

Perspective

Silver Buckshot or Bullet: Is a Future “Energy Mix” Necessary?

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Abstract: To displace fossil fuels and achieve the global greenhouse-gas emissions reductions required to meet the Paris Agreement on climate change, the prevalent argument is that a mix of different low-carbon energy sources will need to be deployed. Here we seek to challenge that viewpoint. We argue that a completely decarbonized, energy-rich and sustainable future could be achieved with a dominant deployment of next-generation nuclear fission and associated technologies for synthesizing liquid fuels and recycling waste. By contrast, non-dispatchable energy sources like wind and solar energy are arguably superfluous, other than for niche applications, and run the risk of diverting resources away from viable and holistic solutions. For instance, the pairing of variable renewables with natural-gas backup fails to address many of the entrenched problems we seek to solve. Our conclusion is that, given the urgent time frame and massive extent of the energy-replacement challenge, half-measures that distract from or stymie effective policy and infrastructure investment should be avoided.

Keywords: nuclear fission; natural gas; renewable energy; climate change; energy mix

1. Introduction

It is perceived wisdom that the world’s future energy supply must come from a diverse mix of sources. In particular, supply from a mix of electricity generation sources is a key component of the “Energy Trilemma Index” [1]. This need for a “future energy mix” is a fundamental and essentially unchallenged axiom (or at least an unstated assumption) for energy experts [2,3], politicians, environmental advocacy groups, integrated assessment modellers [4] and authoritative organizations such as the Energy Information Administration [5], the International Energy Agency [6] and the Intergovernmental Panel on Climate Change [7]. Energy-supply scenarios produced by these groups are of two general types: “no climate policy” scenarios (often but inaccurately, referred to as “business-as-usual”; BAU) and “stabilization” (greenhouse-gas emissions mitigation) pathways, with the latter invariably comprised of a mix of energy technologies.

Scenario development typically begins with a projection of overall energy growth under the assumption of no new policies beyond those already implemented, based on population and economic forecasts, coupled with estimates of future technology changes (e.g., [8]), cast forward 20–100 years. Then mitigation scenarios are spun off from this by assuming various mitigation policies are implemented over coming decades, often optimizing the choice of policies on the basis of cost effectiveness. The scenarios are partitioned in some way among energy sources (fossil, nuclear and renewable) and the effects of changes in end-use efficiency and conservation measures. The actual proportions represented by these three broad classes of energy supply and demand management

depends on the objectives of the modelling but some measure of economic, environmental, scientific and socio-political considerations inevitably exert an influence on the character and assumptions of the exercise and thus on the outcome.

Depending on how the modellers weight these factors, the range of possible modelling assumptions and options is almost infinite [9,10]. Some scenarios (e.g., [11–14]) define arbitrary mitigation “wedges” based on a cursory evaluation of the feasibility of their technical, economic and logistic underpinnings [15] and often ignoring the fact that a substantial fraction of the suggested wedge technologies is likely to be implemented spontaneously, even in the absence of policies [10]. Others more rigorously attempt to weigh a multitude of limiting factors, such as past experience, technological maturity and development pathways, current and projected costs including associated financial risks, fuel availability and security, material use, generation reliability, dispatchability, current political policies and so on [3,4,16,17]. A problem with this “mechanistic” approach, however, is that, historically, forecasts of this kind have usually borne little resemblance to what actually eventuated over subsequent decades [15,18,19]. In their recently published papers, Jacobson et al. [20,21] and others [22] argue that the entire energy demand of the United States, including transport, heat and electricity, can be supplied entirely by intermittent renewable energy sources (principally wind, solar and hydro). However, their arguments have faced strong criticism by a number of energy researchers [23–25] in regard to their assumptions and modelling methods.

The scenarios used by authoritative bodies like the International Energy Agency and Energy Information Administration tend to be quite conservative, projecting only gradual and incremental changes in energy sources. In particular, the forecast global energy pie in coming decades continues to have large slices of coal, oil and gas. In addition, they often have an ambitious outlook for new fossil-fuel technologies (such as carbon-capture-and sequestration) when stabilization scenarios are modelled but with only small portions of nuclear and hydro and growing but persistently minor roles for wind, solar and other non-hydro renewables. The time course of deviations from the current energy mix in these stabilization scenarios is tortuously slow, which is surprising given the urgency of mitigating the rise in global temperature and its consequences [22]. In short, the forecasts of these energy agencies could certainly never be characterized as visions of the possibly radical and wholesale transformation in our energy systems that many think will be necessary to reduce the probability of dangerous anthropogenic interference (DAI) with the climate system to acceptable levels [26].

