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Positioning Nuclear Power in the Low-Carbon Electricity Transition

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Academic Editor: Barry D. Solomon
Received: 4 December 2016; Accepted: 18 January 2017; Published: 23 January 2017

Abstract: Addressing climate change requires de-carbonizing future energy supplies in an increasingly energy-dependent world. The IEA and the IPCC (2014) mention the following as low-carbon energy supply options: 'renewable energy, nuclear power and fossil fuels with carbon capture and storage'. Positioning nuclear power in the decarbonization transition is a problematic issue and is overridden by ill-conceived axioms. Before probing these axioms, we provide an overview of five major, postwar energy-related legacies and some insight into who is engaged in nuclear activities. We check whether low-carbon nuclear power passes the full sustainability test and whether it is compatible with the unfettered deployment of variable renewable power sourced from the sun and from wind and water currents, which delivers two negative answers. We show that the best approach of the sustainable energy transition was Germany's 2011 decision to phase out nuclear power for a fast development and full deployment of renewable power. This is the best approach for the sustainable energy transition. We offer five practical suggestions to strengthen and accelerate carbon- and nuclear-free transitions. They are related to institutional issues like the role of cost-benefit analysis and the mission of the International Atomic Energy Agency, to the costs of nuclear risks and catastrophes, and to the historical record of nuclear technology and business.

Keywords: nuclear power; nuclear risks; sustainability; low-carbon transition; electricity sector; renewable energy; IAEA International Atomic Energy Agency; IPCC Intergovernmental Panel on Climate Change

1. Introduction

At COP21 in Paris in 2015 and COP22 in Marrakech world leaders have declared commitment to low-carbon energy transition. Many international institutions and programmes, e.g., the World Bank, the United Nations Council for Sustainable Development, and governmental initiatives, e.g., Energiewende in Germany, EU Climate Action programme, PowerAfrica, and the US Agency for International Development, already actively support deployment of low-carbon electricity generation capacity. Two main options for sourcing low carbon electricity are currently on the table: first, renewable energy resources (variable currents most notably solar photovoltaics (PV) and wind power, plus stock sources, most notably dam hydro, biomass and geothermal); and second, nuclear power. In practice, atomic energy conversion delivers only electric power; therefore, positioning nuclear power focuses on the transition of the electricity supply sector, as the spearhead of the overall energy transition. It is not helpful to argue about the position of nuclear power with gross primary energy statistics, as done by Cao et al. [1]. The new impetus given to low carbon transition requires thorough consideration of the energy sources and technologies that the global community will be passing onto the future generations. In that respect, nuclear power cannot be considered a sustainable, responsible option for the low carbon transition.

This paper offers a composite critique of methods widely utilized in energy sourcing decision-making; of the role and function of institutions governing and monitoring low-carbon transition; of approaches to the legacy, risks, and future threats of nuclear power; and of the to-date failure of the nuclear power cycle to deliver on announced declarations, such as solving the issues of safety and waste, or low-cost alternatives for substituting fossil fuels. In Section 2 we discuss five main energy-related anthropogenic legacies: growth in fossil fuel consumption, atoms for peace, renewable energy development surfing on non-energy science and technology, the move to sustainable development, and climate change. In Section 3, we discuss the official climate policy discourse including three juxtaposed low-carbon energy supply options: renewable energy, nuclear power and fossil fuels with carbon capture and storage [2,3]. Their sustainability and mutual compatibility are adopted without proof, axiomatically. Interests shield their discourse axioms against contradictory empirical evidence; for example, IAEA and IPCC (2014) bypass the sustainability assessment of nuclear power [4]. Li, Geng, and Li [5] provide a list of eleven publications addressing aspects of sustainability for a variety of energy conversion systems. However, the selection of attributes and the quality of implied information is difficult to compare, and the results are not comparable either. The incompatibilities between the full deployment of variable renewable power and nuclear power in a 100% carbon free integrated power supply system are not addressed by the emission scenario models used for designing official climate policy [2]. We question nuclear power's sustainability and its compatibility with high deployment rates of variable renewable power (mainly solar, wind, and water currents). We refer to the selective group of countries and companies who own and export nuclear power. In Section 4, we offer five arguments for a sustainable energy transition plan without nuclear power: (1) think beyond the reductionist cost-benefit analysis framework because of huge uncertainty and ignorance, very long time horizons and duly irreversible impacts; (2) limit IAEA's tasks to control of nuclear activities and forbid direct and indirect promotional actions for nuclear power generation; (3) the possibility of accidents should be taken seriously, replacing the ostrich attitude that catastrophes cannot happen; (4) treat risks as real costs to be covered by the plant owners, and stop labeling the rational risk-adverse attitude of citizens as barriers to nuclear power deployment; and (5) evaluate nuclear power's failures since the 1950s to meet its self-announced projections and created expectations as a substitute for fossil fuels. Brief conclusions are presented in Section 5.

