Energy Policy 42 (2012) 4–8

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Viewpoint

Could nuclear fission energy, etc., solve the greenhouse problem? The affirmative case

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ARTICLE INFO

Article history:
Received 29 August 2011
Accepted 10 November 2011
Available online 16 December 2011

Keywords:
Future scenario
Generation IV nuclear
Synfuels

ABSTRACT

For effective climate change mitigation, the global use of fossil fuels for electricity generation, transportation and other industrial uses, will need to be substantially curtailed this century. In a recent Viewpoint in *Energy Policy*, Trainer (2010) argued that non-carbon energy sources will be insufficient to meet this goal, due to cost, variability, energy storage requirements and other technical limitations. However, his dismissal of nuclear fission energy was cursory and inadequate. Here I argue that fossil fuel replacement this century could, on technical grounds, be achieved via a mix of fission, renewables and fossil fuels with carbon sequestration, with a high degree of electrification, and nuclear supplying over half of final energy. I show that the principal limitations on nuclear fission are not technical, economic or fuel-related, but are instead linked to complex issues of societal acceptance, fiscal and political inertia, and inadequate critical evaluation of the real-world constraints facing low-carbon alternatives.

> I can still remember the thrill that came with my realization that the (*nuclear fission*) breeder meant inexhaustible energy… I became obsessed with the idea that humankind's whole future depended on the breeder (Alvin M. Weinberg, 1994, The First Nuclear Era).

1. Introduction

Carbon-based fuels are the energy bedrock upon which modern industrial civilization has been built, but the end of the oil, gas and coal era now approaches—perhaps sooner than many realize (Nel and Cooper, 2009). The reasons are manifold, but focus chiefly on economic supply limits, national imperatives of long-term energy independence, and the accumulating toll of exacted by fossil-fuel combustion on local environments and the global climate system. In this context of needing to replace fossil fuels with some alternative(s), Trainer (2010) examined critically the adequacy of renewable sources in achieving this energy transition. He concluded that general climate change and energy problems cannot be solved without large-scale reductions in rates of economic production and consumption.

However, Trainer's (2010) sub-analysis of nuclear energy's technical potential involved only a cursory dismissal on the grounds of uranium supply and life-cycle emissions. There are also significant societal concerns that may stymie the adoption of nuclear energy, exemplified by the recent decision in Germany to close down all of its atomic power stations by 2022 due to public anxiety following the 2011 Fukushima Daiichi nuclear crisis.[1] Authoritative forecasts from the International Energy Agency (IEA, 2010) and integrated assessment modeling (IAM; Clarke et al., 2007) project a larger future role for nuclear, yet, despite recent critiques (e.g., Höök et al., 2010), also assume a large – indeed growing – contribution of fossil fuels (potentially with carbon capture and storage (CCS)) through to the year 2030 and beyond.

In this paper, in contrast to Trainer (2010) and others (e.g., Mortimer, 1991; Sovacool, 2008), I argue that on technical and economic grounds, nuclear fission could play a major role (in combination with likely significant expansion in renewables) in future stationary and transportation energy supply, thereby solving the greenhouse gas mitigation problem. The principle limitations against a large role for nuclear energy will be societal acceptance.

2. Assumptions

Before the technical potential of nuclear fission and complementary low-carbon energy technologies (renewables and fossil fuels with CCS), a scenario must be set against which plausibility

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[1] http://www.world-nuclear.org/info/inf43.html

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doi:10.1016/j.enpol.2011.11.041

and sustainability can be assessed objectively. Following Moriarty and Honnery (2009) and others, Trainer (2010) set this at 1000 EJ/yr (for primary energy) by mid-century; here I also adopt this approximate figure (representing roughly 15 TW of average power); for the purposes of calculating growth rates of different technologies, I will assume that this is reached by 2060, fifty years in the future. The actual date that this global primary energy demand is achieved is obviously uncertain, but will probably occur between 2040 and 2070 given current levels of growth (EIA, 2010). For greenhouse reduction criteria, I assume that the average emissions intensity of world electricity generation will need to fall to below 50 kg CO_2eq/MWh globally by 2060 to meet the Intergovernmental Panel on Climate Change's 85% reduction target (IPCC, 2007; Nicholson et al., 2011).

