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IT IS 5 MINUTES TO MIDNIGHT

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Limits to growth: Can nuclear power supply the world's needs?

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Abstract

Could nuclear power be rapidly expanded on a global scale? There are a number of practical limiting factors, including site availability and acceptability, nuclear waste disposal issues, and the risks of accidents and proliferation. But there are also a variety of resource limitations. One particular resource limitation that has not been clearly articulated in the nuclear debate thus far is the availability of the relatively scarce metals used in the construction of the reactor vessel and core. While this scarcity is not of immediate concern, it would present a hard limit to the ultimate expansion of nuclear power. This limit appears to be a harder one than the supply of uranium fuel. An increased demand for rare metals—such as hafnium, beryllium, zirconium, and niobium, for example—would also increase their price volatility and limit their rate of uptake in nuclear power stations. Metals used in the nuclear vessel eventually become radioactive and, on decommissioning, those with long half-lives cannot be recycled on timescales useful to human civilization. Thus, a large-scale expansion of nuclear power would reduce "elemental diversity" by depleting the world's supply of some elements and making them unavailable to future generations.

Keywords

elemental diversity, nuclear power, resource limits, scalability, solar thermal, uranium

Nuclear power advocates can be broadly described in two categories: nuclear realists and nuclear utopians. A nuclear realist suggests something on the order of 1 terawatt of nuclear power as part of the global energy mix, providing security in terms of energy diversity and reduced carbon emissions. Nuclear power is attractive, for example, for highly industrialized populations living on islands with a paucity of natural resources. It can also be argued that nuclear power has a key role to play in meeting emissions targets (Brook, 2012) for mitigating climate change.[1]

A nuclear utopian goes much further and suggests that nuclear power can potentially supply the bulk of the world's energy needs for many thousands of years to come and that perhaps a mix of renewables with nuclear power as the backbone supply is the long-term energy future (Manheimer, 2006). Given the awesome power density delivered by nuclear stations, it makes sense to ask whether nuclear power can be massively scaled up to meet global energy needs.[2] If the utopian vision is a valid one, then it provides considerable impetus to pull together and solve the various practical, safety, and economic problems that currently limit the rapid expansion of nuclear power.

Currently, the total global power consumption is about 15 terawatts (EIA, 2011). If nuclear power can feasibly supply at least this much power, investments in improving and scaling up nuclear technology are justified.[3] However, if there are drastic limits to scaling up nuclear power, it might be better to invest in other technologies instead. As these limits are not entirely independent from each other, it is important to understand their interplay.

Let's assume that the conversion of nuclear thermal energy to electricity is 100 percent efficient. For the purpose of large-scale calculations, this generous assumption makes little difference to the conclusions. Now imagine a world where 15 terawatts is supplied by 15,000 1-gigawatt reactors. Let's explore the limiting factors in such a world.

Site selection

Today there are about 430 commercial nuclear reactors worldwide (Schneider et al., 2012). Expanding that to 15,000 reactors requires finding locations away from densely populated areas and natural disaster zones, and near massive bodies of coolant water. The United States, for example, already has more than 60 commercial reactor locations and would need about 4,000 in a nuclear utopia. Finding as few as 100 new sites in the United States is potentially a considerable challenge. As an exercise, take a map of any country and try to mark only 10 additional locations where nuclear stations could realistically be placed. You will quickly see that 15,000 is a daunting number.

Co-locating reactors can reduce this problem, but doing so increases the risk of common-cause failures. Also, in places where rivers are tapped for coolant water, co-located nuclear stations are likely to push the temperature of the rivers beyond acceptable limits. Locating reactors away from large water sources and cooling them with air increases cost and decreases the availability of coolant water for emergencies.

Taking into account not just the footprint of a nuclear power station but also its exclusion zone, associated enrichment plant, ore processing, and supporting infrastructure, Stanford's Mark Z. Jacobson (2009) has shown that each nuclear power plant draws upon a total land area of as much as 20.5 square kilometers. Unlike certain renewable energy sources, such as solar thermal plants and wind projects, which can be located in remote areas, nuclear stations tend to take up prime real estate adjacent to water sources.

Another factor to consider is land re-use after decommissioning. It may take decades before the land is available for re-use. And in the case of decommissioning by entombment, or at the site of an accident, the land may not be available for re-use at all within a given century.

Metal degradation

All forms of nuclear power emit neutrons that irradiate metal surfaces inside the reactor vessel. Over time, these metal surfaces develop cracks due to neutron embrittlement (Murty and Charit, 2008), causing the nuclear vessel to degrade with age.