2. The Five Main Energy-Related Legacies of the Past 70 Years

Thorough low-carbon energy transitions require urgent and drastic changes [6], including the questioning of vested wisdom treated as axioms and as such left unquestioned. Such biases emerged in the mid-20th century and continue to exert an unjustified impact because they remain backed by interests of agents or vested interests of various kinds (financial, institutional, public funded research and demonstration plants, dedicated and specialized experts, etc.). Over the past 70 years, five main legacies determine current energy interests and discourses related to energy use: growth in fossil fuel consumption, atoms for peace, emerging flow renewable energy technologies (solar, wind) surfing on non-energy science and technology, sustainable development of a new paradigm endorsed by the world political leaders at the 1992 Rio Earth Summit, and climate change also addressed at the Rio Summit by approval of the UN Framework Convention on Climate Change. These legacies were and are particularly influential on official thinking and decision-making.

(1) Expansion in fossil fuel use supports growing economies in industrialized and industrializing nations. Slowly since the industrial revolution but rapidly after 1945, our world has become locked into fossil fuel energy supplies [3] to feed its capital-intensive and long-lasting energy systems for the sake of control over ever-growing energy flows from primary sources abroad to final use in industrialized economies [7]. By 2010, fossil fuel use caused 67 percent of direct anthropogenic greenhouse gas emissions [8] making decarbonization of the energy systems the first necessity in

addressing climate change. Two sizeable options on today's low-carbon menu are, first, flows and stocks of renewable energy, and, second, nuclear power.

(2) The 'Atoms for Peace' program launched in 1953 [9] marked the beginning of the attempt to create a cheap and clean all-electric energy society. This plan received overwhelming support from scientists, industrialists, politicians, journalists, and the public. In fact, substantial contemporary public research funds on energy were spent on nuclear technological development. However, optimism was soon cooled by technical failures and accidents. While the oil crises of 1973 and 1979 stimulated further nuclear plant construction in many countries, the United States sector did not revive due to plant construction cost overruns [10] and safety issues (Browns Ferry fire 1975, Three Mile Island accident 1979). Improved energy efficiency, the Chernobyl disaster (1986), and low oil prices since the mid-1980s slowed the dash for nuclear power. In 2013, after sixty years of continuous, liberal support to nuclear power development, nuclear plants deliver around 10.8 percent of the world's electricity [11], around 2 percent of global energy use [12]. The 1950's ambition of an atomic energy transition faded [13] and reduced to a slogan of the nuclear renaissance campaign: '*Nuclear power is not the only solution, but there is no solution without*' [14]. This cheap slogan needs validation based on empirical evidence and solid logic.

(3) Non-energy science and technology evolved remarkably fast and grew versatile, with deep and broad impact on most societal activities. In the late 1960s to early 1970s the Fordist mass production/mass consumption complex became disintegrated by crises of overproduction and decreasing profitability [15,16]. Global economic growth was revived, mainly through diversification and flexibility of supply [15,16], leading to increased technological innovation and transfer that occurred at inter- and intra-sectorial levels and between different regions of the world, 'space-time compression', and transformation [17]. Continuous and ubiquitous innovation is a key component to the revival. The high degree of technology transfer across sectors enables renewable energy and energy efficiency options to surf on those most successful scientific and technological developments, e.g., fluid dynamics, electronics, new materials, ICT (information and communication technologies).

(4) In 1992, the Rio Earth Summit enacted sustainable development as a human development paradigm to inform major aspects of local, national, and global policy-making as evidenced in "Our Common Future" [18] and in Agenda 21 [19]. The Rio Summit addressed two protracting postwar problems: the heavy burden put by the growth economy on nature and the environment, and the skewed distribution of wealth, with the poor excluded from good living conditions. The endorsement by the global political leadership of sustainable development as a recommended development paradigm mandates that future low-carbon electricity supplies should obey all the various imperatives of sustainability.

(5) The Rio Summit also adopted the UN Framework Convention on Climate Change (UNFCCC). Its mission is to 'avoid dangerous climate change'—intensely related to industrialized energy systems' function and impacts. The convention's mission implementation via annual COPs brought the 1997 Kyoto Protocol, the 2009 Copenhagen Accord and the 2015 Paris Agreement, none being effective so far in halting the growth of energy-related carbon dioxide emissions, while deep decarbonization is necessary [20].

Every legacy implies the existence of particular interests. Some (fossil fuels, nuclear power) are vested and strongly rooted in decision centers from global to local levels. The International Atomic Energy Agency (IAEA) was founded as an autonomous organization in 1957, but reports to the UN General Assembly and Security Council. IAEA is an intergovernmental organization, and enjoys a status above reproach and ample working budgets for promoting the peaceful use of nuclear energy and inhibiting the military use of atomic weaponry. Others (renewable energy, sustainability, decarbonization) are emerging and pushing for disruptive changes in customary practices. Some parts of the constituency and political actors do actively participate and support the change processes (for example, the United States Conference of Mayors). Other parts are indifferent or even hostile to the future innovations (for example, the administration composed by newly elected U.S. president Trump). Some opposition may be explained by the 'Lauderdale paradox', i.e., the lesser exchange value of a good leads to the lesser business interest in producing it as their main concern is profit, not clean air [21]. This is one reason why public policy is crucial to redirect from fossil fuel and nuclear subsidizing to supporting renewable energy science and technology through rapid coordinated international effort [22].

