BEAUTIFUL NUCLEAR

Driving Deep Decarbonisation

2022

"The climate problem is mostly an energy problem."

Sir David MacKay, author,
Sustainable Energy Without the Hot Air

ACKNOWLEDGEMENTS

Beautiful Nuclear: Driving Deep Decarbonisation, 2022

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FOREWORD

This excellent report skilfully shows how nuclear energy helps meet all 17 of the United Nations Sustainable Development Goals. No other electricity generation technology can match this diversity of beneficial impacts.

It rightly emphasises that the priority for preventing irreversible climate change is decarbonisation, not the creation of energy systems which are 100 percent dependent on renewables. In the context of the increasing urgency of the need to replace fossil fuels, the case which it makes for expanding the range of low carbon options to include nuclear is important and unanswerable.

The report wisely calls for a whole system approach to the energy transition and for evidence-based decision making. It advocates extending the resource and effort that has successfully driven down the cost of solar and wind energy, and accelerated their deployment, to all low carbon technologies.

The New Nuclear Watch Institute (NNWI) wholeheartedly supports these recommendations. They will facilitate larger scale and faster decarbonisation. They will also redress the widespread bias against nuclear which has even crept into the thinking of some people who claim to be concerned about climate change.

The trigger for this report has been its authors' worries about constant past failures to meet the emissions reduction targets recognised as essential to keep the rise in global average surface temperature below 2°C. These failures expose the danger of focusing too much on mid-century zero emissions targets. Unless the extent of the progress needed within the next two decades is acknowledged, and this need is met, the 2050 targets may be rendered irrelevant.

The report's reminder that the rapid reductions in the carbon intensity of the energy systems in Sweden and France in the last century were achieved by expanding nuclear capacity is very timely. It justifiably criticises the exclusion of nuclear from the climate mitigation toolset in the original Kyoto Protocol. It points out how this mistake has caused billions of tonnes of unnecessary and avoidable CO_2 emissions.

A selection of trenchant quotations spice up the narrative. Environmental campaigners and writers George Monbiot and Mark Lynas jointly admit their conversion to supporting nuclear was painful. They call shutting down nuclear capacity or failing to replace it "during a climate emergency… a refined form of madness."

The report doesn't shrink from uncomfortable facts. Expected emissions from existing coal-fired power plants, which deliver more than one-third of the world's electricity needs, already exceed the entire safe 2°C budget. Since more than half of these plants are less than 14 years old, they aren't likely to be shut soon.

As electricity demand in Europe is likely to double by 2050, and possibly faster elsewhere, this is another urgent challenge. The coal fired boilers now in use must be replaced with an alternative heat source. At the right price, this could be nuclear. Simply applying common sense and building multiple units using the same design cuts the cost of nuclear substantially.

The report also looks ahead to using nuclear plants to produce hydrogen. It warns of the colossal land use implications of relying on wind and solar as the only sources of clean energy. It extols the safety advantages of nuclear compared with other energy technologies.

It concludes with a list of the priorities for the EU to act on to reach carbon neutrality and recommendations for how to achieve more inclusive and efficient emissions reductions. It should be required reading for everyone whose decisions influence the world's response to climate change.

The NNWI strongly endorses "Beautiful Nuclear: Driving Deep Decarbonisation".

Tim Yeo
Chair, The New Nuclear Watch Institute
and former Chair of the UK Environment Select Committee

"As committed environmentalists, our conversion to the cause of nuclear power was painful and disorienting. All of us carried a cost in changing our position, antagonising friends and alienating colleagues. But we believe that shutting down — or failing to replace — our primary source of low carbon energy during a climate emergency is a refined form of madness."

George Monbiot, Mark Lynas & Chris Goodall

CIVIL SOCIETY DECLARATION

The Civil Society Declaration's 35 signatories from nine countries, including world-renowned climate scientist, James Hansen; President of African Women in Energy and Power, Ms. Bertha Dlamini; National Secretary of Prospect Union, Alan Leighton; former chairman of the Energy and Climate Change Select Committee, Tim Yeo; and climate author, Mark Lynas, **have all called for more inclusive climate and energy policy.**[1]

Figure 1. **Organisations supporting the Civil Society Declaration**

"The scale of our ambition must be commensurate to the scale and urgency required by our current predicament. The last decade has seen the development of wind and solar into affordable technologies that can make major contributions to the decarbonisation of electricity.

In this critical decade we must expand the suite of clean energy options to include nuclear products that are cost competitive, easier to buy, easier to deliver, present lower risk to investors and can meet a broad range of market applications.

In addition to the supply of electricity, which is only one fifth of energy consumption, advanced reactors have the potential to supply heat to homes, businesses and industrial processes; to produce hydrogen and synthetic fuels that will support a transition in transport and the difficult sectors of aviation and shipping; to desalinate seawater in regions suffering water scarcity; to support access to modern energy services in remote and developing communities; as well as to repower the existing global fleet of coal plants as part of a just transition …

We call on all capable countries to collaborate to accelerate the development and commercialisation of advanced reactor technology during the 2020s for rapid global deployment at scale."

Presented to Heads of Delegations at the Canada-UK Nuclear Energy Summit on Thursday 5 March 2020. The Civil Society Declaration Calls for a Critical Decade of Clean Energy Collaboration.

"Nuclear energy is an 'indispensable tool' for achieving the sustainable development goals (SDGs). It has a crucial role in providing affordable energy and climate change mitigation, as well as eliminating poverty, achieving zero hunger, providing clean water, economic growth, and industry innovation."

Expert Group on Resource Management of the
United Nations Economic Commission for Europe (2021)

THE GOALS

The 2030 Agenda for Sustainable Development,[2] adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, today, and into the future. At its core are the **17 Sustainable Development Goals** (SDGs). These are an urgent call for action by all countries — developed and developing — in a global partnership.

The world's energy sector is undergoing a profound transition. This transition is driven by the need to expand access to clean energy in support of socio-economic development, especially in emerging economies, while at the same time limiting the impacts of climate change, pollution, and other unfolding global environmental crises. Fundamentally this transition requires a shift from the use of polluting energy sources towards the use of sustainable alternatives.

The UN's 2030 agenda, distilled in the sustainable development goals, has become an indispensable tool for decision-makers concerned with navigating these difficult decisions. This report explores the potential for nuclear energy as an indispensable tool for sustainable development, as outlined in the recent UNECE report.[3]

1 / NO POVERTY

Nuclear energy helps the economy by supporting direct and indirect jobs during construction and operation. The cost-competitive and stable electricity supplied by nuclear energy attracts and sustains energy-intensive industry, supports economic growth and creates more jobs. Nuclear energy can power the development of local small and medium enterprises and economic development in the form of jobs, revenues and local spending. Nuclear energy is largely immune to fluctuations in the weather, increasing climate resilience for the economy.

2 / ZERO HUNGER

Nuclear energy helps to power sustainable food production. In addition, many countries use nuclear techniques to develop sustainable agricultural practices, establish and improve nutrition programmes and ensure stable supplies of quality food. The sterile insect technique (a method of pest control that uses radiation) for example, is providing a powerful line of defence against agriculture's most damaging pests. Water desalination projects can also be nuclear powered and help to increase climate resilience in agriculture.

3 / GOOD HEALTH & WELL-BEING

Nuclear power provides energy with almost no emissions, helping to ensure clean air, water and land, thereby improving the health of communities. Burning fossil fuels, on the other hand, causes an estimated 8 million premature pollution-related deaths each year.

4 / QUALITY EDUCATION

Nuclear science and technology is used in many fields including energy, medicine and agriculture. The need for skilled technicians, engineers, physicists, radiation experts and medical specialists creates many opportunities for national and international education and training efforts. Opportunities in the nuclear sector can help boost interest in science, technology, engineering and mathematics (STEM) subjects in younger students. Some countries also grant educational scholarships to individuals in energy and medicine to secure the provision of talent needed.

5 / GENDER EQUALITY

Increased access to cheap, reliable energy in developing countries helps enhance labour emancipation and reduce drudgery, which disproportionately affects women. Energy access is also directly correlated with key development metrics like lower maternal mortality, life expectancy, and improved economic opportunities for women.

6 / CLEAN WATER & SANITATION

Co-generated heat from nuclear plants can be used to power desalination facilities and provide clean water to communities in addition to electricity. Saltwater desalination is used around the world to produce potable water. Climate change will greatly increase water stress and the need for desalination. However, desalination is energy-intensive, requiring between 3 – 25 kWh per cubic metre of water. Therefore, using waste heat from nuclear plants for desalination will be highly valuable and highly energy efficient.

7 / AFFORDABLE & CLEAN ENERGY

Nuclear energy can complement renewable energy sources. When used together, these technologies can help to achieve decarbonised electricity systems at low cost to consumers — as has been proven by France, Switzerland, and Sweden. New advanced nuclear technologies will be available in the 2020s offering greater flexibility, efficiency, and a wider range of applications beyond electricity.

8 / DECENT WORK & ECONOMIC GROWTH

The energy industry supports a diverse range of jobs, including various engineering, technical, and other specialist roles. Nuclear sector pay tends to be higher than average, reflecting the specialist skills required. In addition, nuclear energy provides many developing countries with access to cheap, reliable and carbon-free electricity, which improves quality of life and productivity in those economies. These two effects combined act as a 'job-multiplier', greatly boosting regional employment. Nuclear energy projects also involve significant investment and regional infrastructure development.

9 / INDUSTRY, INNOVATION & INFRASTRUCTURE

A nuclear power plant is a major infrastructure development that can operate for 60 years or even longer, making this a highly efficient use of materials and investment in infrastructure. Innovation is integral to achieving this longevity and improving performance levels. Innovation in spin-off technologies is delivering a huge range of benefits across food and agriculture, medicine and public health, materials research and structural mechanics. Nuclear energy can provide secure, reliable and low carbon electricity for critical infrastructure such as data centres and other technology industries.

10 / REDUCED INEQUALITIES

Universal access to low-cost clean electricity will help reduce socio-economic inequalities. In addition, nuclear project developers must typically engage stakeholders in extensive consultation before beginning construction, making sure that different voices are heard, including indigenous and marginalised groups.

11 / SUSTAINABLE CITIES & COMMUNITIES

By 2050, about 70% of the world's population is expected to be living in cities. Nuclear energy can support urban development, economic prosperity and high-quality jobs. By providing affordable reliable electricity, nuclear energy is well suited to supplying cities where there is constant energy demand. Nuclear energy assists in the electrification of public transport, and especially rail networks, without contributing to air pollution. Small modular reactors (SMRs) and microreactors are promising potential sources of electricity, district heating, and desalination, which may be particularly valuable for remote, off-grid communities.

12 / RESPONSIBLE CONSUMPTION & PRODUCTION

Nuclear energy generally requires fewer mineral inputs than other energy sources, including critical raw materials. Its primary mineral input is uranium. The uranium resource is ample and distributed widely across the globe, and its mining and processing are subjected to high standards. Nuclear energy does produce spent fuel, but the volumes are small; its management and disposal is also subject to strict regulation. Most of the materials and components of a plant are suitable for reuse or recycling.

13 / CLIMATE ACTION

Nuclear energy today prevents about two gigatonnes of carbon dioxide every year, and is the world's second-largest source of low-carbon electricity after hydropower. Nuclear power plants can be located where they are needed, independent of auspicious geography. Combining nuclear energy with renewables is the only proven way to decarbonise electricity grids in industrialised economies, in the absence of significant hydro resources. It is also the fastest way to add low-carbon generation and the best proven way to replace coal and gas. New technologies will target difficult-to-decarbonise sectors by supporting the production of hydrogen and synthetic fuels as well as clean heat for homes and industry.

14 / LIFE BELOW WATER

Nuclear science and technology has multiple beneficial applications. Nuclear energy does not produce carbon dioxide emissions which contribute to ocean acidification or other chemical emissions that pollute waterways. Scientists are also using nuclear techniques to monitor and study ocean acidification, in order to understand how it affects marine life and ecosystems and identify ways to protect ocean and coastal communities.

15 / LIFE ON LAND

Nuclear energy has a very high energy density, and facilities take up minimal land. Plant boundaries tend to be set quite large for safety and security purposes, and within these, natural habitats are usually found. Plant operators often support conservation activities, which help to protect local species. Nuclear techniques can be used to assess soil quality and to study how crops take up nutrients, as well as how soil moves. These can also be used to combat desertification.

16 / PEACE, JUSTICE & STRONG INSTITUTIONS

Civil nuclear programmes require the development of strong national institutions, while nuclear facilities are subject to robust regulation that is often backed by international conventions. Notable conventions include the Convention on Nuclear Safety, the Convention on Physical Protection of Nuclear Material as well as the Paris and Vienna conventions (which cover third party liability).

17 / PARTNERSHIPS FOR THE GOALS

The nuclear community has developed partnerships with governments, NGOs, educational institutions and UN bodies, helping them to contribute their skills and resources to the sustainable development of nuclear technology. The International Atomic Energy Agency (IAEA) promotes policy coherence by establishing safety standards, and providing security recommendations and technical guidance to its member states. The IAEA also develops partnerships through technical cooperation programmes. There is enormous potential to support newcomer countries in the development of sustainable nuclear energy pathways.

In this report, we describe how nuclear energy contributes to the Sustainable Development Goals, and how expanding its use could enable faster progress towards a sustainable and prosperous future for all.


THE TIME
IS NOW

THE COP IS ONLY HALF FULL

Weeks after the Paris Agreement was signed, we passed the 'red line' threshold of concentration of CO_2 in the earth's atmosphere, and then kept going. Two years later, we hit a monthly average of 411 parts per million (ppm) CO_2 emissions, with a peak of 414 ppm in May 2019.[4]

In April 2022, the U.S. National Oceanic And Atmospheric Administration (NOAA) reported that, for the second year in a row, scientists observed a record annual increase in atmospheric levels of methane, a powerful, heat-trapping greenhouse gas that's the second biggest contributor to human-caused global warming after carbon dioxide. Meanwhile, levels of CO_2 also continue to increase at historically high rates. The global surface average for CO_2 during 2021 was 414.7 parts per million (ppm), which is an increase of 2.66 ppm over the 2020 average. This marks the 10th consecutive year that carbon dioxide increased by more than 2 parts per million, which represents the fastest sustained rate of increase in the 63 years since monitoring began.[5]

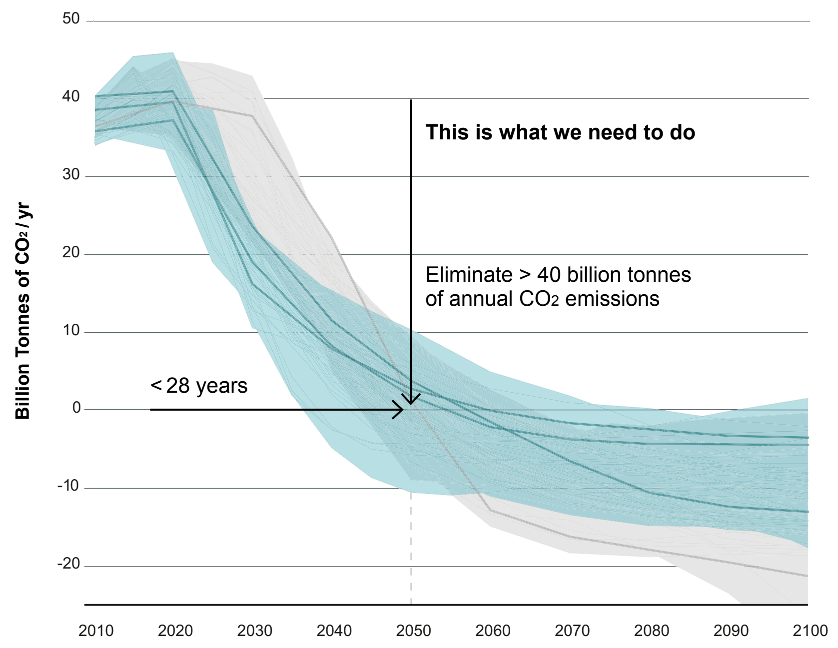
Atmospheric CO_2 peaked for 2021 in May at a monthly average of 419 ppm. There was no discernible signal in the data from the global economic disruption caused by the coronavirus pandemic.

Current climate commitments are insufficient, and so far, no country is on track to meet their commitments anyway. In February 2022, a new report published by the Intergovernmental Panel on Climate Change (IPCC) found that deep divisions between rich and poor nations, and within societies, will determine people's ability to withstand the worst effects of climate change — with huge implications for global politics. The divisions will worsen if countries fail to rein in greenhouse gas emissions, but already present steep challenges.[6]

The report underscores that the countries facing the worst climate impacts are those who contributed the least to global warming — and have the fewest resources to adapt.

> "I have seen many scientific reports in my time, but nothing like this …" He called the findings "an atlas of human suffering and a damning indictment of failed climate leadership."
>
> Antònio Guterres, U.N. Secretary-General

> "'Climate justice' is 'really the key dimension' of the new report. The idea that clearly the most vulnerable people — just about half of humankind — are living in regions that are really highly exposed to climate impacts."
>
> François Gemenne, Lead Author and Director of Belgium's Hugo Observatory



Source: IPCC (2018)

Figure 2. **Projections of global net CO_2 emissions**

Writing for the World Economic Forum in May 2022, IAEA Director General Rafael Mariano Grossi describes how the global energy crisis is changing perceptions of nuclear energy in the energy transition:[7]

> "As a team of International Atomic Energy Agency (IAEA) experts and I made our way to the UN's COP26 climate conference in Glasgow last November, the growing energy crisis was already apparent in queues at petrol stations and among concerned conversations about the 400% rise in natural gas prices.
>
> For the first time, nuclear energy was represented at the COP table and its increasing acceptance, especially among young people, was palpable. It had been a long time coming for nuclear, which produces more low-carbon energy than any other source except hydropower.
>
> Today, just a few months after COP, we are seeing the consequences of military conflict in Ukraine begin to turn that interest into action. Governments from Belgium to Japan have announced their intention to extend the lives of nuclear power plants, citing concerns about geopolitical instability. Across the world, leaders are worried about shortages in the supply of oil and natural gas, and price spikes in electricity and petrol, undermining their nations' economies and political stability.
>
> The head of the International Energy Agency (IEA) calls this our first global energy crisis. There's little doubt this crisis will accelerate a shift in our energy infrastructure. Still to be decided is whether it will be coal and gas, or nuclear, that work together with hydro, wind, solar and other renewables to deliver uninterrupted electricity. If, despite the short-term pressures, governments prioritize moving to more predictable long-term prices, meeting their climate targets, and reducing the 8 million annual deaths caused by air pollution, nuclear capacity will grow."
>
> Rafael Mariano Grossi, Director-General, International Atomic Energy Agency (IAEA)

CLIMATE CHANGE IS AN ENERGY PROBLEM

Climate change is, by and large, an energy problem. More than two thirds of anthropogenic (human-caused) emissions come from the fossil fuels we burn for energy and transportation. In the 2015 Paris Agreement, most nations pledged to try to keep global warming under 2°C or even under 1.5°C. Left unchecked, climate change of 3°C or more will wreak havoc on the world's ecological systems, which would have enormous consequences for people and society.

With 1.5°C of warming, there are still serious risks. Sea level rise could displace millions of people, biodiversity loss could accelerate, and Arctic Sea ice could disappear. Millions more people would die prematurely each year from pollution-related health effects. At 2°C of warming, there is a high risk of Antarctic ice sheet collapse, exposure of half the world's population to summertime 'deadly heat', increased droughts, and forced mass migration as a result of increased food insecurity. In addition to these direct impacts, increased migration and geopolitical tension will also put extreme pressure on democratic institutions and international cooperation.

We need to bring annual emissions down to net zero in the next three decades. This means we must replace all energy we use with clean energy sources by 2050. Because annual emissions accumulate in the atmosphere, it also matters how much CO_2 we emit on the way to 2050. Intermediate targets are useful, because they show us if we are making sufficient progress — we are not. Most 1.5°C pathways show that, by 2030, we need to reduce annual emissions by 45% from 2010 levels. This is no longer a realistic possibility, because instead of decreasing, annual emissions have actually increased from 2010 to 2019, and it will now be impossible to reduce them fast enough to hit that target.

The failure to hit any of these required climate targets is a key reason for producing this report. Could we make more progress if we include robust nuclear deployment as part of our efforts to prevent dangerous climate change?

