Nuclear Technology Development and Economics
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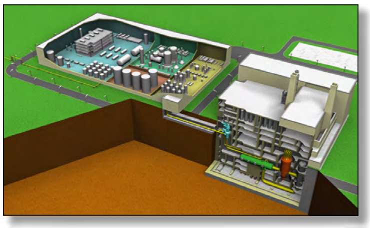
Advanced Nuclear Reactor Systems and Future Energy Market Needs



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Nuclear Technology Development and Economics

Advanced Nuclear Reactor Systems and Future Energy Market Needs

NEA No. 7566

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The mission of the NEA is:

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- to provide authoritative assessments and to forge common understandings on key issues as input to government decisions on nuclear energy policy and to broader OECD analyses in areas such as energy and the sustainable development of low-carbon economies.

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management and decommissioning, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

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Foreword

Energy market needs are changing in the context of global efforts towards decarbonisation. The rapid increase of variable renewable energy sources in electricity systems has resulted in a commensurate increase in the needs or requirements for more flexible operation, for example through demands on the load-following capabilities of more conventional resources such as nuclear power plants. The development of energy storage capacities and demand smoothing could help to moderate these growing demands. Using nuclear power technologies for residential and industrial heat is another potential option that could contribute to further decarbonisation.

Nuclear power plants have already contributed to load-following generation and to industrial and residential heat supply initiatives in some regions. In fact, several countries have decades of experience in load-following operations or cogeneration. More advanced generation III nuclear reactor designs have even greater flexibility than the previous generations of reactors in this regard, and the advanced nuclear reactor systems currently under development are expected to have even more preferential features such as inherent safety and the production of higher temperature heat. Small modular reactors are also of increasing interest for their potential advantages in terms of deployability and compatibility, as well as for their financial characteristics.

Advanced Nuclear Reactor Systems and Future Energy Market Needs investigates the changing needs of energy markets, and the potential role of nuclear energy as a low-carbon energy source. Possible applications for advanced nuclear reactors under development today are examined in detail in the different chapters of this report, exploring to what extent these reactors can address future energy market needs.

Acknowledgements

This report is a reflection of discussions that have taken place over a three-and-a-half-year period since July 2017, and over four meetings of the Nuclear Energy Agency (NEA) Expert Group on Advanced Reactor Systems and Future Energy Market Needs (ARFEM), chaired by Dr Aiden Peakman. The list of members of the ARFEM Expert Group can be found in the Annex of this report. Expert group members have participated in four meetings and two workshops with the advanced reactor stakeholder community, with representatives presenting relevant work in their individual countries. This report could not have been produced without their valuable contributions, or without the work of all of the many experts who helped to collect and assemble information for this report. The NEA would also like to express its sincere gratitude to the members of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) for their valuable comments.

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List of abbreviations and acronyms

ARFEM	Expert Group on Advanced Reactor Systems and Future Energy Market Needs (NEA)
ARS	Advanced nuclear reactor system
BEV	Battery electric vehicle
BNEF	Bloomberg New Energy Finance
CAES	Compressed air energy storage
CCUS	Carbon capture, use and storage
CDF	Core damage frequency
CO_2	Carbon dioxide
CSP	Concentrated solar power
DOE	Department of Energy (United States)
EDF	Électricité de France
EPRI	Electrical Power Research Institute
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
Gen-III/III+	Generation III and III+ (reactors)
Gen-IV	Generation IV (reactors)
GFR	Gas-cooled fast reactor
GHG	Greenhouse gas
GIF	Generation IV International Forum
HTR	High-temperature reactor
HTTR	High Temperature engineering Test Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
JAEA	Japan Atomic Energy Agency

LFR	Lead-cooled fast reactor
LWR	Light water reactor
MSR	Molten salt reactor
NEA	Nuclear Energy Agency
NICE Future Initiative	Nuclear Innovation: Clean Energy Future Initiative
OECD	Organisation for Economic Co-operation and Development
PHS	Pumped hydro storage
P_{ref}	Rated power (reference power)
PV	Photo-voltaic
PWR	Pressurised water reactor
R&D	Research and development
RD&D	Research, development and deployment
RES	Renewable energy sources
SCWR	Supercritical water-cooled reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
VHTR	Very high-temperature reactor
VRE	Variable renewable energy

Executive summary

The needs of energy markets are continuously changing in the context of the global movement towards a carbon neutral economy, increased liberalisation of energy markets and the development of various energy-related technologies. Electricity systems are also changing with increasing penetration of variable renewable energy sources, the enhancement of interconnection capacities and the development of storage technologies. Development of demand-side management technologies and changes in electricity consumption patterns affect not only electricity generation capacity needs but also the needs for reserve and frequency control capacities. In addition to their role in electricity systems, low-carbon energy sources can also help to unlock hard-to-abate sectors, such as heavy industry and transport, and various efforts are underway around the world to develop these alternative energy sources, including low-carbon heat supply and hydrogen production technology.

Currently, various advanced nuclear reactor systems – evolutions of today's generation III and III+ reactors, small modular reactors and generation IV reactors – are under development and are capable of offering more flexible options with respect to energy supply. In order to analyse how and to what extent these technologies will be able to address future energy market needs and conditions, as well as the possible environmental and regulatory constraints that might arise as a result of such technologies, the OECD Nuclear Energy Agency (NEA) established the Expert Group on Advanced Reactor Systems and Future Energy Market Needs (ARFEM). The expert group investigated the current situation and future prospects of energy market needs, as well as the characteristics and prospects in relation to the development of advanced reactor systems. It also identified several key factors that would help maximise the potential benefits of advanced reactor systems in future energy markets.

Future market opportunities and requirements

The needs for flexible power operation from power plants, which cover both shorter-term and longer-term flexibility, are growing as variable renewable sources are increasingly penetrating into electricity grids, with utilities in the United States and Europe recently issuing a new set of requirements regarding the flexibility of future light water reactors.[1] Current generation III/III+ reactor technologies are already compliant with the latest grid operators' requirements. Future advanced reactor system concepts, including small modular reactors and generation IV reactors, have different characteristics (advantages and challenges) for flexible operation, making it important for flexibility requirements to be taken into account by developers.

The role of nuclear power in the electricity system may be more diverse than ever in future, depending on the regional characteristics of the system to which it belongs. While the increasing share of variable renewable energy sources could create further needs or requirements for flexible power operation, the development of electric vehicles, demand-side management and storage technologies could allow conventional plants such as nuclear power plants to operate at high-capacity factors, even under scenarios with significant variable renewable sources deployment. Advanced reactor systems are capable of providing not only firm capacity to help the electricity system ensure sufficient supply and system stability (e.g. inertia) but also to ensure manoeuvrability over a wide range of timescales, from very-short-term (frequency response) to seasonal dispatchability. Ultimately, the benefits that advanced reactor systems will provide to electricity systems will depend on their individual characteristics.

1. For further details, see Section 4.2.1 on manoeuvrability.

The heat sector, which accounted for about 50% of final energy consumption globally in 2018 and about 40% of energy related carbon dioxide (CO_2) emissions, is another area where advanced reactor systems can make a significant contribution to decarbonisation. Low-temperature heat (<300°C) for district heating, seawater desalination and for some industrial process heat systems can be provided by nuclear reactor systems that are already available, and higher temperature heat (<550°C) could be provided by many generation IV concepts under development. A large percentage of the current global heat demand falls in this latter temperature range of heat. In terms of small modular reactor systems, the aim is to achieve higher deployment flexibility in order to allow these systems to be located closer to regions of demand, for example nearby industrial sites.

Hydrogen production by advanced nuclear reactor systems (ARSs) could significantly contribute to the reduction of CO_2 emissions in many sectors. All advanced reactor system concepts can produce hydrogen using the existing low-temperature electrolysis technology, and some concepts could supply process heat at over 750°C, producing hydrogen with even higher efficiency through high-temperature electrolysis or thermo-chemical processes. Alongside infrastructure development for hydrogen use currently under investigation around the world, the role of advanced reactors systems in hydrogen production should also be underlined for the potentially significant contribution it could make to decarbonising hard-to-abate sectors such as industry, buildings and some elements of transport. Some national research and development programmes are working on the economic and technical challenges associated with coupling nuclear reactors to hydrogen-producing facilities.

In addition to the potential benefits associated with closed fuel cycles, for example minimising radioactive waste and enhancing resource use in the longer term, other potential benefits of generation IV systems, particularly the higher temperatures, may prove to be another strong motivation for deploying such systems in the short to medium term. For those generation IV systems that can demonstrate high levels of passive safety over conventional reactor systems, co-location on certain sites (e.g. industrial facilities) may also be a valuable option.

Policy recommendations

The characteristics and needs of energy markets are becoming more diverse, and the strategies being employed in global efforts to reach carbon neutrality vary depending on the geological and social conditions of different countries or regions. Advanced reactor systems could adapt to such diverse needs and contribute in a variety of ways to the reliability and decarbonisation of future energy systems. In order to maximise that potential, the NEA is proposing the following policy recommendations:

- The potential of advanced reactor systems as a low-carbon, cost-effective means to support country policies with respect to low-carbon emission targets and variable renewable energy deployment should be recognised.
- Non-electric applications involving advanced reactor systems should be included in policymaking considerations.
- Governments and industry should work together to demonstrate the current capabilities of advanced reactor systems in target markets.
- International collaboration should be promoted to improve the economic viability of advanced reactor system development.
- Public understanding for advanced reactor systems should be continuously fostered.

1. Introduction

With the adoption of the United Nations Sustainable Development Goals and the Paris Agreement in 2015, many countries are making major efforts to decarbonise their economies. The electricity sector is said to be the vanguard for decarbonisation because of the commercial availability of a diverse suite of low-emission technologies. The average carbon intensity of electricity improved by 10% between 2010 and 2018 as the result of efforts including energy efficiency improvements and low-carbon technology deployment (IEA, 2019a). However, the electricity sector is still the largest emitter of carbon dioxide (CO_2), accounting for around 40% of energy related CO_2 emissions in 2020. CO_2 emissions from the global electricity sector have been increasing even as global deployment of low-carbon energy technologies have expanded, largely because growth in demand has offset the gains associated with the reduced emission intensity of grids (IEA, 2021).

Electricity systems across the world are rapidly changing, with an increasing share of renewable or decentralised electricity sources such as solar photo-voltaic (PV) and wind power plants (IEA, 2018). The high penetration of renewables has however led to considerable challenges. The intermittent characteristics of renewable energy sources, for example, increase the need for flexibility from other power supply sources, leading to questions about the resiliency of the electric grid associated with variable supply and demand need scenarios. Under these circumstances, the majority of advanced nuclear reactor systems (ARSs) under development are taking into account such elements in order to provide the required support to the grid. Conventional nuclear power plants, for their part, have recently been re-evaluated in relation to their actual and/or potential contributions to grid stability through inertia and frequency responses (EDF, 2018; Tielens, 2019).

In this context, the world nuclear community has been raising some important questions. For example, what is the role of the advanced nuclear reactor system in the future electricity system? How are current designs under development taking into account future energy market considerations? What are the challenges, including with respect to flexibility, to be resolved in order for nuclear power to fulfil its role in future electricity systems?

In addition to potential contributions to the electricity system, there is growing interest in the diverse uses of nuclear energy for decarbonising the energy sector. Heat represents a significant proportion of final energy consumption and CO_2 emissions globally (IEA, 2019b). Existing nuclear power plant technology has already proven that it can supply district heat, with several countries having extensive experience in this sector, although the overall contribution of nuclear energy to this sector is negligible to date (IAEA, 2017; IEA, 2014). Hydrogen is considered to have great potential for decarbonisation in various sectors, and particularly as an energy carrier that can replace fossil fuels. Different means of low-carbon hydrogen production are currently under development, including ones employing nuclear power (IEA, 2019c).

Given that the future potential of nuclear power extends beyond electricity systems to the various energy sectors mentioned above, in May 2017, the Nuclear Energy Agency (NEA) created the Expert Group on Advanced Reactor Systems and Future Energy Market Needs (ARFEM) to analyse what the future energy market would look like. The ARFEM was tasked with examining how and to what extent the technical features of ARSs, such as flexible operation and non-electricity applications, could address future energy market needs. The expert group would also examine external conditions, including regulations and policies. Apart from expert group meetings, two NEA workshops were held in April 2017 and September 2019, with experts attending from around the world. These experts represented industry (vendors, utilities), research institutions, regulatory authorities, grid operators, energy analysts and economists.

Advanced Nuclear Reactor Systems and Future Energy Market Needs is the result of these discussions. The report aims to provide non-technical readers with an understanding of the overall characteristics and potential advantages of advanced nuclear reactor technologies under development for the future energy system. It is divided into the following chapters:

- Chapter 2: Understanding future energy markets, including the electricity system, non-electric market and energy storage.
- Chapter 3: Overview of advanced reactor systems, including generation III and III+ reactors, small modular reactors, and generation IV reactors.
- Chapter 4: Analysis of the flexibility of advanced reactor system, exploring flexible operations that include load following and frequency control, flexible deployment such as scalability and siting, and flexible products, including non-electric applications.
- Chapter 5: Conclusions, including key findings and recommendations for future actions.

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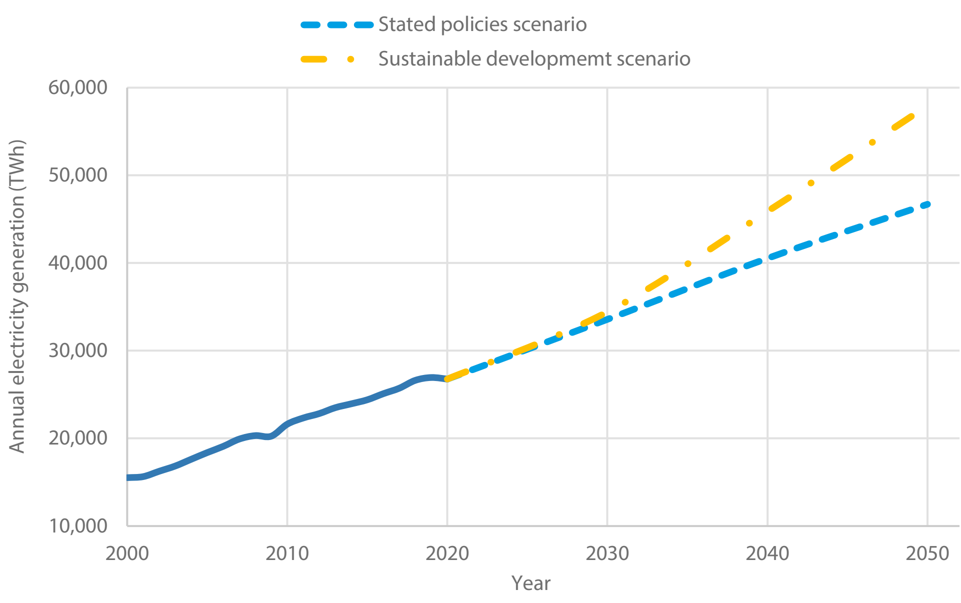
2. Understanding future energy markets

This chapter provides an overview of the current situation and future prospects for energy market needs, more specifically in relation to electricity and heat markets, which the NEA Expert Group on Advanced Reactor Systems and Future Energy Market Needs (ARFEM) found to be the most relevant markets where advanced nuclear reactor systems (ARSs) could participate in the future. The potential of hydrogen as a future energy carrier that can be produced by either electricity or process heat is also discussed.

2.1 Electricity

Electricity consumption has been increasing steadily around the world, and this trend is expected to continue in the future (see Figure 2.1.1). Recent years have seen a remarkable increase in this consumption in non-OECD countries as global access to electricity increases alongside new uses, such as transport and digital technologies. Worldwide, electricity generation represented 26 762 terawatt hours (TWh) in 2020, with almost two-thirds produced from fossil fuels, 10% from nuclear, 16% from hydro, 3% from biomass and 9% from wind and solar (see Figure 2.1.2), accounting for around 20% of total energy consumption and 40% of global energy related carbon dioxide (CO_2) emissions (IEA, 2021).

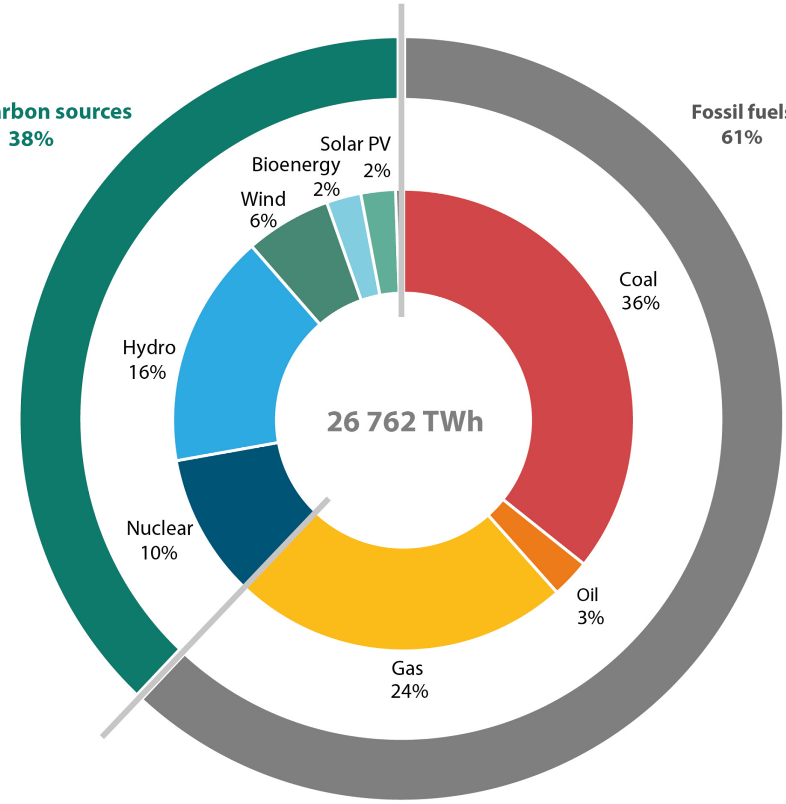
Figure 2.1.1: World annual electricity generation growth under three scenarios



Note: The stated policies scenario considers current and planned policies, including nationally determined commitments under the Paris Agreement on climate change. The sustainable development scenario is aligned with the Paris Agreement and the goals of providing energy access to all while ensuring cleaner air, which involves sharp cuts in emissions across all sectors to limit the global temperature rise below 2ºC.

