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Evaluating nuclear power's suitability for climate change mitigation: technical risks, economic implications and incompatibility with renewable energy systems

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This paper presents a comprehensive analysis of the suitability of nuclear power as an option to combat the escalating climate emergency. Summarizing and evaluating key arguments, we elucidate why nuclear power is unsuitable for addressing climate change. The primary argument centers around the unresolved technical and human risks of accidents and proliferation, which are unlikely to be effectively mitigated in the future. Furthermore, we highlight the significant cost disparities between nuclear power and other non-fossil energy sources, such as solar photovoltaics and wind power, considering levelized costs of electricity. We also address the incompatibility of nuclear power with renewable energy systems, emphasizing the need for flexibility in the face of variable solar and wind resources. Alternative reactor technologies will not be available in time to make a major contribution. Nuclear power also poses challenges in power plant operation amid climate change and war. Ultimately, we argue that other motivations should be explored to explain the continued interest in nuclear power in some countries, as energy supply arguments alone are insufficient to justify new investments.

KEYWORDS

nuclear power, climate change mitigation, risks, economics, energy system, renewables

1 Introduction

Given the escalating climate emergency, there is an increasing focus on the significance of nuclear power in addressing climate-related risks. Presently, nuclear power accounts for ~9.8% of worldwide electricity production, equivalent to around 2,800 TWh (BP, 2022). Numerous influential entities, including international organizations (IEA, 2019, 2021; IAEA, 2020) and private enterprises (Gates, 2021), advocate for an increased prominence of nuclear power in the energy sector. The Intergovernmental Panel on Climate Change (IPCC) also includes varying amounts of nuclear power in its scenarios selected for its assessment and special reports (IPCC, 2018, 2022). However, the history of nuclear power is full of unresolved technical challenges that can only be controlled to some extent, so security risks and economic failures remain (MIT, 2018; OECD and NEA, 2020). From a technological innovation systems perspective, nuclear power is on the decline for quite some time (Markard et al., 2020) and it has never become an economic technology able to compete with others (Davis, 2012; Wealer et al., 2021a; Aghahosseini et al., 2023; Haywood et al., 2023).

Within this paper, we undertake a comprehensive assessment of the technical, economic, and political arguments surrounding the debate on nuclear power's role in combating climate change. Through our evaluation, we determine that nuclear power does not offer a viable contribution to climate change mitigation, but rather presents an impediment to this endeavor. The evidence-based explanations provide arguments for politicians and decision-makers, as well as developers of energy scenarios to abandon the use of nuclear power or not to enter a nuclear system. The subsequent sections present the arguments organized by topic, followed by a concluding section that synthesizes our findings.

2 Nuclear power is dangerous and accidents cannot be avoided

Even if there is no way to reliably quantify the risk of nuclear accidents (Downer and Ramana, 2021) it can be stated, that nuclear power is a dangerous technology that has proven impossible to avoid major accidents. Nuclear fission converts very large amounts of energy and resulting radioactive radiation, that persist well-beyond the operational lifespan of commercial reactors. Ensuring safety during the lifetime of the reactor and beyond involves addressing three critical objectives: (i) effectively confining radioactive fuel elements and other materials, (ii) consistently monitoring and controlling reactivity, and (iii) adequately managing and dissipation the heat generated within reactor cores and continuous cooling of the fuel elements. These safety considerations extend not only throughout the reactor's operational lifespan but also for hundreds of thousands of years beyond that.[1]

From the inception of nuclear power to the present, the prevention of severe accidents and attainment of security levels deemed socially acceptable, i.e., those for which society can establish safeguards, have remained unattainable. Incidents ("events") and accidents have repeatedly occurred since the very beginning of nuclear power. Early examples are the partial core meltdown in Chalk River (Canada, 1952), the fire in the reactor core of the Windscale nuclear power plant (1957), and the explosion of radioactive material in the Soviet nuclear complex of Mayak (Soviet Union, 1957, see Wealer et al., 2021b, p. 56).

