Does Nuclear Power Comply With the DNSH Criteria of the EU Taxonomy for Sustainable Activities?
A Literature Review

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Content

1 Summary

The 'Taxonomy Regulation' refers to three criteria, which have to be met so that an economic activity can be classified as contributing to sustainable development: (1) a 'substantial' contribution to at least one of the six environmental objectives (or at least enabling others), (2) does not significantly harm any of the environmental objectives, and (3) is carried out in compliance with the international social standards listed in the Taxonomy.

This literature review examines to what extent nuclear power corresponds to the criteria laid out in the Taxonomy Regulation.

Criterion 1: Nuclear power is recognised as an energy source with low greenhouse gas emissions compared to fossil fuels, and thus basically meets the criterion regarding the reduction or stabilisation of greenhouse gases. However, there is controversial discussion whether this technology should be included in a future sustainable energy mix with significant CO_2 reductions. It is questioned whether nuclear power corresponds to the 'best-in-class approach' in the energy sector (and can thereby be classified as 'transition activity'), and it is argued that there are alternative energy sources with even lower greenhouse gas emissions which do not compromise the relatively good climate protection performance by comparatively high risks.

Criterion 2: Based on this literature study, meeting the criterion "Do No Significant Harm" for all environmental objectives[1] can be summarised as follows.

Although the risks of nuclear accidents can be reduced, they can never be excluded. The resilience of nuclear power production is further challenged by increasing costs for construction and operation of nuclear power plants to protect against the impacts of climate change. Nuclear power plants require concentrated, large amounts of blue water. Increased water temperatures and reduced river flows have already led to reductions or even interruptions of electricity generation in recent years. For this reason, new cooling technologies are being developed, resulting again in higher costs. Forzieri et al. (2018) estimate that drought and heat damage in Europe will account for 67% and 27% of all hazard consequences for the energy sector by the end of this century (currently 31% and 9% respectively).

The literature has sufficiently documented the negative consequences of high-dose ionising radiation on human health. However, whether low-dose radiation has a negative effect on human health is controversial, as it is unclear at what exposure level negative consequences occur.

Uranium mining generates considerable quantities of waste materials and process water containing low-level radioactive substances, metals and acids. Although the link between the provision of nuclear power and biodiversity and ecosystems has not yet been sufficiently studied, recent findings suggest that uranium mining has negative impacts, especially on freshwater ecosystems.

After 40-50 years of development of the nuclear sector, the issue of high-level nuclear waste storage, with its very long-term consequences, is still heavily under discussion, mainly because of uncertainties

[1] The six environmental criteria cover climate change mitigation (already mentioned in criterion one), climate change adaptation, sustainable use and protection of water and marine resources, transition to a circular economy, pollution prevention and control, protection and restoration of biodiversity and ecosystems.

due to unforeseen geological movements and radioactive leakage into groundwater. High-level radioactive waste is still stored temporarily, thus posing another threat for which no far-reaching solutions exist. High-cost options are under consideration occasionally and under implementation in one case in Finland. Further, uranium mine remediation is still an unresolved topic, with thousands of banned uranium mines left in various parts of the globe.

Criterion 3: Uranium mining and milling has been struggling with human rights and safety issues throughout its history in different parts of the globe. This concerns workers in the mines as well as the human right to access to resources, e.g. clean water and used land, which might impact neighbouring communities.

Cross-cutting issues: Beyond the environmental objectives of the Taxonomy, governance aspects are relevant. The IPCC (2018) concluded that the political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically in recent years, while nuclear energy and carbon capture and storage in the electricity sector have not seen similar improvements.

In addition, nuclear power struggles with social acceptance in wider parts of society and with long development times (in democratic societies 10-19 years per plant). A major shift to nuclear power would imply that many of the current fossil-fuelled power plants would stay in operation for that period and thus delay their decommissioning, making it impossible to achieve the climate targets.

From an economic point of view, it has been noted that the business case for nuclear energy has weakened in recent decades. Based on a full cost accounting for Europe, this is partly due to the recent success of renewables, where the cost of PV modules has fallen by 80% within 10 years and that of wind turbines by 30%. In this way, renewable energy systems are not only feasible, but already economically viable and cheaper every year.

The risks of nuclear accidents will continue to exist. Further barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapons proliferation concerns, and adverse public opinion. The complex issue of highly radioactive waste will remain. We already live in a world with more than a quarter of a million tonnes of highly radioactive waste from nuclear power production, all in interim storage including potential leakage, which could increase to more than one million tonnes worldwide by 2100.

According to the literature, nuclear power can also not be seen as a **transition or bridging technology** because it misses to be the 'best-in-class' in the sector concerning its climate mitigation potential. Moreover, it would lead to a lock-in of carbon-intensive coal plants for up to 10-20 years until the new built nuclear plants to replace them would become operational. It even can be seen to hamper the deployment of other low-carbon alternatives due to its high capital intensity, which could be devoted to the scale-up of alternative energy sources like solar, wind and water.

2 Background

This literature review examines to what extent nuclear power corresponds to the criteria laid out in the Regulation (EU) 2020/852 of the European Parliament and of the Council on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 for establishing a common (EU) classification system for environmentally sustainable economic activities, called in short the 'Taxonomy Regulation'.

Article 3 of the regulation on the 'criteria for environmentally sustainable economic activities' defines that economic activity shall qualify as environmentally sustainable where that economic activity (a) contributes substantially to one or more of the environmental objectives set out in Article 9 in accordance with Articles 10 to 16; (b) does not significantly harm any of the environmental objectives set out in Article 9 in accordance with Article 17; (c) is carried out in compliance with the minimum safeguards laid down in Article 18; and (d) complies with technical screening criteria that have been established by the Commission in accordance with Article 10(3), 11(3), 12(2), 13(2), 14(2) or 15(2). These so-called DNSH (do no significant harm) criteria defined in Article 3 (a - d) and the environmental objectives set out in Article 9 are taken to structure this report to ensure their comprehensive coverage and should give an easily accessible overview of relevant aspects for discussion.

On the one hand, this report examines nuclear power against the DNSH criteria of the Taxonomy. On the other hand, the literature review also considers the economic viability 'in the sense of a broader concept of sustainability'. In doing so, economic considerations of electricity generation, taking into account different externalities, are compared with each other based on methodological conventions on full cost calculations.

This study relies exclusively on peer-reviewed journal articles and reports from international and supranational organisations, which rely on original data and peer-reviewed journal articles for their analyses. Thus, the results of the study should provide decision makers as far as possible with objective, scientifically sound information inter alia as an input for discussions on the EU 'Platform on Sustainable Finance', which will be established later in the year 2020 as stipulated in the Taxonomy Regulation.

3 Criterion 1: Substantial contribution to realise at least one of the environmental objectives

Criterion 1 requires a substantial contribution to the realisation of one or more environmental objectives set out in Article 9 in accordance with Articles 10 to 16.

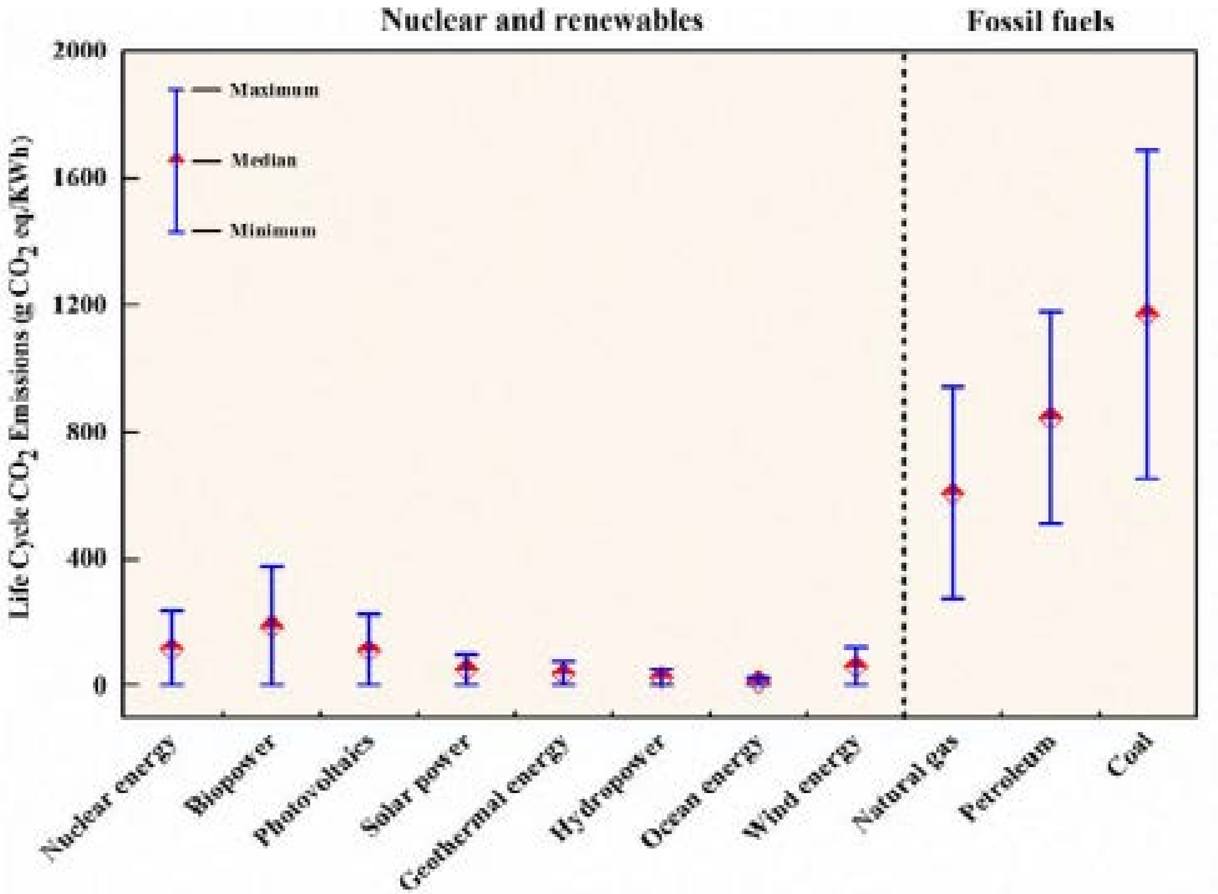
3.1 Climate change mitigation (Article 10 (1))

According to Article 10, a substantial contribution to climate change (CC) mitigation facilitates the stabilisation of greenhouse gas concentrations in the atmosphere consistent with the long-term temperature goal of the Paris Agreement.

There is a considerable body of research into the amount of embodied energy and greenhouse gas emissions associated with nuclear-generated electricity. While nuclear power generation has historically been associated with relatively little greenhouse gas emissions in the electricity generation phase (its direct contribution to climate mitigation targets, e.g. IPCC 2014), the majority of greenhouse gas emissions in the nuclear fuel cycle are caused in processing stages upstream and downstream from the plant (indirect effects, e.g. Sovacool 2008, Warner and Heath 2012). CO_2 emissions are estimated to come from the construction of nuclear power plants (12%), uranium mining and enrichment (38%), operation (17%), nuclear fuel processing and storage (15%) and decommissioning activities of the power plant (18%) (Sovacool 2008).

The common t-CO_2/GWh value in nuclear power generation reported in the literature varies widely, depending on the different model assumptions and system boundaries involved in the life cycle, indicating measurement reliability problems (Warner and Heath 2012, Nian et al. 2014, Dong et al. 2018). Nevertheless, most of the literature seems to converge towards the global assessment that the CO_2 emissions of a nuclear power plant throughout its life cycle are "similar to those of renewables" (e.g. Prăvălie and Bandoc 2018), although we see some heterogeneity even within these options. Dong et al (2018) provide an overview in the following figure.