Source: IEA (2021), *World Energy Outlook 2021*.

Figure 2.1.2: World annual electricity generation by source in 2020



Source: IEA (2021), *World Energy Outlook 2021*.

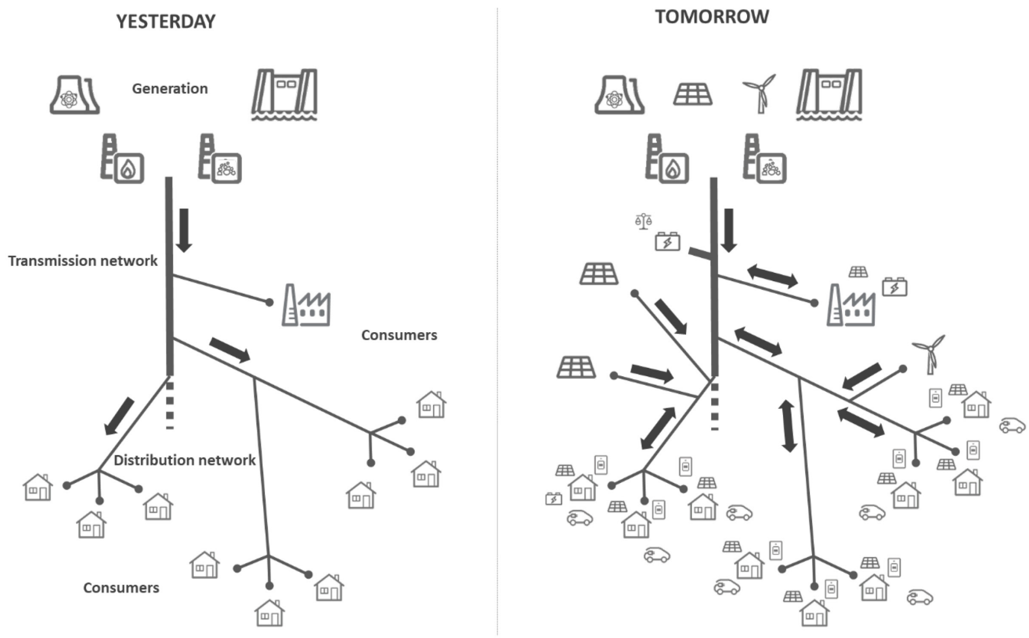
2.1.1 Today's power system

As shown in Figure 2.1.3, a power system is a complex system composed of three main components: power generators, networks (transmission and distribution) and consumers, with the overarching goal of delivering electricity to consumers in real time. The left side of Figure 2.1.3 demonstrates how power systems have traditionally worked (also see Section 2.1.2), and the right side explains how power systems are changing.

In power systems, most power plants are generally centralised, dispatchable[1] units with a sizeable production connected directly to high-voltage transmission lines, as is the case for coal, gas, nuclear or hydro power plants. These plants use fuel to produce electricity, and that fuel acts as a large, long-term storage that contributes to the resilience[2] of the system. Electricity in plants is produced through a synchronous, rotating alternator that contributes to the stability of the system. As a result of public policies and a sharp drop in the cost of solar panels and wind farms, these energy sources are developing rapidly in power systems. Such technologies differ from previous power plants in several ways. Their fuel (i.e. wind and solar radiation) cannot be directly stored. They are connected either to the distribution or the transmission networks through power electronics and are not able to provide the same inertia[3] response as synchronous generators in the case of a system disturbance.

1. A dispatchable plant is a plant that has a predictable production and can adjust its production to the needs of the power system operator.
2. Resilience describes the property of a power system that is able to cope with most uncertainties so as to deliver power with a good level of quality and with very few hours of loss of load.
3. Inertia refers to the tendency to remain unchanged. Inertia provides the ability to autonomously moderate frequency changes in power systems.

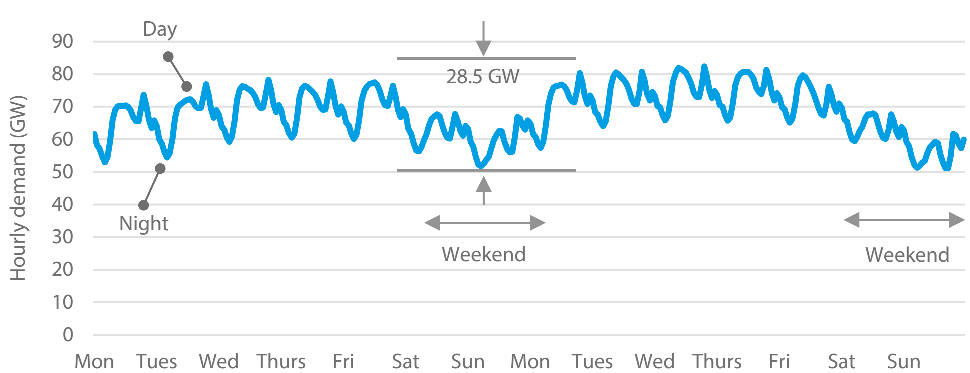
Figure 2.1.3: Evolution of power systems



Power generation is linked to end consumers through a network consisting of several levels. When applicable, a transmission, high voltage network meshes a country or a balancing zone with interconnections to neighbouring zones. The distribution network then lowers the voltage and delivers the power to the consumer in a tree-like network. The use of a large-scale network increases the resilience of the system as well as the quality of the service and ensures cost optimisation, making room for baseload plants and thereby reducing the overall price paid by consumers.

Throughout the day, consumers use electricity for very diverse needs, and overall consumption fluctuates greatly. It also varies between workdays, weekends and holidays, as well as between seasons in most areas of the world, depending on climate and heating or cooling needs as shown in Figure 2.1.4. Power production must nonetheless match the demand in real time since electricity cannot be stored by the grid. In other words, the energy injected by production needs to be immediately withdrawn by consumers.

Figure 2.1.4: Changes in hourly demand during a two-week period in France



Source: RTE eCO2Mix (2016), www.rte-france.com/eco2mix.

Achieving a real-time balance of supply and demand needs to be anticipated many years in advance to the planning of investment to ensure that enough generation capacity is available, as well as network reinforcements, such as increases in transmission capacity or in grid density and grid interconnections. A few months ahead of time, plant maintenance, as well as fuel procurement and reloading, is planned to ensure availability when needed. A day ahead of real time, several iterations of successive scheduling of production are made to match plant generation with increasingly finer predictions of demand, taking into consideration the increasingly accurate forecasted generation for wind and solar generation, as depicted in Figure 2.1.5. The scheduling is carried out taking into account ascending plant variable costs,[4] which differ widely depending on technologies, so as to minimise the final price of electricity as shown in Figure 2.1.6. The last step of the scheduling process is carried out in real time with reserves ensuring a balance of production and demand.

Figure 2.1.5: Steps in planning and scheduling to balance production and demand in real time

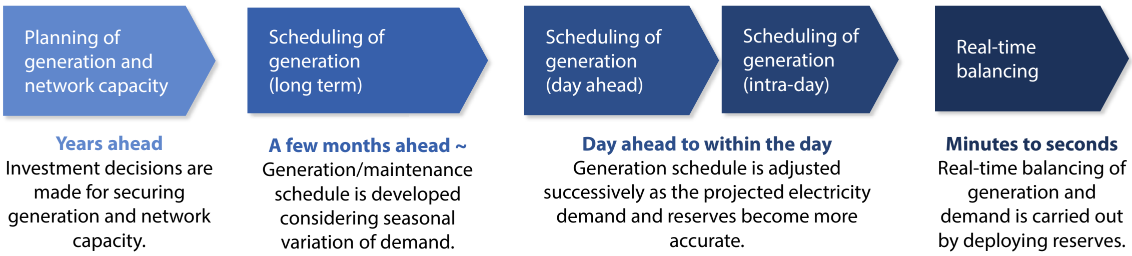
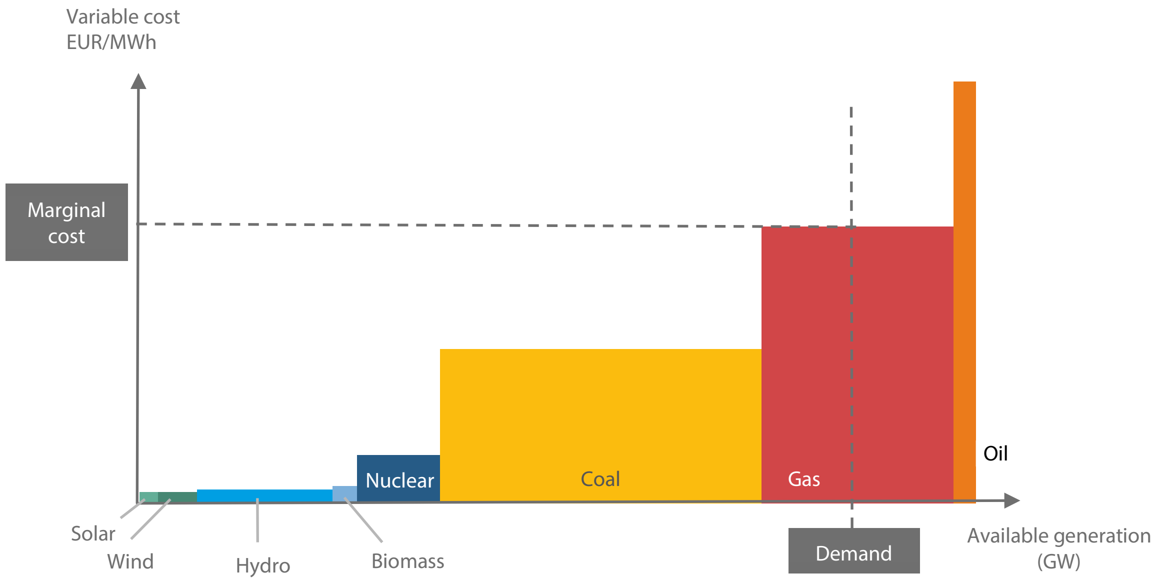


Figure 2.1.6: Simplified schematic representation of hourly scheduling according to ascending plant variable costs



Notes: The marginal cost for the power system is the cost associated with producing an additional megawatt hour (MWh).

4. Variable costs include fuel costs, as well as operation and maintenance costs. They do not include fixed costs, such as capital (investments) costs.

2.1.2 Tomorrow's power system

In 2020 electricity represented 20% of final energy consumption (IEA, 2021). This share has been growing steadily and is set to continue growing in the future with more people getting access to electricity in non-OECD countries. New uses of electricity worldwide will also contribute to this increasing share. These new uses of electricity will include electric vehicles, heat pumps for heating and cooling and green hydrogen obtained through electrolysis, for example, using decarbonised sources of electricity. The electricity sector is at the forefront of ongoing decarbonisation efforts to migrate the energy sector from fossil-fuel based to net zero emissions. Low-carbon technologies to produce electricity are indeed readily available today: renewable energies (hydro, biomass, wind and solar) and nuclear energy. The share of electricity could therefore reach upwards of 50% of final energy consumption with fossil fuel usage ultimately being replaced partially by electricity (IRENA, 2019).

2.1.2.1 Large-scale development of renewable energy sources and impacts on the power system

A massive development of low-carbon electricity generation from variable renewable energy (VRE) sources is currently underway in most of the world's electricity systems and is largely based on the development of hydro, wind and solar photo-voltaic (PV) energy sources. In OECD countries, where hydro is already well exploited, deployment mainly relies on wind and PV development (IEA, 2019a).

VRE generation is mostly decentralised and depends on atmospheric conditions controlling the availability of their primary energy source (i.e. the wind and sun). Their generation can therefore only be forecasted, adding new uncertainties and challenges for power systems.

Wind speeds and solar radiation highly depend on location. Generation at the farm level is very irregular, but generation at a larger scale, such as by region or country, yields a smoother profile. Adding a large share of intermittent VRE into the power system therefore requires a simultaneous and co-ordinated development of transmission and distribution networks, or reinforcements when necessary. Appropriate development of interconnections will make it easier to find a balance between supply and demand, mainly via two means: 1) by allowing more power to be transported from one area to another, and 2) by transforming the issue of managing intermittency at the local distribution network level to handling variability at the level of the interconnected system. This represents an incentive for the aggregation of VRE generation. At the same time, self-supply is a trend that is currently being developed at the level of a building or a neighbourhood in OECD countries where the scale of installations remains small (kilowatts [kW] versus megawatts [MW] for large plants or farms). It is already the norm in countries where the power network is not yet developed.

Aggregating VRE sources over large geographical areas (at a national or a continental level) will allow grids to benefit from geographical diversity, with smart grids[5] further easing the integration of VRE sources. Variability will nevertheless remain high due to both climate effects and the correlation between wind and solar regimes across large geographical areas. With a high share of VRE sources, the exposure of a network to climate conditions and their associated uncertainties will increase significantly.

Large-scale simulations (Burtin and Silva, 2015) show that the traditional generation mix must be adapted because integrating renewable energy yields a reduction of baseload generation and an important increase in the peaking plants that are used as back up. New VRE capacity does not replace conventional plants with a ratio of 1 to 1, as a result of both a low-capacity factor and of the high dependence on atmospheric conditions for VRE sources. The ratio is in fact closer to 1 to 7, i.e. 100 MW of conventional capacity is removed for 700 MW of newly connected VRE sources – these results are based on the European grid, with 60% of VRE sources and an additive of 100 MW of wind turbines.

5. Smart grid: the electricity network system that can control and optimise the flow of electricity from both sides of supply and demand. It is often supported by digital technologies.

The power system will need to be generally more flexible with timescales depending on VRE source integration as shown in Table 2.1.1 (IEA, 2017a, 2017b). For early phases, the system will need to cope with flexibility on short timescales. Conventional plants are thus necessary to achieve a balance of supply and demand at times when VRE sources cannot, and will be, asked to be more flexible so as to adjust to an increasing net demand[6] variability. For later phases of VRE penetration, the need for flexibility moves both to increasingly longer timescales (to meet demand when the availability of wind and solar is low) and to shorter timescales (e.g. frequency response and ramping). Because conventional plants with native, long-term storage and reserves through fuel are being replaced by wind and solar, for which fuel cannot be stored, external storage will become a requirement. The interface of VRE sources with power electronics displaces system inertia and could create more frequent stability issues on the grid after a power imbalance. To ensure adequate system inertia, new services like fast frequency response[7] and kinetic energy supply[8] have become necessary. To a certain extent, storage and active demand may also supplement generation so as to balance supply and demand. During the final stages of VRE penetration, seasonal displacements of generation will become necessary, and low-carbon generation, such as nuclear and hydro, as well as seasonal storage through synthetic fuels such as hydrogen, permits a shift in the generation to times when VRE sources are not available. During the VRE integration process, an optimisation of the pace of deployment will limit the costs of storage or excessive curtailment.

Table 2.1.1: Needs for power system flexibility depending on VRE source integration

<table>
<tr><th>Phase 1</th><th>Phase 2</th><th>Phase 3</th><th>Phase 4</th><th>Phase 5</th><th>Phase 6</th></tr>
<tr><td>No relevant impact</td><td>Impact on net load</td><td>Flexibility key</td><td>Short-term stability problems</td><td>Demand shifting</td><td>Seasonal storage</td></tr>
<tr><td rowspan="5">Typically, no system flexibility issues</td><td></td><td></td><td>Ultra-short-term flexibility (seconds)</td><td></td><td></td></tr>
<tr><td colspan="2">Short-term flexibility (minutes to hours)</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">Medium-term flexibility (hours to days)</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="2">Long-term flexibility (days to months)</td><td></td></tr>
<tr><td></td><td></td><td></td><td colspan="2">Very long-term flexibility (months to years)</td></tr>
<tr><td>India, Mexico</td><td>Australia, People's Republic of China, Japan, United States.</td><td>Greece, Germany, Italy, Portugal, Spain, Sweden, United Kingdom.
California, Texas (United States).</td><td>Ireland, Denmark. South Australia.</td><td></td><td></td></tr>
</table>

Source: IEA (2017a), Getting Wind and Sun onto the Grid: A Manual for Policy Makers. IEA (2017b), Renewables 2017: Analysis and Forecasts to 2022.

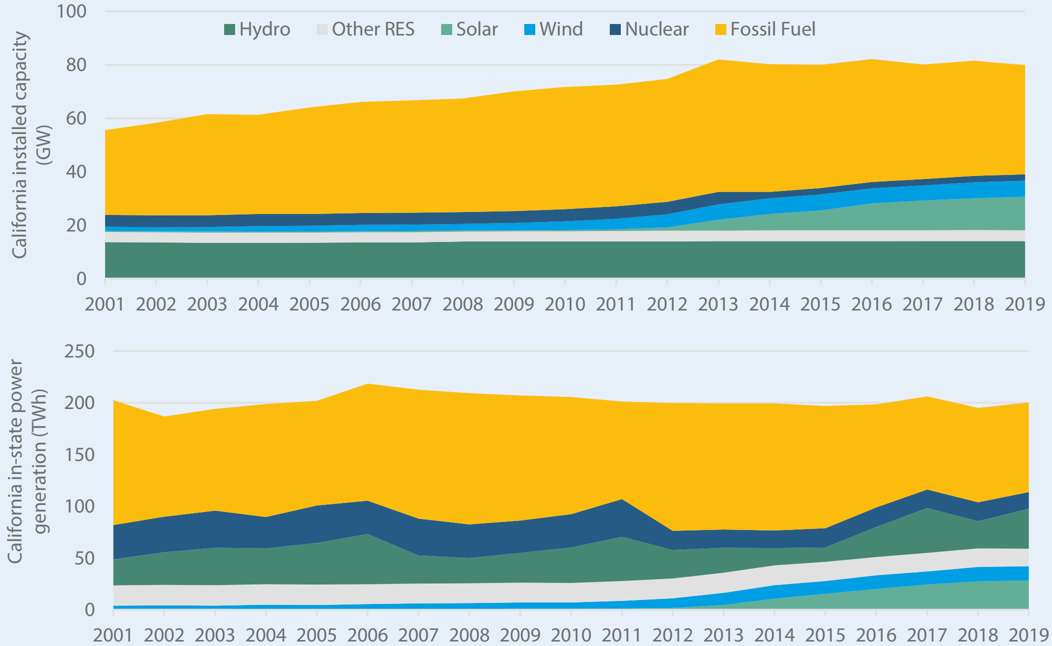
The 2020 heatwave in California highlights some of the difficulties that power systems may encounter in the transition to higher shares of renewables (see Box 1). The need for a global increase in the flexibility of the power system calls for adequate market designs and investment frameworks to ensure that power plants, grids, energy storage and new services, such as demand response, can meet evolving power system requirements.