Yet, given the combination of “wicked problems” [27] that must be faced and conquered by humanity this century, including global climate change, ocean acidification, biodiversity loss and provision of adequate necessities for a human population that will soon approach 10 billion, a business-as-usual or conservatively incremental mitigation approach may well not be a viable or acceptable socio-political strategy. Indeed, if we continue to rely on fossil fuels for energy and fail to practice stewardship of the Earth System, many of the incredible advances and benefits won by modern civilization over the last few centuries may be severely degraded or lost. A future energy system that delivers substantial and timely mitigation of carbon and other greenhouse-gas emissions, while providing abundant energy for human development, is essential [28,29].

2. Alternative Energy Mixes and the “Silver Buckshot”

But how do we achieve the emissions reductions required to avoid DAI? (Or as Prins and Rayner put it, “fire the ‘silver buckshot’”; [30]) Or is there a silver bullet after all? In this and the following sections, we argue that balanced and diverse “energy mixes” are probably unnecessary, or at least suboptimal, and that a completely decarbonized, energy-rich and sustainable future could be achieved through the timely deployment of next-generation nuclear energy and associated technologies for synfuel production and materials recycling alone. We acknowledge that this proposition is a radical one but the time for subtleties has long passed. What global society now needs is a workable and holistic “prescription for the planet” [31].

The most widely discussed pathways for an alternative energy future involve the massively expanded deployment of a wide range of “renewable” technologies, including harnessing the energy in wind, sunlight, ocean waves and tides, as well as more traditional (and dispatchable—electricity generation sources that can be generated at any time at the request of electricity network operators or demand) hydropower and biomass combustion. Most advocates of these energy technologies shun any use of nuclear power [13,32–34] and the majority of those who acknowledge its role view it as simply (a small) part of the low-carbon energy jigsaw puzzle [35]. Some argue that an all-out pursuit of a diverse mix of systems that harness sunlight, wind, waves and plant life at continental scales, combined with vast improvements in energy efficiency and energy conservation for both production and consumption sides and cheap energy storage, are “the answer” for global decarbonization. In some published scenarios, arbitrary allocations of wind, water and sunlight are accumulated to reach a total target energy supply [11–13]. In other modelled futures, attempts are made to balance electricity demand with supply at all times, using gas (bio or fossil), hydro, stored heat and dispersed “supergrids” to try to cover shortfalls [16,36–39].

Given these ideas, what is stopping nations from following through with these visions to replace coal, oil and gas infrastructure with renewable energy? It is probably not because of any strong, society-wide opposition to a switch to renewables, but, rather, a combination of economic uncertainty, the undeniably diffuse and intermittent nature of the energy sources themselves, technological immaturity and prudent financial risk management [3,40,41]. A key factor, therefore, is that economically harnessing renewable energy such that it provides a reliable, dispatch-on-demand power supply, still faces many technical challenges [15,17,41–43], not the least of which include the laws of physics, in terms of energy density.

The highly diffuse nature of all the energy sources described above means that they require the exploitation of extensive geographical areas to capture large amounts of energy. In some favourable locations like Australia (with high solar insolation and low population density), this is not, in itself, a major problem. For other countries, like Japan, South Korea or most European nations with high population density, however, this presents a severe constraint [44]. Transmission requirements also present problems arising from cost of transmission lines and power losses over long distances [45]. Another difficulty is that the technosolar energy sources are inherently variable and intermittent—sometimes they deliver a lot of power and sometimes little or none, for short or extended periods [24,45,46]. This means that to satisfy the needs of an “always on” power demand, even with a multi-source interconnected distributed network, ways must be found to store vast amounts of heat or electricity to cover the non-generating periods [47], or else keep fossil-fuel or nuclear plants as a backup [17,45,48]. It is in the local-to-transnational scaling up process that technical difficulties, costs and time-scales amplify [18].