2.1. Baseline 2060 energy demand targets

The future energy target is summarized in Table 1, which shows world electricity demand in 2010 based on IEA data (http://www.iea.org/stats), as well as the projected 2060 (~1000 EJ primary energy) demand. The 2060 scenario uses the forecast values from Trainer (2010) for energy efficiency/conservation, direct electricity, transport electricity (e.g., battery electric vehicles) and liquid fuels; however, my estimate of the *source* of liquid fuels is different.

In Table 1 there is an overall 3.6-fold increase in world electricity use between 2010 and 2060 (to 277 EJ), compared to an approximate doubling of overall (primary) energy usage. Primary energy growth figures are in general agreement with the estimates of Starr (1993) and other recent forecasts (e.g., EIA, 2010; IEA, 2010; IPCC, 2007). A 5-year joint study by the World Energy Council and Institute for Applied Systems Analysis (Nakićenović et al., 1998, p. 88) estimated the 2050 demand for electricity could rise to 4800 GWyr (i.e., 151 EJ); similarly, the IGSM, MERGE and MiniCAM integrated assessment models (IAM) project electricity use in 2060 to be between 160 and 210 EJ/yr (Clarke et al., 2007). All of these authoritative forecasts are lower than the 277 EJ I use in Table 1b scenario because they did not model the wholesale replacement of oil/gas for transport fuels as I have done.

Trainer (2010) assumes that up to 50 EJ/yr of liquid fuels will come from biomass-derived cellulosic ethanol (requiring 1 billion ha and 7 t/ha yield); he also leaves an unmet deficit of 12 EJ/yr. In Table 1 scenario, I have assumed a lower contribution from biofuels of 15 EJ/yr (300 million ha). The remaining 47 EJ/yr of primary energy from liquid fuels is assumed to instead come from synfuels (e.g., hydrogen and hydrogen–nitrogen or hydrogen–carbon derivatives such as ammonia, hydrazine and methanol), which are manufactured using nuclear fission energy and atmospheric gases (Forsberg, 2009).

With reference to the detailed discussion of the synfuel manufacturing in Eerkens (2006, pp. 54–56), I assume:

(i) One-third of hydrogen (16 EJ) will come from electrolysis at a 30% electricity-to-hydrogen conversion efficiency: this will require 52 EJ of electricity input.
(ii) Two-thirds of the hydrogen (32 EJ) will come from direct nuclear heat via high-temperature thermochemical water decomposition, catalyzed using the hybrid S–I or Cu–Cl cycles (Orhan et al., 2010), at a 60% heat-to-hydrogen conversion efficiency. This thermal energy requirement is the equivalent of 550 GW of electricity plant, if one assumes a 33% Carnot-cycle efficiency that is typical for thermal-to-electrical conversion in fission reactors (Ion, 2007).

The ratio of direct electricity use to the final energy used in synfuel manufacture (via electrolysis and nuclear heat) in Table 1b is 0.31. By comparison, Eerkens (2006, p. 135) estimated a ratio of 0.4, but did not include battery electric vehicles or biofuels.

2.2. Technology mix scenario for 2060

The future energy mix scenario offered in Table 2 should not be considered a prediction – it is better thought of as a 'working hypothesis' (*sensu* Elliott and Brook, 2007) – consistent with the projected demand (Table 1b) and IPCC greenhouse gas emissions reduction targets – against which the sustainability of large-scale nuclear fission power (the key focus of this *Viewpoint* article) can be assessed quantitatively.

In this scenario, all existing non-fossil-fuel energy sources are expected to increase, with the highest rates of growth anticipated for wind/solar and nuclear fission. Comparing and contrasting my 2060 scenario with that of Trainer (2010, his Table 1), I have:

1. Hydro growing by 50% on today's energy share (similar to Trainer's 19 EJ).
2. Fossil fuels with CCS increases from virtually zero in 2010 to 26 EJ (this is half of the maximum 51 EJ allocated by Trainer).
3. Biomass and waste used for direct electricity generation increases ten-fold; the majority of crop energy is used to supply 15 EJ of ethanol (see Table 1b).

Table 1
(a) Electricity production data for 2010 from non-fossil-fuel sources, plus world total including fossil fuel generation; (b) global electricity demand in 2060, assuming a 1000 EJ of primary energy demand with a 33% increase in end-use efficiency.

