World Nuclear Association input into the OHCHR special rapporteur investigation – The toxic impacts of some climate change solutions

Dear Special Rapporteur, Dr Marcos Orellana

We welcome the opportunity to submit evidence to the OHCHR investigation into the potentially toxic impacts of climate change solutions. Our submission provides an overview of the entire nuclear fuel cycle but goes into depth on uranium mining, as we expect mining to be a focus of your report. We have provided the most up to date information of which we are aware to better inform the discussion of nuclear energy. In addition, we have also provided evidence on the mining, operational and waste impacts of certain renewable energy forms – a topic where we believe that awareness is generally lacking and that more and better evidence is sorely needed.

It is unfortunately the case that there are still many misconceptions about nuclear energy. We believe that an evidence-based lifecycle assessment of the impacts of energy sources reveals that – far from being an '*ultra-hazardous*' technology– nuclear energy is in generally one of the most societally and environmentally benign energy sources available to power the low carbon transition. While there were some poor safety practises in the early days of uranium mining which led to health consequences in workers, standards have now evolved to the point where uranium mining can be considered one of the most regulated and sustainable of all mining activities. Nuclear energy waste streams are similarly well-managed and have never led to a significant environmental impact of which we are aware.

This submission provides:

- Section 1: An overview of the life-cycle assessment and environmental impacts of nuclear energy
- Section 2: A description of the impacts of uranium mining (and minerals requirements for renewables)
- Section 3: A description of the impacts of conversion, enrichment and fabrication
- Section 4: A description of the Impacts of nuclear power generation (and land use of renewables)
- Section 5: A description of the impacts of nuclear waste management and disposal (and renewables waste streams)

World Nuclear Association represents the companies that constitute the worldwide nuclear industry. Our mission is to promote a wider understanding of nuclear energy among key international influencers by producing authoritative information, developing common industry positions, and contributing productively to the energy debate.

We would welcome the opportunity to take part in a deeper discussion on any topic raised here.

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1. General Introduction – Environmental impacts of nuclear energy

There are currently 438 operable power reactors in 32 countries, which provide approximately 10% of global electricity. These plants are supported by a complex fuel cycle which handles the extraction and processing of uranium as well as the storage, treatment and ultimate disposition of radioactive materials and wastes. The fuel cycle is covered in detail in the World Nuclear Associations information paper – *Nuclear Fuel cycle Overview*[1].

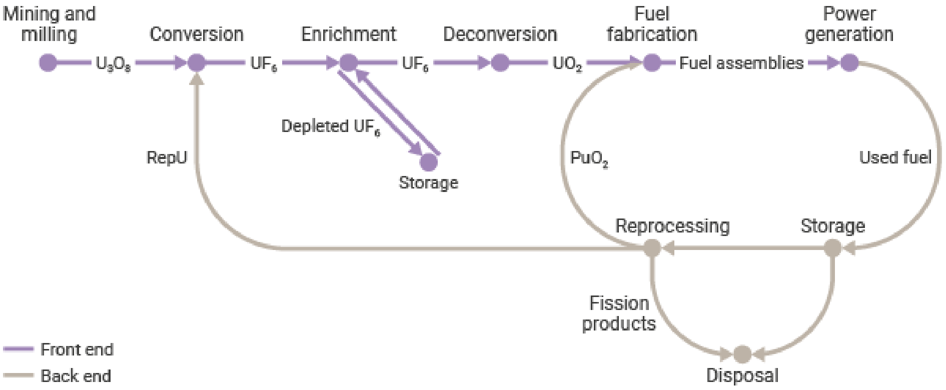

Figure 1: The nuclear fuel cycle

Despite this complexity, environmental impacts across the entire nuclear fuel cycle are generally low. This was made clear in a recent lifecycle assessment carried out by the Luxembourg Institute of Science and Technology on behalf of the United Nations Economic Commission for Europe (UNECE)[2]. This important study was the first LCA carried out by a UN body to include nuclear energy and therefore addressed a critical information deficit in the understanding of the environmental impacts of energy technologies. The LCA incorporated recent data inputs and updated assumptions about the types and performance of key energy facilities. The LCA found that not only was nuclear energy low-carbon, but that it was the lowest carbon energy source amongst currently available options. In fact, nuclear energy also presented low impacts across the-full spectrum of environmental indicators, with impacts broadly similar to both wind and solar, on an unweighted basis.

The UNECE report also presented the LCA for the lifecycle and fuel cycle (where applicable) of individual energy technologies. For nuclear energy it reveals that mining operation, rather than nuclear power plants, are responsible for most of the impacts. This motivates a closer look at these fuel cycle activities from an environmental perspective.

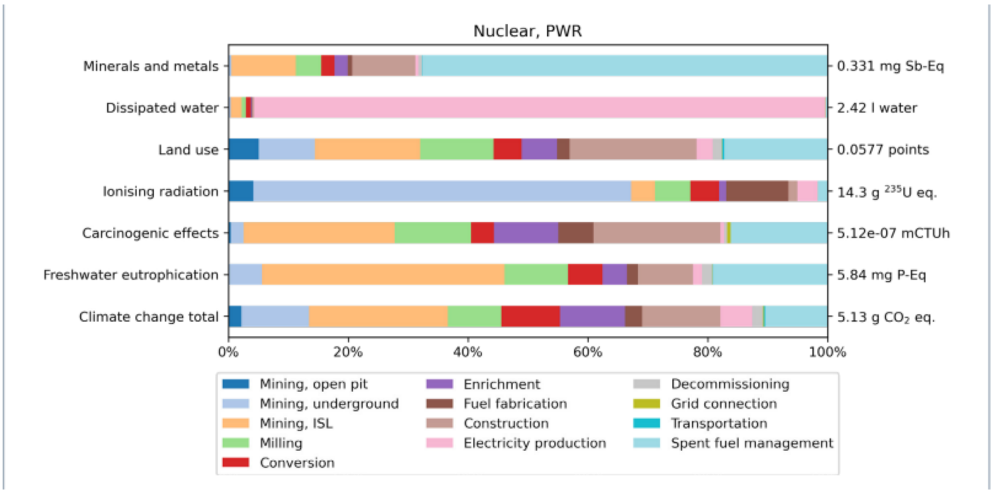

Figure 2: Lifecycle impacts of nuclear power, global average, per kWh and activity[3]

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[1] WNA, Nuclear Fuel Cycle Overview https://world-nuclear.org/information-library/nuclear-fuel-cycle/introduction/nuclear-fuel-cycle-overview.aspx

[2] UNECE, 2021, *Lifecycle Assessment of Electricity Generating Options*

[3] UNECE, 2021, *Lifecycle Assessment of Electricity Generating Options (fig 35)*

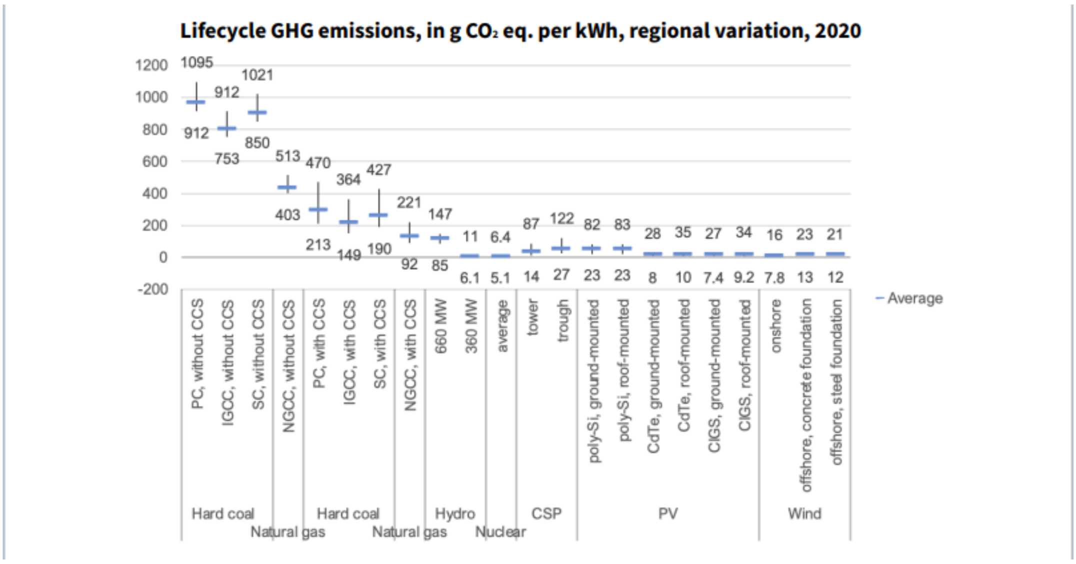

Figure 3: Lifecycle greenhouse gas emission ranges for major energy technologies[4]