The problem of short-term intermittency (days to a week) for individual households (or a local area) can be solved by improving energy storage systems (e.g., battery banks like the Tesla Powerwall; [49–51]) and establishing proper economic mechanisms to encourage deployment [52]. However, for a country level in places such as the United Kingdom, where the seasonal energy demand between winter (4.5 TWh day^{-1}) and summer (1.5 TWh day^{-1}) varies significantly [53], the current capacity (technical, economic and volumetric) of energy storage dictates that it cannot play an important role in reducing seasonal peak demand: as such, gas will remain as a major source of peak electricity supply and heat [54].

Usually, scenarios that include a large-scale expansion of renewable energy also assume a massive increase in the efficiency of energy consumption and fossil-fuel-derived production, leading to substantially lower demand profiles than present systems [4,37,55]. The desirability of becoming more efficient at how we generate and use energy is self-evident. Yet, in the broader context, to envisage that the global human enterprise will use less energy per capita in the future through the overwhelming success of end-use efficiencies, is contrary to the ongoing 21st-century trend of rapid economic development in non-OECD countries and in the context of a still energy-starved developing world,

largely irrelevant [18,19]. A few studies have shown that economic growth will increase energy demand, or vice versa, with the history of energy use being characterized by the quest for ever cheaper sources that provide higher and higher “power densities” [41]. We need to work with, not against, these realities and seek to deliver these aspirations in an environmentally sustainable way.

Indeed, recent peer-reviewed critiques of the future global role of renewable energy [22,24,41,43] provide exhaustive details on the constraints imposed by variability, dispatchability, large-scale energy storage, the need for overbuilding and geographical replication (and the likely consequence: “dumping” of unused excess energy), low energy returned on energy invested and other key points. There are also recent meta-reviews that consider technological maturity, fit-for-service replacement capacity, cost and life-cycle emissions, as constraints on renewables capacity to displace fossil fuels [7,41,56]. The stark conclusion from these studies is that renewables alone will never be able to solve the greenhouse problem. Ironically, empirical studies found that a policy attempt at expanding renewables might not even reduce coal-based electricity and embedded greenhouse-gas emissions (e.g., [57]). Ultimately, as the urgency of climate change mitigation mounts and as requirements for sustainable growth in developing economies and the replacement of aging infrastructure in the developed world come to the fore, pragmatic decisions on the economic and logistical viability of all types of non-fossil technologies will have to be made rationally and with consideration to their respective benefits and limitations [58].

3. Integral Fast Reactors—An Exemplar “Silver Bullet” Clean-Energy Technology

An exemplar of the idea of an energy “silver bullet” (a single energy source that could *potentially* meet all of civilization’s needs), as opposed to the “silver buckshot” discussed above, is fourth-generation nuclear energy. It has all of the crucial attributions required of a clean-energy “techno-fix”, in that: (i) it offers the feasible prospect of a “plug in” replacement for coal- and gas-fired electricity; (ii) its process heat or excess electrical output can be used for synfuel manufacture and other industrial applications to replace oil; and (iii) this next generation of nuclear power systems avoids many of the real and perceived problems of current-generation reactor technology [31,58–61].

But is there not a danger of “putting all of our (energy) eggs in one basket”? Certainly, the path to an energy future that is dominated by advanced nuclear fission would have to overcome some major challenges and solve the most significant problems and perceptions of nuclear power systems in use today. The legacy of long-lived “nuclear waste” is one of the first objections to nuclear power that one hears in any public discussion [62]. Safety is likewise prominent, especially in the wake of the Fukushima crisis of 2011. Concerns regarding weapons proliferation risk, construction times and cost and the assurance of a fuel supply that will last into the future, are also frequently expressed [2,48].

These apprehensions are not new. Indeed, a group of scientists at the U.S. Argonne National Laboratory West (now Idaho National Laboratory) considered these same issues in the early 1980s and reasoned that if the world was to have any hope of continued and increasing utilization of the energy locked in the atom, all of these problem areas would have to be addressed and solutions to all of them would have to be found. No stone was to be left unturned, no loose ends left for others to deal with in the future [61]. The result of this decade-long project at America’s premier nuclear research centre was the Integral Fast Reactor (IFR) that solves virtually all the serious problems of nuclear power [61,63]. Just as the final stage of the project was to be demonstrated, however, it was cut short by a purely political decision that eliminated the funding and shut down the program [31,61,64].

