Nuclear Power and Sustainability

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Abstract

A comprehensive coverage starts with a clear view on the three sources of energy for generating electricity. Two of them, fossil and atomic fuels, are converted in hot gases or steam, needing cumbersome and wasteful processes. By skipping this mess, harvested renewable currents (wind, light, and water) conquer a central position in the transition to a low-carbon future. Knowing highlights of eighty-year nuclear history is prerequisite for apprehending today's position of nuclear

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power, shielded by peculiar nuclear advocacy. The sustainability degree of nuclear power is assessed on criteria helpful for measuring performance in politics, planet, prosperity, people, and risk as fundamental dimensions. Except for low-carbon, nuclear power fails on all criteria. Nuclear proponents gloss over the essential criteria by magnifying low-carbon. The advocacy is simultaneously secret and vocal. In aggregated power systems, harvesting renewable currents and nuclear power deliver incompatible power supplies. NP ruins the business model of wind and PV, and vice versa, depending on assigned priority in consecutive real-time load stackings.

NP is financially very expensive, without accounting costs of decommissioning, waste management, associated risks of nuclear accidents, and weaponry proliferation. Similar conditions apply on announced small modular reactors, revival of failed breeders, high-temperature reactors, etc. (GEN4), and fusion (GEN5). On top of NP's societal hazards and risks, climate change itself implies additional risks for NP. The protracting quest for the NP utopia is deleterious for sustainability.

Keywords

Sustainable development · Sustainability assessment · Nuclear power · Nuclear power economics · Nuclear risks · Low-carbon transition · Electricity system

1 Introduction

Writing about nuclear power (NP) is demanding because of its long history and its embedment in the extensive sector of energy supply.

In the 1950s to the 1970s, NP was seen as a proper substitute for fossil fuels (coal, petroleum, and natural gas). It received overwhelming societal agreement and lavish financial support yet could not realize the announced supply of safe, abundant, and cheap electric current. Already the Brundtland report Our Common Future (OCF) offered a balanced analysis in its section III. NUCLEAR ENERGY: UNSOLVED PROBLEMS in chapter 7 ▶ "Energy: Choices for Environment and Development" (WCED 1987, pp. 181–189). OCF saw three possible positions for governments: "(1) remain non-nuclear and develop other sources of energy; (2) regard their present nuclear power capacity as necessary during a finite period of transition to safer alternative energy sources; (3) adopt and develop nuclear energy with the conviction that the associated problems and risks can and must be solved with a level of safety that is both nationally and internationally acceptable." OCF continued: "But whichever policy is adopted, it is important that the vigorous promotion of energy-efficient practices in all energy sectors and large-scale programs of research, development, and demonstration for the safe and environmentally benign use of all promising energy sources, especially renewables, be given the highest priority" (WCED 1987, pp. 187–188). To this latter OCF recommendation, the world nations' responses were uneven and mostly lukewarm. Yet, energy efficiency and renewable energy are

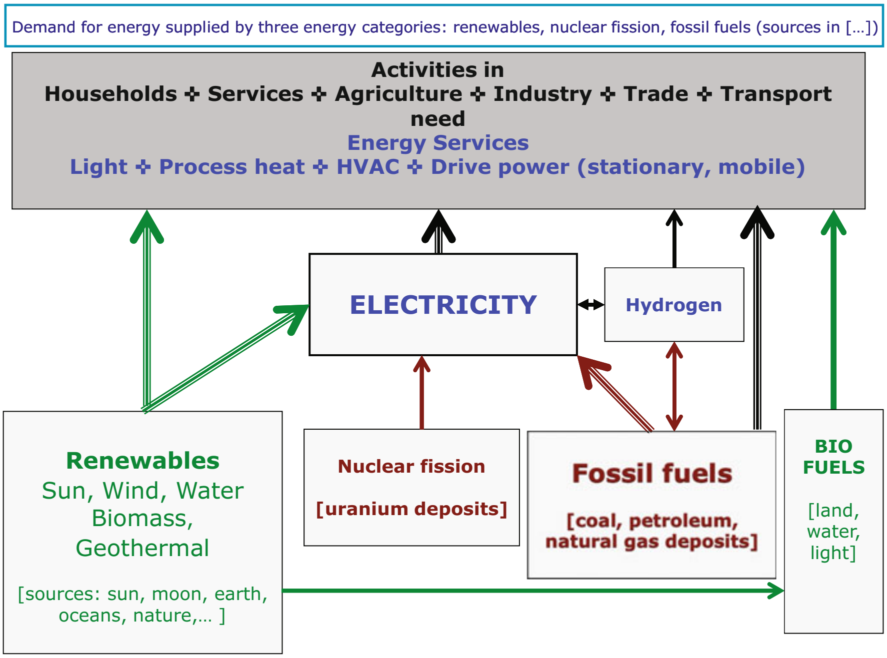

Fig. 1 Demand for energy supplied by three energy categories: renewables, nuclear fission, and fossil fuels' energy sources

proving to be the most successful ways for obtaining sustainable energy supplies, in particular electric power. Following fossil fuels and renewable energy, atomic nuclear energy is the third way for people to obtain electric power (Fig. 1).

Electricity holds a central position in the transition to a low-carbon future. NP proponents claim a significant role for nuclear energy in this transition. The claim and role are contentious. Participating in the debate is more meaningful when the basic attributes of the physical phenomenon electricity are known: Electricity is a transient current, not storable but moving over grids at electronic speed; the movements of electric current are submitted to tight standards, monitored and enforced in continuous, real time by grid system operators. Hazardous lightening or static electrical discharges aside, electricity is not as such available on Earth. Hence, electric current is obtained by converting other energy currents. In the 1880s, cities in industrialized countries started the construction of electric grids. Fast-growing demand for electricity was mostly met by coal-fired plants or by hydropower. Such power plants request significant installations and operations to source the necessary energy currents for feeding the turbines which spinning axis drives an alternator delivering electric current. The demand for electricity skyrocketed. Because of limited hydropower opportunities in most countries, thermal power plants supplied the lion's share of the world's electricity use. Obtaining the thermal flows requests fuels and many cumbersome infrastructures, as does discarding the worked-out

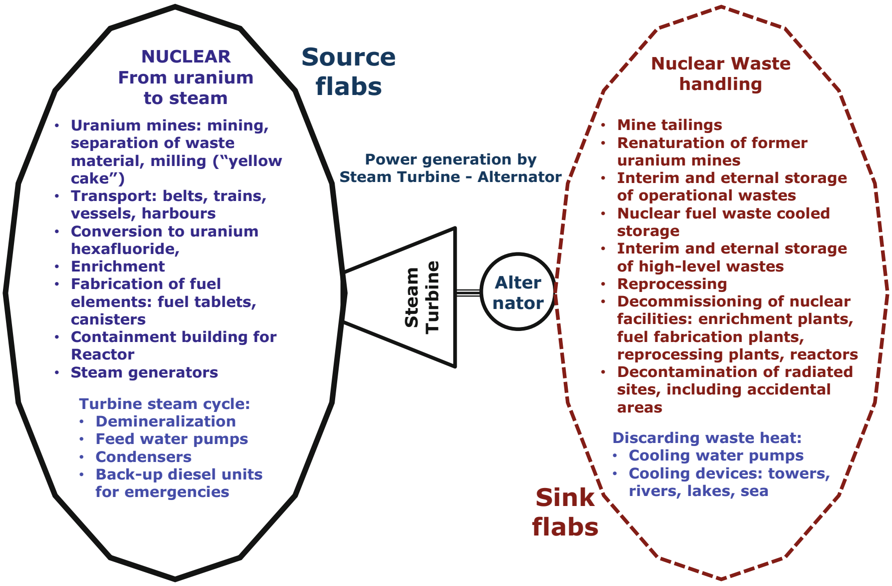

Fig. 2 Steam electricity generation source and sink flabs in case of nuclear power

flows. This is the case for fossil fuel-fired plants, as it is for nuclear plants. The latter also serve to boil water for steam for spinning turbines. Worked-out steam is discarded to the environment. Equipping nuclear-driven steam cycles with cogeneration facilities is not practical due to technical and economic parameters (Verbruggen 1982). About two-third of the energy generated in a pressurized water reactor (PWR) is discarded in cooling towers, rivers, lakes, or seas.

