INSTITUTE FOR ENERGY AND
ENVIRONMENTAL RESEARCH

6935 Laurel Avenue, Suite 201
Takoma Park, MD 20912

Phone: (301) 270-5500
FAX: (301) 270-3029
e-mail: ieer@ieer.org
http://www.ieer.org

Short paper on Nuclear Power and Low-Carbon Alternatives

Prepared for the Nuclear Fuel Cycle Royal Commission
Public Session of 1 October 2015

Arjun Makhijani[1]

1. Nuclear energy generation

It is generally accepted that climate protection considerations necessitate that CO_2 emissions be reduced by 80 percent or more within the next three to four decades, especially in the developed world, given inequality in past emissions. There is no shortage of low-carbon energy sources: solar and wind are plentiful, and, in principle, so is nuclear fuel. The critical parameters for climate policy are time and money: both are in short supply and that should be a central consideration in making energy choices. I focus here on supply only, noting that implementation of energy efficiency makes the transition to a low-CO_2 system faster and more economical. Using that as the first screen, there is a credible case for carbon emission reductions only for well-established existing technologies; basically light water reactors (LWRs) and possibly pressurized heavy water reactors (PHWRs).

a. Current technology

Both LWRs and PHWRs fail the primary screening criteria of time and cost. Typically they take a decade to build – with carbon emissions occurring in the meantime. Costs are high and cost escalations are routine. The United States attempted to create a streamlined one-step licensing process, using a combined construction and operating license (in place of the prior two-step process of a construction license followed by a separate operating license, after completion of construction). This process has failed to eliminate the problems of cost overruns, long construction times, and serial delays in the two projects that are actually being built (with two new reactors at each site). Both projects are funded in large measure by a charge known as "construction work in progress", which offloads the risk onto ratepayers.

[1] President, Institute for Energy and Environmental Research (IEER). Dr. Makhijani's C.V. can be found at http://ieer.org/wp/wp-content/uploads/2011/11/cvarjun.pdf.

While nuclear plants take a decade, solar installations can be up in a few months (small-scale projects) to a couple of years, with the latter timescale also applying to wind farms. These differing time scales have considerable risk implications. Short time scales mean that it is not necessary to project electricity use out for a decade or more. Since 1973, such projections have been notoriously wrong, at least in the United States – with the utilities generally overestimating electricity use. That was a principal reason for scores of nuclear plants being cancelled in the United States from the 1970s to the 1990s. It is also worthy of note that if projections are wrong, a half built nuclear reactor produces no electricity, in contrast to half a solar plant or half a wind farm.

The U.S. "nuclear renaissance" is essentially dead – apart from the four new reactors under construction and one 1970s era reactor (Watts Bar 2) that was reincarnated 2007; it too has had serious cost overruns and delays. Around that time, 2007, there were announcements for about 30 new reactors.

Poor electricity use projections (due in part to inadequate estimation of efficiency increases) and the low cost of natural gas combined cycle plants, wind farms, and, increasingly, solar PV generation are the reasons for the demise of the nuclear renaissance in the United States. Even many existing nuclear power plants are at economic risk due to relatively high operating costs.

The French have fared no better. The French-designed EPR being built in Finland has faced many technical, cost, and schedule problems, as has the one reactor being built in France at Flamanville. As for the PHWR, plans for two new reactors in Canada have been put on the shelf. There is significant nuclear construction in China – there are 26 reactors in operation and 25 under construction.[2] But even there nuclear power is being eclipsed by wind and solar energy.

The world's nuclear generation was stagnant between 2006 and 2010 and has declined since then.[3] Vigorous government efforts in many key countries, including the United States, to promote new nuclear plants, have not improved the picture. New reactor capacity is being offset by reactors that are shutting down, many prematurely.

Costs of nuclear energy generation are estimated by Lazard at $90 to $134 per megawatt-hour (MWh).[4] Recently, the CEO of First Solar announced that his company expects to build tracking utility-scale solar PV plants in the western United States for less than a dollar per watt starting in 2017.[5] So even without the 30 percent investment tax credit

---

[2] World Nuclear Association. *Nuclear Power in China*. London: WNA, updated August 2015. On the Web at http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Power.

[3] World Nuclear Association. *Nuclear Power in the World Today*. London: WNA, updated February 2015. On the Web at http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today/.