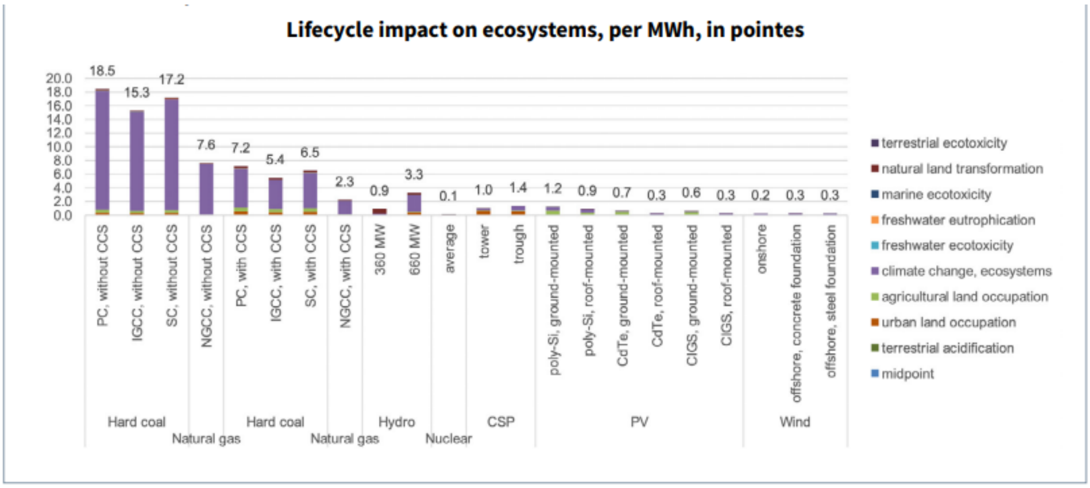

Figure 4: Lifecycle impacts on ecosystem (in points), including climate change, of major energy technologies[5]

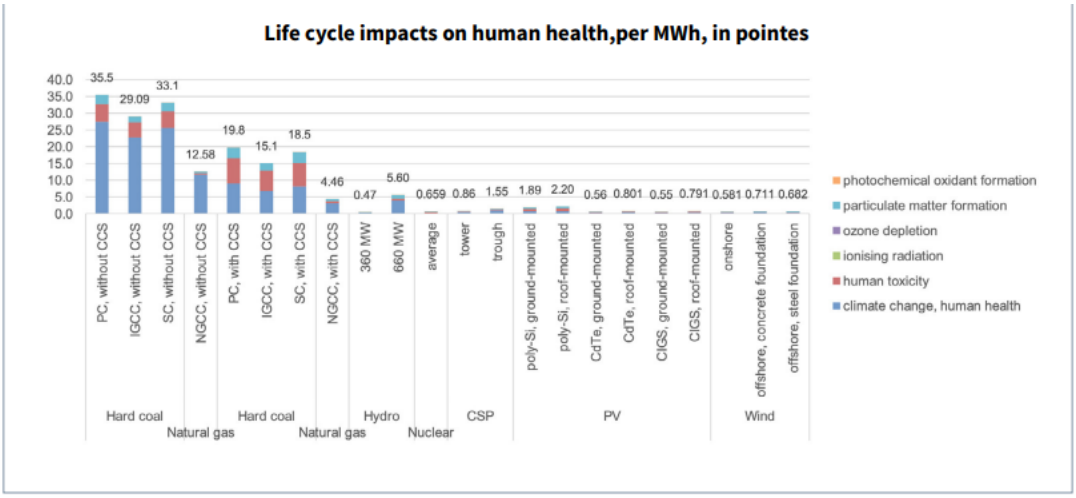

Figure 5: Lifecycle impacts in human health (in points), including climate change, of major energy technologies [6]

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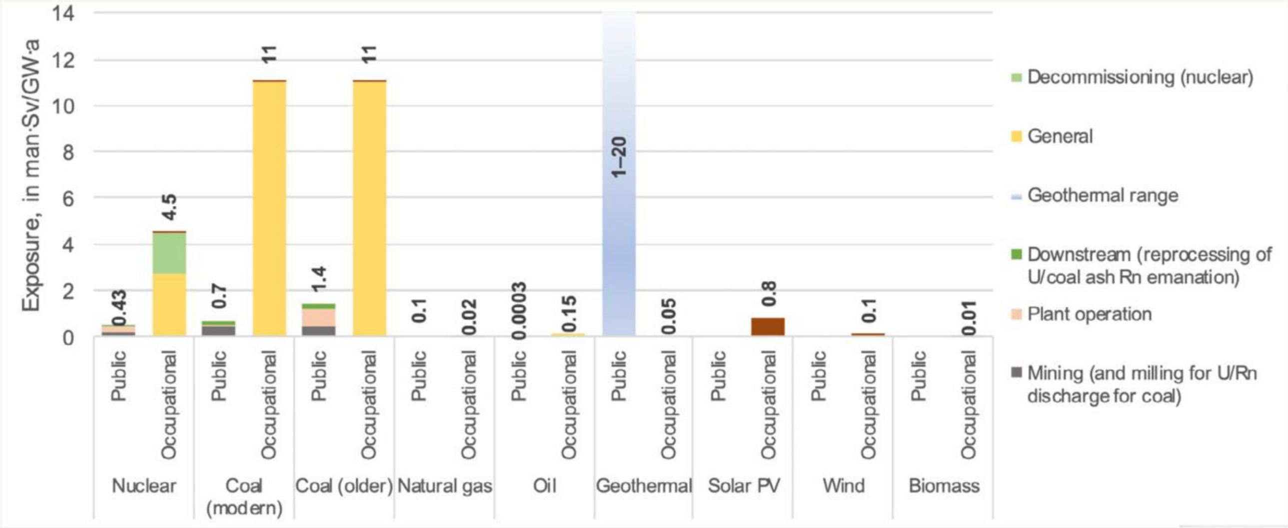
[4] Ibid (figure 1)

[5] Ibid (figure 48)

[6] Ibid (figure 50)

The low lifecycle impacts of nuclear energy are overwhelmingly due to two factors. The first is that nuclear plants generate heat but without the emissions of carbon dioxide, greenhouse gases and other pollutants that come routinely with combustion and which routinely contaminate air and water bodies. Nuclear energy is produced by fission, and the hazardous materials produced via this process remained locked-up inside the fuel matrix and are prevented from entering the environment as a matter of standard industrial practise. The other factor is the high energy density of nuclear fuel. This means that smaller volumes of fuel need to be mined and transported, and that the land footprint of nuclear facilities can be kept comparatively small.

The special hazard confronting the nuclear sector is of course radiation that is produced via the fission process. Therefore, key to the sustainable use of this energy source is that radiation doses to workers and the public are kept as low reasonably achievable (ALARA). This requires the management of radioactive materials across the entire nuclear fuel cycle to make sure that they are contained, and that any discharges to the environment do not noticeably change the radiation background levels. While it is a special hazard confronting the nuclear industry, it is not a unique one and LCA reveals that other energy sources also result in radiological impacts. However, these are not monitored as carefully as in the nuclear sector and therefore the numbers are less precise.



Source: *United Nations Scientific Committee on the Effects of Atomic Radiation [2].*

Figure 6: Public and occupational exposures from electricity generation, normalized to electricity generated, in man-Sievert per GW-annum (8760 GWh).[7]

Radiation is known to cause harm to human health in two ways. At instantaneous doses of 1 Sievert it can cause acute sickness (radiation sickness) but not death. A dose of about 4 - 5 Sieverts induces radiation sickness that would kill roughly half of people exposed to it within one month. An 8 Sievert dose is invariably fatal. At lower doses radiation is a known carcinogen, however its carcinogenic power is relatively weak. An instantaneous dose of 1 Sievert raises the risk of dying from cancer by only 5%. There is also some evidence that radiation can increase the rate of cataracts.

It must be appreciated that we live on a radioactive planet and that every person is exposed to radiation on a daily basis. At low doses, close to the basic universal natural background exposure of 2-5 mSv/yr, there is no evidence of adverse health effects. This level covers all the allowed public radiation exposure and most of the occupational exposure within the nuclear industry. Both public and occupational exposure to radiation from the nuclear industry has fallen sharply over the years as a result of strong regulation and improved operating practise. A comparison of the global occupational exposure due to exposure to natural sources and human-made sources of radiation for the periods 1995–1999 and 2010–2014 is illustrated in Figure 7. Exposure to natural sources of radiation (including coal mining and minerals), is 4-5 times higher than exposure to human-made sources of radiation (including medical and nuclear fuel cycle). Moreover, the greatest contribution for exposure to human-made resources comes from medical uses of radiation, not nuclear power[8]

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[7] Ibid (figure 40)

[8] UNSCEAR, 2022, "Evaluation of occupational exposure to ionizing radiation" https://www.unscear.org/unscear/uploads/documents/publications/UNSCEAR_2020_21_Annex-D.pdf

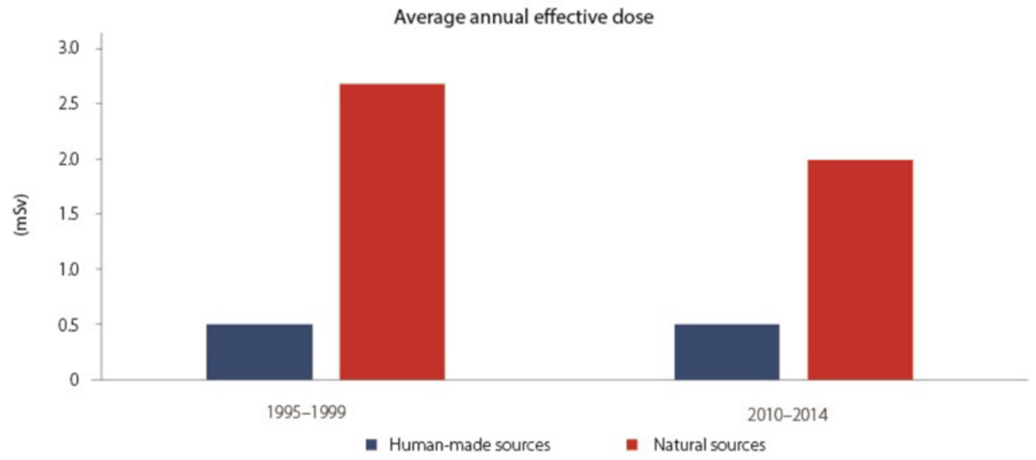

Figure 7: Comparison of worldwide levels of occupational exposure due to exposure to natural and human-made sources of radiation between 1995–1999 and 2010–2014 Average Annual effective occupational dose over time[9]

Nuclear power plants produce significant quantities of radioactive material which must be contained. Preventing the accidental releases of these materials is the primary safety objective of this stage of the nuclear fuel cycle and the stages that follow. This is achieved through a combination of high standards, independent regulation, international cooperation, and the adoption of a global industry-wide safety culture which prioritises health and environmental considerations over other operational and management concerns.