Neutrons are not necessarily the only source of embrittlement. In thorium reactors that use components made of a nickel-based alloy called Hastelloy-N, for example, both neutron and alpha particles react with the boron and nickel in the alloy—creating helium bubbles that cause helium embrittlement. Also, tellurium fission products cause intergranular cracking of the alloy (Rodriguez, 1981). Aging caused by embrittlement is an inevitable consequence of any form of nuclear power.

Particle bombardment of metal surfaces is not the only degradation mechanism in the nuclear vessel. The metal structure is also subject to everything from corrosion and thermal creep to fracture, radiation-induced segregation, and cavitation (Murty and Charit, 2008).[4] These aging factors, all acting together, unavoidably lead to plant shutdown after 50 to 60 years of operation.

Proposed Generation IV reactors may age even faster, because their vessels are exposed to higher temperatures, higher neutron doses, and a more corrosive environment (Murty and Charit, 2008). There are thus significant challenges to materials selection for Generation IV reactors, and this is one of the key uncertainties in their commercial realization.

In a nuclear power station, entropy is inescapable. Large amounts of energy have to be contained within a complex structure. Maintaining order in such a situation is challenging, and this leads to a trade-off between reliability and efficiency. 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, because the power density is then distributed over a larger surface area. But just as any electrical device or machine heats up and eventually fails, the same is inexorably true for a nuclear station.

If nuclear stations need replacement every 50 years on average, producing 15 terawatts of nuclear power would mean building one new nuclear power station—and decommissioning another—somewhere in the world every day.[5] This is questionable, given that nuclear stations today typically take 6 to 12 years to build (Ramana, 2009) and 20 to 50 years to decommission.[6]

Radioactive waste

After more than 60 years of nuclear technology, there is still no universally accepted mode of disposal (Pickard, 2010), and nuclear waste still raises heated controversy. It would appear irresponsible to leap toward 15,000 reactors before the waste problem is settled. Spent fuel is not the only problem; there is also the question of where to put thousands of decommissioned reactor vessels. Burial might result in radioactive leakage into groundwater due to unforeseen geological movement. If thousands of reactors were to be commissioned across the planet, waste management over such a wide geopolitical spectrum would give rise to high levels of uncertainty.

Accident rates

To date, about 580 nuclear reactors worldwide have operated for a cumulative total of 14,000 reactor years, with at least 11 accidents resulting in a full or partial core melt (Cochran, 2011). At that rate, if the world had only one reactor, it would have a major accident about once every 1,300 years, on average.[7] But in a world with 15,000 reactors, we might expect a major accident somewhere in the world every month.[8]

Is it justifiable to use historical data to make these accident projections? Although the engineering of safety features for nuclear plants has surely improved, major nuclear accidents are rare events that are not possible to model in a system as complex as a nuclear station. There are many unforeseen pathways to an accident, and rare but large events can knock out redundant backup systems. Because a nuclear station is a complex system, and redundant subsystems are necessarily co-located, redundancy can fail and can even have a negative impact (Sagan, 2004).

Considering the uncertainty involved, the numbers could well be worse. A scale-up to 15,000 reactors could attract even more problems that are not factored. For example, the combinatorial possibilities for human error rapidly increase with scale.

Nuclear proliferation

The presence of nuclear power creates an infrastructure where materials and expertise for weapons making can proliferate (Cochran et al., 2010). Different types of reactors have different levels of proliferation resistance, but no matter how they are badged, 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. With a scale-up to 15,000 reactors worldwide, it would be nearly impossible to keep track of all fissile materials. Indeed, it is already challenging for today's relatively small nuclear industry to provide assurance that materials have not been diverted for weapons.

Uranium supply

As high-grade uranium ores become depleted, the trend is to move to ores with lower concentrations of uranium. The energy required for mining and milling the uranium ore then increases, as it does for low-grade ores of any mineral (Mudd, 2010). A typical figure for total energy consumed in mining uranium is 0.2 gigajoules per kilogram (Mudd, 2010). To break even, an ore concentration of about 340 parts per million is needed.[9] 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 parts per million would not be worth the energy required for extraction. This consideration sets a limit on the viable uranium ore resource available with current technology.

The World Nuclear Association (2011) conservatively projects 80 years of economically extractable uranium at the current rate of consumption using conventional reactors. The 2010 figure for installed nuclear capacity worldwide is 375 gigawatts. If this were to be scaled up to 15 terawatts, the 80-year uranium supply would last less than five years.