Despite the controversial nature of methodologies employed to assess nuclear accidents, all indicators consistently point to a significant number of accidents persisting, even with the advent of new reactor generations. International Atomic Energy Agency (IAEA) classifies events using the International Nuclear Event Scale (INES Scale), which ranges from 0 to 7.[2] However, the INES Scale has faced criticism due to its failure to capture all relevant incidents and the lack of meaningful significance in accident scaling. The Fukushima disaster, for instance, would correspond to a level of 10.6 on the INES Scale, surpassing the highest designated LEVEL of 7 (Wheatley et al., 2016, p. 98). To address these limitations, an alternative approach could involve adopting the Nuclear Accident Magnitude Scale of Radiation Release, which refers to the magnitude of radioactivity released and does not impose an upper limit (Smythe, 2011).

Translating accidents and events into monetary costs helps to understand the overall impact and the risks involved. Thus, Wheatley et al. (2016) found that while the frequency of serious accidents has shown a declining trend on average since the 1970s, there have been serious accidents or incidents every decade.[3] Furthermore, there have been smaller-scale incidents resulting in damages of up to 20 million US$, with the expected value of such occurrences escalating annually. Statistically speaking, an accident to the extent of the Fukushima disaster will occur every 60–150 years with 50% probability, and an incident such as Three Mile Island occurs every 10–20 years. Interestingly, "the average cost of events per year is around the cost of the construction of a new plant" (Wheatley et al., 2016, p. 96).

Low utilization rates and uncertain outage times also suggest substantial problems in mastering nuclear technology at scale. Thus, the aggregated capital utilization factor of all nuclear power plants since the 1970s is 66%, meaning over a third of the capacity has not been used to generate electricity, largely due to long outages.[4] Even though this value has increased to 80% in the 2000s, this still leaves one fifth of capacity idle.

Looking at the history of commercial nuclear power reveals that questions of reactor safety were largely ignored in the beginning of the nuclear age. Thus, on the one hand, the US Atomic Energy Commission announced nuclear power to become "too cheap to meter" (The New York Times, 1954) in what would become a "plutonium economy" (Seaborg, 1970). But on the other hand, during the development of commercial nuclear power, both the energy and insurance sectors operated under the assumption that society would bear the responsibility for these risks. This fact still applies today: Risks stemming from nuclear energy are uninsurable, with nuclear power plant operators only bearing symbolic liability.[5] None of the nuclear plant operators around the world is appropriately insured against the risk of accidents

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[1] See for details (Wealer et al., 2021b), on which this section is based.

[2] INES Scale: Level 0: Deviation, Level 1: Anomaly, Level 2: Incident, Level 3: Serious incident, Level 4: Accident with local consequences, Level 5: Accident with wider consequences, Level 6: Serious accident, and Level 7: Major accident. See https://www.iaea.org/resources/databases/international-nuclear-and-radiological-event-scale (last inspection March, 22, 2022).

[3] See https://www.iaea.org/sites/default/files/ines.pdf.

[4] Authors' own calculations using data from the IAEA PRIS database (available online).

[5] Estimates of the total external costs of nuclear power range between about 1 US$cent/kWh (Friedrich and Voss, 1993) to 34 US$cents/kWh (Meyer, 2012).

(Kåberger, 2019). For example, in the United States (US), the Price-Anderson Act of 1957 exempts nuclear companies from having to ensure against accidents, only obliging them to pay a little fee. In Germany, all operators of nuclear power plants shared the risks of potential accidents, but this was capped to € 2.5 bn., a very modest sum when compared with the potential costs of accidents.

