

Article

The Nuclear Power Dilemma—Between Perception and Reality

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Abstract: Motivated by the environmental challenges and the increase in energy demand, this review assesses the suitability of nuclear power production as an alternative option to using fossil fuels. First, we assess the competitiveness of nuclear power compared to other power sources considering its economic efficiency, environmental impact and implications for health, and conclude that this is a viable option to serve in addition to and as a backup to renewable sources. Second, we review previous findings in various fields on advantages and disadvantages of nuclear power technology and conclude that there is a gap between reality and perception. Third, we discuss challenges related to nuclear weapons proliferation and misperceived public opinion on nuclear power. We conclude that the gap between perception and reality stems from a lack of consolidated interdisciplinary view, media communications focusing mainly on unilateral assessments.

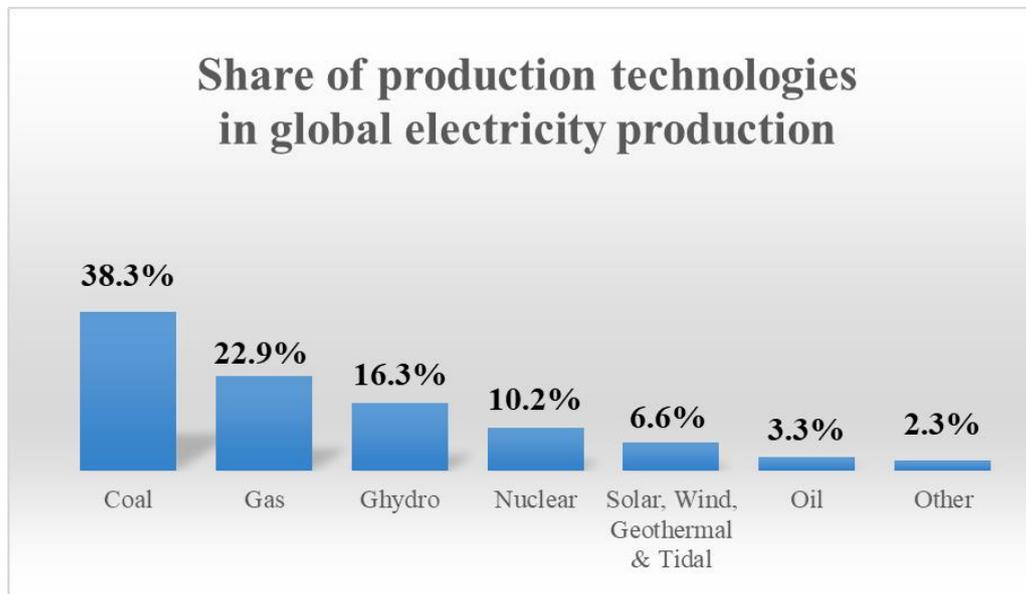
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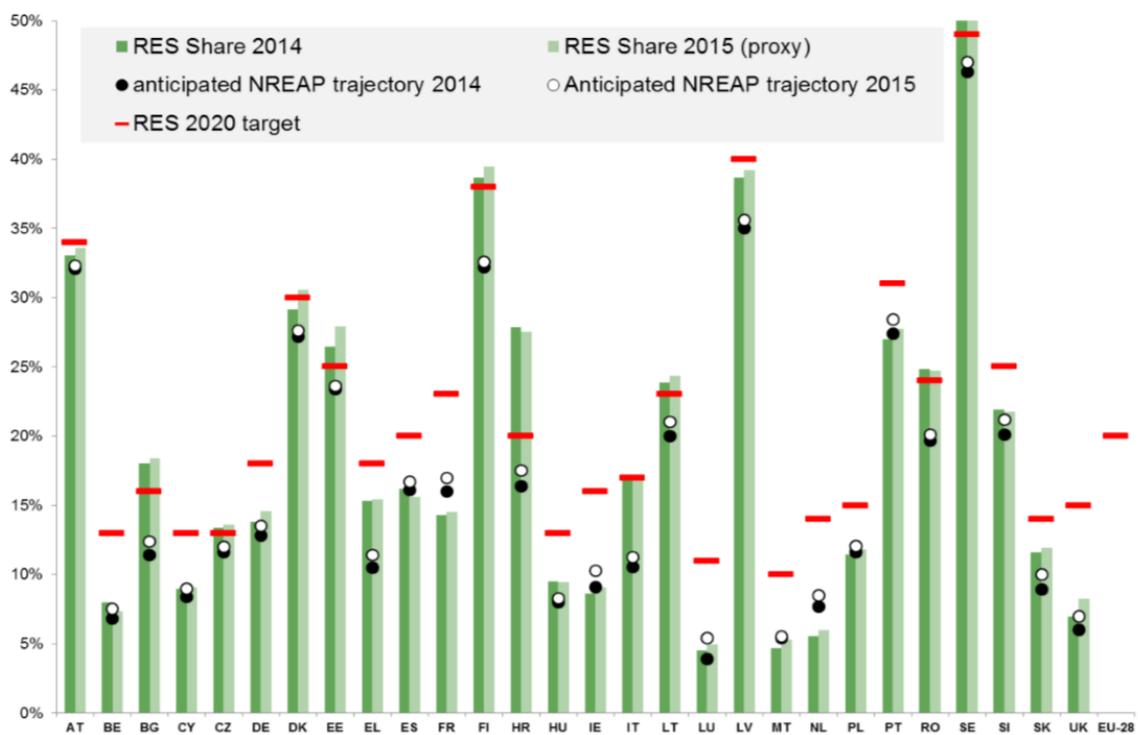
1. Introduction

Within 2050, the increase in demand for electricity is expected to be 60–100%, mostly driven by a growing middle class in India and China. Furthermore, the rise in demand is also driven by transitioning from powering transportation and industry using fossil fuels to using electricity, e.g., substituting traditional cars with electric cars and electrification of offshore oil production. Currently, fossil fuels account for 64% of global electricity production [1]. Hence, transitioning to electricity will only perpetuate the emissions, unless alternative electricity production technologies are exploited. UN Environment Program (UNEP) states that a yearly decrease in global emissions of 7.6% is necessary not to exceed a 1.5 °C temperature rise, which is considered to have disastrous consequences [2]. Facing the environmental issues as well as covering the unprecedented increase in demand for energy requires significant investments in non-emitting energy generation. Renewable power sources such as wind and solar power will naturally play a leading part in the energy transition, as they are sustainable and low-carbon. Although their share in the global electricity production is still low (see Figure 1b), the 2020 target of the European Commission states that 20% of the final energy consumption should come from renewable sources. In Figure 1a, we show the member states'

progress towards their 2015/2016 indicative renewable energy development (RED) targets. The national renewables 2020 targets range from 10% in Malta to 49% in Sweden [3]. The new target for 2030 states that at least 27% of final energy consumption should come from renewable sources in the EU. Some of the countries, such as Germany, subsidized considerably renewable energies and have significantly higher fraction of wind or solar than the world average.