As Figure 2 shows, the later we start serious reductions in annual emissions, the more carbon dioxide we need to remove from the atmosphere later this century.[8] The steeper pathways, which are the ones that remain, show the need to remove ~15 gigatonnes of CO_2 per year. Approximately 500 gigawatts of baseload electricity generation capacity will be needed just to power these carbon capture technologies, which, based on projected performance, would consume 1.3-times the current annual electricity consumption of Europe.

Importantly, these rapid reductions in emissions cannot come at the cost of the future prosperity of developing nations. Access to modern energy is directly related to development, quality of life, opportunity for education, increased life expectancy, and reduced maternal and child mortality rates. Higher levels of wealth and development will also make people less vulnerable to the negative effects of climate change.

We are faced with an 'energy trilemma'. Energy not only needs to become clean, but also affordable and reliable. These three elements are critical to averting global catastrophe and meeting fundamental needs like healthcare, welfare, education, security, while enabling every country to share in global prosperity. The United Nations Sustainable Development Goals call for rapidly and cohesively addressing all these societal needs. Today, most of the world's population lives in poor countries in which more than 90% of people live on less than $30 per day (adjusted for purchasing power parity). An analysis by Our World in Data[9] suggests that the global economy would need to increase fivefold to substantially reduce poverty.

Fortunately, there is abundant evidence that we can decarbonise significant parts of our energy systems at the required speed. Countries like Sweden, Finland, and France were able to rapidly decarbonise while supporting economic growth and increasing per capita energy consumption through a combination of nuclear energy and hydro power. As other countries plan significant increases in clean energy, the success of Sweden, Finland, and France provides powerful examples to follow.

Later in this report we explore nuclear power as an extraordinarily sustainable and efficient tool that can help power civilisation without emissions — enabling rapid and large-scale decarbonisation of major sectors of the global economy, including power, heat, transportation, and industry. In recent years, many have raised their voices in support of nuclear power as an efficient tool to reduce our emissions. We add our voices to that chorus of support.

"The climate emergency is here — with millions of people living in coastal areas, if we don't make drastic changes, we are talking about crises of migration, politics, and security. We need to find solutions now — as we did with vaccines during the pandemic."

Shauna Aminath, Cabinet Minister of Environment & Climate Change for the Maldives

NUCLEAR IN EUROPE

To meet the decarbonisation challenge in less than three decades, more low-carbon energy generation needs to be licensed, built, and brought online than ever before. What is surprising to many people is that building nuclear plants has been, and still is, the fastest way to add clean electricity production per capita. Experience shows that EU member states deploying nuclear programmes have managed to rapidly reduce carbon intensity. Sweden, for instance, built its first light water reactor (LWR) in 1972. By 1986, half of Sweden's national electric capacity came from nuclear power plants, and total emissions per capita decreased by 75% from peak levels in the 1970s (Figure 3).[10] Similarly, France implemented a transition to 80% nuclear power in under two decades, which rolled its per capita emissions back to 1960's levels while expanding energy supply to meet rapidly growing demand.

However, in the original Kyoto Protocol, nuclear energy was excluded from the climate mitigation toolset, and the reference year was set to 1990, not capturing most of the nuclear deployments that had already radically reduced carbon emissions in key countries. This exclusion, and the failure to examine the reasons behind it, has caused billions of tonnes of otherwise avoidable CO_2 emissions, and cost humanity decades of valuable time. Meanwhile, global emissions continue to rise each year. It is now too risky not to include nuclear as a foundational part of our climate mitigation efforts.

Europe has the world's largest reactor fleet. There are 103 power reactors (100 GWe) operating in 13 of the 27 EU member states.[11] As the single biggest source of electricity, nuclear provides almost half of Europe's clean electricity, and over a quarter of all electricity. Most of Europe's cleanest power grids include a significant proportion of nuclear, including in Sweden, France, and Switzerland, for example. These countries have had very clean electricity grids with emissions around or below 50g CO_2/kWh for years, even decades.[12] Low emissions electricity grids are the first important step towards economy-wide decarbonisation. Except for those with exceptional hydro or geothermal resources, significant nuclear energy production has been the only way that modern industrialised economies have successfully and significantly reduced carbon emissions from their electric grids. So far, no modern industrialised nation has achieved the required level of emissions reduction with wind and solar alone.

Finland, Spain, the UK, and Belgium also have relatively clean grids thanks to a combination of renewables and nuclear. Finland and the UK are planning and building new nuclear, while Spain is holding to its current fleet for now. Germany, Switzerland and Belgium are prematurely closing down their nuclear plants and planning to replace them with wind power and natural gas. This is a step backward that increases emissions from their electricity sector.

Nuclear in the Nordics

> "No other carbon-neutral electricity source has been expanded anywhere near as fast as nuclear."
>
> Barry Brook & Staffan Qvist

Sweden

The Swedish energy transition over the last 50 years shows us that replacement of current fossil fuel electricity by nuclear at a pace which might limit the more severe effects of climate change is technologically and industrially possible. Whether this will happen depends primarily on political will, strategic economic planning, and public acceptance.

In under two decades Sweden decarbonised its electricity grid and decreased its per capita emissions by 75% while simultaneously growing its economy and maintaining some of the lowest electricity prices in Europe. Sweden achieved this by building twelve nuclear reactors, or roughly 10 gigawatts (GW) of generating capacity, to complement its sizeable hydropower and biomass resources. Today, Sweden retains a fleet of six reactors, which generate around 7GW, or approximately 40% of the country's electricity.

The Swedish energy transition also illustrates the challenges of politics and policy making. The U.S. Three Mile Island accident in 1979 (despite not harming public health) prompted a referendum on nuclear in Sweden and slowed nuclear deployment in many other countries as well. Sweden voted to phase out nuclear energy by 2010. The Swedish nuclear industry, having once been a source of national pride, expansion, and great export potential, stagnated.

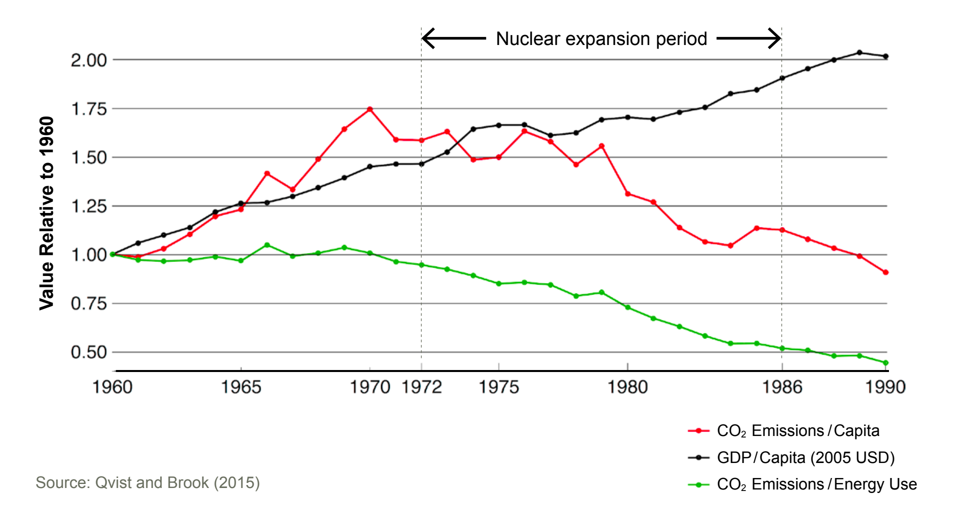


Figure 3. **Swedish total CO_2 emissions & GDP / capita, 1960 – 1990**

After the referendum and decision to shut down the industry, it faced decades of decline. In the late 1990s, the Swedish government introduced a special nuclear capacity tax that almost forced the shutdown of the whole fleet as electricity prices fell so low that the tax crippled the competitiveness of the operating plants. The tax was phased out in 2018 to prevent the shutdown. Meanwhile, six of the original twelve reactors were shut down prematurely between 1999 and 2020.

In 2004 the original phase-out by 2010 was cancelled, and the strict ban on building any new nuclear plants removed in 2009. Since the decision to remove the nuclear capacity tax in 2016, the discussion about nuclear energy in Sweden has been shifting, in recognition of the need to maintain affordable and reliable clean electricity supply, and to further expand this supply for decarbonisation of industries and transportation. Due to this increased use, electricity demand is expected to more than double by mid-century. In Sweden, the Sunrise Program at KTH Royal Institute of Technology is funding a start-up that is developing lead-cooled technology and exploring siting a lead-cooled reactor at Oskarshamn.

Recent developments include Swedish government approval of a final repository for high-level waste and spent nuclear fuel; and grants from the Swedish Energy Agency for the establishment of the ANITA SMR national competence centre and for Lead Cold, the advanced reactor developer.

Finland

Finland built four reactors at two sites from 1971 to the early 1980s, which today produce some 35% of the country's electricity.[13] That project alone substantially decarbonised Finnish electricity production at a pace not surpassed since.

Finland has successfully started up and begun operating one new reactor at Olkiluoto. The planned construction of another at Hanhikivi, which was being developed by Rosatom, has stalled due to Russia's invasion of Ukraine. Both of these plants utilise the unique Mankala principle, which is a non-profit cooperative of utilities and industry that pools resources and jointly invests in projects, giving owners the ability to buy electricity at cost, per their ownership share. The wide range of owner organisations distributed geographically around the country creates strong political and public support. Mankala companies pay low interest rates for financing projects, resulting in low electricity prices for the owners.

Today, Finland enjoys record levels of public support for nuclear energy and is looking into new technologies in addition to large reactors. In 2020, the state-owned VTT Technical Research Centre of Finland started developing its own mini-reactor to provide district heating. Legislation and regulations are being reformed for small reactors and new applications. The regulator is collaborating with the industry-led KELPO project to standardise and streamline licensing of non-critical components, which could lead to both significant cost-savings and safety improvements.

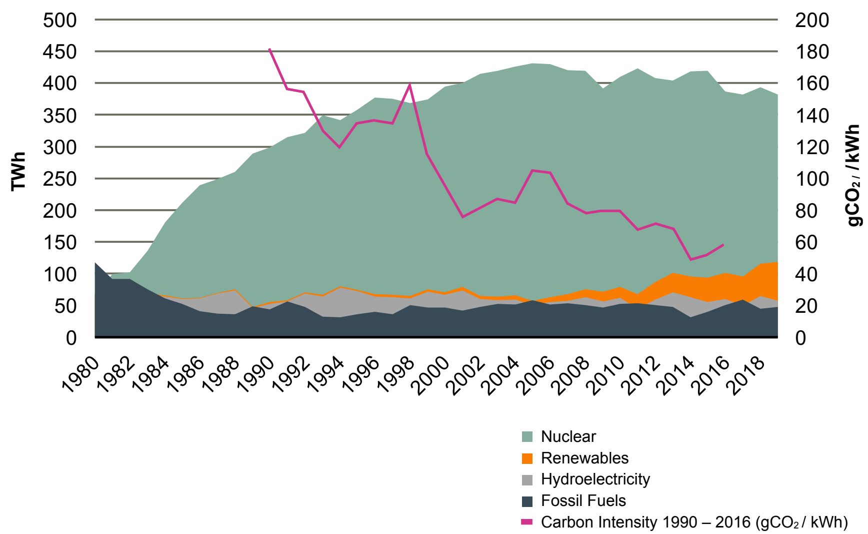
The decarbonisation roadmaps of Finnish industries suggest a doubling in electricity demand by 2050. Meanwhile, much of the remaining use of fossil fuels and peat for electricity and heat production will be phased out during the next decade or two. As with Sweden, this presents a significant opportunity for a programme build, to bring costs down and establish significant skills and capabilities to deliver projects cost-competitively, rapidly, and at a scale that is relevant to the urgent climate challenge.

Nuclear in France, UK & Rest of Europe

France

France is one of the very few countries that has managed to decarbonise its electricity production almost completely. The French success is particularly important because it was achieved without significant hydro or geothermal resources.

With 56 reactors and over 60 GW of capacity,[14] France is the second largest nuclear producer in the world after the U.S. France rapidly deployed new civilian nuclear energy capacity in response to the 1970s oil shock to reduce its dependency on



Source: U.S. Energy Information Administration (2018) and European Environment Agency (2020)

Figure 4. **Decarbonisation of France's electric grid**

imported fossil fuels, especially oil. The country successfully implemented a transition to 80% nuclear power in under two decades, from the mid-1970s to early 1990s.

France derives 70 – 75% of its electricity from nuclear power and receives some €3 billion per year for exporting clean electricity to its neighbours. It is the world's largest exporter of electricity (Figure 4).[15]

Today, France has plans to meet incremental demand for electricity with new renewables, which as demand for electricity doubles will lower the share of nuclear in its electricity mix to around 50% by 2035, which is desirable to the extent it can be done without significant increases in emissions or power prices. In early 2022, President Emmanuel Macron announced that France will construct six new nuclear power reactors, is considering building a further eight, and will push ahead with the development of small modular reactors. The French vision also includes the production of clean hydrogen with nuclear energy.

UK

The UK initiated an ambitious domestic nuclear programme after World War II and developed a unique reactor technology, the Advanced Gas-cooled Reactor (AGR), also intended for export, which was never realised at any notable scale. Due to their age, most of these AGRs are facing closure within the next 5 – 10 years, so there is an urgent need and strong political push for another nuclear programme, especially given the country's strict climate targets.

In December 2015, the UK started to build its first new plant in a generation, the Hinkley Point C, a dual-EPR (European Pressurized Water Reactor) power plant of 3200 MW capacity, which is expected to produce 7% of the country's electricity. The two reactors at Hinkley Point C will offset nine million tonnes of carbon dioxide emissions per year — equivalent to taking nearly four million cars off the road. Plans for a sister-plant, Sizewell C, are also proceeding.

If Sizewell C were to be financed in the way that transmission lines are financed, the cost to consumers would be approximately £40/MWh, which is comparable to offshore wind.

The UK government is also considering several small reactor designs for flexible generation, hydrogen, and heat production in support of Net Zero goals.

Rest of Europe

Many East European nations have significant shares of nuclear power in their mix. Ukraine produces most of its electricity using nuclear power. The Czech Republic and Slovakia also have significant shares of nuclear power, as do Hungary, Romania, and Bulgaria. Slovenia shares ownership of its nuclear plant with Croatia. Many of these countries have expressed the desire to build new nuclear capacity or have already begun. As with all clean energy technologies, where fuel is not a significant cost, the price of electricity from nuclear power plants is strongly influenced by the cost of financing these projects. Equitable access to low-cost financing mechanisms is of great importance to these countries' decarbonisation prospects.

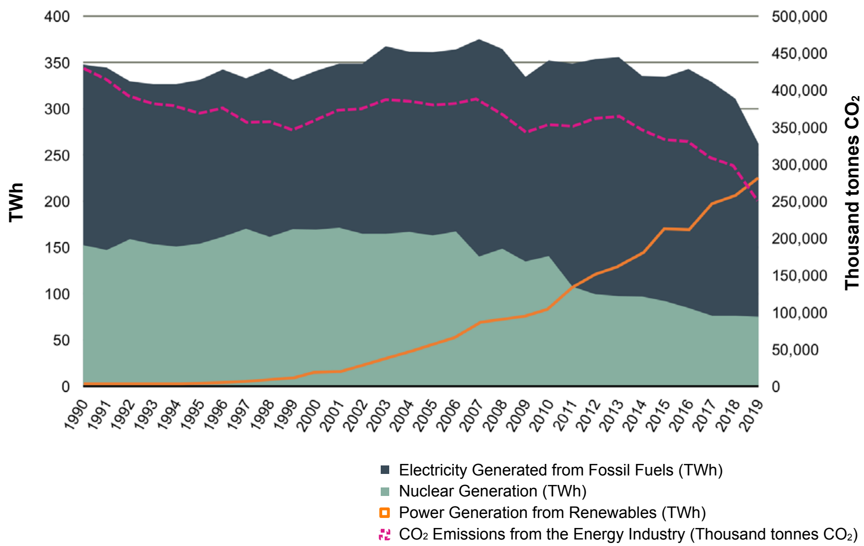
Poland is planning a large nuclear programme to replace some of its coal fleet, with construction scheduled to begin in 2026. In addition, the industrial group Synthos, supported by Excelon Generation, is pursuing deployments of GE Hitachi's SMR.[16]

In the Baltics, Estonia has formed a governmental nuclear energy working group to consider SMRs for carbon neutrality and security of supply.[17] Lithuania, which imports much of its electricity, is also considering a new nuclear plant to be built by GE Hitachi. It had two Soviet-era RBMK reactors at the Ignalina power station, which were closed as a condition for the country's entrance into the European Union.

Nuclear Fence-Sitters

The Netherlands has a single small reactor, which supplies about 3% of its electricity. Having previously decided to phase out nuclear altogether, the country has now reversed that policy, and decided instead to phase out coal generating capacity by 2030. In 2020, the Dutch government decided to launch a consultation on building new nuclear power plants as an option for decarbonisation. Proponents of nuclear new build envision 3 – 10 new reactors, with construction starting in the mid-2020s so that the first plants would come online in the 2030s.

Spain currently has 7 reactors generating a fifth of the country's electricity. Though government commitment to nuclear has waxed and waned in recent years, operating plants continue to receive long-term operation license extensions.



Source: BP (2020) and UmweltBundesamt (2021)

Figure 5. **Recarbonisation of Germany's electric grid**

Phase-Out & Anti-Nuclear Countries

Several countries, including Austria, Italy, Luxemburg, and Denmark, have chosen not to build nuclear power and even to pass legislation banning it. Other countries, such as Germany, Belgium, and Switzerland, plan to prematurely phase out their existing nuclear fleet in the 2020s.

Switzerland has one of the cleanest grids in Europe thanks to nuclear and hydro. However, in a recent referendum, its citizens voted to transition to 100% renewable energy by 2050, even though they had just voted against an accelerated phase-out of nuclear in a referendum a few years ago.

Belgium also has one of the cleanest grids in Europe due to its sizeable nuclear fleet. In 2020, however, the newly appointed Minister of Energy from the Green Party confirmed the previous phase-out date of 2025 for all the country's operating reactors. Belgium had planned to subsidise natural gas plants to keep its grid stable and as a result, Belgium would have been the only country in the EU to significantly increase emissions from its power sector, according to a recent report by Ember. All of this is now under review in light of Russia's invasion of Ukraine, which has prompted calls for Europe to eliminate dependence on Russian gas.[18]

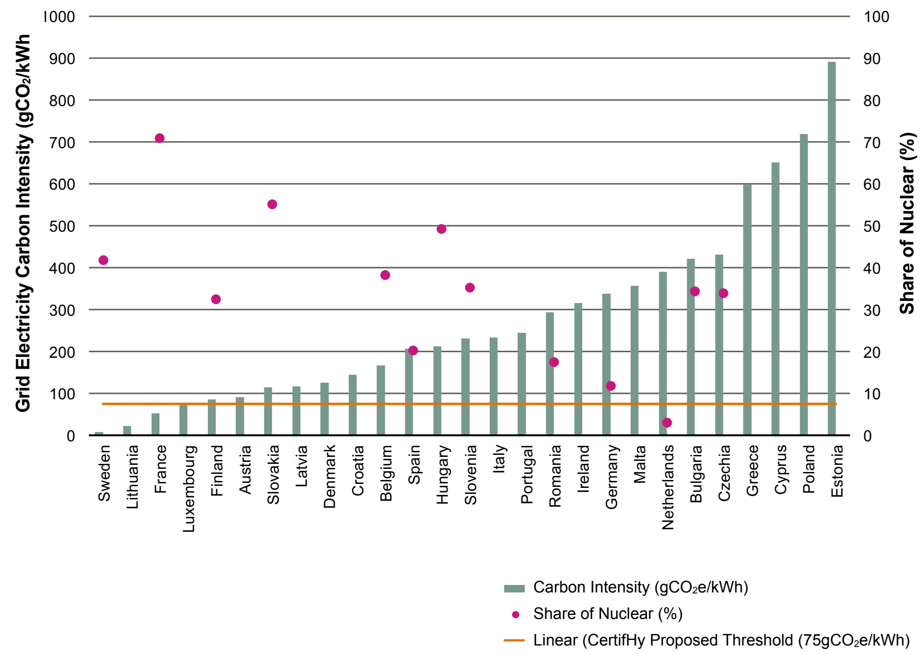
In 2000, Germany started its 'Nuclear Exit by 2022'; at the same time, it began subsidising renewable energy heavily (Figure 5).[19] This 'Nuclear Exit' was briefly reversed just months before the Fukushima Daiichi accident in 2011; the government cited climate mitigation as the main reason for cancelling the premature nuclear phase-out. After Fukushima, the government reversed its decision again, and since then Germany has been building more wind, solar, and bioenergy, along with new coal plants, and recently shifted away from the Nord Stream 1 and 2 natural gas pipelines from Russia. The recent energy crisis in Europe, inflamed by Russia's invasion of Ukraine has highlighted over-dependence on imported fossil gas in the 'clean' energy transition. As the EU Commissioner said at the World Nuclear Exhibition, in November 2021:[20]

> "There is a growing sense of realism about the need for complementing renewables with baseload electricity production. This leads to renewed interest for nuclear energy as a part of the new energy future… right now, nuclear power is the most prevalent low-carbon source providing the baseload needed for the stability of the electricity grid. And also one that helps reduce reliance on imported fossil fuels, contributing to energy stability and security."
>
> Kadri Simson, EU Commissioner

Climate & EU

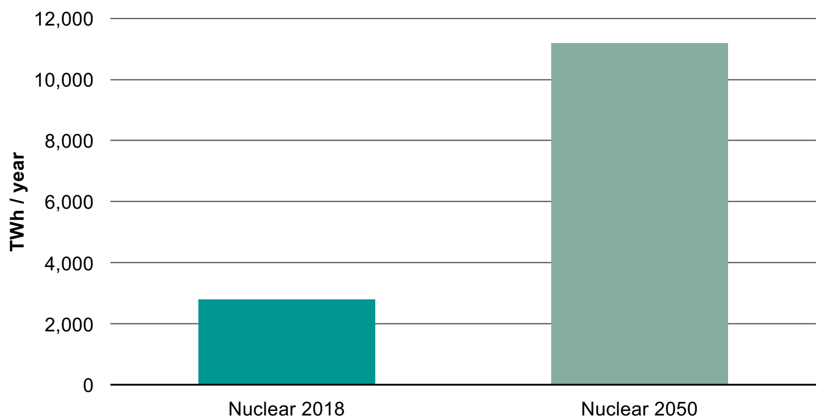
The European Union is discussing tightening its emissions reduction targets to be compatible with the Paris Agreement, and decarbonising its energy supply is one key aspect. Doing what Sweden and the other countries did with nuclear several decades ago would be a good start, but it would only be a start. Most of Europe is far behind, still struggling to decarbonise even the electricity sector (Figure 7).[21] Most countries are far from adding new net clean electricity production, because while they are adding one type of clean electricity, they are shutting down another, spending billions, wasting decades, and getting nowhere in terms of increased clean energy generation and reduced emissions.