3. A Tedious "Axiom" of Global Energy and Climate Policy

Today's dominant discourse fosters a default axiom of global energy-climate policy: 'The atomic legacy matches the Rio legacy in reducing global carbon dioxide emissions'. Axioms are accepted without proof. Unlike the axioms of physics, this highly relevant political axiom is not the result of meticulous observation and study of empirical evidence, but a normative position spread by vested interests concealing the facts and experiences with nuclear power since the 1950s. The probe of the political axiom questions the nuclear power legacy and its performance on at least two major issues, its sustainability (Lemma 1) and its compatibility with the most sustainable power supply options being the direct conversions from natural currents like solar light and wind (see Lemma 2 below).

Lemma 1. *Nuclear power does not satisfy the basic sustainable development conditions.*

Nuclear power is being advocated as a main option for sustainable energy supply in the immediate future, without solid argumentation as to why this assertion is valid [1,23,24]. Effective assessment of nuclear fission power in terms of sustainability requires an elaborated set of nineteen criteria on the four main sustainability dimensions i.e.,. Planet, Prosperity, People, Politics, with added sustainable development dimensions of Peace and Partnership [18,25] and complemented with special attention to risks [26]. Comprehensive assessment concludes that nuclear power does not perform well on all the relevant sustainability criteria, except the low carbon emissions attribute. But this single performance does not suffice to ignore the other eighteen criteria. Ignoring them is standard in official rhetoric about the future role of nuclear power [1–3].

In terms of the planet/environmental preservation criterion, while nuclear power appears to be a reasonable low carbon option in comparison to power generation from fossil fuels, the potential results are overshadowed by the incompatibility of the nuclear expansion with full renewable energy deployment ([4,26], see Lemma 2 below).

As for prosperity, the externalities of nuclear fission power and the related fuel cycle, particularly in the long run, are virtually impossible to estimate. This is so mainly due to unknown future risks and associated with very distant time horizons (centuries, millenniums) and irreversibility traps in cases of potential and actual (Chernobyl, Fukushima) disasters. Construction costs are unreliably high. Thus, the only two nuclear power plant reactors under construction in the EU are unduly overrunning in terms of construction times and expenses. In Finland, the EPR (European Pressurized Reactor) contract was signed in 2003 for €3 bn and delivery in 2009; in 2012 the budget was raised to €8.5 bn with delivery in 2018. The French EPR under construction already faced €10.5 bn expenses and is seven years behind schedule [27]. Although IAEA is promoting nuclear reactors worldwide, nuclear building is not accessible for most developing countries. These countries are restricted by the high capital costs of nuclear construction and their infrastructure and geography of electricity demand require distributed rather than centralised electricity supply systems. Next, nuclear fission power plants are unable to obtain full indemnity insurance in the regular insurance markets to cover third party liabilities, because the global re-insurance sector assesses the associated risks as too high [28]. Such lack of corporate insurance pushes the risks onto citizens-taxpayers who in the end bear both the physical and financial burden in case of a nuclear disaster.

The people's interest criterion is harder to assess as it is deeply intertwined with the other criteria. Therefore it is hard to separate and to measure, and to be seen and heard in the conflicts of interests.

Costs, both current and future, are a big concern in this respect. In term of immediate utility bills nuclear in some countries may offer a financially attractive option in the short run, mainly for base-load industries procuring base-load power. These short-term financial gains provide support for nuclear plant construction in some countries, e.g., France, South Korea, China. However, the potential costs associated with nuclear externalities heavily outweigh the short-term benefits [29]. For example, if the risk premium of potential disasters could be included in the standard utility bills, nuclear power will be higher priced than other electricity supply options. When a nuclear disaster happens, the disruption to power supply wreaks havoc in the supply systems as the Fukushima accident avidly testifies. High costs and non-insurable risks are created with increasing reliance on nuclear power because accidents cause spill over effects. Additional risks are associated with military security and security of public and planetary health.

Finally, in terms of politics and societal decision-making on nuclear issues, private supplier and engineering companies and 'government technocracy' take precedence over democratic engagement, let alone control. Moreover, democratic engagement and public interest guarantee are often compromised due to the lack of an open scientific debate on the nuclear issues and influential governments' collusion within nuclear conglomerates. Via direct ownership in companies operating nuclear plants, governments are de facto nuclear producers in several countries, e.g., France, Sweden, Japan, Russia, and China. This may cause conflicts of interest when governments, whose role is to protect public interest and guarantee multilevel public security (economic, social, military, health, etc.), are concerned with keeping nuclear producers in business and with paving the way for increased nuclear exports.