6. Net demand: total demand minus VRE production.
7. Fast frequency response: the technology that prevents frequency interference in the power grid by injecting power, or reducing the load in less than a minute in response to a system frequency disturbance. It is often equipped with large-scale batteries.
8. Kinetic energy supply: the technology that provides power grids with inertia to absorb fluctuations in power supply and demand and stabilise the frequency, for example through flywheels.

Box 1: A large blackout caused by a record heat wave in California in 2020

California has set ambitious renewable energy targets, and renewable installed capacities have increased sharply in between 2009 and 2019 as seen in Figure B.1.1 below, reaching 13 GW of solar and 6 GW of wind in 2019. In 2019, renewables represented 49% of the total in-state power generation, with 21% from wind and solar, while Figure B.1.1 shows that the total in-state power generation has remained fairly constant since 2001. At the same time, California relies heavily on imports from neighbouring states, from the northwest and the southwest, for about a third of its power consumption.

Figure B.1.1: California in-state installed capacity (GW) and electricity generation (TWh) from 2001 to 2019



Source: California Energy Commission.

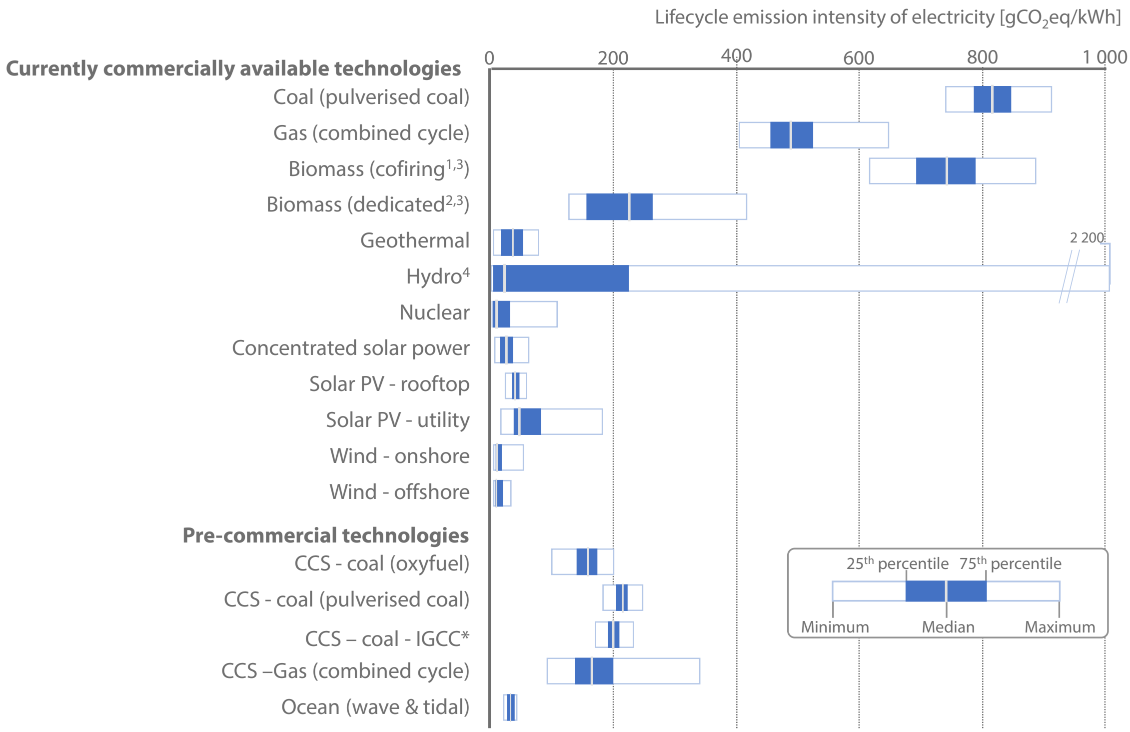
California experienced a record heatwave between 14 and 19 August 2020, increasing the demand for air-conditioning. The power demand was therefore higher than usual as temperatures soared across the west. In addition, the stay-in-place order in effect in California at the time, because of the COVID-19 pandemic, further increased demand. However, the supply could not safely match demand, and several independent events led the Californian Independent System Operator to activate rolling blackouts, leaving hundreds of thousands of California homes and businesses in the dark. The lack of solar generation at night, an abrupt loss of 1 GW of wind, low hydro resources because of the drought and the low snow cover of the previous year all combined with outages on gas power plants and limited availability of import volumes from neighbouring states that needed to supply the higher demand in their own states. Californians were also asked to reduce their power demand so as to minimise the need for further blackouts. A stage-3 emergency had to be issued on Saturday, 15 August at 6:28 p.m. and lifted at 6:48 p.m. when wind generation picked up again. A stage-3 emergency means that the system operator is unable to meet the minimum contingency reserve requirements, and a loss of power is either imminent or already in progress. During the different episodes, deficits in generation were significant. The shortfall was of roughly 1 000 MW on Friday, 500 MW on 15 August and 4 400 MW on the afternoon of 17 August 2020. The system operator had been warning that shortfalls would be imminent following the decommissioning of conventional power plants, including gas thermal and nuclear power plants in California. After the blackout event, plans to shut down high-carbon emitting power plants in southern California, scheduled for the end of the year, were postponed to minimise the impact associated with the further loss of conventional power plants.

This episode highlights the additional challenges that variable renewable energies introduce in terms of management of the power system. It also demonstrates the important role that dispatchable plants (nuclear, hydro, thermal) have to play in ensuring the overall safety of the power system.

2.1.2.2 Towards the goal of decarbonisation

CO_2 is a greenhouse gas (GHG) that contributes to the increase in global temperature, and sharply lowering CO_2 emissions is essential to hold this temperature increase to below 2°C, as stipulated in the Paris Agreement, or even to under 1.5°C in order to limit the ill-effects on large populations in exposed areas. Europe, for example, is targeting a carbon-neutral power sector by 2050, with a patchwork of starting points for each country depending on local resources and political choices. Some countries have large natural resources, such as hydro or biomass, and others rely on nuclear power plants that result in a much lower level of carbon emissions in their power system compared to other countries. The contributions of these different generation sources are shown in Figure 2.1.7. However, worldwide CO_2 emissions continue to steadily rise, and energy related emissions are hitting record high levels, led by coal power generation in Asia. Coal is the largest source of emissions worldwide and is associated with one-third of global warming to date (IEA, 2021).

Figure 2.1.7: Comparative life cycles lifecycles for greenhouse gas emissions from electricity generation



1) Assuming biomass feedstocks are dedicated energy plants and crop residues and 80-95% coal input. 2) Assuming feedstocks are dedicated energy plants and crop residues. 3) LifecycleLife cycle emissions include albedo effect. 4) Emissions of about 2 000 gCO_2eq/kWh come from a few reservoirs with a large area in relation to electricity production and low power intensity. * Integrated coal gasification combined cycle.

Source: Reproduced from IPCC (2014), *Climate Change 2014: Mitigation of Climate Change*. Figure 7.7 (p. 541, 542), by extracting information related to life cycle emission intensity and adjusting the appearance.

Renewable energies are being introduced massively in the power system as a way to lower CO_2 emissions from the power sector. This solution benefits existing power systems with high levels of CO_2 emissions, but not those with already low CO_2 emissions. Evidence provided in large scale-simulations (Burtin and Silva, 2015; Tapia-Ahumada et al., 2019) has confirmed that the high penetrations of VRE sources in sufficiently interconnected networks will permit significant reductions in CO_2 emissions, and that a very low emission factor could only be achieved with a mix combining VRE sources with carbon-free firm capacity plants.

In terms of economic impacts, the increasing share of VRE sources on the grid could increase the cost of electricity for consumers. An NEA report examining the full costs of electricity (NEA, 2018) concluded that the grid-level system costs associated with VRE generation are large and increase with the penetration level of VRE sources. In comparison, the system costs of dispatchable technologies, such as nuclear power, are at least one order of magnitude lower. A later NEA study on the costs of decarbonisation (NEA, 2019) assessed the costs of low-carbon electricity systems capable of achieving strict carbon emission reductions to 50 g of CO_2 per kWh with different shares of renewable and nuclear sources. The study shows that the system costs of electricity provision increase with a greater share of VRE sources in the electricity mix.

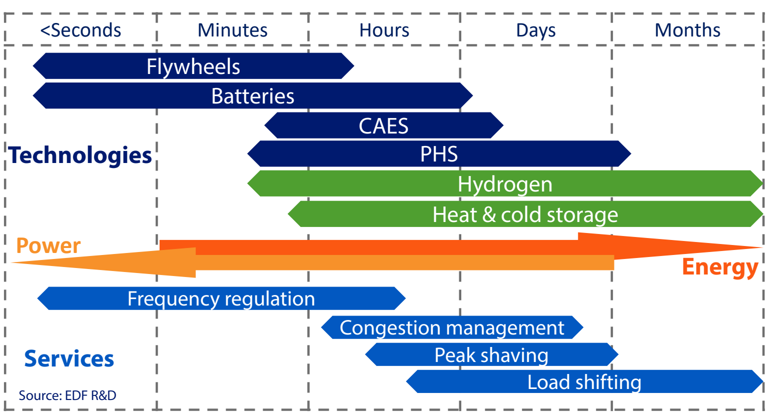
In addition to the existing electricity grids, there will be a growing need to decarbonise remote and off-grid energy applications, such as remote mining operations and remote communities. Micro modular reactors, which are certain types of advanced nuclear reactors with small output of up to 20 MWe, have been proposed for remote applications and are being pursued by some developers (NEA 2021).

It is evident from the above studies that the two pillars for decarbonisation of the power system are renewables along with low-carbon, dispatchable energy sources. A mix of solutions can provide the necessary additional flexibility through demand response, storage at different scales, including long-term seasonal storage (see Table 2.1.1), power-to-X,[9] and carbon capture, use and storage (CCUS). Nuclear energy can therefore provide an important contribution towards a power system with very low levels of CO_2 emissions (FTI-CL ENERGY, 2018), in particular in countries with no or very limited hydro resources. In the short term, nuclear power keeps CO_2 emissions low and avoids locking in fossil fuel investments. In the long term, it provides carbon-free, flexible electricity (see Sections 3.1.1, 3.1.2, and 4.2.1).

2.1.3 Energy storage

This section provides an overview of power storage technologies and costs, as well as their uses. Figure 2.1.8 and Table 2.1.2 compare the key attributes of different storage technologies. Figure 2.1.8 shows that the range of services provided by electricity storage have different time horizons, and therefore different applications, i.e. frequency control, congestion management, peak shaving[10] and load shifting.

Figure 2.1.8: Comparison of energy storage systems by duration characteristics



Source: Bart, J-B. et al. (2017), *Le stockage d'electricité, un défi pour la transition énergétique*,

9. Power-to-X involves conversion technologies that decouple power from the electricity sector for use in other sectors, for example the production of hydrogen through water-splitting using electricity from VRE sources, or the production of other kinds of liquid fuels and chemical materials via the processing of the hydrogen produced.
10. Peak shaving refers to levelling peaks of electricity demand.

Table 2.1.2: Macro characteristics

Type of storage	Round-trip efficiency	Timescale of storage	Power capital cost (USD/kW)	Energy capital cost (USD/kWh)	Maturity
Hydrogen	30%-40% power to power	Hours to weeks	Med-high	Low	Medium
Pumped storage	75-80%	Hours to days	Medium	Low	High
Lithium-ion battery	~85%	1 hour to 4 hours	Med	Med	Med-high
Redox flow battery	~70%	~10 hours	Med-high	Low-med	Medium
Flywheel	90%	~1 minute	Low	Med-high	High

There are several technologies well-suited to electricity storage, namely:

- Pumped hydro storage (PHS)

PHS was one of the most common storage methods in service until 2012, contributing more than 90% of current storage capacity (Luo, et al., 2015). The role of PHS is to provide daily and weekly load following capability in order to maintain balance between supply and demand, as well as to provide reserves for the power system. Pumped storage is already widely deployed in many countries, but it is likely to prove difficult to develop new sites since most of the suitable geological sites have already been exploited.

- Flywheels

Flywheels are mechanical devices that can store energy in the form of rotational kinetic energy. They are generally considered to offer very limited storage capacity but are a mature and well-established technology. While the storage capacity of flywheels is limited, they have been successfully deployed as a means to minimise fluctuations associated with PV farms, and they act as a small buffer during cloud cover.

- Compressed Air Energy Storage (CAES)

CAES has received considerable attention historically, but it has been superseded by the technologies listed in Table 2.1.2. It is generally seen to offer storage for relatively short timescales and has few secondary service benefits. The relatively low efficiency of CAES and high operation and maintenance costs are significant drawbacks.

- Hydrogen

Hydrogen storage is currently the only means to offer storage capacity to cover changes in energy demand over relatively long periods of time (i.e. weeks). Hydrogen storage is considered relatively mature given the current commercial demands and some deployment in early trials of refuelling stations.

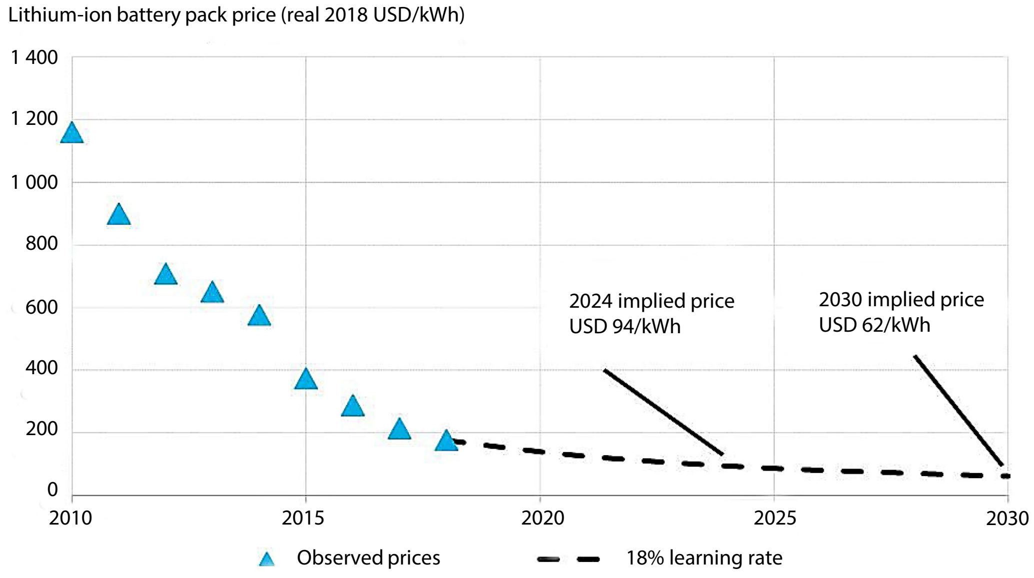
- Lithium-ion batteries

One of the first impacts of the integration of variable renewable energy sources has been the need for short-term flexibility. In scenarios with far higher deployment rates of VRE sources, essentially replacing conventional power plants, long-term storage needs have become a critical technology. Lithium-ion batteries working on short timescales are therefore increasingly being deployed to provide frequency response, guaranteeing system stability. Their price also has significantly decreased in recent years (see Figure 2.1.9).

As Figure.2.1.9 demonstrates, the mass production of large batteries for electric vehicles (EVs) – with the datasets for large-scale mass production relating to batteries from Tesla and Nissan electric vehicles – has resulted in a large initial gain, with battery costs dropping by around 60% (from around USD 1 200/kWh to USD 500/kWh). It is important to place realistic expectations on technology development, particularly if the aim is to widely deploy a particular technology so as to provide a vital function, such as ensuring sufficient energy is available for society when there are extended reductions in supply. Current battery costs are estimated to be around USD 200/kWh (UBS, 2017; BNEF, 2019), with significant but lower reductions in battery costs predicted in the short to medium term (see Figure 2.1.9). As of 2020, an approximately 190 MWh storage facility using a lithium-ion battery is operating in South Australia (Tomevska, 2020).

The development of electric vehicles is an opportunity for additional, albeit slower, price drops for lithium-ion batteries. It will lead to a large volume of EV batteries in the power system, providing a new source of flexibility.

Figure 2.1.9: Prices of battery packs in electric vehicles



Source: BNEF (2019).

- Redox flow batteries

This technology covers solutions based on different active materials with different maturity levels (from medium to low). The two, main technologies are made with vanadium or zinc-bromine. They use tanks and pumps to ensure electricity storage or to provide electricity. The power density for redox flow batteries is quite low. It needs time to start in order to provide electricity or to store it. The quantity of energy to be stored drives the tank volumes and also battery costs. Redox flow batteries could be adapted to remote grid applications or to provide medium-term electricity storage solutions.

In addition to electricity storage, there are a number of technologies that are designed to store excess thermal energy, which can then be used hours, days or even months later, as outlined in Box 2. Given the high level of heat demand (as outlined in Section 2.2), and the need to decarbonise this demand, heat storage is likely to play an increasingly important role in the future.