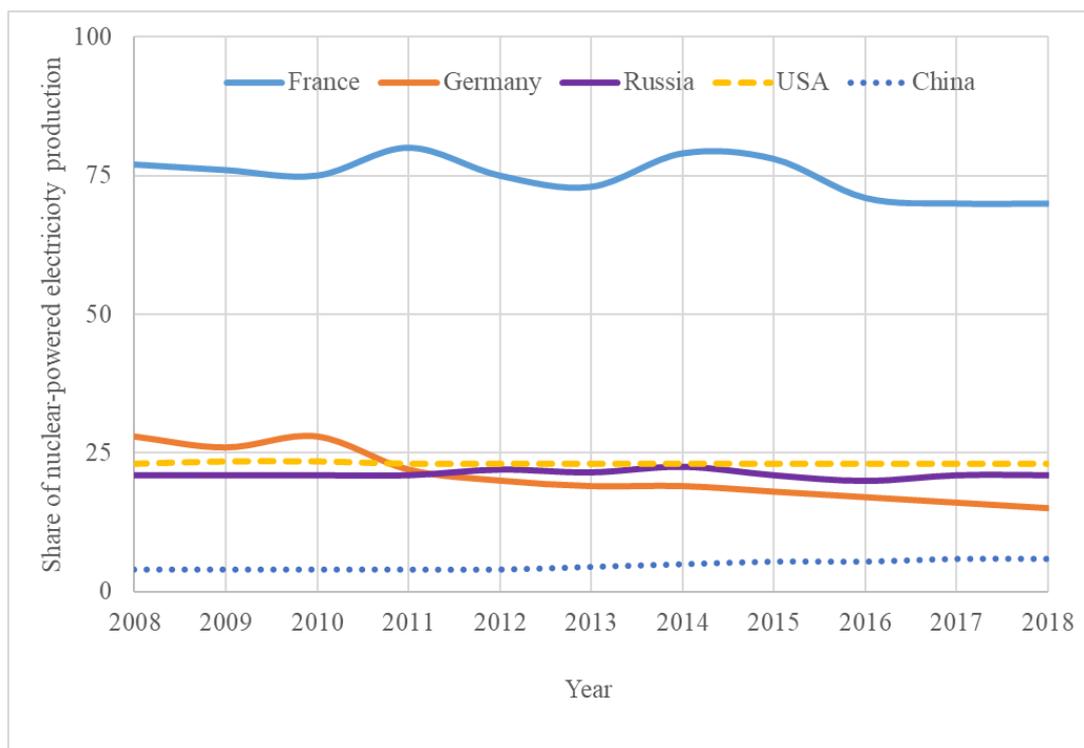


(a)



(b)

Figure 1. Cont.



(c)

Figure 1. (a) Share of global electricity production [1]; (b) Member States progress towards their 2013/2014 and 2015/2016 indicative red targets versus RES 2020 target. National renewable energy action plan, data from member states (NREAP), RES. Source: [3]; (c) Share of nuclear-powered electricity production [4].

However, renewables are sensitive to climate and weather conditions entitling large implementation costs related to building the effective units, which are further enhanced by additional costs for necessary grid enhancements to balance out the surplus of intermittent renewables infeed. One example in this case is the German energy market, where massive investments into the country's power grid are required in order to be able to transfer efficiently the surplus of wind generation in the Northern part of the country towards the southern industrialized regions, to balance out excess demand (see [5]). Furthermore, reductions in fossil fuel capacity will indirectly affect the value of renewable energies due to the lack of backup capacity during periods of rapid changes in renewables output and consequently to the need to shift larger amounts of energy from hours with higher- to hours with lower renewables infeed (see [6]). This increases the need for battery storage, which ultimately results in higher system costs. Thus, despite their gradual growth in the production mix, it is unlikely that we will be able to rely solely on renewable sources in the foreseeable future.

As of now, the primary backup sources to the long-run unreliability on renewable power are the fossil-fuels, but there exists an economically viable, low-carbon, available and reliable option for electricity generation: nuclear power. Indeed, any of the advanced nuclear systems that operate at steady 100% thermal output can accommodate the intermittency of renewables and back-up with power and heat when renewables are not available (e.g., on cloudy or windless days), as discussed in [6]. (In practice, there are annual revisions (planned) and sometimes unplanned shutdowns, so the plants are not running 100%). Given that the energy and environmental open issues urge feasibility solutions, nuclear power provides a probable partial solution to the challenges ahead.

Policies regarding nuclear power vary significantly across countries (see Figure 1c). For example, in Germany the energy system is drastically stepping down the nuclear-powered energy production, while China is in the process of building more than 50 new plants [4]. The debates on nuclear

power are controversial and highly complex, often unilateral views being insufficient for correct assessments. In countries where nuclear is significantly undervalued, the source of the problem does not relate to technical aspects, but rather to broader public policies regarding renewables and nuclear [6]. Thus, energy policies related to nuclear power shape market outcomes. Adequately assessing the benefits and environmental challenges related to nuclear power production requires interdisciplinary expert knowledge in a broad range of fields such as physics, economic theory, psychology or political sciences.

The aim of this paper is to review studies in which the topic has been approached unilaterally, field-specific, and combine the individual knowledge to get a comprehensive picture of advantages and disadvantages of nuclear power production. We thus analyze the feasibility of nuclear power in an interdisciplinary approach, combining expert knowledge from several scientific fields and comparing our insights to media communications and energy policy issues. We further shed light on the suitability of nuclear power production as a substitute to fossil fuels, especially to coal, which is the cheapest and most used fuel for electricity production (accounting for 40% of the electricity generation). We discuss the reasons behind the different policies in different countries, the role nuclear power should play in the energy transition, and the necessary actions to ensure a beneficial exploitation of the technology. We conclude that there is a gap between the general perception, often reflecting local energy policy regulations, and statistics drawn from interdisciplinary academic research.

2. Economics of Nuclear Power

Different power sources have different capacity factors. The capacity factor is defined as the ratio of the actual energy output of an energy source over a period of time to its maximum output possible [7–9].

Figure 2 shows the capacity factors of several power sources. It is evident that nuclear power outperforms the other power sources on the capacity factor. The capacity factor of the geothermal power is high because it operates constantly and is independent of climate [9]. The high capacity factor of nuclear power is due to the fact that the nuclear power plants require less maintenance and refueling than other energy resources such as coal or gas [8]. Renewable energy resources (solar and wind) have the lowest capacity factors. This is because they are dependent on natural power sources like sun and wind, which are hard to predict, leading to intermittent production. Thus, by contrary to fossil fuel or nuclear power generation, renewable energy cannot be produced always on demand, being quite challenging for production planning. Renewables are not a reliable back-up capacity [10] due to their intermittency, which enhances the need for battery storage, increasing ultimately the financial costs [11].

