoped to contribute to “assuring a new generation of engineers and scientists necessary for pursuing nuclear power—a safe, reliable, affordable and *emissions-free* source of energy” [19]. In addition, the urgent need to prevent GHG emissions has moved many energy experts to reconsider the use of nuclear energy specifically to slow climate destabilization [20–24]. This misrepresentation is repeated continually in the policy spectrum. For example, the U.S. National Energy Policy Development Group

stated, “Nuclear power today accounts for 20 percent of our country’s electricity. This power source, *which causes no greenhouse gas emissions*, can play an expanding part in our energy future” [22]. In addition, many famous environmentalists have argued for aggressive expansion of nuclear power to stave off climate change such as James Lovelock, the father of the *Gaia theory*, Stewart Brand, the founder of the *Whole Earth Catalog*, the late British Bishop Hugh Montefiore, founder and director of Friends of the Earth, and Greenpeace founder, Patrick Moore [25]. Moore recently argued that “Nuclear energy is the only large-scale, cost-effective energy source that can reduce these (greenhouse gas) emissions while continuing to satisfy a growing demand for power” [25]. Unfortunately, however, these views are naïve, when viewed over the nuclear fuel life cycle; every kilowatt-hour of nuclear energy is responsible for CO₂ emissions; the amount depends on the location and a number of technical factors. Nuclear power is simply not greenhouse gas emissions free. For example, depending on the source and quality of the ore, milling, mining and transporting of uranium, some studies have shown nuclear plants can even emit about the same amount of CO₂ per unit of electricity as a natural gas power plant [26]. GHG emissions from nuclear power are normally much lower than fossil fuel plants as discussed below, however, life cycle nuclear GHG emissions can be substantial.

It should be pointed out here that there is serious disagreement between different studies in the literature as to the actual mass of CO₂ equivalent GHG emissions per unit energy (g CO₂ eq./kW-hr) found for the nuclear fuel cycle and the reader must take extreme care when comparing studies with each other and with those carried out on fossil fuels. Differences found in the studies for CO₂ eq./kW-hr of nuclear power are in part due to different energy efficiencies of enrichment techniques, different energy mixes of the geographical regions/countries being studied, and different methodologies. Many studies, normally sponsored by the nuclear industry itself, used process-based (PB) analyses, which do not fully capture the real impact of GHG emissions. For example, instrumentation and control related energy is not included in any of the PB or materials-based analyses [27]. Not surprisingly, such studies, found extremely low values for the nuclear fuel cycle such as 3.48 g CO₂ eq./kW-hr [28]. A more complete method of calculating the emissions of any energy producing technology is economic input/output (EIO) analysis. EIO analysis can capture emissions associated with, for example, incremental energy required for the fabrication of complicated high-specification non-mass manufactured components, which is ignored by the more restricted methods. Although it is more complete, EIO can, however, capture embodied energy outside of the system being studied, which makes accurate energy accounting challenging. Hondo used a mixture of EIO analysis and PB analysis to find 24.2 g-CO₂/kW-hr for the nuclear cycle, which compares quite favorably to fossil fuel sources: coal—975.2, oil—742.1, LNG-fired—607.6, and LNGCC—518.8 [29]. However, as discussed below, this non-zero level of emissions associated with nuclear power provides a need to investigate the potential of nuclear energy cannibalism if nuclear power grows rapidly this century to replace fossil fuels.

A review of the life cycle analysis (LCA) of nuclear energy found the total lifetime GHG emissions nuclear-fuel cycles in the U.S. were determined to be between 16–55 g CO₂-eq./kWh [27]. This work was based in the U.S., which thus did not include reprocessing that does not occur in the U.S., but included additional stages that earlier work [30] omitted such as spent-fuel disposal and the deconversion of depleted uranium. The lower value is primarily derived from the PB studies, while the higher number utilized primarily EIO based analysis. The average life-cycle GHG emission factor of

the U.S. electric mix (which includes coal, natural gas, hydroelectric, nuclear, and some non-hydro renewable energy sources such as wind and solar) is about 695 g CO₂-eq./kW-hr [31]. Thus, in the more thorough LCA case, U.S. nuclear energy only provides about a factor of 12 fewer emissions than the status quo. It should be noted that in the status quo nuclear power currently provides about 20% of the U.S. electrical supply [18].

Emissions from fossil fuels not only need to be eliminated, but they must be eliminated quickly not only to reduce the most dangerous risks from climate destabilization, but also to maintain civilization's relatively energy-intensive standard of living in light of recent work on the long term production of fossil fuels. Nuclear power is primarily seen as an alternative to base-load coal power plants. Thus, it is instructive to look at long term coal production scenarios to obtain a sense of time scale for instituting such alternatives. A recent Caltech study found that 90% of the total world-wide coal production will have taken place by 2070 [32], which is somewhat less than the current reserves plus cumulative production, 1163 Gt [33], and significantly less than the IPCC assumptions from the maximum cumulative coal production through 2100, which is 3500 Gt [34]. The analysis below looks at a more comprehensive replacement of fossil fuels for energy.

