# CLIMATE CHANGE AND NUCLEAR POWER 2020

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# Foreword

## by Rafael Mariano Grossi
## Director General

The climate emergency is one of the greatest challenges facing the world. The production and use of energy account for around two thirds of total greenhouse gas emissions and must therefore be an important focus of the global response to climate change. I firmly believe that nuclear power can help to create a cleaner planet Earth with abundant supplies of energy.

Nuclear power plants produce virtually no greenhouse gas emissions or air pollutants during their operation and only very low emissions over their full life cycle. They deliver reliable, affordable and clean energy to support economic and social development. Nuclear power, currently being generated in 30 countries, is already reducing carbon dioxide emissions by about two gigatonnes per year. That is the equivalent of taking more than 400 million cars off the road — every year.

If countries scale back their use of nuclear power, their greenhouse gas emissions rise. That is not a matter of opinion. It is a scientific fact. If any major users of nuclear power were to stop using it overnight, this would immediately and dramatically increase carbon dioxide emissions.

Nuclear power now provides about 10% of the world's electricity, but it contributes almost 30% of all low carbon electricity. Nuclear power will be essential for achieving the low carbon future which world leaders have agreed to strive for.

We should not see nuclear energy and renewables such as wind and solar power as being competitors. On the contrary, they complement one another. Renewables will continue to grow in importance. Nuclear energy offers a steady, reliable supply of electricity. It can provide continuous, low carbon power, unlocking the potential of renewables by providing flexible support — day or night, rain or shine.

This edition of the IAEA's Climate Change and Nuclear Power publication updates our previous analyses of the role of nuclear energy, together with other low carbon sources, in mitigation strategies that will help the world to limit global warming to 1.5°C in line with the 2015 Paris Agreement. Broader factors affecting the transition to a low carbon energy system are reviewed. Challenges to nuclear power achieving its full potential are highlighted and possible solutions are identified. Technological advances and new funding models that could improve the economic attractiveness, safety and cost effectiveness of nuclear power are considered.

The IAEA is committed to assisting Member States in making optimal use of nuclear science and technology in order to improve the well being and prosperity of their people. I hope this publication will prove to be a valuable contribution to the discussion on how to achieve sustainable development and meet climate change goals while ensuring secure supplies of energy.

## Acknowledgements

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# CONTENTS

# SUMMARY

Climate change is widely recognized as a major threat to humanity and much of the natural world. According to the Intergovernmental Panel on Climate Change (IPCC), in order to limit the average global temperature increase to 1.5°C, global energy production and use need to be fully decarbonized by around 2050, with rapid reductions in emissions starting immediately. Electricity production, like other energy sectors, faces the immense challenge of shifting almost entirely to low carbon energy sources in just 30 years, from a system dominated today by fossil fuels.

The focus of the 2020 edition of this publication is on the significant role of nuclear energy in climate change mitigation scenarios and the challenges of realizing this role in a low carbon energy system. Many organizations are analysing the decarbonization of the energy system, and many of their scenarios, including all four illustrative scenarios described by the IPCC in its 2018 Special Report on Global Warming of 1.5°C, call for a substantial increase in global nuclear power capacity. This publication elaborates on how this energy source could be optimally enabled to take its place in an integrated decarbonized energy system and outlines the developments needed to realize a large scale capacity increase to rapidly decarbonize the global energy system in line with limiting global warming to 1.5°C. To that effect, the role of nuclear power includes maintaining existing low carbon capacity by extending the operational life of the current nuclear fleet as well as expanding low carbon capacity through the construction of new facilities.

**Climate change and energy:** Global emissions of greenhouse gases (GHGs) have been increasing almost continuously since the start of the industrial revolution and have nearly doubled since 1970. The production and use of energy currently account for around two thirds of total GHG emissions, and electricity generation in turn accounts for one third of these energy related emissions. Emissions from the electricity sector are growing rapidly and have more than tripled since 1970.

The 2015 Paris Agreement set a goal of holding "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". Since then, the international community has increasingly recognized the need to achieve the more ambitious 1.5°C goal. This was reinforced by the IPCC Special Report on Global Warming of 1.5°C, which outlined the additional risks to natural and human systems from warming of 2°C compared with 1.5°C. However, climate change mitigation targets and actions set out in countries' first

nationally determined contributions under the Paris Agreement are insufficient to reduce emissions to a level consistent with 1.5°C.

A synthesis of over 400 recent long term scenarios of energy demand from international, governmental, non-governmental, private sector and scientific organizations, including the IPCC, illustrates the challenges and opportunities of reducing emissions while simultaneously supplying energy for economic and social development. Several scenarios identify an opportunity to reduce final energy consumption by 2050. All project an increase in electricity consumption, ranging from 20% to 330%. In scenarios in which ambitious mitigation targets are achieved, electricity generally plays a larger role to support decarbonization of other energy uses (e.g. by electrifying transport and industry). The four illustrative 1.5°C pathways from the IPCC Special Report all see the share of electricity in final energy consumption reaching 40–60% by 2050, compared with just below 20% in 2018.

The increasing importance of electricity in future energy systems brings into focus the technology options for low carbon electricity generation. Nuclear power, hydroelectricity, wind and solar produce the lowest GHG emissions per unit of electricity on a life cycle basis. However, these technologies have a more varied impact on material requirements and associated environmental impacts, which are likely to become increasingly important in a low carbon electricity system. Technologies with lower material resource requirements include nuclear, hydroelectric and natural gas combined cycle power plants, owing to their higher power densities and capacity factors. In contrast, wind power and especially solar photovoltaic generation require significantly more material resources per unit of electricity, which may create additional environmental burdens.

Low carbon electricity generation technologies have helped to avoid the use of significant quantities of fossil fuels. These technologies are estimated to have reduced direct power sector carbon dioxide ($CO_2$) emissions by up to one third over the period 1971–2018. After expanding rapidly from the early 1970s onwards, nuclear power has contributed substantially to reducing emissions, supplying close to 50% of low carbon electricity in the 1990s. Annual emissions would have been around 2 gigatonnes (Gt) of $CO_2$ higher over the past decade if electricity from nuclear power plants (NPPs) had instead been supplied using the average global fossil fuel generation mix. The IAEA estimates that over the period 1971–2018, nuclear power avoided a total of 74 Gt $CO_2$, equivalent to the cumulative emissions from the entire power sector for the six years from 2013 to 2018.

The potential future contribution of nuclear energy to climate change mitigation has been analysed across 400 recently published scenarios, including those from the IPCC Special Report. These scenarios present a wide range of future estimates reflecting many uncertain technical, economic, social and policy factors. However, an increasing role for nuclear power is seen across many of the scenarios, particularly in those with lower $CO_2$ emissions that achieve more stringent mitigation targets. For example, in the full set of IPCC pathways compatible with the 1.5°C goal, average nuclear generation triples by 2050 from 2018 levels. Compared with the IAEA's low and high projections of nuclear electricity generation to 2050, derived from a bottom-up project by project assessment, higher levels of nuclear generation are seen in other scenarios, including the IPCC's four illustrative pathways, implying significant additional market and policy action beyond the current trends reflected in the IAEA projections. Achieving such high levels of nuclear power deployment is likely to require a rapid expansion of global supply chains, human capital and other physical and institutional infrastructure.

The characteristics and assumptions of the four IPCC illustrative pathways and other scenarios projecting a strong increase in nuclear capacity highlight several potentially important enabling factors for capitalizing on nuclear power's mitigation potential: (a) a strong mitigation target, and related consistent policy signals; (b) control of nuclear costs and, implicitly, access to finance; (c) a moderate degree of social acceptance; and (d) recognition of the value of nuclear power to the stable operation and management of the electricity system or grid.

Global trends in the nuclear fleet provide a base for scaling up action. Recent nuclear power developments and projects provide an indication of whether and how a rapid and large scale expansion of the nuclear industry could be realized by 2050. In the period 1999–2019, net nuclear electrical capacity increased by a modest 14%. At the start of 2020, there were 52 reactors under construction in 19 countries, equating to over 13% of current global nuclear capacity. This includes projects in countries with established nuclear power programmes as well as in 'newcomer' countries constructing their first NPPs, such as Bangladesh, Belarus, Turkey and the United Arab Emirates, illustrating the potential for nuclear power to provide low carbon energy to emerging economies.

Several countries have signalled their plans to utilize nuclear power in their first nationally determined contributions under the Paris Agreement. However, these plans are not sufficient to meet the goal of limiting the increase in average global temperature to well below 2°C or 1.5°C. Countries will need to commit to more ambitious action in their updated 2020 and future nationally determined contributions. Given its mitigation potential, nuclear power could enhance such ambitious action. The 30 countries using nuclear power today have the capacity, in terms of infrastructure and experience, to ramp up nuclear power on a scale that could make a significant difference to global emissions. Over the medium term, the adoption of nuclear power by additional countries, particularly emerging economies that will drive a greater share of future emissions growth, can support broader climate mitigation action.

**Low carbon energy systems:** A future low carbon energy system will comprise a diverse suite of technologies and resources working in synergy. The transition towards such a system requires a radical transformation of how energy services are produced, provided and used. The electricity system will become increasingly complex and highly integrated, with more distributed generation and storage as well as tighter coupling with transport and the broader energy sector. While a low carbon electricity system will be central to the clean energy transition, other low carbon energy carriers — such as hydrogen and heat — will play an increasing role in fully decarbonizing sectors such as industry and transport.

The transition to a low carbon electricity system will also create challenges. With growing shares of variable renewable energy generation in the power system, residual demand — i.e. the difference between total electricity demand and generation from variable renewables — will become increasingly volatile, with more extreme load variations and more frequent and steeper ramping requirements. The residual load is also expected to become more unpredictable, and both short term and seasonal storage capacity needs are expected to grow.

These and other developments have resulted in growing electricity market price volatility, which has significantly increased the risks for investment in capital intensive technologies — i.e. the very investments needed for the transition towards a low carbon system. This has prompted a discussion among policy makers, regulators and system operators on the extent to which deregulated electricity markets can deliver the transition to a low carbon power system while ensuring an adequate level of supply security and sufficient investment in network and generation capacities.

Even though a growing number of NPP operators in several countries are responding to increasing load variations and volatility by implementing procedures to operate their plants flexibly, in the absence of specific market arrangements for flexible operation, plant operators face a decrease in revenues when compared with baseload operation owing to lower load factors. Therefore, increasing the flexibility of nuclear generation to accommodate variable renewable generation will require new regulatory practices to allow for the recovery of additional costs and to compensate for the provision of these flexibility services. Today, flexibility market revenues are substantially lower than energy market revenues. Similarly, market and policy signals are providing only limited support for a transition to low carbon energy carriers other than electricity. For instance, in the case of low carbon hydrogen and heat produced from nuclear power — which could be flexibly cogenerated with electricity to enable NPPs to run at full power constantly — both historical and recent developments have been limited to technical demonstration projects rather than large scale commercialization to support the low carbon transition.

A key impediment to a rapid transition to a low carbon energy system is the lack of incentives provided by existing policy and regulatory frameworks, including the current design of power markets in many countries. In addition to a firm political commitment to full decarbonization in the long run, several elements can support the transition to a reliable, low carbon energy system in liberalized markets: (a) competitive short term electricity markets for efficient dispatch; (b) frameworks for the adequate provision of capacity, flexibility and infrastructure for transmission and distribution; (c) measures to foster long term investment in low carbon technologies; (d) internalization of system costs; and (e) carbon pricing. In terms of supporting investment, large energy infrastructure projects, including nuclear, offshore wind and solar thermal plants, offer significant mitigation potential but remain high risk for private investors. Some forms of government support and market measures to manage and share risks are often necessary to facilitate such investments. Government involvement can range from direct public investment and ownership, often seen in regulated markets in emerging economies, to more novel approaches to reduce risk exposure such as contracts for difference and regulated asset base models with enhanced government protection during plant construction, as is being considered in the United Kingdom to support nuclear new build projects. Other instruments such as feed-in tariffs, premiums, power purchase agreements, green certificates and obligations have also been deployed in recent years, mainly in support of renewable energy sources. More systemic measures include carbon pricing regimes, which are often viewed as the optimal economic instrument to curb GHG emissions. However, to date, carbon price levels have generally been far too low to deter fossil fuel investment and will need to increase significantly in order to become effective.

Energy investment flows are another indicator of the pace and direction of energy system development, and a good predictor of the sustainability of future energy systems. The transition to low carbon electricity systems will gain more traction once capital investment patterns shift, across the board, away from unabated fossil fuel projects. Between 2015 and 2018, average investments in nuclear and renewable energy totalled 38% of low carbon investments. Almost half of this low carbon energy investment was made in China and the United States of America, although they account for less than a quarter of the global population. While these countries account for a substantial amount of global energy demand, there is clearly significant potential to improve access to finance mechanisms designed to support low carbon investments for other recipients, particularly those facing a lack of domestic capacity and resources.

Critically, policy and investment incentives will also need to deliver an energy system that is resilient to the impacts of climate change. While the vulnerability of different electricity generating technologies varies, NPPs have shown themselves to be relatively resistant to weather events, with limited forced outages in most cases despite a high frequency of extreme weather events in some regions.

**Realizing the mitigation potential of nuclear power:** Within well designed policy and market frameworks to drive the clean energy transition, several additional elements can unlock the mitigation potential of nuclear power. Nuclear power projects and programmes are characterized by large capital investment requirements and long construction times, typically around seven years. To ensure that nuclear power can contribute economically to a low carbon system, investment costs can be contained effectively through multiunit construction programmes allowing plant developers, vendors, work crews and regulators to gain experience over time. Another key element is managing and sharing the risks associated with large, complex and capital intensive nuclear projects. To this end, various financing and risk sharing models have emerged across different markets, reflecting local conditions and ownership structures.

Robust supply chains, capable of delivering equipment, systems and services with the highest quality levels, are also vital to the success of nuclear new build projects. In some parts of the world, declining orders for new nuclear power stations have led to a general weakening of the subcontractor network and to a relative increase in construction costs and delivery times. In comparison, successful nuclear projects are generally backed by vendors and supply chains built up across a steady series of projects, enabling subcontractors to develop and retain experienced and skilled teams.

Complementing new nuclear projects, extending the operational lifetimes of existing NPPs is expected to continue to deliver significant short to medium term contributions to climate change mitigation, while reducing air pollution and enhancing security of supply. Experience shows that this can be realized with a modest investment to replace and refurbish major components to ensure plant operation in line with current expectations. Compared with a nuclear new build project, lifetime extension projects are less capital intensive, feature significantly shorter construction and payback times, and have a good track record in terms of cost control and limiting construction delays.

Advanced and emerging nuclear energy technologies could also augment the contribution of nuclear power to climate change mitigation. Small modular reactors (SMRs) could be deployed in markets and applications less suited to other low carbon technologies (including conventional NPPs) owing to geographical, technical or financial constraints. For example, SMRs could be well suited to small islands, remote regions, areas with limited cooling water availability and regions with small grids, and they could be attractive to investors with limited access to capital. A successful SMR demonstration project will be critical as a proof of concept before governments and utilities will seriously consider the option. In recent years, several government-led as well as private initiatives have been developed.

While SMRs appear to be a promising complement to conventional NPPs in the energy transition, one factor affecting the uptake of all nuclear energy technologies is the level of public and political acceptance. A culture of transparency and openness is essential for addressing the legitimate concerns of stakeholders regarding nuclear power, including safety, nuclear waste and nuclear energy's role in climate change mitigation. In addition to the general public, any new nuclear programme should expect to engage local communities, the media, vendors, government authorities and decision makers, professional bodies and special interest groups, including established local and international anti-nuclear environmental organizations. Important factors influencing the acceptance of nuclear power include both the level of information and knowledge people have and their perception of feeling informed about nuclear energy. This requires a coherent factual narrative on nuclear power, with understandable messages delivered by trusted third party sources. Such stakeholder engagement is a critical component in a robust system of institutional, regulatory, legal, industrial and other infrastructure required for any nuclear power programme.

Successfully integrating these factors, together with the technical, financial and policy elements mentioned above, can enable nuclear energy to play a substantially expanded and proportionate role in addressing the climate and energy challenge.

# 1. INTRODUCTION

## 1.1. BACKGROUND

Climate change is widely recognized as a major threat to humanity and much of the natural world. Increasing atmospheric concentrations of greenhouse gases (GHGs) are driving changes in global and regional temperatures, precipitation patterns and other climate attributes, increasing the risk of extreme weather events and sea level rise, and impacting human health, livelihoods, food security and water supply, as well as biodiversity on land and in oceans [1, 2]. Displacement from climate events could result in millions of climate refugees around the world. Carbon dioxide ($CO_2$) emissions from burning fossil fuels and other industrial activities, along with emissions from agriculture and land use, are the principal drivers of climate change.

With the adoption of the Paris Agreement in 2015, nearly all parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to prepare nationally determined contributions (NDCs) to control GHG emissions and limit the increase of global mean surface temperature to below 2°C relative to pre-industrial levels. Since then, increasing scientific understanding of the significant risks associated with warming of 2°C [2], along with increasing societal concern, have established the need for more urgent and ambitious action to avoid the worst impacts of climate change by limiting warming to 1.5°C by the end of the century.

Reflecting this urgency, the United Nations Secretary-General convened the Climate Action Summit in September 2019 and called on world leaders to enhance their NDCs by 2020 with the aim of reducing emissions by 45% by 2030 and achieving net zero emissions by 2050. Expectations that the 25th Conference of the Parties (COP25) to the UNFCCC in December would build on this momentum attracted significant international media and public attention to the event. However, the outcome of COP25 was considered disappointing [3–5], and further efforts are needed to improve climate strategies and ramp up ambition in NDCs. In particular, delegates failed to agree on key modalities for establishing a carbon market to facilitate increased ambition, and on support for developing countries in finance, technology and capacity building [6]. However, 72 countries (plus the European Union (EU)) representing around 15% of global $CO_2$ emissions from energy, signalled their goal of achieving net zero GHG emissions by 2050 [7, 8]. Additional countries have adopted similar targets following COP25.

According to the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR15) [2], in order to limit the average global temperature increase to 1.5°C, global energy production and use need to be fully decarbonized by around 2050, with rapid reductions in emissions starting immediately. The electricity sector faces the immense challenge of shifting almost entirely to low carbon energy sources in just 30 years, from a system dominated today by fossil fuels, as illustrated in Fig. 1. Since energy infrastructure tends to have a lifespan measured in decades, immediate action is needed to make this rapid transition possible.

The potential of nuclear power — which currently supplies almost 30% of low carbon electricity [9, 10] — to contribute to this transformation is illustrated in the long term 1.5°C pathways considered by the IPCC, which envisage a substantial increase in global nuclear generation (of 100–500% by 2050 in the IPCC's four illustrative pathways) [2]. Nuclear power's role in mitigation is also recognized in a recent report from the International Energy Agency (IEA), a special body of the Organisation for Economic Co-operation and Development (OECD), entitled Nuclear Power in a Clean Energy System [11]. Besides electricity generation, nuclear power could provide a significant contribution to decarbonizing the non-electric energy sector, an undertaking that has proved to be more challenging. For instance, the share of polluting fossil fuels in the global energy mix is not yet decreasing (as of 2019, it remained at about 63%, the same level as in the 1990s [12]).

To provide a platform to discuss objectively the scientific and technical aspects of the role of nuclear power in combating climate change, the IAEA held its first International Conference on Climate Change and the Role of Nuclear Power in October 2019, with over 500 participants from 79 Member States and 18 international organizations [13]. Delegates called for urgent and ambitious climate action, making use of all low carbon energy sources to slash emissions and avoid the worst impacts of climate change. Participants also heard how, with constant technical innovation and advancement, nuclear power is becoming more sustainable and flexible in terms of integration with other low carbon energy

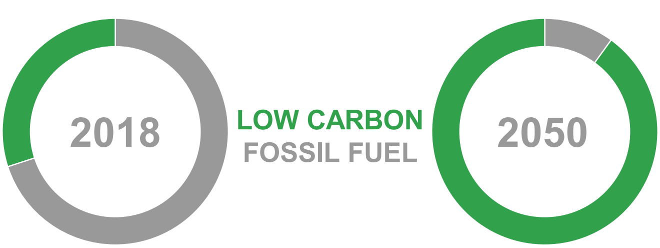


*FIG. 1. The share of low carbon generation in 2018 and the share that needs to be attained by 2050 to meet the climate challenge. Source: IAEA estimates based on Refs [2, 9].*

sources, which further enhances its potential in supporting a low carbon energy transition. Content from a selection of materials presented during the conference is cited in this publication.

## 1.2. OBJECTIVE

This publication provides an update on the current status and prospects of the contribution of nuclear power, together with other low carbon energy sources, to ambitious climate change mitigation. This is the eleventh edition of Climate Change and Nuclear Power, which the IAEA first issued in 2000 to support both those Member States that choose to include nuclear power in their energy system and those considering other mitigation strategies. The focus of the 2020 edition is on the significant potential of nuclear energy in climate change mitigation that aims to reach the 1.5°C target, and the developments and challenges of realizing this potential in a low carbon energy system.

## 1.3. SCOPE

This publication explains the complementary role of nuclear energy in an energy system with ambitious GHG emissions mitigation, together with other low carbon sources. Multiple organizations are analysing the necessary decarbonization of the energy system, and many of their scenarios, including all four illustrative scenarios from the IPCC's SR15, include a substantial increase of global nuclear power capacity, many of them above the IAEA's projections of future nuclear capacity [10]. This publication also elaborates on how this energy source could be optimally enabled to take its place in an integrated decarbonized energy system and outlines developments needed to realize the large scale capacity increase required to rapidly decarbonize the global energy system in line with limiting global warming to 1.5°C. In this edition, the focus will be on developments in the deployment of nuclear power in the energy system, rather than on developments in nuclear technology itself. To that effect, the role of nuclear power includes maintaining existing low carbon capacity by extending the life of the current nuclear fleet as well as expanding low carbon capacity through the construction of new facilities.

## 1.4. STRUCTURE

This publication provides a review of the low carbon energy transformation required to limit warming to 1.5°C, including a comprehensive assessment of the potential role of nuclear power in climate change mitigation and key elements in realizing this potential. This is delineated across Sections 2–4.

Section 2 first outlines the role of the energy sector in climate change and the challenge of limiting warming to 1.5°C while meeting increasing demands for energy and electricity. Energy technology options for the low carbon transition are then analysed considering GHG emissions, material requirements, and technical and economic attributes. The specific role and mitigation potential of nuclear power is explored in further detail across future energy pathways, focusing on the IPCC's SR15. This potential is then compared with the current status and trends in nuclear power, including national plans to utilize nuclear power in mitigation (specifically in NDCs).

Section 3 then analyses the technical and economic challenges of realizing low carbon power and energy systems and underlines the importance of nuclear energy in complementing other low carbon sources in an optimally configured energy system. It discusses the services delivered by nuclear power plants (NPPs) to an energy system dominated by low carbon sources, as well as the policy and financial instruments necessary to facilitate the energy transition. Finally, this section addresses the vulnerabilities of energy infrastructure to climate change effects.

Section 4 elaborates on several key challenges and opportunities to realize the mitigation potential of nuclear power, including both the optimized use of current facilities within safety and environmental constraints and the design and construction of new NPPs, including emerging technologies. In addition, stakeholder involvement, of specific importance to the nuclear sector, is discussed.