Figure 2 enumerates many cumbersome infrastructures, devices, equipment… linked to NP plants and provides an impression of their tremendous impact on the planet. Similar source and sink flabs are related to thermal power generation from coal, petroleum, and natural gas. The amount and sizes of existent flab issues announce challenging political and economic tasks in scrapping the issues becoming superfluous when fossil and nuclear thermal power are driven from the market. This riddles throughout the entire neoliberal economy, affecting the jobs of many, financial interests, and many industrial sectors.

A future of electricity only forthcoming from renewable energy is part of a thorough energy transformation. Low efficiency and significant spending on source and sink flabs are also the case when thermal power is obtained from biomass fuels. Rich geothermal steam sources can deliver less cumbersome thermal power (for example, in Iceland), and remain part of a low-carbon future. This is also the case for sustainable hydropower, and marine power when technologically and economically competitive.

Wind and photovoltaics (PV) harvest wind currents and light waves from the ambient environment, both without source and sink flabs. This is why such renewable power is structurally and significantly cheaper than thermal power, also when considering the related financial expenses only, not accounting the costly burdens of risks and environmental externalities of thermal power (IRENA 2021). NP is the most expensive thermal power and requires massive amounts of public subsidies to continue construction and operation of power plants. Given the various inferior attributes of NP, subsidizing NP cannot be argued as a reasonable option.

To this introductory background is added a nutshell history of NP (Sect. 2). For a sustainability assessment of NP, politics must construct the proper criteria to measure NP's performance. The criteria need anchoring at the four normative dimensions of *Our Common Future* (Sect. 3). The nuclear performance failures are addressed by NP proponents with advocacy narratives (Sect. 4). In Sect. 5, the incompatibility of harvested renewable power and NP in an integrated power system is shown. NP's disastrous financial economics is a dwarf compared to the huge costs of its operational risks and of its bequest in nuclear waste and global insecurity due to weapon proliferation (Sect. 6). A summary concludes (Sect. 7).

2 Nutshell History of NP

2.1 The Military Cradle

Nuclear power has its historical roots in the development of nuclear weapons. In 1941, the USA launched the Manhattan project to develop nuclear bombs. In 1942, Enrico Fermi and his team at the University of Chicago realized the first nuclear chain reaction. In 1944, weapons-grade plutonium was produced at the US Hanford facility. In August 1945, the uranium bomb *Little Boy* and the plutonium bomb *Fat Man* annihilated Hiroshima and Nagasaki and their inhabitants.

After WW2, the U.S.S.R., the U.K. and France built reactors fueled with natural uranium in a way plutonium was relatively easy to extract. The U.S.S.R. tested a first nuclear bomb in 1949, the U.K. in 1952, France in 1960, and China in 1964.

Military research continued to be the central focus after WW2. In 1954, the USA launched the Nautilus submarine with nuclear propulsion from a Westinghouse-pressurized water reactor. In 1955, the Soviet nuclear-driven icebreaker Lenin started operations.

2.2 Atoms for Peace (and War)

The first reactor for electricity generation went online in 1951 in Idaho (EBR-I: Experimental Breeder Reactor). After a decade of *atoms for war*, costing the USA at least 61 billion USD (Schwartz 1995), in 1953 the USA ringed in the *atoms for peace* age, which comprised selling US technology, nuclear fuel, assistance, equipment . . . to countries willing to deploy nuclear technologies for peaceful purposes (Eisenhower 1953 U.N. speech). "Controlled diffusion" of nuclear technology degraded in wild spreading, accelerating the proliferation of nuclear weapons to some nations (Weiss 2003). For instance, the USA trained (or funded the training of) many nuclear scientists in countries of proliferation concern, e.g., Turkey, Israel, and India. In the *atoms for peace* period, a significant spread of research and experimental reactors occurred, allowing the production of fissile material for weapons production (Lévêque 2014, p. 15). India and Pakistan bought Canadian and US technology and proceeded with testing nuclear bombs (India 1974; Pakistan 1998). France supplied both Israel and South Africa with civilian and military technology, allowing a joint nuclear test off the South African coast in 1979. In 2006, North Korea is the latest country obtaining nuclear weapons. Building and operating research reactors provides experience for building large-scale reactors.

After Eisenhower's speech, the USA passed a new Atomic Energy Act allowing private companies to own nuclear facilities and the Atomic Energy Commission to assign grants to private companies for R&D on prototype plants like breeder reactors (Fermi-1), gas-cooled reactors (Hallam), or a superheated boiling water reactor ("Bonus," boiling nuclear superheater).

NP was seen as the global fix for the world's energy needs and as a *clean* substitute for fossil fuels. Governments, industry, and academics were confident of NP turning economical in the 1960s (Ullmann 1958) and the major producer of electricity (Rose 1974). Especially breeder technology was heralded as the ultimate *technological fix*. Weinberg (1971, p. 416) stated that mid-1980s' commercial breeders would generate electricity "*enormous: enough to last mankind on any reasonable energy budget for many millions of years.*" However, after 60 years and 100 billion USD spent on breeder research (Cochran et al. 2010), the U.K., Germany, Japan, the USA, and in 2019 France have stopped their breeder programs. India, Russia, and China are the countries still spending on breeder technology.

2.3 NP Expansion Accelerates...

In the 1960s, light water reactor (LWR) technology emerged in leading NP "*commercialization*" by Westinghouse and General Electric (GE), funded lavishly by the Atomic Energy Commission. From 1951 to 1971, the USA spent over 16 billion USD-1986 R&D on LWR technology (Cohn 1990). Over the period mid-1970s–2008, OECD countries spent €650 billion on public energy R&D investments, 50% of it on nuclear energy. Including non-OECD countries and over the period 1947–2008, global historic cumulated nuclear R&D investment is estimated at €534 billion (Breyer et al. 2010).

After the first US commercial turnkey NP plant order (Oyster Creek) in 1964, 20 LWR turnkey orders were placed in the following 3 years. Vendors who realized the substantial risks of fixed-price contracts withdrew some offers. GE and Westinghouse subsidized their turnkey offers strategically (Burness et al. 1980). Such *commercial* orders and the availability of US low-priced-enriched uranium boosted the rollout of LWRs in European countries and Japan. In turn, some countries abandoned their national nuclear technology, e.g., Germany, Sweden.