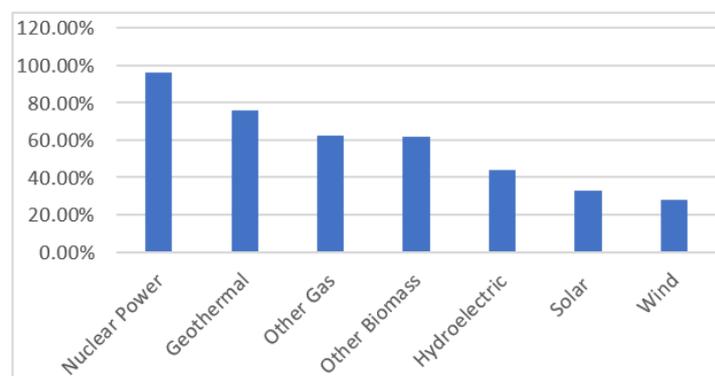


Figure 2. Capacity factors efficiencies of different power sources in 2020 [12].

Figure 3 shows the so-called “merit-order curve” (MO), where the various production technologies are ordered ascendingly with respect to their marginal costs of production. Energy policies target towards greener generation sources by subsidizing renewable energies. Being the technologies with

the lowest (almost zero) marginal costs of production, the increasing renewables infeed over time led to a shift in the merit-order curve, pushing the more expensive technologies, such as oil and gas, out of use (see [5]). Consequently, the electricity demand is now covered by cheaper production technologies on use, resulting in lower electricity prices. The shift in the merit-order curve and further implications on day-ahead or intraday electricity price distributions are detailed in [13–17]. Nuclear power is the technology with only slightly larger marginal costs of production than renewable energies. Similar to renewable energies, building a nuclear power plant involves huge capital.

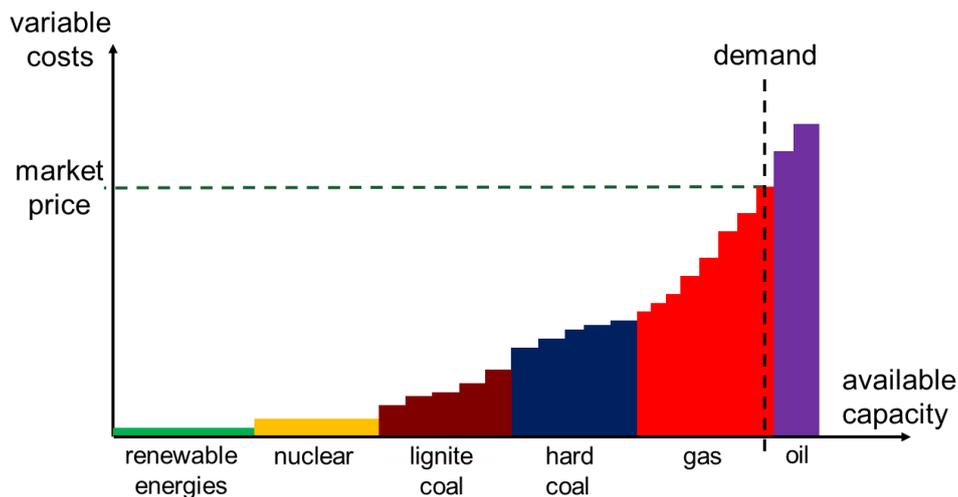


Figure 3. Variable costs of power production [14].

When deciding to build a nuclear power plant or a coal plant, the average cost of the units of electricity over the plants' whole life must be considered. The most common way to compare the economic efficiency of different power sources is with the “levelized cost of electricity” (LCOE). This represents the total costs of building and operating the plant over its lifetime, divided by the total megawatt-hours produced. The metric used when talking about LCOE is dollars per megawatt-hour.

When comparing the LCOE of different power sources, the discount rate is essential to consider, especially when talking about nuclear power which is capital-intensive, meaning that most expenses accrue in the first year of the project. When using a discount rate under 7%, the 2015 edition of the OECD study on Projected Costs of Generating Electricity found that nuclear power is cheaper than coal [18]. For discount rates over 10%, coal is cheaper than nuclear. The discount rate for nuclear power projects in the US is usually about 12.5%, making coal the desirable investment. The high discount rate combined with the high initial capital expenses is the reason why nuclear power is not necessarily considered an economically desirable option in the US. The discount rate for nuclear power is higher in the US than in other leading “nuclear” nations like France or Japan. In France, the discount rate is 8%, while in Japan it lies around 2–3% [18]. This is mostly due to nuclear power being subsidized in these two countries, while it is not the case in the US, where coal and other fossil fuels are both directly and indirectly subsidized. This is a huge incentive for investing in coal plants instead of nuclear plants.

Comparing the LCOE between different energy sources, as shown in Table 1, Ref. [19]'s annual Levelized Cost of Energy Analysis (LCOE 14.0) shows that as the cost of renewable energy continues to decline, certain technologies (e.g., onshore wind and utility-scale solar), which became cost-competitive with conventional generation several years ago on a new-build basis, continue to maintain competitiveness with the marginal cost of existing conventional generation technologies. We furthermore observe that nuclear power shows generally higher LCOE values than the coal but similar values to the gas peaking technologies. It is however worthwhile mentioning that for small nuclear reactors (SMRs), [20] proposes an innovative technology based on up to 12 modules, which can be added to a facility incrementally in response to load growth. This will reduce initial capital costs,

targeting a LCOE of \$65 per megawatt hour. The simplicity of the SMR design provides competitive levelized cost of electricity (LCOE) compared to other low carbon options (see [20]).

Table 1. Levelized cost of Energy Comparison [19].

Energy Source	Levelized Cost (\$\MWh)
Solar PV-Rooftop Residential	150–227\$
Solar PV-Rooftop C&l	74–179\$
Solar PV-Thin Film Utility scale	29–38\$
Wind	26–54\$
Gas peaking	151–198\$
Nuclear	129–198\$
Coal	65–159\$
Gas combined cycle	44–73\$

However, gas combined cycles are clearly most levelized-cost-competitive. This is because the prices of fossil fuels are relatively low these days (Brent oil \$65.44 on 20 February 2020). An advantage of nuclear power is that prices of fossil fuels are very volatile compared to the price of uranium. The low cost of uranium yields low variable costs of every megawatt-hour produced in a nuclear power plant. Thus, the costs of nuclear power are more predictable than for fossil power, which makes it easier to derive future energy scenarios. In addition, investing in nuclear power production can serve as a hedge against increasing fossil fuel prices.