In response, in 2001, nine nations formed the *Generation IV International Forum* to develop sustainable, economic, safe, reliable, proliferation resistant and physically protected nuclear reactors [65]. Founding countries of the Generation IV International Forum (GIF) include Argentina, Brazil, Canada, France, Japan, the Republic of Korea, the Republic of South Africa, the United Kingdom and the United States. Subsequently, Switzerland in 2002, Euratom in 2003, the People’s Republic of China and the Russian Federation in 2006 and Australia in 2016 signed the GIF Charter to become member countries.

The IFR is a development of existing Generation IV reactor systems and experiments in France, Russia and Japan that improves the reactor technology, which links the fast reactor to on-site reprocessing and fuel fabrication components (hence “integral”). It is an elegant solution to the world’s energy problems and is a system that has been proven *capable* of eventually providing not just a slice of the energy pie but the whole pie [60,66]. The IFR can utilize nuclear waste and weapons-grade plutonium and uranium for fuel. A fleet of IFRs could consume both the spent nuclear fuel and the vast inventories of depleted uranium that have resulted from over half a century of nuclear power and weapons programs, for electricity and heat production. The IFR is ultimately capable of using over 99% of the potential energy in uranium and plutonium, via repeated recycling of the used fuel, which means that the existing material that we already have at our disposal could supply all the energy humanity is expected to require for many centuries [67] and more potential IFR fuel will be produced until the point when conventional thermal reactors are no longer used. The IFR achieves this via electrometallurgical pyroprocessing, in which the actinides in spent nuclear fuel are recycled without the need for further mining or enrichment of uranium [61].

Compared with the complicated and relatively expensive fuel fabrication processes for current-day reactors (i.e., generation II and III nuclear reactors) [67], the revolutionary pyroprocessing system used to recycle IFR fuel (and convert used ceramic oxide fuel from light-water reactors), along with the injection-casting method for manufacturing metal-fuel pins that are held within the cladding using a liquid-sodium bond, is remarkably simple, with a small-footprint fuel recycling and fabrication facility to service a plant hosting (e.g.,) four PRISM reactor modules [68]. During the decades-long IFR project, over 30,000 fuel pins were recycled for the EBR-II fast reactor [63]. Further, because pyroprocessing never isolates any actinide elements or isotopes capable of being used in weapons systems, the technology is inherently proliferation-resistant: indeed, at every stage of the fuel cycle, the fuel is too radioactively “hot” to handle. (In other words, additional [and extremely technically challenging] chemical re-processing using specialized radioactive-protected facilities would still be required to *potentially* purify IFR material sufficiently for use as weapons-grade fissile actinides). However, this ultimately has little to do with defending the objectives of this paper, because centralized pyroprocessing/fuel fabrication facilities could be established in Nuclear Weapon States that would cater to the needs of all others by supplying them with nuclear fuel as individual items, i.e., ready fuel elements, or fuel assemblies [69].

The safety of nuclear power plants is one of the foremost expressed concerns of anti-nuclear groups. Following the 2011 Great East Japan Earthquake, four reactors at the Fukushima Daiichi nuclear power plant were damaged, with three cores suffering a meltdown. However, no fatalities directly related to radiation exposure of the accident were reported [70], and the potential future health effects due to the radiation exposure is forecast to remain negligible [71]. The inherent safety features of the IFR prevent any Fukushima-like accident from loss of cooling occurring. The passive safety features of this design allow for shutting the nuclear reactor down without external power sources or human intervention, as demonstrated in a landmark set of tests in 1986 [72]. Although sodium-cooled fast reactors raised public concerns of a sodium reaction with air leading to a potential fire [73], there are other types of Generation IV reactor that avoid such incidents; including lead and lead-bismuth cooled reactors, liquid salt cooled reactors and thermal- or even fast-spectrum molten-salt reactors [65].

The objection that nuclear power plants take too long to build and are far too expensive does not hold up to logic if one considers well-known principles of engineering and systems fabrication. For one thing, General Electric’s Advanced Boiling Water Reactors (ABWRs) have recently demonstrated that modern nuclear power systems can be built both economically and quickly. The first two ABWRs were built in Japan in the 1990s, taking 36 and 39 months to build, even though complex first-of-a-kind systems usually take longer to build than subsequent copies. Studies relying on limited and outdated data from the US and France, which mainly built reactors before 1990, concluded that the construction costs of nuclear power have dramatically increased (e.g., [74,75]). However, a recent study that overviewed the construction costs of 349 nuclear power plants argues that the countries currently

building nuclear reactors actively are experiencing stabilized costs (at around US\$2000 per kWe (2010 dollars) in India) or reducing construction costs (US\$4000 to 2000 per kWe in South Korea) due to standardized designs and appropriate regulations [76].