The number of countries in the nuclear club is limited with the five permanent members of the UN Security Council as its core. The largest nuclear power producers and exporters of nuclear equipment are (in the ascendency order): EDF/France (73 reactors globally), Rosnergoatom/Russia (35 reactors), Korean Electric Power Corporation (KEPCO)/South Korea (20), Tokyo Electric Power Company (TEPCO)/Japan (17), Exelon/USA (17), EOn and Rheinisch-Westfälisches Elektrizitätswerk AG (RWE)/Germany (9 and 5 respectively) [30]. Figure 1 shows the main nuclear power-producing countries, organised by the number of operable reactors.

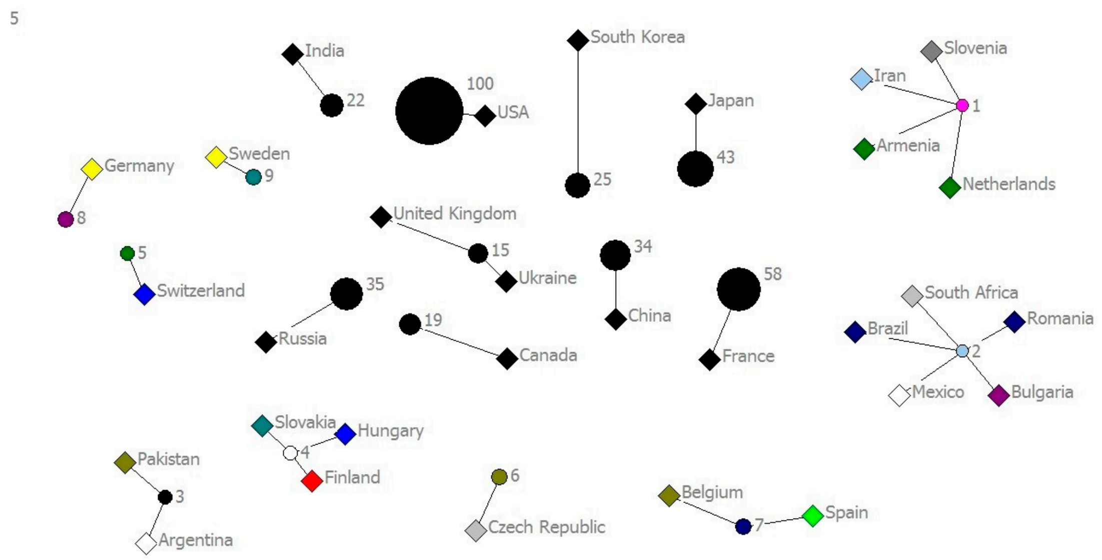

Figure 1. Nuclear energy producing countries by number of operable reactors, 1 September 2016 [30]. (Key: Diamonds are countries, circles are representations of operable reactors size-adjusted by the indicated number of reactors.)

Nuclear conglomeration is partly a result of global patronage by IAEA as an established and endowed intergovernmental agency. More important is how the collusion of interests is fabricated and maintained in the particular national states with nuclear power activities. It requires extensive investigation to clarify the underwater part of the iceberg whose visible part hails nuclear power as a valid future low-carbon option. Cox, Johnstone and Stirling [31] add a 'deep incumbency' hypothesis to the more common explanations of conglomerated nuclear interests for investigating the 'apparent anomaly' of the 'unusual intensity and persistence of official UK policy commitments to civil nuclear power'. Secrecy rules obstruct independent research about the linkages between civil and military applications of nuclear technology.

The nuclear section of Our Common Future ([18], pp. 181–189) concludes with: 'The generation of nuclear power is only justifiable if there are solid solutions to the presently unsolved problems to which it gives rise. The highest priority must be granted to research and development on environmentally sound and economically viable alternatives, as well as on means of increasing safety of nuclear energy.' Recent sustainability assessment of nuclear fission power shows that nuclear power falls short on most sustainability criteria [26].

Lemma 2. *Nuclear power is incompatible with the full deployment of variable renewable power supplies.*

In a world increasingly reliant on power supplies uninterrupted 'power generation on command' is employed as a reference point in evaluating supply systems. On command, power is tapped from storable fuels or reservoirs, mainly fossil fuels, uranium and hydro dams. Variable renewable power supplies from sun, wind, and water currents are seen as endemically disruptive due to their intermittent and stochastic nature. Transitional planning is erroneous when anchored on truths of the fossil fuel era, revealed by a vocabulary of 'integration of variable renewable power' in the existing power systems (for example OECD/IEA Report to the G7: 'System Integration of Renewables' [32]). An effective and efficient thorough transition treats the future sustainability goals as benchmarks for assessing present states of supply systems and required scenarios for their transformation [33]. Contrary to the 'integration' vision, variable renewable power is the standard to be deployed everywhere and with priority for dispersed rather than concentrated and centralised units (rooftop PV, on-land wind turbines, small hydro plants). Such deployment significantly challenges reliability of power supply. Addressing the challenges requires solutions similar to that being developed by the 'integration' approach [34]. But the priorities, rights, duties, and liabilities ingrained in the dominant policy approaches hinder rather than help effective solutions being put in place. The future sustainability solutions must rest with renewable energy, not be ridden with the nuclear and fossil fuel legacies. The transformation of the power systems must be designed and planned out with the sustainable end-goal in mind.