Figure 1 The life-cycle CO_2 emissions for various fuels



Source: Dong et al. (2018: 53), based on data from Jaramillo et al. (2007) and Dong et al. (2017)

It was also the conclusion of an earlier literature review by Lenzen (2008: 2178) that the greenhouse gases from nuclear power generation are, as expected, lower than those from fossil technologies, but higher than the reported figures for wind turbines and hydropower "and in the order of or slightly lower than those of photovoltaics or solar thermal energy". Sovacool (2008) classifies nuclear to produce somewhat higher, and Van der Zwaan (2013) somewhat lower emissions. Godsey (2019) sees small modular reactors to perform slightly better than their larger counterparts. Taken together, we see several variants in the literature that point to underlying measurement problems, partly because nuclear power plants can be built and the raw material can be mined and processed in different ways. Warner and Heath (2012: S73) point out that "the conditions and assumptions under which nuclear power are deployed can have a significant impact on the magnitude of life cycle GHG emissions relative to renewable technologies." For instance, because less uranium rich rocks will tentatively be available in the future, mining and milling will result in a higher content of 'grey energy', and higher CO_2 emissions in the future. Dong et al. (2018: 51) conclude from their more recent analysis of the literature in general, and the data from China in particular, that "the mitigation impact of nuclear power consumption on CO_2 emissions is considerably smaller than that of renewable energy consumption, implying that renewable energy will be the main contributor to CO_2 emissions mitigation in China." Jin and Kim's (2018: 464) results point in the same direction. While analysing data from 30 countries using nuclear power for the period 1990-2014, their tests "indicate that nuclear energy does not contribute to carbon reduction unlike renewable energy."

In a recent study, Akram, Majeed et al. (2020: 18264) included also energy efficiency in their empirical analysis. They learned on the relationship between energy efficiency, renewable energy and CO_2 emissions in BRICS countries (stands for Brazil, Russia, India, China and South Africa, which produce a large share of global CO_2 emissions) that both, energy efficiency and renewable energy strongly contribute to reducing carbon emissions. "Notably, the long-run coefficients of energy efficiency and renewable energy are significantly higher than that of nuclear energy, signifying the importance of energy efficiency and renewable energy in BRICS countries. This result implies that although energy efficiency, renewable energy, and nuclear energy can reduce emissions, energy efficiency and renewable energy will be the primary contributors to CO_2 pollutant reduction in BRICS nations." Although the authors qualify their results insofar that they cannot automatically be transferred to other countries, energy efficiency will always be at the winning side of the equation, being considered as the most cost-effective way of increasing security of supply (import substitutions) and reducing greenhouse gases emissions (Kannelakis et al. 2013). The direct comparison of renewable energy and nuclear power generation depends on the different factor costs and efficiency gains, into which several studies have already looked into (e.g. Gökgöz and Güvercin 2018).

Considering direct and indirect emissions could justify using nuclear power in a mixed context, alongside renewable energies, to provide a viable short- and medium-term solution for the global phase out of fossil fuels (Schiermeier et al. 2008, Chu and Majumdar 2012, Hong et al. 2015), thus function as a 'bridging technology'. This is discussed in the literature in the context of what the appropriate energy mix should be for the transition towards a low carbon economy, where decarbonisation and energy security are the two major goals. The main question is here, whether a low-carbon future can predominantly or entirely be based on a combination of renewable energy and energy efficiency, or should the mix contain (at least for some time) significant contributions from nuclear power (and/or fossil fuels with carbon capture and storage) (Diesendorf and Elliston, 2018). The IPCC (2018 ch.2: 131) concludes in its latest report that there are considerable differences in the consideration of nuclear power between models and across 1.5°C pathways (Kim et al. 2014, Rogelj et al. 2018). One reason is that models considering uranium resource constraints and technology development tend to result in a smaller role for nuclear in the future. Based on this observation, Kim et al. (2014: 443) conclude that "greater clarification of nuclear fuel cycle issues and risk factors associated with nuclear energy use are necessary for understanding the nuclear deployment constraints imposed in models and for improving the assessment of the nuclear energy potential in addressing climate change." Other reasons for this variation is that the future deployment of nuclear can be constrained by different societal preferences assumed (the IPCC cited on this occasion O'Neill et al. 2017, van Vuuren et al. 2017). The IPCC goes on to comment (2018 ch.2: 132) "In addition to the 1.5°C pathways included in the scenario database … there are other analyses in the literature including, for example, sector-based analyses of energy demand and supply options. Even though they were not necessarily developed in the context of the 1.5°C target, they explore in greater detail some options for deep reductions in GHG emissions. For example, there are analyses of transitions to up to 100% renewable energy by 2050 (Creutzig et al. 2017, Jacobson et al. 2017)." These analyses describe the transition of electricity production from renewable energy sources. The underlying assumptions have been questioned by Clack et al. (2017). The discussion on this is currently underway.

In summary, nuclear power is recognised as an energy source with lower greenhouse gas emissions compared to fossil fuels. However, whether it should be included in a future sustainable energy mix with substantial CO_2 reductions is being discussed controversially. A reason for this is that there are alternative energy sources with even lower greenhouse gas emissions, i.e. which do not compromise the good performance on climate mitigation with relatively high risks, which will be discussed in the following chapters of this report.

4 Criterion 2: No significant harm on any of the environmental objectives

Criterion number two requires 'do no significant harm' (DNSH) on any of the environmental objectives as set out in Article 9 in accordance with Article 17, the latter defining what is to be understood as significant harm to each environmental objective.

4.1 Climate change adaptation (Article 11)

CC adaptation addresses in this context primarily reduced disruption and damage arising from acute or chronic effects of CC on nuclear power production, which can also be expressed as the resilience of the nuclear power production system against CC impacts.

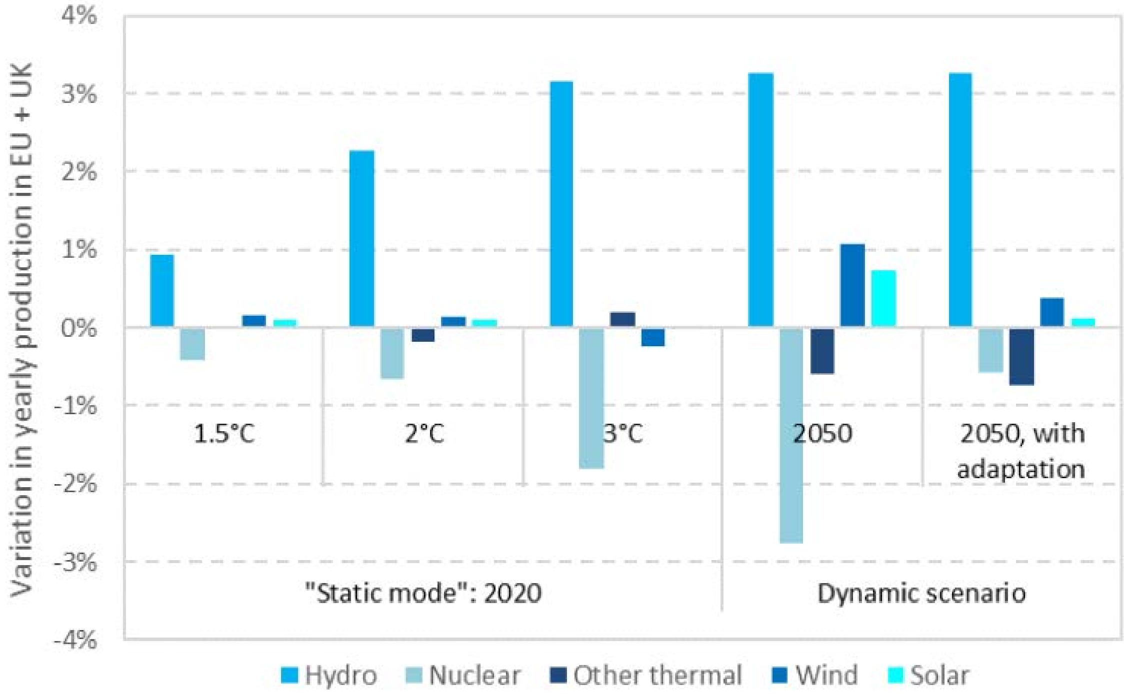
Perera et al. (2020) emphasize that extreme weather events, and thus impacts of CC on peak electricity demand will reach well beyond simple changes in net annual demand and become more critical due to their influence on system design and power supply. These climate-induced extreme weather events and weather variations will affect both energy demand and **energy supply system resilience** and will make CC adaptation difficult. In assessing the role of nuclear power in various CC scenarios, the academic literature is quite unanimous in its analysis: For example, Panteli and Mancarella (2015) point out that changes in precipitation patterns as well as higher frequency and intensity of drought periods will adversely impact water availability for cooling purposes in thermal and nuclear power plants, as well as hydropower generation. Forzieri et al. (2018: 101) investigate potential escalating impacts of climate extremes on critical infrastructures in Europe and conclude: "With the actual damage and degree of change depending on sector-specific vulnerabilities to the different hazards and the rate and magnitude of change in the latter as a result of climate warming … the largest rise in damage for the energy sector relates to energy production − fossil fuel, nuclear, and renewable − as a result of its sensitivity to droughts and heatwaves (e.g. decrease in cooling system efficiency of power plants due to higher water/air temperature). By the end of this century, drought and heat damage in Europe will comprise 67% and 27%, respectively, of all hazard impacts to the energy sector (now 31% and 9%, respectively)."

Kopytko and Perkins (2011: 318) discuss (1) the ability of nuclear power to adapt to CC and (2) the potential for nuclear power operation to hinder CC adaptation. While adapting nuclear power to CC would mean taking especially heat waves, hurricanes, flooding, and sea level rise into account, the authors conclude that it "entails either increased expenses for construction and operation or incurs significant costs to the environment and public health and welfare." The authors identify also some reasons for nuclear power operation to hinder CC adaptation: Be it that the high financial costs necessary for plant commissioning could be used for other provisions, be it that thermal pollution from inland reactors are already altering ecosystems, as they do at coastal areas. Kopytko and Perkins (2011: 332) conclude: "Achieving the desired level of safety and minimizing the impact to climate change adaptation will likely be too expensive at many locations." Schaeffer et al. (2012) review the literature on the topic and come to similar conclusions.

Azzuni and Breyer (2018) define 15 dimensions and related parameters of **energy security** (availability, diversity, cost, technology and efficiency, location, timeframe, resilience, environment, health, culture, literacy, employment, policy, military, and cyber security) in their literature review, and argue that all of these can positively or negatively affect energy security, thus the resilience of energy systems. An ill-balanced energy system is vulnerable on various accounts, which has been shown on many instances during the history of the development of our energy systems. As just one example of many, they describe the security failures of French nuclear power plants during winter 2017, which experienced several short-term shutdowns that led to power supply shortages and imports from neighbouring countries to keep the power system stable; in this case, they see the reason in an ill-balanced diversity of technology in France.

Feyen et al. (2020) emphasize in their report on CC impacts and **adaptation** in Europe that global warming results in an overall increase in hydropower production in the EU and UK, especially in northern regions that rely heavily on hydropower. On the contrary, nuclear power reduces significantly, while other energy sources are only moderately impacted (see the following Figure).

Figure 2 Climate change impacts on power production in Europe



Source: Feyen et al. (2020: 53). Median values of climate ensembles. Impacts of 1.5°C, 2°C and 3°C global warming imposed on today's power system (static scenario), and impacts of 2°C warming on the 2050 power system in line with a 2°C mitigation scenario (dynamic scenario), without and with adaptation of water cooling. Note: "other thermal" designates biomass, coal, gas and oil plants.

When assuming a static 2020 power system, "hydropower production in the EU is expected to increase by 0.9% with 1.5°C global warming (median value) and by 2.3% and 3.2% with 2°C and 3°C warming, respectively. Nuclear production would decrease by 0.5% with 1.5°C warming and by 1.8% in a 3°C warming static scenario. Other thermal, wind and solar plants are barely impacted in the 2020 static study and at EU level" (Feyen et al. 2020: 53).

The dynamic scenario includes changes in the energy mix in line with a 2°C climate mitigation scenario. "When comparing results in 2050, hydropower production increases by 3.3%, pushing out nuclear (-2.8%) and other thermal production (-0.6%), without much adaptation of water cooling technologies. Wind and solar would develop more (+1.1% for wind and +0.7% for solar aggregated over EU + UK), mainly in response to lower hydro and nuclear power production in southern Europe. The evolution of the mix is in itself an adaptation of the energy system to climate change." Thus, the more severe the global warming scenario using current technologies is, the less nuclear power production as a result because existing nuclear power plants require high amounts of water to cool or condense the coolant.

