Is Nuclear Power Globally Scalable?

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While robust debate over climate science and remaining oil reserves exist, what is universally agreed is that the era of "easy" oil is on the decline. It cannot be denied that the global rate of discovery of new large oil fields has been in decline since the 1960s [1] and that discoveries are not replacing oil produced [2]. These facts together with increasing world population, increasing economic activity, and our increasing reliance on an energy-intensive economy lead to price *volatility*.

What matters is not an argument over the absolute amount of remaining fuel reserves, but the mismatch between growth in supply and demand driving price volatility to levels where unprecedented economic instability and civil unrest may become the immediate dangers. The time to act and to begin averting such a crisis is now.

Given the awesome power density delivered by nuclear stations, it is a valid question to ask if nuclear power can be massively scaled in order to meet our global energy needs. We shall explore the consequences of a future where nuclear power is the main[1] energy source. Currently, the total global power consumption by mankind is about 15 terawatts (TW) [4]—so the question we address is: Can nuclear power feasibly supply[2] at least 15 TW?

If we can show that nuclear power can viably provide massive power at this level, for millennia to come, then the investment in improving and scaling-up nuclear technology is justified. However, if we find it does not scale up, then major investment must be redirected to a different solution that is truly scalable. It has been argued that the one renewable energy solution that is scalable well beyond 15 TW is *solar thermal* technology [5]—this is where large mirrors are used to focus sunlight to heat water thereby creating superheated steam, which can then generate electricity via a conventional steam turbine. The potential is enormous, as the amount of solar power that reaches ground level is 5000 times our present world power consumption. Therefore, the pertinent question is to ask how nuclear power compares to solar

[1]With plentiful supply of nuclear power, one might imagine it being tapped to even produce transportation fuel [3].

[2]In a hypothetical nuclear utopia, it would take over one century to build up to a level of 15 TW and by then the world power consumption will be considerably higher. However, for order of magnitude calculations, 15 TW is a reasonable figure for examining the large-scale feasibility of nuclear power. For simplicity, we will generously assume that conversion of nuclear thermal energy to electricity is 100% efficient (i.e., $TW_e = TW_t$)—as we are focussed on large-scale first-order calculations it makes little difference to the final conclusions.

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thermal power as an energy resource on a massive global scale.

I. THE NUCLEAR SITE LOCATION PROBLEM

Currently, there are about 440 commercial nuclear reactors worldwide, and to expand to 15 TW would require in the order of 15 000 reactors. One obvious problem when faced with this number is the question of where to locate them. An interesting exercise for the student is to take a map of any country of the world and try to mark locations where nuclear stations could be realistically placed. One has to find locations away from dense population zones, natural disaster zones, and near to a massive body of coolant water. The United States, for example, already has > 60 commercial reactor locations, and finding as few as 100 more new sites free of impediment is potentially a considerable challenge.

This problem can be reduced by colocating reactors, however, this is at the risk of common mode and common cause failures. Also, in the case of using rivers for coolant water, colocation of nuclear stations will have practical limitations due to consequent temperature increase of the rivers. Locating reactors away from large water sources, by use of air cooling, increases cost and decreases availability of coolant water for emergencies.

II. THE LAND AREA PROBLEM

Taking into account not just the footprint area of a nuclear power station itself, but also its exclusion zone, associated enrichment plant, ore processing, and supporting infrastructure, work at Stanford University, Stanford, CA [6] has shown that each nuclear power plant surprisingly requires an extended land footprint area of as much as 20.5 km^2. While this is a little less than the area it would take for a typical desert-based solar thermal farm (with suitable storage) to generate the same power output, the advantage of solar thermal is in its much lower complexity and its use of unused desert area, whereas nuclear stations tend to take up prime area adjacent to sources of coolant water. Coupling the difficulty of strategic choice of location (as in Section I) with this large area requirement questions the ability to scale up to 15 000 reactors.

Another factor to consider is land reuse after decommissioning. There are uncertainties in the length of time it would take before the land is available for reuse. In the case of decommissioning by entombment or at the site of a prior accident, the land may not be available for reuse at all within a given century.