Thus *nuclear energy cannibalism* is a serious concern as rapid growth is necessary. In order for a nuclear power plant to have a net negative impact on GHG emissions of the energy supply, first it must produce enough emission-less (during production) electricity to offset the emissions that it is responsible for throughout the full life cycle, and then it must continue to produce electricity to offset emissions from existing or potential fossil fuel plants. This can become challenging in view of rapid growth as the construction of additional nuclear power plants to enable the rapid growth rate, create emissions that cannibalize the GHG mitigation potential of all the nuclear power plants viewed as a group. To both replace fossil fuel energy use and meet the future energy demands nuclear energy production would have to increase by 10.5% per year from 2010 to 2050 [35]. This large growth rate creates a cannibalistic effect, where new nuclear energy must be used to supply the energy for future nuclear power plants rather than mitigating GHG emissions [36]. Previous work has shown that an energy payback time within the estimated range and the needed growth rate of non-fossil fuel energy, could limit the ore grade to 0.1% or higher to simply break even for GHG emissions [35]. In addition, the nuclear energy cannibalism study [35] made the assumption that the supply of uranium along with all the other necessary elements would not be a limiting factor. This assumption, which benefits scaling of the nuclear industry, is suspect, given the limitations of the uranium supply and the relative extinction times of several metals necessary for nuclear reactors [37]. This effectively hamstring the ability of nuclear power technology (as practiced currently in the U.S.) to provide a solution to fossil-fuel induced climate change on a global scale.

2.2. Nuclear Energy Externalities

Economists discuss the concept of a negative externality as a cost not transmitted through prices that is incurred by a party who did not agree to the action causing the cost. Nuclear power has a long list of externalities associated with it including: environmental externalities and externalities imposed on future generations. It is beyond the scope of this paper to go into each in detail, however, some of

the fundamental externality challenges to using nuclear energy for widespread electric generation are introduced below.

First, with current commercialized technologies, nuclear power is dependent on the mining of a finite (although sometimes hotly debated quantity/quality) of uranium rich ore. Uranium ore is mined both in surface (strip) mines and deep underground. Much like the mining and processing of other materials, uranium mining, processing and enrichment can leave substantial damage to the nearby ecosystems and waterways [26,38,39]. Similar to the start of the life cycle, during operation there are also negative environmental externalities. Nuclear power plants are almost always built near lakes, rivers and oceans because running a nuclear reactor requires a large amount of cooling water to cool down the equipment and absorb excess heat waste. A typical 1 GW nuclear power reactor needs approximately 476,500 gallons per minute for cooling and this warmer water is then discharged back into the local ecosystem causing many adverse effects for the aquatic life because of the thermal pollution [39].

A larger and more serious externality during operation is *nuclear insecurity*. No matter how small the probability, safety concerns with nuclear power plants pose a real and finite danger. Most visceral in the public mind are the near misses or total disasters at nuclear power plants of: (1) Three Mile Island, (2) Chernobyl (Figure 1a and 1b [40]), and (3) Fukushima Daiichi. It should be pointed out that these three examples in no way are meant to constitute a comprehensive list of nuclear accidents, simply those most likely to be remembered by the public. The real fear these disasters represent must be overcome to establish social sustainability and local public support of nuclear power. For the nuclear power industry, as is normally the case for any industry that provides employment, an increase in public acceptance is likely with increases in local jobs. However, the necessary increased density of nuclear reactors necessary to play a substantial role in eliminating fossil fuel use demands more nuclear power plants in or near population centers, which is likely to aggravate local resistance due in a large part to fear of a disaster. The importance of social sustainability for nuclear power is thus clear. The potential for a nuclear disaster imposes risk related costs to essentially everyone in the world—both currently living and those in the future (see Figure 1b of the CBC map of Chernobyl's radiation fallout [40] as an example of the geographic magnitude). The nuclear industry has learned from each disaster (or near miss) thus reducing the potential for future incidents. However, an aging worldwide reactor fleet might be expected to become less reliable as time goes on and a recent review of the accident record [6] questions the accepted assumption that new designs are less risky. However, these risks of very large-scale problems can not be eliminated entirely, as was made very clear by the recent case involving coupled-challenges such as those provided by natural disasters of the tsunamis and earthquake, which resulted in the Fukushima Daiichi power plant meltdown. In this particular case, humanity was somewhat fortunate when compared to Chernobyl (Figure 1) [41,42]. Radioactive iodine from the Fukushima plant has been detected in the water supply of Tokyo, more than 130 miles (220 kilometers) to the south of the power plant [43], but did not result in levels high enough for evacuation and a new *national sacrifice zone* [44,45]. Risk factors with nuclear power include potential nuclear disasters due to: accidents, negligence, poor design, and natural disasters, terrorism [46] (both as a prime target, but also for theft and the creation of 'dirty bombs'), and the threat multiplication possible with nuclear energy in operation during both international wartime and domestic conflicts [47].

