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Group of Experts on Cleaner Electricity Systems

Draft Nuclear Energy Technology and Policy Brief

Note by the Task Force on Carbon Neutrality

I. Introduction

1. This document is being developed by the United Nations Economic Commission for Europe (ECE) as part of implementation of the extrabudgetary project on “Enhancing the understanding of the implications and opportunities of moving to carbon neutrality in the ECE region across the power and energy intensive industries by 2050” (Carbon Neutrality project).

2. This technology and policy brief on nuclear energy is one of a series of briefs that will be developed as part of the workstream to assess the contribution of selected technologies to attain carbon neutrality under the project.

3. The purpose of this document is to provide a summary on nuclear technologies, both those that are available now as well as those that are in research and development and are expected to be available commercially in the near future. Information is provided on the role that innovative new reactor designs, such as small modular reactors (SMRs), could play in complementing larger reactor technologies and helping to open up new markets and applications for nuclear energy – such as district heating, high temperature process heat and hydrogen production as well as providing electricity to small, distributed or remote power networks. Information is also provided on a range of topical areas including costs, socioeconomic impacts, health and environmental impacts, key innovations and enabling policies.

4. The document is being prepared by the Task Force on Carbon Neutrality for the Group of Experts on Cleaner Electricity Systems (Group of Experts). An initial draft is intended for discussion at the workshop on “Role of Nuclear Energy to Attain Carbon Neutrality in the UNECE region” on 23 November 2020. The objective of the workshop is to improve understanding about nuclear energy technology fundamentals and the role that nuclear energy can play to attain carbon neutrality. The session also will explore the key factors determining future development in nuclear energy.

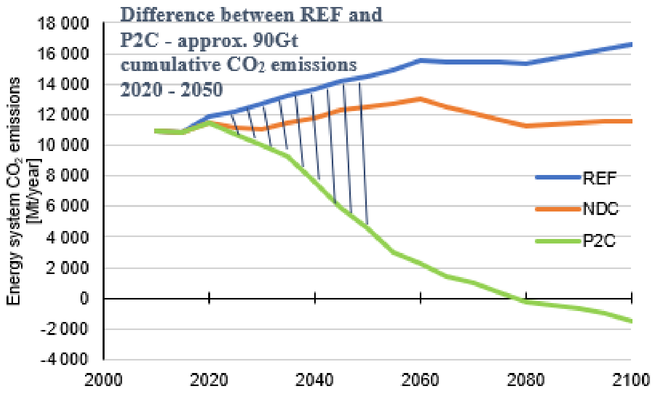
II. Background

5. Energy is critical for the attainment of the 2030 Agenda for Sustainable Development (2030 Agenda). It is the 'golden thread' that runs through all the Sustainable Development Goals (SDGs) and connects them. Achieving greater quality of life in all countries while protecting the natural world will require both expanding energy access and fully transitioning to clean energy technologies over the coming decades.

6. In recent years, the need for urgent climate action (as recognised in SDG 13) has become the focus of ever greater international attention. The United Nations have recognised that we are now in a "climate emergency"[1]. 188 countries are now Parties to the Paris Agreement, that aims to strengthen the global response to the threat of climate change by keeping the global temperature rise well below 2°C above pre-industrial levels. Given that energy production and use is the source of around 75% of global anthropogenic CO_2 and greenhouse gas emissions as a whole[2], successfully achieving this target will require dramatic transformation of the global energy system.

7. Results from an earlier UNECE project called "Strengthening the Capacity of the ECE Member States to Achieve the Energy-related Sustainable Development Goals – Pathways to Sustainable Energy"[3] (Pathways Project) show that the countries in the ECE region will need to reduce their dependence on fossil fuels by switching to low emission energy technologies and also make use of carbon capture technologies to achieve negative emissions. The countries in the ECE region need to cut or capture at least 90 gigatonnes (Gt) of CO_2 emissions by 2050 in order to stay on a pathway that meets the 2ºC target (Figure I). The blue line reflects the level of emissions that are expected if ECE countries continue with business as usual climate policies. The green line, or P2C scenario, shows what must happen for emissions in the region to stay within the 90Gt budget with net emissions going negative after 2080. The orange line shows how much emissions reduction are currently accounted for in nationally determined contributions that ECE countries have pledged as part of the Paris Agreement. There is an enormous gap that needs to be filled and all available low-carbon technologies will need to be deployed at the earliest opportunity. No low-carbon technology can afford to be 'left off the table'.

Figure I: **CO_2 Emissions in the ECE Region by Policy Scenario**[4]



8. Nuclear energy is a low-carbon energy source that has played a major role in avoiding CO_2 emissions. Over the past 50 years, the use of nuclear energy has reduced global CO_2 emissions by about 74Gt, or nearly two years' worth of total global energy-related emissions, as shown in Figure II. Only hydropower has played a greater role in reducing historic

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[1] António Guterres, September 2019, Remarks at 2019 Climate Action Summit,

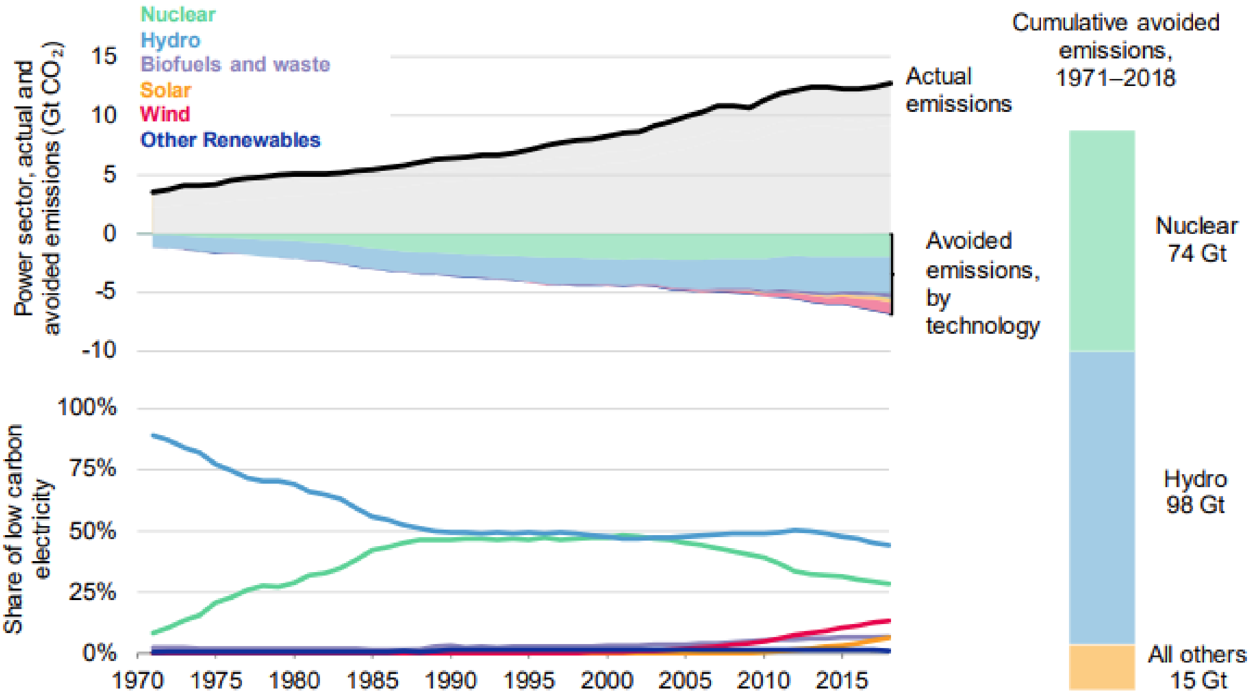
[2] Our World In Data, 18 September 2020, Sector by sector: where do global greenhouse gas emissions come from?

[3] See ECE/ENERGY/GE.5/2020/3

[4] ibid

emissions. Looking forward, for many countries, nuclear energy will form part of the quickest[5], least cost[6] and lowest risk[7] decarbonisation pathway.

Figure II: Cumulative CO_2 emissions avoided by low-carbon energy sources[8]



III. Status of nuclear energy today

9. Today, nuclear energy provides a significant share of low carbon electricity in the UNECE region. Nuclear energy provides the largest contribution of low carbon electricity in EU 27 countries, generating 26.7% of overall supply in 2019, as illustrated in Figure III. However fossil fuels as a whole still provided 42.8% of the total EU generation. Nuclear energy provides the largest source of low-carbon electricity in a number of ECE countries, as shown in Figure IV, including France, Slovenia, Slovakia, Hungary, Sweden, Belgium, Bulgaria, Czech Republic, Finland, Slovenia, Finland, Spain, Ukraine and the United States. As shown in Table 1, 20 ECE Member States currently operate nuclear power plants and 15 countries either have new reactor under construction or are actively planning them. Furthermore 7 ECE member states are in the process of developing nuclear power programmes for the first time[9]. A number of ECE countries – such as Czech Republic, Finland, Hungary, Poland and the United Kingdom – have explicitly stated that nuclear energy will play an important future role in reducing their national emissions in the future.