The oil crisis of the 1970s stimulated reactor building and ordering in many countries. Nevertheless, 1974 marked the end of nuclear ordering in the USA, by the cancelling of all orders since 1974 (Thomas 1988, pp. 74–75). From the 197 reactors on order by 1974, less than half were ever completed. Some were cancelled after spending a billion USD (Bradford 2013), a phenomenon also observed today: In the USA after 1978, only four construction projects were started, and two were abandoned in 2017.

2.3.1 . . . and Nuclear Accidents Accumulate

Nuclear accidents are an integral part of nuclear technology. The first two fatal accidents linked to radiation already occurred during the Manhattan Project. Nuclear accidents occurred on a regular basis: a partial core meltdown in Chalk River, Canada, 1952; fuel cladding in the reactor core, burning during days at Windscale U.K., 1957; a tank with radioactive material exploded at Mayak Soviet Union, 1957; first core melt killing three operators in SL-1 reactor in Idaho Falls, USA, 1961 (Patterson 1986); partial core melt in breeder Fermi-1 Michigan, USA, 1966; fire in tunnel of control links to two reactors in Browns Ferry, USA, 1975; partial reactor core meltdown in Leningrad Soviet Union, 1975; partial reactor core meltdown in Beloyarsk, Soviet Union, 1977; and partial reactor core meltdown in Three Mile Island, USA, 1979 (Walker 2005).

On April 26, 1986, the first major nuclear catastrophe (INES Level 7) occurred at Chernobyl, Ukraine. Thousands of liquidators – civil and military personnel tasked with handling the immediate aftermath – were exposed to radiation during the rescue operations. A radioactive cloud spread across northern Ukraine and Belarus, reaching as far as Central and Western Europe. In the following decades, various incidents and accidents occurred around the world (Wealer et al. 2021b). Chernobyl overshadowed fuel lodging and nuclear dust release in German's thorium high-temperature small (300 MW) reactor, end of April 1986.

A second INES Level 7 accident occurred on March 11, 2011, in Fukushima, Japan. Three reactors experienced meltdowns, leaking large amounts of radioactivity, and resulting in the long-term evacuation of hundreds of thousands of people.

That Three Mile Island and Chernobyl were the main causes of drastic reductions in NP construction is a misconception. Contraction was going on before the accidents, in the USA, driven by declining growth in electricity demand, high interest rates and intractable construction costs, the rise of nonutility generators, structural problems in the nuclear industry, and changing perceptions of the nuclear industry and its safety (Hultman and Koomey 2013).

2.4 The Emergence of China and the Decline in Western Capitalist Societies

In 1985, 20 years after testing its first nuclear bomb, China entered the civil nuclear sector. China pursued a consequent strategy of importing foreign technology (from France, Canada, the USA, and the U.S.S.R.), and tailoring own designs from a multitude of imported equipment (Wealer et al. 2018). China has established itself firmly among the three global nuclear superpowers, alongside or even leading the USA and Russia. It also exported its reactors, e.g., to Pakistan. China is a partner of EDF in constructing Hinkley Point C, UK, and is negotiating with other countries for reactor exports (Thomas 2017).

In Western capitalist market economies, Fukushima accelerated the implosion of nuclear power, with closure of NP plants, often before reaching technical lifetimes, because of bad economics; new construction projects were abandoned. Traditional reactor vendors are in financial turmoil: The French state bailed out Framatome; Westinghouse, USA, went bankrupt.

According to the World Nuclear Industry Status Report (WNISR 2020) in mid-2020, 31 countries operate 408 nuclear reactors worldwide. Annual nuclear electricity generation reached 2657 net terawatt/h. The nuclear share in global commercial electricity generation has steadily declined from its peak 17.5% in 1996 to 10.4% in 2019. In 2019, 52 reactors were listed as *under construction*, several since decades. China is the exception with 15 constructions. Due to the few new-builds worldwide, the average age of the nuclear fleet is rising to 30.7 years in 2019. Most operational reactors were designed for a technical lifetime of 30 to 40 years.

Looking ahead: Announced future reactor technologies are GEN4 (breeders, high-temperature) and GEN5 (fusion). GEN4 has been tried since the dawn of NP and failed by incidents and uncontrollable risks and costs. Fusion is decades away (Jassby 2018). Nonetheless, incumbent nuclear interests still claim a need for more NP and tout it as a sustainable technology.

3 Sustainability Assessment of NP<!–ITerm6--?>

The nutshell history (Sect. 2) reveals the need of NP's thorough assessment, with distinguishing facts from advocacy. A team of people should design, process, and conclude the assessment, the results of which are more coherent, comprehensive, and specific when the team encompasses knowledgeable experts, citizens, and officials committed to independent appraisal. Context and framing (Lakoff 2010) also affect kind, scope, and results of the endeavor.

The context is tackling the climate change challenge by transforming the present, mainly fossil fuel based, energy systems into carbon-free alternatives. Advanced transformation experiments reveal the central role of electrification. Electric current does not emit hazardous gases and matter. It is obtained from other energy currents: pressurized fluids (steam, gas, and water); speedy winds; and light waves (Fig. 1). The majority of carbon dioxide (CO_2) emissions is due to making pressurized steam and gas flows for generating electric power from fossil fuels (coal, natural gas, and oil). In 2019, the global commercial electricity generation was derived from steam or gas flows (62.8% fossil fuels + 10.4% nuclear); water flows (15.6%); and wind currents, light waves, and waste processing (10.4%) (BP 2021).

For phasing out electricity generation from fossil fuels, the two low-carbon contenders are NP and RE. In a future-oriented decision-making frame, the assessment of NP treats the core question: *Is NP a recommendable partner for RE as urgent and full-out substitute for fossil fuel use in electricity generation?*

This section covers the question whether NP is anyhow a valid option for Sustainable Development (SD). First, SD is clarified, based on the foundations of Our Common Future (OCF), further called OCF-SD to distinguish from other SD narratives. Second, IAEA's assessment frame and practice are discussed. Third, a proper assessment frame structured on OCF-SD is presented.

3.1 Our Common Future: Sustainable Development Revisited

In 1983, the World Commission on Environment and Development (WCED) was established, and in 1987 it delivered *Our Common Future* (OCF). For a future, common to all world citizens, Sustainable Development (SD) was recommended as a new socioeconomic paradigm (Garren and Brinkmann 2018). SD is a clear, strongly grounded, and equilibrated message, confronting its opposite: neoliberalism serving vested interests of giant corporations and superrich capital owners, covered up by the fetish of so-called *free* markets (Wolin 2008; Baker 2012, p. 266; Verbruggen 2021). Neoliberalism adherence and impact has been growing since the 1980s. Neoliberal advocacy flattened OCF-SD's radical mission by adjusting the contents of concepts and words and by truncating the substance (Jacques et al. 2008). SD is described as a vague, multi-interpretable concept, unfit for providing guidance, thrashing the radical OCF-SD substance, needs, and limits (Meadowcroft 2012).

OCF-SD is not an indefinite concept. Like *democracy*, it is characterized by explicit goals and constraints, needing historical, anthropological, philosophical, and political implementation in diverse contexts. Such constructive duty exposes OCF-SD to falsification and abuse, something more democracy can help to minimize or prevent. Like society should never give up democracy, it neither should dump OCF-SD. Observed abuses and deformations are no sufficient argument to give up on democracy or on sustainability. Rather they are wake-up calls to focus on the original substance, and an impetus to reclaim their true content.

The OCF quote "*SD is a development that meets the needs of the present generations without compromising the ability of future generations to meet their own needs*" became a one-liner, propagated as a sufficient definition of SD. It is but a goal statement, hence not complete because it lacks the substance of SD (Fig. 3).