In the United States, nuclear power plants which were commercialized in the 1950s and are now used across the world are generated by light water reactors (LWRs). However, safety related concerns raised after the Fukushima accident in 2011 urge to develop less expensive and safer nuclear technologies. An “advanced nuclear reactor” is defined in legislation enacted in 2018 as “a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors”. Major categories of advanced reactors include advanced water-cooled reactors, which would improve safety, efficiency, and other factors over existing commercial reactors [21].

To conclude, from an economic efficiency point of view, operating and well-performing nuclear power plants should not be shut down, as the marginal costs of production are low. However, this is only valid when considering a free energy market, while national regulations and subventions can still lead to a modified picture of the suitability of different production technologies. Furthermore, the construction delays of nuclear power projects are nearly 60 percent higher than it has ever been before due to changes in regulatory procedures, delays in equipment’s delivery and licensing process, lack of availability of skilled workers, an imposed increase in the salaries and the costs of equipment. These financial challenges disturb future nuclear energy projects. However, this problem is country specific and, accordingly, a better evaluation of the role of nuclear power in the decarbonization of energy sector is needed, which takes into account the policies, costs and regulations on the national level [22,23]. Whether or not investing in new nuclear plants is desirable depends further on fossil fuel prices, subsidies and discount rates.

3. Safety Aspects—An Interdisciplinary View

This section discusses the effects of using either coal combustion or nuclear energy as primary energy source on the human health and environment.

3.1. Effects of Coal Combustion on the Human Health and Environment

Coal is currently the largest source of energy on Earth and widely used to generate electricity. The main components of coal are carbon, sulfur, oxygen, hydrogen, nitrogen (in small amounts) and traces of heavy metals. During coal combustion, carbon-sulfur and nitrogen react with oxygen and produce oxides. When these oxides are emitted in the air, they can cause skin, cardiovascular,

brain, blood, and lung diseases, and it can even cause cancer [24]. During combustion, it also occurs an interaction between CO₂ and particulate matter (PM). This can lead to asthma attacks and other respiratory and cardiovascular diseases. Furthermore, when the sulfur in coal oxidizes during combustion, it releases SO_x (SO₂, SO₃, SO₂₋₃, and H₂SO₄). This contaminates the air, water, and land. Other SO_x such as sulfate (SO₂₋₃) and sulfuric acid (H₂SO₄), damage the environment in the form of acid rain. This acid rain can damage skin cells and contaminate flora and fauna by leaching heavy metals [25]. However, it is important to mention that all Sulphur components are filtered in western coal power plants. NO₂ is the main component of acid rain and is related to many skin diseases. High levels of NO₂ (>1500 mg/m³) in the air can cause a reduction in the pulmonary function in humans [26]. Still, nitrogen oxidation can be partly controlled by the temperature and filtration (see [27]).

3.2. Effects of Radiation in the Body

Radiation is a type of energy that travels in the form of high-energy particles or waves. This type of energy can be classified as ionizing or non-ionizing. Non-ionizing sources of radiation include UV-light, infra-red energy, microwaves, and sound waves. The characteristic of these types of radiation is that it can cause atoms to vibrate and move in a molecule, but it is insufficient to displace the electrons from these atoms. Therefore, this type of radiation is not dangerous to humans. Ionizing radiation, on the other hand, can be dangerous in high dosage. This radiation comes from X-rays and gamma-rays, high-energy neutrons, alpha particles (two protons and two neutrons) and beta particles (mainly electrons). It is important to notice that 50% of the total radiation dose in the US comes from medical devices [28].

The biologic effects of radiation are strongly determined by the rate of delivery, the size of the field, and the rate of cell proliferation. The effect of radiant energy is cumulative, meaning that the divided doses allow cells to repair themselves, but this self-repairing mechanism might be incomplete, causing further cellular damage. Smaller doses that are delivered to larger fields may result lethal. The DNA damage is mainly caused by the synthesis of reactive oxygen species from reactions with free radicals, the latter created by the radiolysis of water. The less hypoxic tissue is, the more sensitive it is to radiation. The incidence of cancer in any organ increases after the exposure to ionizing radiation. It has been proven that it has a link to the development of leukemia and solid tumors (including breast, thyroid, and lungs) [29].

3.3. Safety Regulations in the US

Low levels of radiation can count as a minor contributor to cancer risk rather than causing immediate damage. Radiation doses can be expressed in millisieverts, which is an international unit to quantify the effective dose. In the United States, the unit rem is being used. A radiation dose can be determined either from a one-time exposure or from accumulated exposures over-time. 99% of individuals exposed to radiation undergo a single exposure, which usually is insufficient to cause cancer [28]. The main fuel for nuclear reactors is uranium, which creates energy through fission, meaning that it involves the atomic splitting of uranium atoms. Most of the radiation we receive comes from natural sources such as cosmic rays, radon gas, and uranium. The average an American person receives from natural sources is around 300 millirem each year. Each reactor, by law, must report any exceeding of the radiation level limit. If the reactors adhere to this adjustment, the doses from the reactors can become so small, that it is difficult to distinguish them from background radiation [30].

During normal power production, nuclear power plants release meager amounts of radioactive materials into the air. There are federally defined limits for this radioactive air emissions, also being monitored by the United States Nuclear Regulatory Commission (NRC) [28]. Power plants, while operating, may release a certain amount of radioactive material. Due to this reason, the NRC is quite strict about keeping the levels of this radioactive emission low enough to protect the public. The NRC revises the specific license of a reactor and its impact on people, animals, and the environment

in general. They regulate power plants design to keep radioactive materials as low as reasonably achievable. Plant operators must comply with the radiation dose limits (Table 2) for the public and report the plant's results annually to the NRC, which are posted on the NRC website. The radiation exposure of living close to a power plant (<1 mrem, <0.01 msv) [28] does not exceed the regulatory limits shown in Table 2.

Table 2. Radiation dose limits [28].

Annual limit	Total effective dose of ~5 rems (0.05 Sv)—The sum of the deep-dose equivalent and the committed dose equivalent to any individual organ or tissue other than the lens of the eye being equal to 50 rem [0.5 Sv]
Annual limits to the lens of the eye, skin, whole body, and skin of the extremities	Lens dose equivalent to 15 rems (0.15 Sv)—A shallow-dose equivalent to 50 rem (0.5 Sv) to the skin of the whole body or to the skin of the extremities

3.4. Health Impact of Nuclear Power Accidents

The radiation levels during normal operations are below what is considered harmful. However, accidents can lead to greater exposure to radioactive material, resulting in fatal radioactivity levels. Historically, there have been three significant accidents: Three Mile Island 1979, Chernobyl 1986 and Fukushima 2011. The Three Mile Island and Chernobyl accidents were related to technical and human errors which led to a meltdown of the reactor core that however did not get to the outside. In the Chernobyl accident, the reactor also exploded. A loss of power which was triggered by a massive earthquake and by a Station Black-Out (SBO) induced by ocean waves caused the Fukushima accidents, which involved three power stations [31,32].