Box 2: Heat storage coupled with a nuclear power plant

Heat storage technology has been applied to domestic hot water in houses and appears to be very effective in terms of combined demand side management and nuclear plant operation in some countries such as France.

A new application of this technology is now being considered. Various research and development activities are being conducted in order to enable power plants to control electricity generation according to the price fluctuation by storing heat from the heat source (reactor, boiler, etc.) and sending stored heat to the generator. Organisations involved in the development of these technologies have noted that heat storage technologies can be applicable to all heat generating technologies, such as concentrated solar power (CSP), nuclear power and geothermal energy. Multi-gigawatt-hour-scale storage using nitrate salt as a storage material have already been equipped in utility-scale CSP systems in order to avoid selling electricity at times of low prices and enable the sale of electricity at higher prices. In the same way, if applicable, heat storage technology has a potential to enhance the flexibility and profitability of nuclear power plants.

A 2019 assessment showed that the capital cost of large-scale heat storage is lower than other storage technologies by a large margin. It reflects the low cost of heat storage materials (pressurised water, salt, crushed rock, concrete, oil, etc.) relative to other technologies (for batteries, lithium, cobalt, etc.) (Forsberg, Sabharwall, and Gougar, 2019).

Various methods use the different storage materials being considered for nuclear power application as shown in Table C.2.1. Methods are at different stages of development. In addition, each method or storage material has specific operable temperature ranges, from a few hundred to a thousand degrees Celsius. It is therefore important that the choice and development of heat storage technologies are consistent with the development of the advanced reactor technologies with which the storage technology is to be coupled (Forsberg, Sabharwall, and Gougar, 2019).

Table C.2.1: Heat storage option characteristics

Type of storage	Round-trip efficiency	Timescale of storage	Temperature range (°C)	Maturity
Steam accumulator	High	Hours	250-300	Commercial (CSP)
Oil	Medium	Hours	<400	Commercial (CSP)
Concrete	Medium	Hours to days	<400	Laboratory
	High		<600	Pilot plant
Nitrate salts	High	Hours to days	290-565	Commercial (CSP)
Chloride salts	High	Hours to days	500-725	Laboratory scale
Sand	Medium to high	Hours to weeks	<1 000	Pilot plant
Crushed Rock	Medium	Hours to weeks	<800	Pilot plant
Counter-Current Condensing Steam	Very high	Hours	250-300	Laboratory scale

Source: Forsberg, Sabharwall and Gougar (2019).

2.1.4 Transport electrification

The global transport sector is at present experiencing unprecedented changes as a result of the rapid deployment and adoption of EVs, which includes both fully electric and hybrid electric vehicles. Of the total EV deployment, fully electric, battery electric vehicles (BEVs) are emerging as a potentially disruptive technology for both passenger and freight transport services. The battery cost, which comprises the bulk of the BEV cost, has fallen dramatically within the last decade, and continues to do so at a rapid rate (see Figure 2.1.9 in Section 2.1.3). The potentially wider substitution of BEVs for equivalent internal combustion engine vehicles for all modes of transport has tremendous implications for the global energy system and demands for liquid fuels and electricity.

BEVs have several advantages over internal combustion engine vehicle equivalents. BEVs have no tailpipe emissions and do not contribute to air pollution or climate change, if using zero-carbon electricity.[11] BEVs substitute fossil fuels for electricity as a fuel, therefore reducing overall dependence on crude oil while enhancing energy security for regions with limited crude oil resources. The overall energy efficiency of BEV powertrains and reduced maintenance needs relative to internal combustion engine vehicles can improve economic productivity. Although the impact of BEVs on the electricity grid remains uncertain, flexibility in the timing of BEV charging and the potential of BEVs for energy storage may contribute to improving grid stability issues.

While BEV options for passenger, light-duty vehicles have existed for several years, BEV options for other modalities and for a wider range of passenger and freight transport services are under investigation. Applications of the BEV technology compatible with current battery capacities, such as for light and medium-duty buses and trucks, are just now becoming available (BNEF, 2018b; Heid et al., 2017; Bowler, 2019; Wichter, 2019). Improvements in battery capacity, charging times and BEV costs, and the realisation of significant advantages in terms of reducing vehicle tailpipe use and CO_2 emissions, improving fuel efficiency, and lowering fuel and maintenance costs, have all contributed to a vision of a world in which major portions of the global transport system are electrified.

As of 2016, the transport sector as a whole consumed 2.8 billion tonnes of oil equivalent (btoe) of global final energy, or nearly 30% of the world's total. Moreover, 92% of the transport final energy was from refined petroleum products (IEA, 2018a). Because of the high dependence on fossil fuels and the combustion technology, the transport sector is a significant contributor not only to urban air pollution but also to the climate change problem as it accounts for one-quarter of the total global CO_2 emissions (IEA, 2018a). Road transport is particularly important as it comprises 74% of all global transport CO_2 emissions.

Decarbonisation of the transport sector has been one of the most difficult challenges to date because of the limited carbon-free vehicle technology options and the limited impact of carbon pricing on vehicle and modal choice (IPCC, 2014). If historical trends in transport GHG emissions are not mitigated, the transport sector is likely to contribute to a growing share of national and global GHG emissions (IEA, 2018a).

Improvements to BEV performance and costs, and broader applicability to a variety of transport modalities, along with strong motivations for addressing local air pollution and global climate change, have led to significant increases in the global sales of BEVs and EVs in general. The pace of EV sales (including battery electric and plug-in hybrids) is accelerating, with nearly 4 million EVs having been sold globally as of the first half of 2018 (BNEF, 2018a). Of this total, 3.5 million were passenger EVs and 421 thousand were electric buses. The greatest demand for EVs is in the People's Republic of China with 42% share of global sales, followed by Europe with 26% and North America with 25%. Of the total vehicle sales, EV sales are gaining market shares, and the cumulative additions of EVs are rising quickly.

The penetration of EVs and the reduction in the purchase price of BEVs have been supported by the reduction in the cost of lithium-ion batteries. The cost of the battery pack is a significant contributor to the sales price of BEVs, and the average price of lithium-ion battery pack has fallen from just below USD 1 200/kWh in 2010 to around USD 200/kWh in 2017, as shown in Figure 2.1.9 (in Section 2.1.3) (BNEF, 2019). With a continuous, historical learning rate of 18% per year, consistent with the 2010-2017 rate of battery cost improvements, battery pack prices are expected to fall below USD 100/kWh in the near future (BNEF, 2019).

Challenges for the broader public in terms of the acceptability of BEVs include sufficient driving range to overcome driver range anxiety and greater availability of public charging infrastructures. From the very first generation of EVs to newer models currently available on the market, the driving range and battery capacity of BEVs have steadily increased. Currently available BEVs have driving ranges from 93 km (58 miles) to 507 km (315 miles) and can provide

11. Although EVs have emission profiles resulting from the material components, a study implies that greenhouse gas emissions during their life cycles are much less than conventional vehicles (Petit, 2017).

sufficient range for the majority of driving needs. A higher driving range, however, increases the purchase cost of BEVs since larger capacity battery packs are required, and so determining the optimal and appropriate size of the battery pack is important for maintaining competitive vehicle pricing while alleviating consumer concerns. Transport surveys show that average daily personal travel distance is less 64 km/day (40 miles/day) in the United States (DOT, 2017) and from 40 km/day (25 miles/day) to 80 km/day (50 miles/day) in Europe (EC, 2012). Recent discussions on the optimal range for BEVs to meet most driver needs indicate that the range is about 320 km (200 miles) or less (Miles, 2018; Edelson, 2017). Most EV manufactures appear to be on the cusp of providing up to 200 miles of electric driving range at competitive vehicle pricing.

The limited number of charging stations and high-power fast chargers are current bottlenecks for the greater adoption of BEVs (Engle, 2018). Charging infrastructure needs nonetheless vary across regions. In the United States, with the high penetration of single-family homes, less expensive home-based charging is able to support BEV deployment in the near-term. In China and Europe, where multi-unit apartments dwellings prevail, the availability of public charging options is necessary to support greater BEV adoption. While the economics of home- and work-based standard, alternating, current chargers are straightforward, the business case for public options using higher power and more expensive direct current chargers is not as clear. For heavy-duty vehicles, alternative charging technologies, such as the application of proven pantograph [12] technology, are emerging as a viable charging option, in addition to overnight plug-in charging (De Pee et al., 2018). Although the specific characteristics and type of future charging infrastructure is uncertain, the total number of EV charging installations around the world are projected to grow rapidly. Global installations of electric light-duty vehicles chargers exceeded 5 million units in 2018, up 44% from the prior year (IEA, 2019b).

The projections for EV use show tremendous growth, with scenarios from the IEA for global EV deployment reaching up to 125 to 220 million EVs by 2030 (IEA, 2018b). According to Bloomberg New Energy Finance (BNEF), 55% of new car sales and 33% of the global fleet will be electric by 2040 (BNEF, 2018c). The consequences of large EV penetration in these scenarios are the significant new demand for electricity throughout the world. For the IEA scenarios, approximately 400 to 900 TWh of new electricity demand is projected by 2030. For the BNEF projections, the new electricity demand is around 2 000 TWh in 2040 and 3 400 TWh by 2050, at which time EVs will account for 9% of total electricity demand. Other more aggressive transport electrification studies for the United States project up to a 30% increase in electricity demand by 2050 (EPRI, 2018).

The additional demand for electricity can be supplied by a variety of power generation options. However, motivations for EV adoption, which will help improve local air quality and address climate change, are better supported if non-emitting power generation options, such as nuclear power and renewable energy, play a more prominent role for new electricity supplies.

The significant new demand for electricity and the flexibility in the timing and method of BEV charging present an opportunity for integrating electricity demand with renewable energy supplies. Strategies for electricity demand-side management and shifting BEV charging to coincide with the timing of renewable energy production or off-peak hours of electricity demand can offer EV customers lower electricity prices, support increased use of renewable energy and lower GHG emissions (Bird and Huchinson, 2019; Trabish, 2019). Moreover, shifting the electricity demand profile could potentially benefit other dispatchable power generation options, including baseload generation, since demand-side flexibility is used for responding to variable renewable energy production rather than for any reliance on supply-side flexibility of dispatchable and baseload generation.

12. A pantograph is a device to collect power through contact with power lines and which is generally mounted on the roof of a train, tram or electric bus.

The choice of power generation options for supporting EV penetration will depend on multiple regional factors, such as the future cost and availability of alternative power generation options, the relative contribution of variable power generation, policies on air pollutants and climate change mitigation, differences in regional transport fuel costs and differences in regional EV penetration rates.

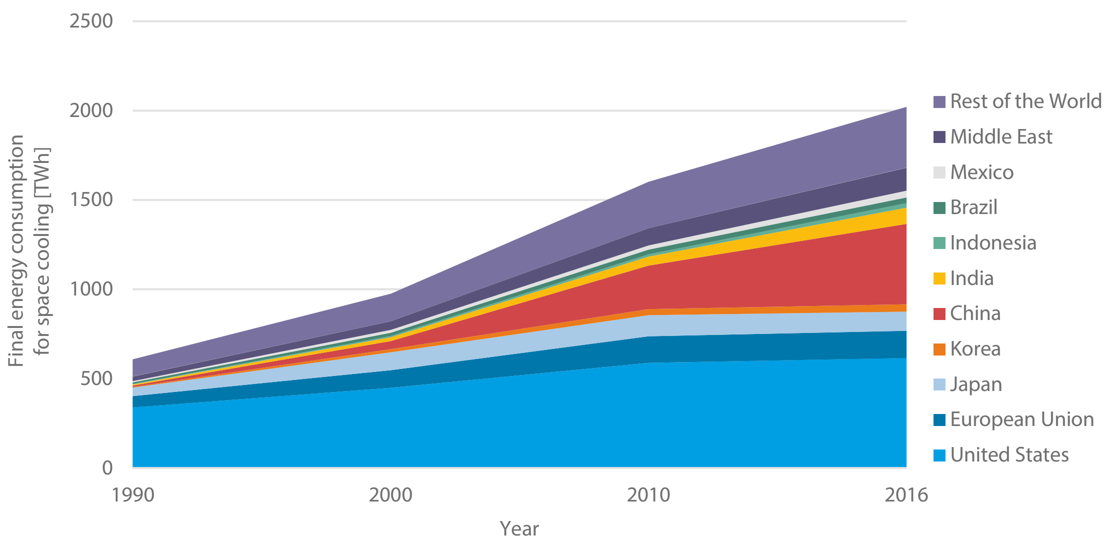
2.1.5 Space cooling

2.1.5.1 Energy use for space cooling

Space cooling is contributing to a strong boost in global electricity consumption. In fact, energy consumption for space cooling has tripled from 1990 to 2016, totalling 2 020 TWh in 2016. Use of air-conditioning (AC) systems, household fans and dedicated dehumidifiers make up the vast majority of devices designed for space cooling, with resulting electricity shares equating to nearly 99% of energy consumption for this purpose.[13] In 2016, almost 20% of the electricity consumption in buildings around the world was for space cooling (IEA, 2018c).

The trend of energy consumption for space cooling varies greatly by region (see Figure 2.1.10). Energy consumption for space cooling in advanced economies, such as United States, the European Union and Japan, has become saturated in recent years (but is still modestly increasing) as a result of improvements in the energy efficiency of air conditioners, which partly offsets the impact of cooling demand growth. In contrast, in emerging economies, most of which have warm climates, the energy consumption for space cooling is sharply increasing. China showed a 68-fold increase from 6.6 TWh in 1990 to 450 TWh in 2016. There have also been remarkable increases in other countries or regions, such as 15-fold increase in India, 13-fold in Indonesia, about 5-fold in Mexico and the Middle East. Despite this rapid increase and the fact that some of these emerging countries are located in the hottest climates (i.e. India, Indonesia and Brazil), the per capita energy consumption of space cooling in these areas is far from the level of the United States, Japan or Korea, and is even lower than Europe where the climate is relatively modest (see Figure 2.1.11) (IEA, 2018c).

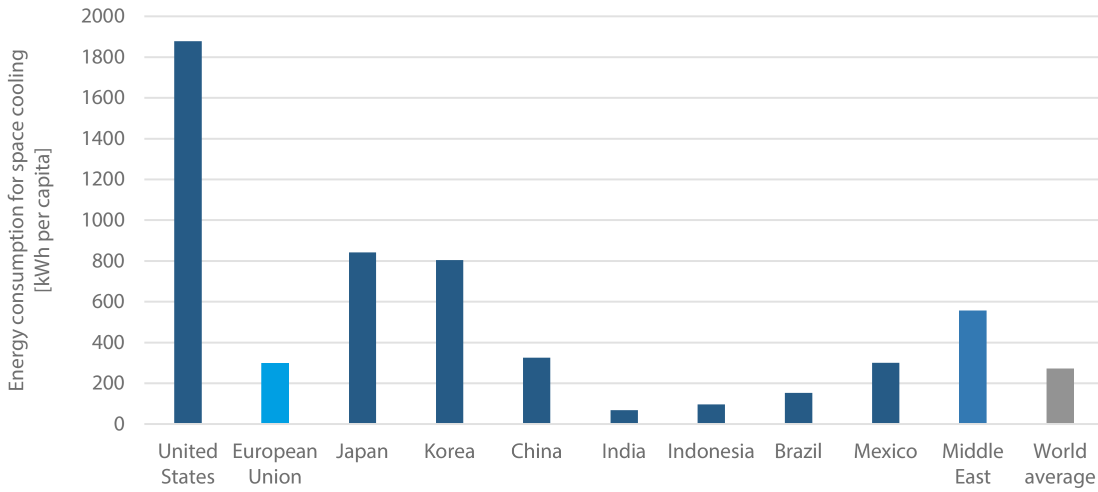
Figure 2.1.10: The growth of world energy consumption for space cooling in buildings



Source: IEA (2018c), *The Future of Cooling.*

13. The remaining 1% is met via natural gas, which is mostly used for thermal-driven chiller systems in commercial buildings (IEA, 2018).

Figure 2.1.11: Per capita Energy consumption for space cooling by country/region in 2016



Source: IEA (2018c), *The Future of Cooling.*

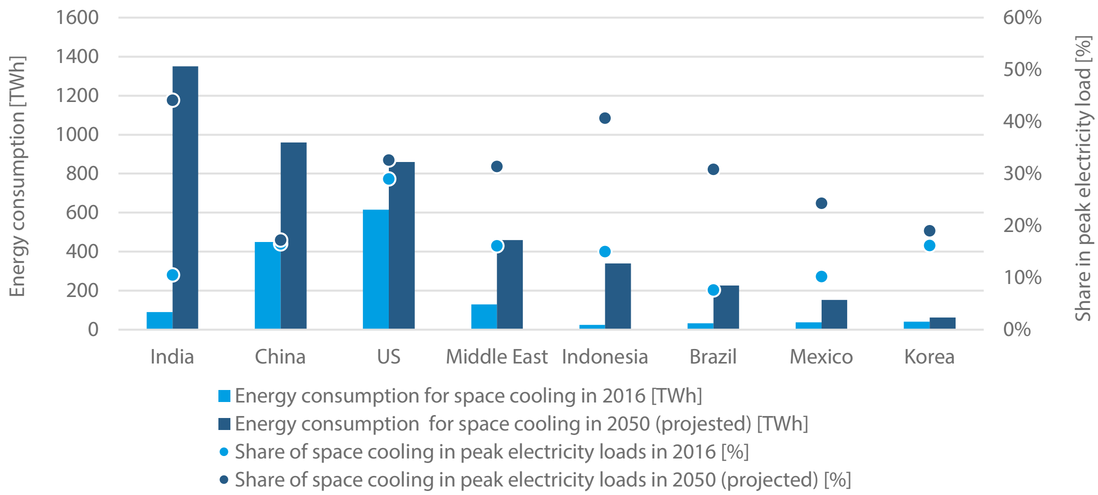
2.1.5.2 Future growth of space cooling and its impact on electricity systems

The underlying driver of the space cooling demand is climate change, or rising outside temperatures. Economic development is also contributing to demand growth by increasing buildings or spaces that require cooling, as well as by stimulating people's needs for thermal comfort through rising income levels and living standards. The latter has also meant that more people can afford cooling devices such as air conditioners and electrical fans to meet their cooling needs. Population growth is another contributor to increasing energy consumption for space cooling. The combined effect of these three factors (climate change, economic development and population growth), in particular in emerging countries, coupled with a high population density in many cases, is expected to accelerate the demand for space cooling and associated energy consumption (IEA, 2018c).