# 2. CLIMATE CHANGE AND ENERGY

## 2.1. TRENDS, TARGETS AND CHALLENGES FOR MITIGATION

Global emissions of GHGs from anthropogenic sources have been increasing almost continuously since the start of the industrial revolution [14, 15] and have nearly doubled since 1970, as shown in Fig. 2. As a result, atmospheric concentrations of $CO_2$ — the principal GHG — reached almost 408 parts per million (ppm) in 2018 [21], up from around 280 ppm before the industrial revolution [14, 15]. The decade 2010–2019 was the warmest on record, with global mean temperature reaching around 1.1°C above pre-industrial levels in 2019 [21].

### 2.1.1. Energy accounts for most emissions, with electricity driving growth

The production and use of energy represent the largest source of GHG emissions, accounting for around two thirds of total emissions in recent years (Fig. 2). Emissions from energy comprise predominantly $CO_2$ from the burning of fossil fuels, methane released mainly during fuel extraction and nitrous oxide formed during combustion. Around half of total energy emissions are produced from the direct use of fossil fuels in industry, transport and buildings, with emissions from transport increasing markedly (2.5-fold) since 1970. However, emissions from electricity generation have grown even faster, more than tripling since 1970. Electricity generation now accounts for one third of total emissions from energy production and use and 22% of emissions from all sources (compared with 12% in 1970), highlighting its critical and increasing importance for climate change mitigation.

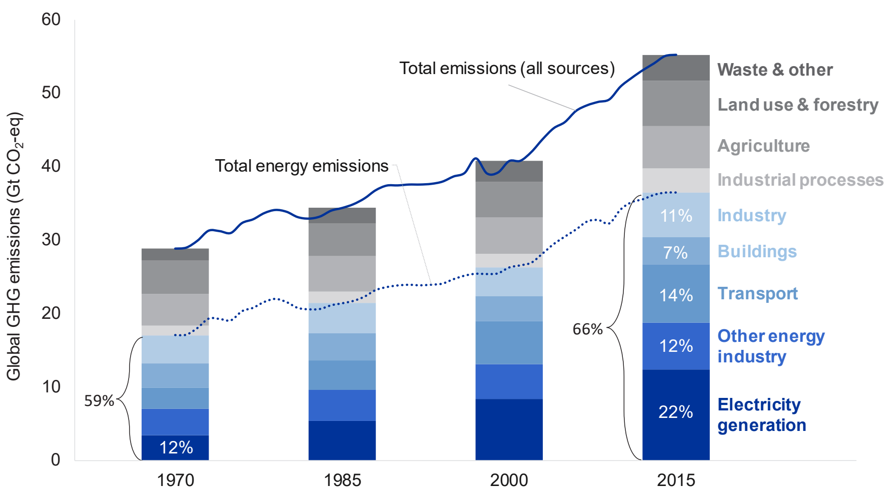


*FIG. 2. Global greenhouse gas emissions from all sources, 1970–2015. Source: Refs [8, 9, 16–20]. Note: 'Other energy industry' refers to energy production and transformation activities other than electricity generation, such as oil and gas extraction, oil refining and heat production; Gt $CO_2$-eq — gigatonnes of carbon dioxide equivalent.*

### 2.1.2. Rapid decarbonization of energy is needed to limit warming to 1.5°C

To respond to increasing emissions and impacts [1], in 1992 the international community adopted the UNFCCC, which provides a legal framework for stabilizing atmospheric concentrations of GHGs to avoid "dangerous anthropogenic interference with the climate system" [22]. This was followed by a series of efforts to negotiate and implement an effective legal instrument to set targets and timeframes for limiting GHG emissions, starting with a top-down approach in the 1997 Kyoto Protocol to set targets for a limited group of countries [23] and culminating in the 2015 Paris Agreement, the first universal and legally binding global accord to mitigate climate change [24]. The Paris Agreement is based on a bottom-up approach in which countries specify and communicate national mitigation targets and planned actions in the form of regularly updated NDCs, with the first updates scheduled for 2020.

Based on the scientific understanding of climate change in 2015 [25], the Paris Agreement aims at:

> "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" [24].

With the IPCC's subsequent publication of SR15 [2], which outlined the additional risks to natural and human systems from warming of 2°C compared with 1.5°C, the international community is increasingly recognizing the need to achieve the more ambitious 1.5°C goal.

However, while many countries have adopted net zero GHG emissions targets for 2050 [7], the targets and actions in current NDCs are insufficient to reduce emissions to a level consistent with 1.5°C (or 2°C) [26], as illustrated in Fig. 3. The level of GHG emissions in 2030 implied by *conditional* NDC targets — that is, the most ambitious national targets that are conditional on receiving international support — is approximately 12 gigatonnes (Gt) $CO_2$-equivalent ($CO_2$-eq) above the median level consistent with 2°C, and 29 Gt $CO_2$-eq above the level consistent with 1.5°C [26]. Continuing the level of climate action in conditional NDCs to 2100 is estimated to lead to an increase in average global temperature of 2.7–3.2°C [2].

In the longer term to 2050, emissions from all sources will need to be reduced further, to median levels close to 20 Gt $CO_2$-eq and 5 Gt $CO_2$-eq for 2°C and 1.5°C, respectively. As illustrated in Fig. 3 (inset), energy emissions will need to decrease immediately and reach net zero around 2050 for 1.5°C (and around

2075 to achieve 2°C), according to the scenarios of the IPCC's SR15. Given the long lifetimes of energy infrastructure, this indicates the need for urgent action. Similarly, global electricity generation will also need to be fully decarbonized around 2050: in IPCC scenarios compatible with warming of 1.5°C, low carbon technologies (nuclear power and renewables) account for an average of almost 90% of electricity generation by 2050 [27, 29]. Figure 3 (inset) also shows the emissions trajectories of the four illustrative 1.5°C pathways selected by the IPCC (P1–P4), which assume different patterns of socioeconomic development and encompass different mitigation strategies discussed further below and in Section 2.3 (see also the Appendix) [2, 28–30].

### 2.1.3. Trends in energy demand create challenges and opportunities

The need for ambitious mitigation coincides with continued growth in global population and economic activity [31], as well as efforts to ensure "access to affordable, reliable, sustainable and modern energy for all" in order to achieve the United Nations Sustainable Development Goals, in particular Goal 7 [32]; as of 2018, around 860 million people worldwide did not have access to electricity and around 2.6 billion were unable to access clean cooking technologies and fuels [12]. How these developments unfold, along with technological and policy

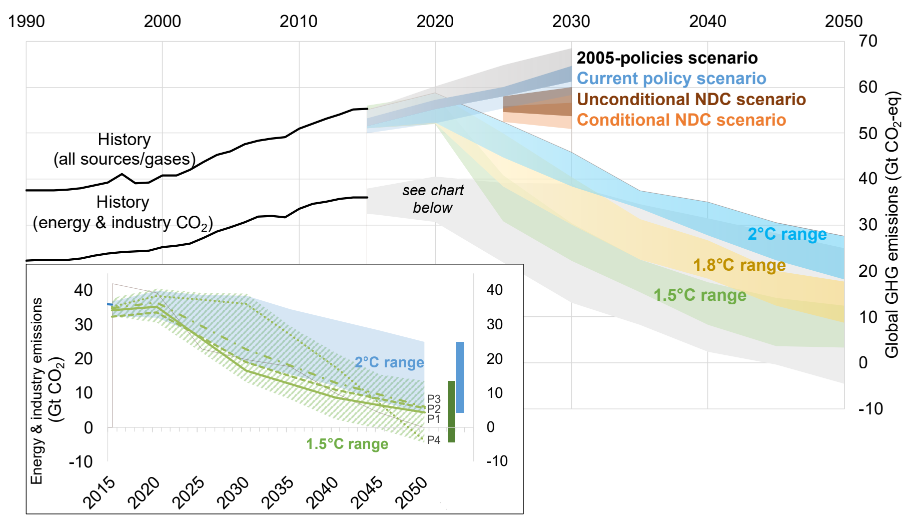


*FIG. 3. Global greenhouse gas emissions across different mitigation scenarios, 1990–2050. Source: Refs [2, 8, 9, 16–20, 26–28]. Note: the lower panel shows the 5th to 95th percentile range of emissions across scenarios compatible with 1.5°C and 2°C; P1, P2, P3 and P4 denote the IPCC's four illustrative 1.5°C pathways [2] (see below); Gt $CO_2$ — gigatonnes of carbon dioxide; Gt $CO_2$-eq — gigatonnes of carbon dioxide equivalent.*

factors, will determine future energy and electricity demands and influence the realization of ambitious mitigation targets. The high level of uncertainty underlying many of these drivers is reflected in the wide range covered by future estimates of energy demand, as illustrated in Fig. 4, which presents a synthesis of over 400 recent scenarios of energy demand from international, governmental, non-governmental, private sector and academic organizations — including the IPCC's SR15 [2]. Across these scenarios, final energy consumption in 2050 ranges from 220 to 900 exajoules (EJ), compared with around 415 EJ in 2018, reflecting different assumptions and approaches regarding key driving factors: some scenarios track the development of the global energy system based on current and emerging trends and policies (to explore the question 'where are we heading?'), while others apply different assumptions to explore energy system development in the context of achieving specific outcomes, such as limiting warming to 2°C or 1.5°C (to explore the question 'where do we need to go?'). As seen in Fig. 4, scenarios that achieve the goal of limiting global warming to 1.5°C without a substantial overshoot in temperature (including the SR15 illustrative pathways P1–P3) generally feature high energy efficiency and hence lower final energy demand. For electricity demand, however, all scenarios project an increase from 22 petawatt-hours (PW·h) in 2018 to between 27 and 95 PW·h in 2050. This increasing demand for electricity is driven by assumed economic and population growth and a continuation of long term electrification trends. In scenarios that achieve ambitious mitigation targets, electricity generally plays an even larger role to support decarbonization of other energy uses (e.g. by electrifying transport and industry): in the IPCC's four illustrative 1.5°C pathways (P1–P4), the share of electricity in final energy consumption reaches 40–60% compared with below 20% in 2018.

Despite the potential for increasing energy and electricity demand to lead to higher GHG emissions, the mitigation pathways presented in Fig. 4 — for example, P1–P4 — illustrate how low carbon technologies such as nuclear power and renewables, combined with energy efficiency, increasing electrification and a shift to other low carbon energy carriers (such as hydrogen, synthetic fuels and heat), can potentially satisfy future demands while achieving ambitious GHG abatement goals. Section 2.2 explores in more detail the characteristics of some of these key low carbon energy technologies.

## 2.2. ENERGY TECHNOLOGIES FOR THE LOW CARBON TRANSITION

The trend towards increased electrification of global energy demand, as seen in Section 2.1, brings into focus the critical role of power generation in the clean energy transition. The future power system will need to rely on a broad range of technologies working in synergy in a more integrated and complex system. However, the available technology options exhibit different characteristics, such as power densities, capacity factors, carbon intensities, modularity, deployment requirements (resources, capital etc.) and capabilities to provide services to the electricity system. These differences influence the suitability of each technology option to contribute to a low carbon, affordable and reliable power system.

This section first briefly discusses the main characteristics of current electricity generation technologies in terms of carbon emissions and material requirements, generation patterns and ability to provide services to the system, before focusing on the economics and financing of these technologies.

### 2.2.1. Nuclear power and hydroelectricity have the lowest life cycle greenhouse gas emissions of electricity generating technologies

As discussed in Section 2.1, realizing the 1.5°C goal implies a continuous reduction in global energy emissions to reach net zero around 2050 with full decarbonization of the power sector. This implies that the future role of fossil fuels in power generation will need to be minimal and most likely confined to

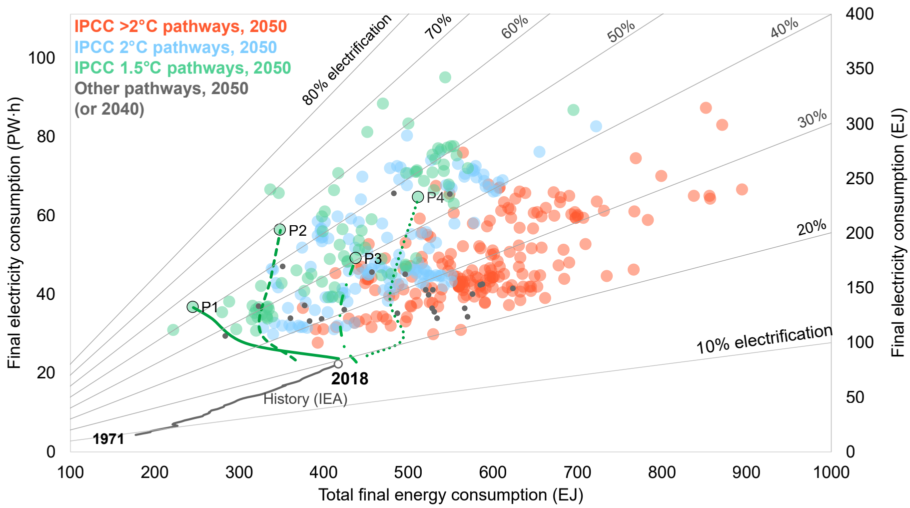


*FIG. 4. Global final energy and electricity demand across different scenarios, 1971–2050. Source: Refs [9, 10, 12, 27, 28, 33–45]. Note: Each circle represents a different scenario in 2050; for studies that analyse a shorter time horizon (such as Refs [12] and [41]), scenario data for 2040 are presented; P1, P2, P3 and P4 denote the IPCC's four illustrative 1.5°C pathways [2]; PW·h — petawatt-hours.*

providing reserve capacity; even the most efficient combined cycle natural gas turbine (CCGT) power plant produces roughly 400 grams (g) of $CO_2$-eq per kilowatt-hour (kW·h) or more (see Fig. 5), making it incompatible with a low carbon electricity system. Furthermore, current forecasts for the carbon intensity of fossil generation equipped with carbon capture and storage (CCS), with emission estimated to be at least 200 g $CO_2$-eq/kW·h [2], imply a very limited role for this technology by 2050.

Under such constraints, power generation systems will need to rely on low carbon energy sources. Figure 5 shows that over the entire life cycle, from resource extraction to decommissioning, nuclear power and hydroelectricity have the lowest median GHG emissions per unit of electricity output, closely followed by wind power, while solar photovoltaic (PV) and thermal plants have somewhat higher emissions.

The differences between these low carbon sources arise mainly in the life cycle stages of material extraction, processing, equipment manufacturing and decommissioning, which vary in energy requirements and intensities. It is important to note that low carbon electricity generation technologies emit

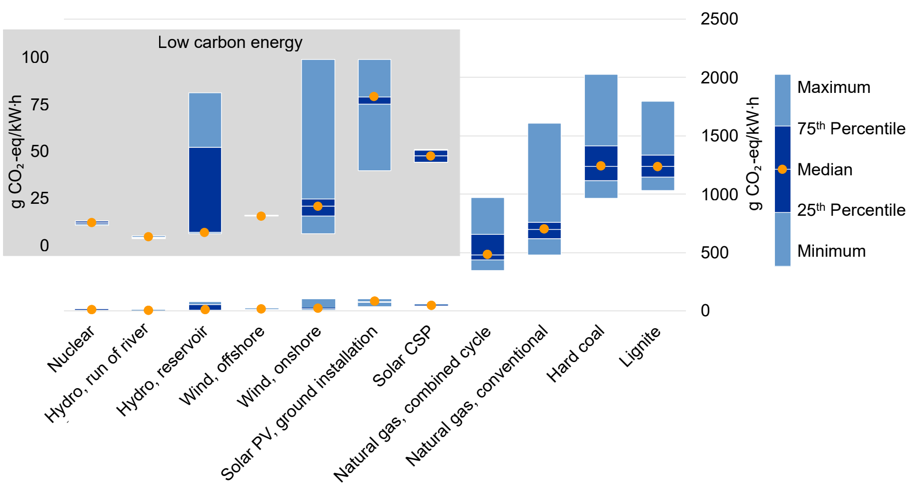


*FIG. 5. Life cycle greenhouse gas emission of different electricity generation technologies, including detailed view on low carbon sources. Source: Ref. [46]. Note: fossil technologies equipped with carbon capture are excluded because estimates based on a consistent methodology are unavailable (partly owing to limited empirical data); however, estimates with other methodologies exceed 200 g $CO_2$-eq/kW·h [2]; ground installation refers to solar panels mounted on the ground rather than a roof to maximize exposure; CSP — concentrated solar power.*

practically zero GHGs during operation, as opposed to fossil fuel generators that generate the bulk of their emissions during this stage.

Decarbonization of the energy supply used in material production chains, as well as technology improvements, will inevitably lower emissions during the production of low carbon electricity technologies. Depending on the global energy development pathway, a substantial decrease in carbon footprints can be expected by 2050 for solar PV (over 50%) and wind power (over 20%), while hydroelectric and nuclear power are estimated to have lower emissions reduction potentials [47], given their lower material intensities and high power densities and capacity factors.

### 2.2.2. Material use shapes the emissions footprint of low carbon electricity technologies

As mentioned above, the life cycle GHG emissions of low carbon energy technologies are predominantly dependent on their supply and production chains. Specifically, resource extraction, transport, processing and disposal of materials represent key factors determining emissions (see Fig. 6). These material requirements may also correlate with broader environmental impacts related to associated pollutant emissions, resource depletion and waste flows that ultimately affect ecosystems and human health.

A technology's material intensity per unit of electricity generation — and related emissions from material supply chains — can be measured using different methods and metrics. However, a similar pattern is seen across methods and metrics, with nuclear, hydroelectric and natural gas requiring the least material resources for the same electricity output as a result of their high power densities and capacity factors, while wind and solar are at the opposite end of the spectrum: regional differences in wind and solar load factors can also significantly influence material use per unit of generation.

While material intensity is a defining factor in life cycle emissions for low carbon technologies, a composite view of material and emissions intensity also illustrates potential trade-offs between climate change mitigation and material use (see Fig. 7). As energy systems move to low carbon sources, energy development plans will need to respond to the likely shift in environmental burdens from GHG emissions to other impacts.

### 2.2.3. Low carbon technologies vary in their contribution to a reliable electricity system

In addition to the environmental and resource implications of future electricity technology deployment, the impact on the technical and economic

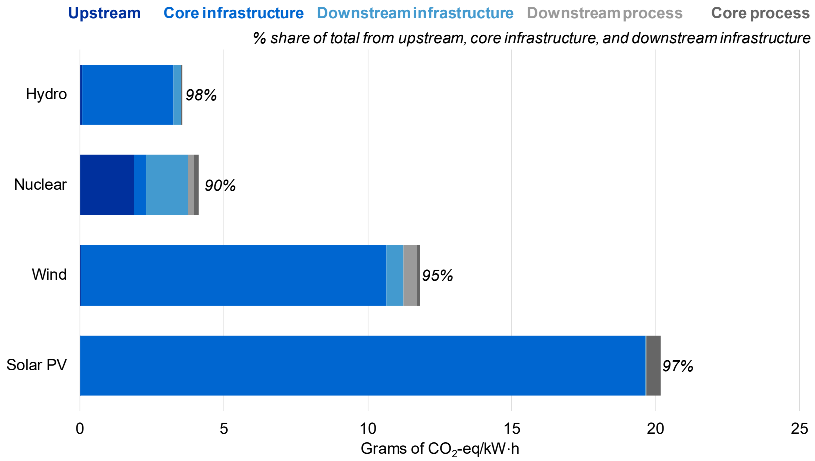


*FIG. 6. Contribution of material related emissions to total emissions per unit of output for low carbon energy sources. Source: Ref. [48]. Note: Upstream — production and transport of all necessary ancillary substances for operation (e.g. fuels, oils, lubricants etc); core infrastructure — from the extraction of the raw materials needed to build the power plant, until its dismantling and corresponding end of life material treatment; downstream infrastructure — construction and decommissioning of the electrical grid; downstream process — electrical losses; core process — operation and maintenance impacts.*

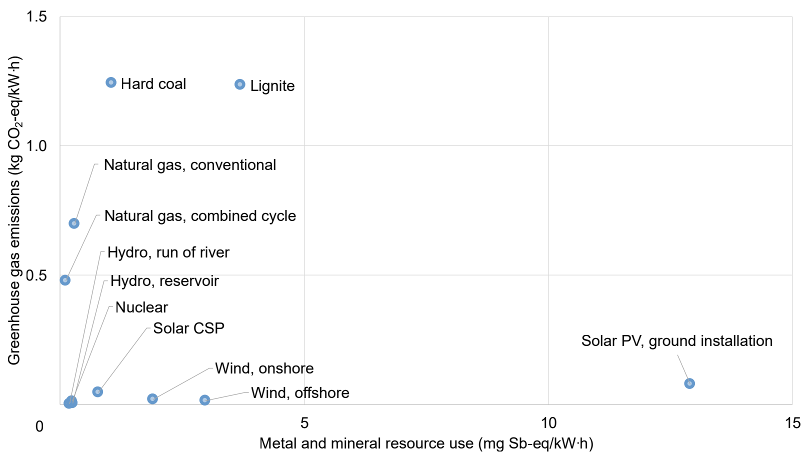


*FIG. 7. Life cycle greenhouse gas emissions and resource use per kW·h for different electricity generation technologies, based on median values. Source: Ref. [46], ILCD 2.0, median values for minerals and metals and climate change. Note: ILCD — International Reference Life Cycle Data System; Sb-eq — antimony equivalent; CSP — concentrated solar power; kg — kilogram, mg — milligram.*

performance of the electricity system — and in turn the reliability, affordability and accessibility of the electricity supply — represents another critical consideration for the energy transformation. Electricity is a non-homogeneous good, whose value depends strongly on when, where and how it is generated. Moreover, many services beyond pure electricity generation are required for the reliable operation of the power system.

Low carbon technologies differ significantly in the way they generate electricity — specifically in their dispatchability versus variability — and in their capability to provide services to the system. Generation technologies relying on natural resources, such as wind and solar PV, have a variable output that cannot easily adapt to the needs of the system. Also, the quantity of power generated cannot be forecast with precision, although uncertainty diminishes as the time of delivery approaches. By contrast, all thermal power plants (using nuclear, biomass or fossil fuel) are fully dispatchable and their output can be adapted to the system's needs. Forced outages, unplanned shutdowns or restrictions in power production are infrequent events with which the system is well designed to cope. These different characteristics have an impact on the value of the electricity generated by different technologies: the value of the power generated by dispatchable sources is generally higher than that of variable renewable energy (VRE) sources (see Section 3.1). At the other end of the spectrum, some hydroelectric plants such as those employing reservoirs or pumped storage can be operated to generate power only when it is most needed by the system (subject to environmental constraints on water flows), thus maximizing the value of their limited water resources.

The so called 'capacity credit' constitutes a good example of the contribution of each technology to the overall reliability of the system. The capacity credit, often expressed as a percentage, indicates the capability of a generation unit to contribute to peak demand. A low capacity credit, or more properly a low ratio of capacity credit to load factor, indicates that a power plant is less likely to provide firm capacity in the most critical moments. In general, the capacity credit of wind and solar PV technologies is much lower than that of dispatchable power plants, and substantially lower than their load factors. In addition, the capacity credit decreases rapidly with the share of wind and PV in the generation mix, whereas the capacity credit of dispatchable plants is close to their availability factor, i.e. generally higher than 90%. Thus, a system with a high share of VRE sources still requires a large capacity from dispatchable plants to ensure that demand can be met at all times.