Seawater, which contains large quantities of uranium, has been proposed as a replacement for high-grade uranium ores once they are depleted. Active research on uranium extraction from seawater is a sign of recognition that high-grade uranium ores are rapidly dwindling. The total estimated uranium content of the oceans is enormous at about 4.29 billion tons (Bardi, 2010). Burned in conventional reactors to supply 15 terawatts, this supply would last about 5,300 years[10] (Abbott, 2011). In fast breeder reactors, which theoretically extend uranium use by a factor of 60 or more, the uranium in seawater would last more than 300,000 years—giving a promise of a nuclear utopia for many thousands of centuries.[11]

However, these calculations overlook the rate of extraction. For example, a distant galaxy may contain massive quantities of uranium, but the rate of extraction is precisely zero. In the case of seawater, which has a uranium concentration of a mere 3.3 parts per billion, the rate of extraction is a key factor in assessing feasibility.[12] The appropriate rate calculations (Abbott, 2011) show that a volume of seawater more than six times that of total global river outflow is required to produce 15 terawatts of conventional nuclear power over a 30-year period. This enormous water requirement can be somewhat mitigated by using fast breeder reactors, but many of the other limitations discussed in this article do not augur well for the widespread scaling-up of fast breeder reactors.

Let us leave aside the reliability problems of using liquid sodium coolant, and generously ignore the scalability uptake limits of fast breeder reactors, which take about 10 years to generate enough additional fuel in order to commission a new reactor (Lewellyn-Smith, 2008). The main issue with fast breeder reactors is their economic viability. If the nuclear industry shifts to lower-grade uranium ores, for every tenfold decrease in uranium concentration there is a three-hundredfold increase[13] in recoverable uranium (Deffeyes and MacGregor, 1980). This is nominally at the expense of a tenfold increase in cost. What this means is that the industry would only have to increase its mining costs by 30 percent in order to increase the amount of accessible uranium for fueling conventional nuclear reactors by sixtyfold[14] (Abbott, 2011).

In other words, the relatively minor savings in uranium costs do not justify the extra complexity of a fast breeder reactor. It is better to use a conventional reactor and tolerate an increase in fuel cost. Cost will gradually increase, and fast breeder reactors will always be a step behind conventional reactors. When a cost threshold is eventually crossed where nuclear fuel is no longer viable for conventional reactors, the capital investment in fast breeder reactors will be difficult to justify, particularly if renewables have gained a major foothold by then. A salient reminder is that, as of 2010, the combined worldwide generation capacity of solar and wind power exceeds that of nuclear power (Schneider and Froggatt, 2012; Schneider et al., 2011).

Fusion reactors

An alternative to nuclear fission is nuclear fusion. It promises the dream of virtually limitless energy, because it involves the fusion of deuterium and tritium[15] obtained from water,[16] which is in huge abundance.

Given all the above problems with nuclear fission, can nuclear fusion lead us to a nuclear utopia? The answer is no, because the underlying problem of neutron embrittlement 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 other 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 (Abbott, 2010). It is also suggested that tokomaks, which use a toroidal geometry to magnetically confine the hot plasma during nuclear fusion, have fundamental issues with instability (Abbott, 2011). The problems of both explosive dust and instability suggest that the likelihood of seeing commercial fusion this century is virtually zero.

Material resources

One important question has been neglected in the nuclear debate: What materials make up a nuclear vessel and core? It turns out that a host of exotic, rare metals are used to control and contain the nuclear reaction. For example, hafnium is a neutron absorber; beryllium is a neutron reflector; zirconium is used for fuel cladding; and many other exotic metals, such as niobium, are used to alloy steel to make the vessel withstand 40 to 60 years of neutron embrittlement.

An examination of the relative abundance of chemical elements in Earth's crust shows that many of the metals used for nuclear containment are in low abundance (Abbott, 2011). What is alarming is that the annual growth rates in consumption of these metals (typically in the 10 to 20 percent range)[17] are enormous compared with, say, the growth rate for consumption of crude oil—which has dropped below zero in recent years (Abbott, 2011). If we were to scale up to 15,000 reactors, we would either rapidly exhaust these materials or drive them into a high-price-volatility regime, creating market instability. In a nuclear utopia, a new nuclear station would need to be finished every day. In such a scenario, the supply of containment materials would not be able to keep up with the construction demand.

Depletion of elemental diversity

Because the metal walls of a nuclear vessel become radioactive (Ishikawa et al., 1990), a decommissioned nuclear core and vessel must be buried for many generations, and 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?

