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International Atomic Energy Agency

Nuclear Energy in Mitigation Pathways to Net Zero

"'Nuclear energy *or* renewables' is a false narrative. Such false narratives are to the detriment of everyone, especially when it comes to achieving a fair and enabling investment environment."

IAEA Director General, Rafael Mariano Grossi

1.5°C

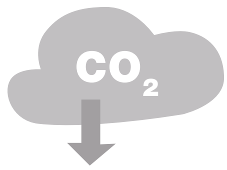
All low carbon energy technologies, including nuclear power, are needed to maximize our chances of meeting the goals of the Paris Agreement.

Global mitigation scenario pathways show more nuclear electricity is needed to limit global warming to 1.5 or 2°C. The United Nations Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report and the International Energy Agency (IEA) World Energy Outlook highlight an important role for nuclear energy, in combination with other low carbon energy sources, in transition pathways compatible with the goals of the Paris Agreement. Most low carbon pathways project a doubling or more of global nuclear electricity generation by 2050.

Mitigation scenarios can be enhanced with a richer representation of nuclear heat and hydrogen. Beyond electricity, the mitigation potential of nuclear energy in non-electric applications — for example, the use of nuclear heat and hydrogen to decarbonize hard-to-abate activities in heavy industry and transportation — may not be fully reflected in current scenario pathways. This identifies an opportunity to enhance the representation of relevant technologies and processes in future analyses to further support effective climate action.

Nuclear energy can be deployed rapidly to realize the potential in mitigation pathways. Nuclear energy has a proven track record of rapid deployment, including in recent projects, which is critical for urgently decarbonizing the global energy system in line with IPCC and other mitigation pathways.

Nuclear energy today provides around one quarter of global low carbon electricity, helping to avoid more than one billion tonnes of carbon dioxide (CO_2) emissions annually while supporting energy system reliability and security [1]. Nevertheless, despite the contribution of nuclear and other low carbon energy sources, global greenhouse gas emissions remain well above the levels required to limit the global average temperature increase to below 1.5°C or 2°C — the key goal of the Paris Agreement (see Fig. 1). To avoid warming above these levels, the global energy system will need to transition to net zero CO_2 emissions by around 2050 (for 1.5°C) or soon after (for 2°C).



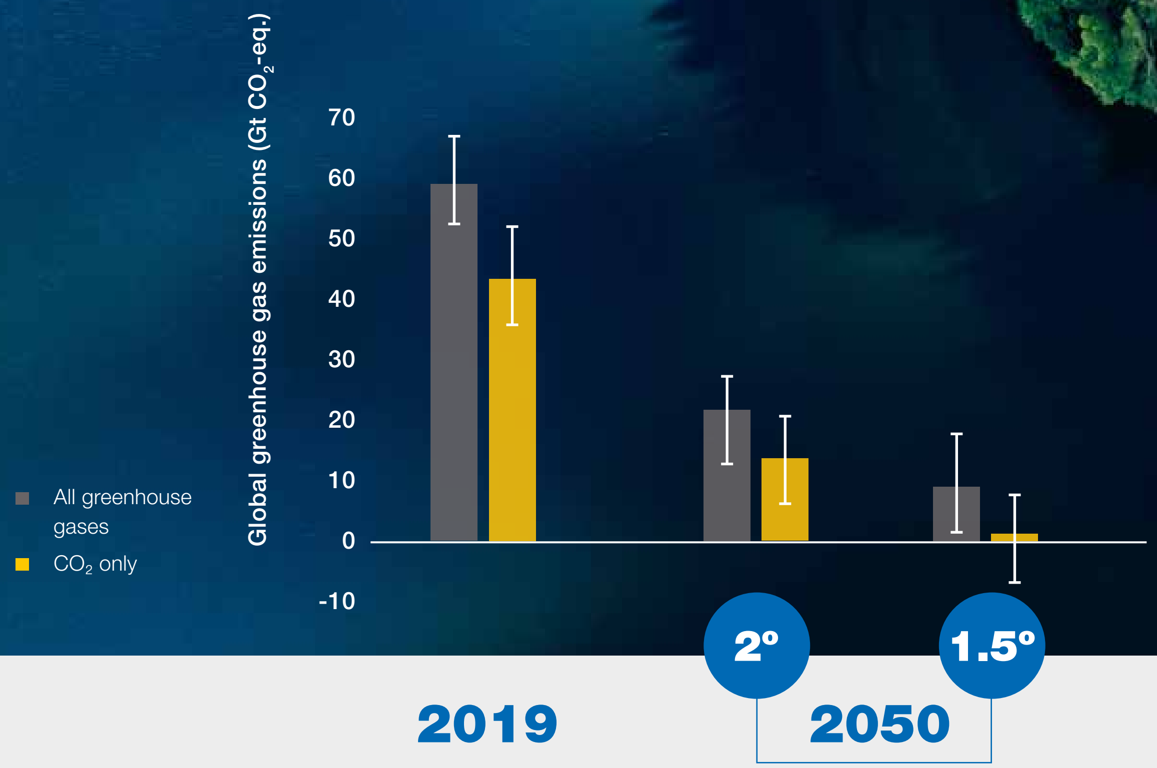


Fig. 1. Global greenhouse gas emissions, 2019 and estimated 2050 targets for 2°C and 1.5°C. Reproduced from Ref. [2] with permission.