In contrast to these recent light-water-reactor projects, the General Electric-Hitachi PRISM (Power Reactor Innovative Small Module)—the blueprint of a commercial design for an IFR reactor—is an entirely modular system, with components that can be mass-produced in factories and trucked or shipped to the power plant site [77]. The diameter of the reactor vessel of the PRISM IFR (nameplate capacity of 311 MWe, though capable of 380 MWe) is about 10 m, compared with ~6 m for a large wind turbine with a nameplate capacity of 3 MWe [78]. The simplicity of the IFR design—due in no small part to the fact that it operates at atmospheric pressure—leads it to require far fewer pumps, valves and other control systems than any other nuclear plants in use or under construction today. In such manufacturing, simplified systems with fewer parts that are capable of utilizing mass-production end up costing less [79]. First-of-a-kind commercial PRISM (and similar) reactors are expected to be >15% (maximum 55%) more expensive compared with subsequent reactors [80]. Deploying the Generation III+ reactors designed with the enhanced safety systems could reduce the uncertainty and risk to the first buyers by demonstrating the maturity of passive safety systems.

How might the IFR scale up as a “silver bullet”? This can most certainly be done at a far faster rate than France converted their country to nuclear generation, considering that they evinced no great sense of urgency and were building far more complex, non-modular systems. France was able to shift from approximately <20–80% nuclear electricity in just 11 years [58] and Sweden had similar success with a mix of nuclear and hydro [81,82]. For another comparison, being a simple and replicable design, the factory production of IFR PRISMs would be of comparable complexity to building heavy bombers during World War II. In 1944–1945, the United States alone built 22,915 heavy and superfortress bombers, without the aid of automated welding technology and other robotics [83]. About 7700×311 MWe PRISMs would be required to produce as much electricity as the entire world produced from all sources in 2012. (See Supplementary Information for a more detailed analysis on the IFR deployment rate required to meet the Paris Agreement climate targets.) When it comes to both rapid mass production and cost reduction, a critical advantage of fast reactors is that they operate at or very near atmospheric pressure, thus avoiding the industrial bottleneck of having to build robust pressure vessels, while having the advantage of the inherent safety of low-pressure operation. When these advantages are combined with small modular design, it portends a transformative future for nuclear power that opens the door for virtually any developed country to switch to nuclear power as its primary power source in less than a decade. Political will, not safety or economics, will be the limiting factor.

For total electricity replacement with the IFR, however, we would need a generating capacity (currently met primarily by today’s fossil fuel plants) that is capable of meeting not only baseload requirements but also peak demand. The IFR, because of its potential load-following capability, can provide both. Then, once all today’s fossil fuel generating capacity is converted to IFRs, we would have a system capable of meeting all facets of demand based on a technology that is able to operate constantly at full power (unlike variable renewables) and for which the fuel is essentially free—for centuries. Given that peak demand is typically two to three times greater than average demand (depending on location, season, industrial versus residential use, etc.), IFR technology can produce what is essentially “free” excess energy, which could be used to produce hydrogen either via electrolysis or, more efficiently, via direct heat in catalytic reactions [84]. Mixed with carbon dioxide (captured and stored from burning fossil fuels, or absorbed from the atmosphere [85]) or nitrogen, that hydrogen can be used to fabricate virtually any of the liquid fuels we use today, including gasoline and jet fuel, butanol, methanol, ammonia, etc. [86,87] or more exotic energy-storage media based on refined metals [31,88]. Advanced energy storage integrated with IFRs will provide greater flexibility of the reactor operation and higher energy efficiency that can replace the use of “backup” open-cycle gas generation entirely [89].

In addition, we could deploy desalination projects [90] on a hitherto unimagined scale (and the necessary pipeline and canal systems to get the water to where it would be needed). This capability is an important co-benefit of IFR technology, vital for providing domestic and agricultural water needs for a world expected to house billions more people by mid-century [91,92]. The Ras Al-Khair plant, which is operated in Saudi Arabia, has a production capacity of 2400 MWe of electricity from gas and 1 million m³ of desalinated water a day [93,94]. Excess energy can also power plasma-arc torches to transform solid waste streams into syngas and other products for efficient recycling of virtually any waste materials [31,95].