10. While the global growth of nuclear energy is considered necessary to reach climate targets, the current rate of nuclear growth globally is not fast enough to prevent a temperature rise of greater than 2°C. For example, the 89 mitigation scenarios in the IPCC 1.5°C report published late in 2018 postulate that nuclear generation grows by around 2.5 times by 2050 from today's level. In addition, the 'middle-of-the-road' illustrative scenario in which social, economic, and technological trends follow current patterns and there are no major changes to diet and travel habits, for example, sees the need for nuclear increase by six times globally by 2050, providing 25% of electricity. Nuclear deployment would need to accelerate dramatically in the years ahead to meet these targets.

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[5] See figure 2 Cao et al, 05 August 2015, China-U.S. cooperation to advance nuclear power

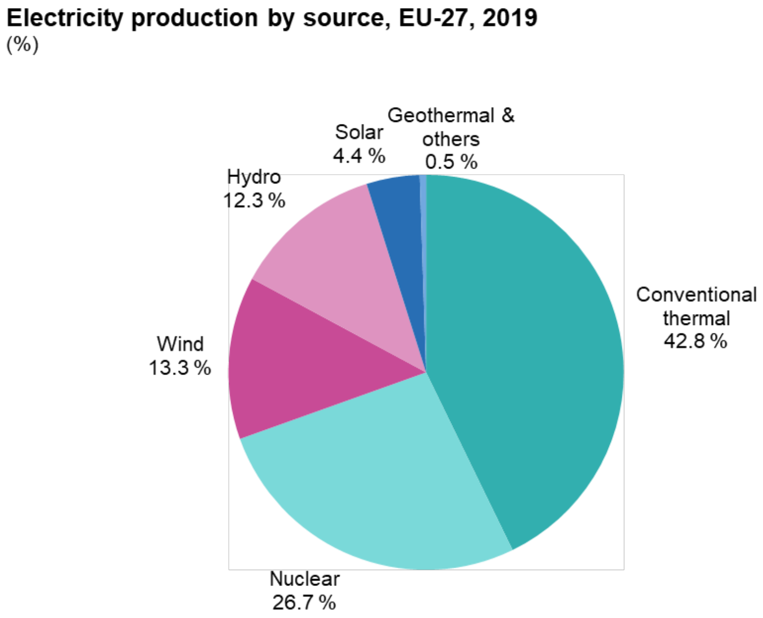
[6] MIT, 2018, The Future of Nuclear Energy in a Carbon Constrained World,

[7] Jenkins et al, November 2018, Getting to Zero Carbon Emissions in the Electric Power Sector, Joule

[8] Image source IAEA, Nuclear Power and Climate Change (2020 edition)

[9] See World Nuclear News, 09 September 2020, Poland plans USD40bn investment in new nuclear plants

Figure III: EU 27 Electricity Statistics in EU 27 countries 2019



Source: Eurostat (online data code: nrg_cb_pem)

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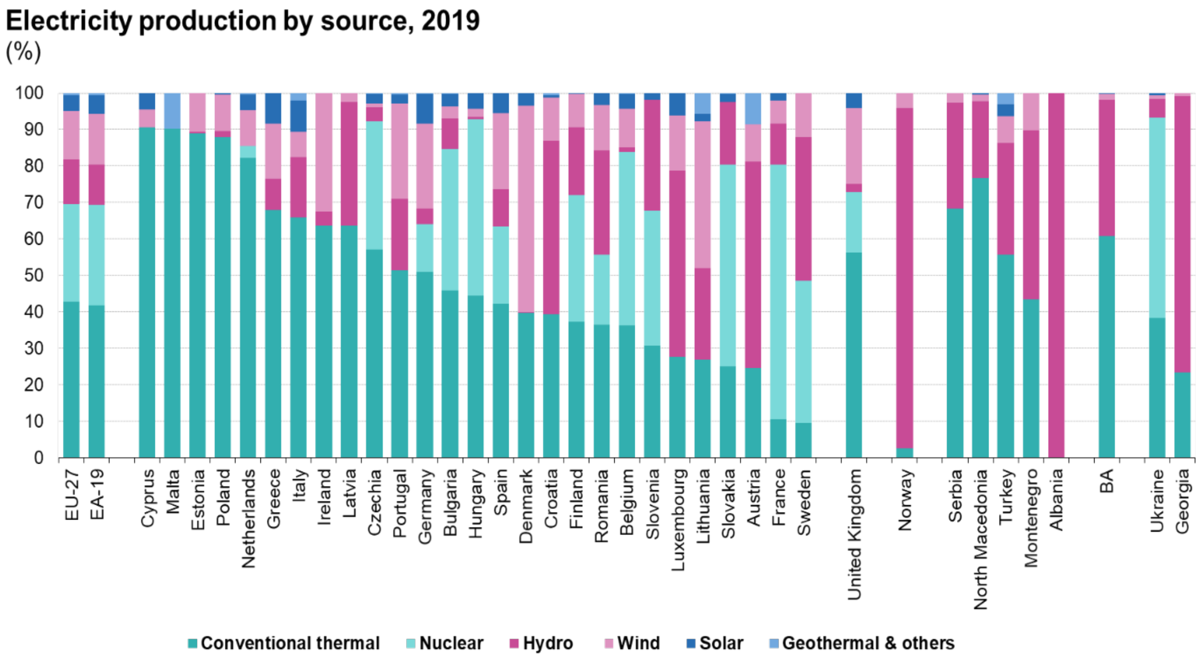
Figure IV: EU 27 Electricity production by source 2019



Source: Eurostat (online data codes: nrg_cb_em, nrg_cb_pem)

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Table I: Nuclear energy in UNECE member countries

ECE Countries with operating power reactors	number of operating power reactors	installed nuclear capacity (MW)	nuclear percentage of electricity (2019)	Number under construction	current nuclear plans
ARMENIA	1	375	28	0	1 new reactor proposed. Long term operation of existing reactor
BELGIUM	7	5930	48	0	Phase out by 2025
BULGARIA	2	2006	38	0	At least one new reactor currently planned. Investigating SMRs
CANADA	19	13554	15	0	Actively licensing multiple SMRs* and investigating potential
CZECH REPUBLIC	6	3932	35	0	At least 1 new large reactor currently planned. Investigating SMRs
FINLAND	4	2794	35	1	1 new large reactor planned. Actively investigating SMRs
FRANCE	56	61370	71	1	6 new reactors proposed. Government intends to reduce nuclear to 50% of mix
GERMANY	6	8113		0	Phase out by 2023
HUNGARY	4	1902	49	0	2 new large reactors planned
NETHERLANDS	1	482	3	0	Currently consulting on new build
ROMANIA	2	1300	19	0	2 new large reactors currently planned. Investigating SMRs
RUSSIA	38	28437	20	4	21 new reactors planned. Further 26 proposed (mix SMRs and large)
SLOVAKIA	4	1814	54	2	At least 1 further large reactor proposed
SLOVENIA	1	688	37	0	1 new large reactor proposed
SPAIN	7	7121	21	0	No new reactors currently planned
SWEDEN	7	7740	34	0	No new reactors currently planned
SWITZERLAND	4	2960	24	0	All new nuclear build is currently forbidden
UKRAINE	15	13107	54	2	At least 2 new reactors
UNITED KINGDOM	15	8923	16	2	At least 4 new large reactors currently planned. SMR development funded
UNITED STATES OF AMERICA	95	97154	20	2	10 New large reactor projects authorised. Multiple SMRs being developed One SMR design now licensed
Newcomers in ECE region					
BELARUS	0	0	0	2	1 new large reactor under construction. First reactor now connected to grid and approaching commercial operation
ESTONIA	0	0	0	0	Actively investigating SMR deployment
KAZAKHSTAN	0	0	0	0	At least one large reactor proposed. SMRs are being investigated
LITHUANIA**	0	0	0	0	2 new large reactors proposed (suspended)
POLAND	0	0	0	0	6 new reactors planned by 2040
TURKEY	0	0	0	2	2 units under construction and 2 others planned. 8 further large reactors proposed
UZBEKISTAN	0	0	0	0	2 -4 new large reactors planned. Investigating SMRs

* SMRs are small modular reactors. See section on nuclear technology and applications

**Lithuania used to have a nuclear plant operation. It is listed here although not technically a nuclear ‘newcomer’

IV. Nuclear energy technologies and applications

11. Nuclear energy is a well-established, proven source of electricity and a vital tool for helping the world successfully mitigate the impacts of climate change. It continues to evolve with new technologies under development that promise to expand the envelope of nuclear energy applications and increase its integration with variable renewable energy sources in a future, decarbonised energy mix.