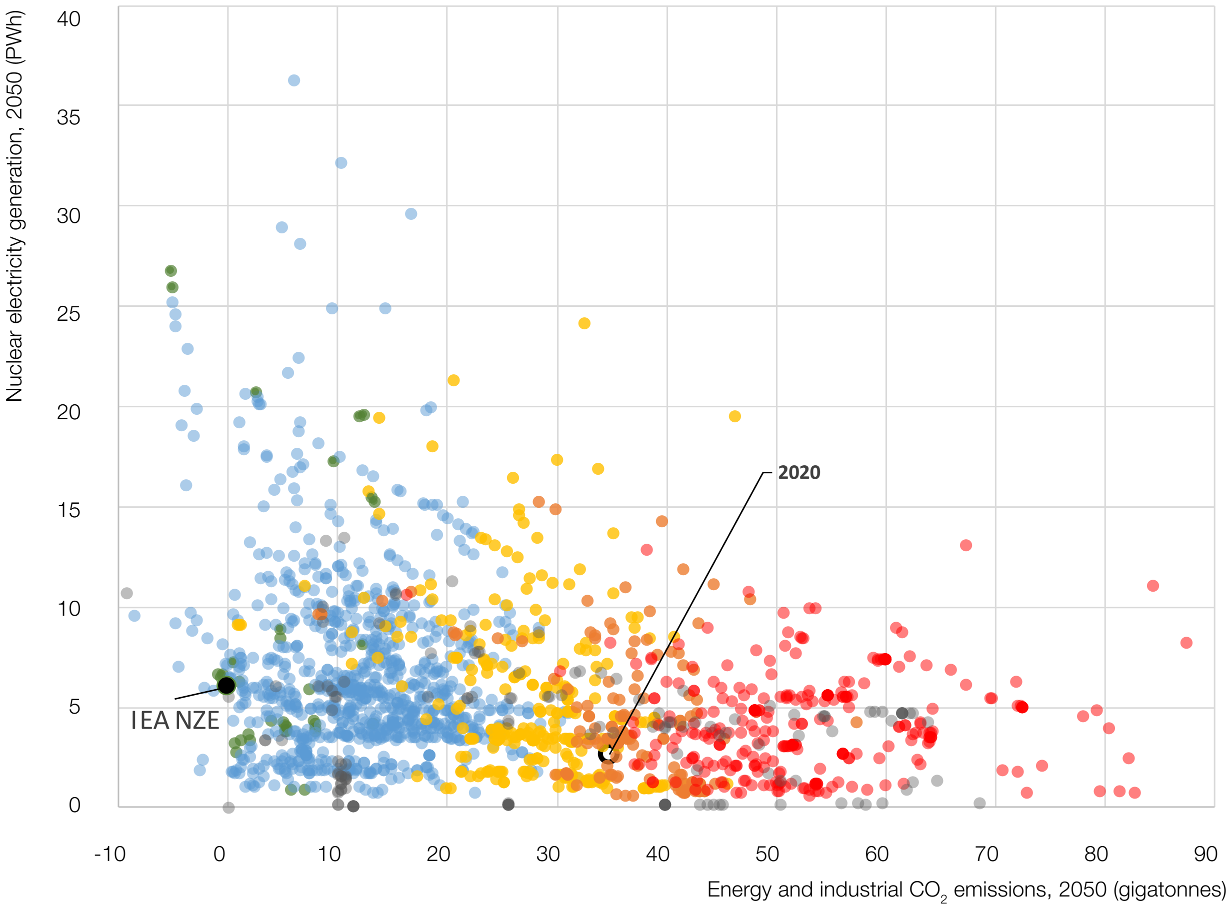
NUCLEAR ENERGY IN PATHWAYS TO NET ZERO

The IPCC compiled and assessed more than 3000 peer reviewed scenarios related to climate change mitigation as part of its Sixth Assessment Report published between 2021 and 2023 [2—5]. These scenarios cover a wide range of perspectives on energy transitions and provide extensive insights into the role of different low carbon energy sources in reaching climate change mitigation targets. The IEA has also published scenarios exploring pathways of global energy system development in their annual World Energy Outlook [6].

The contribution of nuclear energy varies widely across these scenario pathways. This is illustrated in Fig. 2, which plots global nuclear electricity generation and energy related CO_2 emissions in 2050, with each dot representing a different scenario from the IPCC Sixth Assessment Report, coloured according to the projected level of warming (with >50% probability) [7][1]. For comparison, the current (2020) level of nuclear electricity generation and energy emissions is plotted as a circle.