If CC affects the temperature, the quality, or quantity of water, then keeping nuclear power plants under operation becomes more risky (Kopytko and Perkins 2011). More efficient cooling technologies (air-cooling) could offer a way out, but this increases again costs. This poses a constraint for CC adaptation / security of supply and/or keeps a system vulnerable because the electricity production process becomes less efficient, with potential blackouts under a CC scenario, but it also leads us to the following topic on sustainable use of water.

4.2 Sustainable use and protection of water and marine resources (Article 12)

The Taxonomy defines sustainable use and protection of water and marine resources as where that activity either contributes substantially to achieving the good status of bodies of water or to preventing its deterioration.

Thermoelectric production contributed to around 80% of global electricity production (Byers et al. 2014), which directly depend on the availability and temperature of water resources for cooling. Its vulnerability to CC in inland waterways is owed to the combined impacts of lower summer river flows and higher river water temperatures (Van Vliet et al. 2012) and extreme events; coastal plants are threatened by sea-level rise, cyclones and hurricanes (IPCC 2018). When compared with other sectors, thermoelectric power is one of the largest water users in industrialised countries (e.g. US: 40% and Europe: 43% of total surface water withdrawals) with other countries catching up as they develop their industries and standards of living.

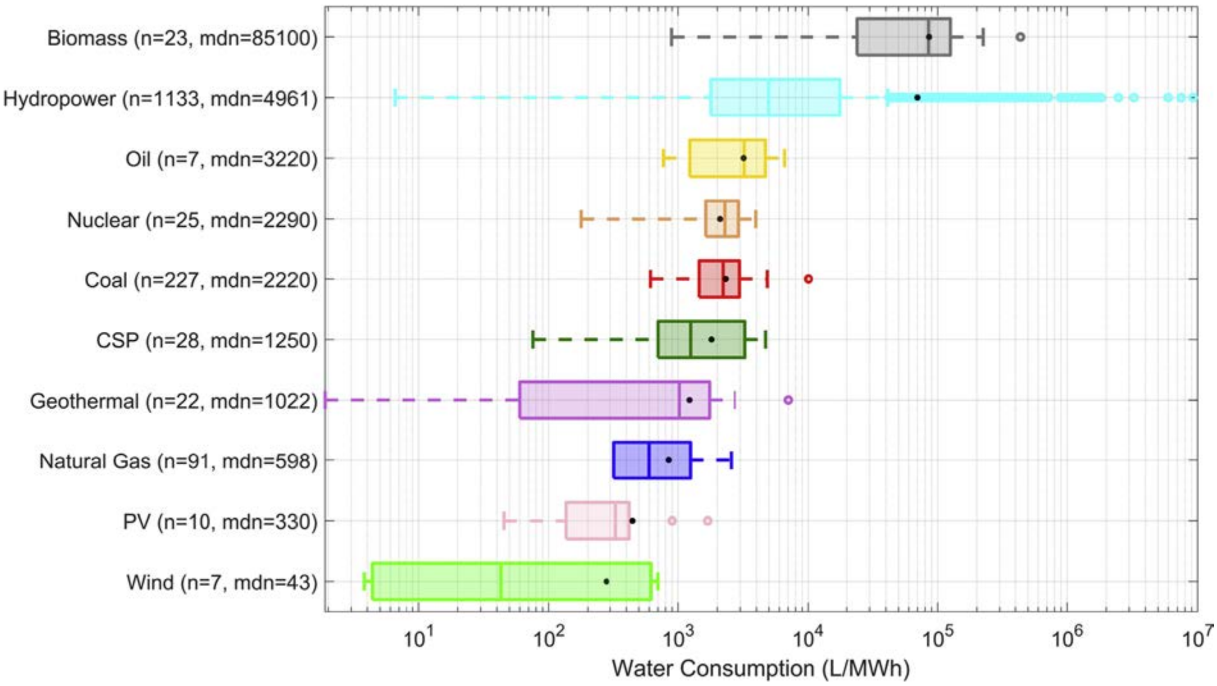
Increased water temperatures and reduced river flow have led to forced reductions or even interruptions in power generation worldwide in recent years (Azzuni and Breyer 2018, Lohrmann et al. 2019, Naumann et al. 2020, Roehrkasten et al. 2015). This limitation to electricity supply, coupled with rising production costs, may also lead to a higher volatility in the electricity market with sharp rises in electricity prices during dry spells and endangered energy security (van Vliet et al. 2012, Lohrmann et al. 2019). Current nuclear power generation requires larger quantities of water for cooling which can lead to water stress and the resulting cooling effluents can cause thermal pollution in rivers and oceans (Webster et al. 2013, Fricko et al. 2016, Raptis et al. 2016, Jin et al. 2019). Also the IPCC (2018 ch.5: 464-465) come on the basis for their literature review to the same conclusion, whereby they stress the effects of water stress being relevant for several energy sources like bioenergy, centralized solar power, nuclear and hydropower technologies. Interestingly, they do not differentiate between the impact of energy production on the quality and quantity of water supply and/or the impact of water stress (due to CC or thermal/environmental pollution) on energy production, which would open up a more differentiated discussion. For example, a nuclear power plant emits thermal pollution and low-level radioactive metals and acids into the wastewater (Brugge and Buchner 2011). On the other hand, nuclear plants need to be switched off, if water levels drop below a certain threshold. Bartos and Chester (2015) estimate for vulnerable power stations in the Western United States that CC may reduce average summertime generating capacity by 1.1 - 3.0%, with reductions of up to 7.2 - 8.8% under a ten-year drought, which become more frequent and are not accounted for in development plans. For Europe, Feyen et al. (2020: 5) point out that the burden of climate change shows a clear north-south divide, with southern regions in Europe much more affected through the impacts of extreme heat, water scarcity, drought, forest fires and agriculture losses.

Mouratiadou et al. (2018) find in their analysis on the basis of five integrated models that electricity sector decarbonisation results in co-benefits for water resources, which are primarily due to the phase-out of water-intensive coal-based thermoelectric power generation and replace them with very low water consuming technologies like wind power and solar PV systems. But they also emphasize that further expansion of nuclear may result in increased pressures on the water environment on a general level. More concretely, Behrens et al. (2017: 2) report in their analysis of electricity generation and water stress in the European Union that water basins located mainly in the Mediterranean countries with several others in Bulgaria, France and Germany exhibited very high withdrawals during the year

2014. They identified coal and nuclear generation explaining the high vulnerability especially in Bulgaria and France because these plants have high water demands for cooling. Roehrkasten et al. (2015) also point out that potential water constraints are often not properly incorporated in energy decision-making and propose that the energy sector's charges for its water use should reflect the actual costs and scarcities to indicate the correct 'market signals'.

As Jin et al. (2019) rightly point out, rising water stress is of increasing concern to both renewable and non-renewable power production, and lacking standardisation of measurement (mostly purely volume-based, sometimes regionalized impact indicators included) and different system boundaries taken in studies reveal variable results in the literature. The following figure pictures a comparison of different electricity generation types based on the volume of water use in logarithmic scale so that data points over a wide range of values can be pictured in a compact way. One needs to keep in mind, though, that the deployment of power plants, cooling water sources, and in the case of nuclear also the type of mining activities and enrichment (in-situ leaching, surface mines, and underground mines) result in considerable differences to the blue water use of power production.

Figure 3 Blue water consumption (use of surface or groundwater) over the life cycle across energy generation types



Source: Jin et al. (2019). Water consumption is visualized on a log scale. n = number of studies, mdn = median value of water consumption for each fuel type. The lower and upper bounds of the boxes represent the 1st and 3rd quartiles, respectively, and the line within is the median. Whiskers show the minimum and maximum range, excluding outliers. Circles represent the outliers, while the dots represent the average for each power type.

Blue water consumption of nuclear power production is similar to coal and somewhat below oil, in the lower upper half in comparison with other technologies. Because water consumption is not only influenced by the final demand by households, Wang et al. (2019: 104453) make a plea for proper planning because generation and cooling technologies "greatly influence the water consumption and withdrawal for electricity generation" and are heavily influenced through spatial disparities of local water resources and electricity generation. Further, electricity generation interplays with final consumption, where large potentials for increasing technological as well as behavioural energy efficiencies can still be found.

In summary, nuclear power is above-average in terms of blue water consumption, which it needs in concentrated quantities and below a certain temperature threshold for cooling. This makes it vulnerable to climate change scenarios. Increased water temperatures and reduced river flows have led to forced reductions or even interruptions in power generation worldwide in recent years, leading to higher costs and vulnerabilities. This is why new cooling technologies are explored, but which come at somewhat higher costs.

4.3 Transition to a circular economy (Article 13)

The Taxonomy defines 'circular economy' as an economic system whereby the value of products, materials and other resources in the economy is maintained for as long as possible, enhancing their efficient use in production and consumption, thereby reducing the environmental impact of their use, prevents or reduces waste generation and of hazardous substances at all stages of their life cycle, including through the application of the waste hierarchy (waste prevention, re-use and recycling).

Implementing a circular economy necessitates measures on the supply side (energy generation) and on the demand side (energy consumption) whereby the definition above only addresses the supply side. In the case of nuclear electricity production and its life-cycle considerations, the main issues are the following.

Longevity of materials used, reduction of environmental impact of their use, prevention or reduction of waste generation and of hazardous substances addresses several dimensions of nuclear electricity generation also elsewhere discussed in this report: The whole life-cycle of the power plant construction, maintenance and decommissioning, the cradle-to-grave perspective used including the mining of nuclear material and its use and disposal.

Uranium is the most important resource for nuclear power generation. According to NEA and IAEA (2016), there are 5.7 million tonnes of uranium in known reserves (almost all of it outside the EU).[2] Under the current exploitation rate between 55,000 and 65,000 tonnes/year[3], the uranium resources would be sufficient for around 90-100 years of nuclear electricity production (Carvalho 2017, Prăvălie and Bandoc 2018), though it will become more resource intensive and more expensive to mine when the uranium sources become less productive because high grade minerals will become less available and the industry will have to focus on lower grade ores (Mudd 2014). Although the industry does currently not see this as a viral shortage, it needs to be accounted for in strategic decision making. In the case of potentially increased use of uranium, the timespan of available uranium would reduce accordingly, even if in the case of increased weapon disarmament further secondary nuclear material would become available as a resource for electricity production (which would extend the timespan again for some time). This is one reason why the industry explores thorium as a potential alternate source of nuclear fuel.

[2] Additionally, around 13% of the current worldwide demand is covered by disarmament programmes (Megatonns to Megawatts).

[3] See: Uranium production overview by the International Atomic Energy Agency (accessed: 12.6.2020)

Negative impacts from upstream uranium mining and milling are “comparable to those of coal, hence replacing fossil fuel combustion by nuclear power would be neutral in that aspect” (IPCC 2018, ch.5: 485).

Prăvălie and Bandoc (2018: 88) compiled some quantitative estimates from the literature on the still unsolved radiant waste issue. The generation rate of high-level waste (HLW) was estimated at around ~12.000 tons/year (Gerstner 2009); considering that each reactor (of the then 448 operational worldwide, of which 143 in the EU)[4] produces about 25-30 tons HLW annually (IAEA 2009, Rosa et al. 2010), this translates to an estimate of over 250.000 tons of HLW by now that need safe permanent disposal worldwide, whose radioactivity levels can remain high for centuries to come. The global political and scientific consensus on the most viable long-term management of highly radioactive waste is storage in deep geological repositories (NEA 2010). “The procedure entails storing HLW at a depth of at least several hundred meters and isolating the waste with anthropogenic (e.g. especially-designed containers) and natural (e.g. underground locations with extremely low permeability surrounding rocks, in tectonically-stable areas) barriers, in order to minimize the risk of radionuclide release into the environment” (Prăvălie and Bandoc 2018: 88). There is currently only one site under construction worldwide, which is in Finland. Getting local communities to accept a geological repository for nuclear waste in their neighbourhood certainly remains a challenge, which entails in most (democratic) countries longstanding participatory processes with stakeholders with an uncertain outcome.[5] Other countries have not chosen any sites for a repository yet.