In addition, to the risk factors mentioned above, the presence of any form of nuclear power necessarily creates an infrastructure where nuclear materials and expertise for nuclear weapon fabrication may proliferate [48]. Thus, continued use and development of nuclear technology carries serious proliferation risks [49], especially in light of the 9/11 terrorist attacks against the U.S., as well as continued unrest in the Middle East. Weapons-applicable nuclear technology has been developed or obtained by non-signatory Nuclear Proliferation Treaty countries such as India, North Korea and Pakistan.

Figure 1. (a) Chernobyl aerial view into the core, smoke from the graphite fire and core melt down. The photo was taken from a helicopter on May 3, 1986, of the destroyed Unit 4. (b) Radiation fallout from Chernobyl [40].



Finally, at the end of the life cycle there are externalities that continue for generations. Safe and secure ultra-long-term storage of nuclear waste is still un-resolved and poses a serious challenge given that the half-life of spent fuel is in the range of $\sim 25,000$ years although some long-lived fission products last much longer. This waste containment problem includes not only the spent fuel rods, but also upon decommissioning of a nuclear power plant, the building, equipment and the surrounding land also contribute to the total waste. Both current temporary storage methods and planned methods of burying underground are inherently inequitable as those who bear the consequences including future generations and minorities/socio-economic disadvantaged living near facilities have little or no say in the decisions (e.g., some geographic locations become the permanent dump sites for the rest of the world) [49]. This results in an externality borne by those in geographic proximity to both the nuclear power plants and the waste sites. In addition to greater risk costs there are also well documented economic penalties such as decreased house values in the vicinity of both nuclear plants and nuclear waste repositories [50–52]. Finally, there are future externalities that are very difficult to quantify. These externalities include: human health effects, biodiversity loss, land degradation, diverse social costs, *etc.* For example, the metal walls of a nuclear vessel become radioactive and thus when decommissioned they are buried for many generations. In addition, the nuclear fuels themselves are irreversibly transmuted. This effectively depletes the reserve of base elements available on Earth and

could lead to an elemental diversity problem, the cost of which could be trivial or enormous and is all but impossible to calculate or predict [37].

2.3. Nuclear Energy Economic Sustainability and Insurability

Although nuclear power has many potential challenges as outlined above, perhaps the most difficult to overcome is simply economics. Nuclear power plants have become notorious for high construction costs—as many projects throughout the world have resulted in construction costs that doubled or tripled the original estimate, followed by frequent and expensive repairs [49,53,54]. This was the fundamental reason for the dearth of new nuclear power plant orders in the last few decades [55]. The world's economy, however, is far from a free market, so it is possible to influence the cost of nuclear power using government regulation and subsidies. Overall, the nuclear industry has been heavily subsidized by many governments since WWII, but is yet to be competitive on its own without subsidies. Despite the majority of direct and indirect subsidies for over 50 years, the average cost of electricity generation from nuclear power is in the range of \$5,000 per kW of capacity [56–58]. This could be argued by climate change mitigation advocates as sufficient, if there were not already other alternative energy sources to the pollution of fossil fuels that now have lower costs. For example, solar energy is already a less expensive alternative in some parts of the U.S. in the current subsidized landscape [54] and the levelized cost of electricity from solar photovoltaic-generated electricity in particular has dropped precipitously in the last year to be competitive with grid electricity in many regions without subsidies [59].

An illustration of how serious an *economic* challenge nuclear energy poses, lies in the fact that insurance agencies refuse to cover full liability and indemnity for nuclear utilities in case of a nuclear accident [60]. This is primarily because in the case of a catastrophic nuclear accident, the sheer magnitude of such a devastating event would likely bankrupt any company (or companies) held responsible. Therefore to make nuclear power generations possible, governments worldwide have to guarantee they will cover any exceeding costs past a certain liability cap, and thus any liabilities in excess of an arbitrary financial cap are covered by the taxpayer of the given country [61]. Thus, the nuclear power industry is relieved of any liability beyond the insured amount for any incident involving radiation or radioactive releases regardless of the fault or the cause. Trebilcock and Winter point out how such incomplete insurance liability can act as a disincentive for safety, and in addition skew the economics of nuclear viability as the industry is not responsible for full damages [62]. Initially, such laws like the Price-Anderson Nuclear Industries Indemnity Act (PPA) in the U.S. [63], were intended to be temporary, as it was assumed that once the companies had demonstrated a record of safe operation they would be able to obtain insurance in the private market. This did not happen. As former U.S. Vice-President Dick Cheney pointed out in 2001, without the PPA “nobody’s going to invest in nuclear power plants” [64]. Even today, nuclear power remains un-insurable in the free market [61] and governments have had to provide some form of limited liability for nuclear utilities for any company to consider building a reactor. Largely depending on the geographic location of the nuclear power plant, the devastating economic consequences of a catastrophic nuclear accident are in the order of hundreds of billions [65–67]. Thus, the U.S. Nuclear Regulatory Commission (NRC) concluded that the liability limits were sufficiently significant to constitute a “subsidy”; however, a