III. THE EMBRITTLEMENT PROBLEM

All forms of nuclear power, whether thorium or uranium, fission or fusion, emit neutrons that irradiate all metal surfaces inside the nuclear vessel. Over time these metal surfaces develop cracks due to *neutron embrittlement* [7]. It is an unavoidable consequence of any form of nuclear power and is part of the aging process that requires every nuclear power station to be decommissioned after 40–60 years of operation. Thus, if nuclear stations need replacement every 50 years on average, then in the steady state for 15 TW, one nuclear power station needs to be built and another decommissioned somewhere in the world every day. This is questionable, given that nuclear stations are complex as evidenced by the fact they take on the order of 6–12 years to build [8], and then around 20–50 years to decommission.[3]

Note, for example, if a reactor operates for 60 years and takes 20 years to decommission, then the land utility for power production, in watts per square meter, is effectively reduced by 25%.

[3]In practice, there is a tradeoff between decommission time and cost—allowing more time for radioactive products to decay reduces cost; as then there are fewer contaminants to deal with. Currently, cost-cutting measures usually drive the situation toward taking longer decommission times.

IV. THE ENTROPY PROBLEM

In a nuclear power station, entropy is an unavoidable byproduct of the generation of large amounts of energy. These large energy densities, in a given time, have to be contained within an ordered structure. Maintaining order while subjected to a high entropy condition is a challenging situation, and this leads to a tradeoff between reliability and efficiency. In the same way that any electrical device or machine heats up and eventually fails, the same is inexorably true for a nuclear station.

In Section III, neutron bombardment of the metal surfaces is pointed out as a key degradation mechanism in the nuclear vessel. However, it should be noted that this is not the only effect. Together with embrittlement, the metal structure is also subject to corrosion, oxidation, thermal creep, irradiation creep, phase instability, volumetric swelling, void swelling, grain boundary sliding, intergranular degradation, fracture, cavitation, and radiation-induced segregation (RIS) [7]. It is all these aging factors acting together that unavoidably lead to plant shutdown after 50–60 years of operation.

The situation in proposed Generation IV reactors is worsened where the vessel is 1) exposed to higher temperatures, 2) higher neutron doses, and 3) a greater corrosive environment [7]. There are thus significant challenges to materials selection for Generation IV proposals and this is one of the key uncertainties in their commercial realization.

The effects of entropy leading to disorder in the metal lattice of the nuclear vessel can be mitigated to some extent by opting for modular arrays of small reactors, rather than building large nuclear reactors, as the power density is then distributed over a larger surface area. However, as we will see, in Section XIII, there are resource considerations that limit all forms of nuclear power.

V. THE NUCLEAR WASTE PROBLEM

After 60 years of nuclear technology, there is still no universally agreed mode of disposal [9] and nuclear waste still raises heated controversy. As mankind has not progressed past this first base, it would appear irresponsible to leap toward 15 000 reactors before the problem is settled. At this massive scale, there is not only the problem of spent fuel, but the problem of where to put all the decommissioned reactors. Burial of waste has uncertainty in terms of unforeseen geological movement and radioactive leakage into groundwater. If thousands of reactors were to be commissioned across the planet, the waste management over such a wide geopolitical spectrum would give rise to high levels of uncertainty.

VI. THE ACCIDENT RATE PROBLEM

To date, globally, there have been ~580 nuclear reactors that have operated for a cumulated total of 14 000 reactor years, with about 11 accidents of the magnitude of a full or partial core melt [10]—this corresponds to failure rate of $11 \times 100/580 = 2\%$. Thus, if the world had a single reactor, it would take on average 14 000/11 ~1300 years to have an accident of a similar magnitude. Thus, for a scaleup to 15 000 reactors we would have a major accident somewhere in the world every month.

But are we justified in using historical data for these statistics, when the engineering of safety features for nuclear plants has surely improved? The answer is we are not justified in evaluating the likelihood of a large accident in any other way, as we are talking about *rare* events that are not even possible to model in a system as complex as a nuclear station. There are many unforeseen pathways to an accident and there are large rare events that can knock out redundant backup systems in parallel.