The Three Mile Island is the least harmful of the three in matter of immediate (direct) fatalities (see [33]). There were no deaths directly related to the accident or from diseases caused by the radiation. The Chernobyl accident, instead, resulted in 31 immediate fatalities. Probabilistic Safety Assessment (PSA)-based maximum consequences including expected latent (indirect) fatalities ranged from about 9000 for Ukraine, Russia and Belarus to about 33,000 for the whole northern hemisphere in the next 70 years [34]. According to a comprehensive study by numerous United Nations organizations, up to 4000 persons could die due to radiation exposure in the most contaminated areas [35]. This estimate is substantially lower than the upper limit of the PSA interval, which, however, was not restricted to the most contaminated areas.

There are no direct deaths linked to the Fukushima accident. However, the indirect casualties of these two accidents are in the thousands [36–38]. As already mentioned, a high dosage of radiation may cause cancer. The radiation death toll from Fukushima varies a lot with different studies, as it is hard to prove that radiation was the reason for getting cancer. Thus, as shown in [33], the discussion on the number of deaths related to nuclear accidents is questionable, because there are no clear data available. Published health effects of the Fukushima Daiichi nuclear accident show large variations, which is partially attributable to different assumptions and methods used. For example, ref. [39] estimated additional 130 worldwide cancer related latent fatalities, ref. [40] about 1000, and [10] about 600. Additional evidence of nuclear accident fatalities is provided in [41,42]. However, ref. [43] reported a much higher value of 10,000 cancer related and some rather extreme sensitivity cases summing up to 300,000 latent fatalities.

Prior research concludes that from all deaths resulting of the Fukushima accident, a large proportion is estimated to have died from evacuation stress. Radioactive contamination from the Fukushima plant implied the evacuation of communities up to 25 miles away affecting about 100,000 residents, although it did not cause any direct fatalities (see [32]). A precautionary evacuation over a 3 km radius around the plant was enforced on the day of the tsunami. On the next day, elevated dose rates were detected at the plant site and the evacuation was expanded to a 20 km radius. Radioactive contamination of the

ocean became in addition an international concern. Still, exact numbers of fatalities resulting from evacuation stress vary significantly across studies and must be treated with caution, as counting in the death cases from evacuations to the death toll of nuclear power is a stretch. It is worth mentioning that nuclear policy (including evacuation policies) is driven by incredibly low radiation dose limits. Furthermore, nuclear power is much more strictly regulated than the coal sector.

When comparing nuclear fatalities to the ones of coal, they are low. This is because normal operation of coal power plants without filters results in fatalities, whereas nuclear power plants may result in fatalities only after accidents, causing thus indirect fatalities, determined, among others, by evacuation stress. Thus, for coal most accidents are associated with mining activities, while the nuclear is a special case with very limited historical experience in terms of accidents with fatalities. An overview of accident risks in the coal industry shows that fatality rates for coal are the highest compared to nuclear power, gas, and oil [33,44–46]. In a recent study, ref. [45] offer an updated comparison of fatality rates for fossil, hydro, nuclear and renewables in OECD, EU28 and non-OECD countries for the period 1970–2016. The authors conclude that for nuclear, fatality rates are among the lowest, particularly for the new generation III (EPR) reactors, given their improved safety systems. Finally, new renewables have clearly lower fatality rates than fossil chains and are fully comparable to modern nuclear power plants.

All in all, although nuclear plant catastrophes are disastrous for both workers and the population nearby, the risk of severe accidents is still relatively low. Ref. [47] show a comparative analysis of health effects in terms of reduced life expectancy in the context of normal operations of a broad spectrum of electricity supply technologies. Further, estimates of health risks from normal operation are compared with those due to severe accidents or expected terrorist attacks. The authors conclude that the mortality due to severe accidents is, for comparable technologies, typically significantly lower than for normal operations. Furthermore, nuclear performs best with lowest mortality impacts of both normal operations and severe accidents (see [47], Figure 9). In case of coal, mortality impacts are highest for both categories. For nuclear, during normal operation conditions, the radiation levels are below the natural radiation, and they are not considered harmful. The deliberate radiation emission from medical procedures is much higher than that of nuclear power plants. Still, socially speaking, even mild radiation will result in stress and cause indirect fatalities or migration of people away from affected regions. Furthermore, the accident risk in this energy sector is of major concern to policy makers worldwide. This concern has been further enhanced post Fukushima 2011 by extensive media proliferation, which shaped the public opinion against nuclear power.

Clearly, a direct comparison of fatalities (direct and indirect) between nuclear and other technologies is not straightforward. Overall, prior research concludes that fatality rates (denoting expected risk) are significantly lower for nuclear than for coal, if comparing immediate fatalities. Maximum consequences (number of fatalities) can serve as a measure of risk aversion. For nuclear, it is however meaningful to include also the indirect/latent fatalities, leading to much higher numbers than for coal. Additionally, the catastrophic potential for a coal mining accident is limited by mine size, i.e., the maximum number of people at work, which can be highest during shift change (Soma accident in Turkey). Thus, depending on stakeholder preferences, giving higher weight to latent fatality rates over maximum consequences can lead to a different view on which technology is preferred in terms of accident risk. (We thank Peter Burgherr from Paul Scherrer Institute for very useful discussions and for his meaningful input to our review of energy supply accident risks.)

Further research could focus on a public survey in nuclear phasing-out countries investigating what counts more for individuals: (1) having nuclear-free energy mix or (2) decrease the CO₂ emissions? However, the decision of reducing greenhouse gas (GHG) emissions cannot be attributed solely to a tradeoff between coal and nuclear, but it implies a more complex mechanism. For example, Switzerland wants to phase out nuclear and the hydro production cannot be further increased. This can be supplemented by either a higher PV infeed that needs to be stabilized/stored, natural gas (with carbon capture) or electricity imports. Overall, in terms of GHG emissions, the key challenge is to use

low-carbon technologies, but if one considers the whole energy sector and not just the electricity production, we need negative emissions (net-zero), since some sectors can simply not be reduced to zero.

3.5. Safety Measures

Prior studies of the Fukushima disaster have identified market design changes and major safety improvements that could have reduced or eliminated the amount of radioactivity released from the plant. As a result, the Fukushima accident determined a reexamination of nuclear plant safety requirements around the world, including in the United States (see [32]). Aspects of nuclear plant safety imposed by the Fukushima accident were assessed in 143 nuclear reactors in the EU's 27 member states and their neighboring states that accepted to take part. The goal of these "stress tests" were several comprehensive and transparent nuclear risk and safety assessments involving reexaminations of each power reactor's safety margins in the light of extreme natural events, such as earthquakes and flooding. Further stress scenarios related to losses of safety functions and severe accident management following any initiating event were derived. They were conducted from June 2011 to April 2012. The stress testing exercise required considerable expertise in different countries (500 man-years) under the supervision of each national Safety Authority within the framework of the European Nuclear Safety Regulators Group (ENSREG) [48].