Concerning waste prevention, re-use, and recycling, nuclear power does currently not quite fit under a circular economy paradigm. Each step in nuclear power production, from uranium mining to radioactive waste disposal (with reprocessing sometimes included – in France and UK), leads to radioactive and chemical emissions and waste. Although extending the lifetime of power plants is a common practice (unless a country decides to exit the nuclear option) and the reprocessing of spent nuclear fuel is partly feasible. Either spent fuel is disposed in a waste repository, or reusable components are separated out for recycling, with the residual waste being disposed. Because of technical challenges and cost reasons (part-recycling is more expensive than direct disposal until uranium prices grow severalfold - Ramana 2009), the amount of spent fuel is interim-stored rather than disposed of or reprocessed and recycled. “Simple estimates suggest that, if nothing else is done, there could be over a million tonnes of spent fuel in interim storage worldwide by 2100 (Taylor 2015: xxi). This is why several nuclear companies want to make the nuclear fuel cycle more efficient by introducing Generation IV fast reactor systems aiming at the middle of the century for deployment, which could enhance the product-lifecycle efficiency. But even if more efficient fuel cycles will materialise by then, it will require a disposal facility for high-level wastes from reprocessing (Taylor 2015: xxii).

Under the heading of a circular economy, we also need to mention the legacy of contaminated sites from uranium mining, where tailings and acid mine drainage are “sources of radioactive contaminants enhancing environmental radioactivity in water, soils, and agriculture products (IAEA 2005, Merkel &

[4] Nuclear energy now provides about 10% of the world's electricity from about 440 power reactors, of which there were 126 nuclear power reactors left in operation in 14 EU member states in 2019 (IEA 2020; World Nuclear Assocation (accessed: 12.6.2020)).

[5] This is why countries with lower levels of democratic development are now more likely to introduce additional nuclear power (Neumann et al. 2020).

Arab 2015, Carvalho et al. 2014, 2016, all cited in Carvalho 2017: 69). Former uranium sites in Europe and the U.S. (e.g. Wismut in DE, Straz pod Raskem in CZ) went through costly clean up and remediation measures, paid by the public, which included relocations of waste, "coverage of solid waste, and treatment of radioactive water and even replacement of water supplies in contaminated areas with noncontaminated water brought from elsewhere" to lessen the impacts from uranium leaching into the groundwater. It is still unclear, how and when these sites can be used for different purposes. Chapter 5 in this report mentions thousands abandoned and contaminated sites elsewhere on the globe, which were treated less after the closure of the mines.

4.4 Pollution prevention and control (Article 14)

A substantial contribution to pollution prevention and control requires according to Article 14 (a) preventing / reducing pollutant emissions into air, water or land, other than greenhouse gases, (b) improving levels of air, water or soil quality whilst minimising any adverse impact on human health and the environment or the risk thereof, (c) preventing or minimising any adverse impact on human health and the environment of the production, use or disposal of chemicals; (d) cleaning-up litter and other pollution, or (e) enabling the above.

Recent studies have significantly advanced our understanding of species-level radiation effects for a limited range of test organisms. But in general, the interpretation of **studies on effects of radiation on the environment** or wildlife have been an area of scientific disagreement (e.g. Beresford et al. 2016, 2019a; Chesser & Baker 2006; Mousseau & Møller 2009, 2011; Smith 2019, all cited by Beresford et al. 2019). While some studies conducted into the effects of the Chernobyl and Fukushima accidents report significant impacts of radiation on wildlife even at low-dose rates, others could not find substantial effects of excess radiation on wildlife in the Chernobyl Exclusion Zone. There are quite many factors given as possible reasons for this disagreement, which are mainly methodological in nature. Also Lecomte-Pradines et al. (2020) confirm the above findings by and large and develop 15 recommendations for improving the methodology for future field studies. See also the following chapter 3.5 in this report concerning potential effects on biodiversity and ecosystems.

Uranium mining can contaminate air, water, and soil (Brugge and Buchner 2011) by generating considerable waste material (tailings and rock) and process water, which contains low-level radioactivity, metals, and acids. Historically, most epidemiology on uranium mining has focused on mine workers and radon exposure. Although that situation is still overwhelmingly prevailing, a smaller emerging literature has begun to form around environmental exposure in residential areas near uranium mining and processing facilities. See also the IPCC (2018, ch.5: 500) and the literature cited there.

Relating to consequences of radiation on **human health**, the literature puts most attention on health consequences of radiation following (a) constant low-dose radiation on people working in, or living close to mines, plants, or waste disposal sites, as well as (b) high-dose radiation impacts following accidents. In the context of radiation and health effects, the academic literature mostly investigate possible effects like cancer and leukaemia, non-cancer diseases and genetic effects and teratogenic effects like congenital malformations.

While it is clear that ionizing radiation is a potent carcinogen, inducing cancer through DNA damage (Behjati et al. 2016, Volkova et al. 2020), it has traditionally been less clear which level of exposure suffices to trigger cancer over and above the naturally occurring radiation in nature.

From the recent literature on **cancer risks in children**, Mazzei-Abba et al. (2020: R1) concluded, after screening a large body of literature, that the empirical estimation of cancer risks in children associated with **low-dose** ionising radiation (<100 mSv) remains a challenge. The authors see as the main reason "that the required combination of large sample sizes with accurate and comprehensive exposure assessment is difficult to achieve. ... The main challenge is to accurately assess children's individual exposure to radiation from natural sources and from other sources, as well as potentially confounding non-radiation exposures, in such large study populations."

From the recent literature on **cancer risks in nuclear workers**, a multinational cohort study published in Lancet Hematology had a rather large impact on the academic discussion. It suggests "strong evidence of positive associations between protracted **low-dose** radiation exposure and excess leukaemia" in nuclear workers. The relevance of this cohort study is based on the large sample of more than 300,000 nuclear workers included in the analysis, 147,000 from the UK – the remaining from the US and France (Leuraud et al., 2015: e276). At the same time, the study team (Richardson et al. 2015: h5359) suggested a linear increase in the relative rate of cancer with increasing exposure to radiation. These results have been backed up by some complementary research published since: e.g. Grellier et al. (2017) show 'strong evidence' for associations between low doses from alpha-emitters and lung cancer risk, Deas et al. (2017: 167) also suggest, based on a literature survey, "evidence for increased lung cancer risk in industrial radiation workers, especially those who process plutonium and may inhale radioactive particles." See also Natl. Res. Counc. (2006), Grosche et al. (2006), and Muirhead et al. (2009). But these kinds of studies are also criticised (Scott 2018, Vaiserman et al. 2018, Shibamoto and Nakamura 2018), suggesting that other studies indicate beneficial effects of low doses of radiation, and arguing that epidemiological studies are inherently associated with biases. Shibamoto and Nakamura (2018) propose that controlled laboratory studies may be more appropriate to evaluate the effects of low-dose radiation.

Gillies et al. (2017: 276) tried to confirm past study results for **low-dose** radiation and found that the associations between radiation dose and **non-cancer** mortality are generally consistent with those observed in atomic bomb survivor studies, but potential confounders associated with lifestyle factors could still influence the results.[6] These results are largely in line with an earlier study by Muirhead et al. (2009), who found some evidence of an increasing trend with dose in mortality from all circulatory diseases that may be, at least partly, due to confounding by smoking.

From the recent literature on **cancer risks** primarily of populations exposed to **high-dose** ionizing radiation, a positive association between external radiation dose and cancer (as well as non-cancer mortality) have been found in a number of studies. For instance, Bazyka et al. (2018) found a significant effect on different kinds of cancers in Ukrainian clean-up workers after the Chornobyl accident.

In summary, the academic literature on the impact of ionizing radiation on human health is clear on the negative consequences of high-dose ionizing radiation. Whether low-dose radiation impacts

[6] Confounding means the distortion of the association between the independent and dependent variables because a third variable is independently associated with both.

human health negatively is disputed: the literature seems to disagree on the level of exposure, above which negative consequences would occur, and which the research methodologies applied so far have not been able to clarify. Uranium mining generates significant amounts of waste materials and process water containing low-level radioactive materials, metals and acids (which to a certain extent also applies to other mining activities). The effects of radiation on the environment and wildlife are traditionally regarded as a blind spot in the research landscape, which will be further investigated in the following chapter.

4.5 Protection and restoration of biodiversity and ecosystems (Article 15)

A substantial contribution to the protection and restoration of biodiversity and ecosystems requires, according to Article 15, protecting, conserving or restoring biodiversity or achieving the good condition of ecosystems, or protecting ecosystems that are already in good condition.

Energy production impacts on biodiversity and natural areas mainly through extraction of raw materials, but also by discharge of used water and waste disposal. As always, the framing/focus and system boundaries set for an analysis are important when it comes to developing conclusions. This is also why researchers come to different conclusions on the question whether nuclear power impacts biodiversity and ecosystem functions. For instance, Brook and Bradshaw (2015) frame their study to investigate different energy options to identify the best options using a multicriteria analytic approach covering the whole life-cycle, and conclude that nuclear power is a good option for biodiversity conservation. Though, Diesendorf (2016: 668) ridicules their assumptions and choices on proliferation, land use, life cycle CO_2 emissions, safety, reliability, and cost of electricity supply, which he attributes to omissions and "inherent value judgments, all of which seem to favour nuclear energy".

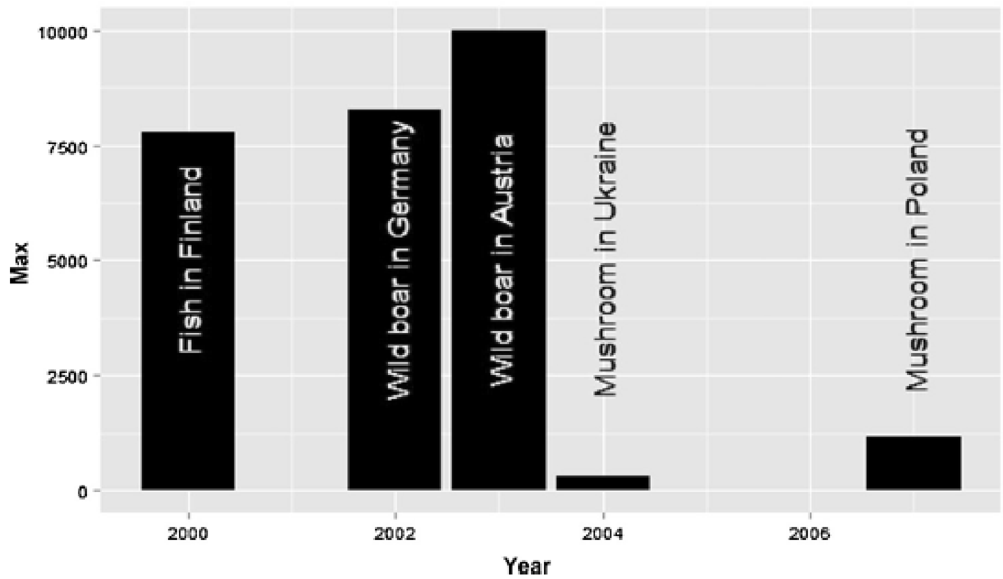
On the other hand, the IPCC (2018, ch.5: 500) concludes on the theme 'Healthy Terrestrial Ecosystems' that (advanced) nuclear options are still riddled with safety and waste concerns from uranium mining and milling, while referring to Bickerstaff et al. (2008), Sjoberg and Sjoberg (2009), Ahearne (2011), Corner et al. (2011), Visschers and Siegrist (2012), and IPCC (2014). From the more recent literature, one can add Lourenço et al. (2017) for the negative effects of uranium mining wastes for freshwater ecosystems, showing this by using the example of fish embryos, and Zhou et al. (2020) for potential negative effects of contamination around an uranium mine for the ecosystem and health of local communities in East China.