The second main characteristic differentiating technologies relates to their ability to provide services essential for the reliability of the power system. Such 'system services' comprise a broad array of essential services — frequency response, balancing services, voltage control and so on — needed to ensure the balance between load and generation at all times. To provide some of these services, power plants often need to operate at a power level below their maximum output to allow upward and downward power changes to correct system imbalances. All dispatchable power plants (e.g. gas, coal, nuclear and hydroelectric power plants) are capable of providing these grid services; however, in most countries, they are generally provided by hydroelectric reservoirs and by peak or mid-load generators, given their higher variable costs. In comparison, both current and emerging VRE technologies have a limited capability to provide such services.

Finally, solar PV and wind differ from other generation technologies — thermal and hydroelectric — as they are not synchronized with the grid and cannot provide inertia to the system. Lower levels of inertia exacerbate drops or spikes in frequency after an unplanned event (e.g. unexpected loss of a generator or of a large load) and therefore have an impact on the overall robustness of the power system. While this is not yet an issue in most regions at current levels of VRE penetration, it imposes a maximum limit on the non-synchronous resources instantaneously present in the system, and thus on the maximum generation share of VRE sources.

### 2.2.4. Low carbon generation technologies are increasingly competitive, but sensitive to financial risk

The economic landscape in power generation has significantly changed in the last decade. So called 'overnight costs' — i.e. construction costs excluding interest incurred during construction — have declined significantly for some technologies, notably onshore wind, concentrated solar power and solar PV. According to the International Renewable Energy Agency, installation costs for solar PV declined by a factor of four between 2010 and 2018, and those for onshore wind decreased by more than 20% [49]. The levelized cost of electricity (LCOE) — i.e. the average cost of generation over the plant lifetime — from these energy sources has declined by roughly the same proportions. A similar trend is reported by Lazard, a financial advisory and asset manager, for utility scale plants: costs have declined over the last 10 years by 20% per year for solar PV and 11% for onshore wind power [50]. While the rate at which costs are decreasing is diminishing, it remains significant — the LCOE for solar PV and onshore wind power decreased on average by 13% and 7%, respectively, per year over the past five years. Further cost reductions are expected. Over the same timeframe, the LCOE of thermal power technologies did not change significantly [51–53].

Owing to these declining costs, VRE technologies are no longer outliers in terms of LCOE [53]. In some regions, generation costs of VRE are on par with, or even lower than, those of dispatchable technologies. However, significant variations are observed owing to regional differences in construction costs, fuel prices and achievable load factors from renewables (see Fig. 8) [53]. Across different countries, electricity generation costs are generally lower in Asia, where nuclear power also generally performs better than other technologies. Very low gas prices in the United States of America (USA) tend to make CCGT the cheapest generation technology in North America. Another factor of paramount importance for determining the relative competitiveness of various technologies is the discount rate: lower discount rates favour capital intensive technologies such as nuclear and VRE technologies, whereas higher discount rates favour gas and coal plants. At a 3% discount rate, nuclear power is estimated to be the cheapest generation technology across all regions, followed by VRE sources. By contrast, at a 10% discount rate, all low carbon technologies lose competitiveness: under these conditions gas becomes the most economical alternative in North America, and coal in Asia and Europe.

However, there is a growing recognition that pure generation costs alone will play a less prominent role in future low carbon systems; the extent to which a technology can be integrated and contribute other services to the whole system will be of increasing importance (these aspects are discussed in more detail in Section 3.1).

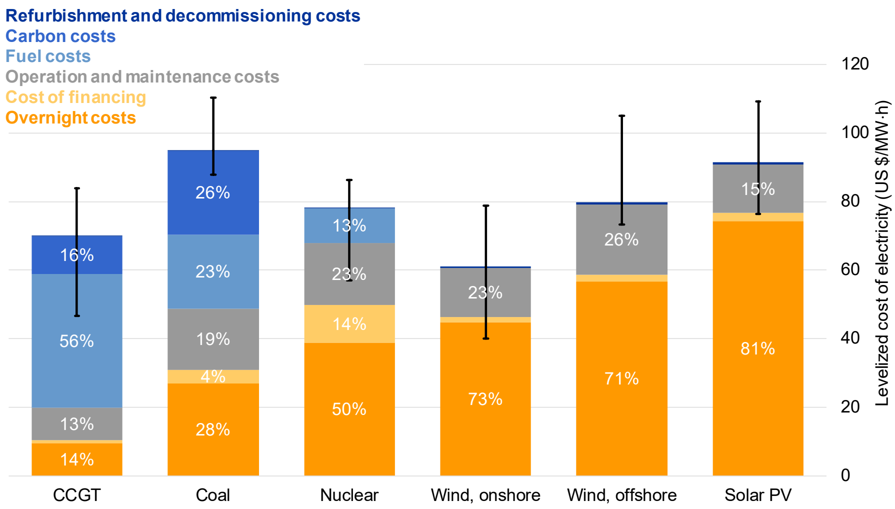


*FIG. 8. Median values for the LCOE generation for different technologies, assuming a discount rate of 7% and carbon cost of US $30/tonne, with error bars representing the first and third quartiles for the lower and upper bounds, respectively. Source: Ref. [53]. Note: MW·h — megawatt-hour.*

Other elements beyond pure generation costs have an impact on the economics of generation technologies. The cost structure of electricity generation — i.e. the time at which expenditures occur over the lifetime of the plant — has significant impacts on the financial risk of every technology and hence on their overall competitiveness. All low carbon technologies, including nuclear power, are characterized by a high proportion of overnight investment and financing costs: at a 7% real discount rate, these represent over 70% of the total costs for onshore wind generation, almost 80% for solar PV (see Fig. 8) and an even larger share for hydroelectric plants. For nuclear projects, the overnight investment costs and interest accrued during construction constitute about two thirds of the total generation costs. Most of the lifetime costs for these technologies need to be committed before the plant generates a single kilowatt-hour of electricity. In return, operation and maintenance costs are limited and almost independent of the effective generation level of the plant, while fuel costs are zero (for VRE technologies) or low (for nuclear power). The variable costs of generation for these technologies are very low (for nuclear power) or almost zero (for VRE and hydroelectric plants). The situation is reversed for fossil fuel technologies: capital costs constitute only 10–15% of lifetime generation costs for a gas plant, and roughly 30% for a coal plant. For these plants, generation costs are dominated by fuel costs (and, recently, costs applied to carbon emissions) and are therefore variable.[1]

The generation cost of capital intensive technologies is extremely sensitive to the cost of capital, as well as to the effective load factor achieved. A single percentage point increase in the cost of capital (from 7% to 8%) raises the lifetime cost of an NPP by 13%; similarly, lowering the load factor of solar PV from 15% to 14% increases its LCOE by over 7% [52]. In comparison, the generation cost of fossil fuel plants is much less sensitive to changes in the cost of capital or load factor.

In liberalized markets, VRE and nuclear technologies, with large sunk costs and very low variable costs, rely on stable electricity prices to pay back their investment costs (infra-marginal rent) and have no option to leave the market in the event of a decline in electricity prices. These technologies are therefore exposed to a much higher market risk than fossil fuel technologies. A transition to a low carbon power system will make the generation mix increasingly capital intensive and will expose investors to higher levels of market risk. New mechanisms to mitigate market risk and thus reduce the cost of capital for low carbon projects are needed to ensure that such transition occurs at a minimal cost (see Sections 3.1 and 3.3 for a more detailed discussion of these issues).

[1] Adding the equipment needed for CCS would increase the capital intensity of these technologies by adding capital costs and reducing the costs associated with carbon emissions.

Among the low carbon options described in this section, nuclear power has several valuable characteristics, including low emissions intensity and material requirements, dispatchability, the ability to provide system services, and competitive economics. Given these features, nuclear power is already widely used and has the potential to contribute further to achieving ambitious climate change mitigation goals, as discussed in the following section.

## 2.3. THE POTENTIAL OF NUCLEAR POWER FOR CLIMATE CHANGE MITIGATION

### 2.3.1. Low carbon nuclear power has slowed growth in global emissions

As outlined in Section 2.1, GHG emissions from electricity generation have grown rapidly since the 1970s. Over this period, emissions from coal and gas fired power plants — together accounting for close to 95% of direct $CO_2$ emissions from electricity generation — increased 4-fold and 6-fold, respectively. These emissions would have been higher if not for the use of low carbon nuclear power, hydroelectricity and other renewables. By avoiding the use of fossil fuels, these technologies are estimated to have reduced direct power sector $CO_2$ emissions by up to one third over the period 1971–2018. Figure 9 shows actual emissions and estimated avoided emissions from low carbon electricity generation, assuming this electricity would otherwise have been supplied using the global average fossil generation mix in each year. The lower panel shows the share of low carbon electricity generated by each source.

Throughout the period 1971–2018, hydroelectricity and nuclear power provided the vast majority of low carbon generation, with nuclear power supplying close to 50% in the 1990s. Assuming electricity from NPPs would otherwise have been supplied using the average fossil fuel mix, nuclear power is estimated to have avoided a total of 74 gigatonnes of carbon dioxide (Gt $CO_2$) over this period, equivalent to cumulative emissions from the entire power sector for the six years from 2013 to 2018. Over the same period, the estimate for hydroelectricity is 98 Gt $CO_2$ and that for other renewables is 15 Gt $CO_2$.

Over the past decade, nuclear power and hydroelectricity are estimated to have avoided annual emissions of around 2 Gt $CO_2$ and 2.5–3 Gt $CO_2$, respectively. These quantities are comparable to other estimates based on different assumptions — for example, Ref. [54] estimates avoided emissions from nuclear power of 1.7 Gt $CO_2$ for 2012, assuming that fossil fuels and additional hydroelectricity would have been used instead. The other renewables (solar, wind, geothermal and bioenergy) began to make a noticeable contribution to low carbon generation from around 2000, and in 2018 are estimated to have

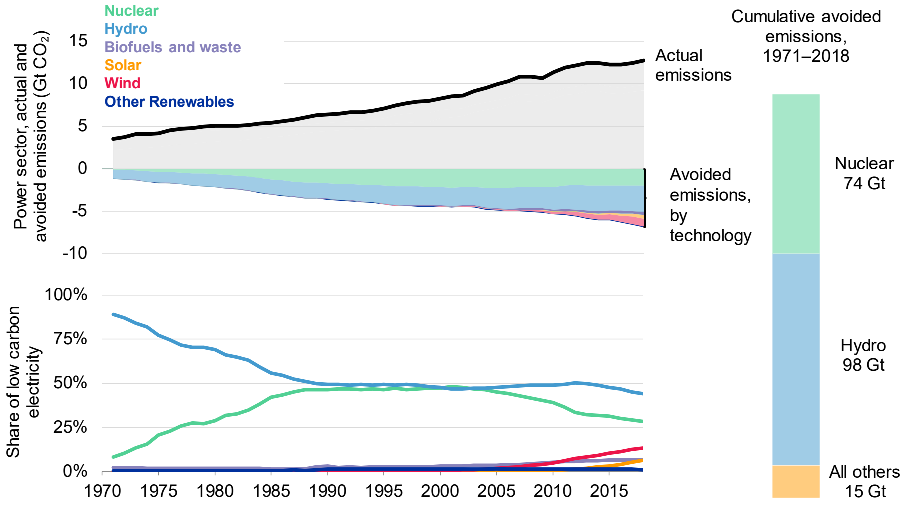


*FIG. 9. Global $CO_2$ emissions from the electricity generation, estimated emissions avoided by low carbon technologies (upper panel) and share of low carbon electricity (lower panel), 1971–2018. Source: IAEA calculations based on Refs [8, 9, 12]. Note: Gt $CO_2$ — gigatonnes of carbon dioxide.*

avoided around 0.9 Gt $CO_2$ (wind), 0.45 Gt $CO_2$ (solar) and 0.34 Gt $CO_2$ (biofuels and waste) and supplied 13%, 7% and 6% of low carbon electricity, respectively. The annual growth rate of avoided emissions from renewables since 2000 (16%) is almost identical to that of nuclear power over the period 1971–1990.

Given the need to decarbonize electricity generation worldwide by the middle of the century, as described in Section 2.1, all of these proven low carbon sources will likely need to play a substantially larger role in the future. In this context, the following section explores in detail the potential long term contribution of nuclear power.

### 2.3.2. Nuclear power can play a larger role in ambitious decarbonization

The contribution of nuclear energy to climate change mitigation over the next decades will be determined by several factors. These include the performance of the nuclear power industry itself, including continued safe and reliable operation, the implementation of plant life extensions, technological innovations, economic competitiveness and public acceptance, which are discussed in Section 4. Further, broader techno-economic developments in energy supply, distribution and demand will also have a large influence. For example, the continuation of long term electrification trends, accelerated by mitigation efforts (see Section 2.1.3), will increase the role of electricity and low carbon generation such as nuclear power. Finally, the broader economic and policy agenda — including mitigation policy — will affect the choices of different countries in favour of or against nuclear power and other energy sources.

The uncertain evolution of these factors is reflected in the wide range of estimates of nuclear electricity generation to 2050 in Fig. 10, which synthesizes over 400 recently published scenario studies including the IPCC's SR15 [2]. As discussed in Section 2.1, these include both scenarios that seek to track current developments in the energy system and scenarios describing energy pathways that achieve a specific outcome. Owing to the large number of scenarios, only the IPCC's four illustrative 1.5°C pathways (P1–P4) are explicitly indicated in Fig. 10, while overall ranges are given for others, with details reported elsewhere [57]. To compare the scenarios in relation to climate change mitigation goals, Fig. 10 also plots energy related $CO_2$ emissions and nuclear electricity generation for the single year 2050 — each of the 400-plus scenarios is indicated by a circle coloured according to the level of mitigation. An increasing role for nuclear power compared with 2018 (also shown) is seen across many of the scenarios, particularly in those with lower $CO_2$ emissions that achieve more stringent mitigation targets. For instance, in IPCC pathways compatible with 1.5°C, nuclear generation averages 7.9 PW·h in 2050 (equivalent to a tripling from 2018).

Figure 10 also shows the latest IAEA low and high projections of nuclear electricity generation to 2050, which are derived from a bottom-up project by project assessment [10]. The low case applies relatively conservative assumptions on the continuation of current market and policy trends, which are relaxed to some degree in the high case. In comparison, higher levels of nuclear generation are seen in other scenarios, many of which limit warming to 1.5°C or 2°C, including the IPCC's four illustrative pathways, implying significant additional market and policy action beyond the current trends reflected in the IAEA projections. Achieving such high levels of nuclear power deployment is likely to require a rapid expansion of global supply chains, human capital and physical infrastructure, as discussed in Section 4 (see also Ref. [58]).

### 2.3.3. Unlocking nuclear power's potential: Insights from 1.5°C pathways

To explore further the mitigation potential of nuclear power in future low carbon energy systems, this section dives deeper into the scenarios of the IPCC's SR15, focusing on insights from the four illustrative 1.5°C pathways (P1–P4). These were selected by the IPCC from a set of 90 pathways compatible with 1.5°C which collectively highlight several key developments to limit global warming to below this target, including rapid decarbonization of the energy

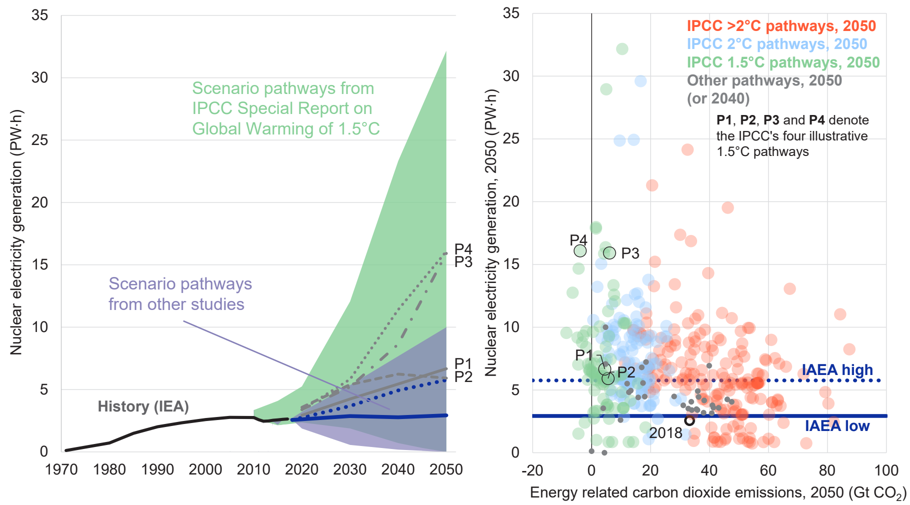


*FIG. 10. Global nuclear electricity generation and $CO_2$ emissions under different scenarios. Source: Refs [9, 10, 12, 27, 28, 33–45, 55, 56]. Note: P1, P2, P3 and P4 denote the IPCC's four illustrative 1.5°C pathways [2] and IAEA high and IAEA low indicate the IAEA's projections [10]; in the right panel, each circle represents a different scenario in 2050; for studies that analyse a shorter time horizon (such as Refs [12] and [41]), scenario data for 2040 are presented.*

sector (see Fig. 3), a substantial increase in electrification (see Fig. 4), major shifts in investment, and the need to align with sustainable development [2]. As mentioned, these pathways were designed to explore energy system developments compatible with 1.5°C — i.e. 'where do we need to go?' — rather than current trends, which are tracking towards a higher temperature range (Section 2.1.2).

While all four illustrative pathways incorporate stringent mitigation policies, with global carbon prices of US $160–700 per tonne (t) $CO_2$ in 2050 (see also Section 3.3), they assume different patterns of socioeconomic development and encompass different strategies to limit warming to 1.5°C. In the case of nuclear electricity generation, the four pathways report an increase from 2.6 PW·h in 2018 to between 5.9 PW·h and 16.1 PW·h by 2050, as seen above in Fig. 10, equating to between 9 and 25% of global electricity generation in 2050. The associated contribution to mitigation of nuclear power and other options in 2050 is estimated for each pathway in Fig. 11, with the trajectory from 2010 to 2050 illustrated for P3. Efficiency, electrification and other fuel switching feature prominently in all pathways, accounting for almost 45% of abatement in 2050 in P3 (relative to a consistent baseline pathway as described in the notes to Fig. 11). On the supply side, nuclear power and CCS contribute around 15%

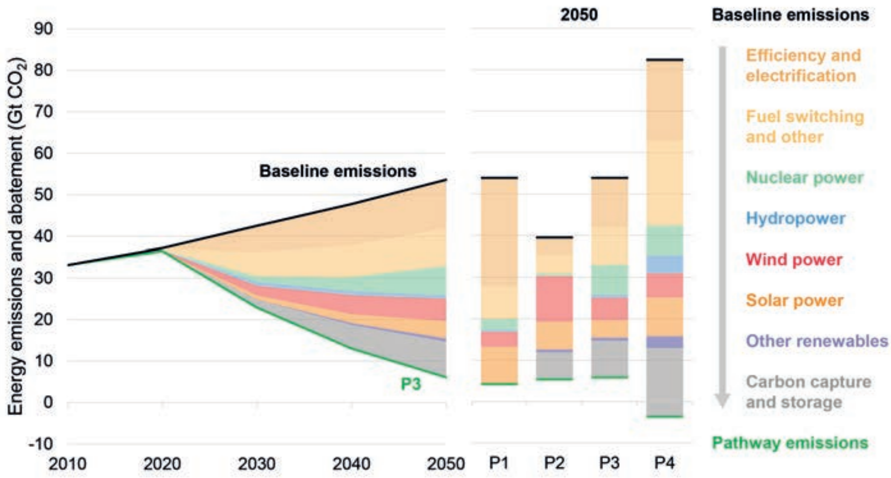


*FIG. 11. Energy related $CO_2$ emissions and abatement in the IPCC illustrative pathways. Source: IAEA estimates based on Refs [2, 27–30, 59–61]. Note: abatement is calculated relative to consistent baseline scenarios of global socioeconomic development quantified with the same methodologies; see also Appendix.*

each to abatement in P3, followed by wind (11%) and solar (9%). While the other pathways incorporate different supply strategies, all reflect historical experience that successful electricity sector decarbonization — which is replicable across countries independent of resource endowments — combines nuclear power and other low carbon energy sources [62]. Nuclear power is estimated to contribute around 7.2 Gt $CO_2$ of abatement in P3 in 2050 (and 2.7, 0.6 and 7.1 Gt $CO_2$ in P1, P2 and P4, respectively) compared with total abatement of 33–86 Gt $CO_2$. Notably, nuclear power's contribution to abatement in P2 is small partly because it already plays an expanded role in the corresponding baseline pathway.

Some of the key factors influencing the role of nuclear energy in each pathway are summarized in Table 1. These include assumptions related to the cost and public acceptance of nuclear power and other low carbon energy technologies, and the extent to which the pathway methodology represents challenges associated with the integration of VRE sources and innovative nuclear applications and technologies. The two illustrative 1.5°C pathways with lower nuclear deployment (P1, P2) assume either very low capital costs for renewable technologies (P1) or low public acceptance of nuclear power (P2), while challenges associated with the integration of VRE sources are also not represented in detail in P2. In pathways with higher nuclear deployment (P3, P4), moderate levels of public acceptance for nuclear power and a conservative trajectory for renewable capital costs are assumed, while the need for increased generation flexibility, backup capacity, storage and/or curtailment to accommodate VRE generation is considered. In all four pathways, nuclear power capital costs are assumed to be relatively moderate (US $2600–4000 per kilowatt (kW)), while advanced technologies are generally excluded (except implicitly for P1) and non-electric applications of nuclear energy are represented to varying degrees.

TABLE 1. IPCC ILLUSTRATIVE 1.5°C PATHWAYS: ASSUMPTIONS, METHODOLOGIES AND KEY FINDINGS FOR NUCLEAR POWER
*Source: Refs. [2, 12, 27–30, 59–61]*

| | | Illustrative IPCC 1.5°C pathway | | | |
|---|---|---|---|---|---|
| | | P1 | P2 | P3 | P4 |
| Overall pathway narrative | | Low energy demand | Green growth sustain-ability | Middle-of-the-road, in line with historical patterns | Rapid development, high demand |
| Methodology scope and detail | Overall energy technology detail | High | Low | High | Med./High |
| | Nuclear technology detail | Medium | Low | Medium | Low/Med. |
| | Representation of VRE grid integration | Implicit | No | Implicit | Explicit |

TABLE 1. IPCC ILLUSTRATIVE 1.5°C PATHWAYS: ASSUMPTIONS, METHODOLOGIES AND KEY FINDINGS FOR NUCLEAR POWER
*Source: Refs. [2, 12, 27–30, 59–61]* (cont.)

| | | Illustrative IPCC 1.5°C pathway | | | |
|---|---|---|---|---|---|
| | | P1 | P2 | P3 | P4 |
| Overall pathway narrative | | Low energy demand | Green growth sustain-ability | Middle-of-the-road, in line with historical patterns | Rapid development, high demand |
| Technology assumptions | Nuclear capital cost | Low/ Med. | Medium | Medium | Medium |
| | Public acceptance of nuclear power | NR | Low | NR | Medium |
| | Renewable capital cost | Low/ Med. | High | High | High |
| | Other nuclear relevant technology assumptions | Modular NPPs, no CCS | High RE prefer-ence | Increasing NPP load factor | Unlimited uranium supply |
| Role of nuclear | Generation, 2050 (PW·h) | 6.7 | 5.9 | 15.9 | 16.1 |
| | Generation share, 2050 (%) | 13 | 9 | 25 | 23 |
| | Mitigation, 2050 (Gt $CO_2$) | 2.7 | 0.6 | 7.2 | 7.1 |

**Note:** Coloured shading indicates expected influence on the role of nuclear power in pathway (green = positive; yellow = neutral; red = negative); mitigation in 2050 is estimated relative to consistent baseline scenarios of global socioeconomic development, quantified with the same methodologies. RE — renewable energy; NR — not reported; Med. — medium. See Appendix for additional detail.