The exotic metals used in nuclear reactors have many competing industrial uses. For example, Intel uses hafnium 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 super-alloys for aircraft engines and in surgical steel for medicine.

Nuclear fuels themselves are transmuted, denying future generations unforeseen applications of these metals. This problem is not unique to fission. Nuclear fusion transmutes lithium, a relatively scarce element used in every laptop computer and mobile phone.

It can be argued that any irreversible consumption of elements is shortsighted and detrimental to future technology. The counter-argument that replenishment of the elements can be achieved from fission products is not credible considering the long half-lives of some products, the costs and practicalities of the post-processing needed, and the small yields in comparison with the large throughput required.

Is there an alternative?

If a nuclear utopia is not feasible, are we doomed? Is there a competitive, massively scalable alternative to fossil fuels? Yes, and it turns out that the only renewable energy solution that is scalable well beyond 15 terawatts is solar thermal technology (Abbott, 2010). This technology uses large mirrors to focus sunlight on water, creating superheated steam that can generate electricity using a conventional steam turbine connected to a generator. The potential is enormous: The amount of solar power that reaches the planet's surface is 5,000 times mankind's current global power consumption, or about 80 petawatts.

Contrast this with the estimated 40 million tons of exploitable land-based uranium. Let us generously assume this is all economically extractable and produces the maximum available energy of 77 terajoules per kilogram (Hermann, 2006). That is roughly equivalent to 80 petawatts of sunlight for only one year. Thus there is almost as much energy in the sunlight falling on Earth in one year as all the known exploitable uranium.[18] Of course, real efficiencies have not been factored in here, but this back-of-the-envelope calculation serves to highlight the sheer magnitude and longevity of solar energy.

While capturing this energy and converting it to electricity obviously requires significant investment in infrastructure, the materials used to construct solar thermal plants are abundant and recyclable—not rare and eventually radioactive, as is the case with materials used in nuclear power plants. Thus we can expect much lower price volatility in a solar utopia than in a nuclear utopia.

Conclusion

There are fundamental engineering and resource limits that make the notion of a nuclear utopia impractical. It can be argued that a nuclear nirvana supplemented by renewables may mitigate the need to reach 15 terawatts by nuclear alone (Manheimer, 2006). However, a reduced goal of several terawatts of nuclear power would still run into many of the limitations described above. Even for a more modest goal of 1 terawatt, one only has to divide the numbers above by 15 to see that a single terawatt still stretches resources and risks considerably.

One then has to consider the cost, safety, complexity, and issues surrounding the governance of nuclear power. If the technology cannot be fundamentally scaled further than 1 terawatt, one has to ask if the same investment would be better spent on a truly scalable technology. For the same investment, solar thermal plants—coupled with energy-storage facilities—could greatly exceed the power output of nuclear stations and eliminate many of the problems associated with them (Abbott, 2010).

The weakness of a scalable renewable solution, such as solar thermal power or wind power, is its intermittency. In the short term, this problem can be addressed by supplementing solar thermal production with natural gas. As storage and grid-balancing technologies come online to address the intermittency problem (Pickard and Abbott, 2012), natural gas can then be gradually phased out.

The sun is nature's nuclear fusion reactor, located at an arguably safe distance from Earth. It generously affords us 5,000 times our current world energy needs and will run reliably over the next billion years with zero downtime. It is uncertain whether man-made fusion reactors will ever become commercially viable. Even if they do, it makes no sense to take on uncertainty—in terms of resource and safety issues—when the sun already provides us with a virtually limitless nuclear resource delivered straight to our doorsteps.