12. Today's nuclear power plants are thermal plants that heat water to create steam in order to turn a turbine generator, just like a coal or gas power plant. However, their fuel consists of processed uranium, plutonium and (potentially) thorium, rather than hydrocarbons, and the heat is produced via nuclear fission rather than chemical combustion. Fission is an incredibly energetic process that releases about a million times more energy than combustion. This means that comparatively small amounts of nuclear fuel are required and it is possible to fully contain the small amounts of waste generated.

13. There are three main classes of reactor technology: large (gigawatt-scale) reactors, small modular reactors (SMRs) and micro-reactors. Large reactors are mature technologies and commercially available today while SMRs and micro-reactors are currently under development with some designs rapidly approaching commercial deployment. A lot of excitement surrounds these emerging new technologies

(a) Large reactors. Over the history of nuclear technology development reactor sizes have grown larger in order to take advantage of economies of scale. A range of mature standardised reactor/nuclear plant designs are currently available that range from about 750MW to 1800MW. These designs are all based on proven technologies and available from well-established international vendors. There are three main technology types on available: the pressurised water reactor (PWR), the boiling water reactor (BWR) and the pressurised heavy water reactor (PHWR). Sodium cooled fast reactors (SFR) are also being pursued by several countries. The main technical differences between these technologies is driven by the choice of moderator and coolant. Today's large reactors are high performance machines capable of achieving capacity factors in excess of 90% and with expected operating lives of at least 60 years. Low fuel and operating costs mean that most operators will prefer to run them as baseload power plants, however they are capable of operating in load following mode if desired and can be adapted for district heating and hydrogen production via electrolysis.

(b) SMRs. Officially, SMR designs can be anywhere up to 300MW in electrical output. It should be noted that the first generation of nuclear power reactors were small, and many small reactors can be found onboard submarines and naval vessels today. What makes SMRs new is the fact that designs deliberately take advantage of their small size to integrate transformative safety features, to exploit new production models (such as enhanced modular construction and standardisation) and take advantage of new business cases. According to the IAEA there are now more than 70 such designs under development for different applications[10]. The range of technologies being developed for SMR include PWRs BWRs and PHWRs, but also a host of 'advanced reactors' technologies that make use of novel materials and configurations. Many SMRs are envisioned for electricity or energy markets where large reactors would not be viable. SMRs could fulfil the need of flexible power generation for a wide range of users and applications, including site replacement of aging fossil power plants, providing cogeneration, for countries with small electricity grids, and remote and off grid areas. Different SMR designs are now at different levels of technical readiness. Some, such as the water-cooled technologies can be considered highly mature, with a floating nuclear plant now built and operating in Russia – see Figure III – and another design now certified for use in the USA. Those based on novel technologies are further out from commercialisation. A

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[10] IAEA, 2020, Advances in Small Modular Reactor Technology Developments

conservative assessment is that water-cooled SMRs will be widely available during the 2030s, while advanced SMRs will be widely available sometime after that.

(c) Micro reactors. While not yet officially defined micro reactors are a subset of SMRs. They are expected to produce between 1 – 20 megawatts of thermal energy (or about 10 megawatts electric) and are designed to be transported as a fully contained heat or power plants both to and from potential sites. Early designs are being tailored for off-grid applications and to power army bases. Some micro reactor designs may be available in Western countries within five years, as they could be commercially viable without any reforms in the niche markets they are targeting (mostly competing with diesel generators in remote communities or facilities), and since designers and regulators are pursuing simplified licensing approaches.

Table II: Summary of nuclear reactor technologies

Reactor class and size	**Likely setting**	**Applications**	**Technologies**	**Readiness level***
Medium to Large Reactors >300MW electric	On-grid	Electricity Hydrogen production Desalination District heating	Reactor types: PWR, BWR, PHWR, sodium-cooled fast reactor (SFR) Conversion: Rankine cycle	PWR, BWR, PHWR TRL: 11 SFR TRL: 8-9
SMRs Up to 300MW electric	On or off-grid Large developed grids Small or non-developed grids Industrial processing Off-grid agriculture	Electricity Hydrogen production Desalination District heating Industrial process heat	Reactor types: PWR, BWR, molten salt reactor (MSR), very high temperature reactor (VHTR), gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR) and SFR Conversion: Rankine cycle, Brayton cycle	PWR SMR TRL : 6 - 9 Other SMRs TRL 2 - 8
Micro Reactors 1MW – 20 MW thermal	Off-grid Industrial facility Mining operations Remote communities Oil and gas platforms Off-grid agriculture	Electricity Desalination Transport District heating Industrial process heat	Reactor types: Fast reactor, high temperature gas-cooled reactor Conversion: Rankine Cycle, Brayton cycle, super critical steam, heat pipes, Stirling engines	TRL 2 - 6

*Based on IEA Energy Technology Perspectives categories[11]

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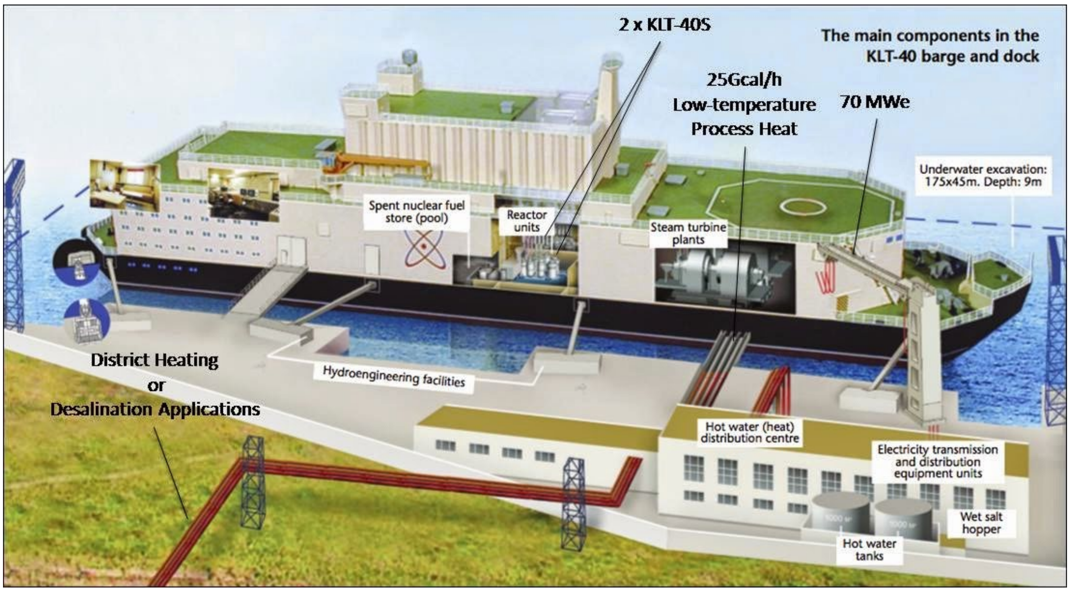
[11] IEA, 2020, ETP Clean Energy Technology Guide

Figure V: Example of an SMR. Schematic of Russia's floating nuclear power plant (now operating off the coast of Pevek)



14. Nuclear plants can be used for hydrogen production and indeed are one of the more promising means by which the production of this vital energy carrier can be decarbonised. Hydrogen has recently become a major focus of European and US climate policy initiatives because of its potential to support the decarbonisation of industry and transport as well as provide long-term seasonal energy storage. Nuclear energy can be used to produce hydrogen via several low-carbon processes:

(a) Low-temperature electrolysis of water (possible with existing reactors).

(b) High-temperature steam electrolysis, using heat and electricity from nuclear reactors (requires 600°C).

(c) High-temperature thermochemical production using nuclear heat (800 – 1000 °C).

Current nuclear reactor technologies and existing nuclear plants can be used for low-temperature electrolysis and offer several potential advantages including high electrolyser utilisation factors, low operating costs and the potential to use hydrogen in plant operations. The USA, UK and France are planning demonstrator nuclear electrolysis hydrogen production facilities. It is possible to use existing nuclear technologies for the last two pathways, but many of the advanced reactor technologies will operate at higher temperature and are expected to better match these requirements.

15. Hydrogen is only one example of a non-electric commodity that can be produced by nuclear technology. Other non-electric uses for nuclear include seawater desalination, district and process heat, synthetic fuels and chemicals, cooling and refrigeration and cogeneration applications. By alternating the production of nuclear plants from electricity to these uses depending on demand, it is possible to create integrated decarbonised energy systems with high of nuclear energy and variable renewable energy sources. While existing reactors are capable of hydrogen production, desalination and district heat they are chiefly geared for the bulk provision of low-cost electricity. Future SMR and advanced reactor designs are expected to provide the needed performance (such as high temperatures) and flexibility (such as co-siting with industrial facilities) to truly open up these markets.