Because a nuclear station is a complex system, and where redundant subsystems are necessarily colocated, redundancy can fail[4] and can even have a negative impact [11]. By contrast, for example, a solar thermal farm is a simple *distributed* modular system and here the concept of redundancy works in its favor.

VII. THE PROLIFERATION PROBLEM

The presence of nuclear power creates an infrastructure where materials and expertise for weapon making can proliferate [12]. Different types of reactors have different levels of proliferation resistance, but no matter how they are badged the fact is that all nuclear fuels and all nuclear products can be utilized in a dirty bomb, if not a nuclear bomb. Even deuterium used in heavy water reactors and fusion reactors, at large volume, is cause for concern as it can be used to make lithium-6 deuteride thermonuclear warheads. It would be near impossible to maintain accountability with a scaleup to 15 000 reactors worldwide. Indeed, it is already challenging for today's relatively small nuclear industry to provide assurance that materials have not been diverted for weapons.

VIII. THE ENERGY OF EXTRACTION PROBLEM

As we use up uranium ores, the trend is to move to lower grade ores with lower concentrations of uranium. The energy of extraction in terms of mining and milling the ore then increases. It is known that energy of extraction sharply increases for low grade ores of any mineral [13], [14]. The question is what is the minimum uranium ore concentration to break even?

A typical figure for total energy consumed in mining uranium is $W =$ 200 GJ/ton or 0.2 GJ/kg [13]. Thus, to break even, we need $mW = mc\eta\epsilon$. The energy in the ore is $mc\eta\epsilon$, where m is the mass of the ore, c is the uranium concentration in the ore, $\eta = 0.007$ is the U^{235} fraction, and $\epsilon = 83.14$ TJ/kg is the energy density. Thus, the ore concentration we need to pay for mW is $c = W/\eta\epsilon = 340$ ppm. Allowing latitude for some variance in the figures and the possibility of more energy efficient mining, this figure would nevertheless suggest that concentrations below 100 ppm would be difficult to justify. This consideration sets a limit to the viable uranium ore resource available with current technology [14].

[4]The possibility of a failure in redundancy can be intuitively seen in the aphorism: "Two birds tied together have four wings yet cannot fly."

IX. THE URANIUM RESOURCE PROBLEM

Given the above constraint on ore concentration, it should be no surprise that the World Nuclear Association projects 80 years of viable uranium at the current rate of consumption with conventional reactors [15]. The 2010 figure for world installed nuclear capacity is 375 GW and, if we scaled this up to 15 TW, the figure of 80 years for uranium supply would drop below 5 years.

X. THE SEAWATER EXTRACTION PROBLEM

When faced with the situation of only low-grade nonviable uranium sources remaining in the crust, seawater is often cited as the solution as it contains large quantities of uranium. Active research in uranium extraction from seawater underscores the acceptance that high grade uranium ores are rapidly depleting.

How much uranium is there in the sea? The total volume of seawater in the world is $V_o = 1.37 \times 10^{18}$ m^3—given a seawater density of 1030 kg/m^3 and a uranium concentration of 3.3 ppb, the total uranium content is enormous at 4.6×10^{12} kg [14], [16].

If we exploit this to provide 15 TW, how long would it last? The fissile

U^{235} is 0.7% of the total uranium, yielding 3.2×10^{10} kg. The U^{235} energy density[5] is 83.14 TJ/kg, giving a total energy content of 2.7×10^{12} TJ. To then, supply 15 TW would last 5700 years. If we use fast breeder reactors (FBRs), which extend uranium use by a factor of 60, we obtain $5700 \times 60 > 300\,000$ years and such a large figure gives promise of a nuclear utopia for thousands of centuries.