The specific radiation challenges of nuclear energy need to be considered in relation to the primary impacts of other low carbon energy technologies, most notably renewables such as wind and solar. The ongoing scaling of these climate solutions is expected to create challenges with respect to mineral availability, as well as potential siting and biodiversity impacts. There is also currently a lack of recycling and regulated disposal infrastructure capacity for renewables, with key challenges remaining both in terms of technical readiness and economic feasibility. The anticipated high volumes of end-of-life batteries, solar and wind units will all require the handling of hazardous and toxic materials along with associated environmental and financial costs which are not fully recognised at this time.

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[9] Ibid (Figure IX)

2. Uranium mining

Uranium mining and milling standards have improved considerably over the decades, and uranium is now possibly the most responsibly-produced mineral on Earth.

Uranium is the primary fuel source of nuclear energy, but uranium itself is only weakly radioactive. The half-life the main isotope of uranium – uranium 238 – is 4.5 billion years, making it practically stable. Most of the radioactivity of uranium mining is therefore associated with mine tailings and especially the production of radon gas (Ra 222). It needs to be emphasised that these are types of naturally occurring radioactive material (NORM) that will be present to a greater or lesser extent in all mining, and especially in the production of rare-earths. In other respects, there is little to differentiate a uranium mine from other types of mine and it may even be associated with the recovery of other minerals such gold, copper and silver (for example, Olympic Dam in Australia) as well as phosphates and the afore-mentioned rare earth minerals.

What determines the impacts of the mine are therefore the standards adopted as well as the regulation and especially the level of commitment to protecting local species, aquatic environment, tails management and the eventual remediation/decommissioning programme. More information on the environmental impacts of uranium mining can be found in the WNA information library[10]. What distinguishes uranium mining is that companies track the radiation doses of workers, monitors radioactive emissions to the environment and seek to strictly control these. This is not always the case with other types of energy mineral extraction. This led to the United Nations Steering Committee on the Effects of Atomic Radiation (UNSCEAR) concluding the following:

> *The Committee also assessed occupational exposures. The largest collective dose to workers per unit of electricity generated resulted from coal mining, because of exposures to naturally occurring radionuclides. Of all the collective doses evaluated, both to the public and to workers, the exposure of workers from coal mining made the largest contribution, although it has fallen over time because of improving mining conditions. With regard to the construction phase of the electricity-generating technologies, by far the largest collective dose to workers per unit of electricity generated was found in the solar power cycle, followed by the wind power cycle. The reason for this is that these technologies require large amounts of rare earth metals, and the mining of low-grade ore exposes workers to natural radionuclides during mining*[11]

Uranium is a relatively common element in the Earth's crust and uranium mines can be found in just about every continent. Major uranium producing nations include Kazakhstan, Namibia, Australia, and Canada. The most recent published estimate suggests that current resources are sufficient for more than 135 years' worth of demand[12], although it should be appreciated that the level of uranium resource has increased fairly consistently over the years. Uranium ore grades vary significantly. Uranium can be economically recovered at ore grades as low as 0.01%, but the highest known uranium ore grade is 20%.

There are three main types of uranium mining, all with their distinct impacts and risks: open pit extraction, underground mining and in-situ leach/recovery (ISL or ISR). Open pit and underground mines are conventional mine types, wherein ore is extracted, then milled and subjected to chemical treatment to extract the valuable minerals. ISL mining involves pumping an extractant into sandy deposits and recovering the pregnant solution. This has the advantage of leaving the surface geology intact, which both minimises the need for eventual site remediation and does not create tailings that require disposal. It can however present increased risks to groundwater and care must be taken in drilling wells to avoid contamination.

In 2021, 48,332 tonnes of uranium were produced (56,995 tonnes U_3O_8) from uranium mines. ISL mining made up 66% of global uranium production – much of this in Kazakhstan which is currently the world's largest uranium producing nation, and which exclusively extracts uranium via this method. By comparison, global coal production is nearly 8000 million tonnes mined annually, about half of which comes from China[13]. More information on uranium production can be found on the WNA website[14]

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[10] WNA, Environmental Impacts of Uranium Mining https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/environmental-aspects-of-uranium-mining.aspx

[11] UNSCEAR, 2016, Sources, Effects and Risks of Ionising Radiation https://www.unscear.org/docs/publications/2016/UNSCEAR_2016_Report.pdf

[12] OECD NEA, Uranium 2020: Resources, Production and Demand https://www.oecd-nea.org/jcms/pl_52718/uranium-2020-resources-production-and-demand

[13] IEA, Global coal production, 2018-2021https://www.iea.org/data-and-statistics/charts/global-coal-production-2018-2021

[14] WNA, World Uranium Mining Production https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx

As with the mining sector generally, mining practises were simply not sufficient in earlier decades to protect human health. Early uranium mining was conducted without protective measures or radiation monitoring, and mines were poorly ventilated. This resulted in miners being exposed to a variety of health hazards including high doses of radiation, but also and often more dangerously, toxic chemicals and dust. Negative public perceptions of uranium mining are largely based on the adverse health and environmental impacts of outdated practices used when uranium mining was undertaken primarily for military purposes.

Uranium mining practises have improved enormously over time, driven both by stricter regulation and industry initiatives. More information on the occupational health and safety practises carried out in a modern uranium mine can again be found in the WNA information library[15]. Negative public attention forced uranium mining companies to embrace higher standards at an earlier stage than for other minerals, and uranium now arguably leads the mining sector in terms of good practise. One example is how uranium mining companies often out-perform regulatory expectations when it comes to annual worker radiation dose. The evolution of these standards and practises is covered in an important OECD Nuclear Energy Agency publication[16], which notes the importance of the following for ensuring minimal impacts:

- establishing the appropriate regulatory framework;
- planning for closure before the mine begins production;
- requiring companies to post financial assurance to cover the costs of remediation;
- applying leading practices to minimise the radiation exposure of workers and the local population, protect water resources and safely manage and dispose of tailings and problematic waste rock;
- instituting a programme of public consultation and information sharing, beginning with an effective and all-encompassing environmental impact assessment process;
- conducting effective environmental monitoring programmes throughout the life of the mine facility.

Embracing the global shift to ESG and non-financial reporting, an increasing share of the world's uranium mining companies have begun to embrace reporting on their sustainability and environmental impacts. Most notably: Kazatomprom publishes an annual integrated report[17]; Cameco publishes an annual online sustainability report[18]; Orano publishes an annual CSR report[19]; CGN mining company publishes an integrated report[20]; Navoi Mining publishes an annual sustainability[21]; ARMZ publish sustainability info in annual reports; BHP publishes an integrated annual report[22] and an environmental report for Olympic Dam[23].

National regulators are also now producing annual reports on uranium mines and mills – notably the Canadian regulator[24] (CNSC) and Australian regulator (ARPANSA).

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[15] WNA, Occupational Safety in Uranium Mining https://world-nuclear.org/information-library/safety-and-security/radiation-and-health/occupational-safety-in-uranium-mining.aspx

[16] OECD NEA, 2016, Managing Environmental and Health Impacts of Uranium Mining' https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/7062-mehium.pdf

[17] https://www.kazatomprom.kz/storage/1e/kazatomprom_iar_2021_engpdf.pdf

[18] https://www.cameco.com/about/sustainability

[19] https://cdn.orano.group/orano/docs/default-source/orano-doc/groupe/publications-reference/orano_mining_rse2021_en2ff4d413d2db4a4c98fd50cd35d59b9c.pdf?sfvrsn=8d892bba_14

[20] http://www.cgnmc.com/en_cgnmc/c101147/2022-04/25/844bccfef96543f6be70e4fcdeede18e/files/1583bfd44bdb4f77aa039b108f15d6a0.pdf

[21] https://www.ngmk.uz/uploads/photo/about-ngmk/infos/NGMK_EN_14-09-22.pdf

[22] https://www.bhp.com/-/media/documents/investors/annual-reports/2022/220906_bhpannualreport2022.pdf

[23] https://www.bhp.com/-/media/bhp/regulatory-information-media/copper/olympic-dam/olympic-dam/annual-environment-reports/fy21-epmp-report.pdf

[24] Regulatory Oversight Report – Uranium Mines and Mills http://nuclearsafety.gc.ca/eng/resources/publications/reports/regulatory-oversight-reports/uranium-mines-and-mills.cfm