Nuclear power is the single largest producer of low-carbon electricity in the EU, responsible for more than 25% of all power, so prolonging the life of existing, safe nuclear plants must be considered a sustainable activity. Figure 6 shows nuclear energy production globally in 2018 and in 2050.[22] The modelled nuclear generation for 2050 is the average value from the four illustrative model pathways in the IPCC's 2018 Special Report on Global Warming of 1.5ºC. The European Union has the largest fleet of nuclear in the world, and has many of the necessary institutions, practices, and frameworks in place, as well as the expertise needed for expansion. The EU can achieve major advantages in maintaining and expanding its nuclear fleet, not shrinking it.



Source: IPCC (2019)

Figure 7. **Carbon intensity & share of nuclear energy in European countries**



Source: IPCC (2018)

Figure 6. **Nuclear generation in 2018 v. 2050 (2050 is IPCC average of four main scenarios)**

"Only a combined strategy employing all the major sustainable clean energy options — including renewables and nuclear — can prevent the worst effects of climate change."

Kenneth Caldeira, Kerry Emanuel,
James E. Hansen & Tom Wigley

GREEN LABEL FOR NUCLEAR

‘Green Label’ for nuclear energy in Taxonomy of Sustainable Finance:

- The EU must decide whether nuclear will be included in the “EU Taxonomy of Sustainable Activities”. The EU Taxonomy is a classification system to determine whether activities qualify for sustainable investment finance.
- If nuclear power falls outside the criteria for sustainable finance, this will affect the conditions for nuclear power to obtain funding from the market and make the green transition significantly more expensive. Nuclear power already and will increasingly play an important role in supporting the achievement of climate objectives in some EU countries.
- Access to finance and policy support from initiatives such as the Just Transition Fund, the European Green New Deal, COVID-relief funds and Clean Hydrogen Strategy, for example, depend on being included in the Taxonomy.
- The heated debates over the potential inclusion of nuclear power and natural gas in the EU taxonomy have again exposed the different interests of EU nations. Nine nations use nuclear for over 30% of their electricity generation mix. Ten nations use gas for over 30%.
- While the Taxonomy is supposed to be technology-neutral, nuclear was initially evaluated using different criteria than any other activity and excluded in the first edition of the Taxonomy published in 2019. Nuclear energy has since been subject to a special evaluation by the European Commission’s Joint Research Centre (JRC).
- The key argument for not including nuclear in the Taxonomy has been the claim that the authors have not had clear enough scientific evidence on whether nuclear is indeed sustainable — in particular, whether it complies with the Taxonomy’s Do-No-Significant-Harm criteria.
- To answer these questions, definitively, once and for all, the European Commission commissioned a thorough review by the Joint Research Centre. The result is an almost 400-page report on the topic; the key findings are as follows:

> “The analyses did not reveal any science-based evidence that nuclear energy does more harm to human health, or to the environment than other electricity production technologies already included in the Taxonomy as activities supporting climate change mitigation.” [23]
>
> European Commission’s Joint Research Centre

In addition, the JRC found that storage of spent fuel in deep geologic formations is **‘appropriate and safe’**, citing countries including France and Finland in advanced stages of developing such sites.

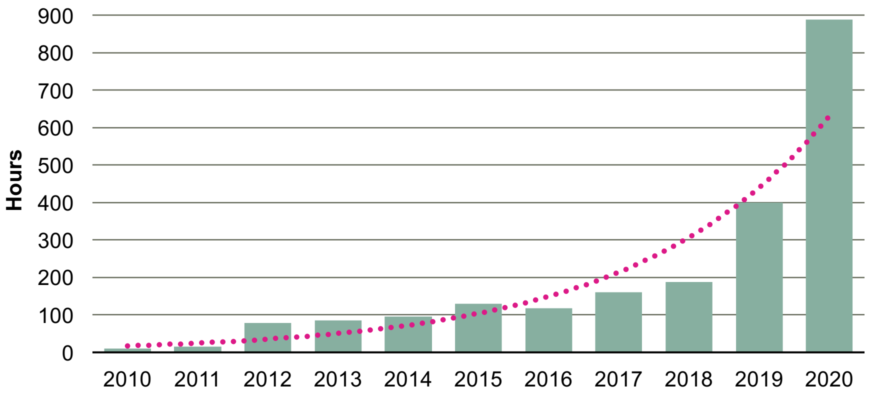
The JRC compared the environmental impacts of various electricity generation technologies on human health and the environment, and found that:

- Average lifecycle GHG emissions determined for electricity production from nuclear are comparable to the values characteristic to hydropower and wind.
- Nuclear energy has very low NO_x (nitrogen oxides), SO_2 (sulphur dioxide), PM (particulate matter) and NMVOC (non-methane volatile organic compounds) emissions. The values are comparable to or better than the corresponding emissions from the solar PV and wind energy chains.
- With regard to acidification and eutrophication potentials, nuclear energy is also comparable to or better than solar PV and wind.
- The same is true for freshwater and marine eco-toxicity; ozone depletion and POCP (photochemical oxidant creation potential).
- Land occupation of nuclear energy generation is about the same as for an equivalent capacity gas-fired power plant, but significantly smaller than wind or solar PV.

The conclusion could not be clearer. Nuclear is as sustainable as any other activity already included in the Taxonomy, or even more so. Based on this evidence, nuclear energy should be included in the EU Sustainable Finance Taxonomy (you can read more about this in the Sustainable Nuclear section).

RELIABILITY OF THE POWER GRID

Nuclear energy is flexible and complements renewables to create a reliable power grid.[24] Flexible advanced reactors complement wind and solar in markets with high penetrations of renewables and can enable high penetrations of variable renewables in future energy systems. Together, renewables plus advanced nuclear (with thermal energy storage) can lower overall system costs, reduce emissions, and improve performance in future electricity grids, lowering overall system cost.[25] A reliable electricity grid is essential to maintaining modern society and helping developing economies grow and modernise. In practice, reliability means that demand and supply must stay in close balance every second. Historically, it has been demand that fluctuated. Management has been relatively easy by matching a mix of baseload and flexible production capacity. Today, many countries are adding more wind and solar to their grids, which increases fluctuation on the supply side as well.



Source: Platts European Electricity Service (2020)

Figure 8. **Number of negative-priced hours in the European electricity market**

Instead of following routine fluctuations in demand, these sources follow the weather, time of day, and seasonal fluctuation. For example, in the winter, the wind often dies down just as temperatures fall significantly and electricity is needed for heating. In warmer countries, the sun starts to set just as the late afternoon electricity demand spike hits. Much of distributed solar capacity is 'behind the meter' (e.g., on rooftops) and therefore invisible to the system operators — making grid management more difficult. Adding supply-side fluctuation to demand side fluctuation results in a less stable power grid, higher price volatility, and higher overall costs for the whole system.

One way to observe this increase in supply and demand side fluctuations due to an increased share of renewables is through the trend of negative-priced hours in the European electricity market (Figure 8).[26] Negative prices indicate a severe supply/demand imbalance when generators have to pay customers to take electricity, or stop production: an unsustainable situation from a business or investment point of view. This number, already reaching 10% of annual hours, has been growing at a rate that seems exponential, while the main reason for this phenomenon — the addition of wind and solar energy production — has been growing linearly.

As can be seen in the map showing carbon intensity in Figure 9, EU countries with significant shares of nuclear in their energy mix, on average, emit much less carbon than countries without nuclear, even with higher shares of renewables.

Countries with nuclear not only have lower-carbon, but also lower-cost electricity. In Germany, where the average retail electricity price for a household in 2021 was roughly €300/MWh, the wholesale electricity price (generation cost) is less than a quarter of this total price. Even if wholesale electricity prices in Germany fall to zero, a regular household will still pay well over €200/MWh in various fees, taxes, and renewable energy subsidies. This high price of electricity, along with much lower prices for natural gas (around €50/MWh), means that Germans will not switch from gas to electric heat pumps. If a country can have both lower cost and lower carbon intensity, why choose higher cost **and** higher carbon emissions?

Adding energy storage, such as large batteries, can mitigate the price volatility and the number of negative price hours, and provide some valuable services such as frequency control. However, they remain an expensive and resource-intensive way to provide dispatchability and grid-scale energy storage.

Nuclear power can significantly contribute to the overall reliability and resilience of electricity systems while keeping overall emissions and prices low. Nuclear plants are engineered to withstand weather-related disruptions better than most other forms of clean energy generation. In Nordic countries, electricity makes up a greater share of overall energy use than in other EU countries. The region mostly relies on hydro, nuclear, wind, and biomass generation. These countries have some of the cleanest electricity generation in Europe (Figure 10).

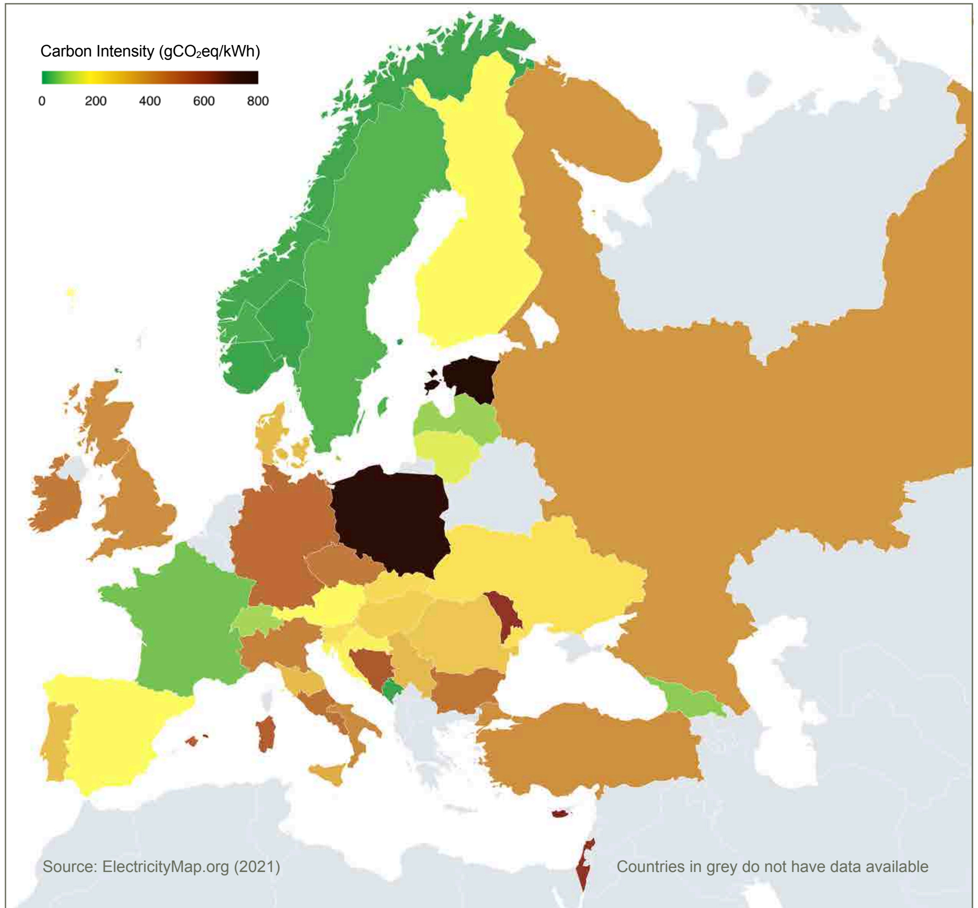


Figure 9. **Carbon intensity of electricity generation in selected countries**

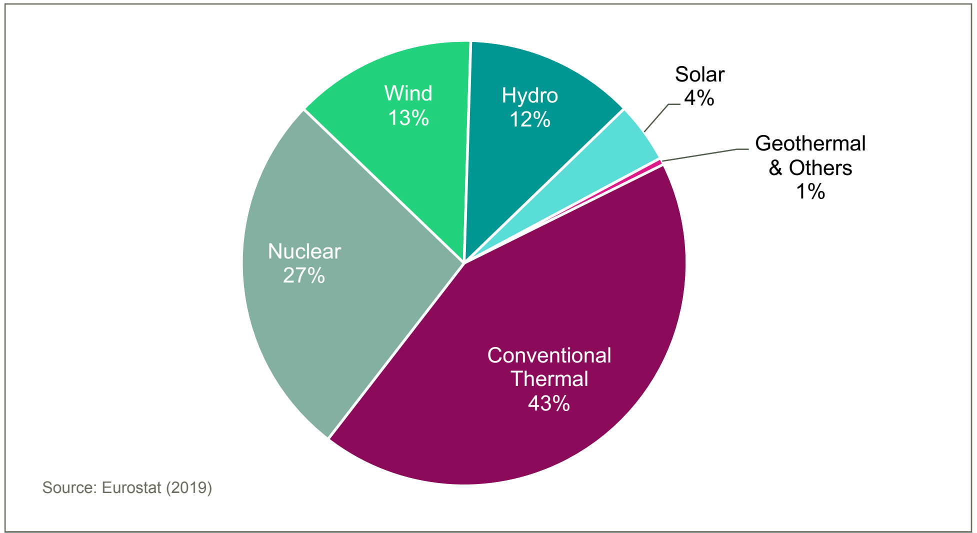


Figure 10. **Electricity production by source in Europe, 2019**

Even so, to meet the additional demand for electricity projected for 2050, the Nordic region will collectively need to produce another 290 terawatt-hours (TWh), a 75% increase from current generation.[27] The majority of European nations are much further behind in their grid decarbonisation than the Nordics and face an even greater challenge: to manage a transition to clean electricity generation whilst maintaining affordability and reliability, and greatly expanding electricity supply to enable electrification of sectors such as heat and transport.

Figure 9 shows the energy generation sources, imports and exports, and emissions of electricity production for Europe in real-time from ElectricityMap.org. This useful site shows which countries have been able to decarbonise their electricity production, to what degree, and how have they done it. Most of the green and light yellow countries have significant shares of nuclear and/or hydro power acting as the backbone of their power grid, along with wind and solar. The 'brown' countries rely more on fossil fuels such as coal and natural gas for the backbone, even though countries like Denmark and Germany have significant shares of wind and/or solar. Figure 10 shows the EU average electricity mix in 2019. Roughly half of clean electricity comes from nuclear power, while 43% still comes from fossil fuels.[28]

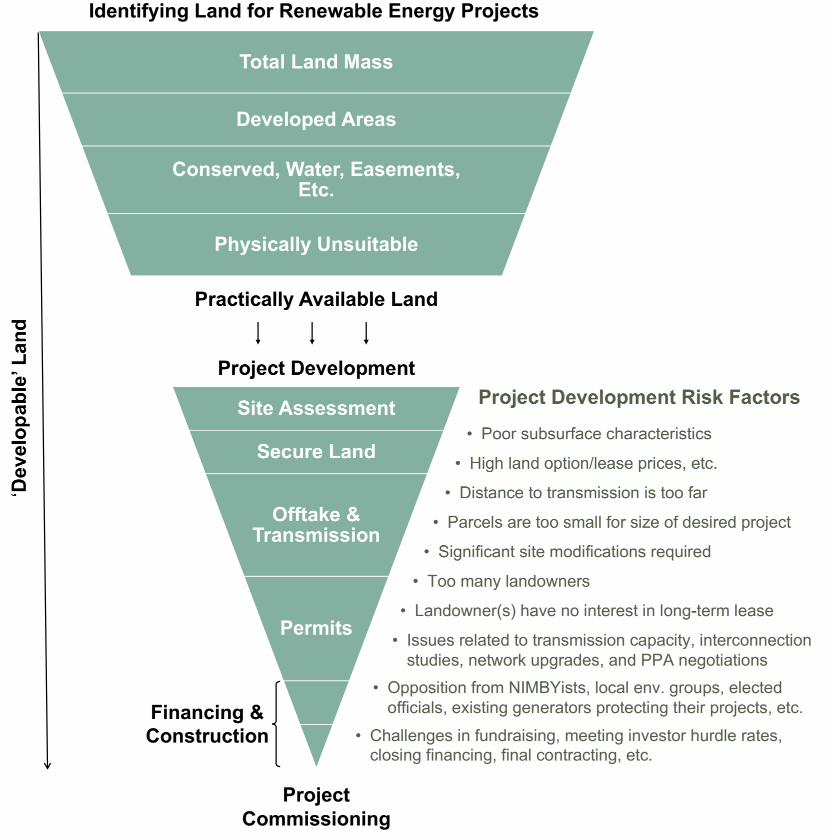
RISKS TO THE CLEAN ENERGY TRANSITION

Net Zero will be difficult to achieve even if we use all zero-carbon energy technologies. If we restrict our options, e.g., to only renewables, we dramatically increase the risks of failing to decarbonise. Each of the zero-carbon energy technologies has advantages and risks/challenges to large-scale deployment. Typically, these risks are less apparent in the early days of deploying a given technology, and become more severe as deployment increases — we note that public opposition to wind and solar projects is growing throughout the world. Wind and solar both require extensive land, impact many landowners and communities, and require extensive transmission build. Because they share these risks, any energy transition plan that primarily uses wind and solar has no way to hedge the risk of public opposition to greenfield projects, interconnections, and transmission build. A way to reduce the risk of failing to decarbonise is to have a portfolio of solutions which do not all share the same risks. For example, complementing a renewables strategy by repowering existing power plant sites with advanced nuclear would enable large clean energy capacity additions without requiring greenfield project development or new transmission lines.

Energy models, upon which all energy transition targets are based, compare the types of generation capacity that we need to deploy by midcentury. These models offer guidance on the scale of the energy infrastructure needed. However, nearly all energy models are optimised on generation cost alone. This means that if a renewables strategy alone is just a few dollars per MWh cheaper, the models recommend decarbonisation with mostly renewables. Most models do not yet consider other factors, particularly those related to deployment feasibility (reflecting various socio-political, cultural, commercial, and financial factors). This creates a widening gap between energy models and the real world of project development. The problem is that policymakers believe the energy models are telling them what is feasible. Consequently, policy targets are not tied to real world challenges and time-sensitive infrastructure implementation plans are not risk-informed. **Principal major risks to the energy transition are outlined below:**

Land

There is a fundamental mismatch between what we consider available land for power projects and what is considered developable by project developers. As shown in Figure 11, the project development process begins once all practically available land is identified (i.e., site assessment). Several milestones need to be achieved before a project is built and each milestone has several associated risk factors.



