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THE FUTURE FOR NUCLEAR ENERGY

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ABSTRACT
Nuclear energy currently accounts for a declining share of global electricity, but it is possible that rising concerns about global climate change and China's ambitious nuclear program could reverse this trend. This paper attempts to assess the global future of nuclear power.

Keywords: climate change, energy forecasting, fusion energy, nuclear energy, renewable energy

NONMENCLATURE

EJ	exajoule = 10^{18} joule
EROI	energy return on energy invested
GHG	greenhouse gas
GW	gigawatt (10^{9} watt)
IPCC	Intergovernmental Panel on Climate Change
MW	megawatt (10^{6} watt)
OECD	Organization for Economic Cooperation and Development
ppm	parts per million
RE	renewable energy
SMR	Small Modular Reactor
TWh	terawatt-hour (10^{12} watt-hour)

1. INTRODUCTION

The first nuclear power plant was connected to the electricity grid in 1956 in the UK. The 1960s and 1970s were times of unbridled optimism for the future of nuclear power. In a 1976 publication, the International Atomic Energy Agency [1] predicted a global nuclear installed capacity of 2500 gigawatt (GW) for year 2000. The actual installed capacity in 2000 was only 348 GW [2]. Global nuclear power output did rise quite rapidly until the late 1980s, but then the annual growth rate fell, as shown in Figure 1. As a share of global electricity, nuclear power peaked at 17.5% as early as 1996, but by 2017 had fallen to only 10.3% [3]. In absolute output, nuclear energy has not yet (2019) surpassed the 2006 value of 2804 terawatt-hours (TWh).

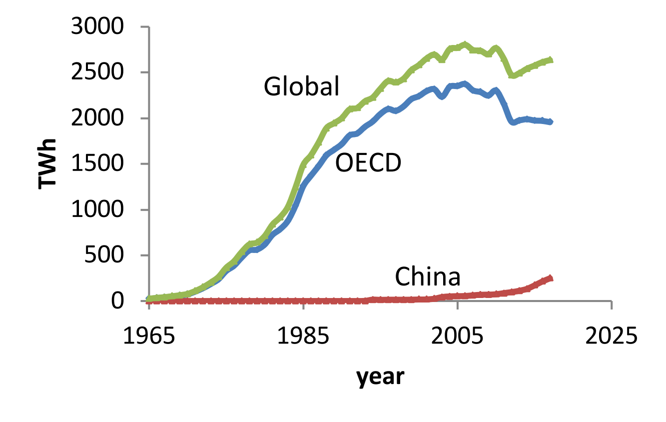

Figure 1. Nuclear power output in TWh for world overall, OECD and China, for years 1965-2017. Source; [3].

As Figure 1 shows, in the OECD countries, which still account for most nuclear energy, output is in decline, the result of opposition to nuclear power and escalating costs of construction. China, and to a lesser extent other rapidly industrializing countries, are seen as providing the main hope for a nuclear power revival. Particularly in OECD countries, nuclear reactors have taken many years to plan and build, partly because of their complexity and partly because of a lack of standardization. Further, as a result of the downturn in new reactor start-ups, the world's reactor fleet is ageing, and many will be shut down in the next decade or so [4]. The result of long construction lead times is that forecasting the maximum possible nuclear output is relatively simple over the next decade or so. After that period, the nuclear future is increasingly uncertain.

2. NUCLEAR POWER CONTROVERSIES

Over the past four decades or so, nuclear energy has generated extraordinary controversy, both at the popular level and in the published literature. While some nuclear power countries in the OECD are committed to closing all nuclear plants, other nations, particularly China, are pushing ahead with ambitious nuclear programs.

Table 1 gives a small selection of published papers from the vast literature on both sides of the controversy for a number of different aspects of nuclear power. Most of the authors listed in one or other entries in the 'Optimistic' column would also be optimistic on the other entries; the same is true for 'Pessimistic' column authors. Researchers are similarly polarised—either 'for' or 'against' nuclear power.

Table 1. Nuclear power controversies

Nuclear Energy controversy	**Optimistic papers**	**Pessimistic papers**
Nuclear power's future	[1, 5]	[6-10]
Nuclear energy essential for climate change mitigation	[11-14]	[15-17]
Energy return on energy invested (EROI) for nuclear energy	[18]	[2, 19]
Future costs for nuclear energy	[20]	[4, 21]
Size and cost of uranium reserves	[5, 22]	[23]
Environmental benefits of nuclear power	[13]	[24]
Dangers of nuclear weapons proliferation	[25]	[2, 8]
Risk from serious nuclear accidents	[5]	[26, 27]
Successful introduction of fusion power	[12, 28]	[29, 30]

One overarching problem facing nuclear power is that for success, nuclear power must score positively on most of the entries, whereas it might only take *one* negative entry to doom this energy source. If the risk of serious nuclear accidents is too great, if uranium reserves are not adequate, or if costs are much greater than alternative energy sources (such as renewable energy), then nuclear power's future is in doubt.