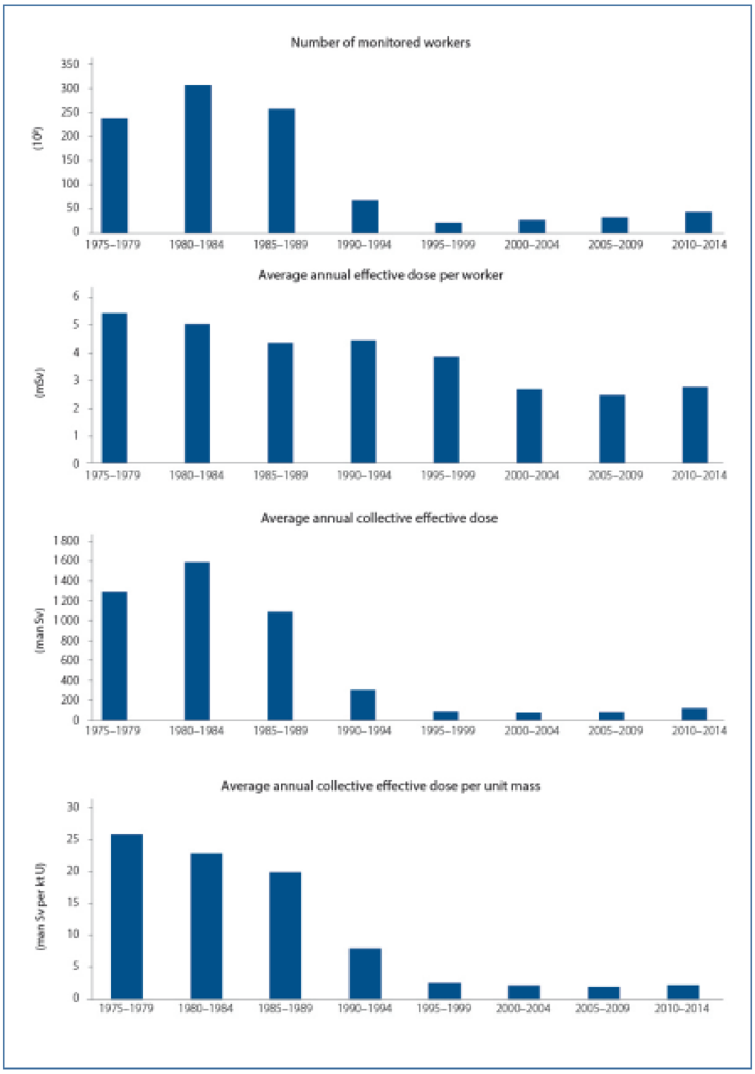

Figure 8: Estimated worldwide trends in occupational exposure due to uranium mining.[25]

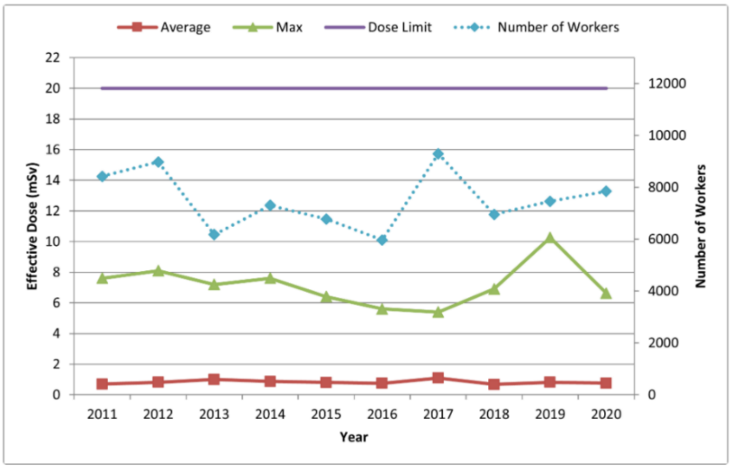

Figure 9: Australian uranium industry average and maximum effective doses with workforce numbers (2011-2020)[26]

2.1 Comparison to mining impacts of renewables

While there is a lot of quality information available on uranium requirements and the potential environmental impacts of extracting this mineral, there appears to be far less for the mineral demands of renewable energy.

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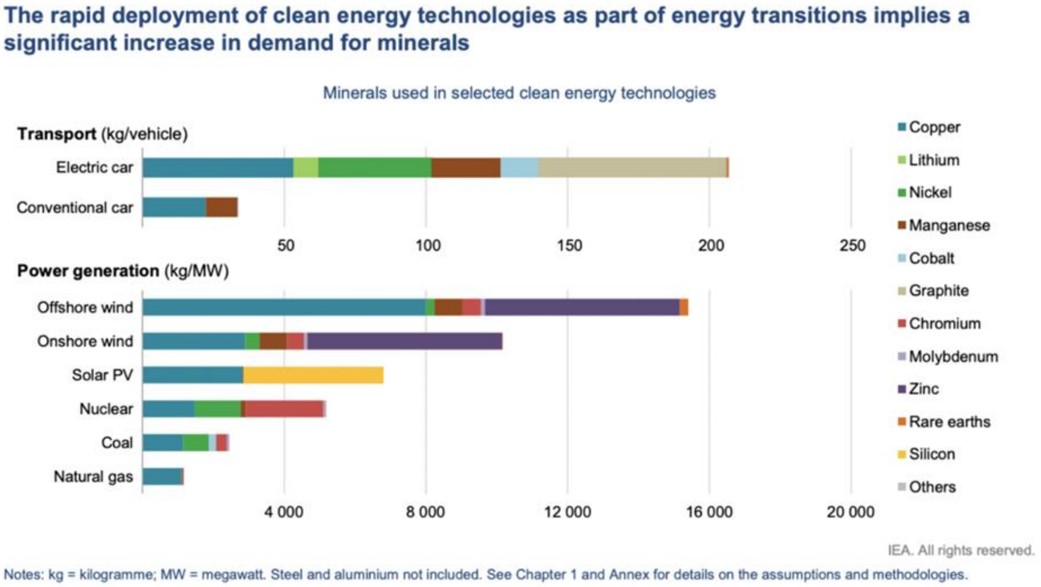
[25] UNSCEAR, 2022, “Evaluation of occupational exposure to ionizing radiation” https://www.unscear.org/unscear/uploads/documents/publications/UNSCEAR_2020_21_Annex-D.pdf

[26] ARPANSA, The Australian National Radiation Dose Register, https://www.arpansa.gov.au/anrdr-review-2020

What we do know with confidence is that the transition to a low-carbon energy system based largely around wind and solar – as well as the accompanying expanded grid and storage infrastructure – will be highly mineral-intensive. This is highlighted in a special IEA report[27]. While the mining and extraction of fossil fuels (and the environmental consequences of that) will be diminished in such a future, this will be offset by the need for more minerals in what the IEA calls "*a shift from a fuel-intensive to a material-intensive energy system*." The report finds that:

> *"In a scenario that meets the Paris Agreement goals, clean energy technologies' share of total demand rises significantly over the next two decades to over 40% for copper and rare earth elements, 60-70% for nickel and cobalt, and almost 90% for lithium. EVs and battery storage have already displaced consumer electronics to become the largest consumer of lithium and are set to take over from stainless steel as the largest end user of nickel by 2040."*


The rapid deployment of clean energy technologies as part of energy transitions implies a significant increase in demand for minerals

Minerals used in selected clean energy technologies

IEA. All rights reserved.

Notes: kg = kilogramme; MW = megawatt. Steel and aluminium not included. See Chapter 1 and Annex for details on the assumptions and methodologies.

Figure 10: Key minerals used in selected clean energy technologies[28]

Other researchers are more pessimistic about the strain this will place on specific minerals and the speed at which their production can be scaled up. A recent and highly detailed report from the Geological Survey of Finland[29] found that the scope of the existing literature was just too narrow and did not adequately consider the impacts of the full energy transition. They found that, in a full decarbonisation scenario including transport and industry, the resulting demand for nearly every necessary mineral, including common ones such as copper, nickel, graphite, and lithium, would exceed known global reserves.

> *A fundamental conclusion is that replacing the existing fossil fuel powered system (oil, gas, and coal), using renewable technologies, such as solar panels or wind turbines, will not be possible for the global human population in just a few decades. There is just not the time, nor resources to do this. What may well happen is a significant reduction of societal demand of all resources of all kinds. This implies a very different social contract and a very different system of governance to what is in place today.*

This raises legitimate concerns about the sustainability of mining requirements of the low-carbon energy transition. Even if standards are generally acceptable the increased demand for these resources is guaranteed to increase their net environmental impacts. The more that system relies on variable renewables like wind and solar, the greater these mineral requirements and associated impacts will be.

However, there are reasons to doubt the sustainability of specific critical mineral classes and their current sources of supply. Currently the production of rare-earth elements is dominated by China, where lack of data availability seriously inhibits useful life-cycle assessment. There is purported evidence of large chemical

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[27] IEA, 2021, the Role of Critical materials in Clean Energy Transitions https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

[28] ibid

[29] GTK, 2021, Assessment of the Extra Capacity Required of Alternative Energy Electrical Power Systems to Completely Replace Fossil Fuels, https://tupa.gtk.fi/raportti/arkisto/42_2021.pdf

requirements, untreated tailings and significant amounts of unmanaged NORM[30]. For wind manufacturers, battery producers and other low carbon technologies which may rely heavily on rare-earths this is a genuine problem and should be addressed as an urgent environmental priority. They will need to either i) secure other more sustainable sources, ii) work with Chinese producers to clean up production or iii) investigate substitutes for these materials.

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[30] Zapp, Schreiber, MRS Bulletin 47, pages267–275 (2022) Environmental impacts of rare earth production https://link.springer.com/article/10.1557/s43577-022-00286-6#Sec12

3. Conversion, enrichment, fabrication

After uranium is mined it must go through a series of three steps – conversion, enrichment and fabrication – before it can be loaded into a nuclear power reactor. These steps do not cause serious environmental impacts or contribute significantly to the overall lifecycle impacts of nuclear energy.