Nuclear energy today provides around one quarter of global low carbon electricity

[1] The full set of scenarios was filtered to select those reporting key variables for 2050, such as global energy related CO_2 emissions, electricity generation and others, corresponding to a subset of more than 1800 scenarios developed with around 30 model families (a model family includes different model versions based on the same underlying model [7]).



Estimated warming (with >50% probability)
<=1.5 °C <=2°C <=2.5°C <=3°C >3°C not specified
(IEA Net Zero Emissions by 2050 Scenario (NZE) also indicated)

80% of scenarios with emissions below 20 gigatonnes see an expanded role for nuclear electricity generation

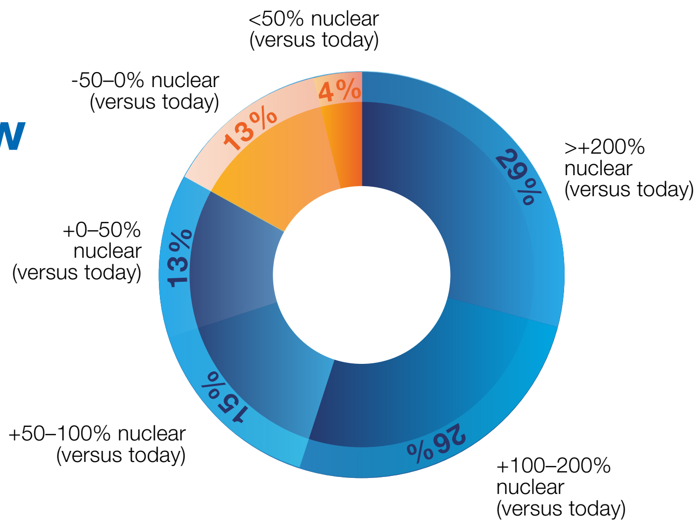


Fig. 2. Global nuclear electricity generation and carbon dioxide emissions in the IPCC mitigation pathways, 2050 [2–5, 6, 8].

Overall, an increasing role for nuclear power by 2050 is seen across a significant majority of the scenarios, particularly in those that achieve substantial reductions in emissions in line with the goals of the Paris Agreement. For instance, more than 80% of scenarios with emissions below 20 gigatonnes of CO_2 in 2050 (roughly corresponding to limiting warming below 2°C) see an expanded role for nuclear electricity generation, with more than half projecting at least a doubling and around 30% projecting a tripling or more compared with 2020 levels (Fig. 2, pie chart). The IEA's Net Zero Emissions by 2050 Scenario also envisages more than a doubling of nuclear electricity generation [6].

Notably, the expansion of nuclear energy across many IPCC mitigation pathways exceeds the increase in the IAEA's high projection [9] (see Box 1) which is derived from a bottom-up, country by country and project by project assessment based on current market and policy trends. Fully capitalizing on the additional mitigation potential identified in the IPCC Sixth Assessment Report scenarios will likely require enhanced market and policy support beyond the levels reflected in the IAEA projections. Additional efforts would also likely be needed to ensure global supply chains, human capital and other infrastructure are in place to support the high levels of nuclear deployment and generation seen in some scenario pathways.

BOX 1: IAEA ENERGY, ELECTRICITY AND NUCLEAR POWER ESTIMATES TO 2050

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The IAEA annually publishes projections of energy, electricity and nuclear power trends for the coming decades [9], based on a critical review of other international and national projections and estimates from national and international experts.

In 2023, for a third successive year, the IAEA revised up its projections of the potential growth of nuclear power to 2050, reflecting a shift in the global debate over energy and the environment: "Climate change is a big driver, but so is security of energy supply," IAEA Director General, Rafael Mariano Grossi noted in October 2023. "Many countries are extending the lifetime of their existing reactors, considering or launching construction of advanced reactor designs and looking into small modular reactors, including for applications beyond the production of electricity" [10].

With the 2023 revision, the IAEA high case projection reaches more than 7000 terawatt-hours (TWh) (net) of nuclear electricity generation in 2050, as shown in Fig. 3, which is relatively conservative compared with many of the scenarios in the IPCC Sixth Assessment Report in Fig. 2. However, the IAEA projections are not intended to reflect the lowest or highest feasible future levels of nuclear generation, but rather reflect contrasting (but not extreme) assumptions on driving factors and current market and policy trends. The IPCC scenarios, on the other hand, help identify a larger mitigation potential that could be tapped with additional market and policy support for nuclear energy, above current trends reflected in the IAEA projections.