As discussed above, the academic discussion on the effects of low-dose radiation is far from being solved. This is one reason why there has been an extensive research programme established following the Fukushima power plant accident, for which the Pale Grass Blue Butterfly was defined as an environmental indicator species for radioactive pollution research. The numerous publications on the topic consistently report genetic modifications following the high-dose exposure, e.g. initial physiological and genetic damage (Hiyama et al. 2012), retention of radioactive caesium in a pupa (Nohara et al. 2014), and transgenerational effects of initial high-dose exposure (Sakauchi et al. 2020).

Wehrden et al. (2012: 81) reviewed 521 studies conducted after the Chernobyl accident. They conclude: "Elevated radiation levels have been recorded among a diversity of species, even up to thousands of kilometres away from the meltdown site, and after more than two decades following the accident. Close to the reactor, physiological and morphological changes have occurred. Negative effects on ecosystem services have been observed, including the contamination of water, soils, and wild food supplies." Beyond that, (p. 85) "near the disaster site, freshwater and associated fish will not be safe for human consumption for multiple decades into the future. Similarly, former agricultural land within the ~2,700 km^2 exclusion zone around the accident site will remain unsuitable for human use in the foreseeable future … Although many ecosystem services have been greatly reduced, especially near the accident site and in the case of provisioning services, some other services seem to have fared more favourably. For example, human depopulation around the Chernobyl site has led to the return of natural vegetation, thereby benefitting some wildlife populations and probably enhancing the regulating service of carbon sequestration (Kuemmerle et al. 2011; Hostert et al. 2011)." In 2020, i.e. 34 years after the accident, the Chernobyl exclusion zone is contaminated in varying degrees, with some hotspot regions, and others where radiation levels are less concerning.[7]

Gralla et al. (2014) analysed peer-reviewed articles related to Chernobyl and Fukushima, which measured increased Cs-137 levels in provisioning ecosystem services. They identified 121 publications that measured Caesium-137 levels in food, fodder and wood.

Figure 4 Examples of long-term radioactive contamination in provisioning ecosystem services more than fifteen years after Chernobyl



Source: Gralla et al. (2014: 5) Examples of maximum radioactivity (Bq/kg) in meat, fish and mushrooms (wet weights) based on samples taken more than fifteen years after Chernobyl.

Many authors (e.g. Bonar et al. 2015; Lovett et al. 2015; Turney and Fthenakis 2011) highlight significant gaps in understanding of interactions between energy systems and ecosystem services on a broader scale. Holland et al. (2016: 183) identify Papathanasopoulou et al. (2015) to be one of the few examples "where a consistent approach has been used to compare multiple ecosystem service impacts across different energy systems." Four main supply options (biomass, natural gas, nuclear and wind) were evaluated. Papathanasopoulou et al. (2015: 918) investigated the impact of different energy systems on marine ecosystem services and concluded that "the nuclear sector has predominantly negative impact on cultural ecosystem services, which entails offshore discharges in the uptake of radionuclides by marine biotic and abiotic components, increased water temperature

[7] See: Chernobyl: The end of a three-decade experiment, 14 February 2019 (accessed: 12.6.2020)

around nuclear offshore discharge tunnels and its effect on ecosystem functioning and changes in water quality and community structures.”

Thus, although the nexus between nuclear power provision and biodiversity and ecosystems is still somewhat underresearched, more recent results point towards negative effects of uranium mining (wastes), especially for freshwater ecosystems but also marine ecosystem services.

5 Criterion 3: Compliance with the minimum social standards laid down in Article 18

The minimum safeguards referred to in Article 18 shall (again along the principle of ‘do no significant harm’) be aligned with the OECD Guidelines for Multinational Enterprises and the UN Guiding Principles on Business and Human Rights, including the principles and rights set out in the eight fundamental conventions identified in the Declaration of the International Labour Organisation on Fundamental Principles and Rights at Work and the International Bill of Human Rights.

The OECD Guidelines for Multinational Enterprises and UN Guiding Principles on Business and Human Rights

The OECD Guidelines for MNE (2011), which incorporate the UN Guiding Principles (2011) are recommendations addressed by governments to multinational enterprises. The Guidelines aim to ensure that the operations of these enterprises are in harmony with government policies, to strengthen the basis of mutual confidence between enterprises and the societies in which they operate. The Guidelines cover the notions of human rights, disclosure, employment and industrial relations (training, health, safety), environment, combating bribery, consumer interests, science and technology, competition and taxation.

The International Labour Organisation’s (‘ILO’) Declaration on Fundamental Principles and Rights at Work

The ILO Declaration on Fundamental Principles and Rights at Work (1998) is all about ensuring equity, social progress and the eradication of poverty. This is followed up by, e.g., the right to collective bargaining, the elimination of compulsory labour, the abolition of child labour, and the elimination of discrimination in respect of employment and occupation.

The eight ILO Core Conventions

The fundamental conventions of the ILO define human and labour rights that undertakings should respect. Several of those international standards are enshrined in the Charter of Fundamental Rights of the European Union, in particular the prohibition of slavery and forced labour and the principle of non-discrimination. Those minimum safeguards are without prejudice to the application of more stringent requirements related to the environment, health, safety and social sustainability set out in Union law, where applicable.

The ILO core conventions (1998) cover subjects that are considered to be fundamental principles and rights at work which cover in its essence the freedom of association and the effective recognition of the right to collective bargaining; the elimination of all forms of forced or compulsory labour; the effective abolition of child labour; and the elimination of discrimination in respect of employment and occupation.

The International Bill of Human Rights

The International Bill of Human Rights consists of the Universal Declaration of Human Rights (adopted in 1948 by the UN General Assembly, which sets forth standards of human rights) and the International Covenant on Civil and Political Rights (1966, which defines specific rights and their limitations). The covenant commits its parties to respect the civil and political rights of individuals, including the right to life, freedom of religion, freedom of speech, freedom of assembly, electoral rights and rights to due process and a fair trial.

Overall assessment for compliance to minimum social standards

The compliance of nuclear power production with the criteria set forth in the above guidelines, declarations, conventions, and bills cover a broad spectrum, which received very heterogeneous attention in the academic literature. This is also why we can cover only a restricted part of the spectrum in this literature review.

For instance, according to the General Policies of the OECD Guidelines for MNE (2011: 19-20), possible conflicts (and perhaps more likely than for other criteria) could arise from the (a) human right to access water in the needed quality and quantity, (b) health and environmental issues arising from the exposure to radiation (on local communities or global in case of accidents) and its disclosure, and again (b) health and environmental issues arising from mining and milling, plant operation, or waste disposal on local communities.

The human right to access to clean water is certainly an issue in mining regions. For instance, Wang et al. (2012) report on highly elevated concentrations of radionuclides and metals in the discharged effluents of extensive mining/milling of uranium in the northern region of Guangdong Province, China, and (2016) on elevated natural radioactivity and assessment of dose to workers around a granitic uranium deposit area.

Potential environmental and health effects of low-dose as well as high-dose radiation (following accidents) are already reviewed in the chapters 3.4 and 3.5 of this report, which is not repeated here.

Sarkar (2019) points at the less stringent regulatory frameworks and poorly enforced labour laws in Asian and African uranium mines, resulting in low operating costs. The author also stresses 'ample evidence' of the industry transgressing environmental regulations as well as unethical practices that pose serious threats to public health (e.g. Postar 2017 and Hecht 2012 for sub-Saharan Africa). Graetz (2014) points at safety and health issues in uranium mines and human rights abuses towards indigenous communities in different parts of the globe (esp. Australia, Canada, the United States and several African states) which have been an issue in the history of uranium mining, which results now in opposition to further exploitation of uranium reserves. Malin & Alexis-Martin (2020: 513) describe in their introduction to a special issue on uranium research that "historical operations such as mines and mills have left thousands of abandoned and contaminated sites, many on public lands and Indigenous lands … even as many mines are now privately owned by multi-national corporations (MNCs). These large non-state organizations often 'race to the bottom' when locating their operations, use regulatory arbitrage to geographically circumvent industrially unfavorable legislation that would offer better protections to mine workers, communities, and ecosystems ... This has profound consequences to environmental and public health policy pertaining to uranium, particularly for less economically developed states (LEDCs), where economics may be prioritised over matters of environmental health, culture, society, and state. … The enormous impacts to Indigenous peoples have been considered in a variety of contexts, including: in Aboriginal Australian communities (Banerjee 2000) and postcolonial contexts of extractive land uses; in India's West Khasi Hills (Karlsson 2009), where uranium deposits have been found near Indigenous and Tribal lands; and in the U.S., where multitudes of Tribal, Pueblo, and other Indigenous communities continue to live with the legacies of uranium contamination – and with contemporary threats of renewed development (Brugge et al. 2007, Pasternak 2010, Malin 2015). The Navajo Nation alone has over 500 abandoned uranium mines (Kapoor 2018, Malin 2018)."

It is basically possible to extract and produce uranium applying occupational safety standards that ensure radiation protection of workers and environment (IAEA, 2014), although the reality of weak public institutions in numerous countries results in not enforcing these standards. "The current big challenge to uranium mining companies is to organize mining and milling in a way that the radiation safety and environmental protection, including after mine remediation, are included in the commodity prices, and to avoid contaminated legacy sites" (Carvalho 2017: 70).

In summarizing, uranium mining and milling has been struggling with human rights and safety issues throughout its history in different parts of the globe, as nearly all uranium is now mined outside the EU. This concerns workers in the mines as well as the human right to access to resources, e.g. clean water and used land, which might impact neighbouring communities.

6 Transition and enabling activities by avoiding lock-ins (Article 10 (2) and Article 16)

According to Article 10 (2), activities that are incompatible with climate neutrality but considered <u>necessary in the transition</u> to a climate-neutral economy are labelled transition activities. In order to be acceptable, they

(a) must have greenhouse gas emission levels corresponding to the best performance in the sector ('best-in-class approach'),
(b) may not hamper the development and deployment of low-carbon alternatives, and
(c) may not lead to a lock-in of carbon-intensive assets, considering the economic lifetime of those assets.

According to Article 16, an economic activity can also qualify as contributing substantially to one or more of the environmental objectives set out in Article 9 by <u>directly enabling other activities</u> to make a substantial contribution to one or more of those objectives, provided that such economic activity

1. does not lead to a lock-in of assets that undermine long-term environmental goals, considering the economic lifetime of those assets, and
2. has a substantial positive environmental impact, on the basis of life-cycle considerations.

According to the IEA (2020: 43) "solid fossil fuels, such as coal or lignite, are excluded, but gas and nuclear energy could potentially be labelled as an enabling or transitional activity".[8]

According to the results reported in chapter 2.1., the group of best-performers in the sector concerning low-GHG emissions are solar power, geothermal energy, hydropower, ocean energy, and wind energy, followed with a gap by photovoltaics, nuclear power and bioenergy. Thus, nuclear power does not quite belong to the best performers in the sector concerning greenhouse gas emissions.

A connection between nuclear power and an enabling role for another well-performing technology is mainly associated in the literature with large-scale clean hydrogen production, which is then linked with nuclear power as the main energy source (e.g. Yildiz & Kazimi 2006, Orhan et al. 2012, El-Emam & Özcan 2019). Because of the energy intensity of the hydrogen production process, the energy source used becomes the main factor to influence its potential environmental benefits, even on the basis of life-cycle considerations. Thus, it very much depends on how the environmental impacts of nuclear power are judged.

A transitional or bridging role for other essential contributions would be viable if the energy system as a whole could not be transformed to a sustainable path without nuclear power. The argumentation in the academic literature has evolved to the effect that, based on detailed simulations (e.g. Jacobson 2011, Aghahosseini et al. 2020) and recent practical experience (e.g. early shutdown of the last coal-fired power plants in Sweden and Austria, continuous addition of renewable resources to the grid in other countries), bridging technologies are not necessary.[9] Other simulation studies for the EU (e.g. Capros et al. 2019: 110960) also show that nuclear energy is "below the 2015 level in most decarbonisation scenarios".

Lock-in describes the phenomenon that it is difficult to set a technical and political system on a new path once it has developed a momentum of its own and once it is "locked in" on a certain path. Several different lock-ins may be relevant, in terms of long-term environmental objectives and technological and economic lock-ins, the latter two being inextricably linked.