Step 1 is conversion[31]. When uranium leaves the mine, it is typically in the form U_3O_8, sometimes known as yellow-cake. This is a stable powder that is suitable for transport and storage and is typically transported in simple steel drums. For the enrichment stage it needs to be converted to a form that can change states into a gas at near-to ambient temperatures. This is a multi-stage chemical conversion process that involves the use of potentially dangerous fluorine base chemicals and needs to be regulated accordingly. The output is uranium hexafluoride (UF_6)

In a gaseous from UF_6 is highly corrosive. It needs to be converted into a solid prior to transport, which requires the use of specially designed slightly pressurised steel shipping cylinders. Following enrichment, up to 90% of the original uranium feed ends up as depleted uranium (DU), which is stored long-term as UF_6 or preferably, after deconversion, as U_3O_8, allowing the HF to be recycled. It may also be de-converted to UF_4, which is more stable, and possessing a much higher temperature of volatilization.

The amassment of DU stockpiles is the most visible impact of the conversion process. These were estimated to be 1.2 million tonnes globally in 2021. While it is important that DU is eventually de-converted and disposed of, there is no urgency here and in fact enrichers consider DU to be a potential asset. In the case of a uranium market swing, DU tails can be put through enrichment again to extract more of the useful uranium isotope. There have been a handful of minor incidents at conversion and deconversion plants worldwide but to the best of knowledge nothing that has escaped the perimeter of the facility. Any spills or contamination would be expected to be remediated as part of site management and or decommissioning.

Figure 11: A worker inspecting UF_6 cylinders

Step 2 is enrichment[32]. At this stage the concentration of U-235 in natural uranium, which is 0.7%, is brought up to a level suitable for a given reactor design. Light water reactors are the most common form of reactors, these typically require enrichment levels of 3.5 – 5%. Many advanced reactors will require enrichment levels of approximately 20%. Enrichment is a form of isotope separation which exploits the small difference in the mass of the uranium 235 and uranium 238 isotopes.

Enrichment is an energy intensive process and arguably the largest environmental impact of this stage of the nuclear fuel cycle comes from the electricity that goes into it. Where this is from nuclear or renewable energy forms the impacts of enrichment will be low and practically negligible. Enrichment technology has evolved since the beginning of the industry, and gaseous diffusion plants have now all been replaced with far more efficient centrifuge technology, which requires just 2% of the electricity to run. The world's last major diffusion plant closed in 2013. The Paducah enrichment plant famously required the electricity from two nearby coal-fired power plants to run. This plant's closure measurably reduced the lifecycle impacts of nuclear energy.

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[31] WNA, Conversion and deconversion, https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/conversion-and-deconversion.aspx

[32] WNA, Uranium Enrichment

Step 3 is fuel fabrication. This involves converting the now enriched UF_6 into a highly stable, temperature resistant compound and then processing this into a form which fits the physical dimensions and chemical conditions inside a specific reactor. For the majority of the world's currently operating reactors, this process involves converting UF_6 to UO_2 powder, slugging this powder into a small pellet, and then loading these pellets into zirconium-alloy fuel assembly. At this stage of the fuel-cycle nuclear fuel becomes bespoke.

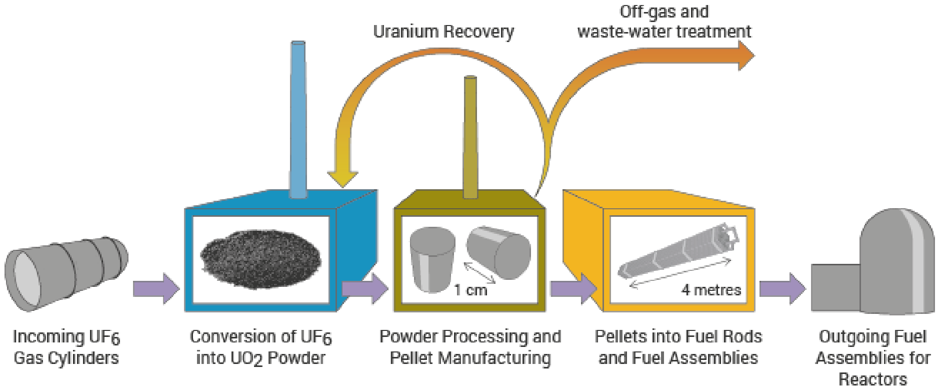

Figure 12 The Nuclear fuel fabrication process

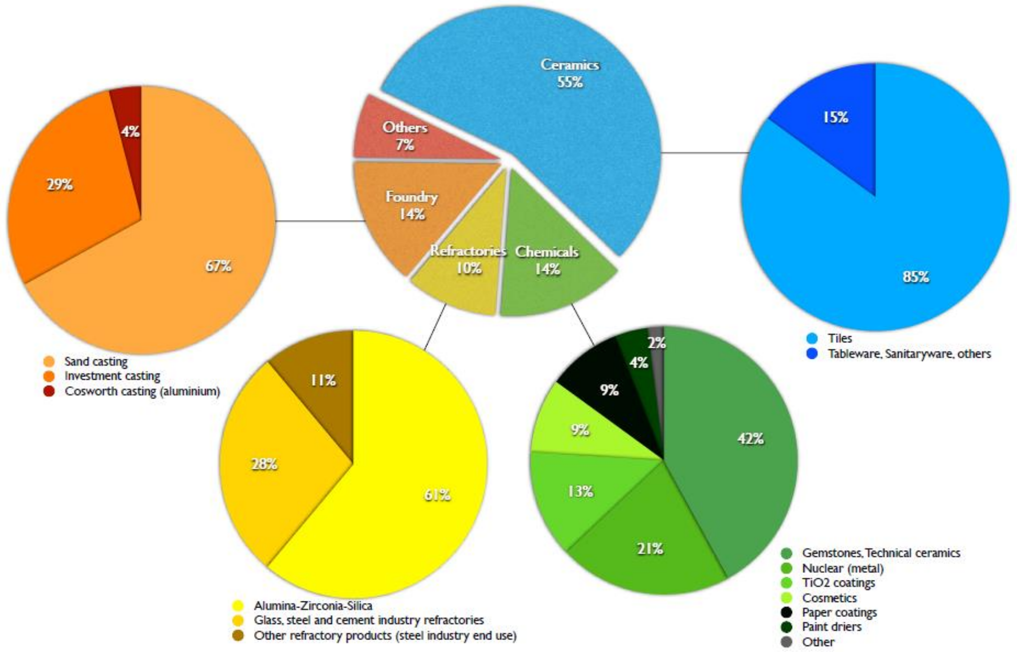

Figure 13: Global zircon consumption by end-use market[33]

The main non-uranium material input at this stage of the process is zirconium alloy. This has the property of being mostly transparent to neutrons and therefore does not interfere with reactivity. The alloy will also contain small amounts of tin, niobium, iron, chromium and nickel to provide necessary strength and corrosion resistance. Hafnium, which typically occurs naturally with zirconium deposits, needs to be removed because of its high neutron absorption cross-section.

The natural mineral zircon (zirconium silicate) is currently mined at a rate of approximately 1.2 million megatonnes per year. Around half the global demand for zircon is for the ceramics industry (as an opacifier/whitener). The balance goes into refractories, foundries, zirconium-based chemicals and specialist applications. Zirconium (Zr) metal (and alloys) fall under the zirconium chemicals section and are produced via a complex chemical route. The nuclear industry consumes only a tiny fraction of the zircon mined annually, but about half of all Zr metal.[34]

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[33] Zirconium Industry Association, Technical Handbook on zirconium and zirconium compounds 2019
[34] Conversation with Zirconium Industry Association

4. Nuclear power generation

Nuclear power plants produce large amounts of reliable low-carbon heat and electricity but without the emissions of fossil fuels and requiring less land and mineral resources than renewables. The main impacts of nuclear power plants are the production of radioactive wastes and local impacts on the aquatic environment.

Nuclear fission takes place inside the fuel that is loaded into the reactor. Each fission event creates useful heat, but also radioactive daughter elements and neutrons which can activate other materials. Whereas fresh nuclear fuel is quite homogenous and consists overwhelmingly of uranium, after it has been in a reactor for a few years a range of new elements will be present and the fuel will become intensely radioactive. Managing radioactive materials produced via fission is considered the principle environmental responsibility of nuclear power operations. This is described further in the next section.

There are a range of nuclear power technologies currently available, and many more becoming available as a result of ongoing R,D & D. While distinct in important ways they almost all follow the basic design parameters. A nuclear power plant can be broken down into two main 'islands', the 'nuclear island' and the 'turbine island'. The nuclear island houses the reactor and the components that together go towards the production of steam. These will be housed within a robust radiation containment structure (typically steel-reinforced concrete), which will usually also contain the fuel storage. The 'turbine island' encompasses the turbine-generator set and condensing equipment. Here the present energy in steam is converted to electricity (via the rankine cycle of thermodynamics) before this residual steam is converted back to water and sent back to the nuclear island.

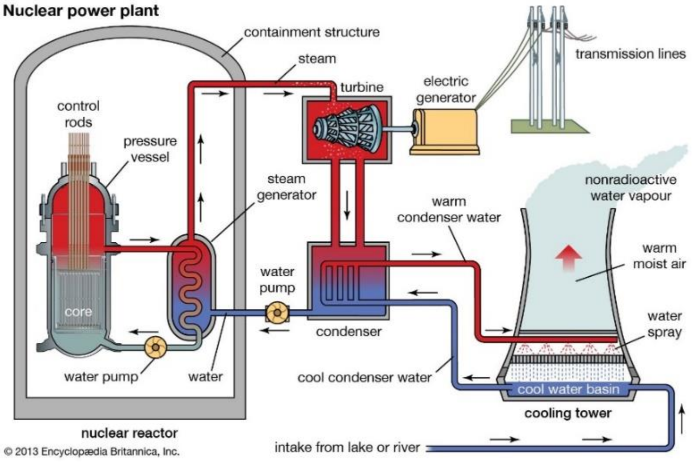

Figure 14: A schematic of a (closed loop pressurised water reactor) nuclear power plant

A key safety responsibility of nuclear power operators is the prevention of the accidental releases of radioactive material. During normal operations the radioactive materials produced from fission stay locked up inside fuel assemblies. This means that the primary hazard is effectively contained and nuclear plants operate with no dangerous environmental emissions. However, if the temperature inside a reactor gets too hot then fuel assemblies will melt and radioactive material will be released, which can depending on the circumstances potentially escape containment. Loss of cooling was the ultimate cause of the three major nuclear accidents that have taken place at the Three Mile Island, Chernobyl and Fukushima nuclear plants.