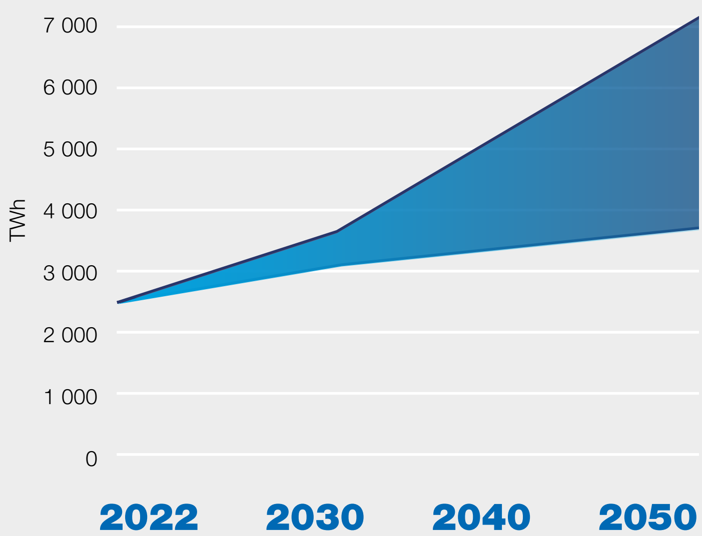

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Fig. 3. Global nuclear net electricity generation in IAEA projections [9].

Turning to the broader energy transition, the IPCC mitigation pathways also highlight the need for a combination of nuclear power and other low carbon energy sources to reach the goals of the Paris Agreement. This is illustrated in Fig. 4, which plots the share of global electricity generation in 2050 from renewables against the share of nuclear generation across the full set of pathways. Again, each scenario is represented by a dot coloured according to the projected level of warming. Historical renewables and nuclear shares from 1971 to 2020 are also shown [8]. Figure 4 shows that the combined share of low carbon renewable and nuclear electricity generation is higher in scenarios with lower levels of warming. For example, most of the scenarios with warming of more than 3°C report a combined share between 20% and 40%, while those in line with the Paris Agreement's 1.5°C and 2°C goals report shares of 60% to 100%. In addition, the figure illustrates how different combinations of renewables and nuclear generation can achieve long term mitigation goals — with up to >45% nuclear and >95% renewable generation — and practically all scenarios include both technologies.