Economic and technology lock-in: Because of the very high initial set-up costs of nuclear power plants, the amortisation of these initial costs is only 'viable' if the plants have a long lifespan. This is the reason, why it is rather common to expand the lifetime of old nuclear plants beyond the planned life, but these need to be replaced every 50 years on average. Nuclear power plants take around 6-12 years to build, and then around 20-50 years to decommission (Abbott 2011), and the land being set-aside afterwards for a considerable period, not ready for other uses; plus the radiant waste issue mentioned elsewhere in this report, locking-in future taxpayers in safety and security and clean-up costs. Economic and technology lock-in becomes also relevant, when social acceptance of nuclear power production plummets after accidents, as we can see with opting-out countries like Germany, Switzerland, Belgium, Sweden, and Spain after the Fukushima accident, and which has also been documented in multiple studies (e.g. Tsujikawa et al. 2016, Visschers & Siegrist 2013, Sun et al. 2016).

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[8] See: European Parliament press release on the adoption of criteria for sustainable investment (accessed on 18.6.2020)

[9] See: CNBC report: Austria's last coal-fired power station closes as the country pushes renewables; EURACTIV report: Sweden adds name to growing list of coal-free states in Europe (accessed on 10.6.2020)

Abbott (2011) concluded that nuclear power is not scalable and that investments should instead be redirected to truly scalable technologies in support of a sustainable energy transition. Technology and market lock-ins can result from subsidized technologies with long lifetimes, where the argument of heavy subsidies for nuclear energy in the past is provided on several accounts (e.g. Alberici et al. 2014). If other technologies become more cost-efficient during the lifetime of a power plant, the market remains distorted for a considerable duration.

Environmental lock-in: Environmental lock-in refers to the self-perpetuating inertia created by nature-consuming energy systems that inhibits public and private efforts to introduce alternative energy technologies. In relation to nuclear power, numerous environmental lock-ins may exist. The first is finding suitable locations for nuclear power plants, which is a difficult exercise, because a suitable location requires low human population density, the exclusion of natural disaster zones, and access to massive bodies of water (Abbott 2011).

After 40-50 years of development, the issue of high-level nuclear waste storage, with its very long-term consequences, is still heavily under discussion, mainly because of uncertainties due to unforeseen geological movements and radioactive leakage into groundwater. High-cost options are under consideration occasionally and under implementation in one case in Finland. Further, uranium mine remediation is still an unresolved topic, with thousands of banned uranium mines left in the various parts of the globe, now often owned by the energy companies formerly exploiting it or left on Indigenous land, which cannot be used for other purposes for a long time-span (CoRWM 2006, Kapoor 2018, Malin & Alexis-Martin 2020).

7 Cross-cutting issues

7.1 Best-available technology

The International Energy Agency (IEA 2020: 4) underscores that "electricity security needs to be at the heart of the EU's efforts, as the speed of clean energy transitions, extreme weather events and cyber security threats add potential strains on the power system." Here, new technology plays a significant role, whereby cyber security threats are of particular importance, be it through coordination of electricity networks, or be it through securing energy production, thus also nuclear plants, from intrusion. The current and future prospect of nuclear power is discussed in the literature in rather contradictory ways. Some of the more common arguments are formulated as follows:

- Light water-cooled reactors fuelled with 3-4% enriched uranium have been in operation since the 1980's, many having reached a full, 40 year operational life.
- During these decades of experience, a number of safety advances have been made. Most notably, after the core melting accident at Three Mile Island in 1979, extensive retrofits were implemented on pressurised water reactors (PWR), leading to considerable operational and safety improvements.
- Safety of nuclear systems and their components has been important from the outset. Though, unexpected problems are occasionally discovered after years of operation. "One such problem was the discovery of serious corrosion in certain important reactor components, which

resulted in the establishment of regulatory requirements for replacement of the respective parts" (Knapp & Pevec 2018: 96).

- Unlike nuclear fusion, improved nuclear fission is ready for implementation. Proponents expect pronounced effects from standardisation of design in a large-scale nuclear programme putting the primary importance on carbon emission reduction and cost reductions rather than on the introduction of innovative reactor types (e.g. Knapp & Pevec 2018). That is why these authors do not recommend a major introduction of Generation IV nuclear technologies anytime soon because of its inherent challenges (Generation IV reactors aim to develop nuclear fission energy by increasing nuclear fuel efficiency and reducing high-level waste generation).
- One of the more tangible current developments seem to be small modular reactors, which can be made in factories and transported to sites although it is uncertain when this would be available and whether it would make sense from the economic viewpoint.
- Improved cooling technologies have the potential to reduce the negative effects of water scarcity due to climate change, particularly for nuclear plants in southern Europe (Feyen et al. 2020). An important aim is to reduce freshwater consumption, for instance by use of hybrid cooling (Byers et al. 2014), which increases the security of supply with the downside of higher costs. Zhang et al. (2018) show that freshwater withdrawal has been decoupled from thermoelectric power generation growth in China due to the increased adoption of air-cooling and seawater-cooling technologies and advanced large generating units as well as water use efficiency improvements in this period.
- Especially dry cooling technology for thermoelectric power plants aims to improve the resilience of nuclear plants to climate change, because of reduced water availability during dry spells. The downside is that this pushes up the costs of nuclear power provision (and potentially increases climate change relevant emissions), as do other factors influencing the lifespan of nuclear power (at the stages of mining and milling as well as radioactive waste reduction and disposal).
- Breeder reactors are technically immature (with a technology readiness level between 3 and 5 on the nine-tier scale - depending on the design), more costly than light-water reactors, unreliable, potentially unsafe and they pose serious proliferation risks (Brown et al. 2018).
- A new hybrid or integrated nuclear-renewable energy system is promoted by some authors (Suman 2018), where nuclear technology would deliver the base-load and renewable energy the remaining energy demand.
- In the long run, Knapp & Pevec (2018) expect that fuel resources can be covered through the use of the alternatives U238 / Th232, offering very high amounts of energy that would satisfy demand for several centuries. Banerjee & Gupta (2019: 1607) basically support this viewpoint, but also see that "challenging technological tasks such as remote fabrication of U233-based fuel and industrial scale reprocessing of the corresponding spent fuel need to be addressed for operating a sustainable Th-U233 fuel cycle". Others like Uribe (2018) are somewhat less optimistic and point at other, unique, safeguard risks including proliferation risk. In addition to the proliferation risk the Th232 decay chain includes hard beta emitters (Tl and Bi). Also the tritium (H3) production in the reactor is higher. Both causes potential harm to the environment and pose technical challenges (Dodd & van Hienen 1995).
- For the second half of this century, Knapp & Pevec (2018) expect inherently safe molten salt thorium reactors to compete with fusion reactors, but which would even in case of its realisation come late under the current climate change scenario.

Nuclear fusion is expected by optimists to reach maturity at around the middle of the century (Herrera-Velázquez 2007, Pacchioni 2019), though this is very much questioned by the majority of experts. No fusion plant exists today that can generate more energy than it requires to initiate and sustain fusion. Containment materials that can withstand the neutron bombardment without generating long-lived nuclear waste are still under development. Even advocates of fusion do not expect the first commercial plant to go online before 2050. Even if it proves to be technologically feasible and cost-effective (which is not clear at this point), ramping up to a high worldwide penetration will take decades more. That is judged to be too late to tackle global warming (Brown et al. 2018).

Beyond the technology, governance aspects are relevant. The IPCC (2018, ch.4: 315) concluded that the political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically in recent years, while nuclear energy and carbon capture and storage in the electricity sector have not seen similar improvements. "However, because accidents affect worldwide public acceptance of this industry, questions have been raised about the risk of economic and political pressures weakening the safety of the plants (Finon 2013, Budnitz 2016). This raises the issue of international governance of civil nuclear risks and reinforced international cooperation involving governments, companies and engineering (Walker & Lönnroth 1983, Thomas 1988, Finon 2013), based on the experience of the International Atomic Energy Agency."

7.2 Intergenerational risks

Jacobson (2019) distinguishes two categories of risk that are relevant for current and future generations: (1) risks affecting its ability to reduce **climate change and air pollution** (incl. delays between planning and operation, emissions contributing to global warming and air pollution, and costs); and (2) risks affecting its ability to provide energy and environmental (aside from climate and air pollution) **security** (incl. weapons proliferation risk, severe accidents, radioactive waste risk, and mining cancer and land despoilment risks).

In Chapters 2 and 3 we discussed climate change and other sustainability issues pertaining to the use of nuclear power. They are often framed as problems of intergenerational well-being. The case for climate change mitigation and long-term environmental policy is therefore dependent on how the well-being of today's generation is weighed against that of future generations. This makes it a question of moral stance, application of pertinent or no discount rates and may be a stimulus for debt-funded green public investment (Sachs 2015).

One of the greatest risk of nuclear power in the context of energy and environmental security is the **risk of arms proliferation**. The growth of nuclear power has historically increased the ability of nations to obtain or harvest plutonium or enrich uranium to manufacture nuclear weapons. Uranium and Thorium can be used to produce nuclear fuel in a breeder reactor. The presence of nuclear power creates an infrastructure where materials and expertise for weapon making can proliferate. Different types of reactors have different levels of proliferation resistance, but no matter how they are badged the fact is that all nuclear fuels and all nuclear products can be utilized in a dirty bomb, if not a nuclear bomb (Abbott 2011). "Peaceful nuclear cooperation and nuclear weapons are related in two key respects. First, all technology and materials related to a nuclear weapons program have legitimate civilian applications. For example, uranium enrichment and plutonium reprocessing facilities are dual use in nature because they can be used to produce fuel for power reactors or fissile material for nuclear weapons. Second, civilian nuclear cooperation builds-up a knowledge-base in nuclear matters" (Fuhrmann 2009: 12).

The IPCC recognizes this fact. The building of a nuclear reactor for energy production in a country that does not currently have a reactor increases the risk of nuclear weapons development in that country. Specifically, it allows the country to import uranium for use in the nuclear power facility. If the country so chooses, it can secretly enrich the uranium to create weapons grade uranium as well as harvest plutonium from used fuel rods for nuclear weapons. This does not mean any or every country will do this, but historically some have, and the risk is high. The IPCC concludes, with "robust evidence and high agreement" that nuclear weapons proliferation concern is a barrier and risk to the increasing development of nuclear power: "Barriers to and risks associated with an increasing use of nuclear energy include **operational risks** and the associated safety concerns, **uranium mining risks**, financial and regulatory risks, **unresolved waste management issues, nuclear weapons proliferation concerns**, and adverse public opinion" (Bruckner et al. 2014: 517).

The IPCC (2018, ch.5: 485) also notes that „a non-negligible risk for **accidents** in nuclear power plants and waste treatment facilities remains. The **long-term storage of nuclear waste** is a politically fraught subject." CoRWM (2006) systematically reviewed the options for radioactive waste disposal and concluded that while none of the options are ideal, geological disposal would the best available long-term solution and that interim storage is needed in the meantime. But only one serious effort has been made so far in Finland (see above). The more, researchers suggested recently that the "proposed nuclear waste storage materials may have a corrosion problem", increasing the chance of the radioactive waste leaking into the environment (Guo et al. 2020). Beyond the technical considerations, radioactive waste is an ethical issue for several reasons. It is associated with nuclear power, nuclear weapons, and the dangers of proliferation and terrorism, all of which raise ethical concerns. Radioactivity impacts unevenly between places and across generations and raises **ethical issues of fairness**. It is also an ethical issue because its longevity and complexity place it in the realm of both science and values. In making option assessments it is necessary to combine both empirical and ethical knowledge, facts, and values.

7.3 Economics of nuclear power

Some view nuclear as a key technology to address climate change, while others see an industry in decline. From an economic perspective, the inability to reduce costs and address concerns about public acceptance, safety, nuclear waste and proliferation is problematic. Operating capacity has stagnated for more than two decades (Markard et al. 2020).

Almost three decades ago, increasingly **stringent environmental regulations** for generators meant greater capital and operational costs for environmental protection activities (MacKerron 1992). More complex licensing and growing safety concerns drove the decline (Müller & Thurner 2017, Markard et al. 2020).