However, the mistake here is that the *rate* of extraction[6] has been overlooked. For example, a distant galaxy may contain massive quantities of uranium, but the rate of extraction is precisely zero. In our case, a 3.3-ppb concentration[7] is very low and therefore we must consider rates of extraction in assessing feasibility. Using the *mass-balance equation* we can determine the volume flow rate F of water we would need, in order to fuel 15 TW of reactors with sufficient uranium

$$V_o \frac{dc}{dt} = -Fc$$

where c is the uranium concentration. It is tempting to suppose this results in a simple exponential—but this is wrong because c is not independent of F. The concentration continuously drops, as uranium is extracted, while F is forced to increase to keep up the supply of uranium, i.e., $F \propto 1/c$. Thus putting $F = k/c$, we obtain

$$V_o \frac{dc}{dt} = -k$$

and solving this gives

$$F = \frac{V_o F_o}{V_o - F_o t}$$

where $F_o = 7.6 \times 10^6\ \mathrm{m^3/s}$ is the initial flow rate required to supply 15 TW. Notice this formula has a first-order pole, so that F tends to infinity—this means that flow rate cannot ultimately keep up with the drop in concentration.

Infinite flow rate in 5700 years implies that uranium extraction would become uneconomical in a tiny fraction of that time. To appreciate this, let us calculate the total water processed V_{TOT} over a time period T

$$V_{\mathrm{TOT}} = \int_0^T F dt = -V_o \ln(1 - F_o T/V_o).$$

This tells us that, for example, in as little as $T = 30$ years, a volume of seawater of $7 \times 10^{15}\ \mathrm{m^3}$ would need to be processed—this is clearly impractical as it is over six times larger than the volume of total river outflow in the same time. Note that the total river discharge into seawater over this period is about 15% of this volume, and hence our approximation that uranium is not appreciably replenished roughly holds given the current estimates for riverine uranium levels that transfer to seawater [18]. The enormous water requirement can be somewhat mitigated, by use of FBRs, however many of the other limitations discussed in this article do not auger well for widespread scaling up of the number of FBR reactors—in particular, see Section XIII.

A possible solution [19] is that uranium could be absorbed passively by using seaweed or microalgae of surface area S. However, S and F are conjugate variables and S will similarly tend to infinity, if we keep $F = 0$—thus the quantity of absorbent would become unsustainable.

XI. FAST BREEDER REACTORS

FBRs are cited as a possible solution to the uranium supply problem as they extend the use of uranium by a theoretical factor of 60 times. The factor of 60 is quite attractive—it means that if there is currently five years of economically viable uranium left at 15 TW, then with an FBR this extends it out to $60 \times 5 = 300$ years.

We will leave aside the fact that FBRs are fraught with reliability problems as they use liquid sodium coolant. Also let us generously ignore that FBRs have scalability uptake limits, as they take ten years to generate enough additional fuel in order to commission a new FBR [20].

Let us focus on an economic viability issue regarding FBRs. First, recall that if we move to lower grade uranium ores, for every tenfold decrease in uranium concentration there is a 300-fold increase[8] in recoverable uranium [21]. This nominally, of course, is at the expense of a tenfold increase in cost. So if we can afford an increase in cost by a factor p, then our accessible uranium increases by $300 \log(p)$.

Now let us ask what mining cost increase would result in a 60-fold increase in uranium. This will then give us an idea of whether FBRs are really gaining us anything in real economic terms. Thus putting $300 \log(p) = 60$ results in a cost increase of $p = 1.3$. This tells us that if one tolerates a 1.3-fold increase in mining cost for fueling conventional nuclear reactors, one gets an effective increase that matches using an FBR.

This shows that for the extra complexity of an FBR, its ability to extend uranium use is uncompetitive. It is better to use a conventional reactor, and tolerate an increase in fuel cost.

[5]The extractable work or *exergy* is in fact 77 TJ/kg [17] but we will generously use the higher figure and assume it is converted to electrical energy at 100% efficiency.

[6]This is akin to when a communications engineer characterizes channel capacity—it is the bit *rate* that is the important quantity.