3 Nuclear power is not economic…

The industry has taken a large number of precautions against accidents, which, however, were only discovered through accidents ("trial and error"). The claim of "safe and controlled" nuclear fission involves extremely complex technical measures, which have been identified as the main cost drivers (along with inexperience, lack of competence and manpower). Nuclear power is expensive, both for a potential investor considering investing private capital into a nuclear power plant project, and for the society as such that still must deal with the negative environmental effects of accidents, meltdowns, uranium mining, terrorism risk, etc. When assessing the economics of nuclear power plants, it must not be forgotten that the reason that nuclear power was developed at industrial scale in the 1940s was its use as a weapon, the costs of which did not matter (Groves, 1983; Lévêque, 2015). Since World War II, there were expectations that commercial nuclear power would become rapidly economic in the following decade (Ullmann, 1958; Pittman, 1961) and become the major energy source for electricity generation (Seaborg, 1970; Weinberg, 1971; Rose, 1974). Not a single one of the more than 600 reactors built since 1951 has been built solely through private capital and in a competitive market environment (Bradford, 2012; Wealer et al., 2018).

The campus-wide studies by MIT (2003, 2009, 2018) and the University of Chicago (2004, 2011) agree that nuclear power was already uncompetitive with coal and natural gas at the turn of the century—an assessment that remains valid today. Joskow (1982) already reported on economic difficulties of nuclear power, a topic later picked up by Grubler (2010) and Escobar Rangel and Lévêque (2015). Other large-scale exercises include D'haeseleer (2013) and Linares and Conchado (2013). Davis (2012, p. 50) concludes that despite after seven decades of "controlled nuclear fission", there is still an absence of an economic case for nuclear power.

Taking into account current trends in so called "Generation III" nuclear power plants, an analysis of current and prospective investments in nuclear power plants reveals that they do not yield profitable returns. The economic losses can be shown for a specific investment project: The investor into a 1,600 MW Gen III nuclear power plant, i.e., about 10 bn US$, would face a loss, i.e., a negative net present value, in the range of minus five to minus 10 billion US_2018$ (Wealer et al., 2021a). This is exactly what is currently happening in all of the newbuild sites that only survive due to massive subsidies and/or captured consumers, such as the Vogtle project in Georgia (USA), the Olkiluoto (Finland) and Flamanville (France) projects in Europe (Barkatullah and Ahmad, 2017, p. 133–134), and the Hinkley Point C project in the UK.[6] Analyses on the nuclear power export projects have revealed that the economic distress of Chinese, Korean and Russian nuclear power technology is comparable (Ram et al., 2018).

The main reasons for these large losses are high construction costs, including capital costs, long project periods, and uncertain and low revenues. Even an extension of reactor lifetimes to 60 years does not significantly improve the results. Furthermore, additional costs (dismantling, long-term radioactive wastes storage) and the societal costs of accidents are not taken into account in these calculations. The expected levelized costs of electricity in a large-scale Monte Carlo model analysis with varying investment costs, construction duration, and electricity prices, yields an expected value of nuclear electricity 160 US$/MWh, and a distribution of the LCOE between 91 and 222 US$/MWh (Wealer et al., 2021a).

Current calculations of average electricity production costs for the USA confirm the structural cost disadvantages of nuclear power: While the costs of renewable energy sources are falling sharply, the costs of electricity from nuclear power continue to rise (Lazard, 2023). The system costs of the respective technologies are not taken into account, e.g., dismantling, final storage and insurance costs for nuclear power plants and flexibility options in the case of renewables. However, in view of the trend described above, large nuclear power plants are not expected to become competitive. For the renewable sources wind and solar (unsubsidised), LCOEs are now generally around 50 and 60 US$/MWh, respectively (Lazard, 2023, p. 9) at the level of an individual generation unit. Against this, the LCOEs of (unsubsidised) nuclear plants are triple-digit (180 US$/MWh) (Lazard, 2023, p. 9). Detailed analyses conducted at an hourly resolution across 145 regions worldwide, focusing on fully renewable power systems, have revealed that the LCOE on a system-wide scale, incorporating factors such as electricity storage, curtailment, and grid losses, can reach a maximum of twice the LCOE of individual generation units (Ram et al., 2017; Bogdanov et al., 2019). However, even with these additional costs, the total LCOE of renewable generation unit including system costs amounts to an approximately maximum of 80 US$/MWh, which is less than half the cost of nuclear power, while the latter does not match the load variability in contrary to a fully renewable power system in hourly resolution.