An OECD/NEA report in 2010 shows that the frequency of a significant release of radioactivity from a severe nuclear power plant accident has reduced by a factor of 1600 between the originally built Generation I reactors and the Generation III/III+ plants being built today. Earlier designs however have been progressively improved through their operating lives.

The EU nuclear stress testing process was completed at the end of September 2012 with the concluding remarks of the EU Energy Commissioner that the safety of European power reactors was generally satisfactory but improved safety is required in four main areas [4]:

- Assessment of natural hazards and margins beyond design basis.
- Periodic safety reviews and evaluation of natural hazards.
- Urgent measures to protect containment integrity.
- Measures to prevent and mitigate accidents resulting from extreme natural hazards.

The stress tests results showed that European nuclear power plants proved a sufficient safety level, so shutting down any of them would not be required. Still, improvements were needed to enhance their robustness to extreme events.

The USA Nuclear Regulatory Commission (NRC) in March 2012 made orders for immediate post-Fukushima safety enhancements estimated at about \$100 million across the whole US fleet. Among others, the addition of equipment at all plants to help respond to the loss of all electrical power and the loss of the ultimate heat sink for cooling, as well as maintaining containment integrity was enforced. All measures were supported by the industry association, which has further set up about six regional emergency response centers under NRC oversight with additional portable equipment. In Japan, similar stress tests were carried out in 2011 under the previous safety regulator, while reactor restarts were delayed until the newly constituted Nuclear Regulatory Authority which issued new safety guidelines which have been implemented gradually (see [4]).

4. Environmental Impact

This section discusses the environmental challenges related to nuclear waste management and greenhouse gas emissions from nuclear power production.

4.1. Waste Management

All waste from nuclear power is strictly regulated, unlike all other forms of thermal electricity generation [49]. Nuclear power is characterized by a large amount of energy produced from a small

amount of fuel. Hence, the amount of waste produced during this process is relatively small. However, much of the waste produced is radioactive and therefore must be carefully managed as a hazardous material. A major environmental concern related to nuclear power is the creation of radioactive wastes such as uranium mill tailings, spent reactor fuel, and other radioactive wastes [12]. Nuclear waste can have hazardous effects on animals and plant life if not handled properly. However, the waste is usually safely sealed in drums of steel and concrete, but a rare leak can occur. These drums are kept deep in the ground and often in remote places, where they do not cause a problem to the environment even if there is a leak.

About 97% of the waste is considered low- or intermediate-level waste, which accounts for 5% of the radioactivity. The remaining 3% is considered high-level waste (HLW) and accounts for 95% of the reactivity [49]. The total amount of HLW generated in the United States annually is about 2000 tons, which would require about five acres for dry cask storage [50]. An average-sized 1000 MW nuclear reactor produces about 20 tons of spent nuclear fuel each year that must be stored in cooling pools for a few years. Each cask typically holds about 10 tons, so the total waste from a reactor is about 2 casks per year [50].

Storage involves maintaining the waste such that it is isolated from the environment, while also making it retrievable. Different levels of radioactive waste have different requirements for disposal. For example, high-level waste needs to be cooled down, and cannot be disposed of before the radioactivity has decayed to a sufficiently low level. This usually takes about 40–50 years. Waste is commonly stored close to the plant but can also be stored remotely [49]. Lower-levelled waste can be disposed of right after usage. Most low-level waste and short-lived intermediate-level waste are typically sent to land-based disposal immediately after packaging. This means that for the majority (>90% by volume) of all waste types, a near-surface disposal is satisfactory [49].

In the short term, the spent fuel rods (high-level waste) are stored in the cooling pools for several years to allow them to cool and for much of the initial radioactivity to decay. The IAEA estimates that the global disposal volume of the current solid HLW inventory is approximately 22,000 m³ (see [48]). Spent reactor fuel assemblies are highly radioactive and must be stored in specially designed pools of water [12,50]. During that time, all the radioisotopes with lifetimes of less than four years will become negligible, and the heat will be reduced by over 99% [49,50]. Transuranic wastes, sometimes called TRU, account for most of the radioactive hazard remaining in high-level waste after 1000 years. Radioactive isotopes may decay, or disintegrate, to harmless materials. Certain isotopes decay in hours or even minutes, while others decay very slowly. Strontium-90 and cesium-137 have half-lives of about 30 years (half the radioactivity will decay in 30 years). Plutonium-239 has a half-life of 24,000 years (see [51]).

Currently, there are not any operating deep geological repositories for HLW, although researchers addressed this topic over several decades in many underground research laboratories. Finland, France and Sweden made steps forward to the construction and implementation of their own deep geological repository for HLW (see [48]). Finland and Sweden have applied for construction licenses at selected sites in crystalline rock and expect commissioning in the 2020s.

The United States do not currently have a permanent disposal facility for high-level nuclear waste. The short-term solution for storage of high-level waste is called dry cask storage. The waste is placed in an inert gas in steel containers encased in concrete and stored on-site of the plant [12,50]. Dry cask storage is currently being used at many nuclear reactors. This can provide a safe and secure method to handle spent nuclear fuel for the next century and can reduce the need for an immediate solution to the long-term problem of waste storage [50]. Because of the long-time perspective over which waste remains radioactive, the long-term handling and final disposal of the waste is critical [49,50]. Numerous long-term waste management options have been investigated. Geological deep disposal in a mined repository is now the preferred option in most countries. This means that the waste is stored in a corrosion-resistant container and buried deep underground in a stable rock structure [49]. According to [52], the problem of long-term waste storage is primarily political, not of a scientific or

engineering nature. Politics are the main reason why the United States do not currently have a solution to long-term storage [50].

4.2. Green House Gas Emissions

Unlike fossil fuel-fired power plants, nuclear reactors do not produce carbon dioxide while operating [12]. However, nuclear energy is not entirely emission-free of greenhouse gases (GHG). Based on 103 studies of greenhouse gas emissions from nuclear power plants, the mean value of emissions throughout the lifetime of a nuclear reactor is 66 g CO₂e/kWh [47]. The bulk of nuclear related GHG emissions stems from cement production, material production and component manufacturing in the construction phase [53]. Emissions are also affected by reliance on existing fossil-fuel infrastructure for fuel processing along with the energy intensity of uranium mining, enrichment and nuclear-decommissioning [47,53].

From a pure carbon emission point of view, nuclear power is outperforming coal, oil, and natural gas. Coal, oil, diesel, and natural gas generators emitted between 443 and 1050 g CO₂e/kWh, far more than the 66 g CO₂e/kWh from the nuclear life cycle [47]. Ref. [54] found that from the life cycle of 15 separate power sources, all but one, solar photovoltaics (PV), emitted more g CO₂e/kWh than the mean reported from nuclear plants (see Figure 4).