In sum, the characteristics and assumptions of the four IPCC illustrative pathways highlight several potentially important factors for capitalizing on nuclear power's mitigation potential, which are examined further in Sections 3 and 4:

- — A strong mitigation target, and related consistent policy signals including access to climate finance (see Sections 3.3 and 3.4);
- — Control of nuclear costs and, implicitly, access to finance (see Section 4.1);
- — A moderate degree of social acceptance (see Section 4.4);
- — Recognition of the value of nuclear power to the stable operation and management of the electricity system/grid (see Section 3.1).

Before turning to these in detail in the next sections, Section 2.4 concludes the discussion of the role of nuclear power with an outline of the current status and trends in deployment, including current projects, national plans to adopt nuclear power and the representation of nuclear power in national mitigation policies as reflected in NDCs.

## 2.4. NUCLEAR POWER: THE STATE OF PLAY

The majority of long term energy pathways discussed in Section 2.3 foresee an expansion of nuclear power over the next decades. The substantial increase in the role of nuclear power in the four IPCC 1.5°C pathways (in which installed nuclear capacity reaches 960–2300 gigawatts (GW) in 2050 from around 400 GW today) is driven notably by increased awareness of climate change and the threat it poses to the global environment, economy and living standards, as well as the proven profile of nuclear as a low carbon energy technology.

### 2.4.1. Global trends in the nuclear fleet provide a base for scaling up action

Recent trends in nuclear development provide useful indications on whether and how a rapid and large scale expansion of the nuclear industry could be realized (by 2050 and beyond). During the period 1999–2019, the number of reactors in operation worldwide rose modestly from 432 to 447, i.e. by 3.5% (Fig. 12). However, total net electrical capacity increased by 14% — from 347 GW to 396 GW — as newer reactors with higher electrical capacities were connected and older, smaller units were permanently shut down (see the lower panel of Fig. 12). Despite this moderate growth, the average increase of 0.7% per year achieved during the past two decades is around four times lower than the rate implied by many mitigation pathways for the period to 2050 described above. As an example, achieving 960 GW of nuclear capacity by 2050, at the lower end of the range in the IPCC's four illustrative 1.5°C pathways, implies an average capacity increase per year of around 2.8%. These growth rates have been achieved in the past in some countries, and are within reach today if appropriate signals are given to the global nuclear industry [58].

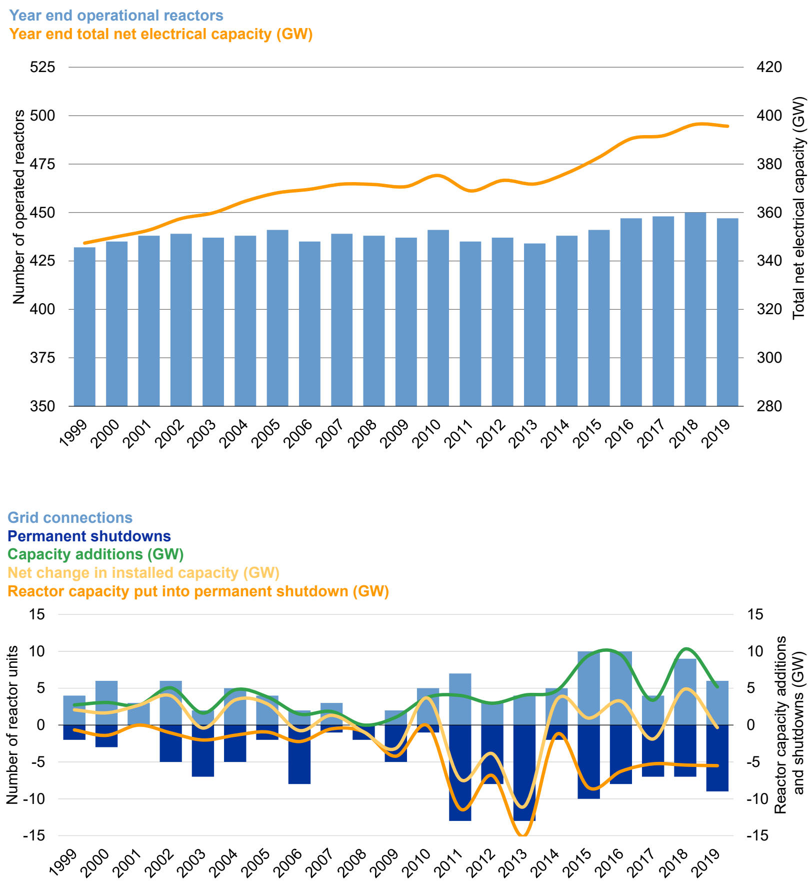


*FIG. 12. Upper panel: year end operational reactors globally (left axis, columns) and year end total net electrical capacity in GW (right axis, line), 1999–2019. Lower panel: number of reactors connected to the grid and reactors permanently shut down (left axis, columns) and total capacity, 1999–2019. Source: Ref. [63]. Note: These figures refer to reactors in operation at the end of the year and include 33 operable reactors in Japan, which were not all on-line in 2019 [63]. Data entries for 2019 are estimates.*

Maintaining current nuclear capacity over the coming decades will require a significant number of nuclear new builds and extended operation of existing reactors (the concept of long term operation (LTO) is discussed in detail in Section 4.2). This is before any further construction of the new reactors necessary to expand global installed nuclear capacity. The evolving economic performance of future NPPs and other technological advancements will determine the characteristics of these new builds.

Finally, a further consideration is scaling up and securing the long term supply of uranium (or other fuels, potentially including thorium). Regular reviews of global uranium resource estimates by the IAEA and OECD Nuclear Energy Agency [64] indicate that resources are abundant relative to current levels of demand. However, as with other mineral resources, these estimates depend on exploration practices, which are driven largely by market developments: if market prices increase owing to rising demand or tighter supply, exploration efforts increase and additional resources are identified. Furthermore, there exists a large potential to extend the lifetime of resources by increasing the efficiency of uranium use with fast reactor technologies.

### 2.4.2. Many countries are constructing and planning new nuclear power plants

At the end of 2019, 52 reactors were under construction in 19 countries, accounting for 54.7 GW of net electrical capacity — over 13% of total current global nuclear capacity (Figs 13 and 14). These reactors are expected to enter service by the end of the 2020s, given construction times of at least five to seven years. This time lag between the decision to construct an NPP and the start of operation is a feature of NPP projects, even for countries with advanced nuclear programmes.

The 19 countries that were developing nuclear projects at the end of 2019 are distinguished by their level of economic development and face different social and economic challenges. Several countries with growing populations and rapidly increasing electricity needs, such as China and India (who have, respectively, 10 and 7 reactors under construction), see nuclear power as a reliable source of energy that can fuel economic expansion, provide electricity services for underserved communities and improve living standards. By displacing coal based power generation and heating, expanded use of nuclear power is also welcomed for its contribution to improving local air quality, particularly around rapidly urbanizing areas.

Similar circumstances are seen in many countries constructing their first NPPs — for example, in Bangladesh, Belarus, Turkey and the United Arab Emirates, which are in some cases building multiple reactors. The total

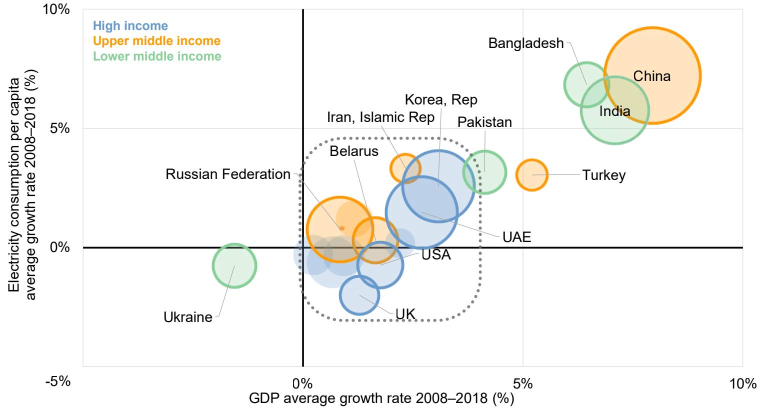


*FIG. 13. Average growth rates of GDP and electricity consumption per capita in 2008–2018, and total net electrical capacity of reactors under construction by country in 2020 (represented by bubble size). Sources: Refs [9, 31, 64, 65]. Note: for the Islamic Republic of Iran, the average GDP growth rate for 2008–2017 is presented, and for Bangladesh and Belarus, the average electricity consumption per capita growth rate for 2008–2017 is presented. The area surrounded by the dotted line is shown in Fig. 14. GDP — gross domestic product; UAE — United Arab Emirates.*

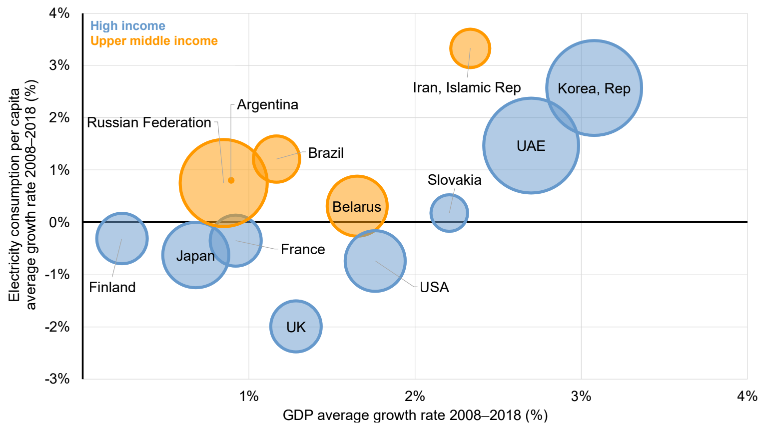


*FIG. 14. Detail of the area surrounded by the dotted line in Fig. 13: average growth rates of GDP and electricity consumption per capita in 2008–2018, and total net electrical capacity of reactors under construction by country in 2020 (represented by bubble size). Sources: Refs [9, 31, 64, 65]. Note: for the Islamic Republic of Iran, the average GDP growth rate for 2008–2017 is presented, and for Belarus, the average electricity consumption per capita growth rate for 2008–2017 is presented. For Argentina (smaller dot) the Central Argentina de Elementos Modulares (CAREM) small modular reactor (SMR) with 25 megawatts (MW) net electrical capacity is indicated; GDP — gross domestic product; UAE — United Arab Emirates.*

capacity of reactors under construction in these countries amounts to 10.9 GW, or around 20% of total construction. Developments in these ‘newcomer’ countries are likely to play an increasingly significant role in the nuclear landscape over the next decades. However, unlike Member States with established nuclear power programmes, these countries generally face longer lead times to establish the supporting infrastructure, technical expertise and institutions. These are among the areas of support covered by the IAEA Milestones approach for development of a nuclear programme, which is available to both newcomers and countries with established programmes [66]. Securing the financing for nuclear power deployment is another key challenge covered by this approach (see also Section 4.1).

Another group of countries constructing NPPs consists of relatively higher income industrialized nations with established nuclear programmes, but with slower economic growth and stagnant (or declining) per capita electricity needs (Fig. 14). In most cases, decreasing per capita electricity consumption is a result of structural changes in these economies and significant improvements in energy efficiency. Despite this trend towards lower consumption, which is most pronounced in the United Kingdom, new NPPs remain an attractive option to replace ageing reactor units and to secure stable, predictable electricity supplies for the long term (current reactor designs are expected to serve for at least 60 years). Nonetheless, despite mature nuclear industries in many of these countries, limited recent experience in new projects has created challenges to NPP deployment (Section 4.1).

Beyond the 52 units under construction, additional reactors are proposed or planned across several countries, although it is uncertain how many projects will eventually materialize. The IAEA regularly conducts a project by project assessment of plausible constructions to 2050 in the preparation of low and high projections of nuclear electricity generation [10], as discussed in Section 2.3. Gross additions to 2050 range from 250 GW (low) to 501 GW (high) based on alternative assumptions on driving factors and current market and policy trends (noting that these projections are not intended to cover the entire feasible range).

### 2.4.3. Nuclear power is increasingly recognized in national climate plans

While current trends and the plans outlined above are insufficient to achieve the level of installed nuclear capacity seen in many 1.5°C pathways, countries are increasingly recognizing the potential of nuclear power in climate policy, creating an opportunity to better align deployment trends with mitigation goals. For example, several countries across emerging and advanced economies have signalled their plans to utilize nuclear power in their NDCs under the Paris Agreement, as illustrated in Fig. 15. These range from general plans to use nuclear power to quantitative deployment targets and timeframes. Notably, only 6 of the 30 countries operating NPPs in 2019 list nuclear power in their NDCs: China, India, the Islamic Republic of Iran (in its intended NDC), Japan, the Republic of Korea and Pakistan.

Crucially, as noted in Section 2.1, current plans in NDCs are not sufficient to meet the goal of limiting the increase in average global temperature to well below 2°C or 1.5°C, and countries will need to commit to more ambitious action in their updated 2020 and future NDC submissions. Given the mitigation potential described in Section 2.3, nuclear power can enable such action. It is significant in this context that the 37 countries using nuclear power today or planning to use nuclear power as reported in their NDCs represent almost 80% of global energy related $CO_2$ emissions, along with more than 75% of emissions growth from 2000 to 2017 [8]. These countries have (or are acquiring) the capacity, in terms of infrastructure and experience, to ramp up nuclear power as part of more ambitious NDCs on a scale that can make a significant difference to global emissions. Over the medium term, the adoption of nuclear power by additional countries, particularly emerging economies that will drive a greater share of future emissions growth, can support broader climate mitigation action globally while enabling these countries to transition directly onto low carbon industrialization pathways.

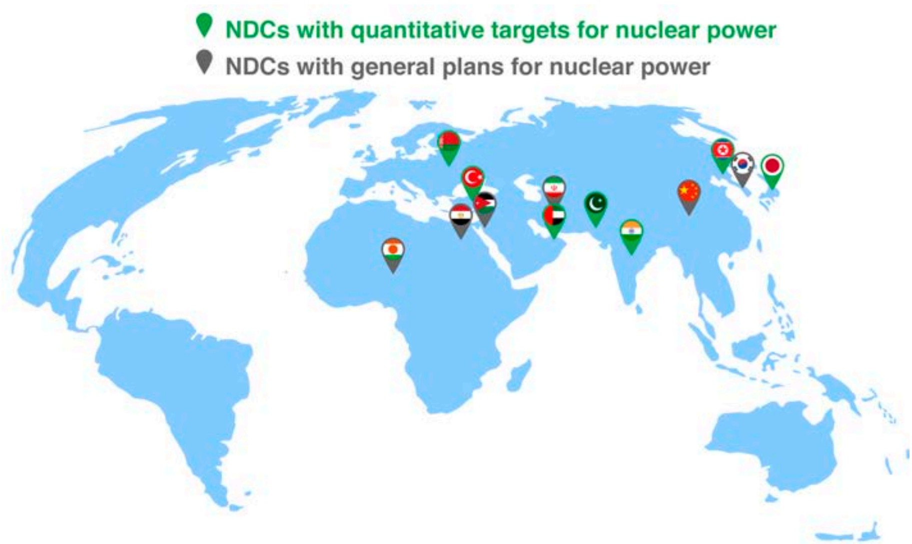


*FIG. 15. Countries including nuclear power in their first NDCs. Source: Ref. [67]. Note: Unlike other countries shown in this figure, the Republic of Korea's NDC indicates that "there are now limits to the extent that [the Republic of Korea] can make use of nuclear energy" [68].*

Nonetheless, realigning current trends in nuclear power deployment towards a rapid and large scale expansion poses several challenges, including the need to scale up supply chains, improve the competitiveness of nuclear new build projects and secure finance, among others. On the other hand, nuclear power has the potential to provide additional benefits to support the realization and operation of decarbonized energy systems — beyond providing low carbon power. These aspects are further elaborated in Sections 3 and 4.

## 3. LOW CARBON ENERGY SYSTEMS

The transition towards the low carbon power and energy systems required to meet the objectives of the Paris Agreement represents an urgent and immense challenge for all countries, as seen in Section 2. It goes well beyond simply substituting carbon intensive technologies and processes with ‘equivalent’ low carbon technologies and processes, instead requiring a radical transformation of how power and energy services are produced, provided and used. At the same time, the energy sector needs to adapt and respond to a changing climate with more extreme conditions.

The power system is already evolving towards a larger, more complex and more integrated system, with tighter coupling between the transport and energy sectors. Achieving a low carbon and climate proof power system will further accelerate this process. This has important implications not only from a technical or engineering perspective, but also for the economic and social dimensions. Also, achieving such a fundamental transformation cost effectively requires the adoption of specific and well designed policies and financial instruments.

This section focuses primarily on the characteristics of a decarbonized power system as well as on the policy options and financial instruments that could facilitate such a transition. Broader implications for other parts of the energy sector are also discussed in Section 3.2.

## 3.1. INTEGRATING LOW CARBON TECHNOLOGIES IN THE POWER SYSTEM

### 3.1.1. A mix of technologies can ensure a reliable and competitive low carbon electricity system

A decarbonized electricity system requires low carbon generation options. While different pathways and technology mixes are compatible with achieving the 1.5°C goal (as seen in Section 2.3), all low carbon scenarios rely mostly on two pillars: (1) a sizeable share of renewable resources, mostly hydroelectric power and VRE sources such as wind and solar PV; and (2) dispatchable low carbon technologies such as nuclear power, fossil fuels with CCS or both. However, owing to their specific characteristics outlined in Section 2.2, integrating significant shares of VRE generation into a low carbon power system poses specific and new challenges, on both technical and economic grounds, that need to be addressed by policy makers pursuing ambitious climate targets.[2]

Flexibility will be a cornerstone of future power systems. Future flexibility needs are likely to go well beyond the levels demanded by today's power systems and will need to increase significantly with the share of VRE sources in the generation mix. An analysis of the residual demand, i.e. the difference between total electricity demand and generation from low variable cost renewable energy sources, provides a good illustration of the flexibility challenge in future decarbonized power systems (see Fig. 16, which compares demand and residual demand at two illustrative VRE generation shares). With growing shares of VRE, the residual demand becomes increasingly volatile, with increased amplitudes of load variations and more frequent and steeper ramps. The residual demand also becomes more unpredictable, being determined more by the uncertain generation from VRE sources than by changes in demand. It also becomes decoupled from well known daily, weekly and seasonal patterns. This has important impacts on the operation of individual power plants and the system as a whole, including on its reliability and the requirements for flexibility.

A low carbon system will require much higher flexibility levels over a wide time range. Short term flexibility, from milliseconds to hours, will be needed to ensure the demand–supply equilibrium in response to much steeper ramp rates in the residual demand. Medium term flexibility, from hours to days, will be needed to compensate for the cyclical production profile of wind and solar resources.

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[2] While the optimal power generation mix and the challenges associated with the integration of VRE are strongly dependent on the characteristics of the electricity system (which vary from country to country), along with the availability and cost of storage and of other flexibility technologies as well as potential synergies with the broader energy sector, the trends and phenomena described in Section 3.1.1 are common to all systems.

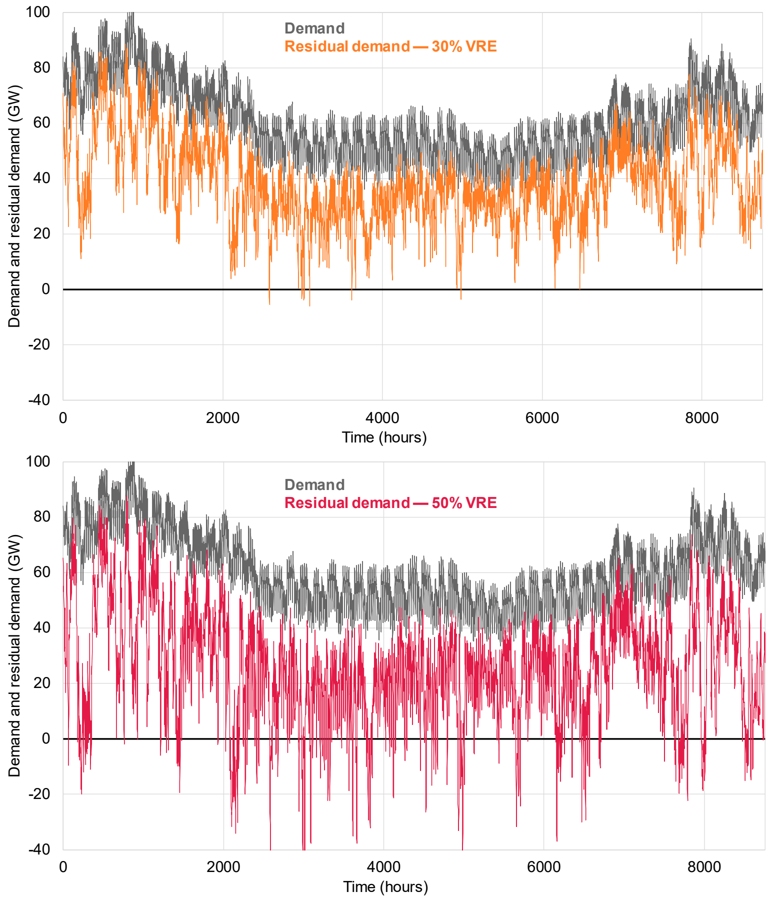


*FIG. 16. Illustrative residual electricity demand over a year (8760 hours) for different VRE shares. Source: based on Ref. [69].*

Additional long term flexibility needs will emerge, particularly with high VRE shares, for large seasonal storage capacity given that generation from renewable sources alone could reach or exceed total demand over extended periods of time. All existing and new sources of flexibility will be needed with a substantial increase from current levels, including interconnections with other networks, existing and new storage technologies, demand-side measures and flexibility from thermal and renewable power plants. Increased coupling with the broader energy sector could also increase the flexibility of the system, in particular by providing seasonal storage.

Increasing shares of variable generation in the power system will also impact the optimal structure and operation of thermal, dispatchable power plants, with a shift from baseload to mid-merit and peaking plants. Such power systems will need to value (and reward) the ability of generators to provide firm capacity, flexibility and other system services rather than pure electricity generation. All thermal power plants will likely experience a decline in the achievable load factors and a strong increase in the requirements for load following and flexibility provision.

The combination of a more variable and unpredictable load increases the difficulties (and costs) of ensuring the equilibrium between supply and demand. If not appropriately addressed, this could have adverse consequences on the reliability and overall adequacy of the electricity system. The experience gained in many countries in dealing with a more variable system and the adaptation of the power market to ensure a more effective provision of flexibility services have ensured, so far, an efficient and smooth operation of power grids in most circumstances. However, there have been a few occurrences of blackouts in developed countries: Box 1 below describes the example of the 2019 United Kingdom blackout.