Three substantial components are growth control, redistribution, and processes of change. Or to quote (WCED 1987, p. 46): "*In essence, SD is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations*."

Neoliberal narratives purvey: *Sustainability allows economic growth, with environmental, social, and economic concerns, reduced to 3P language of Planet, People, and Profit. Companies comply with SD when respecting the 3P bottom*

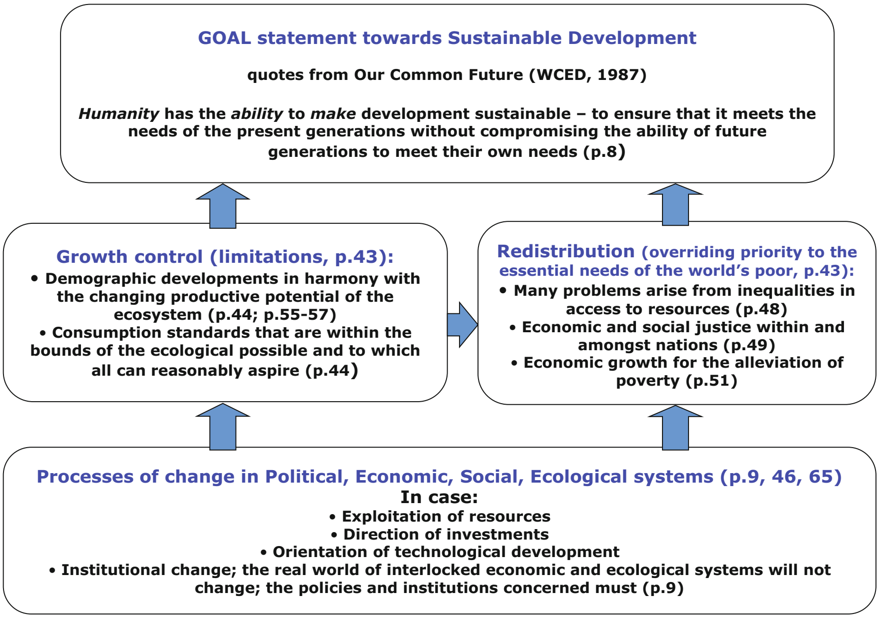

Fig. 3 OCF quotes clarifying goal and substance of sustainable development

line. Society complies with SD when pursuing the voluntary SD Goals (SDGs). Here economic growth is covering neoliberal, uneven, and thoughtless material accumulation, the opposite of OCF's *welfare growth for the alleviation of poverty*. The mix of neoliberal and SD agendas safeguards vested interests (Green 2016), while legitimizing their operations.

Our Common Future is a radical change program, crafted on four core dimensions (Fig. 4): people (in communities), planet (not only climate), prosperity (instead of profit), and politics (public policies) in the center for energizing the other dimensions. The 3P representation is like the blades of a windmill without a dynamo: It delivers no power. This fits the neoliberal hype of *markets solve the problems.* OCF-SD places institutional change and politics central (Meadowcroft 2012), because the public dynamo is crucial for generating the changes. The 3P mantra is a falsification of OCF: It truncates the essential political responsibility, now displaced by voluntary SDGs, also built on 3P reduction (UN 2015). Green (2016, p. 147) qualifies SDGs as "*periodic global updates issued in New York, which have little impact on how governments treat their citizens.*"

3.2 IAEA's Sustainability Assessment of NP

In 2008, the International Atomic Energy Agency (IAEA) developed a methodology for the sustainability assessment (SA) of nuclear energy systems, encompassing all

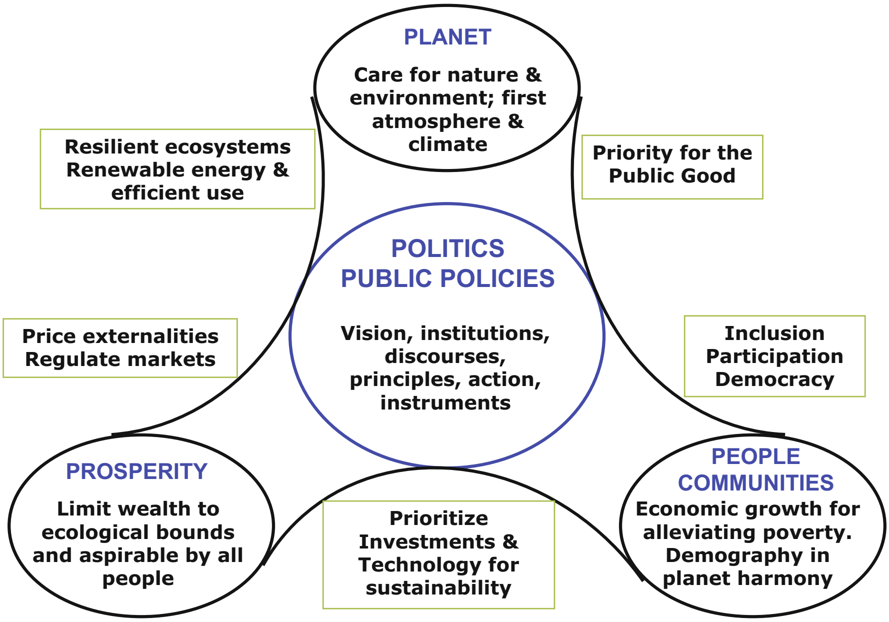

Fig. 4 Dimensions of sustainable development

facilities of the nuclear fuel chain from mining/milling, uranium conversion, enrichment, fuel fabrication, electricity generation, through to final end states for all wastes and permanent disposal of high-level waste, and related institutional measures including legal framework, regulatory bodies, etc. (IAEA 2008). The environmental dimension is confined to arguing for an increased use of nuclear power at the global level. Without further justification, IAEA (2008, p. 2) "*recognizes that*

- *a sustainable energy supply for humanity in the 21st century will require the large-scale deployment of nuclear power as well as other energy sources;*
- *nuclear power is an energy technology that offers practically unlimited energy resources whose deployment can reduce environmental pollution and the volumes of waste needing management, including greenhouse gas emissions*."

The IAEA opinion was challenged by IPCC (2011), Davis and Goldemberg eds. (2012), and others, showing that the energy service needs of a more populated and equitable world, at higher levels of well-being, can be cost-effectively met entirely and solely by renewables.

IAEA's NP assessment is not up to the minimum standards SA requests (Verbruggen and Laes 2015). For example, acceptance of NP is the result of the need for more power derived from an economic power demand and supply modeling (IAEA 2008, pp. 59–69). Also Gibson et al. (2005) explicitly reject the methodological approaches adopted by IAEA as inappropriate for the assessment of sustainability-oriented policies.

The selection of criteria, with their respective indicators and thresholds or acceptance limits, reveals how sustainability is constructed by IAEA (2008, pp. 75–109). For IAEA, *sustainable* is that which is in accordance with the current power supply thinking and practice (our italics): “information provided to the public [which is] *sufficient according to best international practice*” (on infrastructure); “lower consequences *compared to existing facilities*” (on environmental protection); “generation of waste shall be kept to *a practicable minimum*”; and “waste shall be managed in such a way that *undue burdens* are not imposed on future generations” (on waste management).