Energy market liberalization in the 1990s aggravated the situation for nuclear power (Jamasb & Pollitt 2005). In liberalized markets investments are profit motivated, with the choice of technology left to the market. For several reasons, the risks associated with nuclear generation make it unattractive for an investor, even when its levelized costs are similar to the levelized costs of the dominant technology.

(1) Nuclear's **long lead times** (5 years in the most optimistic scenario, 10-19 years observed) run **counter investors preference for a shorter payback period**.

(2) The large size of a typical nuclear unit and the associated **high-required minimum upfront capital** investment reduce the number of potential investors. IPCC (2018) also pointed out that the **costs of nuclear power have increased over time** in some developed nations, principally due to market conditions where increased investment risks of high-capital expenditure technologies have become significant. **'Learning by doing' processes often failed to compensate** for this trend because they were slowed down by the absence of standardization and series effects (Grubler 2010).

(3) The difficulty in obtaining reliable cost estimates is illustrated by the list of seriously delayed construction work and cost overruns. This also explains why so few new nuclear power plants are being built in western liberalized market economies. In centrally planned economies, the cost of capital can be hidden. Moreover, some of the factors that cause high costs can be mitigated in centrally planned economies, e.g. the likelihood of regulatory delays is lower (Difiglio & Wanner 2013). **Countries with liberalized markets that continue to develop nuclear employ de-risking instruments through long-term contracts** with guaranteed sale prices (Finon & Roques 2013). For instance, the United Kingdom works with public guarantees covering part of the upfront investment costs of newly planned nuclear capacity. This dynamic differs in countries such as China and South Korea, where **monopolistic conditions** in the electricity system allow for reducing investment risks, deploying series effects and enhancing the engineering capacities of users due to stable relations between the authorities and builders (Schneider et al. 2017, IPCC 2018).

(4) The greater scale of nuclear technology **exposes investors to greater downside risks**. Small modular reactor systems address this problem, but face other economic problems (Roques et al. 2006).

Financing new nuclear build requires a substantial risk premium over competing technologies due to its capital intensity, cautionary experiences of engineering difficulties and regulatory creep (red tape burden) during construction. Two potentially positive attributes of nuclear power generation that could make it more appealing to investors. (1) Nuclear generation costs are not sensitive to gas and carbon prices. (2) Investments in nuclear power can be considered as a hedge against the volatility and risk of gas and carbon prices for a (large) generating company. However, the cost of generating from renewable energy sources is also insensitive to carbon prices and can be used as a hedge against the volatility and risk mentioned above (Roques et al. 2006).

Small Modular Reactors (SMR) are "deliberately small, i.e. designs that do not scale to large sizes but rather capitalize on their smallness to achieve specific performance characteristics" (Ingersoll 2009: 589). SMR promise manageable construction cost, schedule certainty and reduction, and lower upfront cost. The reduced capacity of SMRs is likely to lead to a shift in cost drivers away from the capital to operations and maintenance costs. The fixed costs for operating an SMR do not scale down with capacity size: so the margin between operating cost and revenue for an SMR is less than that of a large nuclear power plant. None of the SMR designs has all the characteristics that should compensate for the lack of economies of scale. In general, SMRs might reduce the construction cost with respect to large reactors, but it is unlikely that SMRs will present lower costs of generating each unit of electrical energy than large reactors (Mignacca & Locatelli 2020). For making them attractive to investors, SMRs need to prove that the reduced construction risks related to time and cost overruns will mitigate the loss in operating revenue (Agar & Locatelli 2020). However, a 2016 OECD Nuclear Energy Agency report concluded that even electricity produced by a Russian floating plant is expected to cost about 200 US$ (180 €) per megawatt-hour (MWh) with the high cost due to large staffing requirements, high fuel costs, and resources required to maintain the barge and coastal infrastructure (OECD 2016). One would need to build thousands of such reactors to make a significant contribution under the climate change scenario, which is not very plausible for various reasons.

The first operational units for SMR have been announced for years, but none has yet been deployed (Mignacca & Locatelli 2020). The British government aims to have the first SMR operational by 2030. The construction time for ongoing projects seems to be in the range of eight to nine years.

SMRs are only going to heighten the economic challenge. SMRs are economically not competitive with large nuclear reactors (Mignacca & Locatelli 2020). Furthermore, Cooper (2014) argues that there is no reason to believe that SMR characteristics would increase the demand for nuclear power plants. Ramana & Ahmad (2016) highlight that SMRs increase the need for construction sites considering that more SMRs are needed to obtain the same power of a large reactor. Recently, the Australian CSIRO Institute estimated a hopelessly uneconomic construction cost of A$ 16,304 per kilowatt (kW) for SMRs (Graham et al. 2020). The CSIRO report triggered a lively discussion in the industry. It was countered by more optimistic figures on a "hypothetical reactor", but the average of publicly available data slightly exceeds the CSIRO figure.[10]

Very few studies have analysed the operation, maintenance and decommissioning costs of SMR. There is a gap in knowledge about the costs and benefits of the modular construction (Mignacca & Locatelli 2020). Cooper (2014) also points out how challenging and capital intensive the creation of a massive assembly line would be. This approach could also hinder competition driving innovation and cost reduction by committing subsidies and public guarantees in one technology. Furthermore, learning cannot balance the diseconomies of scale because of the difference between learning-on-site and learning-worldwide and because of the large number of SMRs needed to benefit from the learning effect.

Finally, the **recent success of renewable energies** is making it even harder for nuclear to develop (Markard et al. 2020). For example, the levelised cost of energy (LCOE) of solar PV has fallen by more than 60% between 2010 and 2016 (Ram et al. 2018). A comparison with a business-as-usual (BAU) strategy shows that a 100% renewable energy-based power system is 55–69% cheaper than a BAU strategy without and with greenhouse gas emission costs (Aghahosseini et al. 2020). Markard et al. (2020) find that an eroding actor base, shrinking opportunities in liberalized electricity markets, the break-up of existing networks, loss of legitimacy, increasing cost and time overruns, and abandoned projects are indications of decline of nuclear power (Markard et al. 2020).

With regard to nuclear power, the IPCC highlighted the provision of a stable base-load electricity supply, lower price volatility and local employment as positive (IPCC 2014, IPCC 2018, ch.5: 507). On the other hand, the IPCC points at the infrastructural legacy costs of waste and abandoned reactors (Marra & Palmer 2011, Greenberg 2013, Skipperud et al. 2013, Tyler et al. 2013, IPCC 2014).

[10] See Reneweconomy report: Small modular reactor rhetoric hits a hurdle (accessed: 18.6.2020)

According to Verbruggen (2008) and Brown et al. (2018), renewables and nuclear do not mix well. Because of their high capital costs and their slow load change rate (OECD/NEA 2012), nuclear power plants are most economically viable when operated at full power the whole time, whereas the variability of renewables requires a flexible balancing power fleet. But there are also contrasting views on this, e.g. by Suman (2018), arguing that nuclear technology would deliver the base-load and renewable energy the remaining energy demand.

For comparing electricity generation technologies and deciding between them, the energy industry often refers to LCOE, which only include private costs, not externalities (costs of GHG emissions, effects on human health, the environment, long-term waste management, plant decommissioning, financing and budget overruns) and hence not the whole social costs. Earlier versions of full costs calculation in the energy sector can be found in the ExternE Project[11] (Owen 2006, Rafaj & Kypreos 2007). Ram et al. (2018) aim to account for the full costs of electricity generation by internalising GHG emission costs and other external costs across various power generation and storage technologies in all G20 countries.

Three aspects are still not included in Ram et al. (2018) extended version of LCOE calculations, which is an indicator to compare the costs of electricity production between individual technologies, not the overall costs of the energy system:

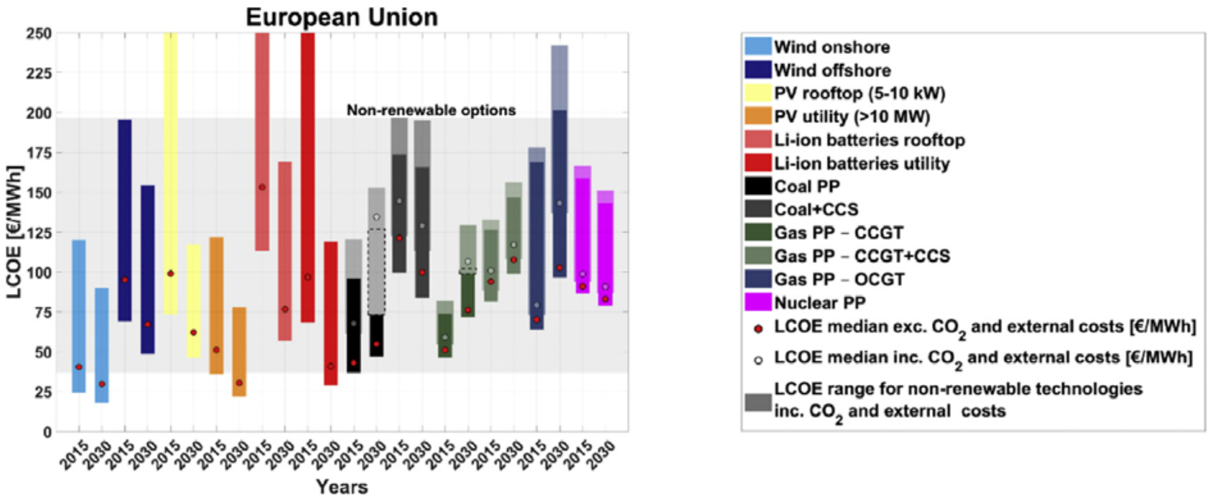
(a) The **costs of managing intermittency**. Higher penetration of solar or wind would mean the need for higher installed capacity compared to the peak load on a grid so that enough 'ready to run' capacity is present in the system when renewables electricity plants cannot run. Inter-connections of the grid to other grids, help reduce the scale of the intermittency problem (Timilsina 2020).

(b) The **modular and distributed** nature of some renewable energy technologies, particularly solar and micro-hydro, has great value for **providing access to electricity in more remote and rural areas** around the world (Timilsina 2020).

(c) The LCOE estimates also do not include the **costs associated with nuclear accidents**. A severe nuclear accident in France could cause costs of around €120 billion and a major nuclear accident around €400 billion (Pascucci-Cahen & Patrick 2013, IRSN 2014, Ashley et al. 2017). According to the heads of nuclear safety and radiation protection authorities, "the possibility of a severe accident scenario (i.e. Fukushima-like) with no or insufficient information on the plant status cannot be completely ruled out" (Bijlholt et al. 2014: 7). The difficult situation, characterised by potentially high costs, risk and uncertainty, is exacerbated by weak institutions. The maximum nuclear liability requirement for the operators of nuclear power plants according to the Revised Paris Convention is limited to €700 million. The need to secure unlimited liability would worsen the economic case for nuclear power. Under current conditions, it is evident that taxpayers will have to pay for damages in the case of a severe or major accident.

[11] See ExternE project: "External Costs of Energy" (accessed: 18.6.2020)

Figure 5 Levelised cost of energy (LCOE) incl. CO_2 costs and other external costs for the European Union in 2015 and 2030 (€/MWh_{el}).



Source: Ram et al. (2018: 699). The range of LCOE values by technology for the years 2015 and 2030 are represented by the bars. The range of LCOE values for conventional technologies (coal, gas and nuclear) also include $CO2_{eq}$ and external costs. The median values for LCOE across the different technologies are represented by the red dots (which do not include the $CO2_{eq}$ and external costs) and the white dots (which include the $CO2_{eq}$ and external costs).

Ram et al. (2018) compiled the LCOE of all technologies into renewables and storage that includes wind onshore, wind offshore, PV rooftop, PV utility, Li-ion batteries rooftop and Li-ion batteries utility, and fossil fuels and nuclear that includes Coal PP, Coal with CCS, CCGT, CCGT with CCS, OCGT and Nuclear PP. In comparison to other LCOE estimates, such as Lazard (2019), IRENA (2017, 2018) and Agora Energiewende (2017), Ram's et al. (2018) estimates seem rather on the conservative side with respect to LCOE values of renewable technologies, specifically utility-scale PV and onshore wind. Further, the LCOE of renewables and storage are evaluated against the LCOE of fossil fuels and nuclear, with and without the consideration of external and $CO2_{eq}$ costs for 2015 as well as 2030.