Source: LucidCatalyst (2021)

Figure 11. **Project development risk factors**

Any one of these risk factors can cause a project to fail. For jurisdictions with poor wind and solar resources that plan on decarbonising with renewables and green hydrogen (e.g., Germany), it is important to note how much land will be needed, and how difficult it will be to secure rights to the land (or sea) and successfully develop enough capacity for economy-wide decarbonisation.

Transmission

Transmission fundamentally governs power project development. Without available capacity to interconnect a project, there is no reason to develop the project. Transmission must be built first, and due to the need to obtain approvals across multiple geographical and governmental jurisdictions, building transmission typically takes much longer than power projects. This makes transmission development a risky endeavour. Further, because of lower capacity factors, transmission dedicated to wind and solar is substantially more expensive on a per unit energy basis. If enough transmission cannot be built in a timely manner (i.e., at an unprecedented rate), there simply is no practical path to achieving decarbonisation.

Public Support / Opposition

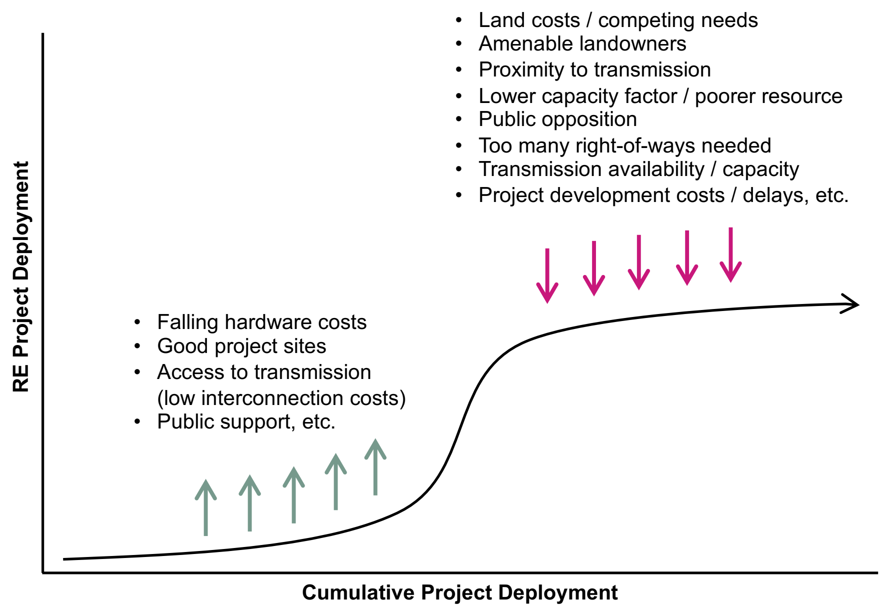
Public opposition to renewable power projects is becoming better organised and more frequent. A growing proportion of opposition is being led by the environmental and conservation communities and others interested in protecting an area's rural character and/or viewshed. Public opposition tends to increase as more projects are deployed in a given area. It will also play a critical role in the build out of transmission as well.

Escalation of Non-Hardware Project Costs & Risks

Fortunately, solar and wind hardware costs have enjoyed a remarkable decline over the past decade. It is likely that non-hardware project costs will escalate as more projects are developed in a given area. In addition, increased project development costs and risks must be paid with project developers' risk capital, which is more expensive and harder to raise than capital to fund project construction. Project developers typically look for factors like low land cost, large parcels in close proximity to planned or existing transmission, landowners who are willing to sign long-term land leases, good solar or wind resources, the need for few right-of-way approvals to interconnect the project, clear public support, favourable energy market environment, etc. Nearly all these essential developer criteria get worse as more projects are deployed in an area. As more land is converted for projects, land costs increase, projects are pushed further from transmission, project capacity factors get worse (as the good sites are taken), the public is less supportive, etc. All these conditions occur simultaneously, compounding project risk and thus cost. Energy models often show increasing deployment over time, as in a 'hockey stick' growth curve. The real factors that affect large-scale project deployment suggest that an 'S-curve' (as shown in Figure 12), is more likely.

Timing & Logistics

The sequencing and time-sensitivity of this massive, simultaneous infrastructure build-out in every country presents an unprecedented logistical challenge. The challenge is not only to build enough clean electricity generation infrastructure, but to build the infrastructure needed to electrify other sectors such as heat and transport. Many potential projects do not make it all the way through the project development process, which means that to commission a gigawatt of solar several gigawatts must make it to late stage development status. This will necessarily require more developers overall, more development capital, and more human resources dedicated to other parts of the process (e.g., permitting, interconnection studies, engineers, financiers, etc.).



Source: LucidCatalyst

Figure 12. **The project development S-curve**

Beyond the Power Sector

Seventy-five percent of primary energy use is outside the power sector. The amount of generation capacity required to develop emissions-free substitute fuels and to decarbonise other carbon-intensive sectors of the economy will require a staggering amount of emissions-free energy.

The scale of investment required, necessary deployment rates, willingness of the public to bear these costs, and available land for development will be major hurdles to the energy transition. In many locations, deployment rates for renewables are far below what would be necessary to achieve renewables-intensive 2050 decarbonisation targets. Advocates for these strategies point to this shortfall and say we need to redouble our efforts. But it would be prudent to consider that these current sluggish levels of deployment may actually be evidence of how difficult large-scale renewables deployment is becoming even though we are just at the beginning of the build up needed for the energy transition. If it is difficult now, at the beginning, it is only going to get more difficult due to the best sites being taken already, lack of transmission, escalation of development risks and cost, and growing public opposition.

The magnitude of the project development challenges highlights the need for energy models to expand beyond simple cost optimisation. There is too much at stake for policy makers not to have the information necessary to develop sound policy and risk-informed implementation plans. Overcommitting to a specific pathway could prove costly and unsuccessful. Every low-carbon option taken off the table makes failure more likely.

IMPOSSIBLE BURGERS

Impossible Burgers for Climate: Oven Ready in 2030[29]
By Kirsty Gogan and Eric Ingersoll, Co-Founders, TerraPraxis

It looks like a burger, tastes like a burger, and is available, for the price of a burger, in any burger joint. Impossible burgers are plant-based meat substitutes that require almost no behaviour change for good effect. In 2030, ‘impossible burgers for climate’ are coming to market.

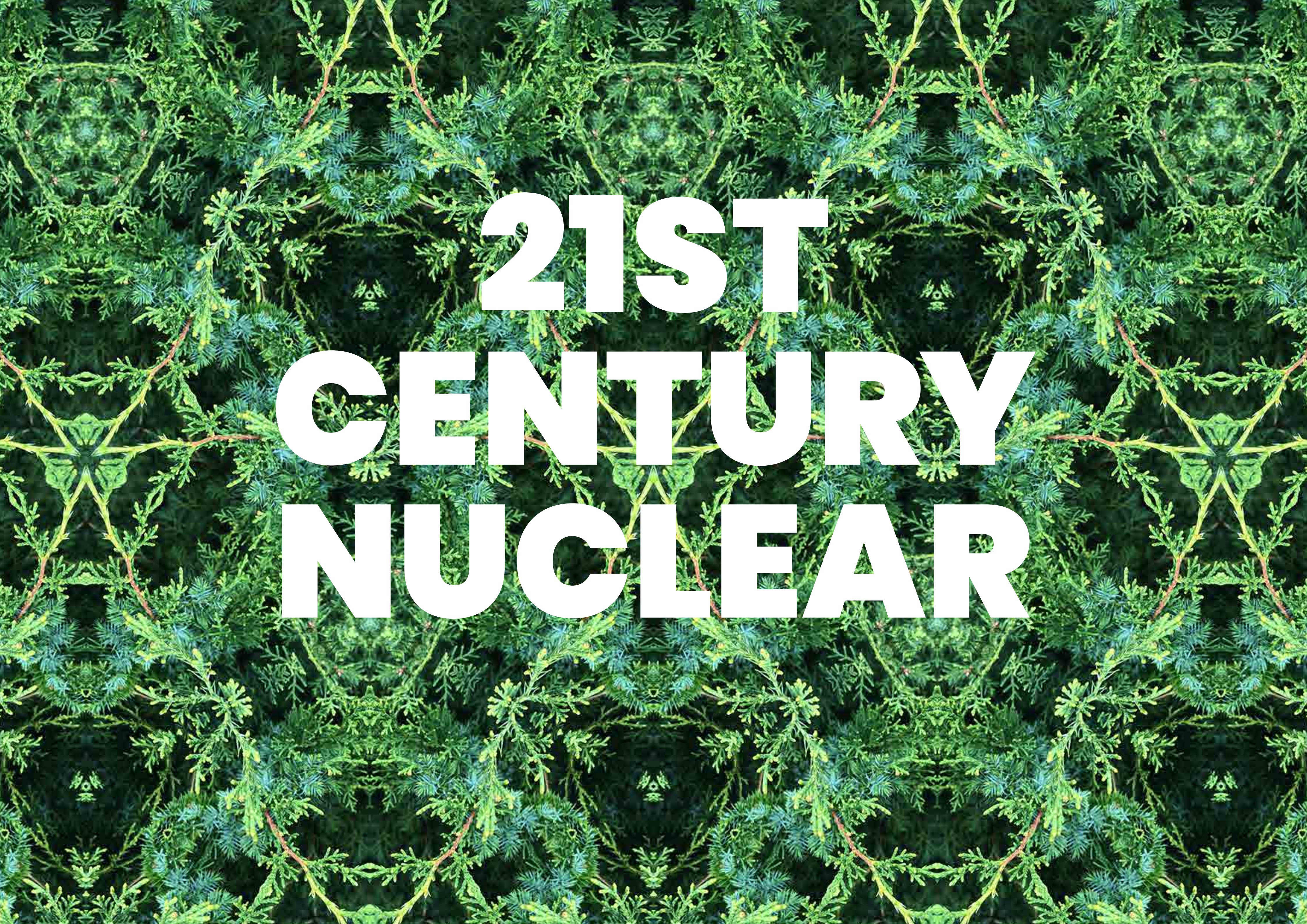
Targeting oil, coal and gas in ‘hard-to-abate’ sectors (e.g., aviation, shipping, cement, coal) that threaten a high-risk 4°C outcome, ‘impossible burgers for climate’ are zero carbon, ‘drop-in’ fuels designed to meet cost, performance and scale requirements for the toughest decarbonisation challenges. These fuels can accelerate decarbonisation by enabling continued use of existing storage, transport, distribution and end-use infrastructure. No behaviour change required.

Throughout the 2020s, more and more people realised that a new generation of advanced heat sources would be transformative for our decarbonisation efforts and worked together to develop multiple applications for widespread deployment into new clean fuels production. Now, all oil and gas investment is flowing into these clean production facilities, leveraging existing supply chains, skills and infrastructure without emissions, disruption or additional costs to consumers.

Replacing 100 million barrels of oil per day at no additional cost, refinery-scale Hydrogen Gigafactories and shipyard-manufactured production platforms will deliver zero carbon, drop-in fuels to keep planes flying, ships sailing, convert coal plants into carbon negative generators, and enable advanced medicine, land- and animal-free agriculture, and even space travel. Nations can thrive while ecosystems are restored as these new energy sources dramatically shrink civilization’s environmental footprint. Energy and emissions can be delinked thanks to this ‘missing link to a livable climate’. In 2030, we now see a path to expand abundant modern energy while ensuring a sustainable future for all.

"Producing clean drop-in substitute fuels at scale will reduce the extent of transformation required to decarbonise the whole economy. This lowers the overall investment, disruption, and behaviour change required to maintain energy services. Essentially, this means decoupling energy from emissions without increasing cost or decreasing performance."

Eric Ingersoll, LucidCatalyst & TerraPraxis



21ST CENTURY NUCLEAR

5 PRIORITIES FOR CLEAN ENERGY TRANSITION

Since the year 2000, the EU's emissions from energy have decreased by roughly 750 million tonnes, from over 4 billion tonnes to 3.3 billion tonnes in 20 years (37.5 megatonnes/year on average). The EU's emissions would need to decrease three-times faster for the next 30 years to reach zero emissions from the energy sector by 2050. Most of these emissions come from sectors other than electricity production (such as industry and transport).

To reach carbon neutrality in Europe, and to support access to clean energy throughout the world, the European Union ought to take the following actions:

1 / EXPAND

Priority 1: Expand clean electricity generation as quickly as possible
Decarbonise current electricity production fully, maintain and expand electricity generation (renewables and nuclear) to support electrification of heat and transport as much as possible. This means extending operations at current nuclear power stations wherever feasible and building new plants along with continued deployment of renewable energy. The advanced reactors being rapidly commercialised today can provide economic, clean, and flexible dispatchable generation that will enable high penetrations of variable renewables in future electricity grids.

2 / REPOWER

Priority 2: Repower coal plants with new heat sources
Phase out and/or repower coal and natural gas plants either by directly replacing the coal boiler with an advanced reactor (or advanced heat source) that can supply steam, or indirectly by converting the natural gas turbine to run on ammonia, hydrogen, or synthetic methane. Advanced clean heat sources can potentially re-power coal plants by offering a 'drop-in' substitute for the coal boiler, enabling emission-free operation of the plant and associated infrastructure, including transmission.

3 / CONVERT

Priority 3: Convert remaining liquid fuel use to carbon-neutral fuels
Some sectors cannot be easily electrified in time to meet the goals of the energy transition. These sectors include aviation, shipping, steel, cement, and chemical industries, all of which use hydrocarbon fuels (either petroleum or natural gas) for energy or as a feedstock. Large investments have been made in the infrastructure that supports the use of these highly emitting fuels. Advanced heat sources can produce large-scale and low-cost hydrogen and synthetic fuels at the scale required to decarbonise global aviation and shipping.

4 / REPLACE

Priority 4: Replace natural gas for industry and heating
Replace natural gas for industrial processes, which cannot be electrified easily either directly by providing process heat, or through synthetic, carbon-neutral fuels such as hydrogen. Advanced heat sources, through district heating networks, also have the potential to supply reliable heat to homes, businesses, and industry.

5 / INCREASE

Priority 5: Massively increase investment in electricity and clean e-fuels production to support global energy access, especially in Africa
We need to grow the energy system to supply rising global demand within all energy sectors, particularly in the developing world where it will increase the most. Equitable access to clean energy services is needed to elevate billions out of poverty and guarantee greater economic opportunity for everyone, including women and girls. Through the provision of low-cost flexible electricity, clean fuels, and heat for industry and desalination, advanced heat sources can provide access to modern energy services in remote and developing communities, in support of a clean energy transition that can benefit society and elevate living standards around the world.

REPOWERING COAL

More than 2,000 GW of coal-fired capacity is operating in the world today. Figure 13 shows the vast extent of coal plants currently operating, under construction, and being planned in the area pictured.[30] According to the International Energy Agency (IEA),[31] coal power adds around 10 billion tonnes of CO_2 emissions to the atmosphere every year, which is almost a third of all energy related emissions. Expected future emissions *from just the existing* coal fleet already exceed the entire 2°C carbon budget. These coal plants will either have to be retired prematurely, or repowered by replacing the coal boiler with an advanced heat source designed for the purpose.

It is very risky to assume that countries will shut down their coal plants prematurely. Coal-fired power plants currently deliver around 37% of global electricity supply. These are surprisingly young assets; of the 2 TW of coal power plant capacity in operation today, more than half is less than 14 years old, and the average age of the global coal fleet is decreasing as the oldest plants retire. It is not realistic to expect these coal plants to be prematurely closed with decades of remaining operating life. Even in Europe, coal plants are relied upon for affordable reliable power, spinning reserves, and other valuable services. This means that it is often not feasible to shut down a large coal plant and 'replace' it with a wind farm hundreds of kilometers away.

The socio-economic costs of abandoning these coal plant assets — the impacts associated with the loss of jobs, revenues, and energy generation — will be too great a price to pay for many countries and local communities. It is unclear whether renewables can replace the lost jobs, revenues, and energy of shuttered coal plants on a like-for-like basis. Further, is it even feasible to do so from a land-use, transmission, and investment perspective when the necessary scale, cost, speed, and space required to achieve the clean energy transition is already so large?

Existing coal-fired power plants have enormous value in terms of established markets for their power, grid connections, access to cooling water, and experienced personnel necessary for the generation and distribution of power. These plants can also act as flexible generators, supporting integration of renewables into electricity grids. Therefore, repowering coal plants with clean heat sources is absolutely vital, both for de-risking the energy transition, as well as for the communities who currently rely on them.

Replacing existing coal-fired boilers with an alternative heat source and thermal energy storage to drive turbines and generators could provide a fast and low-risk contribution to decarbonising the world's power generation.

A recent case-study for Poland indicates that an advanced heat source such as a nuclear reactor designed for the purpose in the $2,000 – 3,000/kW range results in excellent economics for coal plant conversion, making conversion an attractive investment.[32]

These price targets seem low compared to recent nuclear power projects in the West. It is clear we need to make nuclear power affordable.

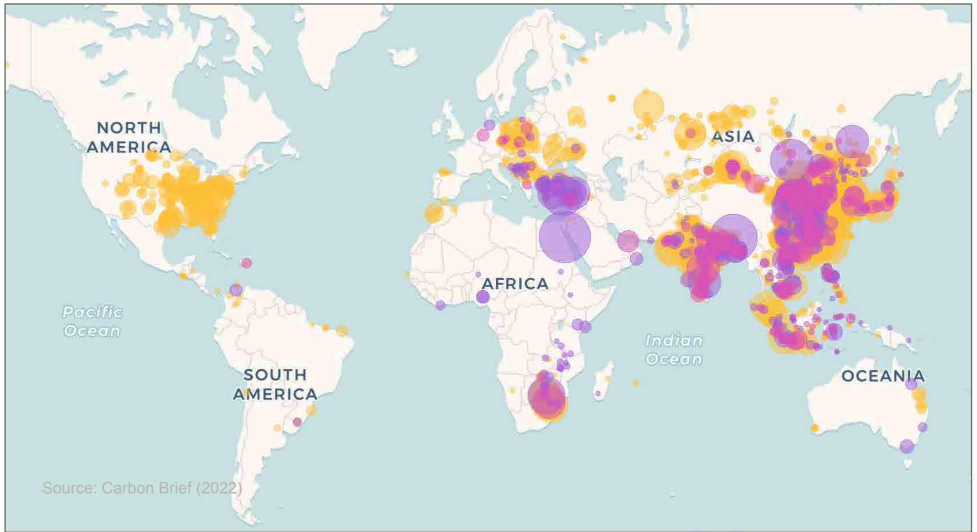


Figure 13. **Coal plants operating (yellow), under construction (pink) & planned (purple)**

"Nuclear is beautiful because its tiny land use and lifecycle footprint protects nature and delivers civilisation-scale, abundant clean energy. Both of these are fundamental to our future health, well-being and prosperity on this planet."

Kirsty Gogan, LucidCatalyst & TerraPraxis

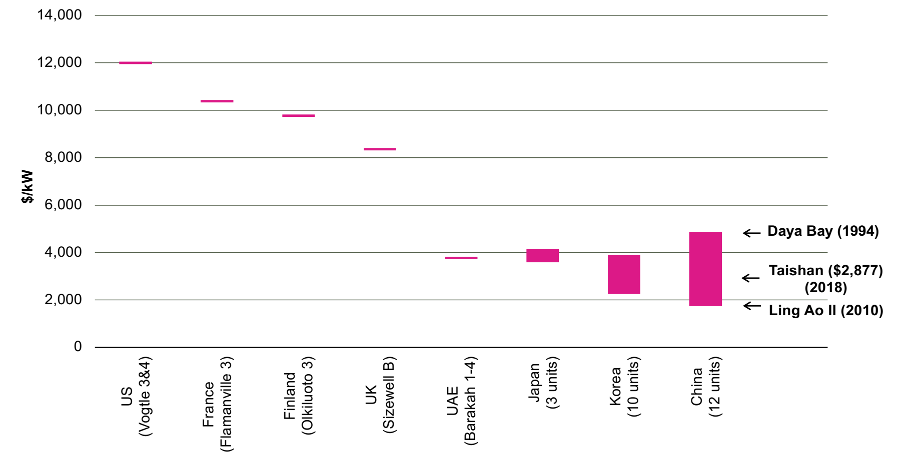
HOW TO MAKE NUCLEAR COST COMPETITIVE

A successful rollout of new capacity requires new projects that can be delivered on schedule and at low cost. Countries like South Korea, Japan, and China have delivered many low-cost, large plants in less than six years over the last decade. By contrast, first-of-a-kind (FOAK), first-in-a-generation projects in Europe and the U.S. seem expensive and slow; understandably giving rise to doubts about the practicality of nuclear playing a role in climate mitigation in the short time frame left. However, those European and U.S. projects included many one-time expenses associated with first-of-a-kind projects.