The nuclear safety paradigm that operators adhere to is complex and extensive. It has an engineering element known as defence in depth, which aims to ensure high quality design and construction, and multiple back ups in case of human error or equipment malfunction. It encompasses human performance and requires that managers create a safety culture that permeates the organisation and makes responsibility part of every worker's job. It requires practise and preparation for what to do in case an accident situation develops. It involves the sharing of information and exchange of best practise among other nuclear operators, so that every incident is learnt from. The World Association of Nuclear Operators, which includes every nuclear operator in the world as members, has published a pocketbook on the traits of a healthy nuclear safety culture[35] More information on nuclear safety practises is contained in the WNA information library[36].

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[35] World Association of Nuclear Operators, 2023, Traits of a healthy Nuclear Safety culture https://www.wano.info/getmedia/49f169b0-a385-4cd2-a7d8-2f64b64cd8d2/WANO-PL-2013-1-Pocketbook-English.pdf.aspx

[36] WNA, Safety of Nuclear Power Reactors https://world-nuclear.org/information-library/safety-and-security/safety-of-plants/safety-of-nuclear-power-reactors.aspx

The three serious nuclear power reactor accident that have occurred have all contributed to strengthening this paradigm. For instance, after the Fukushima Daiichi accident nuclear operators worldwide subjected their facilities to a series of stress tests[37] designed to work out how their plant would respond in the face of multiple simultaneous external ‘cliff-edge’ events (such as an earthquake and tsunami)

One important thing these reactor accidents have taught us is that the radiation risks of nuclear energy have previously been greatly exaggerated. According to UNSCEAR, the Chernobyl accident – universally acknowledged as the worst nuclear accident ever – resulted in 30 near-term fatalities due to burns and acute radiation sickness in plant workers and emergency responders. The only other serious impact attributable to radiation from the accident was an increased rate of thyroid cancer in the region amongst those who were children at the time of the accident. The most recent count of thyroid cancers suggests that around about 5,000 cases can be attributed to the accident[38]. However, the disease is highly treatable with a greater than 99% survival rate reported in the affected populations to date. For the Fukushima nuclear accident, UNSCEAR does not expect researchers to be able to discern any radiation related health impacts at all[39].

Rather than causing fatalities, it has been estimated that since 1970 the operation of nuclear power plants has helped to prevent 1.8 million early fatalities that would have been associated with emissions from other, more polluting, energy sources[40]. Fossil fuel use in power plants, industrial facilities and vehicles are the main cause of outdoor pollution linked to around 4 million premature deaths each year[41] as well as contributing to devastating environmental impacts such as acid rain and climate change. Indoor air pollution from cooking fires in low and middle income countries is estimated to cause a further 3.8 million premature deaths annually that could be avoided if people had improved access to clean energy. These impacts are taken for granted with combustion-based technologies, but the best available evidence shows us that nuclear energy causes relatively few direct impacts to health – even when the effects of serious accidents are considered.

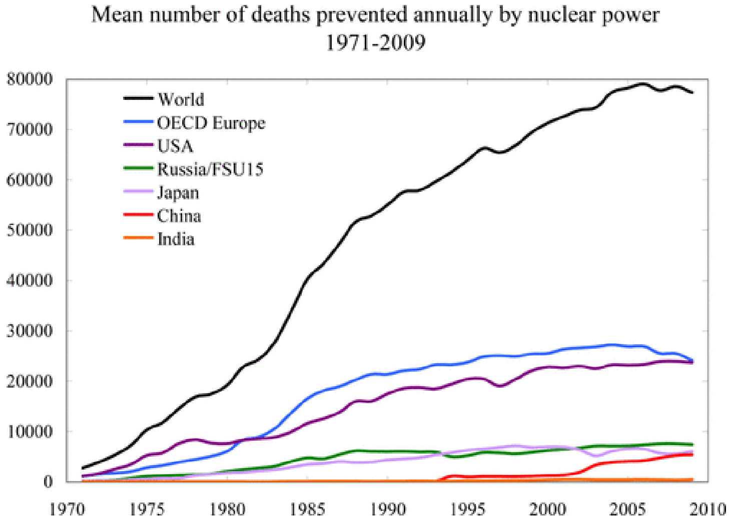

Figure 15: mean number of deaths prevented annually by nuclear power 1971 - 2009[42]

Nuclear power plants are allowed to discharge small amounts of radioactive materials, provided they do not accumulate in the environment or expose nearby members of the public to a dose of greater than 1 milliSievert per year. Chiefly this involves small quantities of inert radioactive gases to the atmosphere (krypton-85 and xenon-133) and tritium released to water. These emissions are tightly regulated.

Besides radiation the other main impact on the environment of nuclear power plants relates to their water requirements. Nuclear power plants require large amounts of water for cooling purposes just like other thermal energy sources such as coal, gas and biomass. The thermal efficiency of a nuclear plant varies according to

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[37] ENSREG, EU Stress tests and follow-up, https://www.ensreg.eu/EU-Stress-Tests

[38] UNSCEAR, 2017, *Evaluation of Data on Thyroid Cancer in Regions Affected by the Chernobyl Accident*

[39] UNSCEAR, 2017, *Developments Since The 2013 Unscear Report On The Levels And Effects Of Radiation Exposure Due To The Nuclear Accident Following The Great East-Japan Earthquake And Tsunami*

[40] Hansen, Kharecha, 2013, *Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power* http://pubs.acs.org/doi/abs/10.1021/es3051197

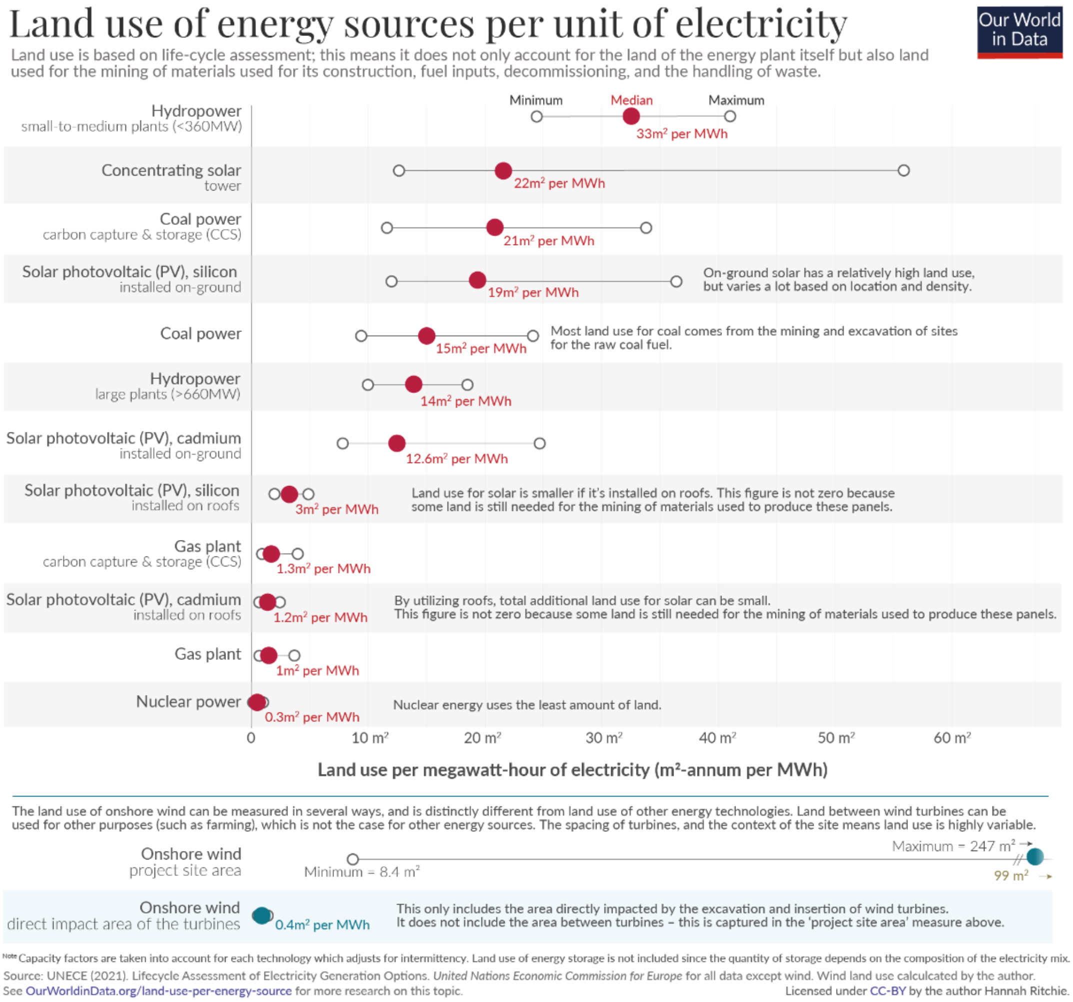
[41] World Health Organisation *Fact sheet on Air Pollution* https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health , (updated 2 May 2018)

[42] Ibid footnote 39

reactor design and the environmental conditions of where it is located, but a typical value is 33 percent. This means that 66 percent is released back into the environment as heat.