Possibly the most important argument in favour of expanding nuclear power is that nuclear power is essential for climate change mitigation [11-14]. At present, despite the rhetoric, climate change is not taken seriously enough to affect emissions; fossil fuel CO_2 emissions and resulting atmospheric CO_2 levels are still growing strongly [3, 14]. But such neglect cannot continue for much longer, so that all alternatives to fossil fuels must be considered. Further, massive and rapid expansion of the other non-carbon energy source, renewable energy, has its own problems [31, 36].

One response to the long lead times and high costs of conventional reactors is to develop Small Modular Reactors (SMRs). They are not really a new idea—interest in them goes back to the 1950s, with a 'second wave of enthusiasm' [32] in the 1980s, but no designs were carried through to the commercial stage. The proposed new reactors, a number of which are now under development in several countries, would be factory made and delivered to site, unlike present large reactors which can have an output of 1000 megawatt (MW) or more. These SMRs, typically sized 10-100 MW, could be used in remote locations, or in countries or regions with electricity demand too small to support a large conventional reactor.

Extravagant claims have been made for these proposed reactors in terms of their safety and utility [32]. To justify the shift away from conventional large reactors, their proponents even acknowledge that conventional reactors carry significant accident risks and waste disposal problems, but claim that SMRs can overcome these challenges. Cost of electricity would likely also be even higher than that for large reactors, because of loss of economies of scale. For industrial plant in general, construction costs per unit of output rise much more slowly with larger plant size.

Fusion reactors, like SMRs, are advocated by their supporters as overcoming the acknowledged problems facing conventional reactors. Since neither type of reactor is in operation, they both have a spotless operating and safety record! Even fusion supporters do not see technical feasibility established before 2035, or its widespread commercial use until at best much later in the century. If the world is to avoid the worst effects of climate change, decisive action cannot wait until late in the century [14].

The tokamak magnetic confinement system is the leading design for fusion power, as used in the ITER plant presently under construction in France. Hirsch [34] has argued that such designs fail on the three criteria for practical fusion power: 'attractive economics, regulatory simplicity, and public acceptance.' For example, the ITER plant has exceeded initial cost estimates by an order of magnitude [34].

3. DISCUSSION AND CONCLUSIONS

3.1 Discussion

This paper is about the *future* of nuclear power. It may be that given the impacts climate change will bring, the past will be a poor guide to our energy future. However, nuclear power shares a vital property with fossil fuels: its continued use will mortgage the future, placing unfair burdens on future generations.

CO_2 is a long lived greenhouse gas (GHG) in the atmosphere, which means that high atmospheric concentrations will persist, even if we stopped emitting CO_2 now. CO_2 atmospheric concentrations have now reached 410 ppm, and the world is already experiencing an increase in the frequency and intensity of extreme weather events such as floods and heat waves [13, 14]. Since further rises in atmospheric CO_2 ppm seem inevitable, our legacy to future generations will be an increasingly hostile environment.

However, nuclear wastes are similarly long lived. Plutonium has a half-life of 22,400 years, which means that a roughly 1000-fold decay needed to render wastes harmless to humans will take 10 half-lives or 224,000 years [2]. For comparison, remember that the nuclear era is only 7-8 decades old. Like CO_2, which also has a long (atmospheric) half-life, radioactive wastes will continue to accumulate, and no permanent waste disposal repositories are operational anywhere on the planet.

The climate is changing and will continue to change in likely unpredictable ways—we are moving toward a 'no-analogue' climate future [34]. We have no real idea of what human settlement patterns will be over the next 250 years, let alone 250 millennia. Nor do we know the future hydrological regimes of proposed repositories. Further, the present standards of temporary above-ground storage do not give confidence that an ever-rising volume of waste will be safely dealt with. Waste disposal is a cost which nuclear operators will attempt to minimise.

Today we have many examples of failed states and on-going civil wars. What if nuclear power spreads to most countries, and the governance standards of a country deteriorates? What will that mean for reactor safety and proper and continued waste disposal and monitoring?

Most discussions on nuclear safety assume that all parties are well-intentioned. Even Charles Perrow's noted book on '*Normal Accidents*' [35] implicitly assumes that any likely serious events *are* accidents, not deliberate acts of sabotage or terrorism.

3.2 Conclusions

As Table 1 showed, there is no agreement on any of the key aspects of nuclear energy, nor are these controversies likely to be satisfactorily settled any time soon. Proponents of nuclear power can point to the urgent need to respond seriously to climate change, and so argue that the current decline in nuclear power's fortunes will soon be revived. Further, the evident problems with present reactors will be solved, they argue, with new reactor types—SMRs and fusion reactors. Opponents can point out unresolved safety, waste disposal and weapons proliferation problems.

In the welcome but unlikely event that unlimited supplies of cheap RE could be rapidly implemented, the controversies would melt away. Given that this is unlikely [31], the arguments are likely to continue. Unfortunately, the controversies might also vanish if further serious nuclear accidents or nuclear terrorism were to occur.