Examples from around the world demonstrate projects can be delivered on time and on budget (see Figure 14)[33] and there are ways to make costs lower still. In fact, there are a relatively small number of well-understood best practices that have been shown to improve cost and speed of project delivery. Luckily, we know how to improve things.

Key actions to make nuclear cost competitive:

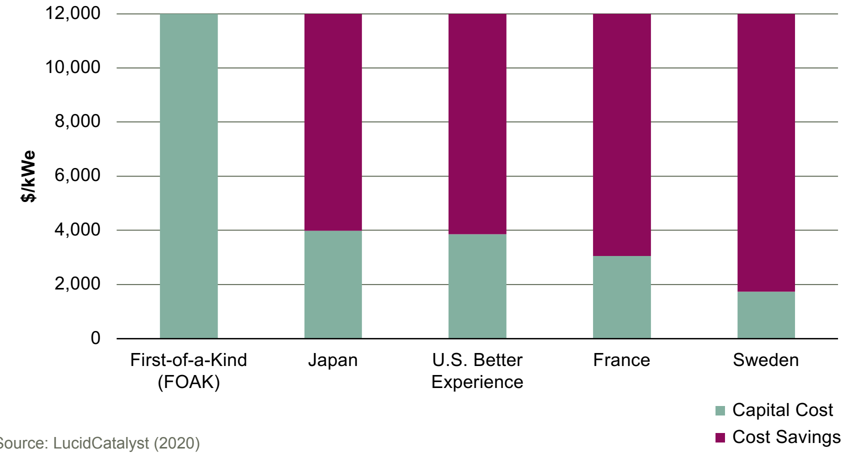
- Just as with off-shore wind, building multiple units one after the other builds experience and expertise for construction, project managers, supply chains, and regulators — especially with smart ways to retain that expertise from one project to the next.
- Standardise on reusable designs, that minimise site-specific engineering so that projects can be planned and delivered more reliably and smoothly.
- Support standardised designs with harmonised regulation to reduce the added costs and delays resulting from the need for country-specific redesign due to differing national regulatory standards.
- Constructing the same design multiple times with the same team and same supply chains, to maximise learning by doing, and economies of scale.
- Constructing multiple units at one site in series, maximises productivity and learning of the working crew staying at the site.



Source: LucidCatalyst (2020)

Figure 14. **Sample of global nuclear project capital costs (with interest)**

These common-sense steps can all apply to current technology and large plants — and projects around the world have already implemented them, as shown on the right side of Figure 14. The first-of-a-kind costs, shown in Figure 15, should only have to be spent once — to license the design, qualify the supply chain, and establish the skills and capability in the workforce and project leadership teams. As the UK offshore wind programme has shown, sustained access to finance, political support for programmatic build, and an industry commitment to cost reduction has led to lower costs and performance improvements.



Source: LucidCatalyst (2020)

Figure 15. **FOAK compared to costs achieved in consistent, real-world build-out programs**

In the 2020s, next generation designs and new deployment models will deliver even lower costs and new high value propositions:

- Serial production of modules, even complete reactor-systems for smaller reactors in a factory, can substantially decrease the duration and cost of construction.
- New manufacturing environments, such as manufactured power and fuel production platforms at shipyards, have higher productivity than traditional construction.
- New siting options, such as shipyard manufactured platforms that can be sited offshore, can reduce costs and construction impacts on local residents.
- Higher temperatures of some new designs enable higher efficiencies for electricity as well as hydrogen production.
- Advanced heat sources can also be used to repower coal plants, enabling the reuse of site infrastructure, including transmission, without emissions — turning polluting imperilled assets into rapidly available, low-cost, high-value, carbon-free generators using only the existing land footprint.
- Innovative designs that make exceptional safety and reliable operations easier to achieve, for example through remote operations and designing reactor systems for passive safety.

All of this requires several things to happen from different actors. The following is an overall picture from each actors' perspective.

Industry

The nuclear industry needs to communicate a more expansive and progressive vision, and targets for construction costs and rates of deployment; utilities and technology vendors need to start preparing their capabilities to deliver against these cost and deployment targets. If benefits, such as learning and cost-reductions from series-production are to be realised, they need to be planned for, and sufficient projects brought forward. European electricity demand is expected to increase by two or more times by 2050, as the chemical industry decarbonises its processes. It may grow substantially more if fossil fuel-based feedstocks are also replaced with carbon neutral ones (such as hydrogen).

In response to individual country or EU needs for clean electricity by 2030, 2040, or 2050 to decarbonise, utilities and vendors need to demonstrate the benefits of their technologies and ability to deliver affordable, reliable, and clean electricity as well as a wide range of energy services including heat, hydrogen production, and direct air capture. They ought to clearly communicate and actively support the critical message that if nuclear energy plays a substantial role alongside other clean technologies, the overall transition to clean energy will be more straightforward and less costly, due to the reduced need for flexibility, energy storage, and dispatchable capacity.

Governments & Policymakers

The nuclear industry needs a clear signal of future demand before it can initiate long-term plans. Technology developers cannot develop new reactors or delivery models if there is uncertainty about siting, permitting, and investment. Similarly, manufacturing partners such as shipyards cannot invest hundreds of millions in new technologies and expertise without clear market signals. Figure 16 shows how these commitments and investments translate into cost reduction and improved project delivery.

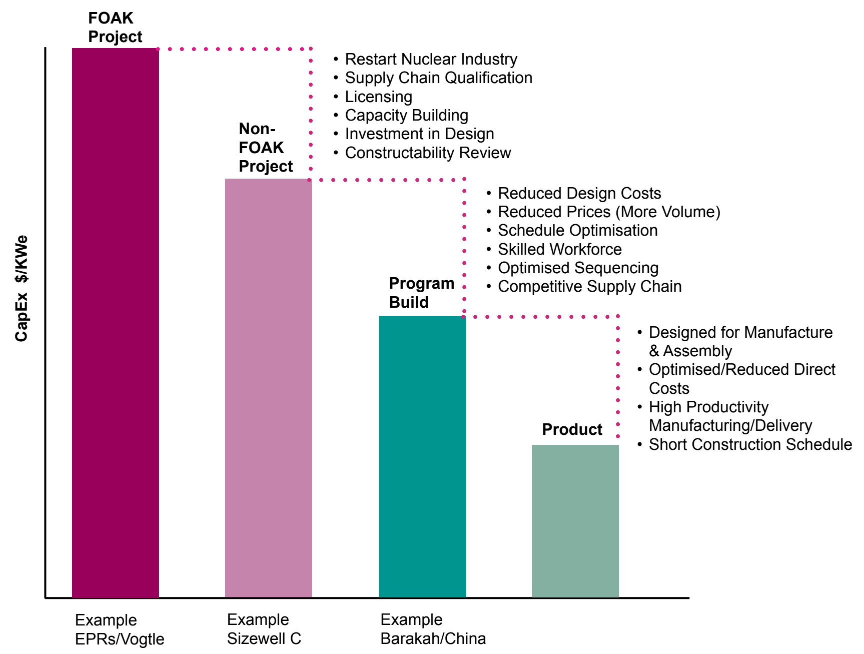
Auctions for renewable energy have proven to be highly successful in stimulating cost competitive projects. Similar auctions could motivate nuclear providers to seek cost-reductions, plan for larger and longer-term projects (instead of 'one-off' projects), and create incentives to deliver on time and on budget. Lowering nuclear costs will require similarly intentional programmes as were used for renewables. Real world experience consistently demonstrates that this is the best way to drive down costs and enable rates of deployment relevant to the challenge of decarbonising our energy systems.

Fleet programmes in Japan, China, South Korea, and the UAE have demonstrated consistently low costs. National programmes in these countries have implemented construction best practices, continuous learning, and economies of scale, while focusing on long-term cost reduction.

Regulators & Regulations

Countries such as Finland, the United States, and Canada, are designing new nuclear regulatory approaches appropriate for new technologies, siting options, uses of nuclear, and addressing the need for making regulation more efficient, fast, low cost, and low risk. A further option would be to move towards a product-based model and licensing approach that enables deployment of these products in multiple countries and locations while meeting high quality and safety standards. To enable this, a new relationship is needed between product designers and national regulators. Each party must take proactive responsibility for achieving this outcome in the interests of society and the environment. Opportunities to license reactors to provide district heat, industrial heat, hydrogen, and other end-products also needs to be addressed.

Strong, independent, and competent regulatory bodies have been, and remain, essential for nuclear operations and new technologies alike. However, nuclear regulation and safety should not exist in a silo of its own, insulated from the rest of the world, because it is already a part of our society and delivering important sustainability benefits for people and the environment. Somewhat surprisingly, nuclear energy is also one of the safest sources of electricity generation, measured in terms of deaths per terawatt-hour of energy production (Figure 30). Regulatory approaches should be well-designed and appropriate to society's needs for clean, reliable, affordable energy that protects people and nature. Risks should be considered in context, and there are increasing calls for a Net Zero duty for regulators to give due consideration to the carbon mitigation impacts of proposed developments. While there is no contradiction between stringent safety requirements and new technical opportunities, if nuclear continues to be complicated and expensive to build, it is highly likely that something more harmful and dangerous will be built instead — leading to an overall increase in harm to public health and well-being, and more severe climate change impacts.



Source: LucidCatalyst (2021)

Figure 16. **Pathway to low-cost nuclear — from project, to programme, to product**

Society

Society needs to consider all types of solutions, including nuclear, and demand strong climate action from their leaders. If nuclear is excluded, or even opposed, we will have slower progress, more risks of taking paths that do not deliver us to our goal (such as variable renewables firmed by natural gas), and more expensive solutions overall, which will decrease people's willingness to tackle climate change and increase the political risks for the necessary measures.

OPPORTUNITIES FOR LIFETIME EXTENSION

Refurbishment and long-term operation (LTO) of existing nuclear power plants are important for ensuring the economic competitiveness of the industry in OECD countries, and prolonging the low-carbon energy contributions of these plants into the future. According to a recent joint report from the OECD-Nuclear Energy Agency (NEA) and the International Energy Agency (IEA),[34] electricity from the long-term operation of power plants constitutes the lowest cost option for low-carbon generation of any kind.

In many OECD countries, such as France and Switzerland, there is no legal end to the operating license of plants, but periodic safety reviews determine whether plants will continue operating. The typical length of the first operating license for existing light water reactors (LWR), the most dominant nuclear technology around the world, is 40 years. Most modern reactors are designed to allow for maintenance and replacement of parts as needed. With proper maintenance, even the current generation of operating plants can last up to 80 or 100 years. According to the IEA,[35] extending long-term operation of the current fleet, normally done 10 – 20 years at a time, is the most cost-effective way to add clean energy production.

According to the IEA's *The Future of Nuclear*, a refurbished plant will have a levelised cost in the range of $40-55 per MWh (€33 – 45/MWh, assuming 8% weighted-average cost of capital, [WACC]). Despite the cost reductions, wind and solar projects are projected to remain above $50/MWh under the same financing conditions. They also produce variable power, which requires backup generation as well as other system costs that are not included in the levelised cost of electricity, but still need to be paid for by consumers.

The policy recommendations regarding LTO could not be clearer: authorise the longest possible lifetime extensions of existing plants, set up risk management and financing frameworks that help mobilise capital for new and existing plants at an acceptable cost, and value the dispatchability and other non-market benefits that nuclear can bring to the power system.

From a policy-perspective, the EU is several steps behind in terms of decarbonising effectively. It needs to move from the retrograde political decisions of shutting down nuclear power plants prematurely (Germany, Belgium, Switzerland, France, Sweden), to encouraging them to extend the life of current plants. The EU should then match the levels of policy support and sustained access to finance for wind and solar, to enable multiple fleets of new-build programmes for both traditional and advanced reactors in member states. The EU needs a policy and financing framework for refurbishment of existing plants as well as new projects to be funded with the lowest cost of capital possible to improve project economics and lower the cost to consumers. Long-term operation allows EU member states to lock in immediate low carbon gains with relatively little additional cost, new infrastructure, or socio-economic disruption.

Investment in LTO will have benefits in both the short and long run, according to OECD-NEA. In the short run, LTO of existing plants that have reached the end of their original operating licenses will complement nuclear new builds. In the long run, the new generation of small modular reactors (SMR) that are easier to finance and with a significant share of factory-produced components, could complement existing large reactors while further contributing to the share of low-carbon electricity as well as the multitude of other energy services discussed earlier. Extending the operational lifetimes of the current fleet as much as possible is the easiest way to bring down the overall levelised cost of electricity (LCOE), lowering the cost of living, and increasing productivity and economic prosperity both for people and industry.

Summary

The 21st century nuclear industry needs to be successful — but this requires a paradigm shift to respond effectively to the scale and urgency of the climate emergency. New visions for how nuclear energy can work with other clean energy technologies to accelerate decarbonisation and increase energy access will help achieve this.

More and better inclusive communication about the value proposition of nuclear energy is needed. All of us need to demand more rapid, effective, technology-neutral climate action. Governments and regulators need to hear all this and start making necessary changes, along with the industry, for legislation, regulation, market design, and clean energy auctions, so that there will be demand for the necessary expansion and new solutions. We have already seen this kind of successful expansion in the renewables industry, so it is by no means impossible. But it might make something that now seems impossible — timely climate mitigation — seem possible again.

"Nuclear is our most misunderstood energy source. It is also our most underused clean energy source. For our failing climate effort, this is great news. We will still have a tool, a 'Dark Horse' with enormous potential that we can throw at the problem."

Rauli Partanen, Think Atom

TOWARDS A BRIGHT FUTURE

FLEXIBLE HEAT & POWER

Current and emerging advanced heat sources can do more than just provide reliable, clean electricity. They can offer added flexibility for power grids, decarbonise heating and industrial processes, as well as produce low-cost hydrogen and synthetic fuels.

Flexible Generation

As discussed above, there is a growing need for flexible capacity because wind and solar make up an increasing share of electric grids. The next generation of advanced reactors are being designed with flexibility in mind. A helpful feature of some advanced designs is the separation of the heat source (reactor) from the turbine-generator that produces the electricity (called the power island) via a thermal energy system. This system includes thermal energy storage that allows the reactor to operate continuously at full capacity (Figure 17). When supply is low and demand (and price) is high, the plant will produce and sell power to the grid. When the price is low, the plant will 'fill up' the thermal storage instead. This kind of system can operate flexibly, much like hydro or natural gas plants, supporting a higher penetration of variable renewable energy at lower overall costs and emissions. Moreover, such thermal interconnection systems could integrate heat-technologies such as concentrated solar collection.

Other benefits from these new designs include a smaller, more focused scope for regulatory oversight, lower relative costs (and construction risks) for the turbine island and balance of plant, a shorter schedule due to opportunities for parallel construction, and greater overall certainty of cost and schedule.

LucidCatalyst's modelling of U.S. electric power grids suggests robust market demand for such advanced systems with thermal energy storage that can achieve the target capital cost of less than $3,000/kW.[36] Transformative design and delivery models enable plants at these price points to supply clean dispatchable power, complementing wind and solar, without raising the overall cost of electricity.

Flexible advanced reactors — in combination with wind, solar, and hydro — can therefore make a substantial contribution towards reliable, responsive, affordable, and clean energy systems supplying clean dispatchable generating capacity.

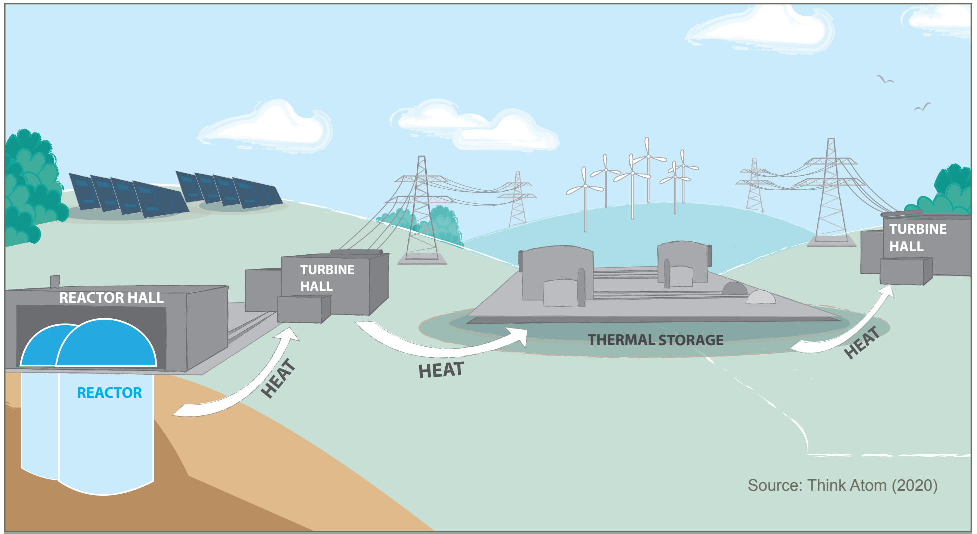


Figure 17. **Advanced nuclear reactor with additional high-temperature thermal storage**

But making the transition to clean electric power — and making sure that plentiful clean power is universally affordable and reliable — is only the first step in solving our global challenges. Electricity only accounts for one-third of global energy related emissions. The other two-thirds come from fossil fuels used for transport, heating, and industrial manufacturing, as well as non-fuel uses such as steel production, oil refining, and fertilizer manufacturing. Many of these sectors are difficult and expensive to run without low-cost, energy dense fuels, which is why they are considered 'difficult-to-decarbonise' sectors.

These sectors alone could emit over 500 Gt of CO_2 between now and 2050. This is 100 Gt more than the total remaining carbon budget for the 1.5°C pathway. Given that hundreds more gigatonnes of fossil fuel emissions are still in the pipeline from the electricity sector (unless repowering coal and gas occurs on a massive scale), failing to address these 'difficult-to-decarbonise' sectors puts even 2°C far out of reach.

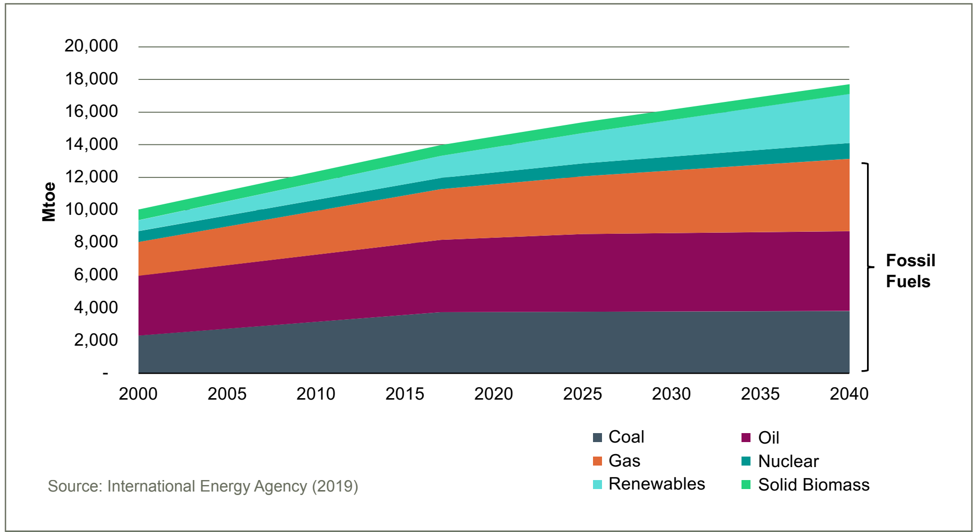


Figure 18. **IEA's stated policies scenario: world energy by source**

While parts of these sectors can and will be electrified, most fuels use cannot readily be shifted to electricity. All mainstream energy systems modelling anticipates that more than half of final energy use will be very hard to electrify and will continue to be supplied by fossil fuels (Figure 18).[37] For example, many large fleets of vessels rely on cheap fuel oil to make long transoceanic voyages, and many industrial processes require reliable, high-temperature steam. Decarbonising these sectors is addressed in the following pages.

Heat & Industrial Processes

Roughly half of all energy is used for heat. While a lot of this can be electrified directly (although the electricity would often need to be provided 24/7) or with heat pumps, a large part of heat use will remain challenging to transition away from fossil fuels. There are few low-carbon alternatives for the production of high-temperature heat used in heavy industry, such as steel, cement, and chemicals. Heavy industry is responsible for 22% of global carbon emissions. Advanced reactors can reliably deliver high-temperature (>400°C) steam to power these sectors. See some of the temperature ranges of various industries and reactor technologies in Figure 19.