Cooling water must be extracted from a local water body and in most cases returned to it or a nearby body in a process which heats and consumes water. This process can harm local aquatic species and especially kill fish eggs larvae in what (superficially) appear to be large numbers. However, whether this adds significantly to ecosystem stress levels depends on the local aquatic context. Water withdrawal and consumption is not an important metric if local water availability is not an issue. Careful plant siting goes a long way to reduce most potential species impacts while there are measures that can be taken to mitigate aquatic stress if it develops. On the other hand, nuclear plants cooling systems can also act as havens for certain species, while the warm regions created at thermal outlets can even support biodioversity and abundance hotspots.

The aquatic impacts of nuclear technologies are similar in nature to the impacts of wind turbines on certain avian species and the local heating/cooling effects these create via atmospheric mixing[43]. Even large-scale solar pojects have been found to give rise to a heat-island effect[44]. However, while the aquatic impacts of nuclear plants will be localised, the low energy density of wind turbines and the larger areas required will invariably mean they end up having a greater impact on biodiversity – especially as this technology scales. Our World In Data has produced this chart highlighting the land use of different energy technologies[45].



Land use of energy sources per unit of electricity

Land use is based on life-cycle assessment; this means it does not only account for the land of the energy plant itself but also land used for the mining of materials used for its construction, fuel inputs, decommissioning, and the handling of waste.

On-ground solar has a relatively high land use, but varies a lot based on location and density.

Most land use for coal comes from the mining and excavation of sites for the raw coal fuel.

Land use for solar is smaller if it's installed on roofs. This figure is not zero because some land is still needed for the mining of materials used to produce these panels.

By utilizing roofs, total additional land use for solar can be small. This figure is not zero because some land is still needed for the mining of materials used to produce these panels.

Nuclear energy uses the least amount of land.

The land use of onshore wind can be measured in several ways, and is distinctly different from land use of other energy technologies. Land between wind turbines can be used for other purposes (such as farming), which is not the case for other energy sources. The spacing of turbines, and the context of the site means land use is highly variable.

This only includes the area directly impacted by the excavation and insertion of wind turbines. It does not include the area between turbines – this is captured in the 'project site area' measure above.

Note Capacity factors are taken into account for each technology which adjusts for intermittency. Land use of energy storage is not included since the quantity of storage depends on the composition of the electricity mix.

Source: UNECE (2021). Lifecycle Assessment of Electricity Generation Options. *United Nations Economic Commission for Europe* for all data except wind. Wind land use calculated by the author.

See OurWorldinData.org/land-use-per-energy-source for more research on this topic. Licensed under CC-BY by the author Hannah Ritchie.

Figure 16: Land use of Energy Sources per unit of electricity

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[43] Qin et al, Environmental Research Letters, Feb 2022, *Impacts of 319 wind farms on surface temperature and vegetation in the United States*

[44] Barron-Gafford et al, Nature Scientific Reports, Oct 2016, *The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures*

[45] Our World in Data, 2022, *How does the land use of different electricity sources compare*? https://ourworldindata.org/land-use-per-energy-source

5. Nuclear waste management and disposal

Radioactive wastes are by-products of the operation of nuclear reactors and related fuel cycle activities. The management of nuclear waste has been meticulously handled since the inception of the civil nuclear industry in the 1950's and there has never been a serious accident in transport or storage.

Radioactive materials and wastes are produced across the nuclear fuel cycle, and especially at the point of nuclear power generation. Where there is no plan to reuse this material it is classified as waste. Like all types of waste, radioactive waste must be managed in ways that safeguard human health and minimize the impact on the environment both over the short and long term. For radioactive waste, this means isolating or diluting it such that the rate or concentration of any radionuclides returned to the biosphere is harmless. To achieve this, practically all radioactive waste is contained and managed, with some needing deep and permanent burial. Waste from nuclear power generation, unlike all other forms of electricity generation, is regulated – none is allowed to cause pollution. More information is available in the WNA information library[46].

The activities connected to the safe management of radioactive waste depend on the type of waste involved. The levels of radioactivity and types of radioactive materials varies greatly, but waste is typically categorised in three or four main classes, as shown in Figure 17. The nuclear industry keeps good tracks of the inventory on waste volumes. No other sector reports so precisely on this impact.

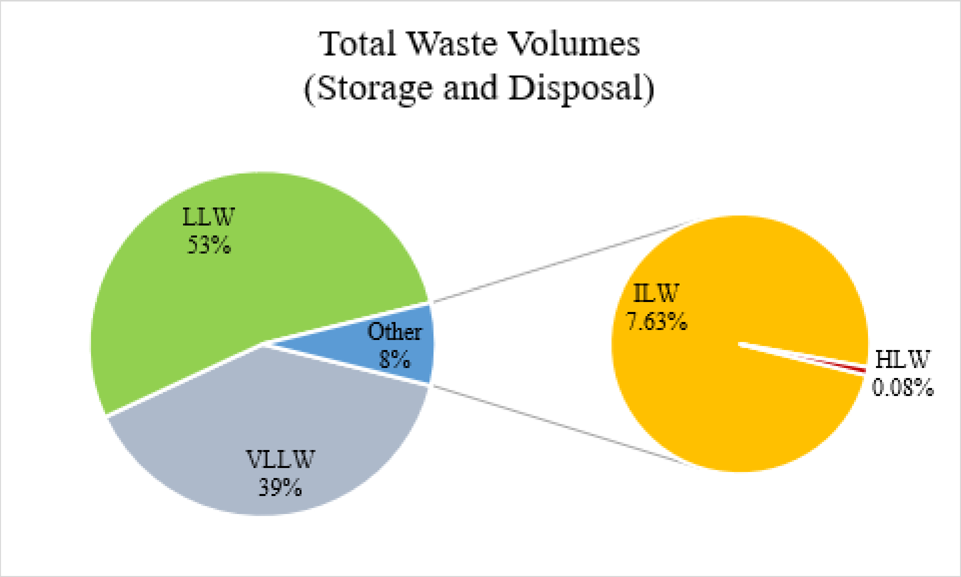

Figure 17: total waste volumes (Storage and disposal) across four classes of nuclear waste (VLLW, LLW, ILW and HLW)[47]

Disposal facilities for Low Level Waste (LLW) and the sub-class Very Low-Level Waste (VLLW) are already in operation in several countries. Taken together these waste streams account for more than 92% of the volume but less than 2% of the radioactivity of all radioactive waste produced in nuclear power sector. LLW does not generally require significant shielding during handling or interim storage, and is suitable for disposal in engineered near-surface facilities.

Most of the radioactivity associated with nuclear energy production is contained in Intermediate Level Waste (ILW) and High Level Waste (HLW) including spent fuel if declared as waste. Taken together, they typically comprise more than 95% of the total radioactivity of the global inventory.

ILW generally contains significant amounts of long-lived radionuclides and therefore requires disposal at depths that will provide isolation from the biosphere over the long term. ILW requires shielding during both handling and storage. The only currently licensed disposal facility for long lived ILW is the Waste Isolation Pilot Plant (WIPP), USA. Here, long lived, non-heat-generating waste from defence activities is disposed of in a geological repository built in salt beds. Elsewhere, ILW is being held in interim storage until a disposal facility suitable for this material becomes available.

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[46] WNA, Radioactive Waste Management https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx

[47] IAEA report on Status and Trends in Spent Fuel and Radioactive Waste Management https://www.iaea.org/publications/14739/status-and-trends-in-spent-fuel-and-radioactive-waste-management

By far the highest level radioactive waste comes in the form of used nuclear fuel. This is intensely radioactive upon discharge from the reactor. While that radioactivity does diminish quickly the long-lived radioactive elements present mean that it will stay radioactive for hundreds of thousands of years and final disposal facility needs to be designed accordingly. Currently two strategies are employed for managing used fuel from power reactors: either it is considered to be waste or it is treated as an asset. In the latter case, additional treatment (known as reprocessing) is necessary to recover and recycle uranium and plutonium, generating High Level Waste (HLW) as a by-product. If the spent fuel is declared as a waste, it is considered as HLW.

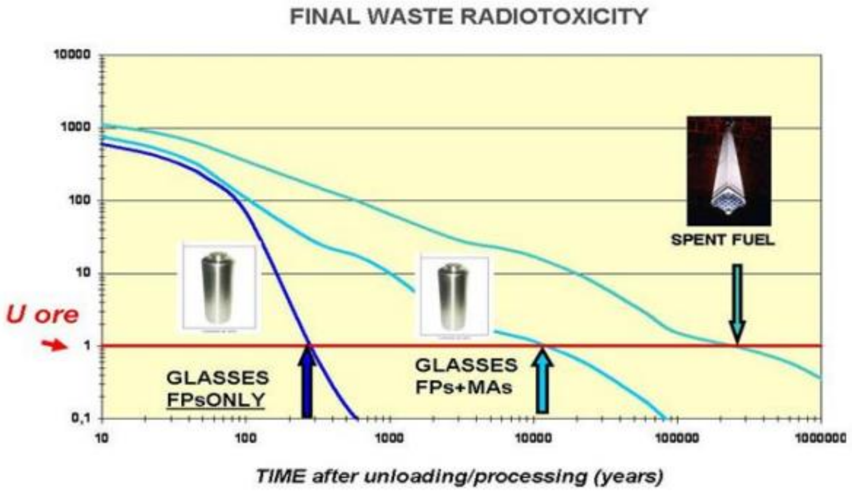

Figure 18: Final radiotoxicity of used nuclear fuel years after discharge from a reactor. FP = fission products. MA =major actinides. These are by-products of reprocessing.