**BOX 1. UNITED KINGDOM BLACKOUT OF 9 AUGUST 2019**

A recent blackout in the United Kingdom, which left more than one million electricity customers without power for (up to) 45 minutes, highlights the need for more flexibility in energy systems. On the late afternoon of Friday, 9 August 2019, Great Britain's electricity system was operating normally, with 30% of the electricity produced from wind, 30% from gas, 20% from nuclear, 10% from network interconnectors and 10% from other sources. Following a lightning strike, electricity output at the Hornsea offshore windfarm and Little Barford gas power station dropped by a total of 1378 MW. Around the same time, there was a loss of approximately 500 MW of embedded generation. These unexpected losses of generation led to a rapid deviation in system frequency outside the normal range of 49.5–50.5 hertz (Hz). While the system operator had 1000 MW of automatic backup power including 472 MW of battery storage available at the time of the event, it could not prevent the frequency from falling to 48.8 Hz. Secondary backup systems then kicked in, disconnecting 5% of Great Britain's electricity demand to protect the remaining system [70]. This resulted in major disruption to parts of the rail network, impacting thousands of passengers, and to a number of critical facilities including a hospital and an airport. While it is unlikely that higher shares of variable generation directly caused the blackout, the need for additional flexible capacity for the transition towards a low carbon energy system became increasingly accepted in its aftermath. Notably, the UK ranks next to last out of nine major European countries for power system flexibility [71].

The value of VRE resources to the power system, and hence the remuneration received from wholesale electricity markets, declines significantly and non-linearly as their share in the power mix increases (see Fig. 17). In fact, each additional unit of solar PV or wind generation installed will reduce the value and market remuneration of all other plants of the same type present in the system. This occurs primarily because the output of VRE plants of the same type, in the same location or nearby, is strongly correlated. The effect is more pronounced for solar PV than for wind, since output of PV is concentrated over a few hours of the day, and less pronounced if generators are more spatially dispersed. Also, it depends significantly on the system considered: a large and well interconnected system, with abundant and cheap flexibility resources will experience a much smoother decline in the value of VRE generation as its share in the system increases compared with a smaller and more inflexible system. The decline in the value of VRE generation imposes an intrinsic limit on the integration of these technologies in any given system and has an impact on the optimal composition of the generation mix. The future share of VRE sources will depend on a complex interplay of different factors: their generation costs relative to other low carbon technologies (see Section 2.2), the availability and cost of flexibility options, and the extent to which the power system is both integrated with the broader energy sector and interconnected with those of neighbouring regions.

As discussed in Section 2.2, all low carbon generation sources (apart from biomass) have a similar economic structure, dominated by fixed costs from investment and operation and maintenance, and with a very low share of

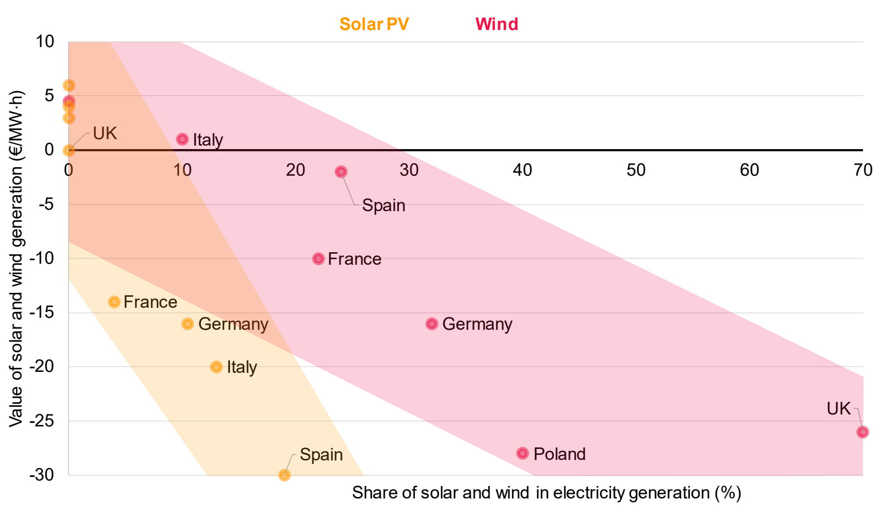


*FIG. 17. Value of VRE generation with electricity mix share. Source: Ref. [72].*

variable costs. All other components of a low carbon system, such as energy efficiency, storage resources, interconnections as well as demand-side measures, also generally share similar economic characteristics. A low carbon system is therefore expected to be much more capital intensive than current systems in many countries, regardless of the mix of technologies adopted. While the variable costs represent over 40% of the total lifetime costs in the current generation mix in OECD countries, a mix with a carbon intensity of 50 g $CO_2$/kW·h (compared with 476 g $CO_2$/kW·h globally in 2018) would see this share reduced to 5–20%, depending on the technologies adopted [12, 69]. Achieving more ambitious carbon reduction targets will likely reduce those values even further. High capital cost and the reliance on technologies with near zero variable costs has important implications for the level and volatility of wholesale electricity prices and thus on the revenue risk for investors in generation capacity.

An important phenomenon in electricity systems with high shares of low carbon generation is the prevalence of very low or even negative wholesale electricity prices, together with an increased frequency of high or very high electricity prices. The frequency of these occurrences is directly linked with the share of variable renewables in the system: at 30% VRE share, zero prices are observed less than 1% of the time, while they occur roughly 15% of the time with a 50% VRE share. A low carbon system dominated by VRE sources would experience zero or potentially negative electricity prices for more than 40% of the time [69]. In addition, especially in systems with large shares of hydroelectric and wind power, electricity prices (and revenues for the plant owners) may fluctuate substantially year on year, depending on annual weather patterns (low electricity prices in windy and wet years and high prices in calm and dry years). Electricity market price volatility significantly increases the risks for all generation technologies, but especially affects investments in capital intensive technologies, i.e. the very investments needed for the transition towards a low carbon system.

A discussion is emerging among policy makers, regulators and system operators regarding the extent to which deregulated electricity markets can deliver a transition to a low carbon power system, while ensuring adequate security of supply and sufficient coordination of investment in network and generation capacities. The experience in deregulated European markets in 2017 was that only 60% of the total costs of generation were covered by market revenues, compared with 80% in 2010. This figure is projected to decrease to 50% in 2025 in the absence of a strong carbon price or other reforms [73]. Consequently, in much of Europe virtually no investments in low carbon generation capacities have been made on a purely market basis in the last decade.

Most likely, a future low carbon system will include a diversity of low carbon resources working in synergy. Attracting the investments needed for the transition to such a system will be challenging. Policies and effective market design should be put in place to ensure that: (a) generators are generally able to recuperate their full costs in a normally functioning market; (b) a level playing field is created among low carbon technologies; and (c) technologies contributing to the security of electricity supply are effectively remunerated for the services provided to the system (see Section 3.3 for further details). As mentioned, among the services needed for supply security and reliability, generation flexibility will become increasingly important. Dispatchable options, including nuclear power, will be needed to provide these services, supporting other low carbon options, as outlined below.

### 3.1.2. Flexible operation of nuclear power plants is valuable in a low carbon electricity system

With high upfront capital costs and relatively low operating costs, the majority of existing NPPs are optimized to operate in 'baseload' mode at steady full power. This mode of operation generally maximizes market revenues for the plant operator. Increasing deployment of intermittent renewables, however, puts conventional dispatchable producers including NPPs under pressure to adjust their output to accommodate temporal variations in VRE generation.

An increasing number of NPP operators in several Member States have implemented (or are in the process of implementing) procedures to operate their plants flexibly. The technical impacts of flexibility on the design and operation of NPPs are largely known and technical solutions have been developed. Experience in France and Germany has demonstrated the technical capability of reactors to handle load variations [74]. In France, for example, NPPs are routinely ramped up and down between 100% and 20% of nominal power twice per day. The total nominal flexible capacity of nuclear units in France is reported to be 15 000 MW, which is sufficient to balance VRE intermittency until 2030 [75].

Information on the costs of flexible operation in NPPs is not readily available [74, 76]. Introducing nuclear flexibility will most likely increase operational and maintenance costs at plants and may also increase occurrences of planned (and possibly unplanned) outages. Several factors — such as age, vintage, design, maintenance activities and operational history — will affect the plant level costs of flexible operation. The frequency and the intensity (rate of change and magnitude of change) of flexibility requirements are further cost related factors to be considered.

Flexible operation of NPPs has been proven successful by several operators, actively contributing to the integration of VRE sources in some jurisdictions. Conversely, the phase out of nuclear power in Germany by 2022 is likely to significantly increase the costs of managing variability [77]. However, in the absence of specific market arrangements that remunerate flexibility services, plant owners and operators may face a decrease in revenues when compared with baseload operation. Therefore, increasing and capitalizing on the flexibility of nuclear generation will require new regulatory practices to value and compensate for the provision of flexibility services. Depending on the market design, the revenue for flexible operation may vary significantly. Today, flexibility market revenues are an order (or orders) of magnitude lower than energy market revenues. Some grid services — for example, reactive power[3] or black start[4] — are barely rewarded. This raises the question of how to adequately reward baseload units for provision of flexibility services to ensure market arrangements provide enough incentives to allocate the additional costs associated with flexible operation.

Assuming suitable market incentives, flexibility services from NPPs can help realize a cost effective and reliable low carbon electricity system, including by complementing and supporting the deployment of VRE technologies. However, while a decarbonized electricity system will be central in achieving ambitious climate change mitigation, reducing emissions from other energy uses, with other low carbon energy carriers, is also critical.

## 3.2. BEYOND ELECTRICITY: HYDROGEN AND OTHER ENERGY CARRIERS

### 3.2.1. Other low carbon energy carriers will complement electricity in full decarbonization

In 2018, around 415 EJ of final energy was consumed across all sectors in the global economy, of which less than one fifth was electricity [9, 12]. As elaborated in Section 2.1, energy is the largest source of GHG emissions, with electricity a key driver of emissions through economic and population growth and increasing rates of electrification. While several previous sections have explored opportunities to realize a low carbon electricity system, two sectors stand out in terms of both their overall energy consumption and their more limited capacity to electrify (and thereby decarbonize), namely, industry and transport, which account for almost 60% of global energy demand [78] and are responsible for 30% of global GHG emissions [2].

A more detailed view shows that while the industrial sector accounts for over 40% of overall electricity consumption, electricity supplies only 28% of the

[3] Reactive power refers to electricity that is generated or absorbed in order to maintain a constant voltage level.

[4] Black start refers to restarting a power station through a dedicated auxiliary power source without relying on the external power transmission network.

total energy used globally by industry, with fossil fuels dominating in applications requiring process heat [9, 12]. Transport accounts for an even smaller share (2%) of total electricity consumption, or 58 terawatt-hours (TW·h), in 2018. Several studies estimate that the deployment of electrical vehicles could result in substantial electrification of passenger road transport (for example, Ref. [79]). However, electrification options are considered to be more limited in the medium term for air transport, shipping and heavy road transport.

To decarbonize industry and transport, beyond those processes and subsectors that are more suited to electrification, energy solutions will be needed that can provide low carbon process heat and alternative energy carriers such as hydrogen to replace the direct use of fossil fuels. Such developments are reflected in the four illustrative 1.5°C pathways of the IPCC [2], which report a combined share of electricity, heat and hydrogen of between 50% and 70% of global final energy use by 2050, up from around 20% in 2018 (Fig. 18). While direct use of hydrogen accounts for an average of 5% of 2050 global energy demand in these pathways, it can also be used to produce synthetic natural gas and liquids, which account for much of the remaining energy demand.

As with electricity, the potential of hydrogen and heat for decarbonization lies in the use of low carbon energy sources; however, currently both rely heavily on fossil fuels, with hydrogen produced through steam reforming of methane. Nuclear power is well suited to provide both heat and electricity, serving industrial processes as well as residential applications. It also has the potential to provide hydrogen for other applications and subsectors that are less suitable for electrification, as discussed further in Section 3.2.2.

### 3.2.2. Nuclear power can be used for large scale production of low carbon hydrogen

Hydrogen has recently been a focus of many government initiatives, programmes and plans, including in France and Japan, and of global organizations and partnerships, such as the Clean Energy Ministerial [80–82]. It is considered an effective vector for decarbonization in sectors such as steelmaking, heavy transport and residential heating, some of which have proven difficult to electrify [83]. It also offers the possibility to store surplus electricity on a large scale and for long periods of time with only limited energy losses, as shown in Fig. 19, providing another means to manage some of the challenges of low carbon electricity systems outlined in Section 3.1, in particular for coping with seasonal imbalances in power demand and supply. Producing hydrogen during periods of excess electricity generation, and using hydrogen to generate electricity during periods of scarcity, can enable higher shares of VRE generation and full load

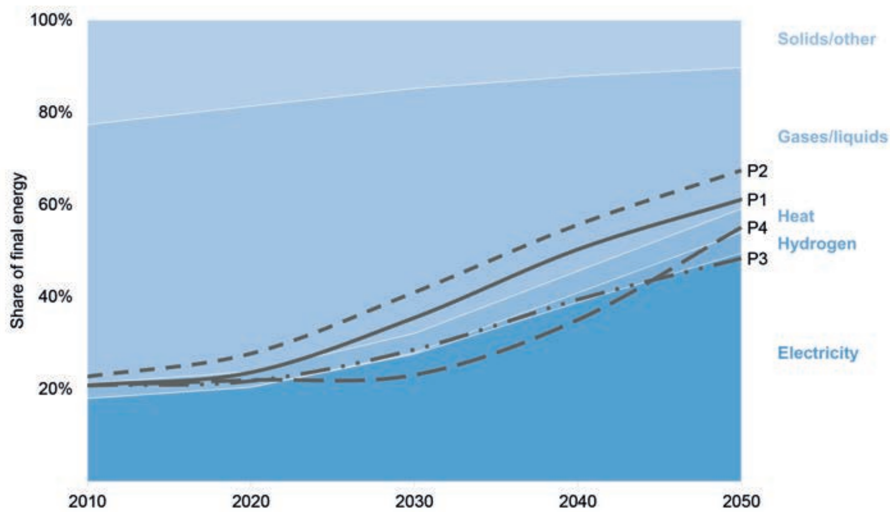


*FIG. 18. Average share of different energy carriers in the four IPCC 1.5°C pathways. The shaded area presents the average mix of all four pathways; grey lines depict the combined shares of electricity, heat and hydrogen for the individual pathways. Source: Refs [2, 27, 28].*

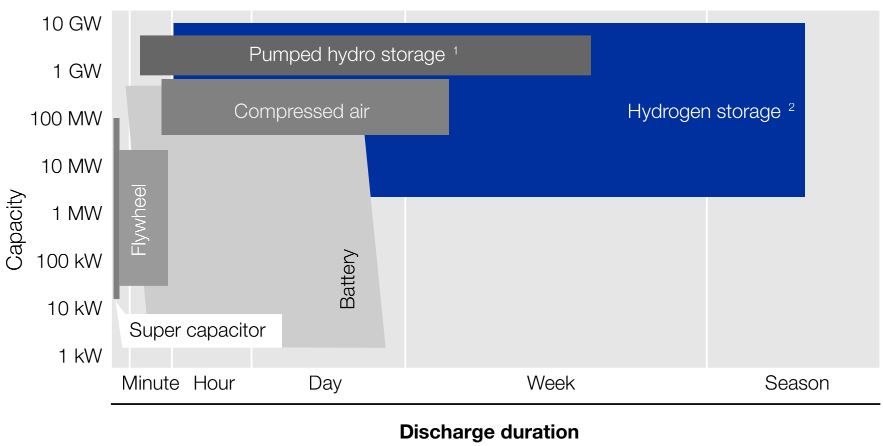


*FIG. 19. Illustration of capacity and discharge duration of various electricity storage systems. Source: IEA (2015), Energy Technology Roadmap: Hydrogen and Fuel Cells. All rights reserved; as modified by IAEA [84]. Note: 1 — limited capacity (<1% of energy demand); 2 — as hydrogen or SNG; SNG — synthetic natural gas.*

operation for NPPs, contributing to climate change mitigation efforts. This could also provide a stabilizing effect on electricity prices.

While conventional electrolysis technologies are applicable for hydrogen production with both VRE and nuclear power, nuclear energy could also be combined with more energy efficient, though less mature, high temperature electrolysis and thermochemical hydrogen production processes. This could potentially enable nuclear power to further increase its contribution to low carbon energy supply beyond electricity. This is a focus of technical research, most notably in China and Japan.

Turning to economics, recent studies foresee a significant role for hydrogen in a 1.5°C world in sectors with limited abatement options if a retail price of US $3.5 per kilogram (kg) hydrogen (around US $25 per gigajoule gross calorific value) can be realized [85]. This is broadly in line with other estimates that hydrogen from electrolysis could be competitive if produced from low carbon electricity costing between US $10 and 40 per megawatt-hour (MW·h), with an annual electrolyser capacity utilization of 3000–6000 hours [86].

Renewables and nuclear power can satisfy both of these conditions for competitive hydrogen production — notably, it is estimated that hydrogen could be generated with nuclear power for a price below US $3.5/kg across a variety of cases and scenarios [87]. In addition, the option to produce storable hydrogen could allow an NPP to operate continuously at full (thermal) power and to direct production to the most valuable output (hydrogen or power). This would greatly improve the ability of NPPs to provide services to the system while maintaining the high load factors needed by capital intensive technologies (see Sections 2.2 and 3.1). Given these features, technical demonstration projects are under way at several existing NPPs in the USA [88], and near term deployable technologies such as high temperature gas cooled reactors are expected to be particularly well suited to this application.

Accordingly, nuclear energy is technically and economically suited to meet the demand for low carbon electric and non-electric energy to support the transition to a low carbon energy system. However, as discussed in Section 3.1, market and policy signals are not currently providing sufficient incentives to drive this transition in the electricity sector, and similar conditions are affecting other energy markets. Some of the key policy and regulatory measures to accelerate the low carbon transition are discussed in the following section.

## 3.3. POLICY AND REGULATORY INSTRUMENTS FOR THE TRANSITION TO LOW CARBON ELECTRICITY SYSTEMS

As outlined in Section 2.1, ambitious climate change mitigation objectives are unlikely to be met with the current slow pace and limited scope of actions promoting energy system transformation. A key impediment to low carbon technology deployment is the lack or misalignment of incentives provided by existing policy and regulatory frameworks, including the current design of power markets in many countries.

### 3.3.1. Strengthened policy frameworks and reformed market designs can foster the low carbon transition

In addition to long term political commitment to full decarbonization, several principles for policy design have been identified to deliver sustainable low carbon electricity markets [69]:

- A robust carbon pricing scheme;
- Competitive short term electricity markets for efficient dispatch, revealing the system value of electricity;
- Transmission and distribution regulations for the adequate provision of capacity, flexibility and infrastructure;
- Mechanisms fostering long term investment in low carbon technologies, including the revision of existing mechanisms;
- Internalization of system costs wherever practical and necessary.

Carbon pricing, competition in wholesale markets leading to efficient dispatch and capacity remuneration mechanisms are already used or are being considered to varying degrees by policy makers and regulators around the world. However, for some of the other principles, their practical implementation remains unclear and untested, potentially challenging operationality and raising concerns in terms of social acceptability. Chief among them are the identification and the remuneration of system services and the internalization of system costs.

Many governments and regulators have initiated power market reforms and are evaluating the effectiveness of policy instruments and regulatory measures in ensuring the financial viability and the timely delivery of clean energy projects. The impacts of these instruments and measures on public finances, energy prices and bills are also under investigation.

Healthy and well functioning electricity markets are supposed to serve a dual purpose by sending short term and long term signals: In the short term, markets need to meet electricity demands in real time, at the lowest cost.

Wholesale prices are expected to raise sufficient revenues to guarantee the economic viability of market operators in the long term so as to incentivize the transformation of sustainable electricity supply in the longer run.

However, markets alone are generally falling short of delivering the energy transition and of directing investments towards low carbon options. Insufficient revenues earned by generators, often resulting from low marginal costs of renewable non-dispatchable technologies, undermine the necessary return on the investment capital required to build future proof energy infrastructure (see Section 3.1).

Some form of policy intervention is thus needed to address these market deficiencies and improve the competitiveness of low carbon technologies vis-à-vis unabated fossil fuel options. The most straightforward and effective policy intervention is the implementation of a carbon penalty charged to coal and natural gas plant operators to deter fossil investments (see Section 3.3.2).

The next crucial question is the degree of market liberalization versus regulation that is most likely to deliver on climate objectives. This question currently leads to heated debates among policy makers, regulators, market players and academics, and a consensus has yet to be reached. Nonetheless, there is a growing recognition that liberalized markets are unable to stimulate clean energy investments at the speed and scale needed.

Recent history shows that most low carbon investments have been realized outside the market, supported by fiscal and financial incentives, or pushed by various quantity based market instruments such as tradable green certificates, obligations and price based market instruments. The market instruments have chiefly been directed towards renewable energy [89]. Many countries have historically applied guaranteed price based market instruments to, for instance, solar and wind projects (e.g. fixed feed-in tariffs or auction based long term price agreements) and sectoral standards targeting specific energy efficient goods and processes.

However, only a regulatory level playing field can guarantee the timely deployment of all low carbon energy sources necessary to meet the 1.5°C goal at an acceptable cost. Some attempts to establish an inclusive framework have been pursued by the USA's Federal Energy Regulatory Commission and the UK Office of Gas and Electricity Markets [89]. The EU has set up a comprehensive taxonomy aimed at streamlining the financing of sustainable technologies based on harmonized criteria [90]. The taxonomy gives priority to renewable energy and energy efficiency measures. Nuclear power is not included in the taxonomy owing to a lack of consensus among EU member countries on its performance in terms of environmental sustainability.

The countries that are currently developing nuclear ambitions, often emerging economies with growing electricity needs, generally feature highly regulated markets and public ownership of assets, thereby reducing investors' risks. However, globally speaking, the deployment of nuclear power technologies lacks sufficient momentum to support climate change mitigation ambitions (Sections 2.3 and 2.4), notably due to a lack of policy support. Large energy infrastructure projects, such as NPPs, offshore wind and solar thermal plants, offer significant mitigation potential but remain high risk for private investors in many places. Some form of government support, including research and development (R&D) support, loan guarantees, power pooling agreements, land lease agreements and non-regulatory policies (i.e. financial and fiscal incentives) are often necessary to justify investment.

Long term, technology neutral contracts, granted via competitive procedures such as auctions, are now seen as viable options to increase the attractiveness of low carbon technologies to investors and operators — and alleviate adjunct problems of security of supply. Such contracts require the coordination of a third party responsible for addressing the shortcomings of wholesale markets and the alignment of investment choices with long term climate goals. Examples of such long term arrangements include the contract for difference originally envisaged for the Hinkley Point C nuclear project in the UK — a form of feed-in tariff — and the associated regulated asset base model with enhanced government protection during the construction phase. Both mechanisms provide greater visibility to investors on cash flows and reduce their risk exposure. The former significantly reduces market risk, by guaranteeing a certain remuneration for the electricity produced. The regulated asset base model is conceptually similar to the enhanced regulation of electricity markets: it aims at shielding the investor, at least partially, from construction and market risks. Consumers eventually benefit from lower electricity generation costs owing to the reduced risk for investors. It is important to note that these proposed sets of rules, including long term contracts but also feed-in tariffs and auction mechanisms, are providing incentives that reduce the pure market influence on operators' behaviour.