Nuclear power and variable renewable supplies are incompatible in the future green transition in terms of five different aspects [35]. First, nuclear power offers no new qualitative progressive policy shift but is a blast from the past resonating since the 1950s. Notwithstanding massive financial and political support for the development of the technology and its civil applications (since Atoms for Peace was launched in 1953), nuclear power did not deliver on the announced energy transitions: the all-electric, nuclear supplies (1950–1960s); significant weakening of the position of petroleum as energy market kingmaker (1970–1980s); and solving the problems of waste and safety for obeying sustainability imperatives (1950–2016). Second, nuclear power requires different ways to balance the power supply than renewable power. Third, the two powers need different types of electricity grids to transmit their outputs—a bulky, centralized top-down type for nuclear outputs and broad dispersed, multilateral network setups for the various and numerous renewable energy suppliers. The disparity is most obvious for supplies outside densely urbanized areas of advanced economies. Fourth, risks and externalities of nuclear power production and permanency of nuclear waste problems highlight the unsustainability of nuclear power [36]. Fifth, nuclear power survival and renewable technology inventions, innovations and development depend both on state support and funding for

R&D. The public budgets are limited, college curricula are competitive, scientists and engineers can be productively used for either nuclear survival or renewable technology inventions and innovations, not both at the same time. The EU has choked its own leadership in renewable energy by changing the state aid guidelines in 2014, fencing in support for distributed renewable projects, while allowing the UK's high price guarantees for new nuclear stations [33]. Nuclear power and renewable power have no common future in safeguarding 'Our Common Future' [35,37].

Detailed technical analysis of dynamic power systems reveals the incompatibility of increasing variable renewable power generation facing nuclear power supplies. However, the prevailing official discourse repeats the mantra of a simple juxtaposition of both kinds of supplies [2,38], as if it were an axiom. This discourse can be continued when the contenders are embedded in separate power systems with ancillary supplies from fossil fuel based, bio-energy or hydropower dam electricity. However, when 100% carbon-free electricity in a single integrated power system is achieved, variable renewable power and nuclear power will collide. Both types of supplies are characterized by inflexibility, but of a very different kind and for different reasons. There is a need for balancing current to fill the power loads on top of their respective base-load supplies. Stapling supplies is the principle in merit order loading, not juxtaposing supplies, because electric current is an ephemeral phenomenon. Figure 2 shows the juxtaposition of atomic and variable renewable supplies in separate power systems, separately serving the electric loads on the two systems. Nuclear power and variable renewable supplies serve separate power loads and require supplementation from flexible power supply units, which can come from fossil fuel combustion, bio-energy based power, hydropower, with added options from load management and storage [39]. Every integrated power supply system requires deeply intertwined interconnections and high compatibility and reliability for smooth operation in technical and economic terms alike.

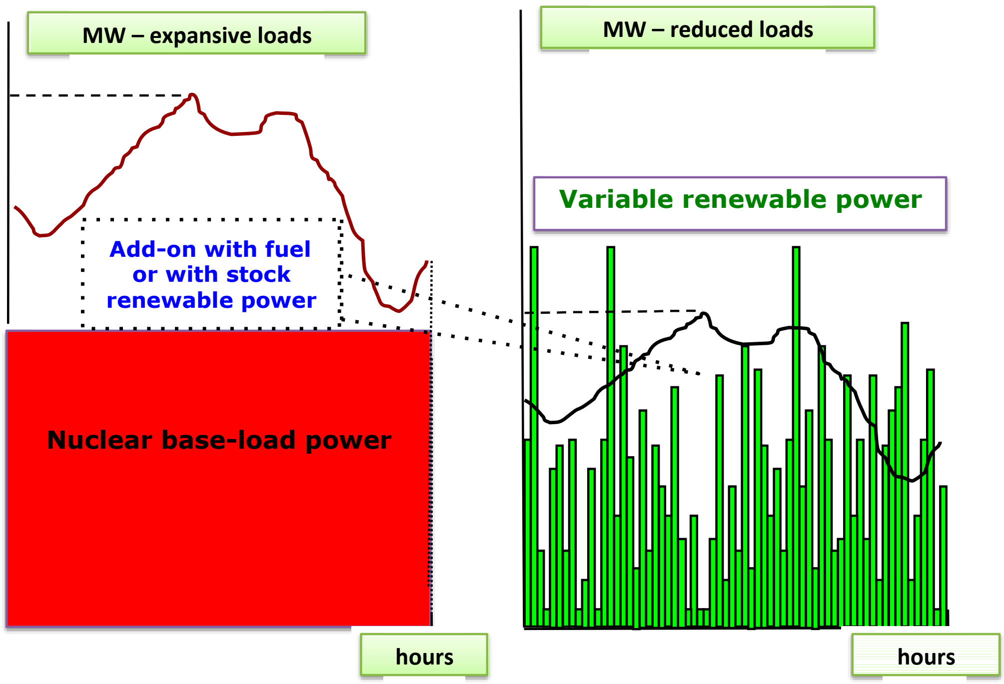

Figure 2. Nuclear versus variable renewable power supplies, separately serving electric loads [35].