[7]To appreciate just how low 3.3 ppb is, let us consider a terrestrial uranium ore of the same concentration. Is the energy content in such an ore enough to pay the mgh energy to lift it out of the mine? To break even, $mgh = mc\eta\epsilon$, and thus the distance $h = c\eta\epsilon/g = 50$ m and is independent of the mass of the ore. Therefore, the energy content in such an ore is well below the energy of extraction.

[8]A principle of the natural world is that small things are more abundant than large things. A fractal has many more smaller branches. A corollary is that smaller concentrations are more common than large concentrations of a resource. If we can tap a resource at lower concentration, we can obtain more of it, though this is at the expense of reduced *rate* of extraction and increased energy of extraction.

Cost will gradually increase, and FBRs will always be a step behind conventional reactors. Then, when a cost threshold is crossed where nuclear fuel is no longer viable for conventional reactors, the capital investment in FBRs will be difficult to justify, particularly if renewables have gained a major foothold by then. A salient reminder is that as of 2010, the world installed generation capacity of solar plus wind exceeds that of nuclear power [22].

XII. FUSION REACTORS

Given all the above problems with nuclear fission, can a nuclear fusion renaissance lead us to a nuclear utopia? The answer is no, because the underlying problem of neutron embrittlement (Section III) will limit scalability as it does with fission. The rate of commissioning and decommissioning fusion reactors would be equally untenable.

There are a number of serious problems that limit practicability. For example, the walls of a fusion reactor absorb tritium and would need regular ablation resulting in the generation of tritium-laden explosive dust [5].

It would also appear that fusion events feed power to the fundamental mode of instability for Tokamaks. This is generally overlooked, as it is assumed that any fusion event will on average inject energy and momentum equally throughout the plasma—but this only applies for an infinite bulk plasma. In a regular Tokamak, as $\nabla B = 0$, the innermost points near the toroidal field coils have the highest magnetic field and fusion events are predominantly located here. As this is the outermost closed surface, any event that generates fusion products heading towards the central hole of the torus results in lost momentum from the net balance. Consequently, the net momentum is outward from the hole in a periodic fashion around the torus in exactly the W2 mode [23].

The problems of both explosive dust and instability suggest that the likelihood of seeing commercial fusion this century is virtually zero. In the following section, we will now articulate an important limit to scalability that applies to all forms of nuclear power, whether fusion or fission, uranium or thorium.

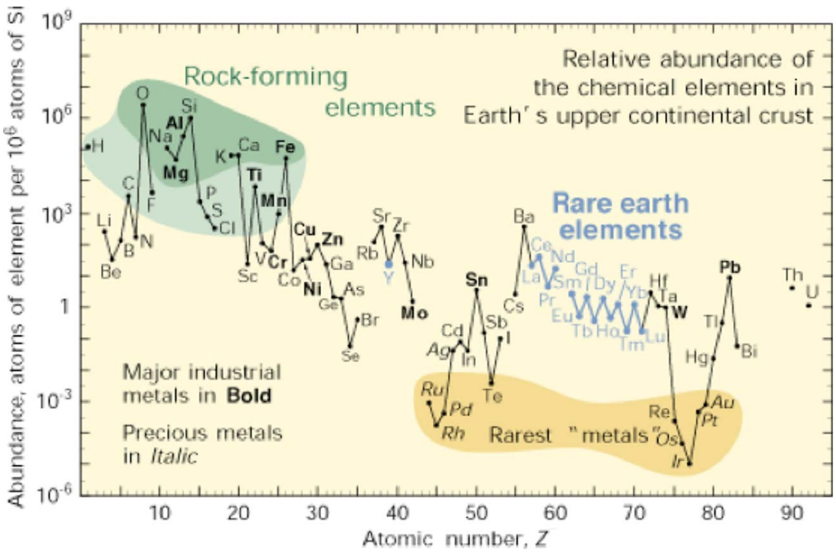

Fig. 1. ***The relative abundance of the elements of the periodic table within the Earth's crust. As the vertical scale is logarithmic the top elements are about a billion times more abundant than the lowest ones on the right-hand side. Notice that the exotic metals used in nuclear power are at the low end, whereas the materials required for solar thermal are in the abundant end. Source: USGS.***

XIII. THE MATERIALS RESOURCE PROBLEM

An important question that has been neglected in the nuclear debate is to ask what materials a nuclear vessel and core are made of. It turns out a whole host of exotic rare metals are used to control and contain the nuclear reaction. For example, hafnium is a neutron absorber, beryllium a neutron reflector, zirconium is used for cladding, and many of the other exotics (e.g., niobium) are used to alloy steel to make the vessel last 40–60 years against neutron embrittlement.