### 3.3.2. Carbon pricing is increasingly recognized as the cornerstone of mitigation policy

Carbon pricing, in the form of a direct carbon tax or tradable carbon emission rights (referred to as an emissions trading system (ETS)), is generally considered to be the economic instrument of choice to curb GHG emissions and a cornerstone of any efficient climate change mitigation policy. These mechanisms are now gaining traction among policy makers: 46 national and 31 subnational jurisdictions are now implementing carbon pricing initiatives, which generated US $44 billion of revenues in 2018 [91]. Climate change is also driving changes to business and financiers' strategies. In 2018–2019, over 1300 companies were using or planning to use internal carbon pricing.

Despite these burgeoning initiatives, only 21% of global GHG emissions are currently or will soon be covered by a carbon penalty. ETS schemes cover a broader range of emissions than the scope of carbon taxes: 16% of GHG emissions fall under ETS obligations compared with a mere 6% in the case of carbon taxes (Fig. 20). On average, the level of carbon taxes implemented across 30 initiatives globally is US \$27/t $CO_2$-eq. In addition, 28 ETS markets are now functioning globally, with two additional markets scheduled nationally in China and at the state level in Virginia, USA. In 2019, the average permit price traded at US \$11/t $CO_2$-eq, about a third of the price observed in the EU ETS (US \$32.50). However, carbon price levels are generally far too low to foster low carbon investments: it is estimated that prices of US \$75–100/t in 2030 are needed to make unabated fossil fuel options uneconomical for electricity or industrial use [12], in line with estimates of the High-Level Commission on Carbon Prices [92]. By 2050, the IPCC's illustrative pathways imply prices of US \$160–700/t $CO_2$ to achieve the 1.5°C goal [28], which is similar to the estimated social cost of carbon (a proxy for the overall marginal damage of $CO_2$ emissions) [2]. To date, carbon taxes above US \$50/t can be found solely in Finland, Liechtenstein, Norway, Sweden and Switzerland.

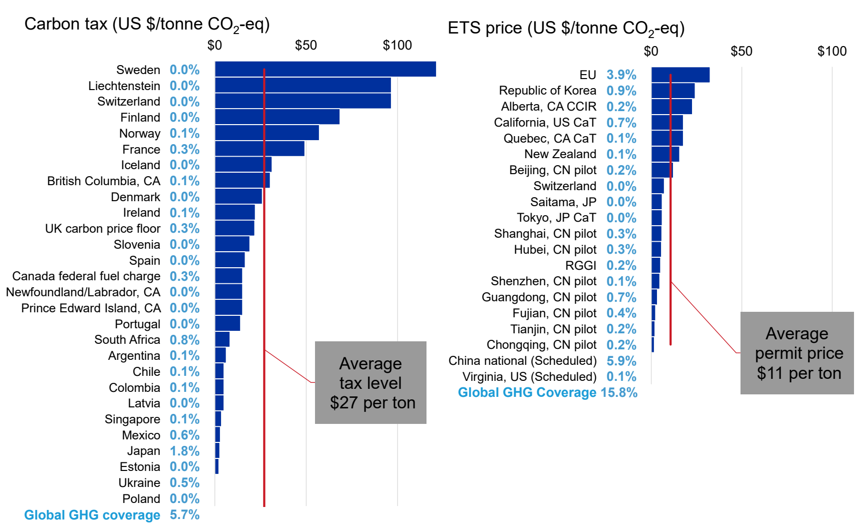


*FIG. 20. Observed 2019 and scheduled carbon prices by instrument and region; coverage as share of global GHG emissions (percentages). Source: Ref. [91]. Note: CaT — cap and trade; CCIR — Carbon Competitiveness Incentive Regulation; $CO_2$-eq — $CO_2$ equivalent; RGGI — Regional Greenhouse Gas Initiative; CA — Canada; CN — China; JP — Japan.*

Carbon pricing schemes are often associated with a perceived risk of a country or business losing competitiveness. A recent assessment from the High-Level Commission on Carbon Pricing and Competitiveness, bringing together private sector leaders and senior government officials, concluded that pricing carbon does not necessarily limit economic and industrial growth, nor does it encourage big polluters to flee to other jurisdictions [93]. Carbon pricing has no more of an impact on a decision to invest or locate than other factors, including corporate tax rates, wage rates, the availability of labour and energy prices. Smart, stable, and tailored policy packages, including tax reductions, technology assistance focused on emerging sectors and border tax adjustments such as charging imports for their embodied carbon footprint, are currently under assessment, notably in the EU, to help mitigate possible risks to global competitiveness and cut the carbon footprint of all manufactured products. Novel hedging mechanisms, including carbon price corridors to avoid undesirable signals from large market swings, are also being considered to increase the effectiveness of carbon pricing policies.

Additional ongoing reforms in the energy sector rest on implicit carbon pricing measures, including reforms of the subsidization of production and consumption of fossil fuels and other taxes. If implemented too forcefully, these reforms, albeit necessary, can be met with public distrust as shown recently by protests in Chile, Ecuador and France. Policymakers should be mindful of the social cost of the transition, be it in terms of local employment or economic activity at risk in unsustainable sectors, increased fiscal pressure or inflated energy prices. In response to these concerns, policy packages under consideration now integrate various redistribution schemes — for example, a partial transfer of carbon pricing revenues to the most vulnerable households and businesses — in order to obtain civil society's buy-in before the enforcement of measures. The policymaking processes should now include thorough and concerted evaluations of policy options, bringing together all stakeholders, including governments, private entities and civil societies.

### 3.3.3. Coordination, flexibility and transparency are key to effective policy making

Overall, competing policy priorities, combined with the vast array of technological options and the complexity of future energy systems, stemming notably from interconnections between centralized and decentralized sources of electricity supply, are major hurdles to effective policy design. The content of a given policy package will depend on factors ranging from political ambition to the level of economic development, existing physical, regulatory and market architectures, the timing and cost of various policy options, the availability of low carbon and affordable energy sources, the business environment and the ease of access to credit [94, 95].

Further policy measures, including support for R&D, support to first-of-a-kind commercialization, broader industrial policy and other parallel objectives such as energy security or air quality, can also indirectly stimulate low carbon investments. Comprehensive policy packages go well beyond the power sector. In particular, the pace and scope of power sector reforms need to be synchronized with other supporting mechanisms favouring the electrification of energy end use.

On the other hand, poorly designed packages and conflicting objectives are likely to raise the cost of transition [95]. Judicious investment plans should therefore distinguish between short term costs of policy and long term dynamic costs resulting from technological innovation [96]. Flexible policy pathways with regular revisions to instruments, measures and targets to accommodate new information, while still providing a stable investment climate, should therefore be put in place to complement the effective design of sustainable technology pathways.

## 3.4. LOW CARBON FINANCE: UPSCALING AND DIVERSIFICATION

The destination of today's energy investment flows is a good predictor of the sustainability of the future energy system, given the long lead times and operational lifetimes of energy assets [97]. The transition to low carbon electricity systems will gain more traction once capital investment patterns thoroughly shift away from unabated fossil fuel energy.

Despite evidence of an ongoing energy transition, the current policy and market environment is still supporting unsustainable investments. For instance, although average fossil fuel investments in the power sector have declined by 15% annually since 2010, almost US $130 billion was still allocated to carbon intensive power projects in 2018, roughly a quarter of total power generation investments. Coal remains an attractive option in China, India, South-East Asia and Africa, where the immediate necessity to fund new infrastructure is sometimes prioritized over energy sustainability goals. These unsustainable investment decisions are not compatible with long term decarbonization objectives. They may lead to stranded assets in the future as climate action gains momentum and emissions restrictions strengthen.

Low carbon investments are progressively closing the gap with fossil fuel investments, thanks to favourable policies, technological advances and market forces. In 2018, clean energy investments, including spending on the extension and modernization of electricity networks, as well as energy efficiency measures, amounted to almost US $900 billion (Fig. 21). Between 2015 and 2018, average investments in nuclear and renewable energy totalled 38% of low carbon energy investments. About 30% of nuclear spending went to existing plants for LTO (see Section 4.2). Almost half of all low carbon energy investment was made in China and the United States of America, although they account for less than a quarter of the global population, suggesting some imbalance in climate finance allocation. Entrepreneurs addressing markets that are less attractive to international investors often face challenges to fund projects with domestic finance. There is thus potential for improving the accessibility of climate finance mechanisms to underserved recipients, which are often disadvantaged by a lack of domestic capacity and resources to engage with complex accreditation requirements [103].

Building climate resilient energy systems would not necessarily come at considerable expense and would provide sizeable benefits to society if externalities are adequately accounted for. If planned wisely, with a long term orientation, a thorough sustainable energy strategy would only require 15% in extra investment overall, compared with unsustainable outcomes, with especially large opportunities in emerging markets (Fig. 22) [12, 104]. Moreover, bold climate action, requiring 50% and 90% more capital for nuclear and renewables respectively through to 2030, may deliver at least US $26 trillion in net economic benefits, equivalent to about one third of current world GDP [105].

Technological progress and innovation are essential to reduce the financial burden of the transition. The emergence of economical battery storage solutions provides further impetus to the deployment of more flexible and decentralized energy systems worldwide. According to the IEA, less than US $30 billion would be required annually to deploy 550 GW of storage capacity by 2040 — which is a conservative estimate compared with other capacity projections [106] — and foster the further electrification of energy use. Energy storage projects are already burgeoning worldwide.

While expectations for COP25 in December 2019 were high, the results were considered disappointing [3–5]. COP25 left decision makers without guiding rules to accelerate the shift in financial flows from carbon to low carbon investment and monitor healthy markets of clean energy. In the absence of a global rulebook, coalitions of government representatives, like-minded market players and large private and institutional fund managers are already forming and developing their own sets of rules and other sustainable investment strategies on a voluntary basis to direct the estimated US $360 trillion of resources of the global financial system [107]. An example is the EU taxonomy (also discussed in Section 3.3) recently adopted by the European Parliament, providing investors with clarity on which activities are considered environmentally and socially sustainable. Scientific assessments are being conducted and selection criteria are

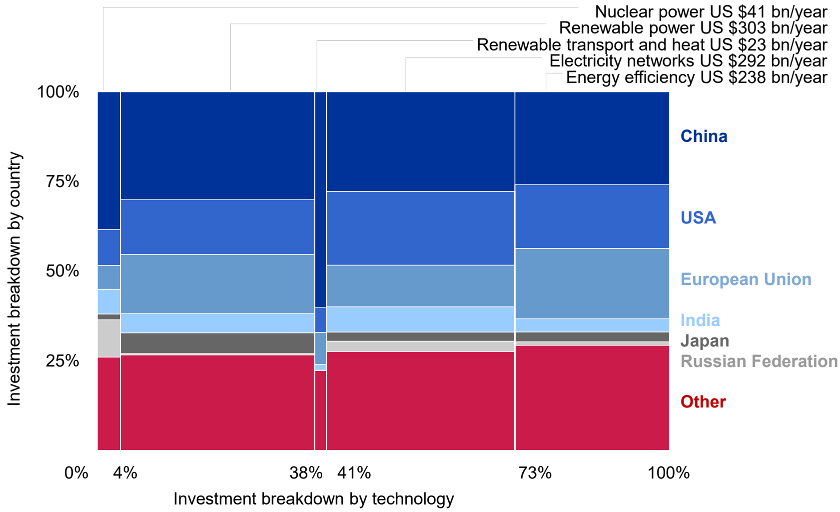


*FIG. 21. Global cumulative investments in low carbon technologies (annual average 2016–2019). Source: Refs [98–102]. Note: bn — billion.*

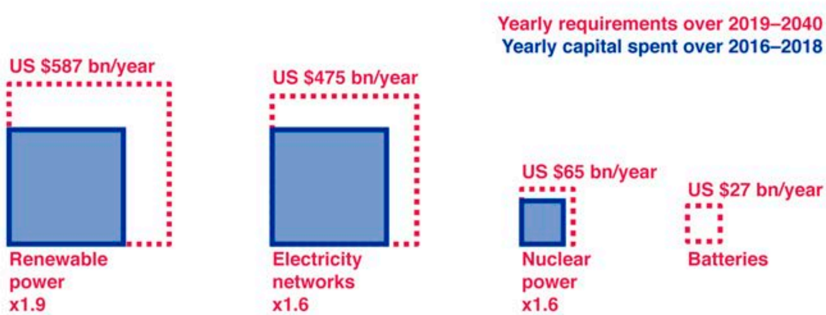


*FIG. 22. Low carbon power sector investment requirements in line with the Paris Agreement (annual average 2019–2040). Source: Ref. [12] Note: bn — billion.*

being applied to decide on the sustainability of nuclear power and its inclusion in the taxonomy.

Critically, the financing of and investment in low carbon energy infrastructure are taking place against the backdrop of a changing climate. A sustainable energy transition therefore encompasses not only climate change mitigation and ensuring energy access for un- and underserved populations, but also requires that the energy system be increasingly resilient to climate change, including sea level rise, higher temperatures, changing precipitation, and an increasing frequency and severity of extreme events, as discussed in the following section.

## 3.5. CLIMATE-PROOFING ENERGY INFRASTRUCTURE

Extreme weather events are among the five ‘reasons for concern’ identified by the IPCC to categorize the key impacts and risks of global warming across sectors and regions [2]. The manifestation of more frequent and damaging events, in addition to insufficient climate change mitigation action, are perceived by world leaders as being a critical risk to our societies [108].

Extreme weather events over the last decades have often caused power outages, in addition to other disruptions and damage to other types of infrastructure (Fig. 23). In the USA and the EU, 44% and 37% of power outages, respectively, stemmed from such natural shocks, contributing in turn to reduced economic activity and increased vulnerability of the poor [119]. In many situations, the cost of repair has proved very large, often in the range of several billion dollars. For instance, Hurricane Sandy in 2012 is estimated to have cost utilities more than US $2 billion, while restoring electricity systems in Puerto Rico after Hurricanes Irma and Maria in 2017 cost US $17 billion [120]. Moreover, many assets at risk remain at best only partly covered by insurance policies.

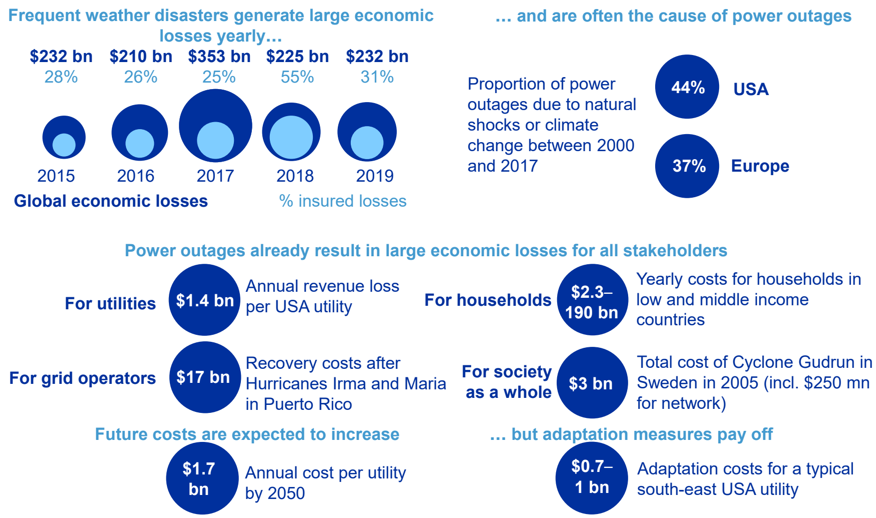


*FIG. 23. Selected economic impacts of recent extreme weather events. Sources: Refs [109–118]. Note: Amounts refer to US $; bn — billion; mn — million.*

Extreme weather events tend to have distinct impacts on different types of energy infrastructure. Depending on their location and initial design, renewable energy sources are potentially vulnerable to weather conditions. For instance, in 2014 a polar vortex interrupted wind and solar generation in the central and eastern USA. However, fossil energy infrastructure was also vulnerable during the same outbreak, which shut down natural gas and coal fired power plants. Likewise, Hurricane Harvey in 2017 forced a 20% cut in the USA's oil production, with gas futures and retail gasoline prices hitting a two year high. Power grids, a critical component of future energy systems, also appear quite vulnerable to weather related natural disasters. In 2012, Hurricane Sandy caused major damage to the electrical grid in the north-east USA, leaving NPPs, however, relatively unaffected. During the 2017 summer heatwave in the USA, NPPs were also able to maintain capacity factors up to 96% [121].

While NPPs were relatively unaffected by these specific events and have indeed greatly contributed to the resilience of power systems in the events mentioned above, their operations may be affected by extreme events in the future. NPPs may be particularly exposed to increasing storm intensity and sea level rise from climate change, with more than 40% of them being located near shorelines. Inland NPPs, on the other hand, are more likely to be affected by severe wildfires and warmer fresh water temperatures [122]. However, the track record of NPPs in terms of outages due to environmental conditions suggests a strong overall resilience to extreme weather events [64]. Power outages may also be implemented during periods of extremely hot weather as a precautionary measure to avoid plant damage. On average, the production foregone owing to 230 such events, as recorded in 20 countries over the last 15 years, corresponds to 0.11% of the nuclear electricity produced during that period (Fig. 24). Sixty per cent of these power outages occurred in France and the USA alone. Aggregate production losses per year tend to be connected to the impact of one or two severe events rather than the total number of outages. Hence, it is difficult to predict and avert large impacts.

Severe environmental conditions, including heatwaves, water stress, storms and floods, are expected to increase in frequency and severity in the future and will periodically threaten and test the entire energy infrastructure, with economic consequences across the board due to the interdependence of critical infrastructure systems [123]. Building future proof, resilient infrastructure is therefore of utmost importance in order to reduce risk exposure and inherent economic losses. Resilience-by-design and regulatory frameworks adapted to increased climate variability, including fluctuations in temperature and water availability, should become mainstream. The representation of extreme weather risks in energy planning should also be improved. Financiers supporting the energy transition and insurance and reinsurance companies covering large risks should redesign

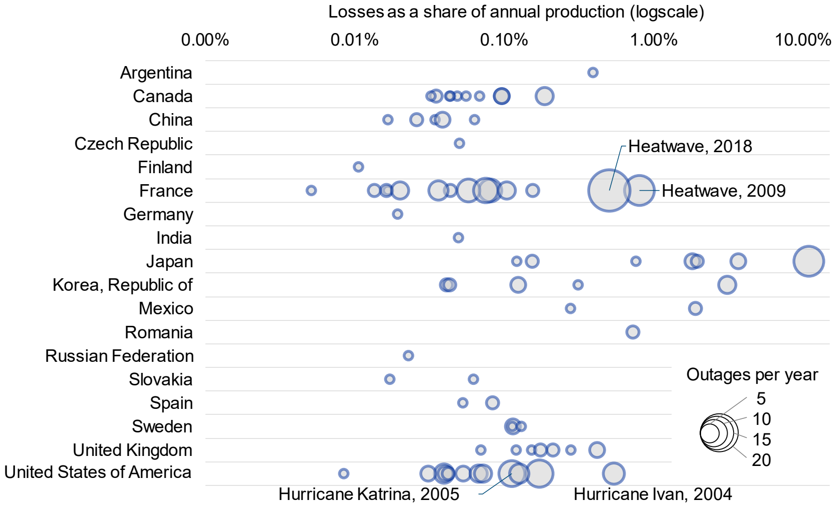


*FIG. 24. History of NPP outages due to environmental conditions by country (losses expressed as shares of annual production), 2004–2019. Note: The largest outage in Japan refers to NPP shutdowns following the Tōhoku earthquake and tsunami, rather than climate related events. This does not reflect the ongoing extent of these shutdowns [64].*

their products and value propositions to better account for low probability/high risk outcomes, increase the attractiveness of more resilient energy assets and reduce the gap between insured assets and actual losses. As climate risks become legal liabilities for the energy sector, industrial players and operators also have a key role to play to define their strategies and portfolios wisely.

The integration of resilience and adaptation represents one of several key elements outlined in Section 3 that need to be brought together to realize the transition towards reliable and low carbon energy systems necessary to hold global warming to 1.5°C. To summarize, these include the system and market integration of low carbon electricity generation technologies, and increased coupling between electricity, other low carbon energy carriers and energy demands (as described in Sections 3.1 and 3.2). These can only be realized with an effective policy and regulatory environment with specific measures and instruments such as carbon pricing that can mobilize the private sector and finance system to ensure the energy transformation responds to both climate change mitigation and adaptation (Sections 3.3 to 3.5). Against this backdrop, Section 4 now turns to the question of how, in practical terms, the potential of nuclear power in this transition to resilient, low carbon energy systems can be realized.

# 4. REALIZING THE MITIGATION POTENTIAL OF NUCLEAR POWER

## 4.1. DEPLOYMENT OF NEW NUCLEAR CAPACITY

In order to realize the potential of nuclear power in combating climate change (see Section 2.3), a significant number of new reactors will need to be brought on-line over the coming decades. This presents several challenges, as nuclear projects exhibit specific features and risk profiles, making them challenging to finance compared with other electricity generation technologies. To better understand the options available for financing NPP construction projects, this section explores in detail the capital requirements and financing of nuclear new builds, along with options to bolster supply chains and restore construction capabilities.

### 4.1.1. Effective planning and partnerships can reduce costs and construction times in new nuclear power projects

Building an NPP requires thousands of workers, vast amounts of materials, particularly steel and concrete, and a wide variety of specialized components, equipment and systems, all manufactured, tested, inspected and assembled to the highest standards (Table 2). The construction time of an NPP is usually defined as the duration between pouring the first concrete and connecting the plant to the grid. Seven years is a typical timeframe for NPP construction, but shorter construction times have been achieved in the past — for example, the two units at the Kashiwazaki-Kariwa NPP in Japan took only four years to build [125] — and are common in countries with large ongoing nuclear programmes.

TABLE 2. ILLUSTRATIVE NUCLEAR CONSTRUCTION: QUANTITIES AND VOLUMES INVOLVED AND HUMAN RESOURCES AT PEAK
*Source: Adapted from Ref.* [124].

| Quantities and volumes involved (approximate) | | Peak human resources (full time positions) | |
|---|---|---|---|
| Pieces of mechanical equipment | 8 000 | Project management | 30 |
| Pieces of electrical equipment | 1 660 | Construction management | 205 |

TABLE 2. ILLUSTRATIVE NUCLEAR CONSTRUCTION: QUANTITIES AND VOLUMES INVOLVED AND HUMAN RESOURCES AT PEAK
*Source: Adapted from Ref.* [124]. (cont.)

| Quantities and volumes involved (approximate) | | Peak human resources (full time positions) | |
|---|---|---|---|
| Instruments | 60 000 | Commissioning management | 338 |
| Large valves | 18 000 | Operation and maintenance | 330 |
| Large pipe spools | 25 000 | Design engineering | 440 |
| Small pipe spools | 40 000 | Manufacturing | 700 |
| HVAC duct (tonnes) | 1 400 | Construction management | 400 |
| Cable trays | 18 000 | Construction workforce | 4 200 |
| Cable (km) | 3 500 | | |
| Concrete ($m^3$) | 490 000 | | |
| Structural steel (tonnes) | 16 000 | Total human resources | 6 643 |

**Note:** Unless otherwise indicated, values refer to the number of units; HVAC — heating, ventilation and air-conditioning.