The private perspective adopted above does not consider a large range of other costs to society. Following the production chain, these include significant assessable external costs, e.g., lung cancer from uranium mining (Jacobson, 2020), emissions from construction and mining, and other health risks from normal operation, decommissioning and disposal. Additionally, adopting an intergenerational perspective indicates that the limited benefits offered by nuclear power in the present are overshadowed by the burdens imposed on future generations, who would bear substantial costs for storage and disposal (Barron and Hill, 2019). Schulze et al. (1981) presented an early rationale for considering the wellbeing of future generations through the appropriate choice of a social discount rate.

As there is no economic basis for the usage of nuclear power plant, alternative motivations must be taken into account. Among the motivations are attempts to maintain civil nuclear power as a complement to military activities (Cox et al., 2016).

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[6] In other countries such as Russia or China, the entire nuclear industry is state-owned, so that no reliable data on costs or levelized costs is available, let alone comparable with market-based values.

4 ...Nor are lifetime extensions

Over two thirds of the 415 reactors online in 2021, have exceeded the 30-year mark in terms of their operational lifespan (IAEA, 2022b). Given that these nuclear reactors were originally designed for an intended operational period of 30–40 years, there arises the need for either their replacement with other generation technologies, new reactors or lifetime extensions. The longer lifetimes come with high costs due to increasing maintenance costs and needed safety investments and upgrades. The International Energy Agency (IEA) (2019) therefore calls for subsidies to extend the lifetimes of the existing reactors. A key aspect is the supervisory authorities' assessment of what measures are required to bring the system up to the "state of the art" (INRAG et al., 2021). This represents significant financial obstacles. For example, in France, the country with the most standardized reactor fleet worldwide, the Court of Auditors estimated that operator EDF would need to invest up to 100 billion € by 2030 to extend the life of its reactor fleet by 10 years (from 40 to 50 years). This represents more than three times EDF's stock market value and an average of 1.7 billion € per reactor, or about 1,500 €/kW of lifetime extension investment, or about 55 US$/MWh to keep it running for 10 more years (Cour des Comptes, 2016; IEA, 2019). Overall, the IEA estimates the cost of electricity for lifetime extensions of 10–20 years to be between 40 US$ and 55 US$/MWh. This is roughly equivalent to the current cost of electricity from renewables. Thus, there is no economic advantage to be gained from lifetime extensions compared to the expansion of renewable energy.

Even extended lifetimes do not guarantee that the respective plant can survive in the electricity market. Data from the US show that older plants have significantly higher operations and maintenance costs, and need regular capital additions, so that they cannot withhold competition in the electricity market auctions (Bradford, 2013; see for example Lovins, 2013, 2017; Schneider et al., 2019, p. 238). Recent years have seen utilities actively pursuing state legislation and contracts to provide financial support for economically unviable reactors. Among the 23 reactors scheduled for early retirement between 2009 and 2025, 13 have already been closed, eight have experienced delayed closure due to subsidy programs, and the fate of two reactors at Diablo Canyon remains uncertain (Schneider et al., 2023).

5 The expansion of nuclear power cannot be accelerated adequately

Even in the scenario of public financial support for constructing economically unviable nuclear power plants, as happened in the past, the lengthy timescales required for their expansion render them incapable of making a significant contribution to a large-scale decarbonisation endeavor. The process of planning, designing, and constructing nuclear power plants is characterized by a substantial and time-consuming duration. In the US, the median duration for nuclear power plant construction since the 1970s was ∼9 years (Koomey and Hultman, 2007, p. 5634), while on a global scale, it was 7.4 years in 2015 (Berthélemy and Escobar Rangel, 2015, p. 125). The time required for planning, e.g., obtaining a construction site and permit, engineering, financing, needs to be added to this. Jacobson (2020) estimates the overall time for nuclear power plants to go online between 10 and 19 years.