Source	TWyr	EJ
(a) 2010 global electricity genertion		
Nuclear	0.316	9.96
Hydro	0.391	12.34
Wind	0.044	1.39
Solar	0.005	0.15
Geothermal	0.008	0.26
Biomass+waste	0.027	0.86
Total world electricity demand (all sources)	2.460	77.6
(b) 2060 global energy demand scenario		
Direct (stationary) electricity	3.68	116
Transport electricity (e.g. BEVs)	2.92	92
Synfuels: electrolysis-derived hydrogen	1.64	52
Synfuels: nuclear heat (electricity equivalent)	0.55	17
Biofuels (primary energy)	0.48	15[a]
Total world 2060 electricity demand	8.78	277

[a] Not included in total electricity summation.

Table 2
Hypothetical scenario for global low-emissions electricity supply for 2060. The assumed energy mix is 52% nuclear fission and 48% non-nuclear. Nameplate (installed) capacity is approximate, based on average capacity factors of hydro 0.45, wind/solar 0.3, other 0.5, biomass, fossil CCS and nuclear 0.85. The % annual growth rate (GR) of energy supplied assumes an exponential rate of change from today's levels over a 50-year period. World total supply (277 EJ) matches the demand forecast in Table 1b.

Supply source	EJ	GW_e av	Nameplate	% Share	% GR/yr
Hydro	18.5	587	1332	6.7	0.8
Wind/solar	77.3	2449	8164	27.9	8.1
Other renewables	2.6	84	167	1.0	4.7
Biomass+waste	8.6	273	321	3.1	4.7
Fossil CCS	26.0	824	970	9.4	N/A
Non-nuclear[a]	133	4217	10,955	48	4.5
Nuclear	144	4566	5372	52	5.5
World total supply	277	8783	16,327	100	

[a] Excludes fossil fuels without CCS.

4. Wind and solar output collectively expand 50-fold on today's levels.
5. Nuclear fission growth is then set to balance the total projected demand. This results in a nearly 15-fold increase on the 2010 share of ~310 GWe average (Table 1a).

The final ratio of 52% nuclear fission to 48% non-nuclear energy sources is lower than the national domestic electricity mix of France today (currently 78%[2]), but the 2060 scenario differs in modeling the replacement of total final energy (including all stationary electricity and transport/industrial energy). This scenario is consistent with the conclusions of Jean-Baptiste and Ducroux (2003) and Sailor et al. (2000), who forecast a requirement of >100 EJ of nuclear energy by 2050 for significant greenhouse gas abatement.

In reality, there may be a greater or lesser supply from any of these low-carbon energy sources (i.e., the relative mix of nuclear fission, various renewable technologies, and CCS); this will depend on a broad range of complex factors, including carbon prices, subsidies and tariffs, energy security considerations, fossil fuel supply constraints, and technological, logistical, economic and socio-political circumstances (Clift, 2007; Hoffert et al., 2002; Kyle et al., 2009; Nicholson et al., 2011; Utgikar and Scott, 2006). For instance, the Level 1 greenhouse gas stabilization scenario for the MERGE IAM includes 240 EJ/yr of primary energy from nuclear power (~90 EJ electrical energy) in 2100, whereas the IGSM IAM assumes no increase after 2000 (Clarke et al., 2007, p. 101), with the differences dependent on socio-economic assumptions. In this context, Table 2 scenario presented in this paper is offered as one that (i) meets a number of first-order logical and sustainability criteria, and (ii) is consistent with the authoritative energy systems analysis literature.

3. Assessment of the sustainability of large-scale nuclear fission

3.1. Technology options

A future extensive deployment of nuclear fission would certainly rely on a large tranche of already commercial Generation III/III+ moderated-thermal reactor technology, with an open fuel cycle. Within a few decades, a build-out of currently demonstration-stage Generation IV units that fully close the fuel cycle and use some mix of uranium, plutonium and thorium as their fuel is also likely (Grover and Chandra, 2006; Hyde et al., 2008; Jeong et al., 2010). Beyond the fuel sustainability implications of nuclear waste recycle (see Section 3.2), the Generation IV fission reactor designs also offer large advantages in terms of inherent safety systems (via metal or fluid fuels and liquid-metal or molten-salt coolants) that are highly resilient to events such as extended station blackout (the Achilles heel of Fukushima Daiichi[3]), as well as permitting compact, factory-produced modular construction thanks to higher temperatures and greater power densities (Abram and Ion, 2008; Hannum, 1997). These features offer the potential to achieve lower construction costs and accelerated deployment timeframes.