Overnight construction costs, construction duration and the cost of capital are key drivers affecting power generation costs, as measured by the LCOE metric [52]. In 2015, overnight construction costs for nuclear were estimated to fall within the range of US $2000–6200/kW [52]. The expenditures associated with procuring and erecting the systems and components of the nuclear island, the turbine island, the building and structures, and the electrical, instrumentation and control systems are the most important contributors to overnight construction costs [126].

Delivering nuclear new build projects also involves a long, complex and costly regulatory process. Environmental impact assessments and public consultations are also needed, as they are for all megaprojects. Finally, nuclear projects are also subject to political risks — a major concern for investors and lenders — that are not easy to evaluate or to mitigate.

In the past decade, a small number of nuclear new build projects have suffered delays and cost overruns, particularly in Western Europe and the USA.

Yet, in many countries, new nuclear power projects are being delivered on time and on budget, including in Belarus, China, the Republic of Korea and the Russian Federation. In fact, nuclear power costs are highly region, country and site specific (Fig. 25). The prevailing conditions at the local level — for example, labour, shipping and material, site preparation and connection costs — and the capabilities of the supply chain supporting the nuclear new build project, are key factors affecting costs and delivery times. Studies have shown that the main route to low nuclear construction costs is a multiunit programme allowing plant developers, vendors, work crews and regulators to gain experience over time and to build an efficient supply chain [128–130]. Innovations in plant design, advanced materials and modular construction technologies can certainly help, but the most important factors for project success are human ones: careful planning, effective collaboration and shared commitment [131].

### 4.1.2. De-risking nuclear projects can unlock access to financing

The expansion of low carbon energy sources, including nuclear power, requires actions from both governments and plant owners/operators. Governments have a critical role in funding and establishing legal frameworks and market and regulatory bodies, supporting the development of human resources and, in the case of nuclear power, setting up the institution tasked with implementing the

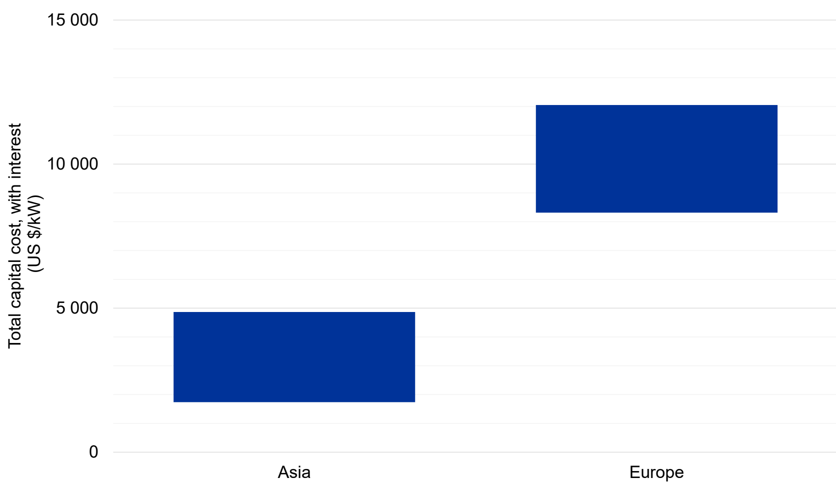


*FIG. 25. Construction cost ranges for recent nuclear new build projects in Western Europe (Finland, France and the UK) and Asia (China, Japan, the Republic of Korea and the United Arab Emirates). Source: adapted from Ref [127].*

nuclear power programme, preparing for emergency contingencies, and creating mechanisms for funding radioactive waste disposal and NPP decommissioning. The owner/operator (which may be a private or government entity) is responsible for the financing of the project, in addition to design, procurement, construction, commissioning and operation.

From an investor's point of view, only projects that are considered viable and profitable can attract financing. Financial institutions consider nuclear projects challenging to finance because of their long time horizons, complex regulatory processes and exposure to political risks, among other challenges. Accordingly, governments worldwide also have an additional key role in 'de-risking' nuclear projects by providing guarantees to debt and equity providers over the lifetime of a nuclear project (see Box 2).

**BOX 2. DE-RISKING NUCLEAR NEW BUILD PROJECTS**

Long construction times, complexity in design and in manufacturing, and first-of-a-kind issues are reasons behind the high construction costs and delivery times for nuclear new build projects compared with projects based on other generating technologies. Successful nuclear projects in the recent past have been delivered by vendors and supply chains with a steady inflow of projects, which allowed them to develop and retain experience and skilled teams (see Section 4.1.3). Other key success factors include the following [132]:

— Using simple and proven designs (with an operating reference plant);
— Working in close cooperation with the regulator;
— Having sensible, risk informed contracting models;
— Employing proven contractors with experienced teams;
— Profiting from 'lessons learned' from other NPP projects;
— Taking state of the art approaches to project and risk management;
— Relying on IAEA peer review missions and advisory services.

Financing any large scale infrastructure project in the power sector is a complex undertaking. Funds — both equity and debt — could be obtained in a variety of ways [133, 134] (Fig. 26). Historically, NPPs have relied on public financing, which allowed for the most efficient risk allocation model in then regulated national electricity markets such as France, the Russian Federation and the USA, and later including China, Japan and the Republic of Korea. In the corporate financing model, the owner assumes most of the risk, which can be mitigated with various schemes — for example, the contract for difference in

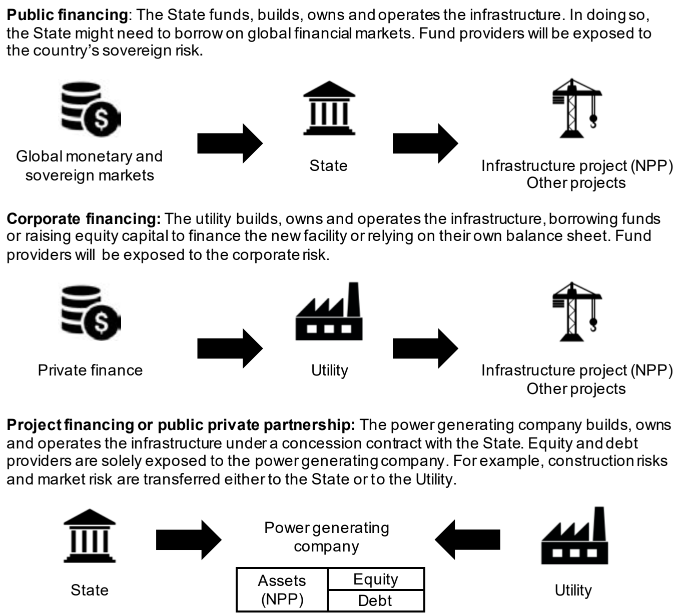


*FIG. 26. Financing models for nuclear power projects. Source: Ref. [133].*

the UK mitigated electricity market risk by securing revenue streams through a power purchase agreement. Pure project finance has not been implemented for nuclear new build projects, but the model is a promising possibility for the next generation of nuclear projects, in particular for small modular reactors (SMRs; see Section 4.3).

In developing economies, development finance institutions (DFIs), such as the World Bank, are playing an important role in funding and financing the transition to a low carbon economy. In the past, major DFIs excluded nuclear new build projects from financing for multiple reasons, including their size, complexity and risk profile [135]. Addressing DFIs' concerns about financing nuclear power is key to unlocking the potential of nuclear power in low carbon electricity generation.

### 4.1.3. Construction capability and supply chains will be critical

Robust supply chains, capable of delivering equipment, systems and services of the highest quality, are vital to the success of nuclear new build projects as well as the efficient operation of existing NPPs and the decommissioning of nuclear facilities.

Figure 27 illustrates key activities supported by the nuclear supply chain throughout the lifetime of an NPP, from design, construction and commissioning, to operation, decommissioning and the long term management of spent nuclear fuel and radioactive waste. Figure 28 focuses on nuclear new build projects, and lists examples of systems, equipment and facilities procured during plant construction. Once the NPP has been built and commissioned, the supply chain provides facility management and support services, routine and specialized maintenance, and engineering support.

The main functions of procurement engineering are to identify technical items and quality and commercial requirements, and to perform item equivalency evaluations and commercial grade dedication in a timely manner [137]. The main attributes of top suppliers are the following:

- Quality culture;
- Quality assurance process;
- Management of requirements, exceptions and final certifications;
- Commercial grade dedication process;
- Internal audit process;
- Subsupplier audit and survey process;
- Corrective action programme.

The requirements and expectations placed on the suppliers of products and services and their subcontractors are phase specific, varying over the life cycle of the NPP. During the commissioning phase, for example, the contractor should be able to demonstrate the correct function of each piece of equipment, both as an individual item and as a component of a larger system of the NPP [138].

Most of the world's NPP fleet was built and commissioned between the 1970s and the 1990s. In some years, the nuclear industry was able to build more than 30 NPPs [64]. In the past 20 years, orders for new nuclear power stations decreased in certain parts of the world — especially in Western Europe and the USA. Too few projects, without continuity between them, led to a general weakening of the subcontractor network, first-of-a-kind and quality issues, and a relative increase in construction costs and delivery times compared with the initial estimates. Conversely, nuclear projects that have well functioning supply chains are delivered on time and within budget, as discussed in Section 4.1.1.

Restoring nuclear supply chains, and maintaining and improving know-how, require a stable and sustained demand for NPPs and components. Environments that enable learning, as well as the standardization of reactor designs and the harmonization of codes and standards are also key to achieving a competitive and integrated nuclear supply chain (Fig. 29).

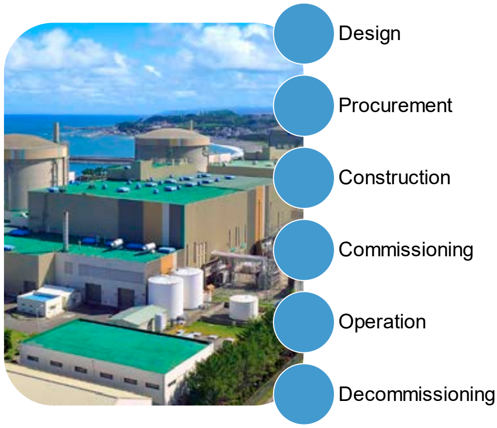


*FIG. 27. Activities supported by the nuclear supply chain throughout the lifetime of an NPP.*

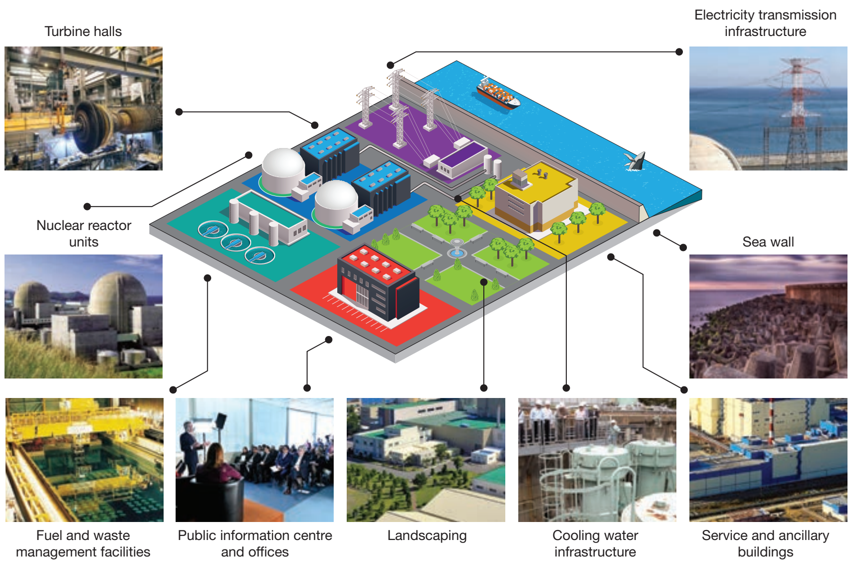


*FIG. 28. Examples of systems, equipment and facilities procured during plant construction. Source: Ref. [136].*

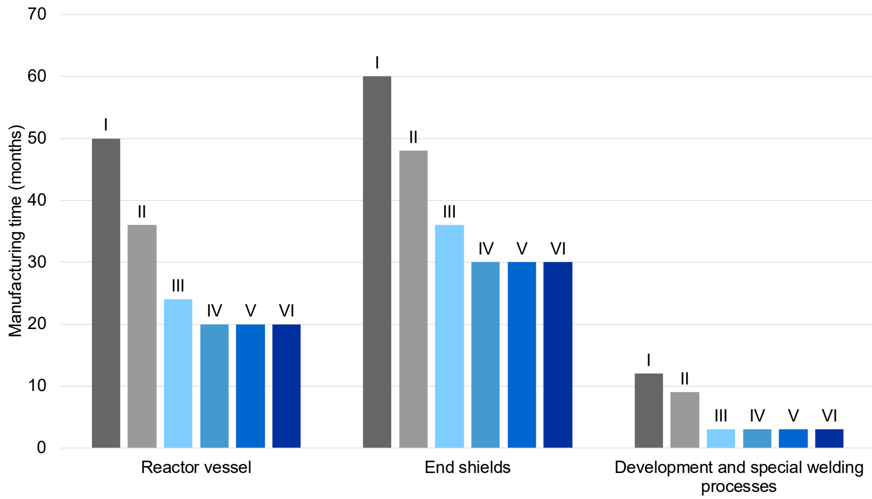


*FIG. 29. The manufacturing time of nuclear reactor components is reduced as NPP units (I to VI) are built. Source: Refs [139, 140].*

Nuclear new build projects around the world, SMR development programmes (Section 4.3) and NPP refurbishments (Section 4.2), which are planned or under way in many countries, provide an opportunity for the global nuclear supply chain to build skills and increase capacity. This also provides economic benefits — direct, indirect and induced — both in the country where the project is taking place and outside it (see Box 3).

Governments worldwide will have a major role to play in creating an enabling environment such as that described in Section 3.3, including by developing energy policies and industrial strategies, removing barriers, encouraging competition and supporting innovation through national institutions. In addition to deploying new NPPs for the energy transition, an important complement is to ensure existing plants continue to supply low carbon electricity, given that these plants are currently helping to avoid close to 2 Gt $CO_2$ per year (Section 2.3.1). The following section outlines the steps to securing this LTO of existing NPPs.

**BOX 3. MACROECONOMIC IMPACTS ATTACHED TO NUCLEAR NEW BUILD PROJECTS**

Investment programmes in nuclear power have been shown to generate multiple benefits in countries and communities hosting NPPs. In joint projects between countries — for example, if a country takes a sovereign decision to engage with foreign suppliers — associated benefits such as increased employment are shared between a vendor country (or multiple countries) supplying nuclear technology and the host country where the NPP is being constructed. The exact distribution of benefits between participating countries is determined by a variety of factors and may vary over time.

For a supplier country, the largest macroeconomic benefits are estimated to occur during NPP construction. Economic activity is generated in the supply chain related to designing and engineering the NPP components, manufacturing major subcomponents and delivering fuel and other items. The manufacturing of machinery and equipment is estimated to experience the largest increase in economic output, followed by financial services and electrical equipment manufacturing.

By contrast, the recipient country is more likely to benefit during the operation of the NPP. One of the major drivers of this distribution is the creation of jobs in close proximity to an NPP. However, prior to the plant commissioning, two sectors are likely to benefit most: construction and manufacturing of machinery and equipment. Benefits in a recipient country largely depend on local participation in those parts of the supply chain where national industrial companies can competitively meet the high standards of the nuclear industry. Countries opting for nuclear power typically aspire to increase local participation, which is likely to translate into greater job creation throughout the economy and several other macroeconomic benefits [140, 141]. Maximizing local content — a priority for public stakeholders — may significantly increase project risks and costs. These costs should be weighed against the expected macroeconomic benefits.

## 4.2. EXTENDED OPERATION OF EXISTING NUCLEAR POWER PLANTS

Extending the operational lifetimes of existing NPPs beyond their original design lifetimes represents a cost effective opportunity to maintain low carbon dispatchable capacity and lower the cost of the clean energy transition. While it will take some time to fully capitalize on nuclear new build projects, given their long construction times and the need to re-establish and scale up supply chains outlined in the previous section, lifetime extensions are contributing significantly and immediately to climate change mitigation. In its latest report on nuclear energy, the IEA estimates that "lifetime extensions of nuclear power plants are crucial to getting the energy transition back on track" [11].

The average age of the global nuclear fleet is approximately 30 years, and about two thirds of the nuclear capacity in operation today has been in service for more than 30 years. The operators of many of these reactors are currently facing the crucial decision of whether to make significant investments in LTO programmes to extend their operating licences. This issue is particularly important for the early adopters of civil nuclear power, such as Canada, many EU member countries, Japan, the Russian Federation and the USA (see Fig. 30).

Programmes to extend the original lifetime of NPPs have been successfully implemented in several countries, and considerable technical experience has been gained so far (see Box 4). However, scaling up LTO programmes is critical to avoiding a substantial reduction of nuclear capacity, especially in countries facing challenges in financing new NPPs. The IEA indicates that insufficient investments in new and existing NPPs would have serious implications in terms of emissions, cost and energy security.

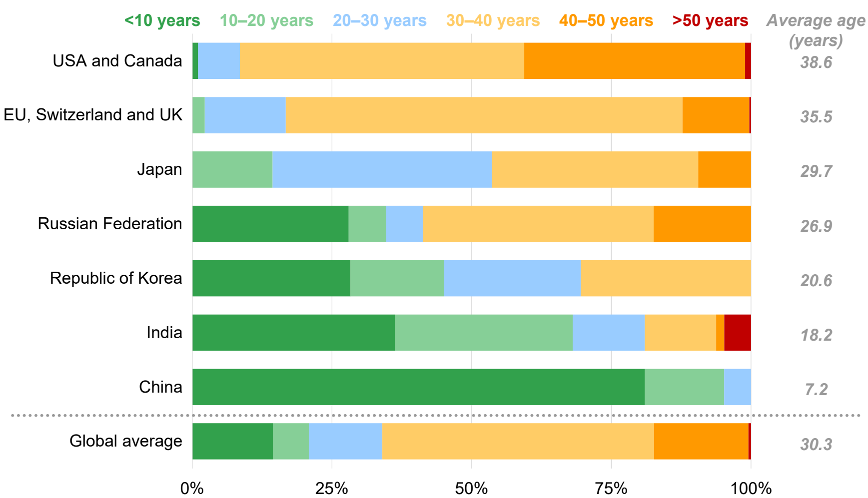


*FIG. 30. Age profile of the nuclear fleet in operation in selected countries (weighted by capacity) as of 2020. Source: Ref. [64].*

**BOX 4. TECHNICAL ASPECTS OF LONG TERM OPERATION OF NUCLEAR POWER PLANTS**

There is no predetermined technical lifetime for an NPP: each component of the plant has a design lifetime, but in principle nearly all components can be replaced. Those few parts which cannot be economically replaced determine the maximum practical plant lifetime. These include the primary piping, the reactor pressure vessel and the concrete containment structures.

The 'design life' of existing NPPs was typically estimated based on assumed operating conditions, including fluctuations in power level and expected irradiation load, and the available knowledge of materials at the time of design. However, since the original design of many existing NPPs, there have been significant improvements in the overall understanding of the behaviour of irradiated material and the ageing process of concrete. In addition, many NPP operators adopted core loading and fuel management strategies to limit the irradiation load on the vessel and operational procedures to reduce the thermal stress to piping, which were not anticipated during the design phase. Also, new inspection techniques have enabled better monitoring of vessel embrittlement and concrete degradation. As a result, from a technical viewpoint, most existing reactors could be safely operated until they are 60 years old or older.

Depending on the design, lifetime extensions have required significant investment to replace and refurbish major components of both the nuclear and conventional islands to ensure plant operation in line with current expectations. Such modifications are usually performed over a few years during carefully planned maintenance outages. In most cases, this enables 10–20 years of extended operation with the added benefit of uprating the plant's power output.

Without ongoing LTO, existing nuclear capacity will decline sharply before 2030, particularly in Europe and North America, with all existing plants retiring by 2060 (see Fig. 31). This could have significant consequences for $CO_2$ emissions, air pollution and the security of the electricity supply. Increasing the lifetime of all NPPs to 50 years would allow for additional cumulative generation of about 26 000 TW·h of low carbon electricity, corresponding to around 1% of average global low carbon generation from 2020 to 2070 in the IPCC's four illustrative 1.5°C pathways [2] (see also Sections 2.1 and 2.3). Extending lifetimes by an additional 10 years (to 60 years) would generate an additional 31 400 TW·h from existing NPPs, representing around 1.8% of average global low carbon generation

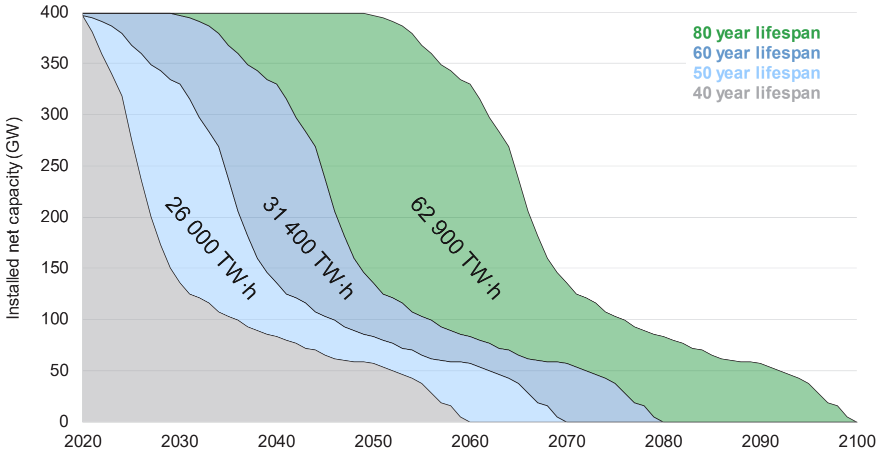


*FIG. 31. Evolution of the existing nuclear capacity for different lifetimes. Source: Ref. [64].*

from 2020 to 2080 in the IPCC's four illustrative pathways. An extension of the lifetime to 80 years would more than double these figures.

Lifetime extensions are not only significantly cheaper than new build projects, but are also currently cost competitive with all low carbon generating technologies; this is projected to remain the case until at least 2040 [142]. Most recent estimates of the capital cost for the LTO of light water reactors range between US $400 and 650/kW for projects in much of Europe and the USA [11, 53, 142–144]. With a 7% real discount rate, the LCOE for nuclear LTO lies in the range of US $30–40/MW·h, based on an extension of 10–20 years and without accounting for the financial benefits of delaying decommissioning costs (see Fig. 32). The power generation costs of other technologies and electricity market prices are likely to stay well above these levels in the next decades, making nuclear LTO an economically attractive proposition in most countries [142].

Compared with a nuclear new build, LTO projects are less capital intensive, feature significantly shorter construction and payback times, and have a good track record in controlling costs and limiting construction delays. Also, the operation period of an LTO project (i.e. up to 20 years in addition to the original lifetime) is similar to the operational lifetimes of many wind and solar PV projects. These aspects are likely to reduce project risk significantly, thus easing financing and allowing for a lower cost of capital.