quantification of the amount of this nuclear insurance subsidy was not attempted [68]. This area of inquiry needs additional research, however, recent preliminary work indicates that if only this one indirect subsidy for nuclear power was diverted to photovoltaic manufacturing, it would result in more installed power and more energy produced by mid-century compared to the nuclear case [69]. The numbers of such a subsidy shift are substantial as by 2110 cumulative electricity output of solar are predicted to provide an additional 48,600 TWh of energy over nuclear valued at more than \$5 trillion [69]. The results clearly show that not only does the indirect insurance liability subsidy play a significant factor for the viability of the nuclear industry, but also how the transfer of such an indirect subsidy from the nuclear to other technically viable alternative energy sources would result in more energy and more financial returns over the life cycle of the technologies.

3. Discussion

As is obvious from the review of challenges to nuclear power today—nuclear power is far from sustainable. This is consistent with past research in the literature and those studies using softer definitions of sustainability such as *intermediate sustainability* [70,71]. It is clear that even if the nuclear power industry is able to find technical solutions to the fundamental environmental challenges to its sustainability outlined in Section 2.1, there are more difficult issues of equity that must be overcome as discussed in Section 2.2 and economics as reviewed in Section 2.3.

Based on the review above, if the concept of *just sustainability* is applied to nuclear energy, a *sustainable nuclear energy* system requires the following:

(1) Radical improvement in GHG emissions intensity. First, the embodied energy of the entire nuclear energy life cycle must be reduced. This reduction can not simply be done by ignoring parts of the life cycle as has been attempted in the past or using weak non-inclusive PB LCAs to make the numbers appear more favorable to the industry. As shown by the climate science community, anthropogenic climate destabilization is a real physical problem that demands real solutions rather than creative uses of emissions accounting. In the short term, previous work has indicated that efforts that improve the GHG emissions of the nuclear energy life cycle should be given a high priority such as (i) transitioning to enrichment based on gas centrifuge technology, (ii) utilizing nuclear plants in combined heat and power (CHP) systems to take advantage of the ‘waste’ heat, (iii) using nuclear power for thermal processing with the attendant increases in efficiency [5], (iv) down blending nuclear weapons stockpiles for nuclear power plant fuel, (v) utilizing only the highest concentration ores [34]. In the medium/long term, there is a dire need for improved nuclear technology of which several options have been described by Grimes and Nuttall [5] that can overcome the energy cannibalism effect while using lower grades of uranium ore if nuclear power is to be used at all. These improvements should be verified by non-industry supported LCAs to improve public trust (see requirement (4) below).

(2) Eliminate nuclear insecurity. On technical grounds, this requirement entails making nuclear power plants that can *not* physically melt down. Again, this requirement does not mean reduce the probability that it can happen—but it must be physically impossible for it to happen by improved reactor design. This would also enable additional increases in efficiency. For example, following suggestion (ii) above nuclear power plants could be placed in the middle of population centers and act as district heating utilities in addition to providing electricity. This would radically (more than double) efficiency.

Although it is not clear how safe a technology must be to be considered sustainable, this CHP application can also be used as a litmus test of the public's view on safety. Although, nuclear power plants are already found in population centers throughout the world, one can perform the following thought experiment on any energy source to determine adequate safety levels for just sustainability: Place the energy source in the middle of the country's largest population center and allow an enemy of the state access to it. Few Americans would tolerate this situation if the energy source was nuclear power—but if it were a hybrid solar photovoltaic thermal plant distributed on the rooftops of New York City the risks would clearly be much lower. This is the challenge that nuclear energy technology must overcome. Can nuclear power be made safe enough so that residents of New York City or Tokyo are tolerant of a reactor in the heart of the city? If this is possible, then insurance companies should be willing to insure nuclear power plants and the nuclear insurance subsidy can be eliminated as it would no longer be necessary for the economic viability of the nuclear industry.

(3) Eliminate radioactive waste and minimize environmental impact during mining and operations.

In order to prevent future humans from being forced to care for current energy-generated waste products a means of eliminating all radioactive waste from the generation of nuclear energy is needed. Using techniques that recycle waste may also reduce the amount of mining necessary and thus could also cut down on environmental impact. In addition, a method to recycle water or the use of other cooling fluids such as air and eliminate all thermal pollution needs to be developed and deployed.