The IEA predicts (2018c) that the global cooling output capacity of air conditioners in residential and commercial sectors will more than triple by 2050, from approximately 11 700 GW in 2016 to approximately 37 000 GW in 2050. Estimated energy use for space cooling could reach up to 6 200 TWh. As shown in Figure 2.1.12, the largest increases by region are expected in India and China, which would make them the largest energy users for space cooling in the world. Similarly, many emerging countries will experience notable increases. The cooling demand in developed countries will also increase, for example, energy consumption in the United States for space cooling is expected to increase by 40%, mainly in the commercial sector (IEA, 2018c).

This significant growth in space cooling demand imposes difficult challenges on the electricity system in terms of addressing high peaks in electricity demand. Space cooling demand has seasonal and daily profiles by nature (i.e. it is the highest in the daytime during the summer months, while lowest at night during other seasons). The impact on peak electricity demand is greatest in most emerging countries (see Figure 2.1.12). From 2016 to 2050, for example, the share of space cooling during peak electricity demand is predicted to rise from 10% to 45% in India, 15% to 40% in Indonesia, and 8% to 30% in Brazil. As a result, the global electricity generation capacity required to meet the cooling demand is projected to quadruple from 850 GW in 2016 to 3 350 GW in 2050, which means adding a generation capacity equivalent to the current total capacity of the United States, Europe and India. The IEA projection shows that renewable energy can serve almost two-thirds of increased capacity needs, though coal and gas are expected to be required to cover a large share of peak demand in India, Indonesia and other developing countries in Asia (IEA, 2018c).

Figure 2.1.12: Future increases of energy use by country/region



Source: IEA (2018c), *The Future of Cooling*.

With respect to Africa, given its warm climate and potential for large population and economic growth, the energy demand for space cooling is also expected to increase, but not as dramatically as in the countries highlighted above (IEA, 2019c). Populations living in African countries where the demand for space cooling systems is expected to be highest was situated around 680 million in 2018, accounting for almost one-quarter of the world population that may need space cooling, and this figure is expected to increase to over 1 billion by 2040. In 2018, the ownership rates of air conditioners (0.06 units per household on average) and electrical fans (0.6 units per household) are very low (IEA 2019c). According to IEA projections based on current policy frameworks and announced policies, the ownership rate of air conditioners in Africa is expected to more than double by 2040 to 0.15 units per household, although it will remain much lower than the world average of 1.15 in the same year (IEA, 2019c). The increase in electricity demand for residential cooling in Africa will reach only around 60 TWh, which means that most of the cooling demand in Africa will remain unmet. The IEA also estimated that, if African Union countries achieved their ambitious visions of economic growth, as outlined in Agenda 2063 or other stated visions, the electricity demand for residential space cooling could reach as much as over 220 TWh by 2040 (IEA, 2019c).

2.1.5.3 Key factors mitigating impacts on electricity systems

As shown above, a massive increase in space cooling demand seems inevitable. The impact on the electricity system, however, can be effectively mitigated by several factors. The most important factor with large potential for mitigating the impact is improvements in the energy efficiency of air conditioners. The IEA estimates that total electricity demand for space cooling can be reduced to 3 400 TWh by 2050, and electricity generation capacity required by 1 170 GW, if the average efficiency of air conditioners installed in the world improves by 50% in 2030 and by 80% in 2050, compared to the projections mentioned above. Even in this scenario, the assumed average efficiency of air conditioners in 2050 is still 40% lower than the most energy efficient air conditioners on the market today (IEA, 2018c). The IEA argues that this goal can be achieved given the successful cases associated with Minimum Energy Performance Standards,[14] which have dramatically improved the energy efficiency of electrical appliances. Other possible

14. Minimum Energy Performance Standards are specifications typically applied to energy consuming devices, such as refrigerators, AC systems and lighting appliances, so as to limit the lowest energy efficiency of products able to be sold in markets or used for commercial purposes. Minimum Energy Performance Standards have already been introduced in most countries and cover around 85% of AC systems sold worldwide in 2016 (IEA, 2020).

contributors to reducing electricity consumption for space cooling include developments in building standards, encouragement of energy saving practices, such as adjusting room temperatures by 1°C higher and installing direct, renewable cooling systems (IEA, 2018c). To address large, daily and seasonal fractions of demands and high peak loads for space cooling, demand side management, or demand response, is considered an economical option to allocate electricity demand from peak periods to others. Since space cooling demand is usually high at peak electricity demand hours in the summer months, lowering demand from air conditioners could effectively reduce peak demand and minimise fluctuations in demand, which would mean avoiding the need to build additional generation capacity or reduce demands on energy storage systems (IEA, 2018c).

2.1.6 Summary

Today, electricity represents 19% of total final energy consumption and 38% of global CO_2 emissions in the energy sector, and its demand is continuously increasing. Electricity systems will continue to play an increasingly important role in energy supply. In addition to meeting increasing demands while reducing CO_2 emissions, flexibility at both plant and system levels will become increasingly important in future.

Current, large-scale development of VRE sources, such as solar PVs and wind turbines, contributes to curbing the increase in CO_2 emissions by replacing electricity generation from fossil fuel sources. However, as VRE sources increase their penetration in the power system, more flexibility and total generation capacity is required because of their intermittency and low-capacity factor. The timescales of flexibility required in the power system start with short-term (minutes to hours) in the early stages and expand both to longer-term (days, months, years) and to shorter-term (seconds), according to the increase in VRE sources. The rapid increase in cooling demand expected in some regions of the world can have a significant impact on the electricity system, both in terms of the large increase in electricity demand, as well as at the higher peak loads.

Energy storage technologies can provide a source of flexibility, and various technologies with different characteristics (i.e. efficiency, timescale) are in different stages of development. Electric vehicles can be a game changer because of the scale of storage that they could provide. Their numbers are increasing as a result of reduced battery costs and improved technology, thus increasing electricity demand as well as providing a source of flexibility when integrated with demand-side management systems.

Flexibility can be identified as a key issue for nuclear power plants so to take full advantage of decarbonisation efforts and security of supply for the electricity system. The extent of flexibility required of nuclear power plants is largely dependent on the future development of VRE sources and other related technologies, as well as on the change of consumption patterns in the market they are involved in. Flexible operation could have an impact on the economy of nuclear power plants. It could, for example, reduce the load factor of nuclear power plants, which would increase the average electricity production cost, in particular if no fuel saving is possible. On the other hand, possibilities for additional revenues from ancillary services or cogeneration exist for flexible nuclear power plants. Features related to flexible operation of nuclear power plants are discussed in Chapters 3 and 4.

2.2 Heat

Heat is the largest energy end-use, accounting for about 50% of global final energy consumption in 2018, which is much larger than transport (29%) or electricity (21%). The majority of heat (77%) is supplied by fossil fuels, and hence this sector contributes to 40% of global energy related CO_2 emissions. Most of the heat produced is consumed in the buildings (46%) and industry (50%) sectors, and a small portion is consumed in the agriculture sector (IEA, 2019e).

2.2.1 Residential and commercial heat demand

Global heat demand in the building sector, or residential and commercial heat demand, is gradually increasing alongside population growth and building floor area expansion. In this sector, heat is consumed for space heating, water heating and cooking. These applications require heat at low temperatures, mainly below 100°C, allowing a variety of technologies, including solar thermal energy, nuclear power and heat pumps using low-carbon electricity, to meet this heat demand (IEA, 2019e). Fossil fuels are currently used to meet about 60% of this low temperature heat demand (IEA, 2014). The remaining 40% of low temperature heat demand is mostly met via biomass combustion. Biomass is considered a renewable energy source and its CO_2 emission intensity is smaller than that of fossil fuels, but the large-scale development of biomass use for energy may lead to 'very significant land-use changes that could conflict with food production and cause various negative impacts on the environment, including pressure on water resources, loss of biodiversity and an increase in greenhouse gas emissions (IEA, 2014).

Many countries have until recently focused on decarbonising residential and commercial heat demand with heat pumps and district heating, using energy from low-carbon sources (ERP, 2011). District heating systems provide an economical means of distributing heat in areas with high heat demand, such as in Europe and North America, with their harsh winters. These systems distribute heat produced in cogeneration plants, dedicated heat plants or surplus industrial heat to buildings for hot water and space heating, as well as low-temperature process-heat for industry. District heating systems are usually based on either hot water or low-pressure steam and the typical temperature range is around 80-150°C (IAEA, 2017). With the increasing concern over climate change, and because of its technological availability, most low-carbon heat is produced by renewable energies such as biomass, solar and geothermal energy via district heating systems. Heat produced by nuclear cogeneration has also been supplied to district heating systems in several countries, but its contribution is currently very small (IAEA, 2017; IEA, 2019e).

One difficulty with heat pumps and district heating technologies is that they are directly coupled to demand so that when demand spikes more heat must be produced by the power plants providing energy. This is particularly problematic for the heat pumps since their efficiency is impacted by the temperature of the reservoir (the outside air, or the ground) from which the heat is extracted. Typically, heat pumps will prove to be very efficient over much of the year, apart from on the occasional, very cold winter day when demand spikes.

Under very cold conditions, heat pump efficiency approaches that of a conventional resistance heating. In the UK, for instance, if heat pumps were to replace gas heating then peak electricity demand would increase by between 180 to 250% depending on the demand reduction measures (such as thermal insulation) pursued alongside the deployment of heat pumps (ERP, 2011). Furthermore, peak heat demand in countries like the United Kingdom is much lower in the summer (~30 gigawatts-thermal [GWth]) than in the winter (~300 GWth) (Sansom, 2015). Building power plants to accommodate these large swings in heat demand would therefore be a poor choice since it would likely result in power plants operating for only one or two weeks during the year to accommodate the large spikes in demand (DECC, 2013).

Such issues relating to large peaks in heat demand and the intermittency in renewable energy sources provide very strong motivations to consider energy storage and/or alternative means to provide heat. Historically, energy storage in many countries has focused on: 1) pumped storage, with many suitable sites already being used; and 2) fossil fuels, which at large-scale are not compatible with global greenhouse gas reduction targets (see Section 2.1.3). Hence, alternative heating technologies, in addition to conventional air and ground source heat pumps, district heating using biomass, nuclear energy and CCUS plants, have been gaining in interest as a means to address the challenges associated with relying heavily on conventional heating technologies (DECC, 2016). These alternative heating technologies include:

- Hybrid heat pumps, and particularly those that include a small gas or hydrogen boiler to boost heat output in times when heat demand is exceptionally high, heat pump efficiency is low and electricity supply is constrained. For much of the year, heat demand would be met using only electricity.

- High temperature heat pumps, which are capable of providing effective space heating with standard high temperature radiator systems and domestic hot water (65°C to 80°C). Conventional heat pumps provide heat below (65°C) which necessitates well insulated homes and a large radiator surface to operate efficiently.

- Large-scale (MW) heat pumps connected to a district heating network, which would avoid the need to locate power systems (e.g. a nuclear power plant) close to heat demand. In this case, the power plant can be located where it is easiest (e.g. minimal regulatory burden or ease of access to the power infrastructure).
- Hydrogen for use in the gas distribution network, potentially making use of the existing infrastructure and avoiding issues around constrained electricity supply.

2.2.2 Industrial heat demand

As is the case for residential and commercial heat demand, global industrial heat demand is also increasing (IEA, 2014), but its dependency on fossil fuels is much larger, accounting for 90% of the total in 2018 (IEA, 2019e). In this sector, heat is used for manufacturing processes related to material transformation and chemical reactions, and encompasses a large temperature range from below 100°C to over 1 000°C. At the European level, the EUROPAIRS study found that about 50% of industrial heat demand is below 550°C, and large part of the remainder is above 1 000°C, with very few processes requiring energy in the temperature range of 550°C and 1 000°C. Most of heat demand below 550°C is for refinery purposes (250°C-550°C), the chemical industry (250°C-550°C) and district heating (<250°C) (Bredimas, 2012). The heat market with this temperature range is an area in which existing nuclear technologies or some of the advanced reactor technologies can take part as low-carbon heat sources (see Sections 3.1.3 and 4.4.1).

The global, total heat market for process heat in the year 2010 was estimated to be around 11 000 to 16 000 TWh/yr, with Europe and the United States comprising around 3 000 and 3 600 TWh/yr, respectively (see Table 2.2.1) (Bredimas, 2012). Not all of this market can be easily accessed by existing or developing nuclear technologies. The district heating market alone, or plug-in market,[15] where the applicability of conventional nuclear cogeneration has already been proven with several decades of experience, accounts for quite a large heat demand, equivalent to around 370 to 630 GWth heat generation capacity globally (Bredimas, 2012). The EUROPAIRS study suggests that polygeneration[16] and pre-heating[17] applications could be a potential short-term market for nuclear cogeneration, which accounts for heat demand equivalent to 13 GWth and 41 GWth capacity, respectively, in Europe (Bredimas, 2014). Limited information appears to exist in the literature regarding how the global process heat market could evolve; however, in scenarios produced by the US Energy Information Administration, global industrial sectors are forecasted to see their energy use (including heat and electricity) increase by around 30% by 2050, relative to 2018 levels (EIA, 2019).

Table 2.2.1: Global estimated process heat market size

Region	Plug-in market	Total market
Europe	~ 800 TWh/y	~3 000 TWh/y
United States	~1 100 TWh/y	~3 600 TWh/y
China		1 200-1 700 TWh/y
India		300-500 TWh/y
Russia		300-500 TWh/y
Brazil		400-500 TWh/y
World total	**3 000-5 000 TWh/y (~ 370-630 GWth)**	**11 000-16 000 TWh/y**

Source: Bredimas, A. (2012), *European Industrial Heat Market Study*.

15. The plug-in market refers to a market where heat and cogeneration plants supply steam or hot water to one or more residential and industrial facilities through pipelines (Bredimas, 2014).
16. Polygeneration refers to the process of co-producing industrial gases such as hydrogen, nitrogen and oxygen beyond electricity generation or cogeneration of heat and electricity near the power plant or cogeneration plant (Bredimas, 2014).
17. Pre-heating refers to that part of the market where heat is provided by boilers and burners within the industrial factory, but could technically be covered by heat supply from external sources (Bredimas, 2014).

2.2.3 Summary

Heat accounts for half of the world's final energy consumption, which depends significantly on fossil fuels and results in 40% of global CO_2 emissions in the energy sector. The majority of global heat demand is at relatively low temperatures. For residential and commercial heat, which accounts for just less than half of world heat demand, the temperature is typically below 150°C and can be distributed via a district heating system. Industrial process heat accounts for the other half of world heat demand, with heat temperatures up to 550°C, accounting for a large proportion of total heat demand (around half in Europe). The plug-in market alone has a considerable market size, which is equivalent to several hundred GWth in terms of capacity. In addition, several other applications, such as polygeneration, pre-heating and hydrogen production, have been suggested as potential markets for nuclear cogeneration. Considering the large demand for relatively low temperature heat, and the availability of existing district heating systems in some areas, there is a large potential market where advanced nuclear technologies could be applied as alternative heat sources as opposed to fossil fuels. Nuclear technologies could in this way contribute to effectively reducing CO_2 emissions.

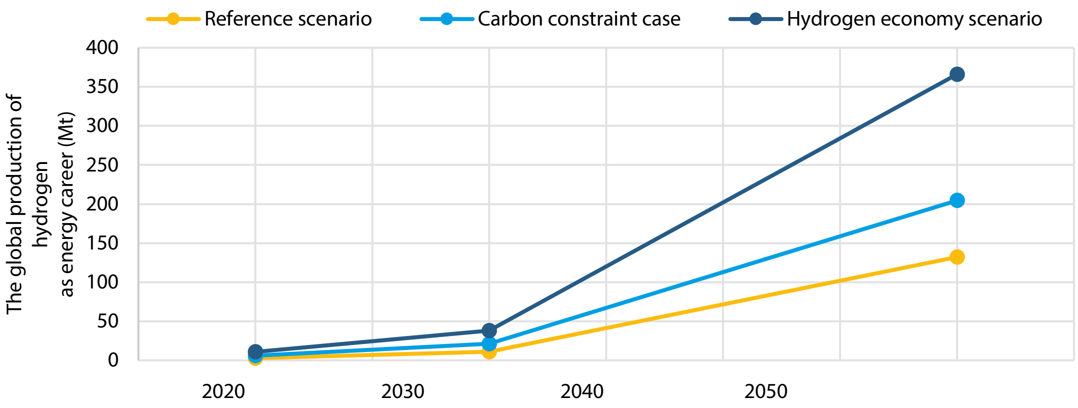
2.3 Hydrogen

Hydrogen is currently used mainly for industrial applications, as further discussed below, but it is being considered for a wider range of applications, including as an energy carrier (IEA, 2019d). In addition to increasing demands for existing applications, its widespread use as an energy carrier could lead to a significant increase in future demand of hydrogen.

2.3.1 Market growth

Global hydrogen demand has been increasing over the past few decades, reaching around 115 megatonnes [Mt] in 2018. Most hydrogen is consumed in the industrial sector, with the top three sectors accounting for more than three-quarters of global demand. These are: 1) chemical production (45 Mt); 2) oil refining (33 Mt); and 3) steel production (4 Mt), all of which are expected to grow steadily to 59 Mt, 41 Mt and 8 Mt, respectively, by 2030. In contrast, hydrogen demand as an energy carrier is currently negligible (IEA, 2019d). According to a study by the European Commission (2006), global hydrogen demand as an energy carrier will significantly increase between 2030 and 2050, with forecasts between 130 Mt and 370 Mt by 2050, depending on the situation related to carbon policies and technological breakthroughs (see Figure 2.3.1).