Obviously, adopting *nuclear sector best practices* is no valid proof that such *best practices* obey OCF-SD standards. IAEA skips the basic best practices of SA and hides NP’s ethical defects: intra- and inter-generational equity, precautionary concerns, and insurability of nuclear activities and of catastrophic impacts.

IAEA pleads to deploy NP r*esponsibly* in accordance with current best international standards. Although the intergovernmental IAEA is somewhat a global regulator of atomic affairs (supervising the Non-Proliferation Treaty), it is arduously promoting NP. Both incompatible roles joined in one agency are exemplary for the irresponsible atomic beliefs in the 1950s.

3.3 Comprehensive Sustainability Assessment

SA is measuring the *actual and expected performance* of a policy, program, technology, activity. . . on a set of sustainability *criteria*. Criteria are “*standards on which a judgment or decision may be based*” (Webster Dictionary); standards are *attributes to own or results to obtain*.

A tree structure helps in assembling sustainability criteria. The stem (politics) and main branches (people, planet, and prosperity) are *normative* for including OCF-SD’s essence. Further branching to formulate specific criteria is the result of a *constructive societal process*. Democratic deliberative processes will deliver the best results. Except for the normative stem, the array of criteria differs by issue. Figure 5 shows an SA tree example for OCF-SD assessment of nuclear fission power.

Few comprehensive sustainability assessments of nuclear power are published.

Verbruggen et al. (2014) collected and reviewed material available in the year 2014 for SA of nuclear fission power. A constructive process delivered 19 criteria (Table 1), further documented in full text.

The exercise revealed NP’s overall defective sustainability, except for criterion N°1 (low-carbon emissions). It explains why NP advocacy magnifies *low-carbon*, glossing over NP’s poor performance on the other criteria. Blind eye deceit also affected the latest IPCC assessment reports (AR), i.e., AR5, 1.5 °C special report (IPCC 2014, 2018), AR6 (forthcoming). The 2014 SA was undertaken by an academic team independent of nuclear interests, explaining the findings being very different from IAEA’s nuclear advocacy.

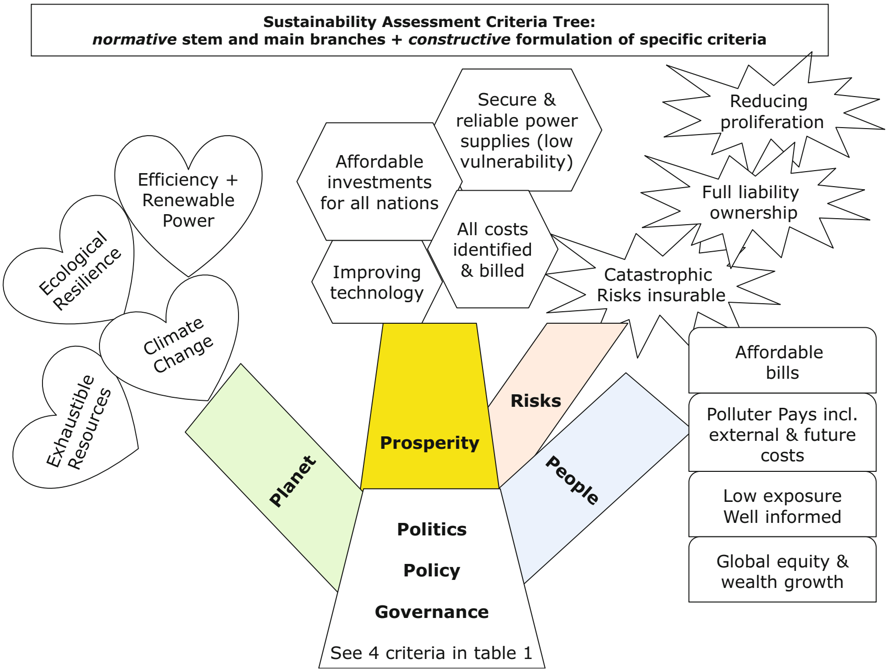

Fig. 5 Sustainability assessment criteria tree: *normative* stem and lateral branches + *constructive* formulation of specific criteria

The team was not mandated by public authorities and not sponsored to engage a citizen panel to coconstruct a richer criteria tree. Public (policy and community) participation will develop more pluralistic and elaborated criteria frames for institutional embedment in comprehensive SA procedures.

4 NP Narratives

Narratives and media have been, and still are, instrumental as "*primary source for constructing meaning about nuclear power*" (Gamson et al. 1992, p. 390). The nuclear power discourse from Hiroshima (1945) to the fallout of the Chernobyl disaster (1986) is neatly analyzed and described by Gamson and Modigliani (1989, pp. 10–30). "*Atoms for Peace*" (1953) promulgated NP as a "*Force for Good*," "*a progress package for the eradication of human misery*" (p. 13). Up to the 1970s, there was no public opposition to NP construction. The partial fuel meltdown of the FERMI1 breeder reactor (Michigan) in October 1966 was "*by almost any reckoning*" an "*extremely serious accident*"; "*plans for the evacuation of a million or more people were discussed by officials but deemed impractical and unnecessary*" (p. 14). The accident seems forgotten in 2021 by advocates of breeders as GEN4 future. The 1970s energy crisis "*stimulated the articulation of a second major pronuclear package, energy independence*" (p. 15).

Table 1 Criteria for assessing whether nuclear power can be a part of sustainable development (Source: Verbruggen et al. 2014)

Dimensions	Criteria [standards on which a judgment is based]. The standards are sustainability attributes to own and results to obtain by a technology
Environmental/ ecological PLANET	1. Climate change problems are relieved (mitigation and adaptation) 2. Ecological resilience of the energy system's embedding environment is preserved 3. Exhaustible finite resources are managed in light of future substitutes 4. Electricity use efficiency and deployment of renewable electricity potentials are stimulated
Economics PROSPERITY	1. All costs related to the nuclear system are identified, measured (or properly assessed), and billed to the end users of nuclear power 2. Technology evolves to higher economic efficiency: more output at reduced costs 3. Capital investments are affordable for most countries in the world 4. The electricity supply industry that results from generation technology choices is secure and reliable, with low vulnerability
Risks	1. Risks should be completely insurable, even catastrophic risks 2. Nuclear plant owners and operators are fully liable for risks, including long-term effects and impacts 3. Proliferation of technologies and know-how that can be used for nuclear weaponry is limited and reduced
Social PEOPLE	1. Electricity bills are affordable (match the expectations of constituencies) 2. External and future costs are allocated according to the polluter pays principle and precluding displacement of problems and risks to the poor, to developing countries, and to future generations 3. Exposure to harmful pressures is low, and proper information on safety and health impacts is available 4. Global redistribution of access to natural resources and of economic wealth growth is stimulated
Governance / Policy POLITICS	1. A global, independent agency studies nuclear power issues and choices in terms of their longevity, uncertainties, and irreversible impacts 2. Independent and accountable nuclear regulatory institutions and processes are established and monitored publicly 3. At national/regional levels, the public interest prevails over private profit, and democratic institutions prevail over technocracy 4. At local levels, citizens can engage in debate about energy system governance, and participate in the deployment of local energy systems

In the 1970s also, opponent packages developed around safety concerns, public accountability, NP being not cost-effective, alternative soft energy paths based on energy efficiency and renewable energy (Lovins 1976). The partial core melt in a fission reactor (TMI, Pennsylvania 1979) broke NP's growth path in the USA. The Chernobyl disaster (1986) propagated NP rejection, moratoria, and phase-out as substitutes for growth (Sect. 2).