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REFERENCES

[1] Krymm R, Woite G. Estimates of future demand for uranium and nuclear fuel cycle services. IAEA Bull 1976;18(5/6).
[2] Moriarty P, Honnery D. Rise and fall of the carbon civilisation. London: Springer; 2011.
[3] BP. BP statistical review of world energy. London: BP; 2018.

[4] Froggatt A, Schneider M. Nuclear power versus renewable energy: a trend analysis. Proc IEEE 2015;103(4):487-490.
[5] Sekimoto H. A roadmap of innovative nuclear energy system. J Phys 2017;Conf Ser 799(012001) (doi:10.1088/1742-6596/799/1/012001).
[6] Kramer D. US nuclear industry fights for survival. Physics Today 2018 71(12), 26 (doi: 10.1063/PT.3.4088).
[7] Grossman L. Nuclear holiday. New Scientist 2017 20 May 20-21.
[8] Johnstone P, Sovacool BK, MacKerron G, Stirling A. Nuclear power: serious risks. Science 2016;354(6316):1112.
[9] Moriarty P, Honnery D. Energy policy and economics under climate change. AIMS Energy 2018;6(2):272–290.
[10] Lovins AB. Nuclear power: deployment speed. Science 2016;354(6316):1112-1113.
[11] Stover D. Kerry Emanuel: A climate scientist for nuclear energy. Bull Atom Sci 2017 73(1):7–12.
[12] Li J, Zhang J, Duan X. Magnetic fusion development for global warming suppression. Nucl. Fusion 2010;50:014005 (5pp).
[13] Kharecha PA, Hansen JE. Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. Environ Sci Technol 2013;47:4889–4895.
[14] Intergovernmental Panel on Climate Change (IPCC). Global warming of 1.5 °C: summary for policy makers 2018. Accessed on 25 February 2019 at (http://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf).
[15] Squassoni S. The incredible shrinking nuclear offset to climate change. Bull Atom Sci 2017;73(1):17-26.
[16] Granger Morgan M, Abdulla A, Ford MJ, Rath M. US nuclear power: The vanishing low-carbon wedge. PNAS 2018 115(28) 7184–7189.
[17] Makhijani A. Nuclear isn't necessary. Nature Reports: Climate Change 2008 ;2:132-134.
[18] McCombie C, Jefferson M. Renewable and nuclear electricity: Comparison of environmental impacts. Energy Policy Energy Policy 2016;96:758–769.
[19] Hall CAS,Lambert JG, Balogh SB. EROI of different fuels and the implications for society. Energy Policy 2014;64:141–152.
[20] Vine D, Juliani T. Climate solutions: the role of nuclear power. Arlington, VA: Center for Climate and Energy Solutions; April 2014, 11pp.
[21] Ramada M. Why India's electricity is likely to remain in short supply: the economics of nuclear power. Bull Atom Sci 2013;69(6):67–78.
[22] Warren P, De Simone G. Fuelling the future? Energy Policy 2014;74:S5-S15.
[23] Dittmar M. The end of cheap uranium. Sci Total Environ 2013;61–462:792–798.
[24] Abbott A. Researchers pin down risks of low-dose radiation. Nature 2015;523:17-18.
[25] Grape S, Svärd SJ, Hellesen C, Jansson P, Lindell MA. New perspectives on nuclear power—Generation IV nuclear energy systems to strengthen nuclear non-proliferation and support nuclear disarmament. Energy Policy 2014;73:815–819.
[26] Perrow C. Fukushima and the inevitability of accidents. Bulletin of the Atomic Scientists 2011;67(6):44–52.
[27] Rose T, Sweeting T. How safe is nuclear power? A statistical study suggests less than expected. Bull Atom Sci 2016;72(2):112–115.
[28] Takeda S, Pearson R. Nuclear fusion power plants. Accessed on 22 February 2018 at (http://dx.doi.org/10.5772/intechopen.80241); 2018.
[29] Moriarty P, Honnery D. Intermittent renewable energy: The only future source of hydrogen? Int J Hydrogen Energy 2007;32:1616–1624.
[30] Kembleton R. Nuclear fusion: What of the future? In Letcher T (ed), Managing global warming an interface of technology and human issues. London: Academic Press; 2019, pp.199-220.
[31] Moriarty P, Honnery D. Can renewable energy power the future? Energy Policy 2016;93:3-7.
[32] Sovacool BK, Ramana MV. Back to the future: small modular reactors, nuclear fantasies, and symbolic convergence. Science, Technology, & Human Values 2015, 40(1) 96-125.
[33] Hirsch RL. Necessary and sufficient conditions for practical fusion power. Phys Today 2017;October:11-13.
[34] Fitzpatrick MC, Blois JL, Williams JW, Nieto-Lugilde D, Maguire KC, Lorenz DJ. How will climate novelty influence ecological forecasts? Using the Quaternary to assess future reliability. Glob Change Biol 2018;24:3575–3586.
[35] Perrow C. Normal accidents: Living with high risk technologies (Updated Edition) Princeton, NJ: Princeton Univ. Press; 1999.
[36] Moriarty P. Wang SJ. Assessing global renewable energy forecasts. Energy Procedia 2015;75:2523-2528.