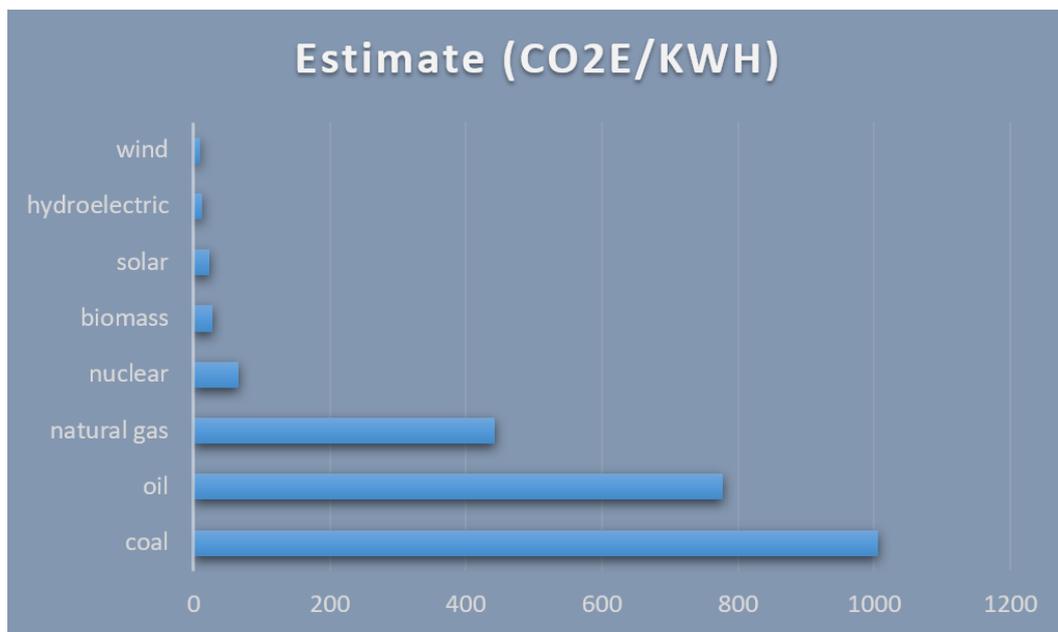


Figure 4. CO₂ equivalent emissions [2].

5. Public Perception & Proliferation

5.1. Public Perception

This section addresses the public perception on nuclear power and its underlying reasons, primarily focusing on the US.

5.1.1. What Is Risk?

Risk can be defined as the individuals' feelings of uncertainty and the possibility to be exposed to danger, the magnitude of risk being determined by the probability of its occurrence and the immensity of the consequences [55,56]. The concept of risk is socially contextualized and constructed. Thus, it varies across different countries [55,57]. Public perceptions of risk are constructed through the interaction of internal beliefs derived from personal events and external views and accidents [58].

This implies that the perception of risk cannot be measured because it is dependent on culture and personal beliefs. Perceived risk influences individuals' opinions and behaviors. Further, different perceptions of risk can cause social/political conflicts, since different groups within the same country perceive risk differently.

Concerning nuclear power, scientists and non-scientists differ in their models of risk assessment. Previous studies show that US scientists consider the anti-nuclear public perceptions and attitudes to be irrational [58]. Ref. [59] further discusses the differences in knowledge, risk perception, and attitudes towards nuclear power between scientists and the general public perception. The authors conclude that among non-experts, negative expectations are given greater value than expected benefits. Moreover, people tend to have stronger and more sensitive reactions to human-made accidents than to natural ones of a similar magnitude.

5.1.2. What Shapes the Public Opinion on Nuclear Power?

The public perception of risk is a key figure that influences attitudes toward nuclear power [58,59]. Public perception analysis relies on two different variables. First, *the perception of risk*, which is pervasive among the public and represents the views on the personal and individual levels. Second, *the perception of benefit*, which reflects the state strategies and ideologies on the country level [60]. In other words, the risk perceptions on the utilization of nuclear energy are multidimensional and entail a distinction between risk and benefits [61]. However, risk and benefit are two ambiguous and abstract concepts that are difficult to measure [60].

Polarized views dominate risk management and assessment. While scientists are objective and analytically grounded in assessing risk, the public assessment is considered in the academic literature as subjective [57,62–64]. Prior research shows that people living in municipalities in the vicinity of nuclear power plant (e.g., the Dukovany nuclear power plant) tend to be more nuclear pro, as they see the economic benefits of nuclear power for their communities, comparing with others living in remote municipalities, who are more concerned with potential risk and negative consequences [65].

Monetary and social costs stemming from the contamination of huge areas around Chernobyl and Fukushima plants have a clear impact on the public opinion. Thus, the Chernobyl disaster had devastating impacts on the communities most severely affected in Russia, Ukraine, and Belarus, increasing social costs and leading to an economic and social decline. The nuclear accidents increase, thus, the burden on national budgets, given the need for social compensation, resettlement, and enhanced health care. "To compound the problem, much of the land was now off limits, so investment fell, industry and agriculture declined, unemployment rose, and workers migrated outside the affected areas" [66]. Similarly, as the long-term health and economic consequences of the Fukushima disaster become more apparent, the Japanese population showed more often feelings of anger and betrayal (see [32]).

Several other factors that affect the rejection or acceptance of nuclear energy are: gender, level of education [60], trust in the experts' views [64], nuclear power related accidents [61], socio-cultural context [67], mass media [60] and social amplification [57,68]. It is well documented in the literature that a higher opposition against nuclear power exists among women compared with men and among people with low levels of education compared with others who hold higher levels of formal education [60,64]. Moreover, trust in the scientists' perspectives alleviates perceived risk and increases perceived benefits of nuclear power.

Studies on public perception in France illustrate that there is a high level of risk perception and a negative attitude towards the use of nuclear power, although French people are good aware of its benefits [61]. Prior research shows that there is an overall declining trend in nuclear power support in the US with no prospects of a new "nuclear renaissance" [69,70]. However, these concerns did not affect the level of reliance on nuclear power, considering that it is embraced in France but not in the US. Moreover, the different attitudes in the reliance on nuclear power despite the similar levels of public objection in both countries can be attributed to several reasons such as: different trust levels in nuclear

power stations derived by inspecting authorities, differences in the public participation in the decision making, or different dissemination levels of scientific results [64].

The US is aware of the need to enhance public participation in the decision making. The public perceptions of nuclear power are considered a crucial factor for establishing nuclear energy policies and programs and determining the investment in energy facilities [71]. Ref. [69] describes the attitude toward establishing nuclear facilities in the US as suffering from “not in my backyard” or NIMBY sentiments (p. 170). The TMI accident has had a psychophysiological impact on people in the US and especially on the residents of the area. Studies show that locals of the TMI area experienced long-term symptoms of stress, depression, anxiety and somatic complaints [72]. Within the US, the TMI accident had the greatest impact on decreasing public support over a 9 or 10-year span [70]. Risks and benefits of nuclear power are controversial topics of debate in the United States.