Taking into account the last decade (2012–2021), this estimation even seems to be very optimistic, as the average construction duration alone (without planning) has risen to 9.2 years for 62 completed reactors, of which 37 have been built in China (Schneider et al., 2022). Looking at the few on-going construction projects in the OECD, the average duration appears even more unfavorable. For instance, the construction of Olkiluoto-3 in Finland spanned a period of 17 years (2005–2022), while Flamanville-3 in France, under construction since 2007, and Vogtle Units 3 and 4 in the United States, initiated in 2013, may potentially require an even longer timeframe for completion.

The scale and time-critical nature of the challenges associated with the socio-ecological transformation is too daunting for nuclear power to play a significant role. To achieve the targets outlined in Pathway 3 of the IPCC's report (IPCC, 2018), which includes a projected increase in nuclear power of 98% by 2030 and 501% by 2050, it would be necessary to double the existing nuclear fleet of ∼440 power plants within the next 10 years and achieve a 6-fold increase within the next three decades (Wealer, 2020).

Even if one neglects the long construction duration, another reason why nuclear power cannot be expanded to a relevant extent is the disintegration of the supply chain. The traditional reactor vendors Westinghouse and Framatome are in financial turmoil and still struggling to survive: Westinghouse went into bankruptcy in 2017, and Framatome (then Areva) was bailed out by the French State with 4–5 bn €. Since 2000, Russia is the emerging nuclear vendor (Drupady, 2019) and dominates the reactor market with more technology agreements than the four next largest suppliers (France, USA, China, Korea) combined (Jewell et al., 2019). Considering the geopolitical imperative to restrict Russian nuclear products, coupled with the struggling state of the Russian economy and China's challenges in securing customers, it is improbable that these two countries can effectively intervene to address the situation (Thomas, 2018, 2019).

6 Small modular reactors and non-conventional reactor concepts take decades and have worse economic prospects

The industry consistently develops new reactor concepts, which are now being discussed in the context of the climate emergency. These concepts include so-called small modular reactors SMR-concepts ("small modular reactors") with relatively low capacity ($<300\ MW_{el}$) and non-conventional reactor designs (i.e., not light-water cooled). The latter category encompasses early nuclear power technologies such as fast breeder reactors, molten salt reactors, and high-temperature reactor concepts. However, non-conventional reactor concepts, including those promoted by the "Generation IV International Forum" (GIF), are still several decades away from potential commercial deployment, if they ever become viable, and are unlikely to achieve competitive status in the near future (Cochran et al., 2010; Lyman, 2021; Pistner et al., 2023; Böse et al., 2024). A summary of the issues at stake is provided by Wimmers et al. (2023).

In addition, looking closer at the proposed and researched reactors, one notices that they are only partly based on fundamentally different technological concepts (Locatelli et al., 2013; Pioro, 2023). Thus, high-temperature reactors have been around for at least half a century, the concepts of fast breeder reactors and thorium reactors even since the 1950s (Weinberg, 1959; Pittman, 1961; Rose, 1974). Nearly all high-temperature or fast breeder projects have been abandoned due to technological problems or for simply being uneconomic. Nevertheless, the technology portfolio of the European Commission Reference scenario until 2050 also includes so-called 4th generation reactor technologies (EC, 2016, p. 41).

Recent experiences with SMRs suggest that competitive commercial breakthroughs are unlikely in the mid-term future. Previously, the industry had sought to build nuclear plants with higher and higher capacities, to reap potential economies of scale. SMRs go the opposite route, being defined by IAEA as "*advanced reactors that produce electric power up to 300 MW_{el}, designed to be built in factories and shipped to utilities for installation as demand arises*".[7] Considerable hopes are currently placed in the development of SMRs as a long-term solution for nuclear power (Lokhov et al., 2013; Locatelli et al., 2014; Sainati et al., 2015; NEA, 2016; Black et al., 2019). In addition, they are advertised as being more flexible, e.g., providing additional features such as district heating. Some US startups are working into this direction, too, such as NuScale or TerraPower supported by Gates (2021).