[4] *Lazard's Levelized Cost of Energy Analysis - Version 8.0*. [New York: Lazard Ltd. Global Power, Energy & Infrastructure Group], September 2014. On the Web at http://www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf. Slide 4

[5] Eric Wesoff. "First Solar CEO: 'By 2017, We'll Be Under $1.00 per Watt Fully Installed': Hughes called the expiration of the ITC 'irrelevant.'" *Greentech Grid*, June 24, 2015. On the Web at

(due to expire on December 31, 2016), the cost of utility scale solar energy will cost around $60 per MWh with no future financial risks or fuel costs, waste disposal, decommissioning, or decades of disruption due to severe accidents. Moreover, solar projects can be built incrementally on time scales of months (tens of kilowatts) to a couple of years (utility-scale). The conditions in the solar-radiation-rich areas of the U.S. West are broadly comparable to those in South Australia.

An objective assessment of the facts leads to the clear conclusion that nuclear power is already economically obsolete, quite apart from a number of other considerations. The same amount of money can produce far greater CO_2 reductions with wind and solar energy than with nuclear. The time-related financial and climate risks (delayed, costly, and cancelled plants) of nuclear power also point in the same direction.

The high use of water is a critical liability of nuclear generation, and all other thermal generation; it is one that will have greater impact as the extremes of weather become more severe. Nuclear power plants consume between about 0.4 and 3 cubic meters (rounded) of water per MWh of generation, depending mainly on the method of cooling.[6] Solar PV and wind generation use essentially none. The vulnerability of nuclear plants to derating and even shutdowns during extreme heat events has already been seen on several occasions in both France and the United States in the last 15 years. Air cooling, if demonstrated, may help in theory but not so much at the worst times – periods of severe hot weather – and then only at a considerable efficiency penalty.

Nuclear power is also the most inflexible in relation to its ramping capability. Of all the conventional sources of electricity, it is therefore the most incompatible with variable wind and solar.

A nuclear reactor makes plutonium just to boil water. The world's commercial separated stocks of surplus commercial plutonium rival the total in all nuclear arsenals combined.[7] The unseparated stocks in spent fuel are far larger. There is no sensible solution to this problem; the least bad option is disposal of spent fuel in a deep geologic repository. As you know, there are considerable technical, political, and social difficulties with such projects. (For the record, I support limiting the future stream of spent fuel and development of properly engineering deep geologic disposal systems.)

---

http://www.greentechmedia.com/articles/read/First-Solar-CEO-By-2017-Well-be-Under-1.00-Per-Watt-Fully-Installed.

[6] Macknick et al., *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies.* Golden, CO: National Renewable Energy Laboratory, March 2011. On the Web at http://www.nrel.gov/docs/fy11osti/50900.pdfTable 2, p. 3

[7] Global Fissile Material Report2015, p. 22. On the Web at http://fissilematerials.org/library/ipfm15.pdf.

A variety of small modular reactors of the light water design have been proposed. They shift rather than solve the essential economic problems. My analysis can be found in a 2013 IEER report.[8]

b. Other reactor designs

Nuclear energy technologies that are not already well-established have no realistic prospect of contributing significantly to reducing carbon emissions by 2050, especially if due attention is given to safety and proliferation issues. Moreover, lack of attention to such issues can, in fact, derail the nuclear industry; one Fukushima-scale accident can (and has) set back the entire industry.

In the United States, which I know best, it would take on the order of a decade for the Nuclear Regulatory Commission to write the rules to certify reactors, examine fault-trees to assess the risks of various types of severe accidents, and another decade or more of operating experience with demonstration reactors. Presuming success, the industry can then gear up for large scale production of reactors. It may well take longer. So in the best of worlds for new designs, it will be around 2035 or 2040 before significant numbers of new reactors can be built. We cannot afford to wait that long or gamble that there will be a positive result.

Two examples illustrate the problem. Sodium-cooled reactors have been offered up since the 1950s as the key technology because the design, with reprocessing, could, in theory, use almost all the uranium resource base, instead of less than one percent in the case of light water reactors, even with reprocessing. After a huge effort – on the order of $100 billion spent worldwide since the 1950s – the design is not commercial; indeed, there is no evidence of a learning curve, since the most recent demonstration reactors, Superphénix and Monju, had a far worse record than several earlier ones (like the Fast Flux Test Reactor or the Experimental Breeder Reactor II). There is no prospect that this design can be commercialized in time for significant impact on CO_2 emissions before 2050.