Figure 2.3.1: Outlook for hydrogen demand for energy applications



Notes: The "reference scenario" assumes the economic and technological trends at the time of the study. The "carbon constraint case" assumes a case where strong objectives to limit global CO_2 emissions are imposed by introducing a carbon price rising from EUR 10 to 200 per tonne of CO_2, aiming for a 50% reduction of GHG in industrialised countries between 1990 and 2050. The "hydrogen economy scenario" assumes a case where a series of technology breakthroughs is achieved, and economics of hydrogen use is significantly improved, in addition to the case of carbon constraint case. (assuming 1 tonne of hydrogen = 2.86 toe)

Source: European Commission (2006), *World Energy Technology Outlook - 2050 - WETO H2.*

As of 2018, various trends were likely to result in an increased use of hydrogen as an energy carrier, particularly in the transport sector. According to the International Energy Agency (2019d), fuel cell electric vehicles (FCEVs) have seen increasing production. Annual sales globally of light-duty FCEVs in 2018 were about 4 000 units, more than 1.5 times the previous year, and the cumulative total reached 11 200 units. The advantage of hydrogen fuel cells is that these could potentially apply to transport cases where battery technologies may prove to be difficult, for example heavy-duty vehicles, light-duty vehicle for very long-distance travel and shipping (CCC, 2018). In practice, fuel cell forklifts are already commercially viable and replacing existing battery electric forklifts (IEA, 2019d). Large-scale demonstration projects of fuel cell buses or trucks are underway in countries such as China, Korea, Japan, the United States and some European countries (IEA, 2019d). With these wider potential applications, free from CO_2 and air pollutant exhaustion, the future market demand of hydrogen for transport is potentially large. Another study by the IEA, in the context of its Hydrogen Implementing Agreement, estimated that the hydrogen requirement for a large fuel-cell vehicle fleet could represent up to 25 Mt of hydrogen per year by 2050 (Drennen and Schoenung, 2014). Regarding the building sector, dozens of demonstration projects are currently underway around the world for space heating through a blend of hydrogen in the gas grid or hydrogen cogeneration. The power sector is also considered as a large potential market for hydrogen, as a source of electricity from hydrogen-fired gas turbines or fuel cells, and as a source of energy storage (IEA, 2019d).

2.3.2 Production of low-carbon hydrogen

Hydrogen must be produced using a primary source of energy, and the energy efficiency of the production process must be such that hydrogen can be economically deployed as an energy carrier. The methods currently used to produce hydrogen are divided into two categories: 1) the extraction of hydrogen from hydrocarbons that dominate the current production routes; and 2) electrolysis of water. In 2018, the former dominated global hydrogen production, with natural gas reforming accounting for 76% and coal gasification accounting for 23%, which resulted in significant CO_2 emissions of 830 Mt in 2018 (IEA, 2019d). In order to reduce these CO_2 emissions from the hydrogen production process, the CCUS technology is now being considered as one, potential solution. CCUS can reduce CO_2 emissions by 60%, or by up to 90% if fully deployed in the system (IEA, 2019d). This solution would inevitably mean more CO_2 emissions[18] than those emitted by low-carbon energy sources, making CCUS a significant CO_2 emissions source if introduced on a large scale in the future (CCC, 2018). Coal gasification is used to produce hydrogen from coal, but it is more costly and emits more CO_2 than methods using natural gas. A variety of biomass gasification methods have recently been proposed as carbon-neutral means of producing hydrogen, but the technology is not yet fully developed (IEA, 2019d).

To produce hydrogen from water, the only mature industrial method is low-temperature electrolysis. Although this method is currently the only solution that can produce low-carbon hydrogen by using low-carbon electricity at commercial scale, it is not competitive in terms of cost with gas reforming, and it contributed only less than 2% of global hydrogen production in 2018, most of which was produced as a by-product in the process of chlorine and caustic soda production (IEA, 2019d). However, the interest in electrolysis as a source of low-carbon hydrogen production is growing with the declining cost of renewable electricity and improving efficiency of electrolyser systems (IEA, 2019d). Considering the lower cost of electricity from nuclear power plants, in particular through the long-term operation of existing plants (IEA/NEA, 2020), low-temperature electrolysis using electricity from existing nuclear power plants could be an economically competitive option for producing low-carbon hydrogen.

As an advanced method to produce low-carbon hydrogen, high-temperature steam electrolysis and thermo-chemical processes are being proposed, and are currently under development. High-temperature steam electrolysis can achieve around 80% of electrical efficiency, higher than around 70% for low-temperature electrolysis, but it requires an operating temperature

18. The United Kingdom Committee on Climate Change estimated in 2018 that hydrogen production from gas reforming with CCUS can emit 15-40% CO2, compared to the case of using natural gas in a boiler, when factoring in CO_2 emissions by extraction and delivery of natural gas.

in the range 650-1 000°C (IEA, 2019d). Some studies have highlighted the technical feasibility and economics of certain types of advanced reactor systems contributing to hydrogen production via high-temperature steam electrolysis (LucidCatalyst, 2020; NuScale, 2020). For a thermo-chemical process, the sulphur-iodine cycle is the most developed and considered to be a promising technology. It requires high-temperature process heat (800-900°C), similar to high-temperature electrolysis, but can achieve higher production efficiencies compared to electrolysis, considering the energy loss for electricity production (IAEA, 2013). High-temperature process heat in this temperature range can be supplied by several ARSs, for example the high-temperature reactor (HTR) and the very high-temperature reactor (VHTR) (see Section 3.1.3 on generation IV reactors). Assuming that ARSs coupled with a thermo-chemical process contribute to 10% of the global hydrogen demand projected in Figure 2.3.1, the market size for nuclear process heat in terms of hydrogen production could be estimated to be the equivalent of around 120 GWth to 340 GWth[19] output capacity in 2050.

2.3.3 Challenges and global efforts

Along with current challenges in the development of low-carbon hydrogen production technologies, additional challenges also exist to maximise the potential of hydrogen for global decarbonisation. The cost for the production and use of low-carbon hydrogen as an energy carrier is currently not competitive, and its future market competitiveness is also uncertain. The hydrogen supply chain from hydrogen production to storage, transmission, distribution and end-use requires large-scale infrastructure development. Large-scale investments for technology and infrastructure development are therefore required along with a corresponding policy framework to aid investment, and long-term governmental commitments regarding the development of a low-carbon hydrogen system. Existing regulations and standards that do not include the new uses of hydrogen as an energy carrier need to be updated, and some important technical or accounting standards for the use of hydrogen will need to be agreed internationally (IEA, 2019d). For the successful adoption of hydrogen use, it will also be important to address public concerns regarding the negatively perceived aspects of hydrogen application, such as safety risks and high upfront infrastructure costs (IEA, 2019d).

To tackle these challenges, various efforts are being made at the national and international levels. In terms of technological development, water-splitting hydrogen production technologies are being developed, for example, in parallel to the development of high-temperature advanced nuclear reactors. China, Korea and Japan are carrying out national research, development and deployment (RD&D) programmes to develop HTR or VHTR technologies and high-temperature steam electrolysis or thermo-chemical process technologies using thermal energy provided by these reactors (GIF, 2017). The Generation IV International Forum (GIF) has a specific project for the development of technologies for hydrogen production as part of VHTR development. An intergovernmental initiative entitled "Nuclear Innovation: Clean Energy Future (NICE Future)" is also promoting nuclear energy for hydrogen production (NICE Future, 2020). A recently announced initiative in the United States will demonstrate hydrogen production using low-temperature electrolysis as a potential solution for improving the economics of current nuclear plants, in the face of the integration of renewables and the resulting low electricity prices (Yurman, 2020).

In addition, efforts to boost these technological developments from a financial standpoint are becoming more active. Increasing numbers of countries have national policies to directly support investments in hydrogen technology deployment. The global government budget for RD&D of hydrogen energy has been rising in recent years, after a significant decline since its peak in 2008 (IEA, 2019d). The Hydrogen Council is one example of international co-operative momentum. The council was established in 2017 as a global initiative to bring together relevant private companies to support the long-term ambition for hydrogen to foster the energy transition. As of 2019, there were a total of 39 steering members and an additional 37 supporting members made up of leading global businesses (Hydrogen Council, 2019). The European Commission (2020) announced "A hydrogen strategy for a climate-neutral Europe", which

19. Energy efficiency for hydrogen production using the thermo-chemical process is assumed to be 45% (Elder and Allen, 2009). A capacity factor of ARSs is assumed to be around 90%.

includes a roadmap for developing the capacity of electrolysis for low-carbon hydrogen in member countries from 1 GW in 2020 to 40 GW by 2030. It would also include expanding hydrogen applications in all hard-to-abate industries from 2030 to 2050. In order to promote and support the implementation of the strategy, the European Clean Hydrogen Alliance was also established as a platform for encouraging diverse investment projects related to hydrogen applications open to both private and public sectors. In December 2020, both Canada and Japan released national strategies for the development of hydrogen technologies, which includes nuclear technologies that would power low-carbon hydrogen production (Government of Canada, 2020; METI, 2020).

2.3.4 Summary

Hydrogen as an energy carrier has the potential to play a key role in the transition to a clean energy system. Demand for hydrogen is expected to increase significantly in the future, alongside with the expansion of hydrogen applications to sectors where hydrogen does not currently play a major role, including transport power generation and buildings. As of today, hydrogen production depends almost entirely on fossil fuel resources, with alternative low-carbon technologies actively being developed. Electrolysis and thermo-chemical processes using low-carbon sources from renewables and nuclear power have significant potential for reducing CO_2 emissions from hydrogen production. Because of the lower cost of electricity from nuclear power plants, in particular through the long-term operation of existing plants and during low electricity demand and price periods, nuclear energy can be an important source of electricity for the production of low-carbon hydrogen via the low-temperature electrolysis that is already a mature industrial method. The development of advanced nuclear technologies, such as the HTR and VHTR, are increasingly attracting global interest for high-efficiency and low-carbon hydrogen production, which uses high-temperature electrolysis and thermo-chemical processes. Multiple projects demonstrating their capabilities are currently being carried out. Although many challenges remain, including, *inter alia*, in relation to the technology, infrastructure, and regulations and standards, both the public and private sectors are working to overcome them.

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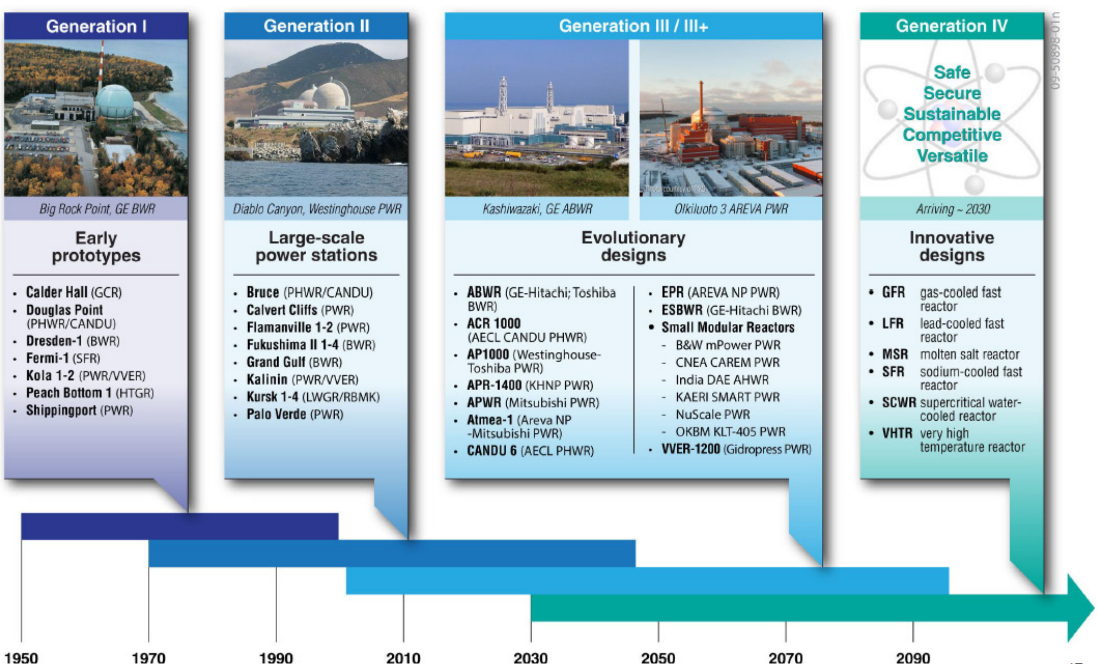
3. Overview of advanced reactor systems

The nuclear industry has been developing and improving reactor technology for more than six decades. As shown in Figure 3.1.1, the development of commercial nuclear power plants began in the 1950s with generation I reactors, followed by generation II reactors with larger capacities in the 1970s. While many generation II reactors are still operating around the world, the recent development of commercial nuclear reactors continues to expand with generation III and III+ (Gen-III/III+) reactors,[1] which have evolutionary designs that include improved fuel technology, thermal efficiency, modularised construction and enhanced safety systems. Further innovation has been seen with generation IV (Gen-IV) reactor technologies, which offer significant improvements compared to current nuclear technologies in terms of closing the fuel cycle, waste minimisation and enhanced resource use, inherent safety, economics, and proliferation resistance and security. Gen-IV technologies are currently in the research and development stages and all developments are being followed closely by the Generation IV International Forum (GIF). There has also been increasing interest in small modular reactor (SMR) technologies in the last decade.

This chapter discusses the characteristics of, and prospects for, the development of advanced nuclear reactor systems (ARSs) including Gen-III/III+ reactors, SMRs and Gen-IV reactors. Opportunities and challenges expected for advanced nuclear technologies are also discussed in this chapter.

Figure 3.1.1: Nuclear evolution



Source: GIF (2020).

1. Generation III+ reactors are sometimes categorised into a different sub-category from generation III reactors, as reactor designs with improvements to the economics of generation III reactors.

3.1 Features and development prospects

3.1.1 Generation III and III+ reactors

Gen-III/III+ reactors have been recognised as an improvement on the Gen-II reactors, and include the advanced boiling water reactor (ABWR), the advanced pressurised water reactor (APWR), the evolutionary power reactor (formerly known as the European Pressurised reactor [EPR]), the AP1000 and the VVER-1200, although the distinction from the previous generation is somewhat arbitrary. The first to start commercial operation was the ABWR in 1996 in Kashiwazaki-Kariwa, Japan. Several Gen-III/III+ reactors are currently operating or are under construction in some countries (WNA, 2020a). Table 3.1.1 provides examples of Gen-III/III+ reactors.

Table 3.1.1: Examples of Gen-III reactor designs

Design	Vendor	Country	Type	Size (MWe)	In operation*	Under construction*
ABWR	GE Hitachi, Toshiba	United States/ Japan	BWR	1 380	4 (Japan)	4 (Japan, Chinese Taipei)
AP1000	Westinghouse	United States	PWR	1 250	4 (China)	2 (United States)
VVER-1200	Rosatom	Russia	PWR	1 200	5 (Russia, Belarus)	5 (Russia, Belarus, Bangladesh, Turkey)
VVER-TOI	Rosatom	Russia	PWR	1 300	0	2 (Russia)
APR1400	KHNP	Korea	PWR	1 450	3 (Korea, UAE)	7 (Korea, UAE)
EPR	EDF (Framatome)	France	PWR	1 750	2 (China)	4 (Finland, France, UK)
Hualong One (HPR1000)	CNNC & CGN	China	PWR	1 170	1 (China)	8 (China)
ESBWR	GE Hitachi	United States	BWR	1 600	0	0
APWR	Mitsubishi	Japan	PWR	1 520	0	0
Atmea1	EDF (Framatome) & Mitsubishi	France/Japan	PWR	1 150	0	0
CAP1400	SNPTC	China	PWR	1 500	0	2 (China)
EC6	SNC-Lavalin	Canada	PHWR	750	0	0

* As of the end of 2020.

Source: IAEA PRIS, WNA Information Library (accessed 27 January 2021).

The general characteristics of the Gen-III/III+ reactor design compared to the previous generation are as follows:

- a more standardised design for each type of reactor so as to reduce capital costs and construction times;
- a simpler and more robust design incorporating many passive or inherent safety features;
- stronger reinforcement against aircraft impact;
- use of higher burn-up fuel[2] to reduce the amount of radioactive waste.

2. Higher burn-up fuel is fuel for which the total amount of heat extracted per fuel assembly is larger than that of conventional fuel.

Among these characteristics, the most significant is said to be improvements in nuclear safety. As a result of applying many passive or inherent safety concepts in its safety design,[3] which require no active controls or operational intervention to avoid accidents in the case of malfunction, Gen-III/III+ reactors have significantly reduced the possibility of core damage accident from the previous generation (WNA, 2020a).[4]

Another advantage of the Gen-III/III+ reactor is related to its manoeuvring capabilities. In contrast to previous generations that were considered as baseload sources of electricity at their initial stage, most Gen-III/III+ reactors are planned and designed to meet the enhanced requirement for manoeuvring capabilities required by grid operators. Since 2001, for example, the European Utility Requirements stipulate that new reactor designs must be capable of continuous operation between 50 and 100% of rated power, must implement scheduled and unscheduled load-following operations, and be capable of taking part in the primary control of the grid within the range of ±2% of the rated power. Some Gen-III/III+ plants that have been certified as complying with European Utility Requirements include: the AP1000, VVER-1200, EPR and ABWR (IAEA, 2018; NEA, 2011). It should be noted that such requirements do not implicate that Gen-II designs are incapable of manoeuvring, or of respecting other European Utility Requirements. In fact, some generation II plants have been operating successfully in load-following mode for many decades in France and Germany. (Box 3 in Chapter 4 details experiences in France.)