When nuclear power and variable renewable power plants operate in the same electricity supply system they undermine each other technically and mainly financially. Figure 3 illustrates that the two contenders will claim the same base-load area when operating in the same integrated power system. When priority is given to nuclear plants (left panel in Figure 3), the variable renewable power capacities will be curtailed almost continuously, in particular when their total capacity will grow towards 100% coverage of the electric loads. Standard merit order logic however gives priority to generation units with the least short-run marginal costs, being the free variable renewable sources in the ambient environment (light, wind, water currents). This is shown in the right panel of Figure 3, illustrating how the base-load area is carved out by the green supplies. No nuclear station is technically flexible enough to ramp up and down for complementing stochastic changes within seconds [34]. When costs do not matter, one could operate nuclear plants at load factors below 50 per cent. But to avoid disturbance and nuisance for their nuclear plants, the large power companies prefer curtailment of variable renewable power generation. Systematic curtailment, not just occasionally for safety reasons, will undermine the appetite of the millions of independent power generators for participating in the low-carbon energy transition.

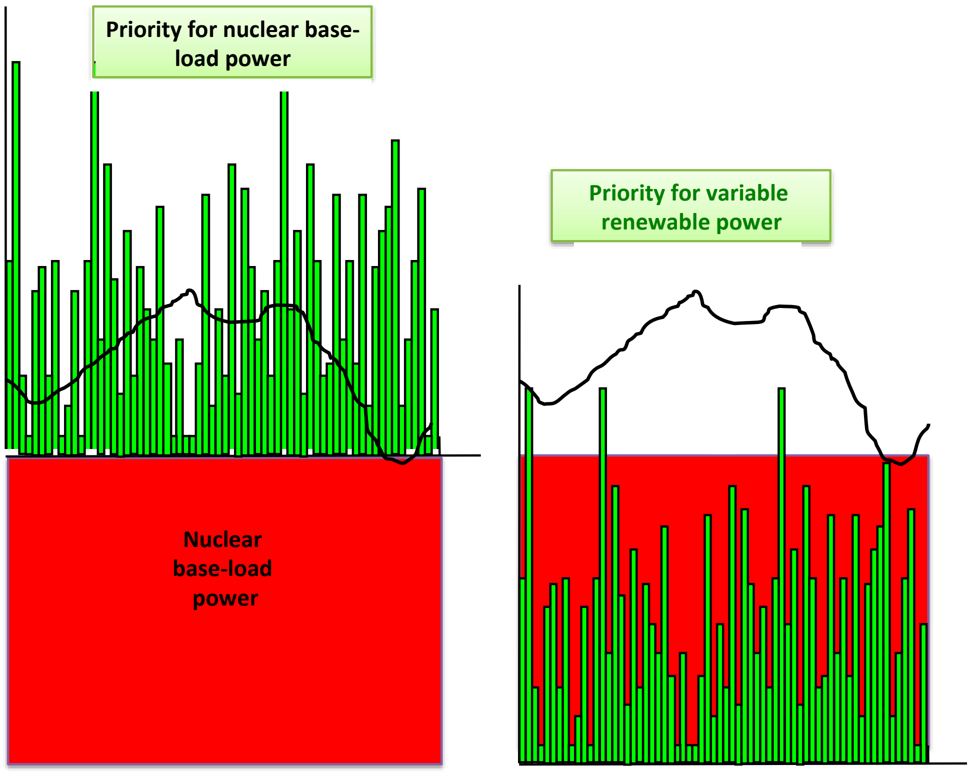

Figure 3. Nuclear and variable renewable supplies mutual impact when operating in the same power system [40].

Figure 4 is borrowed from IEA's World Energy Outlook 2013. It shows how expanding deployment of solar PV cuts the electricity loads during daytime. The three cases represent PV capacity at 25%, 50%, and 100% of the electricity peak load. In the, case (c) in Figure 4 complementing capacities have to reduce their activity to zero output at noon and ramp up again to meet the full demand at the end of the day. Nuclear plants crumble under such a daily regime. Given the rapid decline in PV investment costs, it is economical to install PV panels on every fitting roof. Not only is the situation of 100% capacity likely in the coming years, even more likely is a redundancy of capacities. This redundancy will enlarge the carvings shown in Figure 4, also by adding batteries to the installations. Redundant variable renewable power at zero marginal cost price is a crucial technical challenge for future electric power system operators and a regulatory challenge for public authorities. Several decisions need to be made, i.e., who is allowed to deliver? How many Watts? Under what conditions and at what remuneration rate? These problems are highly intricate. This is why the transition to 100% carbon-free electric power supply goes beyond the issue of 'integration of renewables'.