3.2. Is there enough nuclear fuel?

In Generation III+ reactors (see Section 3.1), the fuel is typically uranium that has been enriched from a natural isotopic composition of 0.71% ^{235}U up to 3–5%; this requires an annual input of approximately 150 t of mined uranium per GWe of capacity.[4] A recent 2011 report by Massachusetts Institute of Technology[5] estimated that there is sufficient uranium in reasonably assured and speculative resources to fuel a substantial expansion of thermal, once-through reactors until beyond 2050. However, for the scenario outlined in Table 2, this implies the requirement of at least 500,000 t of mined uranium per year, compared to the 2009 world production of 50,722 t.[6] Although a substantial expansion of global uranium supply is feasible on geological and economic grounds (Macdonald, 2004), I argue that a more plausible and sustainable pathway to achieving a multi-terawatt expansion of nuclear power is via Generation IV reactor technology coupled to full fuel recycling, based on proliferation-resistant pyroprocessing or similar methods which do not separate pure actinide products (Abram and Ion, 2008; Eerkens, 2006). This would not only extend the uranium resource by up to 150 times, but would also open the way to thorium (Hyde et al., 2008) and complete recycling of existing spent nuclear fuel and depleted uranium stockpiles (Hannum, 1997). On this basis, only 1 t of fertile material (^{238}U or ^{232}Th) would be required annually per GWe, meaning that the Table 2 scenario would involve a demand of less than 6000 t per year. This rate of fuel use is sustainable for thousands of years based on just the reasonably assured resources, and for millions of years if far-future society chose to exploit unconventional sources (Lightfoot et al., 2006).

3.3. Will carbon emissions intensity be sufficiently low to meet IPCC targets?

The 2009 United Nations Climate Change Conference recognized the scientific view that any increase in global temperature should be kept below 2 °C; the International Panel on Climate Change (IPCC) state that this requires atmospheric greenhouse gas levels to be stabilized below 450 ppm carbon dioxide equivalent (CO_2eq) and future emissions to be reduced by 50–85% below 2000 levels by 2050 (IPCC, 2007); this implies an average global emissions intensity (EI) of 50–150 kg CO_2eq per MWh of electricity. In a recent meta-review of 14 authoritative life-cycle assessments of greenhouse gas emissions for energy technology published during the last decade, Nicholson et al. (2011) showed nuclear fission to have a median EI of 20 kg CO_2eq per MWh. By comparison, the EI estimates for coal and gas-fired technologies with CCS was 134–170 kg CO_2eq per MWh.

It has been argued that if nuclear fission is used to replace fossil fuels for electricity generation on a large-scale, then its EI will rise as increasingly lower-grade uranium ores are mined (e.g., Mortimer, 1991; Sovacool, 2008). However, the assumptions underpinning this line of argument do not stand up to scrutiny (Beerten et al., 2009). For instance, if fast spectrum reactors with full fuel recycle are deployed (see Sections 3.1 and 3.2) then this concern is assuaged because there is sufficient spent nuclear fuel and depleted uranium tails to provide a ready supply for many centuries without recourse to mining (Lightfoot et al., 2006). Further, if all future industrial energy inputs–including synthetic transport fuels used for mining operations (see Table 1b)–are derived from some mixture of zero- or low-carbon fission reactors and renewables (Table 2), then the lifetime carbon emissions from the nuclear fuel cycle will decline towards zero, not rise, as sometimes asserted.

3.4. Can nuclear plants be built quickly enough?

Could more than five thousand large nuclear power plants (Table 2) be built worldwide during the next 50 years? The World

[2] http://www.iea.org/stats/electricitydata.asp?COUNTRY_CODE=FR
[3] http://www.world-nuclear.org/info/inf43.html
[4] http://www.ne.doe.gov/pdfFiles/eprTtsUSEPRCoreDesign.pdf
[5] http://web.mit.edu/mitei/research/studies/nuclear-fuel-cycle.shtml
[6] http://www.world-nuclear.org/info/uprod.html

Nuclear Association's *Nuclear Century Outlook*[7] has forecast a high estimate of 1350 GWe of nuclear plant in operation by 2030, based on current national plans. This would leave an additional 4022 GWe to be built between 2030 and 2060 in order to meet the assumptions of Table 2, implying a (linear) rate of 134 GWe per year.