3.1.2 Small modular reactors

SMRs are defined as advanced reactors that produce electricity at roughly 300 MW(e) per reactor (IAEA, 2018). These reactors have advanced engineered features, might be deployable either as a single or multi-module plant and are designed to be largely made of pre-assembled factory-built modules, which can be shipped to construction sites. Some SMR projects are targeting lower power levels (from 1 to 20 MWe) and are called micro modular reactors[5].

The International Atomic Energy Agency (IAEA) currently estimates that there are more than 50 SMR designs and concepts globally, based on the different reactor technologies that may encompass Gen-III/III+ and Gen-IV technologies. These include: water-cooled reactors, high temperature gas-cooled reactors, liquid metal-cooled and gas-cooled reactors with fast neutron spectra and molten salt reactors (IAEA, 2020). Existing SMR designs are in various developmental stages, and though some are claimed to be near-term deployable none have reached a full commercial maturity as yet, apart from the Russian floating nuclear power plant: “Akademik Lomonosov”, with two KLT-40S pressurised water reactors that started commercial operation in May 2021 (ROSATOM 2021).

Over the past five years, the SMR concept has progressed from a hypothetical niche application of nuclear reactor designs to an emerging technology with the potential to add a new dimension to the global nuclear new-build market. The extensive interest encountered by the SMR concept results from the potential new opportunities such reactors might create for nuclear energy, when they become available. In this future nuclear market vision, SMRs and larger nuclear units are not competitors but complementary tools positioned on different market segments, because of their comparative sizes and costs, and their deployability within different time frames. SMRs could also propose an answer to countries’ specific needs that may be difficult to fulfil with medium or large power plants, for example for remote communities

3. Most safety systems equipping generation I or II designs are “active” in the sense that they involve electrical or mechanical operation commands. “Passive” or “inherent” systems can function without operator control and any auxiliary power, depending only on physical phenomena such as convection, gravity or resistance to high temperatures. Some examples are pressure relief valves, gravity injection of cooling water and natural convection of fluid due to temperature difference.
4. A calculated core damage frequency (CDF) is an important indicator of nuclear reactor safety. The United States Nuclear Regulatory Commission (NRC) requirement for CDF is $1x10^{-4}$/reactor-year, and most current US plants have about $5x10^{-5}$. Gen-III/III+ reactors offer improvements of around ten times this figure (WNA, 2020).
5. Micro modular reactors are sometimes described as a different technology than that of SMRs. However, this report considers micro modular reactors as part of the SMR concepts.

with no connected grid. With their lower electrical outputs and deployability, either in single or multi-reactor plants, SMRs may widen the range of possible applications for nuclear technology, to include:

- On-grid electrical production as a replacement for ageing fossil plants, which could provide support to grids with a high rate of deployment of variable renewable energy sources.
- On- and off-grid electrical production in places with reduced access to heat sinks (water resources), to the transmission grid or to grids with limited power transport capacities.
- On- and off-grid heat production for remote or insulated industrial sites, resource extraction sites (e.g. oil sands, mining) or communities.
- Heat production for industrial processes (depending on their technology, SMRs can provide heat at various temperatures for various applications), desalination, urban district heating and other industrial applications. Use of SMRs in hybrid energy systems (combined heat and power), to provide power alternatively or simultaneously to a grid and to a non-electrical application, is also under consideration.

From a technical point of view, SMRs are often cited as flexible enough to be positioned within a grid not only for baseload production but also in mid-merit order. When taken individually (a single reactor), SMR technologies have yet to prove that they will reach high levels of flexibility similar to those reached on some of the current, large units performing real-time load following in countries such as France and Germany (in particular, with a passive design cooling system). When taken as a fleet – in the case that a sufficient number of units will operate on the same grid – they could take advantage of their numbers and provide a flexible and reliable power source able to balance the intermittency of variable renewable energy (VRE) sources, either by adjusting the power output of each reactor or by starting or shutting units down as required by the grid. There will be a growing need to decarbonise remote and off-grid energy applications, such as remote mining operations and remote communities. Micro modular reactors have been proposed for remote applications and are currently being pursued by some developers.

From an economical point of view, SMRs have to offset the size effect. They should benefit from modular production in a series to obtain economies of scale and to reduce their production costs. They will therefore rely on a specific set of success factors to ensure economic competitiveness and technological attractiveness:

- **Modularisation:** streamlining modules via off-site construction, standardising design and mitigating on-site construction risks. In-factory fabrication and modularisation ensure better quality, reduced fabrication costs and construction times on site.
- **Fleet effect:** securing a large project portfolio with standardised modules, driving down unitary production costs.
- **Simplified design:** relying on small cores that allow for simplified designs, with a stringent cost approach (integrating lean and integrated architecture, owner-operator feedback, off-the shelf and standardised equipment and a reduced number of systems) in order to drive down construction costs and schedules, as well as operation and maintenance costs. Small cores with passive systems are often considered in the various designs, both for this purpose and for their safety benefits. Passive safety features would allow SMRs to shut down automatically, remaining cooled without external power or operator intervention for extended periods.
- **Close to consumers**: the benefit of a small core with passive safety systems could lead to a reduction in the radius of the emergency planning zone.
- **Standardisation:** relying on robust and internationally prevalent codes, norms and standards in design, regulatory safety and environmental requirements, as well as manufacturing certification.
- **Full package commercial offer:** developing a one-stop commercial offer covering an integrated SMR-based solution, which could include engineering, procurement, and construction management and services, infrastructure, human capacity building and training, as well as operating and maintenance services and fuel services.

- **Financing**: political support and regulatory environment could help to attract private and public investment and financing.
- **Global market access**: relying on SMR affordability characteristics to establish a diverse international client portfolio with countries invested in a long-term SMR-based new nuclear strategy.

As of 2020, no SMR design has yet to fully reach the commercial stage, with the exception of the Russian Akademik Lomonosov. The current cost estimations of SMR developers are associated with high levels of uncertainty. At this stage, there is no evidence that SMRs could achieve a levelised cost of electricity (LCOE) comparable to those of large reactors, but they may eventually match those currently witnessed, or those expected for the applications previously listed in this section. This would make them competitive with renewables, coal and natural gas, thus ensuring a wide variety of opportunities. SMRs could also be a possible answer to specific country needs with off-grid remote communities.

Finally, it should also be emphasised that – as is often the case when developing new technologies – strong support is required from a variety of stakeholders to create the conditions necessary for the successful deployment of SMRs, including:

- designing a market system that appropriately reflects the value of SMRs (i.e. low-carbon and dispatchable);
- providing investment incentives so that society can ultimately receive the benefits of these new technologies;
- creating strong and efficient supply chains;
- making standardisation a reality by harmonising the various, national, nuclear regulation contexts. Achievements in this area are vital to reach the serial effect sought for SMR production. International bodies and safety authorities throughout the world must be encouraged to co-operate on this issue in the coming years, including by developing new codes and standards.

As of the end of 2020, various national and international initiatives supporting the development of SMRs have emerged, such as Canada's SMR Action Plan (Government of Canada, 2020), the United Kingdom’s support programme for advanced modular reactor development (BEIS, 2020) and the United States Department of Energy (DOE) Advanced SMR R&D programme (DOE, 2020).

3.1.3 Generation IV reactors

3.1.3.1 General characteristics

Gen-IV systems are generally understood to be fission reactor designs, offering prospects for significant improvements in terms of the potential for enhanced resource use, inherent safety, economics and/or proliferation resistance and security. These reactor concepts are still in the development phase and, although there are some research or demonstration reactors, no Gen-IV reactors have been deployed on a commercial scale. Examples of Gen-IV systems are the six advanced reactor systems that are currently the focus of GIF (Peakman and Merk, 2019):

- Gas-cooled fast reactor (GFR) with a closed fuel cycle and with outlet temperatures of up to 850°C targeted.
- Lead-cooled fast reactor (LFR) with a closed fuel cycle. In the near-term, the LFR will have outlet temperatures in the range of 480-570°C, but with the potential to operate at significantly higher temperatures if material challenges can be overcome.
- Molten salt reactor (MSR) with thermal and fast neutron concepts under consideration, and with similar outlet temperatures (around 750°C) and a closed fuel cycle.
- Sodium-cooled fast reactor (SFR) with a closed fuel cycle and outlet temperatures of 500 to 550°C.

- Supercritical water-cooled reactor (SCWR) with fast and thermal neutron concepts (operating with outlet temperatures up to 625°C) and an open or closed fuel cycle under consideration.
- Very high temperature reactor (VHTR), which employs a thermal spectrum, an open fuel cycle and outlet temperatures of 1 000°C targeted. Previous demonstration projects and some early deployment projects have lower outlet temperatures and are commonly known as high temperature reactors (HTRs).

Each of these Gen-IV reactor systems comes in a variety of reactor design concepts, most often including SMR versions.

Gen-IV systems employ a variety of design and technology innovations to achieve the improvements that distinguish them from currently deployed technologies. For example, they strive to compete economically with optimised light water reactors (LWRs) by, *inter alia*, operating at higher temperatures, enabling them to achieve higher thermodynamic efficiencies of over 40% (GIF, 2014). A significantly enhanced safety performance – with the ultimate goal of eliminating the need for off-site emergency response, and thus reducing or eliminating the emergency planning zone – through a variety of mechanisms, would include: coolants and structures with high thermal inertia; highly robust fuel forms; single-phase coolants; maximum size restrictions and natural coolant circulation; passive heat removal; and more generally, a greater use of the inherent and passive safety features that have been introduced into some of the more advanced Gen-III/III+ designs (GIF, 2018a). Beyond performance and safety improvements, Gen-IV systems are aiming at new applications, and/or more sustainable approaches to the management of nuclear materials. High-temperature systems offer the possibility of contributing to efficient process heat applications and eventually to hydrogen production, thus helping to decarbonise the economy beyond the electricity sector. Within the GIF collaboration, the VHTR has been primarily developed for such applications (GIF, 2018a). Enhanced sustainability is also targeted, primarily through the adoption of fast-neutron spectrum reactor designs associated with a closed fuel cycle, including the reprocessing and recycling of plutonium and uranium, and optionally minor actinides, in fast reactors, as well as through high thermal efficiency (GIF, 2018a). This approach provides a significant reduction in uranium resource requirements and radioactive waste generation.

3.1.3.2 High outlet temperature

To make full use of the capabilities of Gen-IV systems (in particular, their higher operating temperatures) they will need to demonstrate flexible operation so as to enable integration with significant shares of variable renewable energy sources (e.g. solar photo-voltaic and wind) and enhanced product flexibility. Gen-IV reactors will thus be required to be flexible in order to meet grid operator requirements, including load following and frequency regulation capability (utilities require new build nuclear plants to provide flexibility to the grid, and they are now proposing requirements for flexible operation of advanced reactors). For those reactors dedicated to electricity production, their design will thus have to accommodate this flexible operation requirement and associated thermal cycling and fatigue, reactivity management and fuel optimisation. In order to increase economic viability through high-capacity factors, nuclear power plants, for their part, can produce alternative energy products in addition to providing flexibility services to the electricity grid. This product flexibility approach is discussed in greater detail in Chapter 4. Nuclear reactors have thus been used, although to a limited extent, for low-temperature cogeneration applications, such as district heating, water desalination, and to a much lesser extent, for process steam. Because of their higher outlet temperatures, Gen-IV systems are well-suited to address additional industrial applications, and in particular a much larger segment of the industrial heat market. They can do so through high-temperature cogeneration and the replacement of fossil-fuel generated heat with nuclear low-carbon heat, which is considered one of the hard-to-abate sectors. The development of high-temperature water-splitting processes also offers opportunities for economical, low-carbon production of hydrogen using high-temperature Gen-IV systems to enable the deployment of hydrogen as an energy carrier (GIF, 2014).

Gen-IV systems, associated with large-scale energy storage technologies will also be more suited for the hybrid energy systems that are proposed for improving both the reliability of power and economics of integrated nuclear-variable renewable energy systems.

The literature on industrial heat demand tends to group industrial heat demand into the following categories (Peakman and Merk, 2019):

- heat demand <300°C;
- heat demand between 300-500°C;
- heat demand between 500-1 000°C;
- heat demand >1 000°C.

Based on this information it is possible to group the Gen-IV systems into the temperature demands they are able to meet, as summarised in Table 3.1.2.

Table 3.1.2: Temperature range of industrial heat demand and operational capability of reactor systems

Temperature	*LWR*	*GFR*	*LFR*	*MSR*	*SFR*	*SCWR*	*VHTR*
<300˚C	✓	✓	✓	✓	✓	✓	✓
300-500˚C	X	✓	✓	✓	✓	✓	✓
500-1 000˚C	X	✓(<850˚C)	X	✓(<750˚C)	X	X	✓
>1 000˚C	X	X	X	X	X	X	X

Source: Peakman, A. and B. Merk (2019), *The Role of Nuclear Power in Meeting Current and Future Industrial Process Heat Demands.*

3.1.3.3 Closed fuel cycle benefits

Significant improvements in resource use can be linked to the ability of a system to operate with a closed fuel cycle.[6] In the case of some solid fuelled reactors, the spent fuel produced can be recycled and manufactured into new fuel. For those using liquid fuel (i.e. molten salt reactors) this recycling can potentially occur during operation. Some Gen-IV systems can produce net quantities of fissile material (Pu-239 for those employing a uranium-plutonium fuel cycle, or U-233 for those employing a thorium fuel cycle). It is worth noting that a recent NEA study (2020) indicates that there are sufficient quantities of uranium resources in the world to support the continued growth of nuclear capacity, which could include electric generation and other applications (e.g. heat supply and hydrogen production), for several decades. However, the study also suggests that the availability of these resources as nuclear fuels will require considerable exploration, development of innovative technologies and timely investment.

When considering the benefits of operating a closed fuel cycle, three broad scenarios are generally considered (Peakman and Gregg, 2020):

- natural uranium or thorium becomes sufficiently scarce, such that a closed fuel cycle is ultimately required at the earliest opportunity;
- natural uranium or thorium becomes sufficiently scarce, but at a date that still allows an intermediate step based on reuse of spent fuel in existing light water reactors (e.g. mixed oxide fuel [MOX] use, prior to transition to a closed fuel cycle;
- natural uranium is plentiful, and there is little need to reduce the amount of spent fuel stored (e.g. it is socially acceptable to commission many repositories).

6. In a closed fuel cycle, various isotopes of uranium and plutonium contained in spent nuclear fuels are extracted and reused in new nuclear fuels.

The first scenario results in the lowest demands on resources of fertile material (uranium and/or thorium) and the lowest volumes of spent fuel sent to repositories, as well as a minimisation of decay heat in terms of the material within the repository (Peakman and Gregg, 2020). Given the timescales to build up sufficient fissile inventories so as to transition to a closed fuel cycle, the second scenario would help manage the interim spent fuel volumes. However, since thermal reactors cannot effectively destroy Am-241 (which is a key component to decay heat output from high-level radioactive waste), in the interim period there would be a negative impact on decay heat relative to scenarios involving more rapid fast reactor deployment. The third scenario is the least sustainable option in terms of uranium use and waste minimisation but is a viable strategy in the event of large uranium reserves and limited concerns around managing large volumes of spent fuel.

In addition to the benefits in terms of resource use, another benefit of a closed fuel cycle relates to the characteristics of radioactive waste. As mentioned above, operating a closed cycle could minimise the decay heat of high-level radioactive waste (as well as the volume and radiotoxicity of this waste), which could reduce the size of the repository required (NEA, 2021). As a result, the overall footprint of the repository could be reduced by between factors of 2 to 5 relative to an open fuel cycle (Bond and Watson, 2012), although the precise reduction factor is dependent on the cooling time assumed and the recycling strategy employed. Considering the challenges related to the social acceptance of repositories, this potential benefit could be an additional motivation to pursue a transition to a closed fuel cycle.

3.1.3.4 Operational flexibility aspects

The Gen-IV reactor concepts that are dedicated to electricity production and have higher technology readiness levels, in particular SFRs, have already taken into account some operational flexibility aspects in their design (Sadhankar, 2019). However, none of the SFRs appear to be operated with a full grid frequency control and/or load following. In France, only the Phoenix reactor has experience with primary frequency control operation, which is a passive control (i.e. no dedicated regulation) resulting from the natural coupling between the turbo-machinery rotating velocity and the grid frequency. There have been challenges for the flexible operation of the early demonstration SFRs (Barbier et al., 2016, 2017), for instance in the case of the Super Phoenix SFR, frequency control was unauthorised because of insufficient demonstration of the fuel behaviour under the frequent power fluctuations associated with fuel cladding interaction concerns. Recent predictive simulations within the framework of the ASTRID project have provided indications that neutronics power variations of a few percent would not induce any consequence for the fuel cladding.

Load following is certainly the main challenge for a pool-type SFR as power variations induce thermal cycling on the non-replaceable emerged inner vessel as a result of changes in the level of the sodium free surface (i.e. the sodium/gas ceiling interface), leading to its progressive deformation. The option designers are investigating so as to address this issue, including the redesign of the inner vessel to avoid thermal gradients and the insertion of a back-pressure to avoid changes in the level of the free surface. Maintaining the reactor at full power whatever the grid load demand by storing excess energy or using it as a by-product (steam or electricity) for industrial processes is an alternative option under consideration.

In addition to SFRs, HTRs also have significant experience. HTRs employ an all-ceramic fuel form with graphite acting as the neutron moderator and helium (He) as the coolant. The materials and choice of coolant employed in HTRs enable the reactor to operate at high temperatures, with most experience operating such systems at temperatures around 800°C (Beck et al., 2008; AREVA, 2011).

Given historic operational experience with HTR technology, it is possible to comment on the power manoeuvrability characteristics of such a technology, particularly with respect to start-up time after refuelling, operational ramp rates and minimum power levels. On the subject of minimum power levels, as is common in many commercial nuclear power plants, as well as conventional (non-nuclear) power stations, HTR designs nominally have minimum power levels of around 20% of rated power (Sadhankar, 2019). The minimum power limits, as is also the case for commercial nuclear and non-nuclear plants (Peakman et al., 2020), is determined by the steam turbine, power conversion technology.