A bell-shaped curve represents people's ambivalent attitudes regarding NP. At one end, a PRO minority favors NP; the other end is an engaged critics ANTI minority. The vast majority (the bell's bulb) is weighing advantages and disadvantages, however, mainly dependent on media information. Framing nuclear issues is a dynamic process of constructing meaning for events in changing contexts, like an unfolding narrative. The media became "*a site on which various social groups, institutions, and ideologies struggle over the definition and construction of social reality*" (Gurevitch and Levy 1985, quoted in Gamson et al. 1992, p. 385). "*(T)he media were more likely to be the primary resource for constructing meaning about nuclear power*" (Gamson et al. 1992, p. 390). This observation about the growth decades of NP (1950–80s) remains valid for the decades of its decline (1980s-2021). Hence, NP interests are intensely active in constructing media meaning for NP adapted to the context of the twenty-first century. They face significant challenges: new Science & Technology-boosting energy efficiency and renewable energy, problematic construction of the few nuclear reactors, and Fukushima disaster (March 2011).

Nuclear interests see climate change, and the money driven media corporations, as opportunities. Advertising, influencing, and substituting imaginaries for facts are tools in exerting discursive power (Fuchs 2007). Language does not aim at accurate expression and information, but at creating and maintaining symbols and narratives. For example:

- "*Nuclear renaissance.*" This conceals a reality of stagnation, failing resurrection, and decline (WNISR 2019).
- "Peoples' non-acceptance of nuclear risks is a major barrier holding up NP." IEA (2012, p. 73) stated: "*to reach nuclear goals, countries need to make significant efforts to convince an increasingly sceptical public that nuclear power should continue to be part of the future energy mix.*" Actual barriers are the real risks; this is confirmed by the global reinsurance underwriters, whose risk premiums are x-fold the kWh price of NP output (VFL 2011), i.e., NP is too risky and not insurable for its calamity impacts (Sect. 6).
- "*NP is necessary as low-carbon electricity source in addressing climate change*" (IAEA, Sect. 3). In some nations or states, NP now holds the position of large (st) low-carbon power supplier. Yet, present and expected market realities boost wind turbines and PV as the preferred power generation technologies. As survival strategy, nuclear companies publicly propose cohabitation with renewable power, although the two are antagonistic (Sect. 5). The Fukushima disaster exposed NP's loss of coolant caused by an extreme natural event; climate change may multiply extreme natural events (IPCC 2018), some infringing on large-scale coolant availability. NP is in practice less available and resilient than in talk.
- "*Zero- and low-carbon energy supply from renewables, nuclear energy and fossil energy with carbon capture and storage*" (IPCC 2014, p. 16) are juxtaposed options for reducing carbon dioxide emissions. The juxtaposition transfers the flawed impression of three seemingly equivalent options. Moreover, RE and NP are conflicting when supplying to a common electric power system (Sect. 5). The triptych mantra is NP's reference for requesting financial support as low-carbon power source (e.g., Hinkley Point C indexed price guarantee).

In 2007, nuclear interests assigned lavish contracts to Saatchi & Saatchi and similar consultancies to design a NP advocacy-advertisement plan, summarized in seven components (Verbruggen 2021):

1. *Confuse the minds of people*. Do not put forward a clear position about the attributes of NP, but create doubt, opacity, to install a feeling of *nobody seems to know well all technicalities and effects of nuclear power; it is all complex*. We, the experts, do not know well, so do you? Or is there anyone who could know? It seems there is no real case, so why should we have "so-called independent" experts? Waste money? When you do not know well what nuclear power implies, it is a bit stupid to be "anti" nuclear, is it not? You are right: Being "pro or anti" depends on personal preferences, something like two supporter groups watching a soccer game.
2. *Adopt a modest slogan*. Dispose the arrogant NP hubris of the 1950–1980s. The new catchphrase is: *Nuclear power is not the solution, but there is no solution without*.
3. *Lime a virtual support*. Revert the counting: In the 1950s–1980s, every person daring to say a critical word or ask a pinching question about nuclear was marked as an opponent. Saatchi & Saatchi advised: Every person not being an informed, fierce critic of nuclear, the nuclear sector counts as a proponent, i.e., the silent majority is included as proponents, so obtaining the majority aura.
4. *Informed opponents must be silenced, eliminated from the public forum*. In July 2007, it was explicitly stated to avoid every meaningful debate about nuclear power. Lavish advertising in the media occupies the space for the nuclear topic. Influencing journalists continues as it went on for decades (Gamson and Modigliani 1989).
5. *Mobilize vocal "neutral" experts, expressing the necessity of nuclear power.* J. Hansen, J. Lovelock, S. Pinker... speak out about the necessity of nuclear power for addressing the climate problem, although the vocal voices lack knowledge about electricity systems, nuclear technology, nuclear facts, etc. For ecomodernists, inanity is a virtue.
6. *Obscure the facts about the nuclear history, failures, hazards,* etc. Talk about illusionary GEN4 and GEN5 technologies, small modular reactors, thorium, fusion, etc. without feasibility assessment, a standard requirement in business economics.
7. *Sell nuclear power as ideal matching partner of renewable electricity.* Actually, nuclear is antagonistic to wind and solar (Sect. 5).

Nuclear advocacy goes on, as does the waste of capital, time, human resources, etc. squandered in the few nuclear construction projects. IAEA plays an important role in the life extension of the nuclear option.

5 NP Hampers Full Harvesting of Renewable Power

Harvesting renewable electricity (RE) from wind and light is the successful challenger for the nonsustainable options to decarbonize electricity generation such as NP (IRENA 2021). Model scenarios, policy reports, media, etc. juxtapose generated GWh of the RE and NP options. Juxtaposition contradicts basic physical properties of grid electric power supplies, which are every other quarter hour stacked for meeting the instantaneous demand for power during that quarter hour. For avoiding brownouts and blackouts, enough power is fed to the grid. However, feeding too much power is more dangerous, and excess supplies are curtailed or purged. Precise matching of demands and supplies is the system operator's task. This duty is easier when the operator can command instantaneously available and flexible electricity generation capacities, for increasing or decreasing supplied power. Integrated power systems are continuously balanced with dam hydropower, spinning reserve capacity, quick-start units, load management, etc.

The low-carbon options NP and harvested RE are poor performers on availability and flexibility standards, however, for very different reasons. NP is unwieldy and extremely capital intensive. NP are baseload plants, permanently loaded at full capacity, not flexible to increase or to decrease in output. Continuous maximum loading is necessary for covering the high-capital costs of NP investments.

RE harvesting shows a kaleidoscope of technologies from tiny (watts and kilowatts) to small-scale (up to ca. 12 megawatts for giant wind turbines) and to very large-scale (when including the gigawatts hydro dam stations). Harvested supplies from wind currents, light waves, and water flows, in the ambient environment, are variable, intermittent, and stochastic. They are available by nature's generosity, not on command by people. Their output cannot be increased beyond nature's instantaneous willingness. Yet, bypassing natural currents is easy for reducing supplies from RE units, but such curtailments mean exclusion of the most sustainable low-carbon energy sources.

There is a growing literature on how integrated power generation systems may embed both harvested RE and NP. At the outset, this literature adopts the present nonsustainable systems as the default position, with wind and solar power as disturbing newcomers. The incumbent position is as follows: *Intermittent and stochastic renewable energy supplies disturb the reliable delivery of power; power on command is the reference*.