(4) The nuclear industry must gain public trust. In many countries, the public does not trust the nuclear energy industry and the government bodies that oversee it. For example, the radioactive releases from Pennsylvania's Three Mile Island have been contentious and there is substantial evidence that the releases were under-reported to the public by officials by at least an order of magnitude. The official NRC value is 10 MCi [72]. Thompson *et al.*, quote more than double that at 22 MCi [73], whereas Gundersen points out that the sum of the NRC releases yields 36 MCi and estimates anywhere between 100 and 1000 times the NRC value [74]. Finally, epidemiological studies point to a significant epidemic of cancer that is clearly related to the Three Mile Island release and that would not have occurred if the NRC values were correct [75–81]. Similarly, more recently in the Fukushima disaster the public found official reports dubious and government officials appeared to be actively preventing citizens from obtaining data [82]. For example, the U.S. refused to post online whatever radiation levels they were monitoring as radiation from Fukushima hit the West Coast. Then there were several reports that their monitors went off line or crashed [83]. A response from citizens in Japan to this misdirection from public officials was to crowd-source radiation Geiger counter readings from across their country using a collection of both open source hardware and open source software [84]. In addition, Softbank recently launched a smartphone in Japan that includes a Geiger counter to track radiation. These developments perhaps provide a warning, that the technical prowess of the public combined with advanced networks is making it increasingly difficult to manage public viewpoints with misinformation. So called *green washing* of nuclear power is simply becoming impossible. Thus this type of disdain by decision makers and government officials for public disclosure of accurate information involving nuclear energy accidents must be completely eliminated. This is most easily done by telling the truth, providing open access to information to the public in real time, and implementing requirements (1–3) as discussed above so there is no need to hide anything

from the public. If this can be done, nuclear power will enjoy a long and sustainable future. If these requirements are not met, nuclear power will be eliminated by more sustainable rival technologies.

4. Conclusions

This paper provided a review and analysis of the challenges that nuclear power must overcome in order to meet the requirements of just sustainable development. The results make it clear that there are two fundamental challenges. First, innovative technical solutions need to be discovered for the fundamental inherent environmental handicaps of nuclear energy technology. Second, the nuclear industry must also address difficult issues of equity both in the present and for future generations. On a global-scale to replace fossil fuel combustion requires the “sustainable nuclear energy system” to do the following: (i) radically improve the energy efficiency and greenhouse gas emissions intensity by improved technology and efficiency through the entire life cycle to prevent energy cannibalism during rapid growth; (ii) eliminate nuclear insecurity to reduce the risks associated with nuclear power so that the free market can insure the nuclear industry without large public nuclear energy insurance subsidies; (iii) eliminate all radioactive waste at the end of life and minimize the environmental impact during mining and operations; and (iv) the nuclear industry must regain public trust or face obsolescence as a steady stream of renewable energy technologies quickly improve both technical and economic performance.

Conflict of Interest

The author declares no conflict of interest.

References

1. International Energy Agency. *World Energy Outlook*; International Energy Agency: Paris, France, 2010.
2. Elliot, D. *Nuclear or Not? Does Nuclear Power Have a Place in Sustainable Energy Future?*; Palgrave Macmillan: Houndmills, Basingstoke, UK, 2007.
3. Goswami, D.Y. A review and future prospects of renewable energy in the global energy system. *Adv. Technol. Electr. Eng. Energy* **2008**, *27*, 55–62.
4. Abbott, D. Keeping the energy debate clean: How do we supply the world’s energy needs? *Proc. IEEE* **2010**, *98*, 42–66.
5. Grimes, R.W.; Nuttall, W.J. Generating the option of a two-stage nuclear renaissance. *Science* **2010**, *329*, 799–803.
6. Sovacool, B. *Contesting the Future of Nuclear Power: A Critical Global Assessment of Atomic Energy*; World Scientific: Hackensack, NJ, USA, 2011.
7. Ferguson, C.D. *Nuclear Energy: Balancing Benefits and Risks*; Council of Foreign Relations: New York, NY, USA, 2007; CRS No. 28.
8. Intergovernmental Panel on Climate Change. *Climate Change 2007: Synthesis Report*. Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2008.