However, despite such attractive economics in the long term, several NPPs have been prematurely shut down in some countries owing to unsustainable wholesale electricity prices, and there is uncertainty over whether or not to

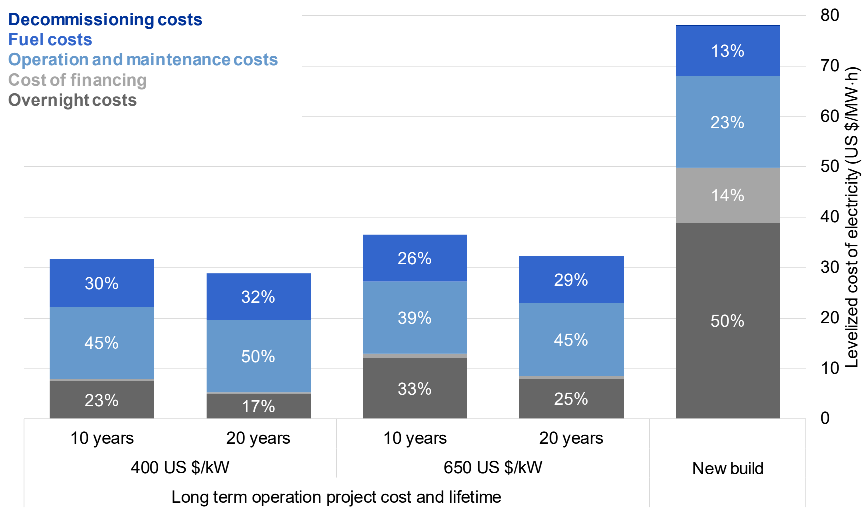


*FIG. 32. LCOE generation: LTO versus new build. Source: IAEA estimates based on Ref. [53].*

embark on LTO in several others. In addition to low electricity prices, the main barriers include insufficient carbon prices and the absence of mechanisms to value and remunerate the system services provided by nuclear power, together with political uncertainty over the future role of nuclear power in some countries (see also discussions in Sections 3.3 and 3.4).

Nonetheless, with effective measures to address these barriers (see Section 3.3), LTO, in combination with new builds of NPPs, responds to the need for both immediate and sustained longer term climate action. Beyond this substantial decarbonization potential of conventional NPPs, emerging NPP designs may provide avenues to reduce emissions in broader applications and markets as discussed in the following section.

## 4.3. DEPLOYMENT VIABILITY OF SMALL MODULAR REACTORS: MARKETS AND ECONOMICS

Smaller NPPs could augment the contribution of nuclear power to climate change mitigation by supplying low carbon energy needs in sizeable niche markets and for applications less suited to other low carbon technologies (including conventional NPPs). An emerging category of small NPPs comprises SMRs, with ‘small’ referring both to the power level and the construction approach. While the power level of conventional nuclear power reactor designs has increased up to 1700 MW over the decades to take advantage of economies of scale, SMRs are purposely designed to deliver 300 MW or less [145]. The modular approach to SMR construction enables standardization and flexible applications: a small plant can be built using a single SMR, a large plant can be built from multiple units or multiple identical units can be built on different sites, managed and maintained by a single company or organization. While all SMRs share these general features, multiple and diverse SMR designs exist at various technology and licensing readiness levels. Proponents of SMRs aim to offset their inherent diseconomies of scale with improved economics of serial production through modularization — this concept and rationale is illustrated in Fig. 33.

Two categories of markets can be identified for SMRs: (1) markets that are equally accessible for traditional NPPs with large reactors and (2) markets and applications that are less suited or inaccessible to large reactors.

The first market category includes electricity supply in countries with well developed grids, in electricity systems driven primarily by economic imperatives. Such systems may already include large NPPs. To be competitive in such markets, the SMR 'diseconomy of scale' needs to be compensated by the 'economy of multiples' that can be achieved with modularization [147].

The benefits of modularization include a faster construction schedule and reduced costs. A study on experience in other sectors (buildings, offshore oil and gas, and submarines) indicates savings on average of 15% in construction costs and 38% in schedule costs [146]. Other factors contributing to the competitiveness of SMRs are the possibility for incremental capacity additions and the learning effect [146, 148].

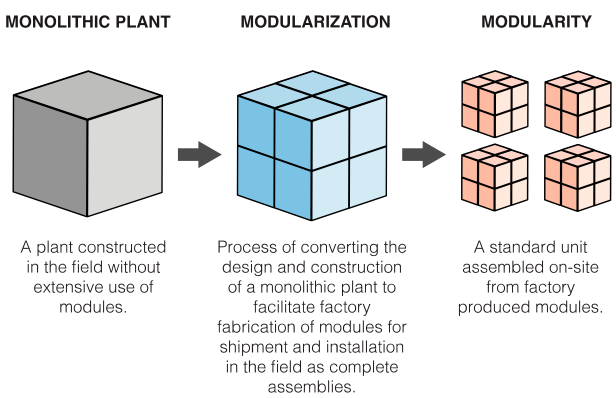


*FIG. 33. Interlinkage of monolithic plant construction, modularization and modularity. Source: Ref [146]. 'Meaning of modularization, modularity, standardization, stick-built' by Mignacca and Locatelli is licensed under CC BY 4.0. To view a copy of this licence, visit https://creativecommons.org/licenses/by/4.0.*

The second potential market for SMRs comprises areas and applications that are less accessible or poorly suited to large NPPs (or other low carbon technologies). This could be related to geography, for example, including small islands (see below) and areas with limited access to cooling water, or to technical (small grids) or financial (limited capital available) conditions which limit the suitability of large scale alternatives. One potential market includes developing economies, for which SMRs could be more affordable in terms of capital cost and easier to finance, with shorter construction times and a different risk profile to conventional NPPs.

As mentioned, SMRs may be well suited for providing power (and potentially heat) on small islands. The economic feasibility of SMRs has been evaluated [147] for three small islands in different parts of the world: Tasmania (Australia), Jeju (Republic of Korea) and Tenerife (Spain). In these cases, SMRs are estimated to be competitive if they can achieve average generation costs of less than US $100/MW·h for Jeju, US $80/MW·h for Tasmania and US $140/MW·h for Tenerife. Similar opportunities exist for other islands, such as many islands of Greece [149].

Another market where interest has been increasing recently is the mining sector, especially among those companies operating in remote locations. This sector has significant energy needs that are currently largely met by diesel. Possible business models could involve partnerships between mine operators and experienced SMR operators to license, build, operate and own the plant and provide combined heat and power services to the mining operation [150].

Significant milestones have been attained in the deployment of demonstration SMR projects. The Akademik Lomonosov, a 70 MW floating power unit comprising two compact pressurized water reactor modules was connected to the electricity grid in Pevek, Russian Federation, in December 2019. This will be followed by startup commissioning of a 210 MW high temperature pebble bed modular reactor in Shidao Bay, China, in 2021. Additionally, a 25 MW integral pressurized water reactor type SMR (CAREM) is at an advanced stage of construction in Atucha, Argentina.

These represent government driven projects with development histories of more than ten years. In recent years, however, multiple new SMR designs have been proposed [151]. While many appear promising in the R&D phase, it remains unclear if and how these designs will progress towards demonstration and commercialization — i.e. which stakeholders, whether utilities, industries or even research laboratories, will be the prime mover of these technologies. In countries with both private and public partners to support a demonstration project, there is a need for appropriate risk sharing between the two, as novel SMR technologies carry unique risks. In addition, if there are only public partners, a proper understanding of project and financial risks is needed.

A successful demonstration project will be critical as a proof of concept before industry can seriously consider the option [150]. However, in recent years, several government-led initiatives have been established. For example, the Canadian Nuclear Laboratories are aiming to demonstrate at least one prototype by 2026 and have called for proposals to site an SMR demonstration unit at one of their campuses. Four companies have entered the process so far, Global First Power, Terrestrial Energy, StarCore Nuclear and U-Battery Canada, each with different SMR designs. Global First Power has submitted an application for a 'Licence to Prepare Site' on the premises of the Canadian Chalk River Laboratories [152]. Similarly, the US Department of Energy is working with NuScale Power and a local utility to develop the so called Joint Use Modular Plant, with the first reactor module of an NPP to be built at Idaho National Laboratory in the mid-2020s and dedicated to nuclear energy research [153].

To support its Member States in making an informed decision on supporting SMRs in their respective countries, the IAEA has developed a set of deployment indicators to evaluate the potential of SMRs in a national energy portfolio. It elaborates the specific attributes of SMRs and evaluates their deployment potential considering energy demand, finance and economics, infrastructure, climate change and energy security. Member States can further adapt the process to specific national needs [151].

While SMRs appear to be a promising and potentially valuable complement to conventional NPPs in the energy transition, one factor affecting their uptake, and that of all nuclear energy technologies, will be the level of public and political acceptance. The urgency of the climate crisis and the mitigation potential of nuclear power identified by the IPCC and others suggest that securing stakeholder support for nuclear power is likely to be key for achieving the 1.5°C goal. The next section reviews several elements for effective stakeholder engagement.

### 4.4. IMPROVED UNDERSTANDING THROUGH STAKEHOLDER INVOLVEMENT

A culture of transparency and openness is the basis for addressing the legitimate concerns of stakeholders regarding nuclear power, including its role in climate change mitigation. These concerns usually include issues very specific to nuclear power generation, such as severe accidents with radioactive releases, nuclear security and radioactive waste management.

An effective stakeholder engagement strategy begins with clear objectives, messages and resources. Stakeholders should be identified and their interests, needs, expectations and concerns researched and recognized. The involvement of relevant stakeholders in a decision making process should also be determined as appropriate. This applies not only to nuclear power generation, but to all large infrastructure projects, including renewable energy projects.

The IAEA's International Conference on Climate Change and the Role of Nuclear Power in 2019 reaffirmed the need to break down barriers around misperceptions of nuclear power and its role in climate change mitigation. The conference also highlighted efforts across Member States to engage a broader range of stakeholders, including environmental groups, and to more effectively communicate about nuclear power using plain language, clear narratives and strong visuals.

In addition to the public, other stakeholders from local communities, the media, vendors, government authorities and decision makers, professional bodies and special interest groups, among others, might be identified. The latter may include "non-governmental organizations such as labour unions, consumer groups, environmental groups and anti-nuclear groups" [154]. Whereas environmental groups usually focus on a variety of causes, often including combating nuclear power, anti-nuclear groups have this as a single focus.

Over the years, some environmental groups have evolved into multimillion dollar international organizations with substantial income from donations and contributions, and with a natural interest to serve their donors. Any new nuclear programme should expect to engage not only with the local public, communities and organizations, but also with established anti-nuclear environmental organizations outside the country where the reactor(s) will be sited.

One of the most pressing objectives for the nuclear power community is to more clearly position itself within the environmental community. As a low carbon energy source, nuclear power is already a key component in climate change mitigation and has the potential to play an even larger role, as illustrated in Section 2.3. Building relationships and partnerships with organizations that are also working to mitigate climate change is one area for the nuclear power community to focus on. This means being ready to answer difficult questions in clear language and being open to participating in challenging conversations. This is part of the process of building trust based on listening to the views of others and finding common ground around shared values. It will never be possible for all stakeholders to agree, but a practice of openness to dialogue is important to cultivate.

An important factor influencing the acceptance of nuclear power is knowledge. It is important that people feel adequately informed about nuclear energy and related issues, including climate change. The low carbon nature of nuclear power, illustrated in Fig. 5, is widely unknown. For example, 51% of Americans think nuclear power worsens climate change, while 60% of Canadians and 70% of the French do not think nuclear power is low carbon [155].

The IAEA's International Conference on Climate Change and the Role of Nuclear Power also considered good practices to increase knowledge about nuclear power, and in turn increase favourability towards it. Figure 34 shows an example from public surveys in the USA of the relationship between favourability to nuclear power and the extent to which the survey respondent feels informed about the technology. It shows a strong correlation between perceived knowledge and favourability; a similar effect was also reported in case studies in 11 other countries [157]. The importance of providing a factual narrative on nuclear power, with understandable messages delivered by trusted third party sources including the climate change community — comprising international and national policy, research and other organizations, including environmental groups — was also broadly underscored at the conference [13].

One role of the IAEA is to help countries that choose to include nuclear power in their energy mix to do so in a sustainable manner. Key entities such as governments, regulatory bodies and the owners and operators of nuclear facilities will have a statutory responsibility to engage with stakeholders. Guidance provided by the IAEA targets those entities, but can also be useful for other groups and organizations looking to participate in a discussion on nuclear power. Capacity building support from the IAEA in the area of stakeholder involvement includes publications, training courses, technical meetings, workshops, expert missions, webinars, scientific visits and the IAEA Nuclear Communicator's Toolbox [158]. In 2019, for example, a webinar series on Stakeholder Involvement Related to

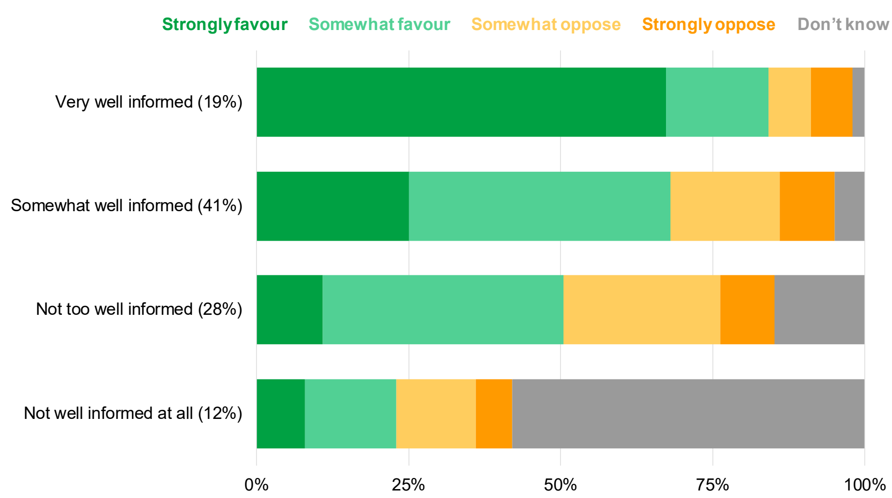


*FIG. 34. Favourability to nuclear energy by level of feeling informed about nuclear energy, based on a 2019 public survey in the USA (adapted from Ref. [156] with permission).*

Nuclear Power [159] was launched to support organizations in developing and implementing effective stakeholder involvement programmes, focusing on topics such as engagement strategies, public information centres, social media, plain language messaging and media relations. Stakeholder engagement is also one of the issues covered in the IAEA's Milestones approach, a structured methodology used by Member States for the development of infrastructure for a new nuclear power programme [66].

The IAEA has also developed guidelines on strategic environmental assessment for governments considering nuclear power programmes [160]. A strategic environmental assessment report should include the engagement and participation process, with the results of stakeholder mapping and an outreach strategy to engage with each of the identified stakeholder groups. With regard to nuclear safety, IAEA Safety Standards Series No. GSG-6, Communication and Consultation with Interested Parties by the Regulatory Body [154], provides guidance on how communication and consultation enable the regulatory body to make informed decisions and on how to develop awareness of safety among interested parties, thereby promoting safety culture.

These and other initiatives can provide a foundation of improved understanding and stakeholder support. This is key not only for capitalizing on the valuable characteristics of nuclear energy for the low carbon transition, but also for planning and realizing the transition more broadly. As discussed earlier, the scale, scope and pace of action needed to meet the 1.5°C goal will require whole-of-society engagement, and decision making that can evaluate and reconcile the synergies and trade-offs associated with different mitigation options and low carbon technologies. Decision makers will need to establish the policy and regulatory frameworks supporting all low carbon technologies and better aligning investment with the 1.5°C goal, while adapting and climate-proofing the energy sector. Within such frameworks, today's nuclear energy industry can provide the foundation to realize the widely recognized mitigation potential of nuclear power and thereby drive more ambitious climate action. This includes ensuring that nuclear power's contribution to mitigation can be maintained in the near term through extended operation of existing plants (which are today providing substantial low carbon power), while scaling up supply chains, unlocking financing and developing advanced technology options to ensure that nuclear energy's role in mitigation matches the scale of the climate and energy challenge.

## Appendix

### IPCC ILLUSTRATIVE 1.5°C PATHWAYS AND NUCLEAR POWER IN SR15: ASSUMPTIONS AND DRIVERS

Table 3 provides additional detail on the methodologies and assumptions underlying the four illustrative 1.5°C pathways from the IPCC's SR15, focusing on factors particularly relevant for the role of nuclear energy. These include features of the methodologies used to quantify the pathway scenarios, including the model concept (e.g. engineering partial equilibrium, economic general equilibrium) and the level of technological detail (e.g. the representation of innovative nuclear applications and technologies and challenges associated with the integration of VRE sources). Scenario assumptions related to the public acceptance and future cost of nuclear power and other low carbon energy technologies are among other key drivers reported in Table 3.

TABLE 3. IPCC ILLUSTRATIVE 1.5°C PATHWAYS AND NUCLEAR POWER IN SR15: ASSUMPTIONS AND DRIVERS
*(data source: Refs [2, 27–30, 59–61, 161])*

| **Pathway** (alternative name) | **P1** (LED) | **P2** (SSP1-19) | **P3** (SSP2-19) | **P4** (SSP5-19) |
|---|---|---|---|---|
| Overall pathway narrative | Low energy demand | Green growth, sustainability | Middle-of-the-road, in line with historical patterns | Rapid development, high demand |
| Methodology and selected assumptions | | | | |
| *Model scope and detail*[a] | | | | |
| Model (Institute) | MESSAGEix GLOBIOM 1.0 (IIASA, Austria) | AIM/CGE 2.0 (NIES, Japan) | MESSAGE GLOBIOM 1.0 (IIASA, Austria) | REMIND-MAgPIE 1.5 (PIK, Germany) |
| Model concept | Energy engineering and land use partial equilibrium models soft linked to general equilibrium model | General equilibrium with technology explicit modules in power sector | Energy engineering and land use partial equilibrium models soft linked to general equilibrium model | Economic growth model coupled with detailed energy system model and simple climate model |
| Advanced, SMR designs | No (see below: ‘Other nuclear assumptions’) | No | No | No |

TABLE 3. IPCC ILLUSTRATIVE 1.5°C PATHWAYS AND NUCLEAR POWER IN SR15: ASSUMPTIONS AND DRIVERS
*(data source: Refs [2, 27–30, 59–61, 161])* (cont.)

| **Pathway** (alternative name) | **P1** (LED) | **P2** (SSP1-19) | **P3** (SSP2-19) | **P4** (SSP5-19) |
|---|---|---|---|---|
| Non-electric nuclear applications | Process heat (plus non-dedicated electrolysis, power-to-gas) | No | Process heat (plus non-dedicated electrolysis, power-to-gas) | No (plus non-dedicated electrolysis) |
| Grid integration of renewables | Implicitly modelled | Not modelled | Implicitly modelled | Explicitly modelled |
| *Technology-specific characteristics* | | | | |
| Nuclear capital cost | 2050: US $2600/kW | Medium progress towards 2050 cost target based on OECD IEA 2012 ($US_{2010}$ $4000/kW) | 2100: Gen II: $US_{2005}$ $3500–4000/kW; Gen III/IV: $US_{2005}$ $3000–3500/kW | US $4000/kW |

TABLE 3. IPCC ILLUSTRATIVE 1.5°C PATHWAYS AND NUCLEAR POWER IN SR15: ASSUMPTIONS AND DRIVERS
*(data source: Refs [2, 27–30, 59–61, 161])* (cont.)

| **Pathway** (alternative name) | **P1** (LED) | **P2** (SSP1-19) | **P3** (SSP2-19) | **P4** (SSP5-19) |
|---|---|---|---|---|
| Other nuclear assumptions | "only reconcilable [with pathway narrative] under assumptions of highly standardized, reduced-complexity modular reactor designs" [30] | Low social acceptance (implemented as 0.1 scaling factor in logit function for allocating investment in generation) | Load factor increases from 70% to 85% (2010 to 2100) | Intermediate outlook with medium/high technology development; uranium supply curve without limit; and medium social acceptance |
| Other low carbon electricity generation capital costs | For 2050 ($US_{2010}$ \$/kW):<br>Wind: 500<br>Solar PV: 120<br>Industrial solar heat: 100<br>Batteries: 100<br>Electrolytic hydrogen: 200 | "High" rate of renewable energy cost decrease<br>For 2050 ($US_{2010}$ \$/kW):[b]<br>Wind (onshore): 1430<br>Solar PV: 750 | For 2100 ($US_{2005}$ \$/kW):<br>Wind: 700<br>Solar PV: 1000 | Floor costs (US $/kW):<br>Wind: 1000<br>Solar PV: 700 |
| Other | No CCS | High renewable energy preference | | |

TABLE 3. IPCC ILLUSTRATIVE 1.5°C PATHWAYS AND NUCLEAR POWER IN SR15: ASSUMPTIONS AND DRIVERS
*(data source: Refs [2, 27–30, 59–61, 161])* (cont.)

| **Pathway** (alternative name) | **P1** (LED) | **P2** (SSP1-19) | **P3** (SSP2-19) | **P4** (SSP5-19) |
|---|---|---|---|---|
| | | **Role of nuclear power** | | |
| Nuclear electricity generation, 2050 (PW·h) | 6.7 | 5.9 | 15.9 | 16.1 |
| Share of low carbon (total) generation, 2050 (%) | 14 (13) | 10 (9) | 29 (25) | 25 (23) |
| | | **References** | | |
| Main source | [30] | [29, 59] | [29, 60] | [29, 61] |

[a] See section 2.SM.2 and table 2.SM.6 in Ref. [161].
[b] IAEA estimate based on Refs [59, 162].

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# ABBREVIATIONS

| | |
|---|---|
| CCGT | combined cycle gas turbine |
| CCS | carbon capture and storage |
| $CO_2$-eq | carbon dioxide equivalent |
| COP25 | 25th Conference of the Parties to the UNFCCC |
| CSP | concentrated solar power |
| DFI | development finance institution |
| ETS | emissions trading system |
| EU | European Union |
| GDP | gross domestic product |
| GHG | greenhouse gas |
| LCOE | levelized cost of electricity |
| LTO | long term operation |
| NDC | nationally determined contribution |
| NPP | nuclear power plant |
| ppm | parts per million |
| PV | photovoltaic |
| R&D | research and development |
| SMR | small modular reactor |
| SR15 | Special Report on Global Warming of 1.5°C (IPCC) |
| UNFCCC | United Nations Framework Convention on Climate Change |
| VRE | variable renewable energy |

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This publication provides an update on the current status of nuclear power and prospects for its contribution, together with other low carbon energy sources, to ambitious mitigation strategies that will help the world limit global warming to 1.5°C in line with the 2015 Paris Agreement. Since 2000, the IAEA has issued such information and analysis regularly, in order to support those Member States that choose to include nuclear power in their energy system as well as those considering other strategies. The focus of the 2020 publication is on the significant potential of nuclear energy, integrated in a low carbon energy system, to contribute to the 1.5°C climate change mitigation target, and the challenges of realizing this potential. Energy system and market related factors affecting the transition to a low carbon energy system are reviewed. This edition also outlines developments needed to realize the large scale capacity increase required to rapidly decarbonize the global energy system in line with limiting global warming to 1.5°C.

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