Molten salt reactors are even farther away. While they have some safety advantages over LWRs, it should be noted that each comes with its own reprocessing plant onsite. A proliferant state which does not now have nuclear-weapons materials could potentially draw out the protactium-233 and make nearly pure weapons usable uranium-233 at every reactor site – giving rise to inspection and verification headaches of an entirely different order of magnitude than current ones. And the road to development may be even longer that for a sodium-cooled reactor.[9] The fluoride fission product wastes arising from

---

[8] Arjun Makhijani. *Light Water Designs of Small Modular Reactors: Facts and Analysis*. September 2013. On the Web at http://ieer.org/wp/wp-content/uploads/2013/08/SmallModularReactors.RevisedSept2013.pdf.

[9] The transcript of a radio debate I had with a molten salt reactor proponent on the National Public Radio program, *Science Friday*, can be found at http://www.npr.org/2012/05/04/152026805/is-thorium-a-magic-bullet-for-our-energy-problems. My analysis of the sodium-cooled "travelling wave" reactors, published in 2013, is at http://ieer.org/wp/wp-content/uploads/2013/09/TravelingWaveReactor-Sept20131.pdf My 2010 analysis of commercial reprocessing (*The Mythology and Messy Reality of Nuclear Fuel Reprocessing*) is

molten salt reactors will present much greater challenges than spent fuel because the fluorides will have to be processed into more stable forms. There are very long-lived fission products in the mix, including technetium-99 and iodine-129 (which is also a major long-term problem for LWR high-level waste disposal). The decommissioning of a small pilot molten salt reactor (8 megawatts-thermal), which operated for just a few years in the 1960s at Oak Ridge, presents huge technical and cost challenges; it has still not been completed.

c. Conclusion regarding nuclear generation

The huge potential uranium resource base is not relevant to the climate problem, or indeed to energy issues. There is no resource problem once solar and wind are commercial – and today they are. Nuclear fission energy is technically, environmentally, and economically obsolete. Phasing it out and managing the waste present challenges that should not be increased when clearly superior alternatives (in several dimensions) are available.

2. Fusion

A brief note on fusion (the topic of my doctoral work). It is funny to say that fusion is always thirty years away; so far it is also true. More seriously, the ITER project is highly unlikely to make fusion attractive even if it works perfectly. Its time scale is too long to make an impact; its size is too huge for sensible investment risk; it will need vast amounts of water. The materials problems of neutron damage to the reactor walls remain a large challenge. I venture to suggest no set of private investors would buy one even if it works as designed. Laser fusion, as represented by the National Ignition Facility, is orders of magnitude away from technical power production feasibility.

There are unconventional fusion approaches that show more promise of becoming practical if they can be shown to work. They are oriented to much smaller reactors; some are pursuing designs that do not use deuterium-tritium reactions. The Lawrenceville Plasma Physics Focus Fusion work is one example.[10] Spreading fusion research investments into approaches that do not liberate most of their energy in neutrons and that could result in much smaller reactors is worth modest investment spread over several technologies. I recommend that the Royal Commission consider these technologies with the possible aim of focusing on one or two of them at one of Australia's leading research institutions. I would not bank on any of them helping significantly on the climate issue. Rather, their long-term advantage is that they could greatly reduce the land needed for energy generation compared to solar and wind systems and may even provide flexible dispatchable power to complement them.

---

at http://ieer.org/wp/wp-content/uploads/2010/04/reprocessing2010.pdf This includes an analysis of the French program and the maximum uranium resource utilization with repeated reprocessing and use in LWRs.

[10] See their website at http://lawrencevilleplasmaphysics.com/. Another experiment is described in *Nature* at http://www.nature.com/news/plasma-physics-the-fusion-upstarts-1.15592.

3. Carbon capture and sequestration

The scale on carbon capture, the immensity of the siting problems, the complexity of verification that huge amounts of CO_2 will, in fact, remain trapped underground, present challenges that I believe cannot be overcome quickly enough. Relying on continued use of fossil fuels in the hope of capturing and sequestering the carbon is a highly risky strategy. The cost and efficiency penalties are also huge.

Even if it were available today, it is not clear that CCS is preferable to simply shutting down coal-fired power plants and building utility-scale or large-scale commercial distributed solar (~1 megawatt per plant). The 2010 report of the U.S. government' Interagency Task Force Report on CCS estimated the cost increase at $60 to $114 per metric ton of CO_2.[11] Since coal-fired power plants emit about a metric ton per MWh, it is not difficult to see that this cost is comparable to or greater than the near-term (before 2020) estimated cost of wind energy or utility-scale solar in sunny areas. Given that there are other enormous advantages to shutting down coal-fired power plants, in terms of health and pollution benefits, it is difficult to justify CCS as a CO_2 reduction strategy at least with coal-fired power plants.