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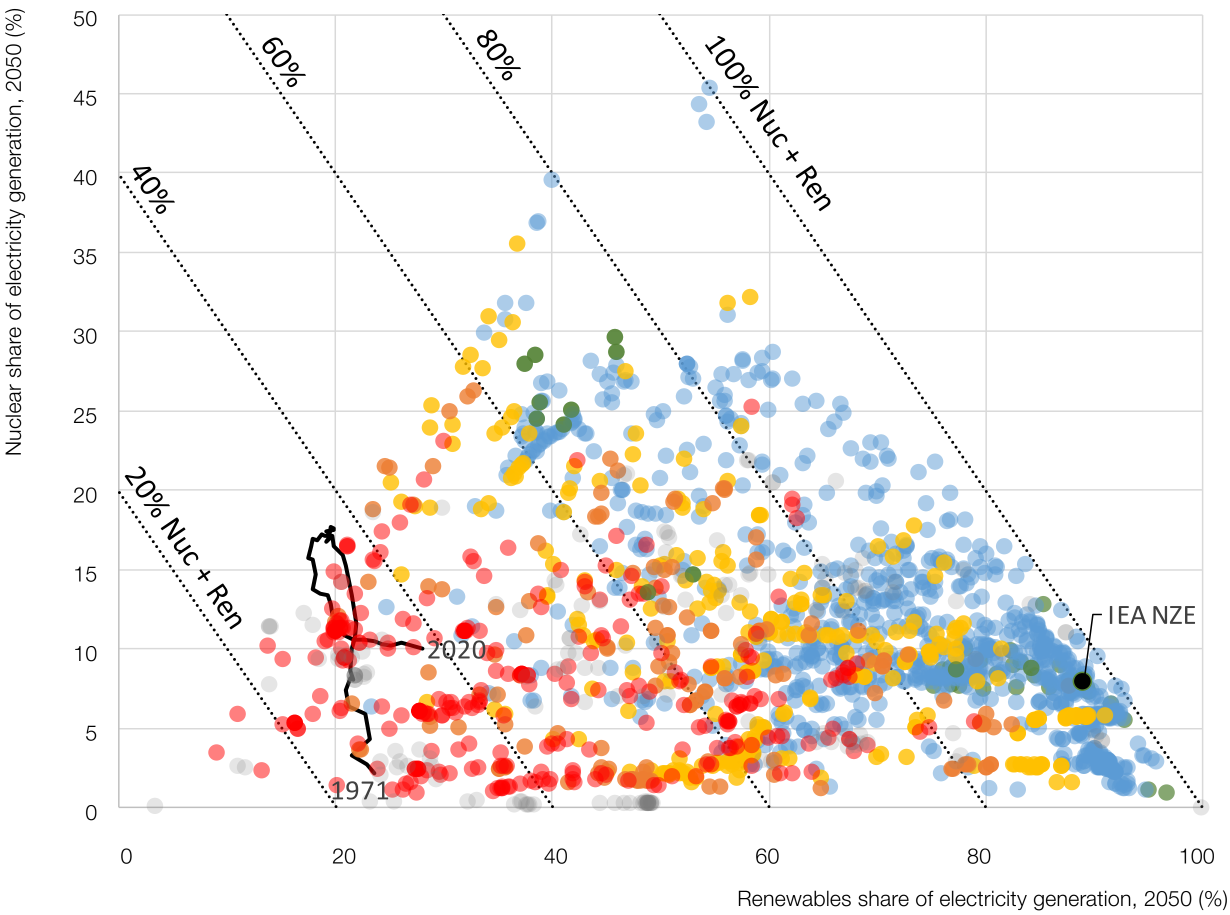
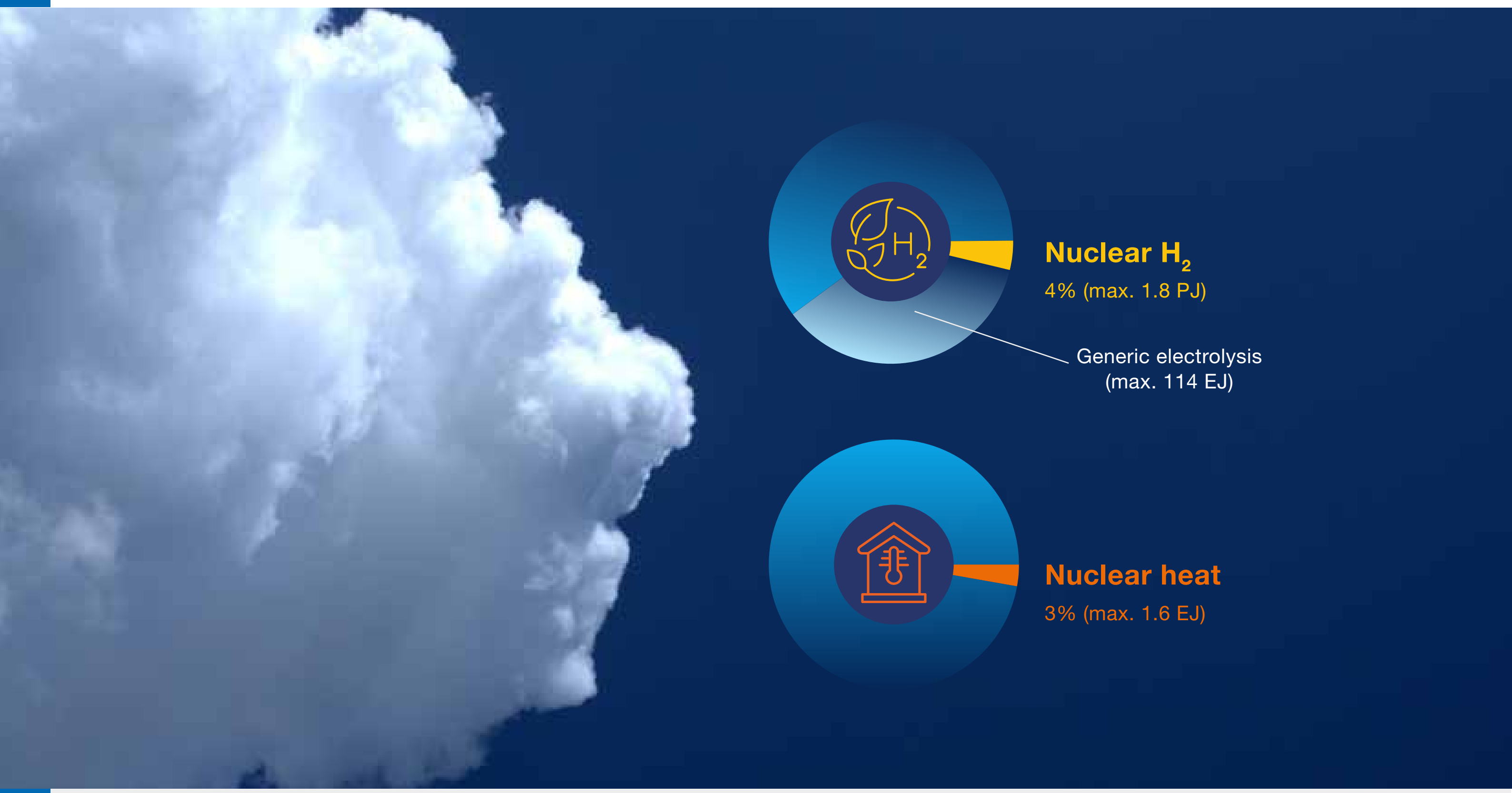


Estimated warming (with >50% probability)
<=1.5 °C <=2°C <=2.5°C <=3°C >3°C not specified
(IEA Net Zero Emissions by 2050 Scenario (NZE) also indicated)

Fig. 4. Global shares of renewable and nuclear electricity generation in IPCC Sixth Assessment Report scenarios, 2050 [2–5, 8].