9. Stern, N. *The Economics of Climate Change: The Stern Review*; Cambridge University Press: Cambridge, UK, 2007.
10. Hoffert, M.I.; Caldeira, K.; Benford, G.; Criswell, D.R.; Green, C.; Herzog, H.; Jain, A.K.; Kheshgi, H.S.; Lackner, K.S.; Lewis, J.S.; *et al.* Advanced technology paths to global climate stability: Energy for a greenhouse planet. *Science* **2002**, *298*, 981–987.
11. Intergovernmental Panel on Climate Change. Summary for Policymakers. In *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Metz, B., Davidson, O.R., Bosch, P.R., Dave, R., Meyer, L.A., Eds.; Cambridge University Press: Cambridge, UK and New York, NY, USA, 2007.
12. Partidario, M.R. *Perspectives on Strategic Environmental Assessment*; CRC Press: Boca Laton, FL, USA, 1999.
13. Agyeman, J. *Sustainable Communities and the Challenge of Environmental Justice*; New York University Press: New York, NY, USA, 2005.
14. Schlosberg, D. *Environmental Justice and the New Pluralism: The Challenge of Difference for Environmentalism*; Oxford University Press: Oxford, UK, 1999.
15. Domenici, P.V. Emissions-Free Nuclear Energy Could Reduce U.S.’s Dangerous Over-Reliance on Natural Gas, Senate Committee on Energy and Natural Resources. U.S. Senate Committee on Energy and Natural Resources. Washington, DC, USA, 2004. Available online: <http://www.energy.senate.gov/public/index.cfm/2004/3/press-122dfd14-13c9-438d-be8f-020259fb42dc> (accessed on 11 April 2012).
16. Voorspools, K.R.; D’haeseleer, W.D. An evaluation method for calculating the emission responsibility of specific electric applications. *Energ. Pol.* **2000**, *28*, 967–980.
17. Voorspools, K.R.; Peersman, I.; D’haeseleer, W.D. A comparative analysis of energy and CO₂ taxes on the primary energy mix for electricity generation. *Int. J. Energy Res.* **2005**, *29*, 879–890.
18. Nuclear Energy Institute. New Nuclear Energy Facilities Will Support Growth, Provide Clean Electricity. 2012. Available online: <http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/factsheet/usneedsnewplants> (accessed on 5 May 2012).
19. U.S. Department of Energy. Department of Energy Issues \$14 Million in Funding Opportunity Announcements to U.S. Universities for Nuclear Research. U.S. Department of Energy, Washington, DC, USA, 2007. Available online: <http://www.ne.doe.gov/newsroom/2007PRs/nePR032807.html> (accessed on 11 April 2012).
20. Johansson, T.; Williams, R.; Ishitani, H.; Edmonds, J. Options for reducing CO₂ emissions from the energy supply sector. *Energ. Pol.* **1996**, *24*, 985–1003.
21. Sailor, W.C.; Bodansky, D.; Braun, C.; Fetter, S.; van der Zwaan, B. Nuclear power: A nuclear solution to climate change? *Science* **2000**, *288*, 1177–1178.
22. Cheney, D.; Powell, C.L.; O’Neill, P.; Norton, G.; Veneman, A.M.; Evans, D.L.; Mineta, N.Y.; Abraham, S.; Allbaugh, J.M.; Whitman, C.T.; *et al.* *National Energy Policy, Report of the National Energy Policy Development Group*; U.S. Government Printing Office: Washington, DC, USA, 2001.
23. Gagnona, L.; Belanger, C.; Uchiyama, Y. Life-cycle assessment of electricity generation options: The status of research in year 2001. *Energ. Pol.* **2002**, *30*, 1267–1278.

24. Rohatgi, U.; Jo, J.H.; Lee, J.C.; Bari, R.A. Impact of the nuclear option on the environment and the economy. *Nuclear Technol.* **2002**, *137*, 252–264.
25. Moore, P. Going Nuclear: A Green Makes the Case. *Washington Post*, April 16, 2006, Page B01.
26. Barnaby, F.; Kemp, J. *Secure Energy? Civil Nuclear Power, Security and Global Warming*; Oxford Research Group: London, UK, March 2007. Available online: http://www.oxfordresearchgroup.org.uk/publications/briefing_papers/secure_energy_civil_nuclear_power_security_and_global_warming (accessed on 11 April 2012).
27. Fthenakis, V.M.; Kim, H.C. Greenhouse-gas emissions from solar electric- and nuclear power: A life-cycle study. *Energ. Pol.* **2007**, *35*, 2549–2557.
28. Vattenfall, A.B. Generation Nordic Countries Certified Environmental Product Declaration of Electricity from Ringhals NPP. 2004; S-P-00026.
29. Hondo, H. Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy* **2005**, *30*, 2042–2056.
30. DeLucchi, M. *Emissions of Greenhouse Gases from the Use of Transportation Fuel and Electricity*; Argonne National Laboratory: Downers Grove, IL, USA, 1991; Volume 2, ANL/ESD/TM-22.
31. Kim, S.; Dale, B.E. Life cycle inventory information of the United States Electricity System. *Int. J. LCA* **2005**, *10*, 294–310.
32. Rutledge, D. Estimating long-term world coal production with logit and probit transforms. *Int. J. Coal Geol.* **2011**, *85*, 23–33.
33. WEC. *WEC, Survey of Energy Resources*; World Energy Council: London, UK, 2010.
34. Volkers, C. *Appendix SRES Version 1.1, an Excel Workbook With a Spreadsheet for Each Scenario*; UNEP: Arendal, Norway, 2010. Available online: <http://www.grida.no/climate/ipcc/emission/data/allscen.xls> (accessed on 1 October, 2010).
35. Pearce, J.M. Thermodynamic limitations to nuclear energy deployment as a greenhouse gas mitigation technology. *Int. J. Nuclear Gov. Econ. Ecol.* **2008**, *2*, 113–130.
36. Kenny, R.; Law, C.; Pearce, J.M. Towards real energy economics: Energy policy driven by life-cycle carbon emission. *Energ. Pol.* **2010**, *38*, 1969–1978.
37. Abbott, D. Is nuclear power globally scalable? *Proc. IEEE* **2011**, *99*, 1611–1617.
38. Antunes, S.C.; Pereira, R.; Marques, S.M.; Castro, B.B.; Gonçalves, F. Impaired microbial activity caused by metal pollution: A field study in a deactivated uranium mining area. *Sci. Total Environ.* **2011**, *410*, 87–95.
39. Lochbaum, D. *Got Water?*; Union of Concerned Scientists: Cambridge, MA, USA, 2007.
40. CBC News. The catastrophe of Chernobyl. CBC News. April 26, 2006. Available online: <http://www.cbc.ca/news/background/ukraine/chernobyl.html> (accessed on 11 April 2012).
41. BBC News. Neighbours Count Cost of Chernobyl Disaster. BBC News, April 26, 1998.
42. UNSCREAR. *Sources and Effects of Ionizing Radiation. Vol. II, Scientific Annexes C, D, E*; United Nations: New York, NY, USA, 2008.
43. Lavelle, M. *A Search for Answers*; National Geographic News: Washington, DC, USA, 2011.
44. Kuletz, V. Invisible Spaces, Violent Places: Cold War Nuclear and Militarised Landscapes. In *Violent Environments*; Peluso, N.L., Watts, M., Eds.; Cornell University Press: Ithaca, NY, USA, 2001.