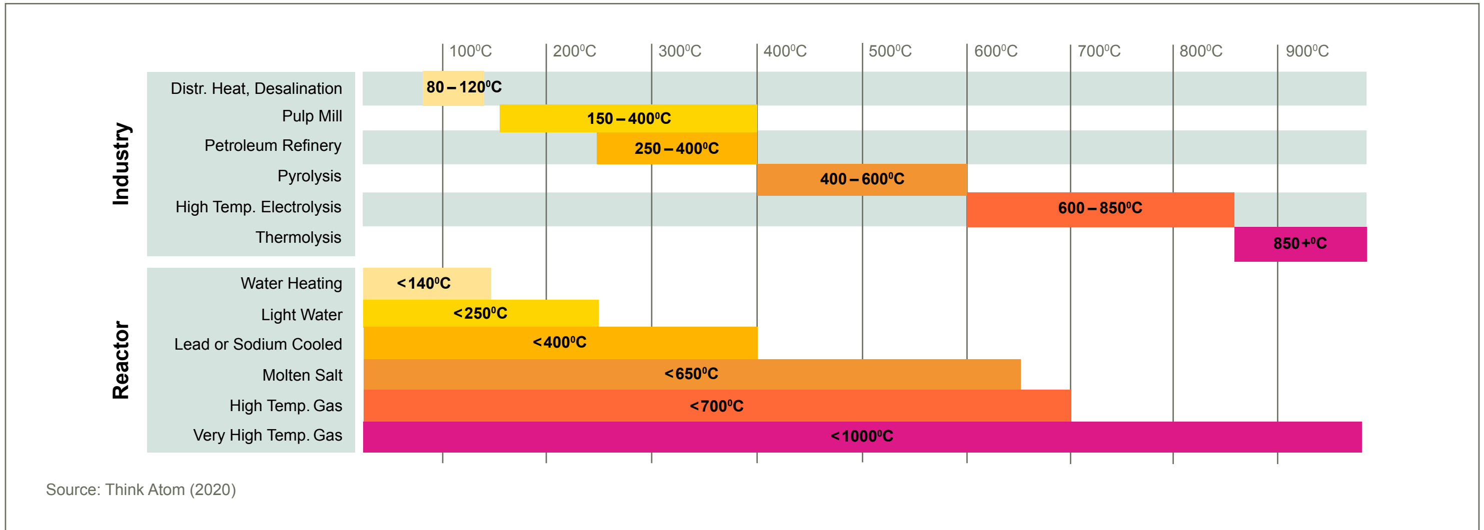


Figure 19. **Industry temperature ranges compared with reactor temperature ranges**

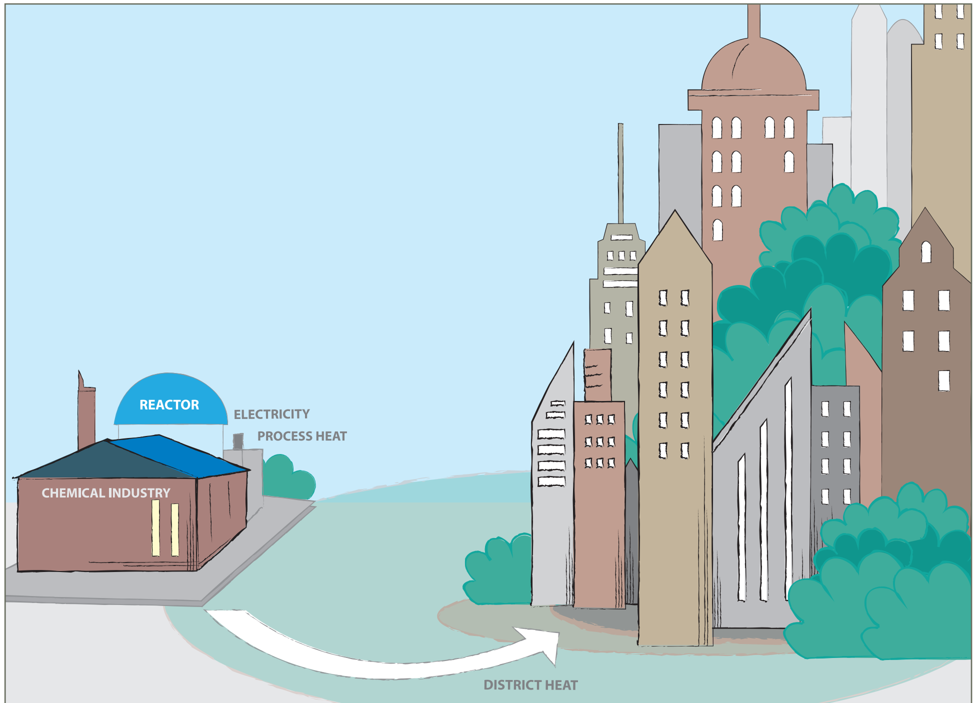
Cogeneration

Currently, 65% of the energy that nuclear power plants produce ends up in the cooling water. Cogeneration, or the production of both electricity and heat, can enable more efficient and flexible use of plants. While a normal power plant can usually turn 35% of the heat it produces into useful energy (electricity) through a steam turbine, a cogeneration plant can utilise well over 80% of the heat it produces for a combination of electricity and low-quality heat for district heating or desalination. For heat-only plants and applications, the total efficiency is almost 100%. Cogeneration increases flexibility, as it can allow a plant to switch seamlessly between electricity and other applications.

Cogeneration of power and heat, or power and hydrogen, can increase the overall efficiency and economics of nuclear plants, while decarbonising heat production and desalination of seawater. Most current generation (II and III) reactors can be retrofitted with cogeneration options if suitable uses for the heat are located nearby, and can produce steam at temperatures up to 250°C. Advanced heat sources (such as molten salt or gas cooled reactors) can produce steam at even higher temperatures, often between 600 – 800°C.

Low-Temperature District Heating

Low-temperature district heating (80 – 120°C) is an ideal form of cogeneration, making economic use of heat that would otherwise be rejected to the condenser of the power plant (illustrated in Figure 20).[38] By raising the temperature of this otherwise wasted heat, there is only a small reduction in electricity generation and all the heat that would otherwise be wasted is delivered to homes and businesses. Space heating and hot water represent a surprisingly large share of energy use (up to one-third in Europe). District heating offers one solution to reduce carbon emissions by providing space and water heating (and potentially cooling) for a city, town, or a district of buildings from a large central heating source through a network of pipelines. Typically, district heating is produced by burning fossil fuels, wood/biomass, peat, or waste. It can also be sourced from nearby industries, such as a pulp mill or a server farm, along with industrial-scale heat pumps.



Source: Think Atom (2020)

Figure 20. **Nuclear can produce both heat & power flexibly, including for district heat**

"It is wrong to pit renewables against nuclear power. We need all hands on deck."

James E. Hansen

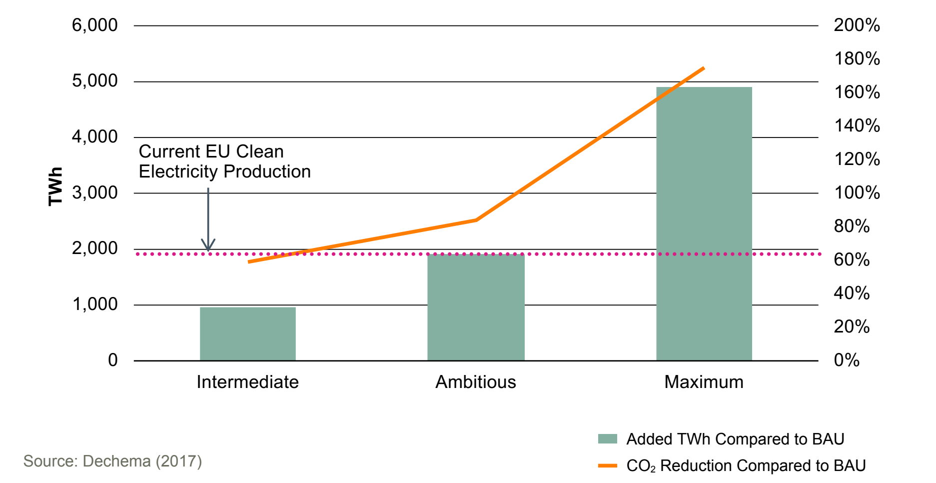
HYDROGEN & E-FUELS

Hydrogen-based synthetic fuels (or ‘synfuels’) are the most heavily researched and economically promising ‘drop-in’ alternative for decarbonising the sectors discussed above. Because most of the energy input for synthetic fuel production is in the form of hydrogen, it is also the principal cost driver for synthetic fuels. Hydrogen-based fuels are made by combining hydrogen extracted from water with carbon sequestered from the atmosphere using carbon capture technology. Hydrogen itself is emissions-free and entirely renewable; it is derived from water and burns back into water.

Today, hydrogen is used in oil refining and ammonia-manufacturing, though it is produced using fossil fuels and causes significant emissions. If clean hydrogen were used to produce synthetic fuels (hydrocarbons or ammonia) on a large scale, it could replace fossil fuels in many other ‘difficult-to-decarbonise’ sectors.

In Europe, there is a lot of existing infrastructure that uses fossil fuels, such as natural gas, for heating and cooking. Where electrification and heat pumps are not plausible, the natural gas needs to be replaced by hydrogen (as a first step, likely only <5% of the total energy content due to pipeline and end-user appliance compatibility issues) and eventually with synthetic methane.

Decarbonising the chemical industry is an enormous undertaking just by itself. To decarbonise its current electricity use, the EU needs to increase clean electricity production by roughly half (~1,200 TWh/y). To decarbonise chemical industry processes by ~85% on top of that, another ~2,000 TWh are needed. Considering just the chemical industry’s fossil-fuel production, it largely means decarbonising its hydrogen feedstocks. Increasing the clean hydrogen supply requires increasing the clean electricity supply. For just the chemical industry, 3,000 to 10,000 additional TWh/year must be added to the EU’s current clean electricity production (Figure 21).[39]



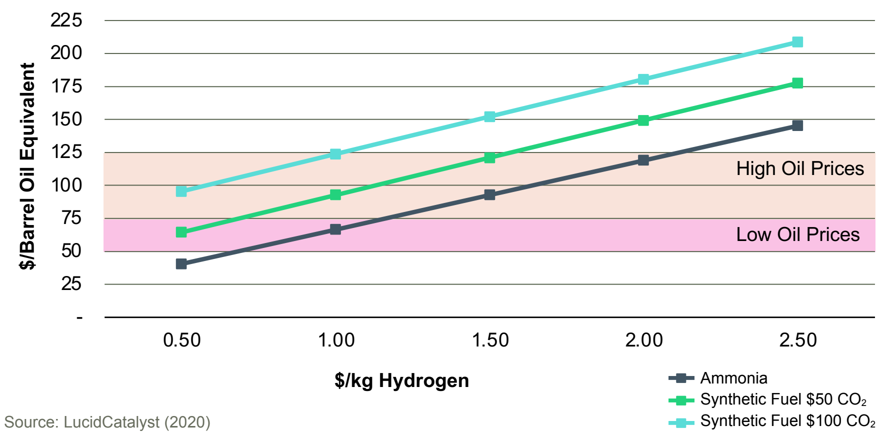
Source: Dechema (2017)

Figure 21. **EU chemical industry, additional clean energy demand by 2050**

Making Hydrogen a Competitive Substitute

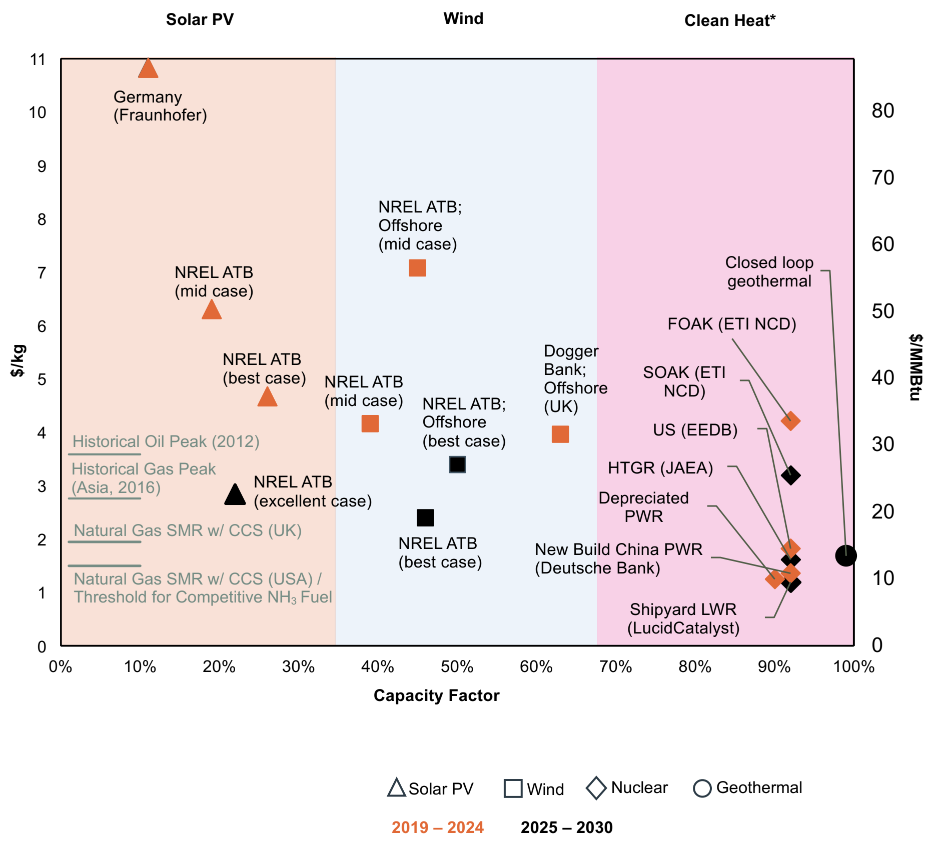
In order to start replacing fossil fuels at scale and in time, hydrogen and synthetic fuels production must be competitive with oil. Figure 22 shows the price of hydrogen required to make synthetic fuels that are cost competitive within the given range of crude oil prices. Two complementary pathways are possible: 1) hydrocarbon and 2) ammonia; both are attractive synthetic fuels. The diagonal lines represent the approximate cost of ammonia and synthetic hydrocarbons with two different cost assumptions for the CO_2 input.

To produce synfuels that are cost competitive with the normal range of crude oil prices requires hydrogen that costs below $1.50/kg, and hydrogen must cost below $0.90/kg to enable synfuels to compete with low crude oil prices. For the next 10 years, the lowest projected cost levels for hydrogen from renewables are double that, or more (Figure 23).



Source: LucidCatalyst (2020)

Figure 22. **Oil price 'guardrails' of the hydrogen economy (US$0.50-$1.50/kg)**



*Includes non-combustion sources of high-capacity factor clean heat, such as fission, geothermal, and fusion (if it becomes available).

Source: LucidCatalyst (2020)

Figure 23. **Hydrogen costs with different technologies today & in the next 10 years**

Because synthetic hydrocarbon production requires a source of carbon as an input, two lines show different input CO_2 costs: $50/tonne and $100/tonne. Figure 23 shows a range of clean hydrogen production options. Renewable costs are sourced from Bloomberg New Energy Finance and the U.S. National Renewable Energy Lab. High capacity factor clean heat sources like geothermal, fission, and fusion are shown on the right side of the chart.

Getting to costs below $1/kg within the decade is challenging, and this is where advanced heat sources come in. They can operate at very high capacity factors, essentially running 24/7, and utilise more efficient high-temperature electrolysis. Already some new nuclear plants in China have low enough costs of energy to produce hydrogen at prices competitive with the current oil market.

Producing Competitive Hydrogen/Synfuels

We need to rethink how we construct nuclear. There are two alternative routes/ production models to achieving a massive rollout of cost-competitive hydrogen/ synfuels: 1) the Hydrogen Gigafactory, and 2) shipyard-based manufacturing.[40]

The first route is a refinery-scale **Hydrogen Gigafactory**, which is constructed by an onsite vertically integrated factory (Figure 24). This approach 'brings the factory to the project'— replacing the traditional construction model with a highly productive manufacturing model. Capital and operating costs are radically reduced by streamlining manufacturing, operations, and maintenance. The buildings shown on the left provide the manufactured components, including dozens of advanced heat sources, that are assembled into the 'reactor farm' shown in the middle. When completed, these supply gigawatts of heat and power required for large-scale hydrogen and synfuels production, on the right. After completion, the manufacturing facilities continue to produce components for other sites. For countries developing such facilities, the Gigafactory provides three important benefits: affordable decarbonisation; the potential to export carbon neutral synthetic fuels; and a world-class domestic supply chain capability for advanced heat sources. It can deliver large quantities of low-cost synfuels, enabled by ultra-low-cost hydrogen at the target cost of less than $1/kg (Figure 22).

The second route to cost-competitive hydrogen is the **Shipyard Manufactured Model** (Figure 25) which 'brings the project to the factory.' Leading shipyards can manufacture large hydrogen production platforms — called floating production, storage, and offloading facilities (FPSOs). These FPSOs, which look like ships, have high-temperature reactors to supply energy for onboard hydrogen and synfuels production equipment.

Figure 24. **Aerial view of hydrogen Gigafactory under construction**

Figure 25. **Shipyard manufactured synthetic fuels production facility under construction**

Figure 26. **Ammonia bunker offloading ammonia from a production platform**

That hydrogen can then be used to produce synthetic hydrocarbons or ammonia, which can be used to fuel marine vessels or transported for other uses. The key innovation here is to transform the currently unproductive, risky, and expensive construction-at-place method of delivering facilities to a highly productive shipyard environment.

Floating production ships can also operate offshore (Figure 26), adding flexibility and safety. Manufacturing in state-of-the-art shipyards dramatically improves productivity; adds innovation, modularity and state-of-the-art manufacturing methods; lowers costs; and makes quality control easier. The world currently has idle shipyard capacity which could be upgraded to create a new industry that attracts investment, boosts employment, generates clean energy, and contributes to decarbonisation.[41] FPSOs close to shore could also produce electricity and desalinated water — enabling low-cost and low-carbon energy services for countries that still lack the necessary institutions and expertise to have domestic nuclear programmes.

Recent modelling done by LucidCatalyst[42] suggests that such a facility could produce ammonia for about $60 per barrel of oil equivalent, which is quite competitive with fossil marine fuel today. It would take about 325 of these facilities to decarbonise the current global shipping industry. By 2050, this number could grow to 600. This is clearly a large, important opportunity for countries to benefit themselves and the world.

Decarbonising Oil & Gas

The rapid achievement of low-cost hydrogen via these innovative delivery models could accelerate deep decarbonisation across sectors using oil and gas. By 2050, low-cost clean hydrogen could help avoid cumulative emissions on a scale measured in the hundreds of gigatonnes, equal to years, if not a decade worth of global emissions. Aided by efficiency improvements in operations, both models could bring down production costs to $0.90/kg by quickly rolling out new units. Scaling up production to sufficient levels to replace global fuels use would require an investment of roughly $17 trillion spent over 30 years from 2021 – 2050. For comparison, the oil and gas industries are expected to spend $25 trillion on exploration and production of fossil oil and gas over the same time period. Producing the equivalent amount of hydrogen using solar and wind would require an investment of $70 trillion (assuming 2040 costs).

The FPSO model can be designed to produce other liquid fuels such as jet fuel, gasoline, and diesel. These scenarios utilise existing and proven chemical technologies and production processes; no further discovery or innovation is needed, although some technologies, such as high-temperature steam electrolysis, would need to be brought to commercial scale. These commodities are drop-in substitutes, therefore they do not require major changes to existing supply chain infrastructure, regulations, or consumer behaviour.