However, urgent decarbonization requires a perspective from the future end-goal state of a zero-carbon power supply, functioning as a benchmark for assessing present states and required evolutions. Then the overarching guidance in the transformation of electricity systems is the following: *Intermittent and stochastic renewable energy delivers the most sustainable supply and merits priority over nonsustainable supplies; this lexicographic priority for RE guides the organization of reliable power supply with extended load management capabilities, energy storage facilities, and adapted transmission links to convey and match renewable power supplies.* Because, in addition, wind and PV generate electricity at almost zero

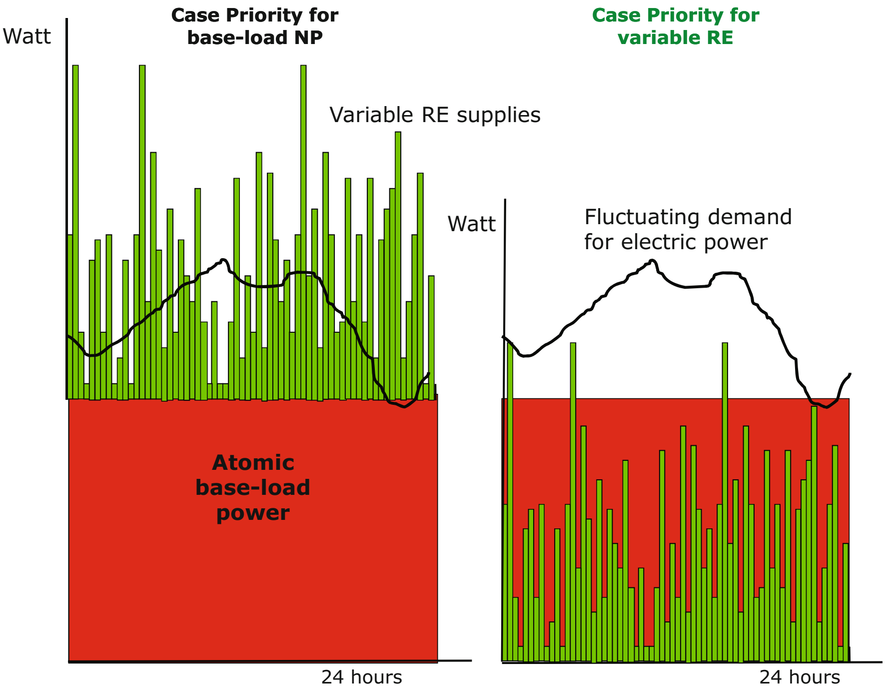

Fig. 6 Priority for NP curtails RE. Priority for RE excavates NP's load factor and financial returns

marginal cost, their priority in the merit order of quarter-hourly supply stacking is economically sound.

Figure 6 shows graphically the bifurcating NP and RE options. The two panels are based on a representative fluctuating demand for electric power during a day. In the left panel, NP gets priority above RE, resulting in the curtailment of all RE supplies above the demand curve. In the right panel, variable RE gets priority, resulting in impossible flexibility for deliveries by unwieldy NP plants. Excavating the base-load coverage for NP is technically problematic, and financially disastrous by lowering the load factors of nuclear plants. NP and harvested RE are, respectively, wrecking the financial-economic case of the other; they are mutually exclusive in a 100% zero-carbon electric power generation system.

Next to their incompatibility in electricity generation, NP and harvested RE are antagonistic on other aspects. First, for spreading the bulky outputs of NP stations, the power grids own a pyramidal structure starting at a high-voltage top (360/450,000 Volt), and devolving down over several voltage levels to final domestic end users at 110/220 Volt. Wind and PV electricity come from millions of distributed small-scale generators; adapted grids consist of diverse horizontal constellations, with high-voltage lines for interconnecting the various zones where RE power is generated at different moments of the day due to natural variabilities.

Second, NP and harvested RE differ profoundly in history, technology, economics, involved people, politics, and more. NP is 1950s' megalomaniac, top-down implemented technology, part and parcel of the expansive "business-as-usual" energy economy since the 1950s; NP overcapacity in the beginning of the 1980s smothered the budding energy-efficiency solutions. Harvested RE is small-scale, grown bottom-up and breaking through by surfing on most new technologies since the 1990s (microelectronics; information and communications technology; new materials; fluid dynamics. . .); RE is a natural ally of energy efficiency for covering the energy needs of households.

Even in narrow economic terms (i.e., only considering expenses, excluding the full costs of risks and externalities), new buildings of NPs are a financial trap (Sect. 6). There are many arguments to redirect all nuclear expertise and resources from new plant construction and life extensions, to a thought-out "Act Now" on global phaseouts, decommissioning, restoration of contaminated sites, handling nuclear waste. . . (Haas et al. 2019a). Fully sustainable renewable energy systems are not only technologically and economically feasible but also the cheapest and only sustainable option for the world's population. Like every successful transition, sustainable energy transitions need profound change in minds, thinking, beliefs, preferences, etc. to adopt the novel paradigm, perspectives, technologies, and practices. Progressive thinking and actions are unlikely to be delivered by those with vested interests.

NP and RE have no common future in safeguarding "Our Common Future" (Verbruggen 2008). Although detailed technical analysis of dynamic power systems reveals the incompatibility of harvested RE and NP supplies, the prevailing discourse repeats the mantra of a simple juxtaposition of both kinds of supplies (IPCC 2014; UNFCCC 2015).

6 NP Economics Out of Kilter

Since 2018, electricity generation from wind and PV undercut any other technology in power generation expenses (IRENA 2020). Thermal power is losing the competition, also in financial cash flow accounting. As the most expensive power source, NP faces difficulties to survive in liberalized electricity markets in all Western countries.

60–80% of NP's levelized cost are capital costs (Haas et al. 2019b). Since the 1970s capital costs in the USA and France are escalating (Koomey and Hultman 2007; Grubler 2010). Lovering et al. (2016) fabricated a hypothesis about NP becoming competitive by technology diffusion, economies of scale, and positive learning. However, they used biased data for Canada, Germany, Japan, India, and Korea, as shown by Koomey et al. (2017).

"*No NP plant has ever bid successfully in a competitive energy market anywhere in the world*" (Bradford 2012, p. 151). The high-nuclear capital costs and related financial risks are assumed by governments, either by direct financing, or by minimizing financial risks (Barkatullah and Ahmad 2017). Most new builds benefit from long-term price guarantees, e.g., in China, Russia, India, and the United Emirates. In the USA since 1978, only two new NP projects were launched, with federal loan guarantees, or under cost of service regulation (Joskow and Parsons 2012). One project (V.C. Summer twin reactors) was cancelled after 4 years, because expected capital costs exceeded USD 25 billion, 75% beyond initial estimate (WNISR 2019).

Despite the void economic basis, nuclear advocacy invokes a *nuclear renaissance* (Wood et al. 2001, p iii): "*modest improvements in the costs of nuclear power plants, coupled with their recent record of substantially improved operational performance, could result in a true "nuclear renaissance" within the next several decades.*" MIT (2003), and University of Chicago (2004), added studies on *the economic future of nuclear power*, assuming that the industry should be capable of achieving capital, operation, and maintenance cost reductions and shorter construction periods. Market-based instruments would provide carbon emission credits for overcoming the competition by coal and gas. After the Fukushima disaster, Joskow and Parsons (2012) qualify nuclear renaissance as "*more hope or hype than it was a realistic forecast of the future of nuclear power even before Fukushima, especially in developed countries* [. . .] *and if there is a major nuclear renaissance it is in China*." However, also China substantially slowed down the acceleration of new-built projects after Fukushima, although approving new-built plans again in 2015 (Thomas 2017). Since 2000, Russia emerged as a main nuclear vendor (Drupady 2019), with strong government backing.