However, the perception of acceptance and rejection can also be influenced by different information channels, such as the mass media, which emphasizes tendentially more the risk-related news. Therefore, the position taken by visual, written or online media channels contributes to forming people’s views in a biased, non-neutral way [60]. Living in a digitalized world allows people to be selective about which channels to follow and how to obtain information. However, the accuracy, objectivity and credibility of online news are a topic of concern worldwide, given that often media channels follow specific ideological or political sides, being very accident-risk biased when it comes to nuclear power. Thus, the Fukushima accident in 2011 had a great impact on forming the public opinion around the nuclear plants, being strongly discussed in the media. Ref. [65] states that a little more than four months after the Fukushima accident began, Google returned 73,700,000 results for the search term “Fukushima” and 22,400,000 results for the search terms “Fukushima and radiation” (p. 55). However, most of these reports do not follow a comprehensive, interdisciplinary scientific approach, but are treating the topic unilaterally, with a great emphasis on the accident risk side, often not backed up by expert knowledge. Further, ref. [65] illustrates that the reliance on internet-based data resulted in laying off many specialized reporters in the US who had the potential to provide balanced pro- and anti-nuclear opinions in an objective and knowledgeable way.

The last factor that contributes to shaping public opinion is called social amplification. Examining the social amplification processes is essential in understanding nuclear energy policies [68]. Individuals act as social agents, and they may amplify risk as they exchange information about a certain event. This informal communication can maximize the negative expectations of an accident. In other words, the public responses are formed through the interaction of a certain accident with the psychosocial and cultural components leading to specific interpretations, which result in either amplifying or alleviating the risk perception. For instance, as [68] mentions “while low-level radiation from sunbathing and medical exposures are often attenuated, radiation risks from nuclear power plants and nuclear waste storage are often amplified” (p. 62).

5.2. Nuclear Weapons Proliferation

Nuclear reactors were developed in the wake of nuclear arms development during the second world war. Furthermore, nuclear weapons play a vital role in the global power balance, and countries initializing or further developing nuclear weapon programs have been a heated political topic for the last 70 years. Nuclear energy development paves the way for weapon development and could lead to nuclear weapons proliferation. The similarity between the technology behind nuclear power and nuclear weapons makes it much easier for a country with a nuclear power program to develop nuclear weapons. The literature defines a concept called nuclear hedging as “a viable option for the relatively rapid acquisition of nuclear weapons, based on an indigenous technical capacity to produce them within a relatively short time frame” [73]. Hence, countries considering developing weapon programs but not wanting to face the consequences of a formal proliferation are incentivized to initialize a power program which also can function as a covert research program for further development of weapons. Consequently, nuclear power production is a political discussion at the highest level.

To prevent spreading of nuclear weapons while promoting peaceful usage of the technology for power purposes, an international treaty called The Non-Proliferation Treaty (NPT) was developed and signed in the late 60s. As of now, the treaty has 190 parties and six non-signatories: India, Israel, North Korea, Pakistan and South Sudan [74]. Of the non-signatory countries, India, Israel, North Korea and Pakistan have developed nuclear weapons using research from nuclear power programs. Furthermore, Iran, which is a party of the treaty, has failed to comply with the NPT agreements regarding reporting on their nuclear operations. Their nuclear programs are currently under dispute. The UN organization International Atomic Energy Agency (IAEA) monitors nuclear power programs by performing investigations to ensure peaceful usage of the technology. Due to the subtle differences between nuclear power- and nuclear weapon programs, it is difficult for IAEA to determine the real purpose of the programs.

In the public perception, further aversion towards nuclear power occurs, thus, due to the misperceived association of nuclear power to nuclear weapons. Still, peaceful nuclear policies are followed by several European countries such as Germany, Italy, Spain, Sweden or Finland, which developed ambitious civil nuclear programs without any military policy [74].

Overall, the fear of nuclear weapons proliferation brings the discussion on nuclear power on a level beyond economic efficiency and environmental impact. It concerns the global power balance, with major impact on the decision making.

6. Conclusions

In this interdisciplinary review study, we shed light on the advantages and disadvantages of nuclear power and assess its social acceptance in the light of media proliferation and energy policies across countries. Combined knowledge from engineering, physics and energy economics reveals that the marginal cost of nuclear power for electricity production is comparable to the cost of conventional coal and other fossil fuels, the technology being economically viable. Furthermore, nuclear power is a greener production source than coal, oil or natural gas, with reduced negative consequences on human health.

Nuclear accidents remain, however, due to their direct and indirect fatalities, of a significant concern, further enhanced by media proliferation. However, considering the low risk of accidents related to nuclear power plants, their overall health and environmental impact is lower than that of fossil-fueled power. Furthermore, the normal condition radiation levels from nuclear power plants are negligible, being lower than the natural radiation and much lower than the deliberate radiation we are exposed to through medical procedures. Strict regulations ensure a low level of radiation from the plants. Waste management is a technically demanding challenge, but sufficient technologies are developed, and it is now a matter of political decisions to invest in the safe and efficient long-term storage facilities. Thus, assessing its economic efficiency along with the health- and environmental impacts, we conclude that nuclear power is a competitive electricity generation source compared to fossil fuels.

However, incentives to keep or invest in nuclear power plants vary across countries, strongly influenced by local subsidy policies. Future utilization of nuclear power requires a deep public understanding and acceptance. Public opinion about nuclear power is, however, far from being neutral or objective, because it is cognitively related to concerns about weapons and historical fingerprints, which makes governmental decisions not straightforward. Furthermore, we show that media tends to proliferate the matter unilaterally, with great emphasis on accident risk or weapon production, which leads to a universally negative sentiment and perception. Combined expert knowledge should however be considered in defining future energy policies on nuclear power, closing the gap between misperception and reality. This is not to say that the public opinion should be suppressed, but rather not to hinder the potential of nuclear energy efficiency because of a fallacy of misperceptions and lack of knowledge.

Many countries are facing severe challenges to meet future energy needs without negatively contributing to the climate change. Refs. [75,76] conclude that the climate crisis will be much harder and expensive to overcome without making use of nuclear power. Our findings are in line with [6], which shows that the discrimination against nuclear as a low-carbon energy source does not relate to technical issues of nuclear power generation or market design. “The public attitudes towards nuclear translate into discriminatory public policies outside of wholesale market rules”. This creates room for some politicians to exploit the public misperception while promoting their agendas, rather than making data-driven decisions. Nuclear power is a viable, available and reliable power source and this fact cannot pass unobserved.

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