What role would the “buckshot” of solar and wind power technologies play in such a “silver bullet” IFR-dominated future? For impassioned advocates of those systems, the inconvenient truth is that, beyond niche roles, they would be merely expensive redundancies, for all the energy humanity demands could readily be met by advanced nuclear power. We can be certain that the opposite dynamic will not apply—wind and solar will not make nuclear or fossil fuels redundant [96]. It is misleading to talk about wind or solar with utility-scale “backup” when, operating at capacity factors of 15–35%, they produce far less usable energy than the natural gas, hydro, coal, nuclear or biofuels that are used to cover for them.

Those who oppose a major role for nuclear in a low-carbon energy future often complain about the opportunity cost against non-hydro renewables when nations choose to invest in nuclear power plants [34]. This position, as we can see, is as inverted as their use of the term “backup”. In fact, society arguably loses out when money is allocated to wind and solar projects, considering that those funds could instead be used to build IFRs that operate constantly with high reliability, are able to supply all the energy we want without emitting any carbon dioxide or other pollutants and, in the process, make wind and solar installations as obsolete as fossil fuels. This is an inconvenient energy truth and possibly one reason why advocates of renewables are often so zealous in their antagonism toward nuclear power. The transition to an IFR world would, furthermore, eliminate the need for the development of inefficient and costly battery storage.

4. Unconventional Fossil Future?

There is another scenario that many policy experts, technologists and economists think is plausible: a modification (but not replacement) of the “business-as-usual” fossil-fuel-dominated energy portfolio. This is a future where not only are huge quantities of coal still burned for baseload electricity but also where oil-dominated industries such as transportation, agriculture and many industrial processes are projected to switch to a reliance on natural gas, driven by low-cost methane that shoulders out supposedly more expensive nuclear and renewable alternatives [97]. In these scenarios, most of the new gas comes from “unconventional” sources such as fractured shales, coal-bed methane, tight sands, and, more speculatively, underground gasified coal and ocean hydrates. The potential resources are undeniably enormous [6], if they can be tapped economically and (more importantly) if environmental concerns are subordinated. Over the last decade, new technology has allowed cheaper and more efficient extraction of “fracked gas,” leading to a glut in supply, low prices and speculation of “centuries” of extractable resources [98]—enough to permit a gradual and measured transition to eventual fossil-fuel-free “alternatives”. Gas, it is argued, is a clean burning and “low-carbon” fuel [99,100] and, if tight CO₂-emission controls are needed, then carbon-capture-and-sequestration (CCS) technology can be scaled up to reduce carbon footprints even further [101]. While gas is a low-CO₂ emitting fuel relative to coal, as explained further below, it is not necessarily a climate-friendly fuel, because there will always be leakage of methane (a much more powerful greenhouse-gas than CO₂) at different stages of the production-to-use cycle and because the attendant reduction in SO₂ emissions will lead to additional warming [102].

From a certain limited perspective, the reasoning seems sound. Gas-fired power plants are cheap to build and while the fuel is abundant, they are also relatively cost-effective to operate. Open-cycle gas turbines are ideal for load following, combined-cycle gas plants are efficient baseload

electricity providers and liquefied natural gas is a useable substitute for many refined petroleum products [98,99,101]. Further, the investment risk for new gas-fired power plants is low, since the public is relatively indifferent to their construction and they can be built quickly. The technology for CCS has been demonstrated at small scales, such as in enhanced-oil-recovery operations and analysis suggests that its additional cost could be supported by a carbon price of about \$50 per ton of CO₂ emitted [41]. Given these realities and the current political and economic landscape that has allowed huge multinational oil and gas companies to exert a massive influence on energy decision making [31], it would seem that a massive expansion of new nuclear power, as outlined in the previous section, is implausible.

But how secure are these “realities” in the medium- to long-term? Some facts, like the low capital cost and operational flexibility of gas-fired power plants and current political favouritism, are beyond dispute. Others are not so certain [103]. For instance, although the gas production rates from fracking are high initially, data from longer-term operations suggests that the decline rates are much faster than in conventional wells [104,105]. This has potentially serious economic implications for any energy system predicated on high gas use and will ultimately dictate what reserves end up being tapped and what resources stay in the ground (and for how long). The claim of “centuries of supply” relies heavily on the ongoing cost competitiveness of methane supply being greater than the upfront capital costs of alternatives like new nuclear, with its forever-miniscule fuel costs [67].