However, among the 80 SMR projects listed by the IAEA (IAEA, 2022a,b) only four pilot plants are currently under construction or already in operation (one in Russia, two in China and one in Argentina) (Böse et al., 2024). Estimates of future production costs are very speculative, yet several analyses indicate that SMRs are more expensive for some time than current, large-scale nuclear power plants. In addition to the higher variable operation and maintenance costs (Carelli et al., 2010; Cooper, 2014), current analyses show that the overnight capital cost are between 6 and a 26% higher than the average cost of current nuclear with high capacities. Alonso et al. (2016) estimate LCOEs of 175 US$/MWh, still above those of current reactors.

It can be considered that non-conventional reactor technologies and SMRs are unlikely to attain significant economies of multiples, as potential learning effects might be limited due to the heterogeneous challenges of national licensing and regulation as well as a limited actor base (Böse et al., 2024). Comparable developments are evident concerning light water reactors. Remember that during the seven decades of "large" nuclear power, learning effects i.e., declining unit capital costs, were never reached. On the contrary, there is evidence suggesting a discontinuity in the learning curves regarding construction costs and construction times (Portugal-Pereira et al., 2018), indicating that standardization and cross-country synergies were not reaped (Grubler, 2010; Rangel and Leveque, 2012). Some of the most ambitious regions, e.g., in the Middle East or Asia, have little experience with safety regulation (Ramana et al., 2013; Yamashita, 2015). Also, a large number of reactors with low capacities implies significant proliferation risks of the fissile material (Glaser et al., 2013; Lyman, 2013). According to a recent survey conducted by Thomas and Ramana (2022), it is revealed that even reactor designs based on thoroughly tested technology cannot be implemented before the year 2030. Furthermore, the survey suggests that more radical designs may potentially never be deployed.

7 Nuclear power is hardly compatible with an energy system based on renewables

The conventional approach to generating and supplying electricity from nuclear power is typically associated with a baseload generation model. However, in an energy system that is progressively relying on variable renewable energies, this baseload generation model is being replaced by a highly flexible, supply-based model, as showed by Hodge et al. (2020). Technical and economic factors impose limitations on the flexibility and ramping rates of nuclear power plants, as recognized by the industry (OECD/NEA, 2012, p. 46). These factors encompass restrictions on cycling operations, such as the need to mitigate material fatigue, as well as must-run constraints and cost considerations. The impact of these limitations becomes more pronounced when evaluating entire fleets of nuclear reactors rather than individual units (Morris, 2018). Nuclear power plants are generally generating electricity in the baseload spectrum with must-run constraints[8] and must be backed up for meeting peak load demands with flexible operating generation units like gas turbines, hard coal-fired power plants, but also dispatchable renewable electricity, in particular hydropower reservoirs, and storage, such as pumped hydro energy storage.

Although newer reactor designs technically possess better capabilities for load-following operations (Cany et al., 2018; Jenkins et al., 2018), existing nuclear power fleets are typically operated as continuous baseload power plants due to economic, technical, and safety considerations. However, achieving flexible nuclear power, as proposed by Duan et al. (2022), necessitates the integration of thermal energy storage and three to four times the steam turbine capacity of a conventional baseload nuclear power plant, assuming a reduction in full load hours from 8,000 to 2,000 per year for flexible electricity supply. This results in worsened economics for new nuclear power plants due to increased capital cost associated with thermal energy storage and higher steam turbine capacity. Additionally, the flexibility provided by thermal energy storage is limited to a few days, constraining its effectiveness in addressing seasonal balancing requirements. Conversely, dispatchable hydropower reservoirs, bioenergy plants, and renewable electricity-based seasonal storage with e-hydrogen or e-methane offer the potential for meeting seasonal demand fluctuations more effectively, as highlighted by Bogdanov et al.