Figure VI: Decarbonisation potential of nuclear for electricity and other vectors[12]

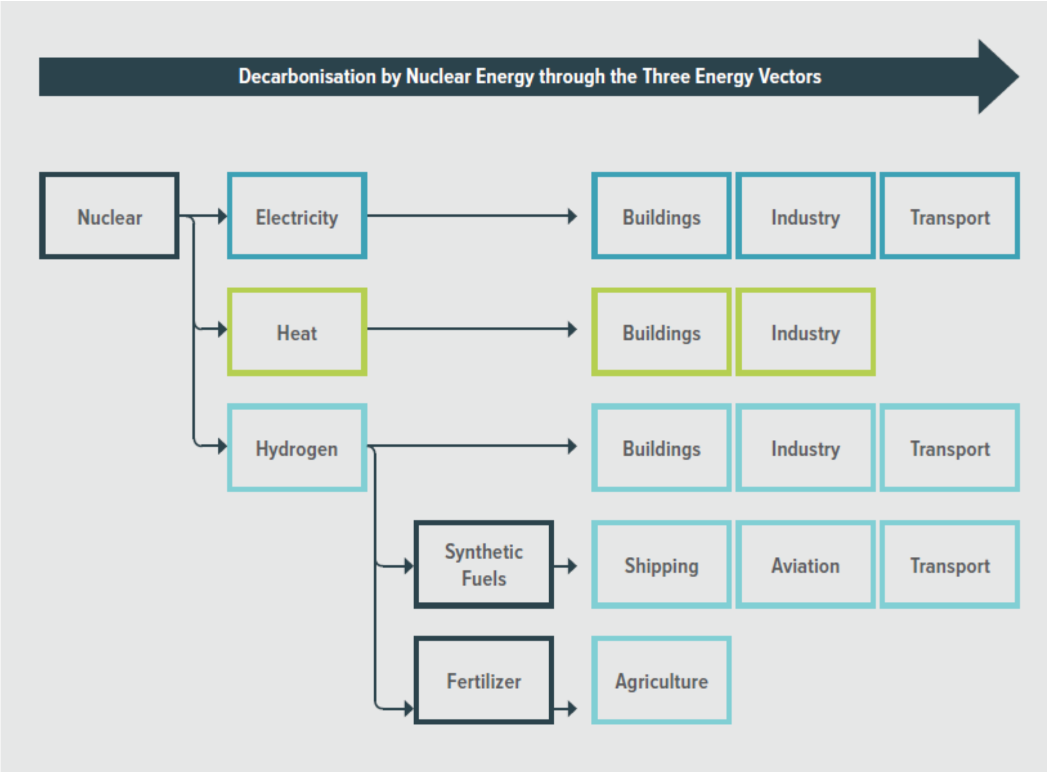
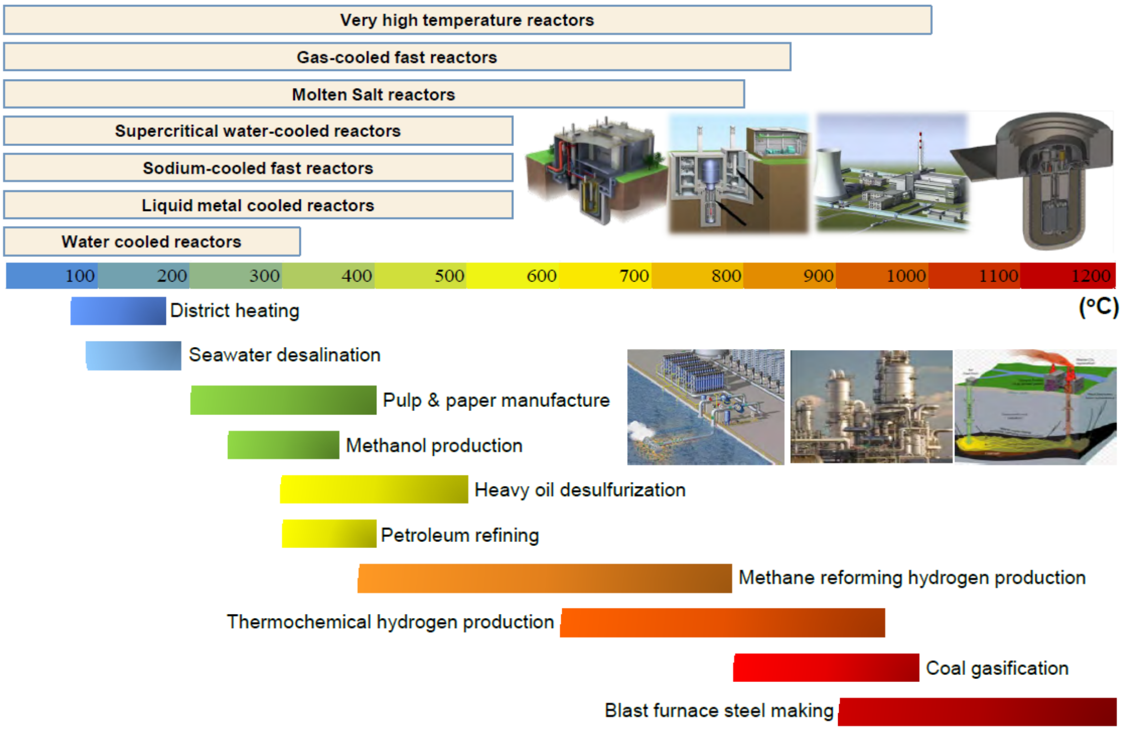


Figure VII: Potential industrial uses of nuclear heat[13]



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[12] Nuclear Innovation and Research Advisory Board (2020) Achieving Net Zero: The role of Nuclear Energy in Decarbonisation

[13] Source IAEA 2020 Advances in Small Modular Reactor Technology Developments

16. A unique characteristic of nuclear energy is that used fuel may be reprocessed to recover materials and provide fresh fuel for existing and future nuclear power plants. In the ECE region both France and Russia possess reprocessing facilities and offer these services internationally, while UK possesses reprocessing capability. At the moment it is only possible to partially recycle fuel at an industrial scale which results in an energy gain of about 25% from the original mined uranium[14], but the future development of fast neutron reactors could increase the energy produced from mined uranium by up to 6,000%[15] compared to what is a. Fast reactor technologies mean that not only used fuel from today's reactors but also the stockpiles of depleted uranium (amounting to about 1.5 million tonnes in 2015) could become a potential fuel source. Russia already has two sodium-cooled reactors operating and the country also plans to develop a 1200MW sodium cooled reactor (BN-1200) as well as a 300MW lead cooled design (BREST-300). There is also renewed development in the USA, where public funding for the Natrium reactor has just been announced[16]. Other ECE countries have built and operated fast reactors in the past including France, UK and Kazakhstan while more are planning them in the future and several start up companies are also pursuing these technologies in North America and Europe. The commercialisation and wide availability of fast reactors in the next twenty years or so would have profound implications for both uranium mining requirements and radioactive waste disposal.

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[14] World Nuclear Association, Processing of used Nuclear Fuel (accessed November 2020)

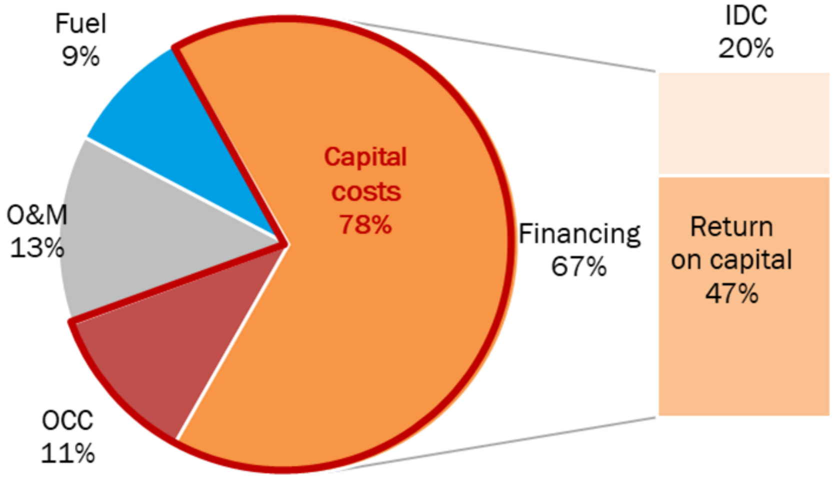
[15] World Nuclear Association, Fast Neutron Reactors