Then, one has to look at the quantities of toxic chemicals one introduces into the environment by extracting these exotic metals from their ores and ask questions about costs, sustainability, and environmental impact.

In Fig. 1, we see the relative abundance of the chemical elements in the Earth's crust—many of the metals used for nuclear containment are in the lower end of the graph; whereas, materials used for solar thermal are in the high end. If we were to scale to 15 000 reactors, are there limits to the uptake in these metal resources? Let us consider the *extinction time* T of a selected example of these metals, as defined by the following equation [24]:

$$T = \frac{1}{k}\ln\left(1 + \frac{kR}{P}\right)$$

where k is annual growth rate in consumption, R is the known reserve base, and P is the annual world consumption of a given resource. Using 2008 U.S. Geological Survey (USGS) figures, we construct Table 1 for a few example metals, found in nuclear power stations, using figures for use across *all* industries. The idea is we are interested in total consumption, not just use in nuclear power station construction, as these metals represent resources with competing applications.

Remember that these figures do not predict actual resource extinction times. If for political, or economic reasons, we suddenly stop using a

Table 1 Extinction Times for Selected Metals Used in Nuclear Reactors

Resource	Reserves R (tonnes)	Ann. Production P (tonnes)	Growth k (/yrs)	Rel. Extinction Time T (yrs)
Beryllium	8.0×10^4	4,470	0.10	10
Niobium	2.9×10^6	6,2000	0.09	19
Zirconium	5.6×10^7	1,280,000	0.04	25
Yttrium	5.4×10^5	400	0.22	26
Hafnium	6.6×10^5	8	0.38	28

resource it will last forever. We cannot predict that. What we are showing are *relative* extinction times, assuming present annual growth rates in consumption and known reserves—this is to be used as a relative figure of merit. What is alarming is that these annual growth rates in consumption are enormous compared to, say, crude oil which has dropped negative in recent years. Then, if we scale up to 15 000 reactors we will either rapidly exhaust these materials or drive them into a high price volatility regime, creating market instability. In solar thermal technology, all the metals are abundant and recyclable, whereas in nuclear technology, the metals are rare and become radioactive. Thus, in the endgame, one expects greater price volatility in a nuclear utopia than in a solar thermal utopia.

In Section III, we indicated that—in a nuclear utopia—a nuclear station would need to be built somewhere in the world every day. In such a regime, we simply do not have the containment materials to keep up with the required construction of nuclear power stations.

XIV. THE ELEMENTAL DIVERSITY PROBLEM

The metal walls of a nuclear vessel become radioactive [25] and thus when we decommission a nuclear station, the core and vessel is buried for many generations—hence the opportunity to recycle key exotic metals is lost. Thus, nuclear power depletes our base of elemental resources—Can we afford to destroy *elemental diversity* in this way?

One has to recognize that these exotic metals have many competing industrial uses. For example, hafnium is used by Intel in its latest microchip technology. Beryllium is used in precision instrumentation and also by the semiconductor industry. Zirconium has a host of industrial uses in ceramics, gas turbines, and jet engines. Yttrium has applications in lasers and in medicine. Niobium is used in superalloys for aircraft engines and in surgical steel for medicine—nuclear fusion would exhaust niobium even faster than fission.

The nuclear fuels themselves are transmuted and we deny future generations unforeseen applications of these metals. In nuclear fusion, lithium is transmuted and it should be noted that we rely on lithium in every laptop computer and mobile phone. It can be argued that any irreversible consumption of the Earth's elements is shortsighted and detrimental to future technology.