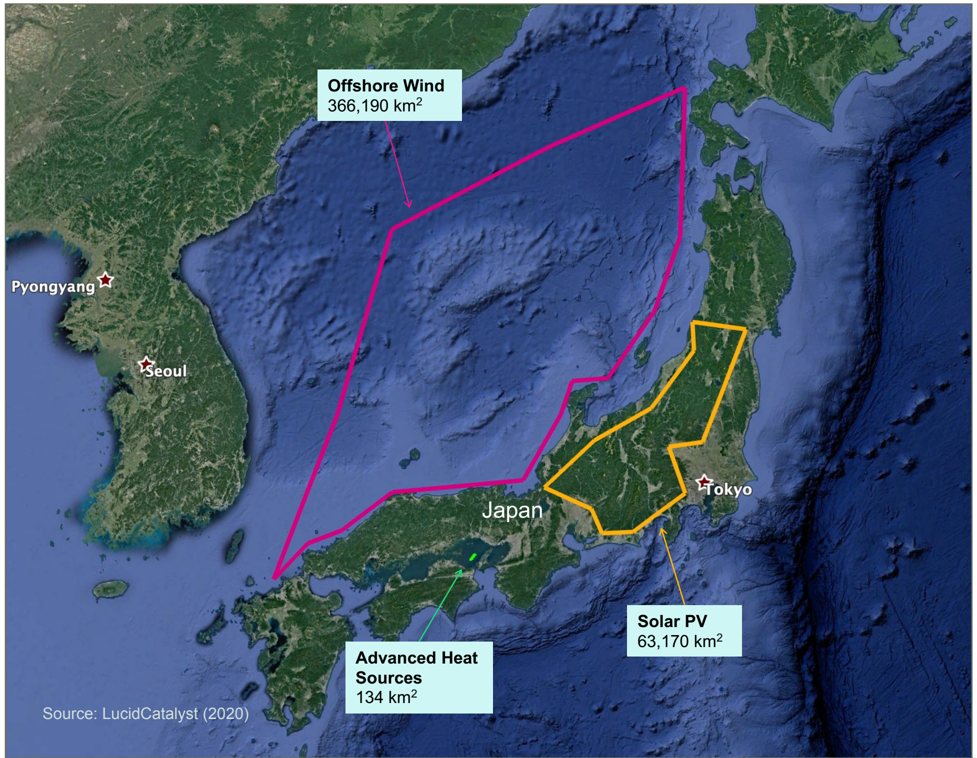


Figure 27. **Area required to replace Japan's current oil consumption with hydrogen**

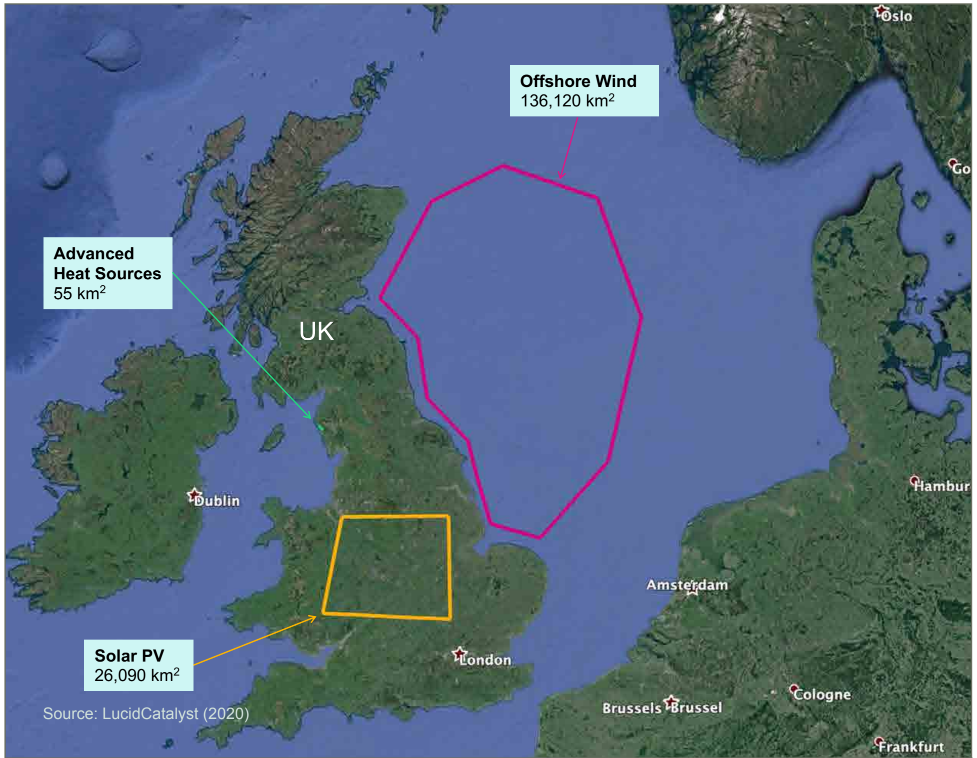


Figure 28. **Area required to replace UK's current oil consumption with hydrogen**

How we expect to produce clean hydrogen and synfuels will make a major difference in their feasibility as a decarbonisation solution. It is important to keep in mind that replacing the world's oil and gas (roughly 100 million barrels of oil-equivalent per day) with clean hydrogen fuels produced mainly with wind and solar energy presents a practically insurmountable challenge in terms of land use, given the massive environmental footprint the renewable energy development would require. Using only wind and solar to produce these fuels would require country-sized build outs. For example, the maps in Figure 27 and Figure 28 illustrate the area that would be required to replace Japan's and the UK's current oil consumption with hydrogen generated from either offshore wind (pink), solar (yellow), or advanced heat sources (the green shapes almost too small to be visible).[43]

To stay within the path of the Paris Agreement and a livable climate, we need low-cost hydrogen and synfuels at massive scales starting this decade and growing rapidly. Advanced heat sources are the most promising technology to deliver that, while also having an acceptable environmental footprint.

Innovative delivery models like shipyard and factory-based manufacturing could transform cost, speed of delivery, finance-ability, scalability, accessibility, and market applications. These models present immediate large-scale investment opportunities for producers, a sustainable source of fuel for critical industries, and an unprecedented means to de-risk global decarbonisation. Hydrogen-enabled synfuels are the 'missing link' to deep decarbonisation, enhanced prosperity, and access to modern energy services for all of humanity.

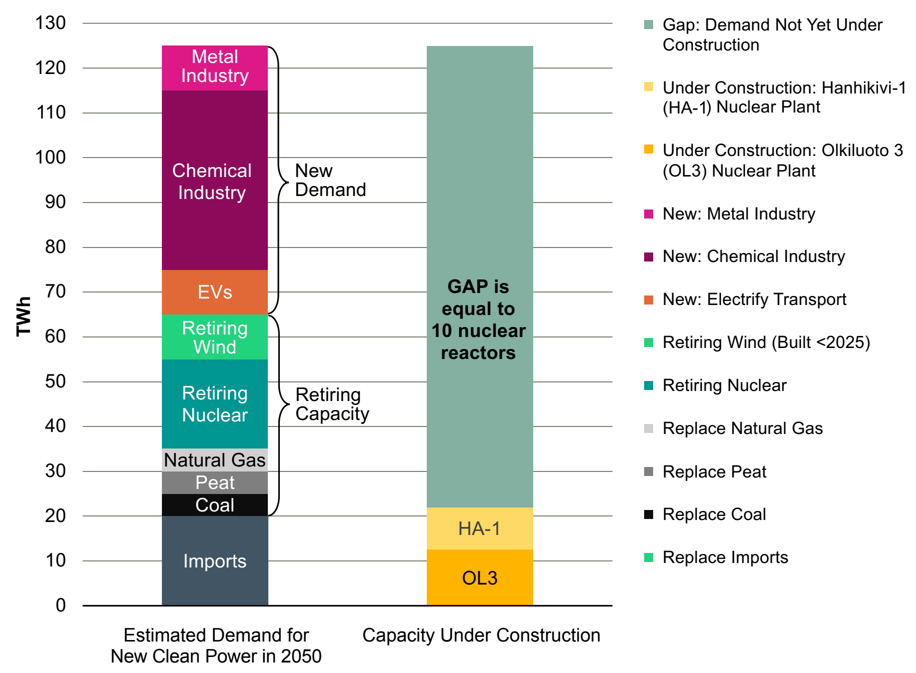
Deep Decarbonisation in the Nordics

The Nordic countries of Sweden and Finland have decarbonised their electricity use to a significant degree, showing mainland Europe a possible path forward. While a good start, they have yet to decarbonise sectors like industry, heating, and transportation fuels. This means they will need to grow their clean energy supply significantly — likely to double or more their current levels, depending on the assumptions, scope, and industrial sectors expected to be operating in 2050 and beyond. On top of this, both countries need to retire and rebuild much of their aging infrastructure by 2050.

In 2020, Finnish industries released their roadmaps to deep decarbonisation. While the Finnish steel industry will require roughly 10 TWh of additional clean electricity, the industry with the biggest projected demand is petro-chemicals, attributable to Finland's oil refining activities. Depending on the scenario and level of ambition, industrial demand for clean, reliable, and affordable electricity will increase Finland's current total demand by 50 – 100%, or more if technologies like algae oil do not scale up as envisioned.

A conservative estimate of demand for new electricity capacity in Finland would require roughly 100 TWh worth of new power generation capacity to be completed by 2050 (Figure 29).[44] Some of that demand will be met by new wind power, but it is highly likely that Finland will need to significantly increase its nuclear fleet as well.

Sweden is in a similar situation: projecting more than double their current electricity demand by 2050. The Nordic countries have successfully led the way in decarbonising their electricity sectors. Now they face the task of decarbonising the balance of their economies, including industry and fuels. Nuclear, as one of our most sustainable and scalable energy sources, is well-suited to play a major role in this important and daunting task. In the final section below, we discuss the various elements of nuclear energy's sustainability in more detail.



Source: Think Atom (2020)

Figure 29. **Finland will need more than 100 TWh of new energy by 2050**

"Many of those opposing nuclear power originally formed their position because of the Chernobyl accident. This is understandable. However, there have been no accidents in plants constructed after 1980,[45] and statistically speaking, nuclear power is actually one of the safest forms of energy. Policy must be based on solid science and evidence."

The Finnish Greens for Science & Technology

SUSTAINABLE NUCLEAR

SAVING LIVES

> "According to Life Cycle Impact Analysis studies analysed, the total impact on human health of both the radiological and non-radiological emissions from the nuclear energy chain are comparable with the human health impact from offshore wind energy."
>
> European Commission's Joint Research Centre

Nuclear power has contributed more to simultaneously reducing global mortality and carbon emissions than any other energy source. In 2017, Kharecha and Hansen estimated that nuclear power has avoided 64 gigatonnes of CO_2-equivalent emissions from replacing coal since the beginning of civilian operation, saving 1.8 million lives.[46]

Nuclear power could have saved significantly more lives, and prevented climate change, over the past four decades had early deployment rates and cost reductions continued. Unfortunately, disruption to the initial rates of new projects occurred in the late 1960s and 1970s. When the first reactor came online in 1954, experts predicted that nuclear power would emulate earlier energy transitions, like the switch from burning wood to coal, and then adding other fuels like oil and gas. It did not, however; the transition rate to nuclear power reached 4% by 1972, then stalled.

The learning curve model suggests a reduction in costs as experience is gained in an industry or technology. Put another way, the fractional reduction in cost per doubling of cumulative production capacity creates a cost-experience curve. Lang et al. examined this curve over the entire period of commercial nuclear power operation and found that the world forfeited substantial benefits as a result.[47]

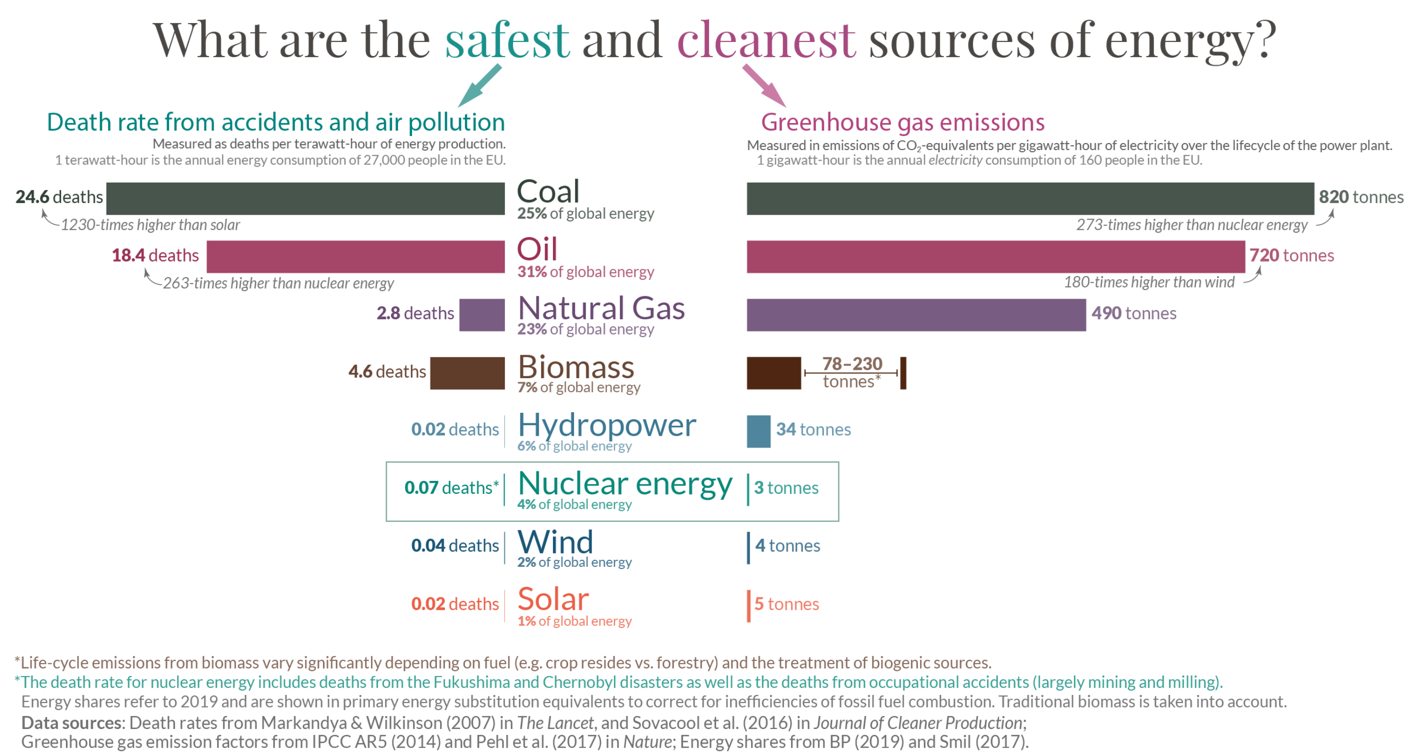
Before 1967, the learning curve allowed Overnight Construction Costs (OCC) to decrease as cumulative capacity increased. Had this trend continued, additional nuclear power could have substituted for 69,000 – 186,000 Terawatt-hours of coal and gas generation, sparing 9.5 million lives and avoiding 174 Gigatonnes of carbon emissions. For perspective, global emissions of CO_2 are 36.2 Gigatonnes per year as of 2018. This suggests that based on historical rates, nuclear power could have prevented annual global industrial emissions five times over.

If nuclear learning rates had continued, the price of electricity would have decreased and more people would have access to clean electricity. The next decade will be critical for dramatically increasing clean energy generating capacity by applying innovative deployment models and lessons learned. To deploy enough nuclear power to meet the unprecedented demand for clean energy, we need to seize existing opportunities to reduce new plant costs, extend the lifetime of existing plants, and create political support for building new advanced heat source capacity.

This final section considers nuclear power's sustainability in more detail with the latest scientific analysis and its findings on this topic, by the European Joint Research Centre.

> "The analyses did not reveal any science-based evidence that nuclear energy does more harm to human health or to the environment than other electricity production technologies already included in the Taxonomy as activities supporting climate change mitigation."[48]
>
> European Commission's Joint Research Centre

Figure 30[49] shows the relative safety and CO_2 emissions of different energy sources. Whenever combustion of fuels (coal, oil, gas, and biomass) is replaced with non-combustion, lives are saved and emissions decrease. But a strategy which aims to replace nuclear power with a combination of renewable energy and natural gas for meeting demand on low production times, means emissions increase and lives are lost.



Source: Our World in Data (2020)

Figure 30. **What are the safest & cleanest sources of energy?**

SMALL ENVIRONMENTAL FOOTPRINT

Because of the scale at which it needs to be deployed, clean power infrastructure must have a minimal impact on its environment. It should not use too much physical space, nor should it have excessive adverse effects on ecosystems or humans. The current energy debate neglects the issues of scale and land area required for the full lifecycle of an energy source. Numbers expressed in hundreds of thousands of square kilometres are hard to visualise. Also, total land use depends on several complex factors.

Nuclear power has the smallest overall environmental footprint of any energy source. Nuclear uses roughly 50 to 500-times less space in total for energy production than wind and solar, and even less compared to bioenergy to produce the same amount of energy (Table 1).[50] This includes mining activities for raw materials, as well as waste management. Nuclear energy uses transmission several times more efficiently than renewables, uses less copper per MWh, and requires fewer rare earth minerals, which have recently been identified as constraints on large-scale renewables deployments. Nuclear power plants have the most rapid energy payback times. The difference in land use is significant, as the more space something takes, the more it can disrupt nearby people or natural systems, leading to potential conflicts and opposition. The less land (or sea) area used for energy production, the more natural land can remain pristine, or be set aside for other uses.

The severity of the impact of this land (or sea) use depends greatly on the location and technologies used. For example, a solar panel on a roof may have no direct impact, while a solar park spanning a large area displaces the local natural ecosystem. To achieve the scale required for a renewable energy led transition will require massive changes to land use with major cultural and biodiversity implications — and frequently the proposal is to impose this development on other people and 'somewhere else'.

The enormous scale required for energy-diffuse renewables to substantially replace energy-dense fossil fuels is not just an increase in the number of gigawatts built but will be a qualitatively different set of impacts in terms of the number of people affected, and competition for land. These risks increase with the scale of deployment. Conflicts with ecological and food-production goals resulting in growing public opposition threaten renewables development at the necessary scale required for green hydrogen before they could ever be built. This public opposition to renewables development, even at low rates of deployment, is already in evidence across the U.S. and Europe.

We make this argument not to discourage the deployment of renewables, but to encourage a fully informed understanding of the types of risks involved in any deployment strategy for decarbonisation. As risks are never entirely avoidable, we need a range of technologies with complementary benefits and orthogonal risks, such that their risks are independent of each other where possible, to make up a safe, clean, stable, and diversified new energy infrastructure.

Nuclear is also our most materials-efficient energy source. It requires fewer bulk materials, like concrete, steel, copper, aluminium, or glass, than energy sources that collect diffuse energy flows like wind and solar. Because these are materials used in all construction, the relative increase in demand for them, even if we significantly ramp up power plant construction, will remain somewhat insignificant.

With regard to acidification, eutrophication, water eco-toxicity, ozone depletion and photochemical oxidants, the JRC found nuclear energy comparable to, or better than, solar PV and wind:

> "Land occupation of nuclear energy generation is significantly smaller than wind or solar PV."
>
> European Commission's Joint Research Committee

	Solar PV	Wind	Nuclear
Power Density (MW/km^2)	**50**	**2.3**	**2,080**
Capacity Factor	**12%**	**50%**	**90%**
Specific Annual Energy Production ($GWh/km^2/year$)	**52.6**	**9.1**	**16,399**
Specific Annual Hydrogen Production ($Tonnes/km^2/year$)	**968**	**167**	**466,979**
Land Requirement (Hectares/GWh/year)	**1.90**	**10.99**	**0.006**

Table 1. **Environmental footprint & energy density of wind, solar, nuclear**

"I think we're going to look back and ask ourselves how did we let at least five million people die from air pollution every year? It's totally obscene."

Isabelle Boemeke, isodope; science communicator

‘WHAT ABOUT THE SPENT FUEL?’

“There is broad scientific and technical consensus that disposal of high-level, long-lived radioactive waste in deep geologic formations is, at the state of today’s knowledge, considered an appropriate and safe means of isolating it from the biosphere for very long time scales.”

European Commission’s Joint Research Centre

Nuclear spent fuel can be stored on an interim basis at the same plant where it is produced. It can then be managed with the same level of care as the operations of the plant itself. Spent fuel is enclosed inside steel and concrete containers at secure storage facilities at nuclear power plant sites. They are fortified against extreme events like earthquakes and fires. See Figure 31 of people hugging spent fuel casks.[51]

In general, nuclear power stations release no harmful pollution into the surrounding environment unlike fossil or biofuels plants. There is no evidence that civilian nuclear spent fuel anywhere has caused any significant harm. Coal’s by-products are much more dangerous because coal releases its waste products directly into the air. By contrast, the nuclear industry has proven to be exemplary in its management of waste streams, with a high level of regulatory oversight. Sweden, Finland, and France are demonstrating practical long-term facilities that meet all the requirements for safe disposition of spent fuel.