NUCLEAR ENERGY FOR HEAT, HYDROGEN AND OTHER NON-ELECTRIC APPLICATIONS IN MITIGATION PATHWAYS: AN OPPORTUNITY FOR THE NEXT GENERATION OF SCENARIOS

In addition to generating clean electricity, nuclear energy has the potential to provide heat and hydrogen that can be used to decarbonize processes and activities that are less suited to electrification. Examples of these so called hard-to-abate activities include processes in the steel, non-ferrous metals, cement and chemical industries, heavy transport and aviation. Despite this potential, very few scenarios in the IPCC Sixth Assessment Report include heat or hydrogen from nuclear energy. Only one pathway includes >1 petajoule (PJ) of nuclear hydrogen production in 2050 (~0.01% of today's nuclear electricity generation), although many scenarios report hydrogen production from (generic) electrolysis, which could be powered by nuclear electricity generation. For heat, only 50 scenarios report non-zero nuclear heat production, with a maximum of 1.6 exajoules (EJ) (~12% of current global heat consumption) [6] (see Fig. 5).



The IEA's Net Zero Emissions by 2050 Scenario also envisages that nuclear electricity generation will more than double.

Fig. 5. Share of scenarios from the IPCC's Sixth Assessment Report reporting nuclear hydrogen (H_2) or nuclear heat production in 2050 [2, 3, 7].
Note: the 2050 maximum nuclear H_2 and heat production levels across the scenarios are given in parentheses.

The negligible contribution of nuclear hydrogen and heat may be explained by the very limited representation of relevant technologies and processes in most scenario models [7], suggesting that this set of mitigation options may be underestimated in the current generation of scenarios. This presents an opportunity to further enhance the modelling of energy transition pathways, and with this in mind the IAEA has recently launched the Atoms4NetZero initiative to support its Member States to better understand the potential of current and emerging nuclear energy technologies in developing their national energy strategies towards reaching net zero emissions (see Box 2).

The IAEA has recently launched the Atoms4NetZero initiative

BOX 2: **SUPPORTING MEMBER STATES EXPLORE PATHWAYS TO NET ZERO: THE IAEA'S ATOMS4NETZERO INITIATIVE**

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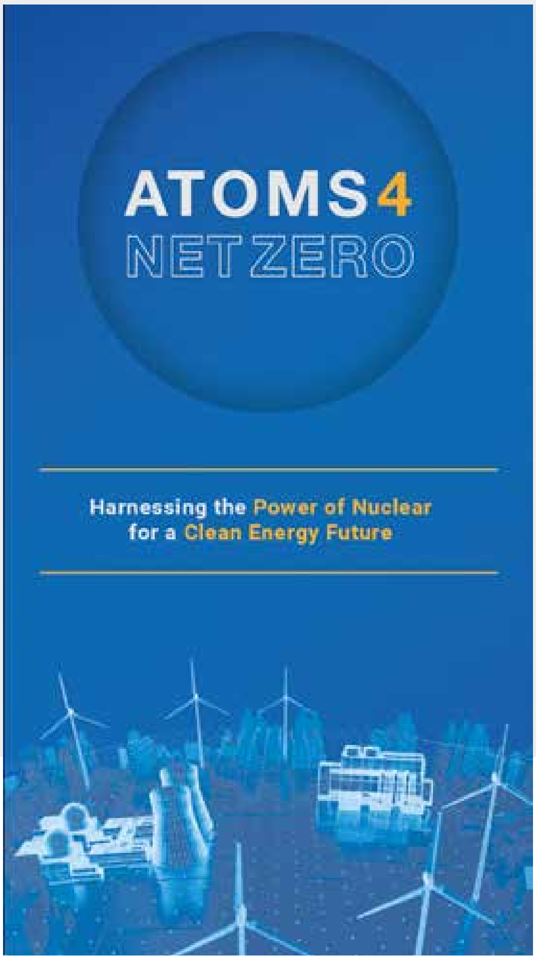

At COP27 (the 2022 UN Climate Change Conference, held in Sharm el-Sheikh, Egypt) IAEA Director General Rafael Mariano Grossi announced the Atoms4NetZero initiative. Building on decades supporting Member States to develop capacity in sustainable energy planning, through this new initiative the IAEA will use its analytical tools and expertise to help countries model how nuclear power can contribute to reducing greenhouse gas emissions to as close to zero as possible by 2050. The Atoms4NetZero initiative will help countries assess the potential of innovative nuclear technologies, including small modular reactors, to support their long term strategies to decarbonize electricity generation and other carbon intensive sectors. The initiative will develop credible scenarios through the IAEA's analytical tools, including MESSAGE (the Model for Energy Supply System Alternatives and their General Environmental Impacts) which is used by more than 100 countries.