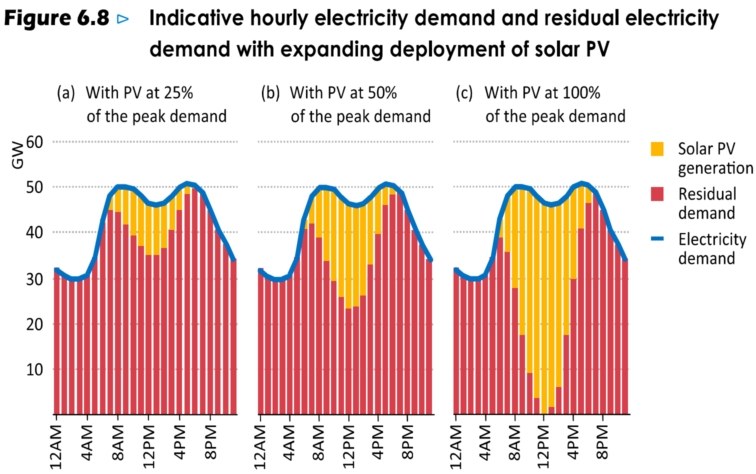

Figure 4. High deployment of photovoltaic panels carves the electric loads during daytime (Source: IEA World Energy Outlook 2013).

Overall, the incompatibility between nuclear and variable renewable power is stronger in terms of sustainability, economics, regulation, and conflicting interests of technologists, owners, and producers than in technical operability.

4. Arguments for a Sustainable Transition Plan, Realistic and Non-Nuclear

Nuclear power technology development is the most subsidized electricity supply technology in history. Since 1945 the bulk of public spending on energy RD&D in the Organisation for Economic Cooperation and Development (OECD) countries has gone to nuclear technology. The continuous subsidies did not succeed in making the plants economically competitive further confirming the high endemic costs and economically debilitating prohibitive risks inherent in the technology. Government financial assistance is crucial for nuclear survival. The pressurized water reactor is a fleshed out technology not able to exceed an efficiency of ca. 35% in its electricity generation process. The Hinkley Point C project in the UK shows technological and economic immaturity of this nuclear power technology [41] which started with a budget of some £18 billion for constructing two EPR plants—with the prospect of soon adding another £2.7 billion [42]. The sensible principle in spending public money on techno-economic projects is that resulting benefits to society should be greater than the projects' costs, including the costs related to decommissioning and to the fuel cycle after closure of the power generation unit. In standard business, there is a practice of ex-post calculation of the profitability of projects, to inform future decisions. It would be very instructive to obtain such ex-post calculations for major nuclear power programs, like the fast neutron (breeder) reactors, the overall profitability of Japan's nuclear sector including the coming years and decades costs due to the Fukushima disaster, the cost-benefit ratio of the experience with nuclear power in developing countries, etc.

Beyond the economic calculations, high-impact societal endeavors (like nuclear power is one) are to be tested on their sustainability performance. Although nuclear power is low-carbon, it performs unfavorably on all other sustainability criteria [26]. How then can the persistent and influential support for nuclear power be explained? It is documented how nuclear advocacy molds perceptions [43–45]. Political choices are often private interest driven, concealed by fabricated discourses. The nuclear interests apply agnotology [46] to spread confusion and deceit. One recent example is how nuclear proponents obtained prevalence in authoring the sections on nuclear issues in IPCC's fifth assessment report [2,4]. In parallel comes the nomination of IAEA as observer to the UN Convention on Climate

Change, as concrete commitment in the Paris Agreement [38,47], one of the exceptionally few concrete commitments in the agreement. The glossing discourse promotes nuclear development in some countries; for example, South Korea considers nuclear power as part of its sustainable energy strategy [48,49]. Conversely, following the advice of an ethics commission [50], Germany is fully opting for solar and wind power [51] and is phasing out nuclear plants by 2023. The UK's record on civil nuclear projects is far from successful, but nuclear is ingrained into the fabric of the state itself. This may be due to the correlation of nuclear power plant construction with a desired nuclear weapons status, in the UK based on submarines with nuclear propulsion [31].

Next we present the five arguments that elaborate the case for ending nuclear power generation for advancing the sustainable energy transition.

First, although contentious, nuclear technology and projects are promoted and adopted in covert technocratic decision processes [52]. Replacing agnotology [46] by transparency on nuclear technical-economic performance and sustainability merits is a prerequisite for improved decision-making. Conventional cost–benefit analysis falls short because atomic issues are exposed to excessive degrees of uncertainty, to extremely long-term horizons not addressable by simple discounting [53], and to truly irreversible harm [54]. The better alternative is societal decision-making in which democratic processes and ethical values are directly involved. Solid foundations for such decision-making are comprehensive, rigorous sustainability assessments, organized and supervised by an international team of independent scientists outside of the nuclear conglomerate. An important component is the enhancement of knowledge about the historical facts and figures of nuclear power. One cannot prepare a better future without learning and accepting the lessons of the past.