[16] World Nuclear News, 14 October 2020,

V.Economics of nuclear energy and the cost of decarbonisation

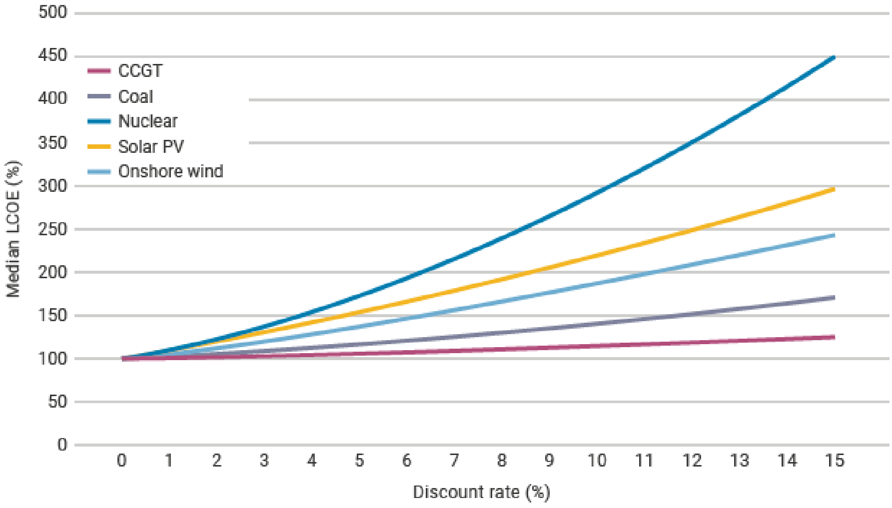
17. There are a range of methods for calculating and comparing the costs of energy projects, however the most widely used is the levelized cost of electricity (LCOE). This is the time-adjusted cost of building operating and decommissioning a power plant per unit of electricity generated through its lifetime. It is sensitive to a range of factors including assumed asset lifetime, capacity factors, capital costs, fuel costs, operating costs etc. The largest contributing factor to the LCOE of nuclear energy is the capital cost of building a nuclear power plant as shown in Figure VIII. The fuel, operating and maintenance costs are typically lower than for fossil plants, which is in fact the chief economic advantage to nuclear energy. Nuclear plants have high up-front capital costs, with investment in a single large nuclear power plant costing 5-10 billion US dollars, but they provide stable low-cost electricity over the long term. Unlike other energy sources, nuclear operators are required to accumulate funds to pay for all waste and decommissioning liabilities over the life of a nuclear power plant. This is typically accounted for in the fuel categories in LCOE estimates.

Figure VIII: Levelised cost of nuclear energy



Above: Breakdown of LCOE for a typical nuclear project. Calculations based on OCC of USD4 500 per kilowatt of electrical capacity (/kW$_e$), a load factor of 85%, 60-year lifetime and 7-year construction time at a real discount rate of 7%. OCC: overnight cost of construction. O&M: operations and maintenance. IDC: interest during construction. Image source: OECD NEA[17]

Below. Sensitivity of nuclear LCOE to financing costs, compared to other technologies



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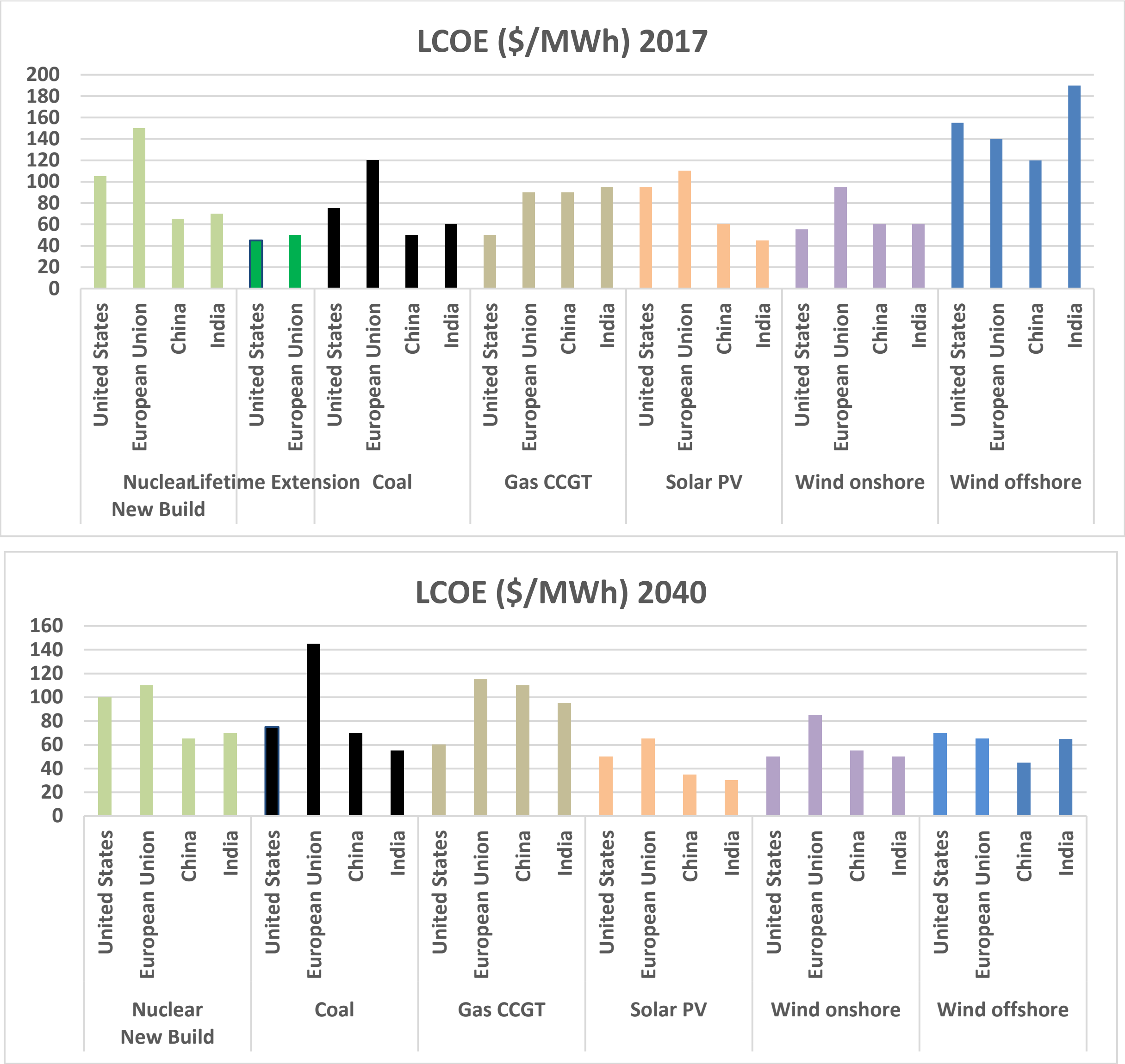
[17] OECD NEA, 2020, Unlocking Reductions in the Construction Costs of Nuclear

18. Capital costs can be broken down further into both construction and financing costs. Nuclear construction costs are influenced by local factors such as resource availability and labour costs, whether it is a first-of-a-kind plant or part of a fleet programme, or whether it contains any design changes from the reference plant. Industry can influence many of these factors and is best placed to handle the technical risks involved. Financing costs (often represented as discount rates or cost of capital) are influenced by interest rates, the presence of any guarantees, the growth rate of the economy, the underlying market structure, the presence or any power purchase agreement and other factors. These factors lie mainly within government's sphere of influence. When financing costs are high they add significantly to the LCOE of nuclear energy.

19. For nuclear power plant projects LCOE varies significantly between countries and regions. However, in many parts of the world nuclear energy is one of the most cost-competitive options for generating electricity as shown in Figure IX. In other parts of the world nuclear energy may be more expensive than alternatives on an LCOE basis but it will still likely form part of a cost-optimised electricity system once efforts are made to account for its proven ability to reduce both system costs and environmental impacts (especially greenhouse gas emissions), while also promoting important socioeconomic benefits[18].

Figure IX: Levelised cost of energy sources in different regions. Source IEA[19]



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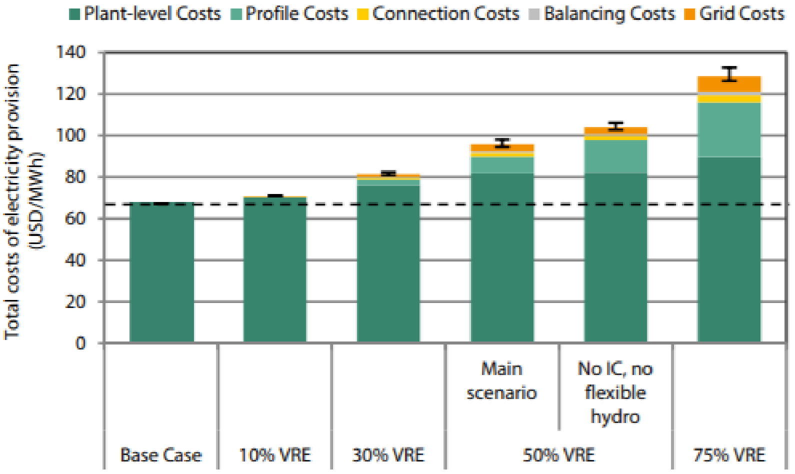
[18] OECD NEA, 2019, The Full costs of Electricity Provision

[19] IEA, 2019, Nuclear Power In a Clean Energy System

20. While variable renewable energy (VRE) sources are reducing in price they also contribute to additional system costs which scale with the penetration of these technologies and increase the overall cost of electricity – as indicated in Figure X. Detailed modelling shows[20] that even in the case of very low-cost VRE sources, for a generalised country lacking hydro-power the least-cost decarbonised electricity mix will consist of a share of 30-40% wind and solar PV supported by a larger share of 40%-60% dispatchable low-carbon technologies such as nuclear, biomass or fossil-fuelled plants with storage CCUS.