The initiative provides technical expertise and scientific evidence on the potential of nuclear energy to decarbonize electricity production as well as hard-to-abate sectors such as industry and transport.

REALIZING THE POTENTIAL OF NUCLEAR — SCALING UP TO TRACK MITIGATION PATHWAYS TO NET ZERO

Decarbonizing the global energy sector by 2050 or soon after, in line with the IPCC mitigation pathways compatible with limiting average temperature increases to below 1.5 or 2°C, will require accelerated deployment of low carbon electricity generation technologies. In this context, nuclear energy has a proven track record of rapid deployment, as shown in Fig. 6, exemplified by the recent experience in the United Arab Emirates. The Barakah nuclear power plant is expected to produce around 25% of the United Arab Emirates' electricity by 2025, largely replacing natural gas generation and nearly halving power sector emissions in the Emirate of Abu Dhabi [12]. With construction starting in 2012, the rate of deployment and decarbonization closely mirrors earlier experiences in Sweden, France and other countries (see Fig. 6). Even in countries that have experienced delays in constructing new first-of-a-kind nuclear power plants, the rate of deployment has also often outpaced the uptake of other low carbon sources — see Box 3.

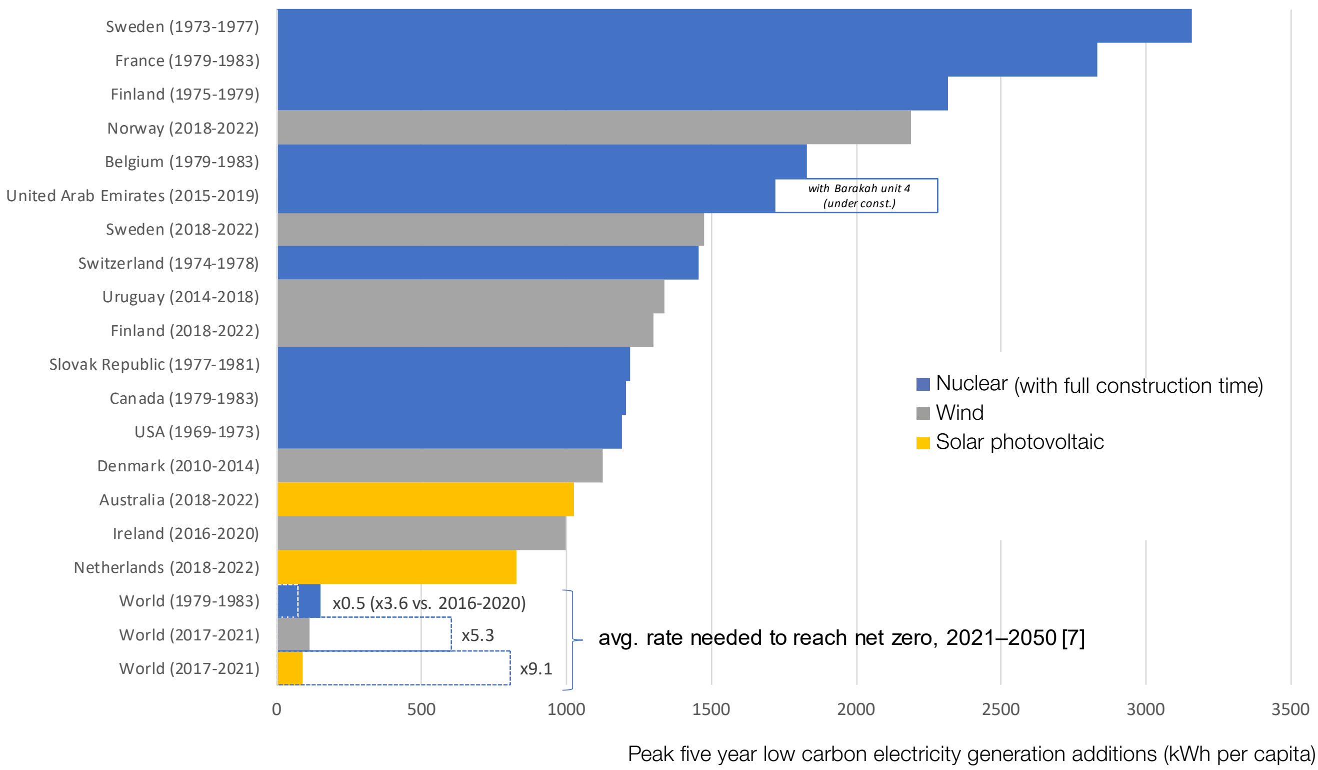

Fig. 6. Peak additions of low carbon electricity generation, kilowatt-hours (kWh) per capita over five years [8, 11].

Note: additions are averaged over the entire period from construction start to grid connection/commercial operation. For wind and solar photovoltaic generation, this is assumed to be one year or less. For nuclear power, the actual dates of construction and grid connection/commercial operation are used. Transparent bars indicate the estimated average deployment rates needed to realize the 2050 electricity mix in the IEA Net Zero Emissions by 2050 Scenario [6].