Nuclear waste inventory (IAEA estimates, 2022)[48]

	Solid radioactive waste in storage (m3)	Solid radioactive waste in disposal (m3)	Proportion of waste type in disposal
VLLW	2,918,000	11,842,000	80%
LLW	1,471,000	18,499,000	92%
ILW	2,740,000	133,000	5%
HLW	29,000	0	0%

*Note: all volumetric figures are provided as estimates based on operating and proposed final disposal solutions for different types of waste. Figures, published in January 2022, are estimates for end of 2016.

While there has been little progress with the disposal of HLW to date, this is slowly beginning to change. Significant developments have recently taken place in several countries. In 2022 the construction licence for the deep geological repository (DGR) was approved in Sweden, while the operational licence was submitted for a deep geological disposal facility in Finland. France officially recognized deep geological disposal as its final disposal solution for high level and intermediate level long lived radioactive waste.

For all countries, key to the assurance of the eventual safe disposal of nuclear wastes is the presence of a funded waste disposal plan. Nuclear facility operators are required to channel money towards this as part of their license to operate. In this way a potential environmental externality is internalised.

The national arrangements for protecting people and the environment from the potential negative effects of ionizing radiation from used fuel and radioactive wastes vary from country to country. However, there are some common features which take into consideration international treaties and standards. A basic prerequisite, as stated in several international instruments including the IAEA's Fundamental Safety Principles[49] , the Joint

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[48] IAEA report on Status and Trends in Spent Fuel and Radioactive Waste Management https://www.iaea.org/publications/14739/status-and-trends-in-spent-fuel-and-radioactive-waste-management

[49] IAEA, Fundamental Safey Principles, Safety Fundamentals SF-1, IAEA, Vienna, 2006.

Convention[50] and the Euratom Waste Directive[51], is that the prime responsibility for ensuring the safety of spent fuel and radioactive waste management rests with the licence holder.

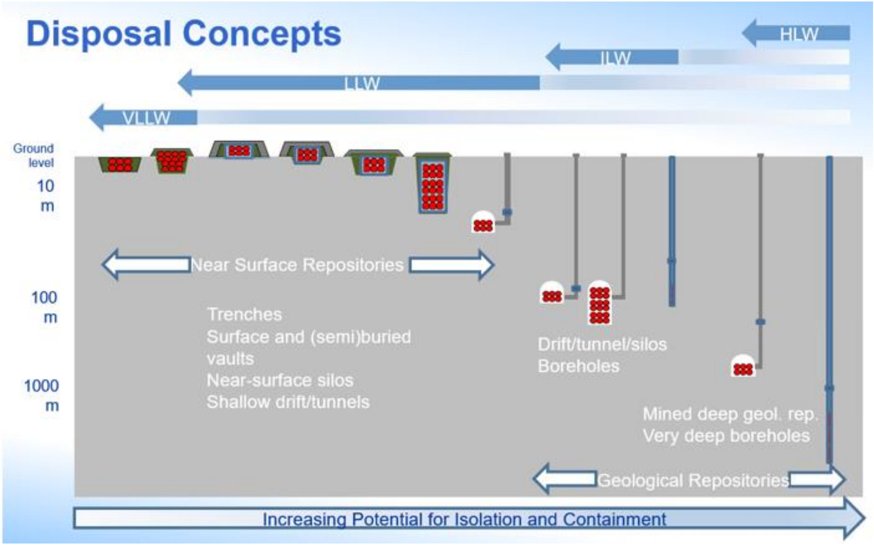

Figure 19: Conceptual illustration of disposal concepts for different classes of radioactive waste[52]

5.1 Comparison to waste streams of renewables

While materials used in nuclear power production are considered ‘cradle-to-grave’, there has been little consideration of waste products and decommissioning for other climate change solutions. Currently there are no significant end-of-life recycling solutions in place for technologies such as wind turbines, solar photovoltaic panels and batteries, which are essential for Europe’s (and indeed the world’s) transition to climate neutrality.

Due to the significantly lower energy density of renewables, and short operational lifetimes (~25 years for wind and solar units), there will be large volumes of toxic waste arising from the energy transition, as shown by the intensity of the minerals required in mining. This waste will also remain toxic indefinitely, with no decrease in toxicity over time as associated with the half-life of radioactivity of nuclear wastes.

Waste arising from end-of-life clean energy infrastructure is projected to grow up to 30-fold over the next 10 years, and will present a significant environmental challenge. Figure 20 shows that substantial amounts of new types of waste will be generated over the coming years by the infrastructure required for the transition to clean energy, while Figure 21 present the cumulative waste volumes of PV panels by 2050 as projected by IRENA.

There is of course potential to safely manage these waste streams, and improved efficiencies, operational lifetimes and performance will help reduce volumes. Similar to nuclear energy, there is also an opportunity to recycle the materials of these units to both reduce consumption of scarce raw materials and reduce the volumes of toxic waste destined for disposal. Circular economy approaches such as repair and upgrading of equipment and recycling of end-of-life infrastructure can underpin the sustainability credentials of Europe’s renewable energy transition.[53]

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[50] Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, “INFCIRC/546,” IAEA, Vienna, 1997.

[51] Council Directive 2011/70/Euratom of July 2011 Establishing a Community framework for the responsible and safe management of spent fuel and radioactive waste,”

[52] IAEA, Status and Trends in Spent Fuel and Radioactive Waste Management, IAEA Nuclear Energy Series No. NW-T-1.14, IAEA, Vienna (2018)

[53] Emerging waste streams: Opportunities and challenges https://www.eea.europa.eu/publications/emerging-waste-streams-opportunities-and

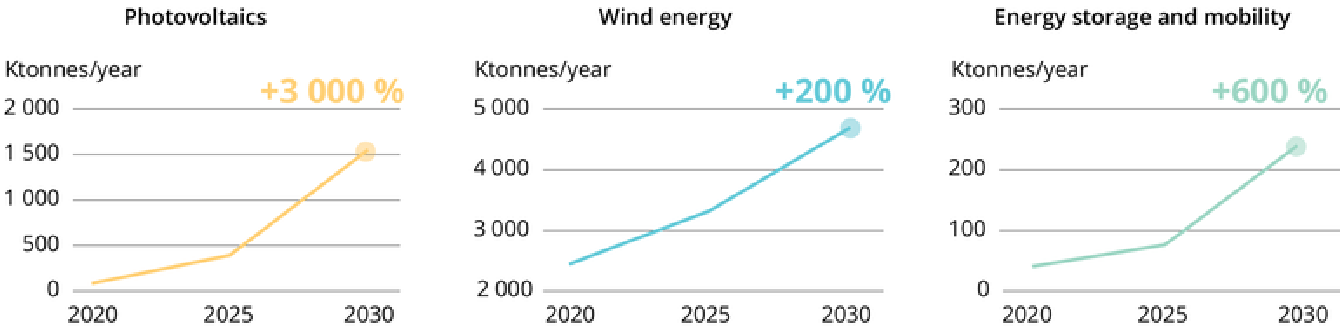

Figure 20: Expected growth of waste materials generated by non-nuclear clean-energy technologies.[54]

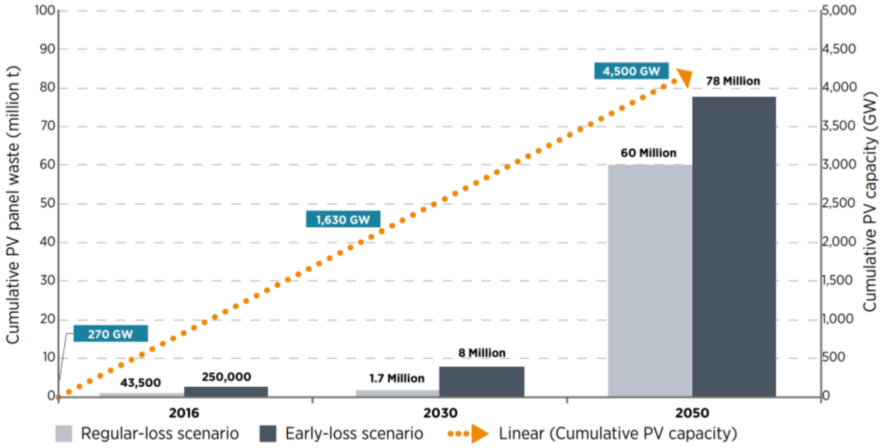

Figure 21: Overview of global PV panel waste projections, 2016-2050[55]

However, there are many difficulties associated with solar, wind and battery recycling. Key challenges remain in PV recycling, both in economic and technological terms, around the delamination, separation and purification of silicon from the glass and the semiconductor thin film. Other challenges for recycling of PV modules come from the presence of hazardous substances such as cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride.

Recycling infrastructure is still under development for wind turbine blades made of lightweight materials like carbon fibre, glass fibre and composite materials, with further research and implementation needed. The huge size of wind turbine blades also make transportation costs prohibitive for long-distance hauls to recycling facilities located far away. Similarly, there is also a lack of battery recycling technologies and large-scale recycling capacities in Europe, and the infrastructure to transport and store the growing number of waste batteries is deficient and needs to be built up to cope with predicted future high volumes of end-of-life batteries.

For all technologies the associated costs would be many times more to recycle than to send units to landfill. As a result, widescale recycling is not likely to take place without an increase in the cost of raw materials and/or disposal, or strict policy and regulation. From this perspective, the nuclear industry offers a useful case study to the renewables sector on how to fund and more sustainably manage the disposal of their waste streams.

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[54] ibid

[55] IRENA, End-of-Life Management: Solar Photovoltaic Panels https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf?rev=49a75178e38c46288a18753346fb0b09