Figure X: Indication of how system costs increase at high renewables penetrations.[21]



profile costs – the costs of covering the increased maintenance requirements and lost efficiencies involved in ramping dispatchable generating technologies more frequently. Balancing costs –the costs of ensuring grid system stability by providing sufficient operating reserve in the face of greater uncertainty of VRE supply. Grid connection costs – the costs of additional wires, transformers and other non-generating electrical infrastructure to deal with the distributed nature and locational constraints of VRE plants.

21. Helping to ensure cost effective decarbonisation is not the only economic benefit of nuclear energy. Nuclear plants help to reduce air pollution and the costs of associated health impacts such as asthma that are worsened through the use of polluting technologies[22]. They also provide enhanced resilience against severe shocks that periodically effect the energy system, such as pandemics and extreme weather events[23]. Perhaps most importantly for the post-Covid-19 recovery period, the nuclear industry makes a very important contribution to the wider economy. Operating plants generate 100s of millions of dollars in revenue annually and contribute significantly to taxes and local expenditures[24]. They are also large regional employers offering long-term skilled jobs that typically pay significantly higher than other energy technologies[25]. Nuclear new build projects especially create thousands of jobs and offer significant potential for countries to ‘build back better’.

22. Crucial to enabling both more cost-effective decarbonisation and a wide range of socioeconomic benefits is reducing the LCOE of nuclear power plants. More specifically this means reducing the capital costs – both construction and financing. Financing is of such overwhelming importance to nuclear and other low carbon energy sources that it will be the focus of a future brief in the Carbon Neutrality project. The only point that will be made here is that there is a clear role for government to facilitate this as private companies will struggle to secure the financing required at affordable rates. Regarding construction costs, a major state of the art report from OECD NEA identifies key drivers for cost reduction[26]. While there have been some well-documented problems with first-of-a-kind and first of a generation reactor projects in some ECE countries – notably within Western Europe and

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[20] OECD NEA, 2019, The Costs of Decarbonisation: System Costs with High Shares of Nuclear and Renewables

[21] ibid

[22] Asthma society of Canada, November 2014, Bruce Power and Asthma Society of Canada release Emissions Report

[23] OECD NEA, 2020 Building low-carbon resilient electricity infrastructures with nuclear energy…

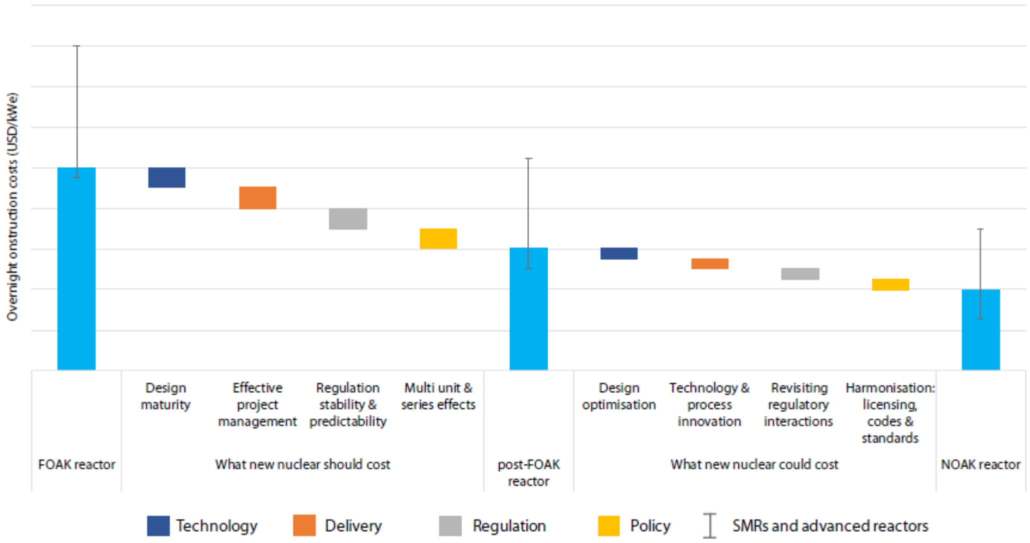
[24] See for example FORATOM (2019) Economic and Social Impact Report, FORATOM, Brussels.

[25] Oxford Economics, 2019, Nuclear Power Pays

[26] OECD NEA,. 2020, Unlocking Reductions in the Construction Costs of Nuclear

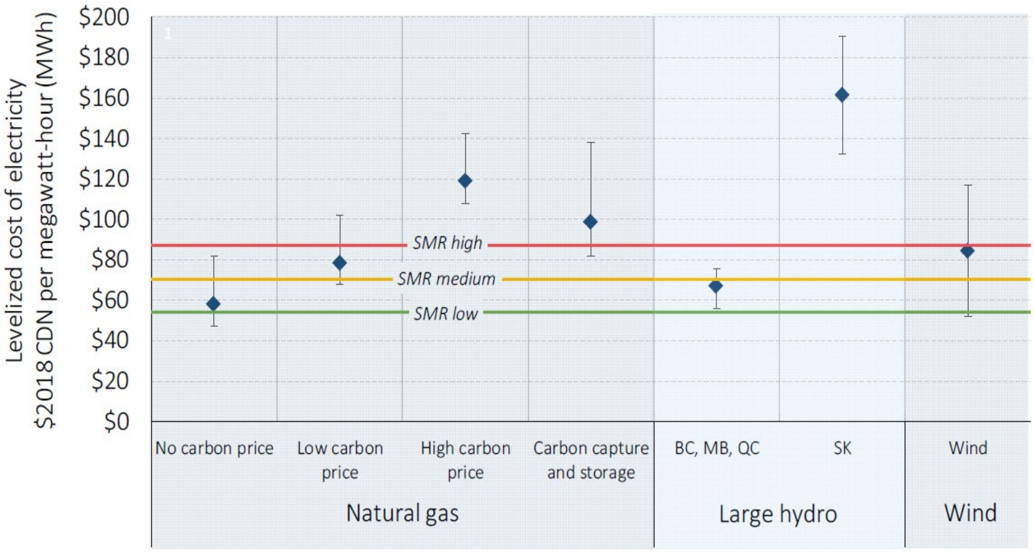
USA – industry is now transitioning from this phase and there is significant potential for near-term cost reduction as shown in Figure XI. By capitalising on the lessons of recent construction projects, prioritising design maturity and regulatory stability, implementing a standardised reactor programme, and pursuing the other recommendation countries can expect to dramatically drive down the cost of nuclear power plant projects over the next decade.

Figure XI: Nuclear Cost and risk reduction drivers



23. The foregoing discussion applies mainly to large gigawatt scale nuclear power plants. but much of it is also relevant to SMRs (and micro reactors). Given their smaller size SMRs will cost less than larger reactors, but it is unclear, yet, whether they will end up costing less per kilowatt-hour than large reactors especially as cost reductions are realised for large designs. The key question is whether cost reductions can be found which compensate for the lost economies of scale that have driven reactor designs to become larger over the decades, and to what extent the overall value proposition of SMRs will make them an attractive low carbon solution in future energy markets. There are factors working in favour of SMRs which may achieve this, including: lower overall investment cost, possibly lower financing costs, greater modularisation and factory assembly, economies of multiples by having more reactors at a single site, greater learning through mass production, and the use of simpler technologies which reduce the costs of complexity. In fact, SMRs do not necessarily need to be cheaper than large reactors to be commercially successful. Rather they need to be cost-effective for the applications and markets they are primarily intended for. This includes providing greater flexibility in terms of load following, cogeneration and industrial applications. For this reason SMRs are often thought of as complementary to large reactor technologies rather than competitive. A Canadian Roadmap for Small Modular Reactors study showed that with the most favourable support for on-grid SMRs, are one of the least expensive options, potentially cheaper than large hydro plants and natural gas, even without a carbon price in place. The estimated levelized cost of electricity from on-grid SMRs is presented in Figure XII.

Figure XII Comparison of levelized cost of electricity from on-grid SMRs with other options (6% discount rate)[27]



VI. Existing reactors - lifetime extensions, flexible operations and other innovations

24. Much excitement typically surrounds new nuclear construction projects and especially advanced nuclear technologies, but the current nuclear fleet also continues to improve in performance. Two notable developments are the approvals of longer lifetimes for nuclear power plants and the increased use of flexible operations to help accommodate the growing share of VRE. These developments further enhance the value of these existing low-carbon assets and should be a major focus for the ECE region, which is home to most of the world's existing nuclear power plants.