Globally, these historical deployment rates are more than sufficient to expand nuclear electricity generation in line with many 1.5°C and 2°C mitigation pathways. For instance, a doubling of nuclear generation by 2050 would require gross annual additions of around 13 kWh per capita globally[2], which is less than half the historical peak deployment rate shown in Fig. 6 (of 150 kWh per capita over five years, or 30 kWh per capita per year). Accordingly, nuclear energy is well placed to play its part in accelerating global mitigation efforts, and moreover, has the potential to play an even larger role, as envisaged in some IPCC mitigation pathways. This extra potential for rapid deployment of nuclear energy may prove critical given the ambitious and unprecedented scaling up of wind and solar PV needed in many mitigation pathways: using the IEA Net Zero Emissions by 2050 Scenario [6] as an example, deployment rates 5–9 times historical peak levels will need to be sustained over the long term for these technologies. Should this not be feasible, it will be important to have other options — including nuclear — that can step up to fill the shortfall.

Despite this potential of nuclear energy, efforts are nonetheless required to scale up global deployment rates from current levels (which are around 3 to 4 times slower than required; see Fig. 6). This can be supported, first and foremost, with consistent set of policy, regulatory, infrastructure and other measures to ensure efficient energy and investment market operation, guide investment (and avoid arbitrary barriers), manage clean energy project risks, facilitate coordination and cooperation across different levels (e.g. public–private sectors, developing–developed countries), and support emerging low carbon new technologies, among others [12, 13].

BOX 3: **FINLAND'S OLKILUOTO NUCLEAR POWER PLANT DELIVERS RAPID DECARBONIZATION DESPITE DELAYS**

Even with nuclear power projects that have faced significant construction delays, the deployment rate remains impressive. For example, although construction of unit 3 of the Olkiluoto nuclear power plant in Finland has taken around 17 years (rather than the originally planned ~5 years), the amount of annual low carbon generation added (12.5 TWh) exceeds the combined wind and solar photovoltaic generation added over the same 17 year period in neighbouring Norway and Denmark (which have comparable population sizes to Finland), as shown in Fig. 7. On a per capita basis, unit 3 at the Olkiluoto nuclear power plant also adds more clean electricity generation than the combined output of all wind and solar photovoltaic plants in Germany.

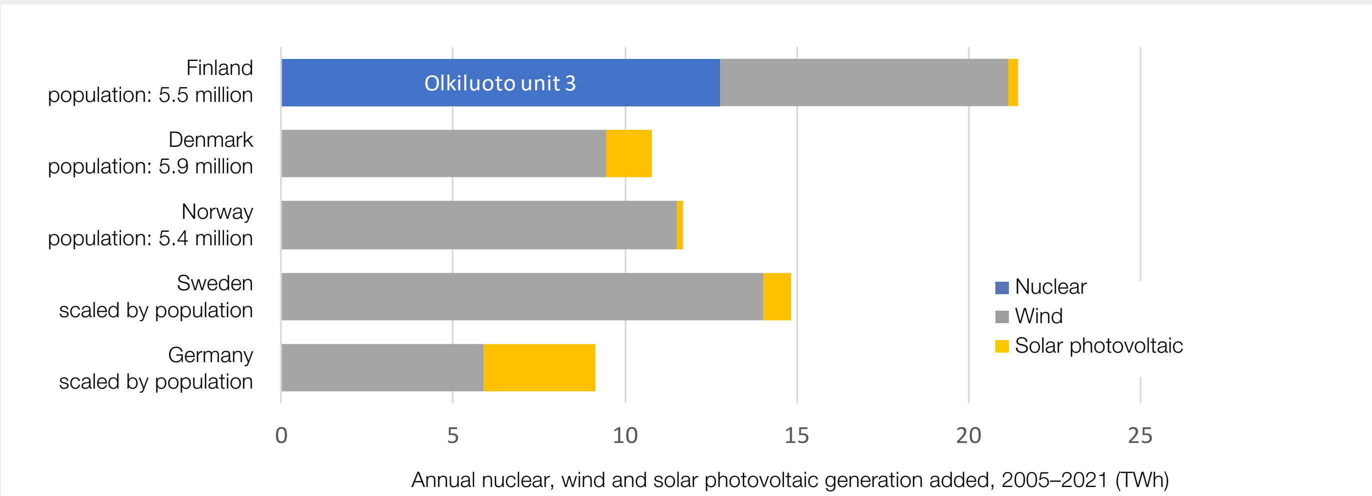

Fig. 7. Cumulative additions of nuclear, wind and solar electricity generation, 2005–2022 [8, 11].

[2] Assuming around 30% of existing capacity is retired (in line with the high case in Ref. [9]), implying gross additions of nearly 3600 TWh by 2050, or 125 TWh per year, or 13 kWh per capita per year (for a global population of 9.7 billion by 2050 [6]).

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