XV. NUCLEAR POWER AND CLIMATE CHANGE

The fervor with which the number of nuclear advocates have taken up the cause of climate change appears some what opportunistic. They propose a rapid upscaled nuclear power program to avert a global warming crisis. This is as deeply suspicious as an undertaker who sponsors a keep-fit program to promote longevity. The proposed rapid uptake is likely to create a mineral resource crisis, as suggested in Section XIII. One can argue that if Intergovernmental Panel on Climate Change (IPCC) scenarios on climate change are on track, as predicted, then nuclear power is inappropriate due to increased risks of weather-related catastrophic accidents—this has been dubbed the *adaptation–mitigation dilemma* [26]. If on the other hand, IPCC scenarios for, say, fossil fuel production are not met, as indicated by the latest work from the California Institute of Technology (Caltech), Pasadena [27], then reasonable climate limits can be maintained by taking no action and the rapid upscale of nuclear power is not required. The conclusion is that nuclear power is an inappropriate response to either of these standpoints.

XVI. CONCLUSION

We have highlighted that there are fundamental engineering and resource scaling limits that make the notion of a nuclear utopia somewhat impractical. There are fundamental limits imposed by embrittlement, accident rate, land resources, fuel resource extraction rate, and mineral resources for making enough nuclear vessels. As the nuclear vessel is irradiated and not recyclable, we highlight that a rapid uptake of nuclear power would seriously limit elemental diversity and would drive up price volatility given there are other significant competing industrial uses of the required metals. Therein lies the rub.

It can be argued that a nuclear nirvana supplemented by renewables may mitigate the need to reach 15 TW by nuclear power alone [28]. Even a lesser goal of several terawatts of nuclear power would run into many of the outlined limitations.Therefore, the notion of a nuclear utopia is a false one. But there are two types of nuclear advocates: the nuclear utopian and the nuclear realist. A nuclear realist would only suggest that we need about 1 TW of nuclear power as part of our world energy mix. However, one only has to divide the results, in this paper, by 15 to see that 1 TW still stretches resources and risks considerably.

One then has to count the cost, consider the safety, the complexity, and the issues surrounding governance of nuclear power. Also if the technology cannot be fundamentally scaled further than 1 TW, one has to ask if the same investment would have been better spent on a truly scalable technology. It has been suggested that for the same investment, solar thermal farms (with storage) would exceed the power output of nuclear stations and eliminate many of the problems [5]. Solar thermal is also scalable as it has the capacity to deliver hundreds of terawatts should mankind require it in the future.

The weakness of a scalable renewable solution, however, is intermittency. In the short term, this problem can be addressed via dual use of solar thermal with natural gas. Then, the natural gas can be phased out, as storage and grid balancing techniques come online to solve the intermittency problem. In a forthcoming Special Issue of PROCEEDINGS OF THE IEEE [29], the intermittency problem will be addressed and a number of technologies for solving this issue will be reviewed. ■

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REFERENCES

[1] *2004 World Energy Outlook*, International Energy Agency (IEA), 2004.

[2] J. Kjärstad and F. Johnsson, "Resources and future supply of oil," *Energy Policy*, vol. 37, pp. 441–464, 2009.

[3] R. B. Duffy, "Nuclear production of hydrogen: When worlds collide," *Int. J. Energy Res.*, vol. 33, no. 2, pp. 126–134, 2008.

[4] *International Energy Outlook 2010*, U.S. Energy Information Administration, DOE/EIA-0484, 2010.

[5] D. Abbott, "Keeping the energy debate clean: How do we supply the world's energy needs?" *Proc. IEEE*, vol. 98, no. 1, pp. 42–66, Jan. 2010.

[6] M. Z. Jacobson, "Review of solutions to global warming, air pollution, and energy security," *Energy Environ. Sci.*, vol. 2, pp. 148–173, 2009.

[7] K. L. Murty and I. Charit, "Structural materials for Gen-IV nuclear reactors: Challenges and opportunities," *J. Nuclear Mater.*, vol. 383, pp. 189–195, 2008.