25. Nuclear power reactors were originally licensed for between 30 and 40 years of operation, but there is in fact no fixed technical limit to the lifespan of a reactor. Operation of nuclear plants beyond their original license lifetime – known as long term operation (LTO) – is now commonplace in many countries, with regulatory compliance, safety and economic performance being assessed on a plant-by-plant basis. A significant milestone occurred in 2019 when the world's five oldest operating reactors, including several reactors located in the ECE region, reached 50 years of operation. Most US nuclear plants have already been granted a 20-year licence renewal that would see them operate for a total of 60 years and many are now pursuing a subsequent licence renewal that would permit them to operate for a total of 80 years, with four units already having received approval. There is no fundamental reason why such lifespans could not be pursued by other countries operating similar (BWR and PWR) reactor technologies. In addition to the climate and socioeconomic benefits of nuclear energy discussed above, LTO is also expected to be one of the lowest cost generating options available to many ECE countries for decades to come, as shown in Figure VII.

26. Despite this, in many ECE countries we have seen nuclear power reactors closing prematurely in the last 20 years either as a result of political decision or due to economic conditions exacerbated by underlying market failure. Recent politically-driven reactor closures have mostly taken place in Europe, particularly Germany after it introduced a phase out in 2011, and in certain Eastern European countries as a condition for joining the European Union. Many of the recent economic closures have taken place in the USA where the emergence of the shale gas revolution has created a very cheap shale gas resource that has caused a steep reduction of wholesale prices. However, the underlying structure of

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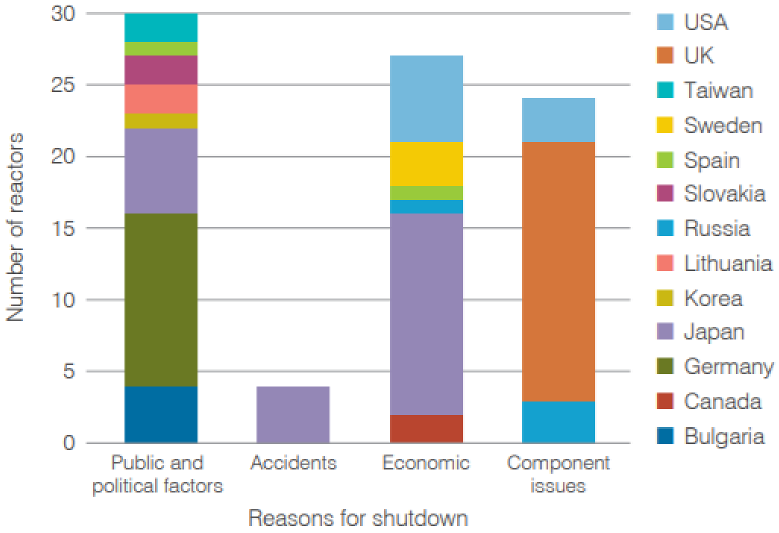
[27] A Canadian Roadmap for Small Modular Reactors. Ottawa, Ontario, Canada A Canadian Roadmap for Small Modular Reactors

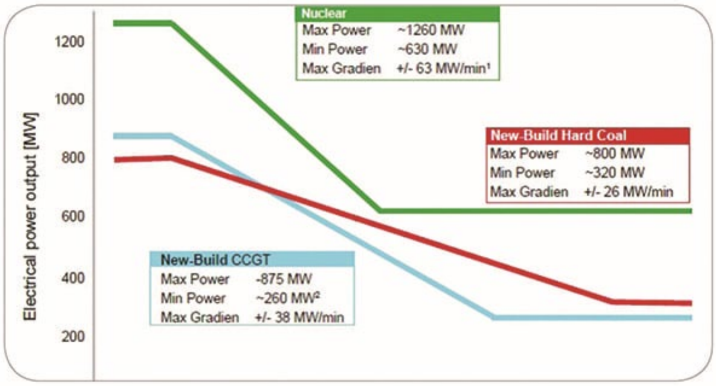
markets and capacity auctions has also played a substantial role. In Sweden and Spain, recent reactor closures are primarily attributable to specific government taxes on nuclear plants. Stopping the premature closure of further nuclear power plants is now seen by certain leading international organisations as the most urgent priority for addressing climate change[28]

Figure XIII: Reactor retirements from 2000 to 2020, listed according to main reason. Source: WNA[29]



27. Today, most nuclear power plants around the world are operated in ‘baseload’ mode. The best performing nuclear plants are regularly capable of achieving annual capacity factors of above 90% - the highest of any form of electricity generation. The economics of nuclear make it more favourable to operate nuclear reactors consistently at baseload optimum power mode. Nuclear plants are specifically designed to vary its power directly and can operate in load following mode if required. There are no technical barriers for nuclear to operate flexibility but electricity markets need to appropriately compensate energy and capacity providers in a competitive and technology-independent manner. Nuclear plants load following capabilities are is illustrated in in Figure IX. As the amount of VRE continues to grow and constraints are put on CO_2 emitting generation, existing nuclear plants can be relied upon as a valuable source of system flexibility alongside energy storage, demand-side management and VRE curtailment[30].

Figure XIV: A 2010 comparison of German nuclear, newly built hard coal, and combined cycle gas turbine power plants’ ability to handle load changes[31]



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[28] Opinion piece by Fatih Boril (IEA head) Rafael Grossi (IAEA head) October 9 2020, Without nuclear power, the world's climate challenge will get a whole lot harder

[29] World Nuclear Association, 2020, The Enduring Value of Nuclear Energy Assets.

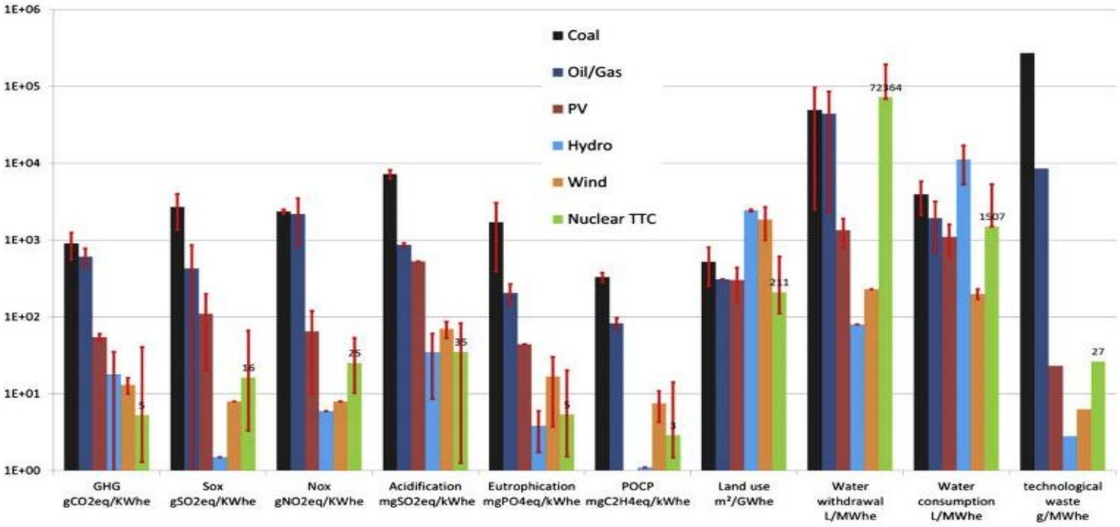
[30] CEM NICE Future report Flexible Nuclear Energy for Clean Energy Systems (2020)

[31] Sustainable Nuclear Energy Technology Platform, 2017, Load Following Capabilities of Nuclear Power Plants

VII. Health and environmental impacts

28. All forms of energy production poses risks and cause environmental and health impacts, and the industrial activities are subject to monitoring and regulation to make sure these impacts are managed to acceptable level. Nuclear energy presents some specific risks such as accidents and radioactive waste management. However, the results of comprehensive lifecycle assessments show that, when assessed across a broad range of environmental indicators, nuclear energy has one of the smallest impact of any energy source, as indicated in Figure X[32]. The risks posed by nuclear radiation should be weighed in this context and not arbitrarily elevated above other impacts.

Figure XV: Results of a comparative life-cycle assessment of different energy sources in France (assumes one time recycling of fuel)



29. One of the most important health environmental challenges facing the world is air pollution – including oxides of sulphur and nitrogen, ozone, and particulate matter. The World Health Organization reports that ambient air pollution is responsible for 4.2 million deaths globally every year and much of this is associated with energy production and use. Household pollution in the form of exposure to smoke in cooking fires causes 3.8 million deaths per year[33]. Nuclear power plants do not contribute to air pollution, and the historic use of the technology is believed to have helped to save over a million lives[34] .

30. Nuclear plants also unequivocally help to reduce CO_2 and other greenhouse gas emissions. The IPCC recognises that the whole lifecycle greenhouse gas emissions of nuclear energy are on a par with renewable sources of energy[35].