45. Hooks, G.; Smith, C.L. The Treadmill of Destruction: National Sacrifice Areas and Native Americans. *Am. Sociol. Rev.* **2004**, *69*, 558–575.
46. Behrens, C.; Holt, M. *Nuclear Power Plants: Vulnerability to Terrorist Attack*; Report for Congress, Order Code RS21131; Congressional Research Service: Washington D.C., USA, 2005.
47. Ramberg, B. Nuclear plants—Military hostages? *Bull. At. Sci.* **1936**, *43*, 3–17.
48. Cochran, T.B.; Feiveson, H.A.; Patterson, W.; Pshakin, G.; Ramana, M.V.; Schneider, M.; Suzuki, T.; von Hippel, F. *Fast Breeder Reactor Programs: History and Status, Report 8 in the International Panel on Fissile Material (IPFM)*; Princeton University: Princeton, NJ, USA, 2010.
49. Deutch, J.M.; Forsberg, C.W.; Kadak, A.C.; Kazimi, M.S.; Moniz, E.J.; Ansolabehere, J.E.; Du, Y.; Pierpoint, L. *Update of the MIT 2003 Future of Nuclear Power: An Interdisciplinary MIT Study*; Massachusetts Institute of Technology: Cambridge, MA, USA, 2009.
50. Clark, D.E.; Allison, T. Spent nuclear fuel and residential property values: The influence of proximity, visual cues and public information. *Papers Reg. Sci.* **1999**, *78*, 403–421.
51. Clark, D.E.; Nieves, L.A. An interregional hedonic analysis of noxious impacts on local wages and property values. *J. Environ. Econ. Manag.* **1994**, *27*, 235–253.
52. Folland, S.; Hough, R. Externalities of nuclear power plants: Further evidence. *J. Reg. Sci.* **2000**, *40*, 735–753.
53. Cooper, M. *All Risk, No Reward for Taxpayers and Ratepayers: The Economics of Subsidizing the 'Nuclear Renaissance' With Loan Guarantees and Construction Work in Progress*; Report of the Institute for Energy and the Environment; Vermont Law School: Royalton, VT, USA, 2009.
54. Blackburn, J.; Cunningham, S. *Solar and Nuclear Costs—The Historic Crossover: Solar Energy is Now the Better Buy*; NC WARN—Waste Awareness & Reduction Network: Durham, NC, USA, 2010. Available online: http://www.ncwarn.org/wp-content/uploads/2010/07/NCW-Solar_Report_final1.pdf (accessed on 11 April 2012).
55. van Leeuwen, J.W.S.; Smith, P. *Nuclear Power—The Energy Balance*; Chaam: Netherlands, 2008. Available online: <http://www.stormsmith.nl> (accessed on 11 April 2012).
56. Goldberg, M. *Federal Energy Subsidies: Not All Technologies Are Created Equal*; Research Report No. 11; Renewable Energy Policy Project: Washington, DC, USA, 2000. Available online: http://www.repp.org/repp_pubs/pdf/subsidies.pdf (accessed on 11 April 2012).
57. Martin, H.D.; Pearson, B., *The Canadian Nuclear Lesson*; Sierra Club of Canada and Greenpeace International Briefing Paper; Sierra Club Canada: Ottawa, Canada, 2001. Available online: <http://www.sierraclub.ca/national/programs/atmosphere-energy/nuclear-free/reactors/nuclear-and-climate-change.pdf> (accessed on 11 April 2012).
58. Slavin, M. The Federal Energy Subsidy Scorecard: How Renewables Stack Up. *Renewable Energy World*, 2009. Available online: <http://www.renewableenergyworld.com/rea/news/article/2009/11/the-federal-energy-subsidy-scorecard-how-renewables-stack-up> (accessed on 21 April 2012).
59. Branker, K.; Pathak, M.J.M.; Pearce, J.M. A review of solar photovoltaic levelized cost of electricity. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4470–4482.
60. McNeil, B. The costs of introducing nuclear power to Australia. *J. Aust. Polit. Econ.* **2007**, *59*, 5–29.