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Notes

1. There is a counterpoint to this position. If the Intergovernmental Panel on Climate Change's high-end-emissions scenario proves to be correct, then nuclear power will face increased risks of weather-related catastrophic accidents—this has been dubbed the "adaptation-mitigation dilemma" (Kopytko and Perkins, 2011). If, on the other hand, the high-end scenarios for fossil fuel production cannot be met due to resource limitations, as indicated by a growing body of literature (Brecha, 2008; Höök et al., 2010a, 2010b; Nel and Cooper, 2009; Rutledge, 2011), then reasonable climate limits can be maintained by taking reduced action, and the rapid scale-up of nuclear power is not required. Thus, it can be argued that nuclear power is an inappropriate response to either of these standpoints.
2. With a plentiful supply of nuclear power, one might imagine it being tapped to produce transportation fuel, as well as electricity (Duffy, 2009).
3. In a hypothetical nuclear utopia, it would take more than a century to build up to a level of 15 terawatts, and by then the world power consumption would be considerably higher. However, for order-of-magnitude calculations, 15 terawatts is a reasonable arbitrary figure for examining the large-scale feasibility of nuclear power.
4. Other issues include irradiation creep, phase instability, volumetric swelling, void swelling, grain boundary sliding, and intergranular degradation.
5. If 15,000 1-gigawatt reactors each operate for an average of 50 years (18,250 days), that means replacing one every 1.2 days on average (18,250/15,000 = 1.2).
6. In practice, there is a trade-off between decommissioning time and cost. Allowing more time for radioactive products to decay reduces cost, because there are fewer contaminants with which to deal. Cost-cutting measures usually lead to longer decommissioning times.
7. 14,000 reactor-years/11 accidents = 1,272 $\approx$ 1,300 reactor-years per accident.
8. 15,000 reactors $\times$ 1 accident/1,272 reactor-years = 11.79 $\approx$ 12 accidents/year.
9. If the total energy consumed in mining uranium is $W = 0.2$ gigajoules (0.0002 terajoules) per kilogram, breaking even requires $mW = mc\eta\varepsilon$. The energy in the ore is $mc\eta\varepsilon$, 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 $\varepsilon = 83.14$ terajoules/kilogram is the energy density. Thus, the ore concentration needed to pay for mW is $c = W/\eta\varepsilon = 344$ parts per million $\approx$340 parts per million.
10. Convert tons to kilograms, total $U^{235} = 4.29 \times 10^{12} \times 0.007 = 30$ billion kilograms. Multiply this by $\varepsilon = 83.14$ terajoules/kilogram and divide by 15 terawatts = 166 billion seconds = 5,264 years $\approx$5,300 years.

11. 5,300 years × 60 = 318,000 years ≈3,000 centuries.
12. To appreciate just how low a concentration of 3.3 parts per billion 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 even lift it out of the mine? The energy in the ore is $mc\eta\varepsilon$, where m is the mass of the ore, c is the uranium concentration in the ore, $\eta = 0.007$ is the U235 fraction, and $\varepsilon = 83.14$ terajoules/kilogram is the energy density. To break even, $mgh = mc\eta\varepsilon$ and thus the distance $h = c\eta\varepsilon/g = 50$ meters and is independent of the mass of the ore. Therefore, the energy content in such an ore is well below the energy of extraction.
13. A principle of the natural world is that small objects are more abundant than large ones. A corollary is that lower concentrations of a resource are more common than higher concentrations. If we can tap a resource at lower concentrations, we can obtain more of it, although this is at the expense of a reduced rate of extraction and increased energy of extraction.
14. 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 sixtyfold increase in uranium. This will then give us an idea of whether fast breeder reactors gain us anything in real economic terms. Thus, putting $300\log(p) = 60$ results in a cost increase of $p = 1.3$—i.e., a 30 percent increase.
15. It is possible to have deuterium-deuterium (D-D) fusion, rather than deuterium-tritium (D-T) fusion. This eliminates the requirement for tritium. However, a D-D cycle requires five times the reaction temperature, which means considerable containment issues, and hence all focus is on the D-T cycle. Peak reaction temperatures in the International Thermonuclear Experimental Reactor (ITER) are already up to the order of 100 million degrees Celsius, which is higher than the temperature at the core of the sun.
16. This is the dream; however, in practice, this is untrue. While deuterium is easily obtained from water, tritium is more difficult to obtain. Tritium can be produced in small quantities when deuterium captures a neutron. But because the capture cross-section is very small, this pathway is questionable as a commercial route. Therefore, in practice, tritium is bred by neutrons bombarding lithium. However, transmuting lithium is not sustainable, because it is not an abundant element and it has many other competing industrial uses (e.g., battery technology, glass, ceramics, and lubricants).
17. These are annual growth rates in consumption of the required metals across all industries and not solely for nuclear power. This is important in order to consider the total consumption across all industries, as the reality is that we have many different industries competing for the same resources.
18. There is an estimated 40 billion kilograms of exploitable uranium. In practice, this may not all be economically extractable. However, if we hypothetically used it all in a conventional reactor at a maximum available energy of 77 terajoules/kilogram, the total energy produced is 3.08 yottajoules (40 billion × 77). This is on the order of 80 petawatts (80 billion megawatts) generated for one year: 3.08 yottajoules/(365 × 24 × 60 × 60) seconds (in one year) = 97 petawatts, which is roughly in the order of 80 petawatts.

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