31. A nuclear power plant is capable of producing multiple gigawatts from a single concentrated site. In terms of structural materials a nuclear plant is mostly just steel and concrete, but it requires about ten times less of these than renewables such as wind, and hydro according to the US Department of Energy[36]. Uranium is the main ongoing raw material requirement of nuclear energy. Authoritative estimates claim the identified resources of uranium are enough to last for over 130 years based on current use, and this

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[32] Poinssot et al, 2014, Energy, Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles.

[33] World Health Organisation, Air Pollution, https://www.who.int/health-topics/air-pollution#tab=tab_3 (accessed April 2020)

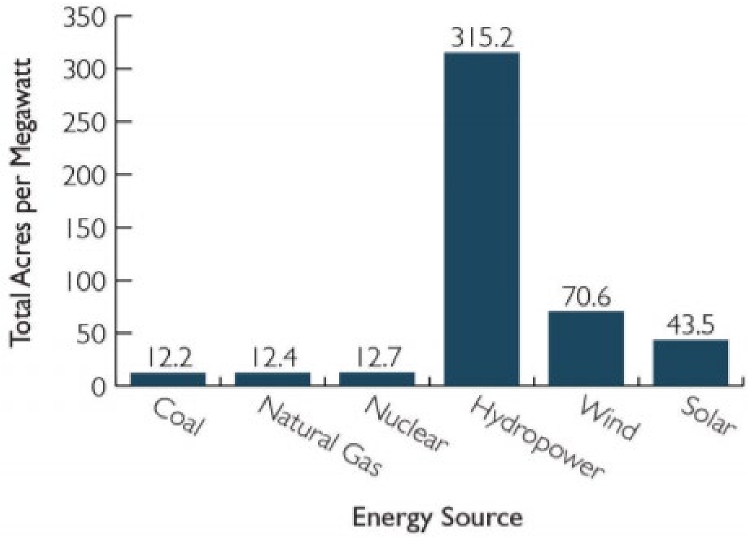
[34] Kharecha, P.A., and J.E. Hansen, 2013: Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. Environ. Sci. Technol., 47, 4889-4895, doi:10.1021/es3051197.

[35] IPCC, 2011, Renewable Energy Sources and Climate Change Mitigation

[36] US DOE, Quadrennial Technology Review 2015, chapter 6. (It should be noted that the materials requirements of solar in this publication is out of date, and does not reflect change of construction. It is likely still reasonably accurate for other energy sources)

extends to 250 years if the entire conventional resource base is included[37], but in fact the amount of identified uranium resource has increased over time and can be expected to increase further with prospecting if nuclear deployment accelerates. The use of fast reactors operated in a closed fuel cycle could increase uranium resource efficiency. Large scale deployment of fast reactors would essentially decouple nuclear energy from uranium. resource availability. This would further enhance the sustainability of nuclear energy. Nuclear plants require water for cooling purposes which need to be managed to prevent impacts on local aquatic ecosystems. This necessitates careful siting and environmental impact assessment. By contrast a World Bank report notes that “Manufacturing solar panels, wind turbines, and batteries will shape the supply and demand for critical minerals for the foreseeable future.” A more detailed assessment of the lifecycle impacts of nuclear energy and other energy sources is expected to be carried out by the UNECE Nuclear Fuels Working Group in 2021.

Figure XVI: Land requirement of different energy sources[38]



32. Nuclear energy present potential radiological health impacts to members of the public and workers. However, radiation occurs naturally and comes from sources all around us. ‘Manmade’ radiation is no different from natural radiation in its effects on people. Nuclear facilities are engineered with multiple protective barriers to protect people and the environment from radiation and radioactive material. The regulatory justification for a proposed UK nuclear power plant estimated that the radiation dose to any member of the UK public per year to be around the radiation from a return flight from the UK to New York. The nuclear energy industry is responsible for less than 0.1% of the radiation that most people are exposed to in their daily lives.

33. The two most serious accidents were those at the Chernobyl nuclear power plant in 1986 and the Fukushima Daiichi nuclear plant in 2011. While these have been the source of much public anxiety the actual radiological health impacts of these incidents, as determined by the United Nations Scientific Committee on the Effects of Atomic Radiation39 have turned out to be much lower than once expected as shown in Table III. The lessons learned from these accidents as well as incidents that have occur during nuclear operations are shared globally and incorporated into regulation, new reactor designs and operating practises. These nuclear accidents should be considered as in the context with other industrial accidents.

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[37] OECD NEA, 2018, Uranium 2018, Resources Production and Demand

[38] Strata, 2017, The Footprint of Energy: Land Use of US Electricity Production

[39] For Chernobyl accident see UNSCEAR 2008, *Sources and Effects of Ionising Radiation Volume II,* and 2018 *Evaluation Of Data On Thyroid Cancer In Regions Affected By The Chernobyl Accident*. For the Fukushima accident see UNSCEAR 2013 *Sources Effects and Risks of Ionising Radiation Volume I*

Table III: Radiation consequences of the Chernobyl and Fukushima Daiichi nuclear accidents

Accident	Initiating event	Direct fatalities with a link to radiation	long term radiation health impacts	Other consequences
Chernobyl 1986	Operator error	47	About 5000 cases of thyroid cancer to the year 2005 (estimates of maybe 20 fatalities)	- 115,000 people evacuated. - Over 200,000 people later re-settled - Serious social and psychological disruption - Long term contamination of the affected area - The increased population of many wild species in the exclusion zone due to the absence of people
Fukushima 2011	Natural disaster	0	No measurable effects expected	- 80,000 people evacuated (source METI) - Serious social and psychological disruption - Medium-term contamination of affected area (a significant portion of the original evacuation zone has now been cleared for return)

34. Radioactive materials are generated in the nuclear energy. Such materials demand sustainable management practices which protect workers and the environment, as well as eventual disposal in appropriately designed facilities. Radioactive wastes are categorized according to the level of radioactivity present as well as the amount of time they stay radioactive, this latter being determined by the half-lives of the radioisotopes present[40] Very low-level waste (VLLW) and low-level (LLW) wastes are wastes that are suitable for disposal in near surface landfill type facilities. Intermediate-level waste (ILW) and high-level waste (HLW) including spent nuclear fuel, require underground disposal. ILW and HLW contain long-lived radionuclides which require disposal depths of the order of 10s to 100s of metres. About 97% of the radioactive waste generated by the nuclear industry is, after radiochemical characterization, classified as either LLW or VLLW[41]. HLW makes up the smallest fraction in terms of volumes (less than 0.1%), but accounts for about 95% of the total radioactivity. HLW mainly consists of spent nuclear fuel or its recycled remains. While there are no final repositories for HLW from nuclear power yet operating in the world, construction is underway on a repository in Finland which is on track to be the world's first when it starts receiving waste in 2020.

35. Most materials used in the generation of nuclear electricity can be recycled and reused. In most cases over 90% of the material used at a nuclear plant should qualify. Even spent nuclear fuel should not automatically be categorized as a waste, since the opportunity exists to recycle it. The term 'radioactive waste' only applies to radioactive materials for which it is considered impractical to reuse them or recycle them, and which are destined for disposal. In this way nuclear energy is highly aligned with the principles of a circular economy.

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[40] International Atomic Energy Agency, Classification of nuclear waste, General Safety Guide, No. GSG-1, 2009

[41] IAEA, 2018, Status and Trends in Spent Fuel and Radioactive Waste Management https://www.iaea.org/publications/11173/status-and-trends-in-spent-fuel-and-radioactive-waste-management

VIII. Policies to facilitate nuclear energy development

36. The Group of Experts is invited to participate actively in policy-dialogues and developments of materials on nuclear energy and to support the Task Force on Carbon Neutrality in project implementation. A draft list of recommendations is included here to stimulate discussion and feedback. Policy makers should:

(a) Encourage investment in all low-carbon technologies by establishing a level playing field that does not discriminate against nuclear technologies. In creating sustainable low-carbon electricity systems, all low-carbon technologies will need to play a role.

(b) Support the long-term operation of existing nuclear power reactors within acceptable safety and economic parameters as a clear and urgent climate priority

(c) Implement carbon pricing, as an efficient approach to decarbonising the electricity supply.

(d) Value system reliability and resilience. Electricity prices should internalise system costs and remunerate each unit of electricity generated at its system value.

(e) Create a predictable pricing environment that enables investment in large capital-intensive and long-lived low-carbon energy infrastructure from a range of investors, and set financing frameworks that reduce the cost of capital of these projects.

(f) Accelerate the development and commercialization of SMRs taking into account the many additional applications they unlock. Countries should address key regulatory challenges that may emerge in SMR licensing discussions, and seek to promote international harmonisation.

(g) Engage with the Environmental Social Governance finance community and multilateral banks on the sustainability of nuclear energy in supporting climate mitigation and sustainable development goals.