Investing in a GEN3 reactor results in business account losses of USD 5–10 billion expected value (Wealer et al. 2021a), while sidelining negative externalities from nuclear accidents, decommissioning, and waste. Decommissioning costs accumulate slowly (Wealer et al. 2019) with worldwide only 20 reactors decommissioned. No large reactor with 40 years operation has been dismantled anywhere (WNISR 2020). The limited experience shows wide expense ranges: USD/kW 280–1500 in the USA, €/kW 1700–9300 in Germany (WNWR 2019). Empirical data for cost estimates of deep geological waste disposal is lacking with no repository operational. The few international cost estimates are difficult to compare: France (€31 billion) stores mainly vitrified waste from reprocessing; USA ($96 billion) refers to high volumes of spent fuel; and Germany (€51 billion) to smaller volumes. Cost numbers for final disposal and for decommissioning are little reliable and likely underestimated due to very long time periods, presumable cost increases, and unwieldy discount rates. Because most countries do not enforce the polluter-pays-principle for nuclear waste disposal, national authorities, i.e., taxpayers, more or less are assuming liability (WNWR 2019).

The exuberant costs of new large reactors boost a new hype: Small Modular Reactors (SMRs). The hype hypothesizes that modular, standardized, factory production of SMRs should reduce capital costs and construction times. However, loss of economies of scale by smaller size is unlikely overcompensated by mass production (Ramana 2021). The actual costs of the few experimental SMRs reactors exceed the estimates at planning (Pistner et al. 2021): The cost of the Chinese CEFR reactor increased more than 15-fold to USD 19,400 /kW; the Russian floating nuclear power plant (“Akademik Lomonosov”) originally estimated at USD 2400 /kW mounted to USD 10,500–14,000 /kW, comparable to current large-scale reactors; and Argentina’s CAREM reactor, starting since 1984, shows tenfold cost rises to USD 14,000/kW in 2020. The NuScale integral pressurized water SMR, originally fixed at USD 2000/kW, puts expected cost in 2020 at USD 6600/kW and is likely more than a decade away from eventual commercial commissioning.

Whether a reactor is large or small, the related risks are too costly for full indemnity insurance. Hence, most liability of NP plant owners is transferred to communities and states. In Belgium and the Netherlands, NP owners are maximally liable for damages up to €1.2 billion. The USA provides a liability of approx. $13 billion (Gaßner and Buchholz 2017). Such provisions fall short of the damages caused by a nuclear accident: JCER (2019) mentions estimated costs for managing the Fukushima Daiichi site and surroundings at USD 330–760 billion. The US Price-Anderson Law (1957) places sole liability on NP plant operators and limits the liability of the nuclear industry, which reduced the investment bills for plant construction (Kåberger 2019). The law has been the blueprint for nuclear accident legislation in many countries and for international treaties (e.g., Vienna convention).

“*Perhaps hardest of all to measure are the risks associated with the proliferation of nuclear weapons*” (Davis 2012, p. 61). Nuclear proliferation is mostly connected to nuclear power, either within nuclear weapons states stockpiling more fissile materials and building new *sophisticated* nuclear weapons, or higher accessibility to nuclear weapons for countries like Iran or Saudi Arabia. Other threats are sabotage and terrorist attacks. Missing adequate and safe waste disposal solutions, lots of spent fuel are stored at NP plant sites, vulnerable for terrorist groups theft (Bunn et al. 2016) or attacks (Gronlund et al. 2007).

On top of NP’s societal hazards and risks, climate change itself may imply additional risks for NP. Global warming causes heatwaves, low-water levels in rivers and lakes, and warmer seas. Shortage of cooling water leads to NP output reductions and shutdowns. Sea level rise, shoreline erosion, coastal storms, or floods cause safety concerns especially for reactors at coastal locations, i.e., a quarter of the world’s nuclear reactors (Kopytko and Perkins 2011). The March 2011 tsunami causing the Fukushima nuclear catastrophe is an exemplary case. Flooding already is occurring more frequently along US coasts, mainly the East and Gulf Coasts, where NP reactors are situated. After reactor shutdown, high-level radioactive waste in spent fuel will remain stored at the site and subject to risks from sea-level rise (Jenkins et al. 2020).

7 Summary

Sustainable energy transition requests sustainable energy supplies, performing well on criteria expressing the constituting dimensions of Sustainable Development according *Our Common Future* (WCED 1987). The emphasis on climate change, possibly turning in climate collapse, highlights the carbon emission attribute of energy supply contenders and assigns a pivotal role to electricity, a carbon-free current made out of input energy currents (pressurized steam or combusted gas, ambient wind, light, and water flows). Renewable currents and sources are the major low-carbon energy suppliers, with NP occupying a second, shrinking place. *Our Common Future* was critical of NP and firmly placed it after renewable energy.

Revisit of NP origins reveals its military cradle and persistent military-civil links. NP's history is an amazing kaleidoscope of heralding nuclear technologies, increasingly expensive experiments and applications, and desperate abandoning of the once believed perpetual solutions, such as breeders. Unwieldy technical and economic problems, incidents, and accidents showcase the reality of NP. Yet, nuclear interests still claim a need for more NP and even tout it as a sustainable technology (IAEA 2008). Society is in dire need for professional, democratic, and transparent sustainability assessments, entirely based on the four dimensions politics, people, planet, and prosperity, skipping the reduced neoliberal 3P narrative dominated by profit. An exemplary such assessment shows NP is failing on all sustainability criteria, except for the low-carbon criterion. It explains why NP advocacy magnifies the *low-carbon* aspect of NP and juxtaposes NP to renewable energy as matching options for reducing carbon dioxide emissions. However, this juxtaposition is flawed. Wind and PV excavate the base-load coverage in supplying electricity with technically problematic and financially negative impacts for NP. Alternatively, NP occupying the base-load spoils the load factors of wind and PV, lowering their profitability. NP and harvested renewable currents are respectively wrecking the financial-economic case of the other; they are mutually exclusive in 100% low-carbon electric power generation systems.

NP is financially very expensive, without accounting costs of decommissioning, waste management, associated risks of nuclear accidents, weapon proliferation, and terrorism. Similar conditions apply on announced small modular reactors, revival of failed breeders, high-temperature reactors, etc. (GEN4), or fusion (GEN5). On top of NP's societal hazards and risks, climate change itself implies additional risks for NP with global warming causing heatwaves, extreme natural events, and low water levels in rivers and lakes, further worsening NP's precarious financial situation, while increasing the risks. The Fukushima disaster exposed NP's loss of coolant caused by an extreme natural event, exhibiting absent resilience of nuclear technology.

The protracting quest for the NP utopia is deleterious for Our Common Future.

8 Cross-References

- ▶ Economic Development and Equity
- ▶ Global Energy Use
- ▶ Gro Brundtland
- ▶ Introduction to Economics and Sustainability
- ▶ Radioactive Waste
- ▶ Solar Energy

- ▶ The United Nations
- ▶ Wind Energy

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