The climate-change arguments against a gas-dominated energy future are arguably even more limiting. When burned in a flexible mix of combined-cycle baseload gas and open-cycle peaking plants, the greenhouse gas emission of methane fuel is ~450 kg CO₂e/kWh [41]. When one also accounts for the reduction in sulphate aerosol dimming caused by switching away from coal combustion [102], and the leakage of methane (a more powerful, albeit shorter-lived climate-forcing agent than carbon dioxide) across the whole production and transportation cycle, the value of natural gas for substantial abatement of greenhouse-gas-induced radiative forcing is dubious at best [106]. For instance, Wigley used MAGICC simulations (Model for the Assessment of Greenhouse-gas Induced Climate Change; [107]) to show that, under a scenario of a 50% reduction in coal and a corresponding increase in natural gas use, global warming by the year 2100 would be reduced by only 0.1 °C if leakage were kept to 2%, or about 0.2 °C with no leaks. In a high methane-leakage-rate scenario of 10%, warming would not be reduced until 2140—far too late to avoid major disruptions to the climate system. A similar result was found in a modelling study by Myhrvold and Caldeira [108].

5. More Silver Bullets

While IFR technology, as described above, is perfectly capable of providing all the energy humanity needs for centuries, there is another nuclear technology that was developed and demonstrated at Oak Ridge National Laboratory in the USA in the 1960s. This is the molten salt reactor (MSR), in which fissile material is dissolved in molten salt, with no solid fuel assemblies. Like the IFR, this project was unceremoniously shelved after being successfully demonstrated but the concept has been resurrected in recent years and, now, several start-ups are seeking to deploy this technology. Its high operating temperature (~700 °C versus ~500–550 °C for IFRs or 350 °C for currently-deployed water reactors) promises greater efficiency and manifold possibilities for industrial process heat, or replacement of coal burners at coal-fired power plants. While the high temperature, corrosion potential of molten salt and embrittlement issues caused by neutron bombardment present demanding materials challenges, there are MSR concepts that very plausibly address these issues, with projected costs that promise to be even cheaper than IFRs (e.g., thorconpower.com). And, like IFRs, these modular reactors operate at atmospheric pressure so that they can be mass produced in great numbers.

When the IFR project was abruptly terminated as earlier described, it was in the final stage of designing and demonstrating the pyroprocessing fuel recycling technology at commercial scale [61]. That design project languished until 2013, when Argonne National Laboratory resumed it with a

broader objective: not only would the commercial-scale plant recycle metal IFR fuel but it would also recycle spent oxide fuel from light water reactors, the so-called “nuclear waste” that is often mischaracterized as a “million-year problem”. Fortuitously, that same pyroprocessing technology can also recycle the spent fuel from molten salt reactors. It is, in effect, a one-size-fits-all nuclear fuel recycling solution. Now, four years after restarting that project, the design is essentially finished and could be built in the near future, at a reasonable cost, demonstrating a solution to the nuclear waste problem and enabling both IFRs and molten salt reactors to be built in the knowledge that their spent fuel will be efficiently recycled.

6. Conclusions

To displace fossil fuels and achieve deep global greenhouse-gas reductions, the quest for a diversified “energy mix” is probably unnecessary and suboptimal. Certainly, energy use in the industrial age to date has been dominated by only a few convenient carbon-rich forms—coal, oil and gas. In this viewpoint, we have argued that the technology already exists to deliver a completely decarbonized, energy-rich and sustainable civilization, via the extensive deployment of next-generation nuclear power systems and associated equipment for synthesizing liquid fuels and recycling waste. Importantly, this transition could be achieved without a major shift in the way our modern economy functions and certainly without a large-scale regression in energy use or reliance on future breakthroughs such as cheap and high-capacity energy-storage (a critical necessity if non-hydro renewables are to have any prospect of providing a large-scale alternative to fossil fuels). A “natural gas economy”, often touted as the bridge from coal to future renewables, does not solve the entrenched environmental and supply problems that 21st-century civilization must seek to remedy and has limited value as a “transitional fuel” because of its climate-forcing impact. Given the urgent time frame and massive extent of the energy-replacement challenge [8], half-measures that distract from, or stymie, effective policy and infrastructure investment, must be avoided.

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