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[7] IAEA (2016): "SMR - Nuclear Power." December 12, 2016. https://www.iaea.org/topics/small-modular-reactors.

[8] The must-run level of the German fleet, which is assumed as the worlds most flexible, is given with 20–50% for pressurized water reactors (PWRs) and 60% for pressurized water reactors (BWRs) (Grünwald and Caviezel, 2017, p. 11).

(2019). Highly renewable energy systems comprise the entire energy system, i.e., power, heat, transport, and industry (Breyer et al., 2022b) and this sector coupling enables additional flexibility and thus energy system efficiency and cost effectiveness (Breyer et al., 2022a). The potential value of flexible nuclear power will be diminished by emerging flexibility options such as smart electric vehicle charging and vehicle-to-grid concepts (Uddin et al., 2018; Yao et al., 2022) which offer flexibility on a range of up to a week for significantly lower cost (Child et al., 2018b; Taljegard et al., 2019). There are assertions suggesting that the continuous baseload supply provided by nuclear power holds a unique significance (Sepulveda et al., 2018). However, it is important to note that such a continuous baseload supply is not essential, as variable renewable energy sources need to accommodate a diverse load profile (Toktarova et al., 2019). Solar photovoltaics and wind power, in combination with short-term and seasonal storage solutions, can deliver a baseload-like generation profile at a lower cost compared to new nuclear power (Fasihi and Breyer, 2020; Lazard, 2021).

The compatibility issues between nuclear power and variable renewable energy sources, particularly solar photovoltaics and wind power, pose additional challenges, considering the projected dominance of these renewables in the electricity supply (Bogdanov et al., 2019; IEA, 2021). These challenges arise from the convergence of generation profiles, making it difficult to integrate and coordinate the operation of nuclear power alongside solar and wind power. The cumulative generation spectrum of electricity from various renewable energy units covers all areas of the load profile, from baseload to peak-load supply and excess electricity (Verbruggen and Yurchenko, 2017). In an energy system predominantly reliant on nuclear power plants, renewable energy sources could theoretically provide peak load power supply when combined with storage and flexibility options. However, in such a scenario, renewables would experience constant curtailment and would be unable to fully realize their economic and system efficiency potential. This would also result in an increased demand for storage capacity (Verbruggen and Yurchenko, 2017), further complicating the integration of these energy sources. Placing priority on renewable energies within the energy system would result in the virtual elimination of baseload-generation demand (Hirth et al., 2015; Bogdanov et al., 2019; Child et al., 2019; Breyer et al., 2022a, Fig. 16). Integrating nuclear power plants into such a system would be challenging, requiring substantial economic drawbacks and technical modifications to accommodate their operation. In fact, energy systems based primarily on variable renewable energies aim for flexibility options, such as dispatchable renewables, sector coupling, power grids and demand response (e.g., electric vehicle charging, heat pumps and electrolysers for e-fuels and e-chemicals production) (Brown et al., 2018; Child et al., 2018a; Bogdanov et al., 2021; Breyer et al., 2022b).

The future trajectory of nuclear power necessitates an examination of its historical context and its implications for socio-ecological transformation processes (Geels et al., 2016; Cherp et al., 2017). Furthermore, the expansion and perpetuation of baseload-generation technologies hinder the transition to a highly flexible, 100% renewable energy system by creating a dual-system framework (fossil-nuclear and renewables), which reinforces the "lock-in" effect associated with baseload-generation logic (REN21, 2017„ p. 158 ff.). Moreover, conflicting potentials emerge at the funding level. Both the continuation and expansion of nuclear power and the transition to a 100% renewable energy system necessitate state funding and public subsidies for research, development, and system conversion. This situation engenders competition between the two paths rather than fostering mutual support.