There is a huge issue of protection of workers and communities now dependent on coal in a transition to renewable energy. I advocate a small charge (on the order of 0.1 to 0. 2 U.S. cents per kWh) on coal-fired power plant electricity to take effect immediately. This should be used to (i) start creating jobs in potentially affected areas and communities now, and (ii) to create a reserve fund for when coal production declines sharply and plants are shut to ensure that workers and communities are not dislocated.

That said, I believe that managing agricultural systems to improve soil storage of carbon (verifiably) is very important since we are likely to need withdrawal of already emitted CO_2 from the atmosphere in the not too distant future.

4. Energy storage, demand response, smart grid

The very rapid development of utility-scale storage batteries and electric vehicles of all types from trucks and tractors to cars to bicycles makes it safe to say that storage will not be a huge technical or economic issue as variable energy sources grow. The model of management of the grid will have to change, but this must happen in any case.

Today, the entire information content of all the on-off switches in the United States can be put on a $15 flash drive. This is one-way communication and brute force operation of the grid. It works, mostly with sufficient capacity, but is prone, at least in the United States, to breakdown under stress.

Smart appliances, two-way communications (between producer-consumers, aggregators, and producers), real-time rates, demand response, energy storage at various scales, and

[11] Interagency Task Force Report, August 2010 at http://www3.epa.gov/climatechange/Downloads/ccs/CCS-Task-Force-Report-2010.pdf. p. 27

other technical, institutional, and economic innovations that are being rapidly developed around the world will ensure that a grid with mainly variable energy supply can be more reliable, resilient, and economical than the present one.

Further, electrolytic hydrogen production, as the proportion of variable energy sources increases, is an important technology that will provide safeguards against insufficient supply. My calculations indicate that distributed hydrogen production can be economically coupled to a grid in which solar and wind are the dominant sources of supply. This hydrogen serves, in effect, as energy storage and can be used as a complement to battery storage and (electric) vehicle-to-grid technology. IEER has developed an elaborate hour-by-hour model of the Maryland electricity system with electric HVAC and transportation, battery storage, and hydrogen- and renewable-methane-driven peaking generation.[12] It would probably be prudent to count on a small amount of natural gas use in such a system at the present time, until sufficiently economical fuel cells have been developed. My colleagues and I estimate that this will be at least as economical as the business-as-usual model and probably more so. In other words, our best estimate of carbon emission reduction cost is zero or less than zero. These results are not final but are at a stage where the broad conclusions regarding grid reliability, resilience, and cost are dependable.

Economical seasonal storage of heat and coldness would enable spring and autumn energy surpluses in a system to be managed more flexibly in some climates. This is not necessary, but developing more options for variable system management, is highly desirable. Such flexibility will be more valuable in the context of a distributed energy system.

5. Conclusions

In a study I completed in 2007, I concluded that a fully renewable energy system was both technically and economically feasible by about 2050.[13] Technical and economic developments since that time have convinced me that the core of that analysis – it could be done at a cost similar to business as usual – is correct. Indeed, progress has been faster than expected. I think we could get there at lower cost than business-as-usual by 2040; certainly it can be done in countries with such abundant renewable resources and technical capabilities like the United States and Australia. Nuclear energy is already obsolete. Its low-carbon attribute has no practical environmental or economic value for making investments to protect climate.

---

[12] In an energy system in which most supply is variable, peak times will be defined by the *relation* between variable (solar and wind) supply, storage, and demand, rather than only by demand as at present. I call this the "*relational peak*." The relational peak may or may not coincide with the demand peak.

[13] The book, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy*, can be downloaded free at http://ieer.org/wp/wp-content/uploads/2007/08/CFNF.pdf.