[8] M. V. Ramana, "Nuclear power: Economic, safety, health, and environmental issues of near-term technologies.," *Annu. Rev. Environ. Resources*, vol. 34, pp. 127–152, 2009.

[9] W. F. Pickard, "Finessing the fuel: Revisiting the challenge of radioactive waste disposal," *Energy Policy*, vol. 38, pp. 709–714, 2010.

[10] T. B. Cochran, "Fukushima nuclear disaster and its implications for U.S. nuclear power reactors," Natural Resources Defense Council (NRDC), Joint Hearings of the Subcommittee on Clean Air and Nuclear Safety and the Committee on Environment and Public Works, United States Senate, Washington, DC, Apr. 2011.

[11] S. D. Sagan, "The problem of redundancy problem: Why more nuclear security forces may produce less nuclear security," *Risk Anal.*, vol. 24, no. 4, pp. 935–946, 2004.

[12] T. B. Cochran, H. A. Feiveson, W. Patterson, G. Pshakin, M. V. Ramana, M. Schneider, T. Suzuki, and F. von Hippel, "Fast breeder reactor programs: History and status," Report 8 in *The International Panel on Fissile Material* (IPFM), Princeton University, NJ, USA, Feb. 2010.

[13] G. M. Mudd, "The environmental sustainability of mining in Australia: key mega-trends and looming constraints," *Resources Policy*, vol. 35, pp. 98–115, 2010.

[14] J. W. S. van Leeuwen, *Nuclear Power—The Energy Balance*, 2007. [Online]. Available: www.stormsmith.nl

[15] World Nuclear Association, 2010. [Online]. Available: http://www.world-nuclear.org/info/inf75.html

[16] U. Bardi, "Extracting minerals from seawater: An energy analysis," *Sustainability*, vol. 2, pp. 980–992, 2010.

[17] W. A. Hermann, "Quantifying global exergy resources," *Energy*, vol. 3, pp. 1685–1702, 2005.

[18] H. Windom, R. Smith, F. Niencheski, and C. Alexander, "Uranium in rivers and estuaries of globally diverse, smaller watersheds," *Mar. Chem.*, vol. 68, pp. 307–321, 2000.

[19] L. Rao, "Recent international R&D activities in the extraction of uranium from seawater," Lawrence Berkeley Nat. Lab., LBNL-4034E, 2011.

[20] C. Llewellyn-Smith, "Energy—The big picture," *Future Energy Mag.*, vol. 3, pp. 58–59, 2008.

[21] K. S. Deffeyes and I. D. MacGregor, "World uranium resources," *Sci. Amer.*, vol. 242, pp. 66–76, 1980.

[22] M. Schneider, A. Froggatt, and S. Thomas, "Nuclear power in a post-Fukushima world," The World Nuclear Industry Status Report 2010–2011, 2011.

[23] W. Hurlbut, Sep. 2010, Microtech Instruments, Inc., Eugene, OR, private communication.

[24] A. A. Bartlett, "Forgotten fundamentals of the energy crisis," *Amer. J. Phys.*, vol. 46, no. 9, pp. 876–888, 1978.

[25] M. Ishikawa, M. Kawasaki, and M. Yokota, "JPDR decommissioning program—Plan and experience," *Nuclear Eng. Design* vol. 122, pp. 357–364, 1990.

[26] N. Kopytko and J. Perkins, "Climate change, nuclear power, and the adaptation-mitigation dilemma," *Energy Policy*, vol. 39, pp. 318–333, 2011.

[27] D. Rutledge, 2011. [Online]. Available: http://rutledge.caltech.edu

[28] W. Manhiemer, "Can fusion and fission breeding help civilization survive?" *J. Fusion Energy*, vol. 25, no. 3–4, pp. 121–139, 2006.

[29] W. F. Pickard, L. di Marco, and D. Abbott, Eds., "Addressing the intermittency challenge: Massive energy storage in a sustainable future," *Proc. IEEE*, 2011.