61. Hans-Holger, R. Carbon Free Energy. In *Proceedings of the 2nd Canadian Climate Change Technology Conference*, Hamilton, Canada, 12–15 May 2009.
62. Trebilcock, M.; Winter, R.A. The economics of nuclear accident law. *Int. Rev. Law Econ.* **1997**, *17*, 215–243.
63. United States General Accounting Office. *Nuclear Regulation: NRC's Liability Insurance Requirements for Nuclear Power Plants Owned by Limited Liability Companies*; Report to Congressional Requesters GAO-04-654; U.S. Government Accountability Office: Washington D.C., USA, May 2004.
64. Reuters. Cheney Says Push Needed to Boost Nuclear Power. Reuters News Service, May 15, 2001.
65. Dubin, J.A.; Rothwell, G.S. Subsidy to nuclear-power through price-anderson liability limit. *Contemp. Policy Issues* **1990**, *8*, 73–79.
66. Heyes, A. Determining the price of price-anderson. *Regulation* **2003**, *25*, 105–110.
67. The Chernobyl Forum. *2003–2005, Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine*, 2nd revised version; IAEA/PI/A.87 Rev.2/06–09181IAEA; Division of Public Information: Vienna, Austria, 2006.
68. United States Nuclear Regulatory Commission. *The Price-Anderson Act: The Third Decade*; NUREG-0957; United States Nuclear Regulatory Commission: Washington, DC, USA, 1983.
69. Zelenika-Zovko, I.; Pearce, J.M. Diverting indirect subsidies from the nuclear industry to the photovoltaic industry: Energy and economic returns. *Energ. Pol.* **2011**, *39*, 2626–2632.
70. Rothwell, G.; van der Zwaan, B.C.C. Are light water reactor systems sustainable? *J. Energy Dev.* **2003**, *29*, 65–79.
71. Adamantiades, A; Kessides, I. Nuclear power for sustainable development: Current status and future prospects. *Energ. Pol.* **2009**, *37*, 5149–5166.
72. President's Commission on the Accident at Three Mile Island. *The Need for Change, the Legacy of TMI: Report of the President's Commission on the Accident at Three Mile Island*; President's Commission: Washington, DC, USA, 1979.
73. Thompson, J.; Thompson, R.; Bear, D. *TMI Assessment, Part 2*. 1995. Available online: <http://www.southernstudies.org/images/sitepieces/ThompsonTMIassessment.pdf> (accessed on 11 April 2012).
74. Gundersen, A. Three Myths of the Three Mile Island Accident. Lecture. Fairewinds Energy Education Corp.: Burlington, VT, USA. 2009.
75. Hatch, M.C.; Beyea, J.; Nieves, J.W.; Susser, M. Cancer near the Three Mile Island nuclear plant: Radiation emissions. *Am. J. Epidemiol.* **1990**, *132*, 397–417.
76. Wing, S.; Richardson, D.; Armstrong, D.; Crawford-Brown, D. A reevaluation of cancer incidence near the Three Mile Island nuclear plant: The collision of evidence and assumptions. *Environ. Health Perspect.* **1997**, *105*, 52–57.
77. Hatch, M.C.; Wallenstein, S.; Beyea, J.; Nieves, J.W.; Susser, M. Cancer rates after the Three Mile Island nuclear accident and proximity of residence to the plant. *Am. J. Public Health* **1991**, *81*, 719–724.

78. Gur, D.; Good, W.F.; Tokuhata, G.K.; Goldhaber, M.K.; Rosen, J.C.; Rao, G.R. Radiation dose assignment to individuals residing near the Three Mile Island nuclear station. *Proc. PA Acad. Sci.* **1983**, *57*, 99–102.
79. Talbott, E.O.; Youk, A.O.; McHugh, K.P.; Shire, J.D.; Zhang, A.; Murphy, B.P.; Engberg, R.A. Mortality among the residents of the Three Mile Island accident area: 1979–1992. *Environ. Health Perspect.* **2000**, *108*, 545–552.
80. Wing, S.; Richardson, D. Collision of evidence and assumptions: TMI déjà view. *Environ. Health Perspect.* **2000**, *108*, A546–A547.
81. Talbott, E.O.; Zhang, A.; Youk, A.O.; McHugh-Pemu, K.P.; Zborowski, J.V. Re: “Collision of evidence and assumptions: TMI déjà view.” *Environ. Health Perspect.* **2000**, *108*, A547–A549.
82. Brasor, P. Public wary of official optimism. The Japan Times. Sunday, March 11, 2012. Available online: <http://www.japantimes.co.jp/text/fd20120311pb.html> (accessed on 11 April 2012).
83. You Can View Official EPA Radiation Readings. Washington Post. Available online: <http://www.washingtonsblog.com/2011/03/you-can-view-official-epa-radiation-readings.html> (accessed on 11 April 2012).
84. Japan Geigermap: At-a-glance. Available online: <http://japan.failedrobot.com/> (accessed on 11 April 2012).

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