6. References

Interagency Task Force 2010	Interagency Task Force on Carbon Capture and Storage. *Report of the Interagency Task Force on Carbon Capture and Storage*. [Washington, DC: U.S. Dept. of Energy and Environmental Protection Agency], August 2010. On the Web at http://www3.epa.gov/climatechange/Downloads/ccs/CCS-Task-Force-Report-2010.pdf.
IPFM 2015	Zia Mian and Alexander Glaser. *Global Fissile Material Report 2015: Nuclear Weapon and Fissile Material Stockpiles and Production*. Revision 3. [Presented at] NPT Review Conference, United Nations, New York, May 8, 2015. Princeton, NJ: International Panel on Fissile Materials, 2015. On the Web at http://fissilematerials.org/library/ipfm15.pdf.
Lazard 2014	Lazard. *Lazard's Levelized Cost of Energy Analysis - Version 8.0*. [New York: Lazard Ltd. Global Power, Energy & Infrastructure Group], September 2014. On the Web at www.lazard.com/PDF/Levelized%20Cost%20of%20Energy%20-%20Version%208.0.pdf.
LPPFusion 2015	Lawrenceville Plasma Physics*. Focus Fusion [home page]*. Middlesex, NJ: LPPFusion, accessed September 17, 2015. On the Web at http://lawrencevilleplasmaphysics.com/. Viewed September 17, 2015.
Macknick et al. 2011	Jordan Macknick, Robin Newmark, Garvin Heath, and KC Hallett. *A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies*. Golden, CO: National Renewable Energy Laboratory, March 2011. On the Web at http://www.nrel.gov/docs/fy11osti/50900.pdf
Makhijani 2007	Arjun Makhijani. *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy.* Takoma Park, MD: IEER Press, 2007; 3rd printing, 2010. On the Web at http://ieer.org/wp/wp-content/uploads/2007/08/CFNF.pdf, with a link from http://ieer.org/resource/reports/carbon-free-and-nuclear-free/.
Makhijani 2010	Arjun Makhijani. *The Mythology and Messy Reality of Nuclear Fuel Reprocessing*. Takoma Park, MD: Institute for Energy and Environmental Research, April 2010. On the Web at http://ieer.org/wp/wp-content/uploads/2010/04/reprocessing2010.pdf, from link at http://ieer.org/resource/reports/mythology-messy-reality-nuclear.
Makhijani 2013 SMR	Arjun Makhijani. *Light Water Designs of Small Modular Reactors: Facts and Analysis*. Takoma Park, MD: Institute for Energy and Environmental Research, revised September 2013; originally published August 2013. On the Web at http://ieer.org/resource/energy-issues/light-water-designs-of-small-modular-reactors-facts-and-analysis/, with link to http://ieer.org/wp/wp-content/uploads/2013/08/SmallModularReactors.RevisedSept2013.pdf.
Makhijani 2013 TWR	Arjun Makhijani. *Traveling Wave Reactors: Sodium-cooled Gold at the End of a Nuclear Rainbow?* Takoma Park, MD: Institute for Energy and Environmental Research, September 2013. On the Web at http://ieer.org/wp/wp-content/uploads/2013/09/TravelingWaveReactor-Sept20131.pdf, from link at http://ieer.org/resource/reports/traveling-wave-reactors-sodium-cooled-gold-at-the-end-of-a-nuclear-rainbow.

Nature 2014	M. Mitchell Waldrop. "Plasma physics: The fusion upstarts: Fuelled by venture capital and a lot of hope, alternative fusion technologies are heating up," *Nature*, 23 July 2014; clarified: 18 September 2014. On the Web at http://www.nature.com/news/plasma-physics-the-fusion-upstarts-1.15592,
Science Friday 2012	"Is Thorium A Magic Bullet For Our Energy Problems?" *Science Friday*, May 4, 2012. On the Web at http://www.npr.org/2012/05/04/152026805/is-thorium-a-magic-bullet-for-our-energy-problems, from link at http://ieer.org/resource/commentary/science-friday-thorium-magic-bullet.
Wesoff 2015	Eric Wesoff. "First Solar CEO: 'By 2017, We'll Be Under $1.00 per Watt Fully Installed': Hughes called the expiration of the ITC 'irrelevant.'" *Greentech Grid*, June 24, 2015. On the Web at http://www.greentechmedia.com/articles/read/First-Solar-CEO-By-2017-Well-be-Under-1.00-Per-Watt-Fully-Installed.
WNA 2015a	World Nuclear Association. *Nuclear Power in China*. London: WNA, updated August 2015. On the Web at http://www.world-nuclear.org/info/Country-Profiles/Countries-A-F/China--Nuclear-Power.
WNA 2015b	World Nuclear Association. *Nuclear Power in the World Today*. London: WNA, updated February 2015. On the Web at http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today/.

7. Erratum

On February 9, 2016, the last full sentence on page 2 of the full report was corrected to read:

"Recently, the CEO of First Solar announced that his company expects to build tracking utility-scale solar PV plants in the western United States for less than a dollar per watt starting in 2017."

That is, "First Energy" was changed to "First Solar."