8 Challenges in nuclear power plant operation amid climate change and war

Although, nuclear power is often touted as a potential solution for climate change mitigation, there is an emerging concern that nuclear power is particularly unfavorable in a future with higher temperatures and more military threats. In a warming world, where reactors are confronted with either low water levels in rivers during heatwaves or warming seas, the loss of cooling water leads to output reductions or even shutdowns (Averyt et al., 2011), while this risk disappears in a highly renewable electricity supply (Lohrmann et al., 2019). Other issues connected to climate change are sea level rise, shoreline erosion, and extreme weather conditions as coastal storms or floods. All these issues raise major safety concerns especially for reactors at coastal locations, as one in four of the world's nuclear reactors is situated on a coastline (Kopytko and Perkins, 2011). Flooding, as the Fukushima accident has shown, can be catastrophic to a nuclear power plant because it can knock out its electrical systems, disabling its cooling mechanisms and leading to overheating and possible meltdown. Flooding already is becoming more frequent along the US coastline with the rate accelerating in many locations along the East and Gulf Coasts, where many reactors are situated. Even after the shutdown of the reactors, high-level radioactive waste in the form of spent fuel is still stored on the site and subject to risks from sea-level rise (Jenkins et al., 2020).

Other threats are nuclear proliferation, sabotage, terrorist attacks and warfare as the Russian war in Ukraine (Schneider et al., 2022, chap. "Nuclear power and war"). The risk of nuclear proliferation is strongly connected to nuclear power, be it vertically with the nuclear weapons states (e.g., USA, UK, France, Russia, China) stockpiling more and building new nuclear weapons (Sorge and Neumann, 2021), or be it horizontally to new countries like for instance Iran and Saudi Arabia.[9] While there is evidence that "the link between nuclear energy programs and proliferation is overstated", (Miller, 2017), risks in relation to proliferation possibilities are serious possibility (Schneider and Ramana, 2023). With no adequate and safe disposal solutions available, nuclear material is still stored on-site or in centralized facilities and hence vulnerable for terrorist groups to get a hold of. Bunn et al. (2016) report that there are multiple cases in which kilogram quantities of plutonium or highly enriched uranium have been stolen. In

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[9] Even though there are states without their own nuclear weapons programs that operate or plan to operate nuclear power plants for reasons of independence (Mazzucchi, 2022) (e.g., Japan, Belgium, Finland, Brazil, and others), the risk of proliferation in these cases remains possible (Schneider and Ramana, 2023).

addition, terrorist groups (among the al Qaeda) may undertake serious efforts to get nuclear weapons (Futter, 2021). Moreover, the majority of the fuel is still stored in spent fuel pools, e.g., 81% of all the European fuel is still in wet storage (Besnard et al., 2019). These pools are often not protected by containment buildings, which makes them highly vulnerable for terrorist attacks (Gronlund et al., 2007).

9 Conclusion

In the context of the climate emergency, there is an intensive debate about the potential of nuclear power to contribute to the decarbonization of the energy systems. In this paper, we have developed and assessed seven arguments, why we consider nuclear power inappropriate to combat climate change. The main argument is a technical one, i.e., the inability to avoid accidents, and the risks linked with it. The substantial costs associated with implementing measures to prevent core meltdowns, radioactive leaks, and other accidents are the primary cause of the high expense involved in the commercial utilization of nuclear energy. Consequently, this cost-intensive nature, coupled with safety considerations, implies that nuclear power is not a sustainable and affordable source of energy for the low-carbon energy transformation. In fact, this is also the reason why nuclear power has been unable to achieve competitiveness with other energy sources, and why lifetime extensions are also expensive. Nuclear power is characterized by very long construction times, and even longer developments of new technical generations, too far away and uncertain to contribute to climate change mitigation anytime soon. From an energy system perspective, nuclear power is not compatible with a system based on renewables, but rather hinders its expansion. Last but not least, nuclear power is particularly unfavorable in a future with higher temperatures and weather extremes and more military threats. In addition to the arguments, future research should explore the relation between nuclear power and the energy transformation processes in more general terms. Our findings also suggest intensifying the search for other reasons (e.g., energy sovereignty) why certain countries are still pursuing nuclear power, while regularly citing the climate as a major motivation.

Author contributions

All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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