So now, if asked: “what about the spent fuel?” — the answer is “there are demonstrated solutions.” Now it is time to turn our attention to waste streams from other energy sources that are today causing material harm to people and the environment — most damaging of all, the 8 million premature deaths caused by air pollution from fossil fuels. This is the waste we should be worried about.

Finland and Sweden are examples of effective waste management. Together, they have developed a geological repository system that will be safe (i.e., it will never cause significant harm to anyone) and will need no active monitoring. Finland has already started constructing a spent fuel repository, and Sweden is following closely behind. All it took was good research, solid engineering, and permission from local residents and government. Most countries struggle with developing and siting repositories due to public and political opposition. But, given its well-designed siting approach, local municipalities in Finland actually competed for the right to host the Onkalo repository.

Source: Stand Up for Nuclear (2019)

Figure 31. **Paris Ortiz Wines, hugging spent fuel casks at Palo Verde, Arizona USA, 2019**

“Onkalo is a game changer for the long-term sustainability of nuclear energy … Finland has had the determination to move forward with the project and to bring it to fruition. Waste management has always been at the centre of many debates about nuclear energy and the sustainability of nuclear activity around the world. Everybody knew of the idea of a geological repository for high-level radioactive nuclear waste, but Finland did it.”

Rafael Mariano Grossi, IAEA Director General

'WHAT ABOUT RADIATION?'

> "With regard to potential radiological impacts on the environment and human health, analyses demonstrate that appropriate measures to prevent occurrence of potentially harmful impacts or mitigate their consequences can be implemented using existing technology at reasonable costs."
>
> European Commission's Joint Research Centre

As seen in Figure 30, nuclear is among our safest sources of energy, including accidents and short- and long-term waste storage. The main hazard of nuclear power is linked to the radioactivity of its fuel, both used fuel and the whole fuel cycle, including mining and other activities. To gauge the overall risk of nuclear, let us examine the dangers of ionising radiation overall, and what part of our daily radiation dose comes from civilian nuclear plants and their full fuel cycle.

The average dose a human gets is around 3 millisieverts (mSv) per year from all sources (Figure 32).[52] Yet local doses of background radiation from natural sources, which can vary by one or even two orders of magnitude, show no statistical impact on human health. From this it is clear that the global average dose, or even ten-times that, poses little to no risk for human health. At annual doses of 100 mSv or more, some studies have found statistical impacts, but these are still much smaller than the impact of diets, such as preference for red meat vs. fish, for example. We make choices every day that affect the amount of radiation we receive more than what we would receive from anything related to a nuclear plant or spent fuel.

The design standard for everything to do with the nuclear energy industry requires that it cannot add anything but an insignificant contribution to background radiation. This is the standard for plants as well as for spent nuclear fuel waste repositories. For instance, nuclear plants are required to be designed and operated such that they cannot contribute any background radiation to their surroundings, including the worst accident scenarios. This discussion is about building lots of new state of the art plants, designed to be safe even in severe accident scenarios.

The Fukushima Daiichi nuclear plant, from the 1960s, was not designed to the level of safety of today's plants. In 2011, it experienced a set of severe accident conditions for which it was not designed, resulting in the worst consequences imaginable: a core meltdown and explosion blowing the roof off the reactor and expelling a radioactive cloud into the environment. And yet, not a single person has died from radiation exposure from the accident. Studies have shown that the health consequences of the Fukushima accident were actually driven by the badly managed evacuation in addition to the stress caused by unfounded, unscientific fears of radiation.

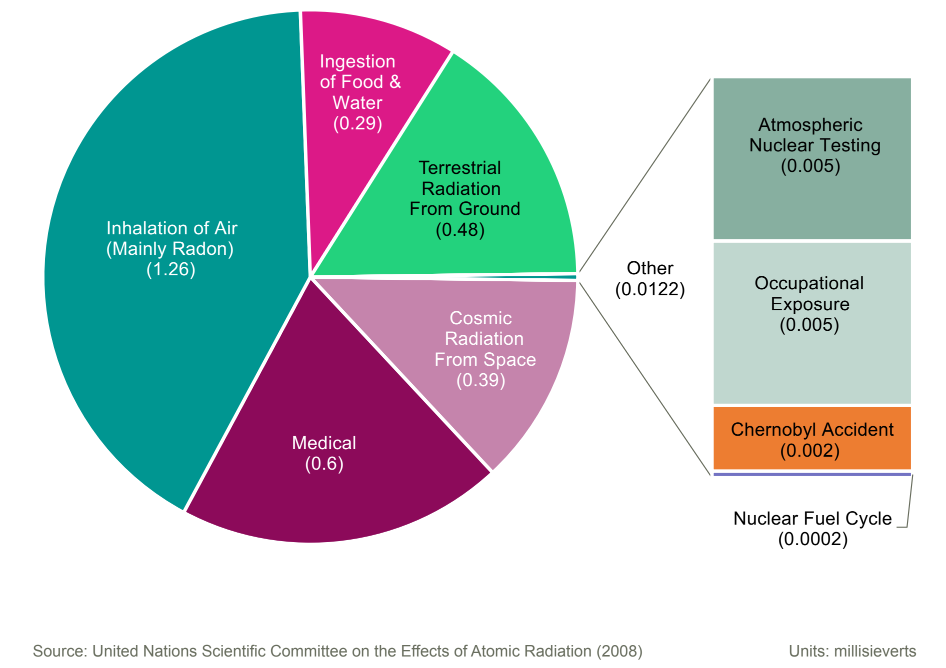


Figure 32. **Sources of global radiation, average annual dose from all sources**

"Provided that all industrial activities in the nuclear fuel cycle comply with regulatory frameworks and related Technical Screening Criteria, measures to control and prevent potentially harmful impacts on human health and the environment are in place to ensure very low impact."

European Commission's Joint Research Centre

"The average annual exposure to a member of the public, due to effects attributable to nuclear energy based electricity production (including mining) is about 0.2 mSv, ten thousand times less than the average annual dose due to natural background radiation."

European Commission's Joint Research Centre

What Happens if a Spent Fuel Repository Leaks?

After decades of careful studies, Finland is now constructing the first geological final repository called Onkalo, and the Swedish government has given the go-ahead for the Swedish final repository to follow suit. The safety analyses done by Posiva show that it has a safety margin of at least 1:1,000,000.[53] That is, if the absolute worst case occurs such that both the copper and the bentonite clay surrounding a waste canister mysteriously disappears after just 1,000 years and a person lives her whole life on the land just above this most contaminated square metre, drinking only the groundwater from this spot, and eating only food grown there (none of this is actually possible; it was just an extreme modelling exercise), the maximum annual dose that person living 10,000 years from now could get is 0.00018 mSv. This is roughly equivalent to the dose of radiation one gets from eating two bananas, or from sleeping next to another person. Remarkably, both of these activities are associated with minuscule traces of radiation. Tweak even one of these unrealistic assumptions to be more realistic, and even the radiation equivalence of eating those bananas starts to disappear. The actual threshold for any noticeable health risk starts to appear statistically at around 100 mSv/year.

The total average radiation dose — background radiation plus radiation from various human activities (Figure 32) — is tiny compared to levels that might start to show as effects in public health statistics. How large a share does the nuclear sector represent of that total dose?

Figure 32 shows how much average radiation comes from the nuclear fuel cycle: less than 0.001% of the average total dose, which in turn is far less than a dose that would actually start to show a meaningful public health impact. It is so small that it fits within a rounding error, many times over. And this includes the whole cycle from mining uranium, transporting and enriching it, fuel fabrication, use in a reactor, intermittent storage for the spent fuel and after that, long-term storage and accidents. Now, one can ask whether this is something we should be very worried about when comparing it to the risk of failing to mitigate climate change in time and at the scale needed?

RADIATION QUIZ

1 / **Long half-life materials give off higher intensity radiation**
(True or False?)

2 / **In an earthquake if waste container splits, solid waste would leak out**
(True or False?)

3 / **Radiation used in medical applications is safer than other radiation**
(True or False?)

4 / **Radioactive substances used by doctors are often made in a nuclear reactor**
(True or False?)

5 / **It is riskier to live in a Fukushima accident zone than in London**
(True or False?)

6 / **Almost all radioactive substances found in soil are from human activity, like nuclear power, weapons testing, and the Chernobyl nuclear accident**
(True or False?)

Answers can be found at the end of this report, after Endnotes

'WHAT ABOUT SAFETY & ACCIDENTS?'

"Fatality rates characterising state-of-the art Gen III NPPs are the lowest of all electricity generation technologies."
European Commission's Joint Research Centre

"Comparison of impacts of various electricity generation technologies on human health and the environment, based on recent Life Cycle Analyses, shows that impacts of nuclear energy are mostly comparable with hydropower and renewables, with regard to non-radiological effects."

European Commission's Joint Research Centre

Nuclear reactors have proven to be exceptionally safe sources of energy. Since they spread no pollution, have a high level of internal work-place safety culture, require very small amounts of fuel, and produce an even smaller amount of manageable waste, they have very few ways to harm people or the environment. One of those few ways is a nuclear accident of the worst kind: a core meltdown. How dangerous are these worst kinds of nuclear accidents? How have these contributed to fear of nuclear energy?

We have three real-life data points to assess the overall harm that nuclear core-meltdown accidents can cause. Three Mile Island (1979, partial core meltdown), Chernobyl (1986, a total meltdown and severe fire in a Soviet-designed reactor without a containment building) and Fukushima Daiichi (2011, a triple-meltdown taking place after roads and infrastructure turned to rubble due to an earthquake of such magnitude that it shifted the earth on its axis, slightly increasing the length of a day, causing a devastating tsunami which caused most of the damage).

In each of these cases the most significant harm to public health was caused not by radiation, but by fear of radiation, including the counter measures undertaken, and their long-term effects on health and mental health. Living in constant fear has a deleterious effect on human health, as research into the after-effects of both Chernobyl and Fukushima has demonstrated. Residents of Chernobyl and Fukushima had higher rates of depression, anxiety, and suicide than normal, even compared with the aftermath of other extreme events such as post-tsunami Japan. Public anxiety coupled with poor infrastructure and lack of economic opportunity make evacuees reluctant to return.[54]

In 2006, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) reported: "The mental health impact of Chernobyl is the largest public health problem caused by the accident to date… Rates of depression doubled. Post-traumatic stress disorder was widespread, anxiety and alcoholism and suicidal thinking increased dramatically. People in the affected areas report negative assessments of their health and well-being, coupled with… belief in a shorter life expectancy. Life expectancy of the evacuees dropped from 65 to 58 years. Anxiety over the health effects of radiation shows no signs of diminishing and may even be spreading."

"A decade after the Fukushima accident: Radiation-linked increases in cancer rates not expected to be seen."

United Nations Scientific Committee on the Effects of Atomic Radiation, March 2021

Lessons from the COVID-19 pandemic are applicable to the nuclear sector:

"Everything in the COVID-19 pandemic is about trust. Innovation is needed in behavioural science on how we as communities and individuals: understand epidemics and behave during them; process information and advice; build trust. That's as scientific as building vaccines."

Dr Mike Ryan, World Health Organisation

'WHAT ABOUT MINING?'

While wind, solar, and hydro do not use 'fuel' to produce electricity, nuclear does. Fuel-based technologies have an advantage when it comes to availability and reliability, as any energy source based on fuel can produce energy on demand, rather than when the weather allows it. Uranium can also be easily stockpiled as in the case of the U.S., and NPPs typically have fuel onsite to prevent disruption. Nuclear power is largely immune to fuel supply disruption and therefore contributes to energy security. Uranium has an advantage over other fuels. It has an energy density over 2 million-times higher, and a volumetric energy density over 35 million-times higher, than the best chemical fuels such as oil and anthracite coal. As a result, a relatively small amount of uranium must be mined every year.

Mining operations are hazardous, and the environmental impacts from uranium mining are comparable to most mineral mining. Due to the radioactivity of the ore and the daughter products present due to radioactive decay (radium, radon, etc.), mining regulations are augmented to attend to radioactivity. Helpfully, due to the small amounts of uranium needed to produce a given amount of energy, the amount of mining activities is small. Indeed, due to the high energy density of uranium, around half of global uranium is produced by in-situ leaching, a process that requires almost no disturbance to the soil and vegetation.[55]

All mining activities, including uranium mining, should be subject to strong regulatory standards to limit the impacts on people and nature. The global nuclear industry today could go further by establishing a 'fair-trade fuel' standard that requires uranium mines to meet the highest social and environmental quality standards.

In many countries, existing spent fuel uranium stockpiles could be used as fuel in next generation reactors to run the country — without mining another scrap of uranium for more than a millennium.[56]

Beyond mining, new technologies are being developed to enable uranium to be extracted from seawater.

Nuclear fuel made with uranium extracted from seawater makes nuclear power completely renewable. It is not just that the 4 billion tonnes of uranium in seawater now would fuel a thousand 1,000-MW nuclear power plants for a 100,000 years — it is that uranium extracted from seawater is replenished continuously, so nuclear becomes as endless as solar, hydro, and wind.[57]

> "Nuclear power's singular environmental advantage can be summed up in the term 'energy density' — consider that a golf-ball-sized lump of uranium, weighing just 780 grammes, can deliver enough energy to cover all your lifetime use, including electricity, car driving, jet flights, and manufactured goods — a total of 6.4 million kWh
>
> To get the same energy output from coal would require 3,200 tonnes of black rock, a mass equivalent to 800 adult elephants and resulting in more than 11,000 tonnes of carbon dioxide. The volume of this pile of coal would be 4,000 cubic metres: you can imagine it as a cube 16 metres in height, depth and width, about the size of a large 5-story building."
>
> Mark Lynas, Nuclear 2.0

"When we talk about 'waste', we usually mean spent fuel. We're talking about the gummy-bear-sized uranium pellets that go into the reactor... to make electricity. 94% of this spent fuel is still uranium, so it can be recycled and used again... If I were to get my whole life's energy from nuclear, at the end of my life I would leave behind one soda can full of uranium pellets."

Isabelle Boemeke, isodope; science communicator


MOVING
FORWARD

DECARBONISING PROSPERITY

Despite three decades of successful political and public support for action on climate change, fossil fuel energy sources currently make up only a slightly smaller share of the global energy supply than they did in 1990. Oil, coal, and gas produced 87.5% of the world's energy in 1990 and 84.9% in 2019. As overall energy consumption has increased substantially since the 1990s, emissions have increased accordingly.

Renewable energy sources including hydropower, biomass, wind, and solar have increased from 6.6% of global energy production to just 10.8% in the last 29 years. Including nuclear, the share of low-carbon energy surpassed 15% in 2019, for the first time in modern history. Globally, our fossil fuels use has grown at an average rate of 1.8% in the 21st century, so low-carbon energy has not grown nearly fast enough.[58]

Since the year 2000, the EU's emissions from energy have decreased by roughly 750 million tonnes, from over 4 billion tonnes, to 3.3 billion tonnes in 20 years (37.5 megatonnes/year on average). The EU's emissions would now need to decrease three-times faster for the next 30 years to reach zero emissions from the energy sector by 2050. Most of these emissions come from sectors other than electricity production.

To reach carbon neutrality, therefore, the European Union needs to act fast on the following priorities:

1/ **Expand clean electricity generation as quickly as possible**

2/ **Repower most coal plants with advanced heat sources**

3/ **Convert remaining liquid fuel use to carbon-neutral fuels**

4/ **Replace natural gas for industry and heat**

5/ **Massively increase investment in clean electricity generation and clean e-fuels production to support global energy access, especially in Africa**

All of this will be made easier through increased efficiencies, better insulation, and smart, hybrid energy systems, but it will not be solved by these measures alone. Given that the Nordic countries, as well as France, already have quite clean and low-carbon electricity and have also already electrified large parts of their economies, they can lead the way in decarbonising these other sectors by building more nuclear energy along with wind and solar, and making clean fuels with these low-carbon energy sources as needed.

As we learned above, the amount of clean energy needed for decarbonising these sectors is immense. Limiting ideas about what it takes to address climate change have created unnecessary conflict and stagnation within the groups of people working to solve it. The idea that we can achieve timely decarbonisation with renewables alone — and should therefore exclude other low- or zero-carbon technologies — is not only toxic for progress, but scientifically unsound. It implies that developing countries should plan their future economic growth on variable renewables alone, something that no industrialised nation has yet come close to doing. This is short-sighted and anti-development.

Ideological biases and preferences have blocked funding and other policy measures that enable nuclear energy to successfully achieve programmatic cost reductions and performance improvements enjoyed by wind and solar industries, denying reliable and cost-effective energy services for citizens and industries in Europe and around the world. This misplaced emphasis on the means (cherry-picked technology) rather than the goal (decarbonisation and access to modern energy services) has contributed to stalled action on climate for three decades.

It is time to look again at nuclear energy. Scalable, reliable, affordable, resilient, and clean power is vital for our well-being and for our future. The EU now has an opportunity to provide leadership in delivering a just and clean energy transition.

RECOMMENDATIONS

Widespread exclusion, under-representation, or misrepresentation of the demonstrated, scalable, cost-effective, and clean option described in this report has severely limited perceived prospects for tackling climate and increasing global energy access in an affordable and timely manner. By widening the range of technologies available to represent more fully and appropriately the scale of the potential contribution from this proven option, we can both de-risk climate mitigation pathways, while relieving pressure across the clean energy transition and creating more prosperity.

To start moving towards more inclusive and efficient emissions reductions, the following actions are needed:

ACCESS TO FINANCE /

In the same way that investors must take a portfolio approach to investments in order to reduce exposure to risk, global efforts to limit climate change should be spread across a portfolio of technology options. Consistent, technology-inclusive access to finance is critical to realising this.

STOP CLOSURES /

Premature closures of nuclear power stations need to stop, and whenever possible, those shut down should be restarted.

EXTEND LIFETIMES /

Operating fleet should seek lifetime extensions whenever possible, and funding for the necessary refurbishment needs to be made available at low interest rates.

DIVERSIFY MODELLING /

Energy system modellers and policy makers should include the wide range of potential applications for advanced heat sources into energy and climate scenario modelling where it is currently absent.

INCLUDE GREEN HYDROGEN /

'Green Hydrogen' and the associated mandates, policy incentives, and financing should include all low-carbon hydrogen production as per their sustainability (carbon intensity, land use, etc.), not just a cherry-picked selection of technologies.

FUNDING COMMERCIALISATION /

Europe should fund the rapid and large-scale commercialisation of new delivery and deployment models for advanced heat sources for re-powering coal plants, hydrogen, heat and power production, with an emphasis on achieving cost-competitiveness and scale relevant to the fossil fuel markets they are designed to address.

"Without an important contribution from nuclear power, the global energy transition will be that much harder."

Fatih Birol, International Energy Agency

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RADIATION QUIZ — ANSWERS

1 / Long half-life materials give off higher intensity radiation

Answer = **False.** The half-life of radioactive materials describes how quickly they 'burn up'. If it were a torch battery, the half-life would describe how long it takes for the battery to drain to 50%. And as the battery drains, the light gets dimmer and dimmer. Long half-life materials radiate more dimly, but do so for a longer time.

2 / In an earthquake if waste container split, the waste would leak out

Answer = **False.** Waste is always disposed of as a solid, so will not leak if the container is damaged. An analogy is that when a green glass bottle breaks, the green doesn't leak out.

3 / Radiation used in medical applications is safer than other radiation

Answer = **False.** Radioactivity used for medical diagnostics and treatments is elementally the same as that used for nuclear power.

4 / Radioactive substances used by doctors are often made in a nuclear reactor

Answer = **True.** Medical isotopes are made in nuclear reactors.

5 / It is riskier to live in a Fukushima accident zone than London

Answer = **False.** A study from the NREFS project (nrefs.org) found that London air pollution poses more health risk than Fukushima accident zone radiation.

6 / Almost all radioactive substances found in soil are from human activity, like nuclear power, weapons testing, and the Chernobyl nuclear accident

Answer = **False.** Radioactive minerals in the environment are mostly natural, with a tiny fraction from human activities. Figure 32 shows how much average radiation comes from the nuclear fuel cycle: less than 0.001% of the average total dose. The vast majority of radiation that we are exposed to occurs naturally in the environment.

About LucidCatalyst

LucidCatalyst is a highly specialised international consultancy offering thought leadership, strategy development and techno-economic expertise. Our mission is to multiply and accelerate zero-carbon technology options available for large-scale, affordable, market-based decarbonisation of the global economy over a wide range of future scenarios.

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