Ram et al. (2018) calculated low, median and high LCOE to account for national differences in LCOE components and variance in energy generation from different technologies. The variance may be due to geographic factors in the case of solar PV and wind energy generation, but also due to how technologies are used in the energy system (peaking vs. baseload plants). The main factors for the variance in LCOE are capital expenditure, investment and overruns, and full load hours. The calculations were criticized by Martikainen (2019), to which Ram et al. (2020) responded with a strong rebuttal.

In the European Union, onshore wind energy currently shows the lowest overall LCOE, especially in regions of high latitudes (either north or south). In 2030, solar PV utility power plants represent the lowest LCOE of all technologies across all the G20 countries with the exception of Northern European countries, where onshore wind continues to have the lowest LCOE.

On a global level represented by all the G20 countries, rooftop solar PV becomes more competitive than conventional energy production (fossil fuels and nuclear) in 2030, especially when a more complete range of costs are internalised for all technologies (Ram et al. 2018).

Conventional fuels become significantly less competitive in 2030 when the costs of CO_{2eq} and other externalities are fully considered. Gas-based technologies, important providers of flexibility to global energy systems, have the potential to reduce overall LCOE through switching from natural gas to more sustainable bio-based or synthetic methane. Carbon capture and storage offers an opportunity to reduce costs associated with fossil fuel combustion, but remains significantly higher in costs than renewable energy generation, even with the anticipated cost reductions due to development of CCS technology. It needs to be noted that net zero emissions are impossible with fossil-fuel based CCS, and still incur higher costs than renewable energy based energy systems (Ram et al. 2018).

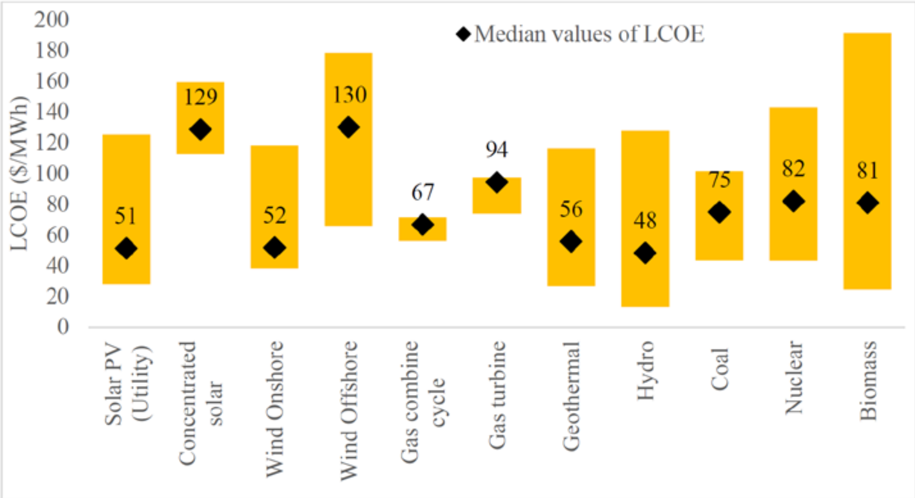
Nuclear power has already lost its competitiveness to wind and solar PV in 2015 in most of the G20 countries and further worsens its relative competitiveness with renewable energy in 2030 when high levels of social, environmental and economic costs are internalised in the LCOE calculations (Ram et al. 2018).

In France and Germany the LCOE of wind onshore power (with 47 and 44 €/MWh_{el}) is presently competitive with fossil fuel based power (with coal having LCOE of 43 and 42 €/MWh_{el}), and by 2030 wind onshore (29 and 28 €/MWh_{el}) and utility-scale PV (32 and 40 €/MWh_{el}) have much lower LCOE. In Italy, fossil fuel produces power (with coal having LCOE of 43 €/MWh_{el}) at a lower LCOE in 2015, whereas by 2030 wind onshore (29 €/MWh_{el}) and utility-scale PV (27 €/MWh_{el}) will have much lower LCOE (Ram et al. 2018).

Cost calculations in Ram et al. (2018) showed that renewables and storage are cheaper than fossil and nuclear sources by 2030, even before considering external costs. The cost decline of wind and solar photovoltaic (PV) technologies have outpaced most industry expectations. Renewables being 'way too expensive' does no longer hold. G20 countries have the opportunity to decrease their energy costs significantly, between now and 2030 by investing in renewables. Renewable energy technologies offer the lowest LCOE ranges across G20 countries in 2030. Utility-scale solar PV generally shows the lowest values ranging from 16 to 117 €/MWh_{el} and onshore wind LCOE range is from 16 to 90 €/MWh_{el}. Rooftop solar PV generally offers the next lowest LCOE ranging from 31 to 126 €/MWh_{el}, followed by LCOE of offshore wind power ranging from 64 to 135 €/MWh_{el}. Solar PV and battery systems are highly competitive on an LCOE basis at utility-scale ranging from 21 to 165 €/MWh_{el} and at residential scale from 40 to 204 €/MWh_{el}. Renewables have substantial co-benefits such as better health of citizens, lower respective health costs and improved energy security.

These findings by Ram et. al (2020) are consistent with another recent study by Timilsina (2020). In terms of median values of LCOEs, hydro, solar PV, onshore wind, and geothermal are cheaper as compared to the remaining technologies. Hydro is the cheapest, followed by solar PV, onshore wind, and geothermal. Only offshore wind fares significantly worse than in Ram et al (2020); concentrated solar power, which was not included in Ram et al. (2020) is the most expensive.

Figure 6 Levelised cost of energy (LCOE) range for the maximum and minimum values of capital costs when other input variables are standardized (€/MWh).



Source: Timilsina (2020: 13).

Timilsina (2020) focuses on the seven factors that primarily influence the LCOE values: discount rate, overnight construction costs, O&M costs, fuel prices, heat rate, capacity availability factor, and economic life. Timilsina (2020) shows that for the lower range of capital costs, the LCOEs of renewable energy technologies, except concentrated solar power and offshore wind, are lower than those of fossil fuel-based and nuclear technologies. Since the capital costs of biomass-based technology vary widely depending upon the feedstock type, the cost competitiveness of biomass with fossil fuels and nuclear depends on the type of feedstock.

Timilsina (2020) illustrates by drawing on many data sources how much values of input variables, particularly capital costs, vary for a given technology. He also presents the effects of various factors on the LCOEs of all the technologies considered in the study. Since capital cost is the main component of the LCOE in renewable technologies, LCOE is sensitive to this variable. The capacity cost elasticities of LCOE of renewables sources are found to vary between 0.7 to 1.0 if the capital costs are not tied with other input variables, such as capacity factors. Renewables are also sensitive to the capacity utilization factors and economic lives of the technologies. This is also true for nuclear technology.

7.4 Time perspective of climate protection measures

By 2030, the transformation of the energy systems and energy infrastructures must be effectively launched. The **current deployment pace of nuclear power is constrained by social acceptability** in many countries due to concerns over risks of accidents and radioactive waste management (IPCC 2014 ch.2 & AR5). The current time span between planning and operation of the plants is estimated for democratic societies at 10-19 years (Lovins et al., 2018), which means that the coal-fired power plants to be replaced would still be in operation for almost 20 years. This delay in decommissioning fossil fuel power plants would be highly problematic, as it would render the achievement of the climate target impossible.

In contrast, **wind energy and PV systems have very short planning and implementation times** (2-5 year for utility solar or wind), and PV systems can often be installed where electricity is actually needed.

For wind, real options for locals to become involved in investing in the wind projects and to build institutional capital (knowledge resources, relational resources and the capacity for mobilisation) through collaborative approaches to planning have helped to reduce the time required for the planning and implementation phases (Wolsink 2007).

Given that nuclear new-built compare unfavourably to renewables on the basis of LCOE as well as on the basis of value-adjusted levelised cost of electricity (VALCOE), the IEA concludes in its latest report that lifetime extension (LTE) and/or long-term operation (LTO) to be promising nuclear options for the foreseeable future. With an average reactor age of around 35 years in the EU, extending the lifetime of existing nuclear power plants that can operate in a safe manner is challenging though (IEA 2020). LTE as a strategy against the listed economic challenges that nuclear new-built faces seems problematic on safety grounds and even with LTE it is necessary to build replacement capacities.

8 Overall assessment

In this meta-review, we screened the academic literature mainly of the last 10-15 years on the different environmental and social objectives covered by the Taxonomy and how they relate to nuclear power.

The Taxonomy includes three criteria, which have to be fulfilled for being classified to contribute to sustainable development: first, a 'substantial contribution' to at least one of the six environmental objectives (or at least enabling others to contribute 'substantially') and, second, meeting the criteria of 'Do No Significant Harm' on <u>all</u> other environmental objectives, and third, compliance with certain international social standards.

This review shall contribute to a clearer picture on the compliance of nuclear power with the DNSH criteria, which has been rather controversial due to complex interrelationships regarding associated risks and the management practices applied to nuclear power production. This goal could be fulfilled to a certain extent. However, scientifically clear results are not available for each of the environmental goals considered. As already mentioned in the Taxonomy Technical Report of June 2019, there are gaps in the data available for important DNHS objectives. Nevertheless, it was possible to go clearly beyond the literature cited in the Taxonomy Technical Report to add to the discussion.

Overall, nuclear power is recognized as a low-GHG emissions energy source in comparison to fossil fuels. Bioenergy, nuclear power and photovoltaics are the three 'low-GHG' energy sources with relatively higher emissions comparing to the 'low-GHG champions' solar, geothermal, hydro, ocean, and wind, which makes nuclear a low GHG technology, but not quite belong to the best performers in the sector ('best-in-class approach'). Due to its long development times of up to 10-20 years (in democratic societies), further deployment of nuclear energy for climate mitigation reasons would lead to a lock-in of carbon-intensive coal plants for that time period until the new built nuclear plants would become operational. These are the reasons why the quickly growing body of research is currently settling on energy efficiency and renewable energy being the primary contributors to CO_2 pollutant reduction in the future.

From an economic point of view, it has been noted that the business case for nuclear energy has weakened in recent decades. Based on a full cost accounting for Europe, this is partly due to the recent success of renewables, where the cost of PV modules has fallen by 80% within 10 years and that of wind turbines by 30%, as well as greater public interest in the co-benefits of renewable energy technologies. In this way, renewable energy systems are not only feasible, but already economically viable and cheaper every year. This is why nuclear energy is already outpriced by renewable energy sources, whereby the difference will very likely even increase in the future.

The risks of nuclear accidents will continue to exist because, while the likelihood of accidents can be reduced, they can never be excluded. Further barriers to and risks associated with an increasing use of nuclear power include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapons proliferation concerns, and often adverse public opinion. In addition, the complex issue of radioactive waste and the challenges related to its acceptance by society remain. We already live in a world with more than a quarter of a million tonnes of highly radioactive waste from nuclear power production, all in interim storage including potential leakage, which could increase to more than one million tonnes worldwide by 2100. Beyond that safety and health issues in uranium mines and human rights abuses towards indigenous communities in different parts of the globe have been an issue throughout the history of uranium mining.

Although the available data and accordingly also the scientific analyses are not always complete to judge nuclear power against each criteria and goal defined in the Taxonomy, thus can be questioned on quite a few instances, the arguments seems sensible that taken together, quite a substantial part of the academic literature has become rather vary of nuclear power production when looking into its environmental, economic, and social effects. The benefits seem to be outweighed by the environmental damages and health risks associated with mining, nuclear power production, and nuclear waste storage, plus the dangers stemming from nuclear accidents.

Whether nuclear power should be included in a future sustainable energy mix with substantial CO_2 reductions is discussed in varying shades in the literature, but increasingly turning more towards phasing out nuclear. The reason is that there are alternative energy sources with partly even lower GHG emissions and lower economic and social costs, which do not compromise the good performance on climate mitigation with comparable associated (intergenerational) risks.

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