The peak global build rate was 30 GWe in 1984; regionally however, France opened 63 GWe of new nuclear capacity between 1977 and 1999—an average rate of over 2.5 GWe per year (Mackay, 2008, p. 171). France's GDP constitutes 4.1% of the combined 2010 total of the European Union, United States, China, Japan, Russia, South Korea, India, Canada, Brazil and Mexico ($51 trillion[8]). If only these nine countries plus the European Union, all with GDP > $USD 1 trillion and already using commercial nuclear power, built additional nuclear capacity at the same rate as France achieved over more than two decades, then this would imply a potential build rate of 70 GWe per year. If France's inflation-adjusted GDP[9] increase of 187% since 1977 is also factored in, the possible rate rises to 130 GWe. Clearly then, a global target of 134 GWe per year between 2030 and 2060, while ambitious, is feasible on historical grounds. This is underscored by the substantial nuclear plans for economically emergent populous countries like China (Zhou, 2010) and India (Grover and Chandra, 2006).

3.5. Safety, proliferation and cost

The concerns around safety, nuclear weapons and cost are associated with the social and economic acceptance of nuclear fission, rather than the technical and logistical limits which was Trainer's (2010) focus. Still, a few pertinent comments are warranted.

A comprehensive study of 4290 energy-related accidents by the European Commission's ExternE research project[10] reviewed the number of deaths per terawatt hour of electricity; the result was 25 for coal, 4 for natural gas and 12 for biomass, whereas nuclear and other renewables both caused <0.2 deaths/TWh. (These figures ignore deaths from pollution and global warming.) Further, as noted above (Section 3.1), Generation III+ and IV nuclear fission technologies rely on passive and inherent safety that is much more 'failsafe' than engineered systems (Eerkens, 2006). On the vexed issue of the control and proliferation of fissile material and associated facilities (e.g., enrichment plants) and possible diversion to nuclear weapons programs, although technical methods such as electrorefining of mixed actinide fuel in the integral fast reactor (Hannum, 1997) can assist, this issue is really one that must be solved through international diplomacy (Hyde et al., 2008; Weinberg, 1994). However, as noted in Section 3.4, a large fraction of global GDP is captured by nations that already use commercial nuclear energy (Ion, 2007). On cost, a recent meta-review of 15 authoritative studies of levelized cost of electricity put nuclear power at US$84/MWh for first-of-a-kind builds and $54/MWh for settled down costs; this compares to $75–$86/MWh for coal and gas with CCS, and $165/MWh for solar thermal with on-site storage (Nicholson et al., 2011). In practice the actual cost of nuclear will depend on many factors, including market structures, regulatory regime and political will (Kessides, 2010).

4. Conclusions

The critique of the future global role of renewable energy by Trainer (2010) underscored many important limitations associated with variability, dispatchability, large-scale energy storage, the need for overbuilding and geographical replication (and the likely consequence: 'dumping' of unused excess energy), energy returned on energy invested, and other key points. The meta-analysis by Nicholson et al. (2011) also considered technological maturity, cost and life-cycle emissions as constraints on renewables' capacity to displace fossil fuels. Although I support Trainer's (2010) conclusion that renewables alone will not be able to 'solve' the greenhouse problem, I argue that his dismissal of a major role for nuclear fission energy, working in complement with other low-carbon energy sources, was unjustified.

The principal limitations on fission energy are not technical, economic or fuel supply—they are instead tied up in the complex issues of societal acceptance and public education (Adamantiades and Kessides, 2009; Pidgeon et al., 2008), fiscal and political inertia (Hyde et al., 2008; Lund, 2010), and inadequate critical evaluation of the alternatives (Jeong et al., 2010; Nicholson et al., 2011; Trainer, 2010). Ultimately, as the urgency of climate change mitigation mounts, and requirements for sustainable growth in developing economies and replacement of aging infrastructure in the developed world come to the fore, pragmatic decisions on the viability of all types of non-fossil technologies will have to be made. Engineering and economics realities point to a large role for fission in this new energy future.

[7] http://www.world-nuclear.org/outlook/nuclear_century_outlook.html
[8] http://www.imf.org/external/ns/cs.aspx?id=29
[9] http://www.tradingeconomics.com/france/gdp-growth-annual
[10] http://www.externe.info/expoltec.pdf

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