Second, for the sake of higher transparency and independence, the mission and activities of the IAEA need revision. The agency is also a controlling [55] as a nuclear power promoting organization. It channels nuclear promotion into other UN organizations (like IPCC and UNFCCC) with an impact on global energy and climate policies. The recommendation is to limit IAEA's task to that of a controller of the non-proliferation treaty and of the global nuclear risks rather than continuing to function as a privileged intergovernmental promoter of nuclear power.

Third, the nuclear sector and governments who advocate nuclear power cannot continue to underestimate the likelihood of accidents and the extent of their impacts. This may be argued from a precautionary principle point of view, with ethical considerations like those used in Germany [50] when the decision to phase out nuclear power was made in 2011. The insurance principle treats risk in a narrower cost-benefit perspective. Mandatory full-liability insurance is a proper provision because the nuclear power companies cannot cover the losses and damages when a catastrophic accident occurs. The global underwriting companies refuse to insure the full risks of nuclear power plants as major nuclear accidents are considered to be highly likely and devastating. Then, it is not in the public interest to accept their construction, operation, and further accumulation of the waste bequest for (quasi all) future human generations.

Fourth, IEA and even IPCC consider the justified fears of citizens as an obstacle to be removed for more nuclear power deployment. IEA and IPCC follow this flawed logic of experts with a blind eye with regard to the literature pointing to the reality of nuclear power. An independent review of the nuclear power risk case is due. Blaming citizens will then be replaced by striving for more safety and risk reduction, for example regarding the formation of explosive hydrogen in case of overheating of the fuel rods, and regarding the siting of emergency control facilities in the paralysis radius of failing nuclear reactors (both examples exacerbated the problems in Fukushima). Prevention is the second-best remedy after precaution, and the best when earlier precaution was neglected. By for example IEA [3], IPCC [2], Cao et al. [1], the rational economic behavior of citizens is labeled as a barrier for building more nuclear power. We think that it is a salutary and necessary barrier.

Fifth, nowadays, IAEA, Foratom, Nuclear Forums in the EU, focus on the 'necessity of nuclear power for addressing climate change' without explaining why nuclear power failed in its intended energy transitions over the last 60 years. In particular, nuclear power's incompatibility with sustainable renewable energy supplies is important to be revealed and discussed in public along the thin assertion that nuclear plants deliver 'necessary power' against the fast technological innovations in generating variable renewable power directly from ambient environment sources. Nuclear power plants are bulky and inflexible; their existence hinders the swift harnessing of abundant variable renewable energy sources. Nuclear power is no ally to a sustainable energy transition and world economy transformation.

5. Conclusions

The dominant discourse, held up by IAEA, IEA, IPCC, UNFCCC and many governments, assumes a future role for nuclear power generation in the low-carbon energy transition as a given. This axiomatic belief is not scrutinized, but extended to labeling nuclear power as sustainable prior to the execution of any meticulous sustainability assessment. When this axiom is probed, it falls apart, as this article has started to document. Before getting into nuclear power analysis and controversies, the background of major energy-related post 1945 legacies is considered. This helps in taking notice of and understanding the persistence and growth of interest clusters and their longevity when they serve mighty economic interests or vested intergovernmental institutes with guaranteed funding, committed experts and bureaucracies.

Referring to recent research [4,26] we reiterate that nuclear power plants fail on all sustainability criteria, except for being low-carbon. These are sufficient grounds to stop investing in nuclear projects. The significant risks and the permanence of the nuclear waste bequest create an irreversible burden, contradictory to the essence of sustainable energy transitions. In addition, the incompatibility between large atomic power capacities and the unfettered deployment of variable renewable power creates unresolvable stalemates. The nuclear business case is disrupted when priority is given to renewable energy, and variable renewable energy is hampered and retarded by dragging out priority for nuclear power. In the EU the conflicts are mounting since 2014, when the energy corporates and EU commissioner Almunia nipped the growth of distributed variable renewable power, and allowed nuclear subsidizing [33].

From our analysis based on factual evidence and on the work of many independent scientists across different social and technical subjects, it follows that nuclear power is not a part of the sustainable energy transition. On the contrary it is counterproductive for the urgent and far-reaching sustainability transition. This leads us to suggest some drastic changes in the present position that nuclear power holds in policy-making to help clear the way for sustainable options.

Author Contributions: Aviel Verbruggen conceived the article and developed the first draft. Both authors have contributed to writing, editing, proofing, and revising the manuscript. Figure 1 was visualized and stylized by Yuliya Yurchenko. Figures 2 and 3 were conceived for earlier lectures by Aviel Verbruggen.

Conflicts of Interest: The authors declare no conflict of interest.

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