The targeted ramp rate during power operation for HTR designs is 5% of rated power per minute (Sadhankar, 2019), which is consistent with the European Utility Requirements outlined in Section 4.2.1. The 5%/min is a design target that is tentatively determined by considering the ramp rates of other types of reactors. The simulation of load-following operation of the GTHTR300C, a commercial HTR cogeneration system designed by the Japan Atomic Energy Agency (JAEA), has shown that load-following operation at 5%/min can be achieved (Yan, 2012). This raises an important point for many new reactor designs based on Gen-IV technology, where there has been limited power manoeuvrability experience – noting that even for systems with some experience operating prototypes, steady-state operation has been the predominant operational regime – there will be a reliance on simulating the impact on system components. While computer simulations are a powerful tool, it must be underlined that when there is limited full-scale experimental or demonstration scale experience, there is a need to ensure the computational models have significant experimental data underpinning the models, and this may not be the case for all advanced reactor systems.

Taking the JAEA design of the GTHTR300 as a prototype of modern HTR systems, the start-up period is around 50 hours (Yan, 2017). The duration is mainly determined by the design limit on the temperature ramp rate of 50°C/hr. This limit was used in the High Temperature engineering Test Reactor (HTTR), a HTR test reactor located at the JAEA Oarai Research and Development Institute. The start-up ramp rate is not prototypical of the time it takes to return to full power in the event of a minor fault. In the event of a fault in power operations of the GTHTR300, the generator is disconnected from the grid and the system is brought to a standby state in which the reactor coolant temperatures remain at the rated condition, whereas the gas turbine speed is maintained constant at full speed with turbine flow bypass control. The bypass causes a reduction in the reactor flow, and therefore reactor power will be automatically reduced to about 60% (Yan, 2017). Since the reactor coolant temperatures remain unchanged, reactor power can be returned to the rated power as quickly as desired, e.g. at 5%/min of the electric output ramp.

3.1.3.5 Summary

The study of Gen-IV systems have all, to some extent, progressed, and in the cases of LFRs, molten salt reactors (MSRs), SFRs and HTRs, experimental or prototype systems have been operated, with a significant amount of prototypical operational data associated with SFRs and HTRs. In the case of SFRs and HTRs, there has also been some experience with flexible power operation. The expectation remains nonetheless that further work is required to investigate the capabilities of SFR and HTR systems with respect to flexible power operation, which includes experimental and theoretical studies. For other Gen-IV systems, greater experimental and theoretical efforts will be required to assess their flexible power capabilities.

While there is significant experience with many of the Gen-IV systems, including operational experience, market conditions have evolved since the first demonstrations. Today, these systems are facing liberalised electricity markets, the increased penetration of variable renewable sources, evolving nuclear regulations and a growing urgency for decarbonisation. These recent changes have created new challenges and opportunities for advanced reactors that are under development. Apart from experience from early demonstrations, advanced reactor developers must also take into account such new challenges and opportunities and be able to demonstrate their technologies at an industrial scale before widespread market and public acceptance. Depending on their respective degree of technical maturity, the first Gen-IV systems are projected to be deployed commercially around mid-century.

3.2 Opportunities and challenges

3.2.1 Opportunities

There are some favourable opportunities for nuclear technologies – including for existing nuclear reactors and advanced nuclear reactors – in future energy markets. First, nuclear power is a low-carbon and stable source of electricity. According to the International Energy Agency (IEA), nuclear power is a major low-carbon source of electricity today, providing 40% of all low-carbon generation in advanced economies in 2018. In fact, nuclear power has provided around one half of all low-carbon electricity over the past 50 years (IEA, 2019). The need for decarbonisation is increasing every day, and nuclear power is expected to play a major role in the future energy system.

Secondly, nuclear power can provide a secure energy source. In countries without sufficient, domestic, natural energy resources, such as oil and gas (e.g. Japan, Korea), nuclear power has contributed to reducing their dependence on imports from other countries and to enhancing security of supply (IEA, 2019). The relatively small share of fuel costs in nuclear operating costs has helped stabilise electricity prices (IEA, 2019). In addition to these contributions, the dispatchability of nuclear power plants is growing in importance. As discussed in the previous chapter, the capabilities of flexible operation are becoming essential for the reliability of the electricity grid with the growing penetration of VRE sources. In practical terms, some countries (e.g. France) have been operating nuclear power plants in a load-following manner for several decades, and some advanced reactors provide, or are expected to provide, higher load-following capabilities in operation than the previous generation of nuclear reactors. An NEA study suggests that nuclear power plants which provide capacities for low-carbon generation and load following could contribute to reducing the cost of building an electricity system with a very low carbon-dioxide (CO_2) intensity, helping consumers to obtain affordable electricity (NEA, 2019).

Moreover, the product flexibility of ARSs will also bring new markets in which nuclear technology can play a role, such as district heat and hydrogen production. Such a feature could play a key role in global decarbonisation by providing an alternative, low-carbon energy source to hard-to abate industrial, building, transport and manufacturing sectors. SMR technologies are suited to smaller grid sizes, expanding the market where large nuclear power plants are not suitable today. As mentioned above, this kind of flexibility is a very important aspect of ARS technologies in future energy markets. The next chapter will therefore discuss the flexibility of ARSs in more detail.

3.2.2 Challenges

Like many other developing technologies, ARS technologies have challenges that must be addressed. First of all, public anxiety about nuclear accidents is a common challenge for all nuclear power plants. Overall, nuclear power reactors have had a strong safety record, and safety improvements have evolved through generations of nuclear technologies. As discussed in this chapter, ARS technologies have also significantly improved safety features by introducing innovative concepts, in particular higher levels of passive or inherent safety features. As for Gen-III/III+ reactors, the theoretically calculated frequency of a large release of radioactivity is much lower than previously anticipated, by a factor of around 1 600 compared to the early generation I reactors (NEA, 2010). SMRs are said to be advantageous in avoiding large releases of radioactivity because of the small source terms in their reactor cores, along with other safety features. As discussed in the previous sections, Gen-IV reactors are expected to achieve much higher levels of safety and reliability.[7] On the other hand, ARSs will have to address some specific safety issues when they are coupled with other applications, such as district heat and hydrogen production, as well as demonstrate safe operation in industrial applications.

Securing water resources can be a constraint for nuclear power plant development and operation. The IEA underlined in its 2016 report the potential impact that water scarcity can have on energy production and reliability. Global water demand is expected to rise by almost 10% in withdrawals and by over 20% in consumption from 2014 to 2040.[8] The availability of water resources varies significantly by country or region, and problems in some countries or regions are affecting energy production, including in several regions in China, India and the Middle East. The uncertainty about future water availability due to the impact of climate change on water resources is also an important factor to be taken into account. Nuclear power, as well

7. The Generation IV International Forum (GIF) has defined eight technology goals, and three of them relate to safety and reliability: 1) excel in safety and reliability; 2) have a very low likelihood and degree of reactor core damage; and 3) eliminate the need for off-site emergency response (GIF, 2014).
8. Water withdrawal is defined as the amount of water removed from the source, and water consumption is defined as the amount of water that is withdrawn and not returned to the source (IEA, 2016).

as a few other low-carbon technologies, such as concentrating solar power and thermal power plants equipped with carbon capture and storage, could increase water demands in future because of the need for larger amounts of cooling water per unit of energy than coal and gas power plants. Although the share of the power sector in water demand is not large today (roughly 9% in withdrawal and 1% in consumption of the total water demand globally), given growing water demand and uncertainty around the future availability of water, the stress on water resources could be exacerbated in some regions (IEA, 2016). While most nuclear power plants employ direct cooling via running water from a large body of water (e.g. the sea or a river), it is possible to use alternative cooling methods if the power plant does not have access to an abundant water supply. Alternative cooling methods include indirect cooling (e.g. cooling tower systems) and dry cooling (e.g. air-cooled condenser systems) (WNA, 2020b). Indeed, NuScale, a SMR developer, is proposing an air-cooled design option that reduces water consumption for generation by more than 90% compared to conventional power plants (NuScale, 2021).

The management of spent nuclear fuel is a common issue with ARSs and conventional nuclear power plants. While some ARS concepts might be able to improve radioactive waste management by reducing decay heat and radiotoxicity, as mentioned in the previous section, adoption of ARSs would not eliminate the need for a radioactive waste repository. In addition, non-conventional fuel forms such as metallic fuels or molten fuels may pose additional waste management challenges (storage and disposal) resulting from their corrosiveness and reactivity. Further research and development are thus necessary to further advance these technologies.

In terms of economic issues, the large capital costs and long construction lead times are also recognised as barriers to new nuclear plant projects, particularly in some liberalised electricity markets. All new construction of large capacity nuclear power plants across Europe and the United States in the previous decades have required investments of several billion USD and lead times of several years or more. In addition, there are increasing concerns about delays in construction periods resulting from a lack of experienced engineers and contractors. To address these issues, various technical features of ARSs, such as the low initial costs and short construction times for SMRs, as well as the flexibilities of ARSs that can diversify revenue flows, can be useful, as can the various political or market measures implemented or being considered.

The political situation also has a great impact on securing investment for new nuclear power plant projects. Although many countries are pursuing, or are considering pursuing, new build (e.g. Poland, Russia, Turkey and the United Kingdom), some countries have already made the decision to phase out nuclear power. Even in countries that continue to use nuclear energy, the stability and predictability of nuclear policies and nuclear regulations are necessary to attract investments to the nuclear sector.

Finally, a variety of advanced reactor types are being proposed or developed today. It is therefore important to have some idea of the choice of technologies that will ultimately be commercialised for effective development towards early commercialisation. The licensing approach should be harmonised with the design features of advanced reactors because the current regulatory framework is optimised for existing technology and not for advanced technologies.

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4. Analysis of the flexibility of advanced reactor systems

In the previous chapters, various kinds of flexibilities were identified as key issues in future energy market needs and as unique features of the advanced reactor systems (ARSs). This chapter further explores flexibility concepts and analyses future market opportunities for ARSs from these perspectives.

4.1 Flexibility

The advent of abundant, variable wind and solar energy resources is one of the main factors driving transformations in power systems. These transformations are compounded by the deployment of decentralised energy resources, including rooftop solar and smart loads, such as electric vehicles and smart appliances (IEA, 2018). Such changes are influencing the way in which power systems are planned and operated.

Over the past two decades, nations around the world have been introducing climate change policies to continue lowering greenhouse gas emissions, and these policies have largely included the adoption of variable renewable energy (VRE) sources (NEA, 2019). The adoption of VRE sources has become an incentive partly because of subsidies (Helm, 2005; Cavicchia, 2017). Some examples of countries that are increasing their share of renewable energy sources as part of their climate change policies are Canada, France, Germany and the United States (National Energy Board, 2016; Eurostat, 2017; EIA, 2017). As shown in previous chapters of this report, however, the increasing use of VRE sources creates grid management challenges (Jones, 2014) requiring the power system to be more flexible.

Various definitions of power system flexibility can be found in the literature. The International Energy Agency (IEA, 2018) defines power system flexibility as all of the relevant characteristics of a power system that facilitate the reliable and cost-effective management of variability and uncertainty in both supply and demand.

The IEA (2018) further categorises flexibility of the power system across the timescale from sub-seconds to years. Flexibility of the power system across all timescales is important for "keeping the lights on". These timescales are broadly classified into three categories as follows:

- short-term flexibility: from sub-seconds to hours, typically referring to frequency control and load following, and more relevant at the plant level;
- medium-term flexibility: from hours to days, relating to scheduling by the system operator;
- long-term flexibility: from days to months, and relating to seasonal variations (NEA, 2019).

Flexibility, as seen from the above categories, is an important attribute both at the system level and at the plant level.

4.1.1 System flexibility

The NEA has identified five different technological options for power system flexibility:

- Flexibility from conventional power plants: conventional power plants include technologies such as fossil fuel, nuclear energy and hydroelectric generation. Most flexibility services are currently provided by conventional plants. Although many nuclear plants operate in baseload mode, they are capable of providing flexibility services. Advanced reactors are being designed to be even more flexible, as will be discussed in more detail later in this chapter.

- Grid integration and network development: larger networks have less variable residual loads.
- Energy storage: energy storage is important to balance the system in the face of fluctuations in generation from VRE sources and fluctuations in demand.
- Demand-side response: provides flexibility by allowing electricity users to redistribute their consumption in response to changes in the system.
- Operational flexibility from VRE sources: includes curtailment of VRE sources or control of VRE generation. Renewables are being given priority when connecting to the grid, meaning that dispatchable generation sources are required to carry out load following so as to meet residual demand (NEA, 2019).

4.1.2 Power plant flexibility

The multinational, Clean Energy Ministerial (CEM) initiative launched an advanced power plant flexibility campaign in 2017 in order to commit governments to making power generation more flexible and ensure the effective integration of VRE sources into their power systems. As part of this campaign, the IEA published a report highlighting the role of power plants in system flexibility, as well as the policies required to advance power system flexibility (IEA, 2018). Although the IEA report was not specific to nuclear power plants, it examined the limitations of the current generation of nuclear power plants and options to enhance their flexibility. It did not, however, consider the advanced reactor concepts under development. The Clean Energy Ministerial also launched the “flexible nuclear” campaign as a joint effort between civil society and governments to enlist global experts to highlight the value of flexible nuclear energy systems working in concert with renewables (NREL, 2020).

Utilities in Europe and the United States have issued requirements for generation III reactors (EUR, 2012; EPRI, 2014) to ensure that new nuclear power plants provide flexibility services to the system. These utility requirements are mainly focused on the operational flexibility of nuclear plants.

As discussed in the previous chapter, the characteristics of ARSs, and particularly of small modular reactors (SMRs) and generation IV (Gen-IV) reactors, are considerably different from existing nuclear power plants, depending on the design concept. To evaluate the flexibility of ARSs, therefore, the Electrical Power Research Institute (EPRI) has proposed expanded flexibility criteria (EPRI, 2017). The EPRI’s flexibility criteria consists of a set of three sub-criteria, each having specific attributes, and all of which will be discussed in detail in the following sections. They are:

- operational flexibility;
- deployment flexibility;
- product flexibility.

4.2 Operational flexibility

Operational flexibility is mentioned as one of the requirements in the EPRI Guide (2018) for owner-operators of advanced reactors. In addition to manoeuvrability, EPRI (2017) has proposed additional attributes for the flexibility of advanced reactors systems. Four of these attributes for operational flexibility are:

- manoeuvrability;
- compatibility with hybrid systems;
- diversified fuel use;
- island mode operation.

4.2.1 Manoeuvrability

As discussed in Chapter 2, the rapid increase in VRE sources has resulted in growing needs for flexibility to maintain frequency and voltage on the grid. Electrical power generation systems connected to the grid are increasingly being required to have ramping and load following capabilities in order to adjust output so that grid utilities ensure a balance between electricity supply and demand throughout the day. Ramping capability is the ability for a generation fleet to change "its output in response to a steady increase or decrease in demand over a few hours", while load following or regulation capability is the ability to respond to fluctuations in demand "in about a five-minute period" (IESO, 2016a).

The relatively low fuel costs of nuclear power plants compared to plants that run on fossil fuels would mean that, in many markets, they are more economically suited for baseload generation, providing power at full output in a continuous manner throughout the year (except during maintenance shutdowns) rather than modulating their production according to the demand for electricity (IEA, 2019). In most countries, nuclear power represents a small share of the energy mix, and therefore manoeuvring the plant is typically limited to safety needs (e.g. safe shutdowns in the case of load rejections) and, when required, frequency regulation. Achieving flexibility at the plant level through load following capabilities is not applicable to every nuclear power plant in the world today as a result of technical characteristics and national safety regulations. Some of the existing nuclear power plants that do not have in-built capabilities for flexible operation may require changes or modifications to the plant design.

At the same time, having relatively large shares of nuclear power and/or a large penetration of VRE sources has acted as an incentive towards nuclear flexible operation in some countries, where it has been practiced for a number of years.

- In Canada, CANDU nuclear power plants located in Ontario usually operate at full capacity (IESO, 2016b), though their power level may be adjusted for seasonality (IESO, 2016c). CANDU reactors at the Bruce nuclear power plant site are considered flexible (Tayal et al., 1999; Jones, 2011), and were operated in load-following mode in the early 1980s. To achieve load following, the Bruce B nuclear power plant uses steam bypass and control rods, which can achieve a reduction in power from 100% to about 60% of full power, at a rate of 10% per minute (Jones, 2011).
- In France, for example, nuclear generation accounts for a high share in overall power generation and has thus encouraged the incorporation of flexibility into reactor designs to allow some plants to ramp up and down their output quickly at short notice (Cany et al., 2016; IEA, 2018). About half to two thirds of the plants in the French nuclear fleet participate at any one time in load following and power ramping. These plants can provide primary frequency control up to ±2.5% of the capacity in response to a signal from the grid. In addition, the plants can respond to a secondary frequency control up to ±5% of the capacity. Demand for load following is likely to increase as France, with plans to increase the share of renewables to 40% by 2030 (Cany et al., 2016).
- In Germany, nuclear power plants are required to operate in load following mode because of the large share (~31%) of variable renewable resources. KWU/Siemens nuclear power plants have integrated enhanced load-following capabilities at the design stage, which allows them to conduct these operations throughout the fuel cycle and with higher ramp rates (up to 140 MW/min in Konvoi reactors). The remaining nuclear power plants in Germany have recently increased their flexible operations in response to the increasing penetration of renewables in the country.
- Russian designed pressurised water reactors (VVER-1000[1]) , are capable of achieving ramp up rates of ±3-4% per minute with 70% of the fuel cycle, and ±1-1.5% per minute thereafter (NEA, 2011).
- In the United States, Nuclear Regulatory Commission (NRC) regulations prohibit nuclear power plant systems from interfacing with the grid control system; however, they do

1. VVER-1000 type reactors are operating in Bulgaria, China, Czech Republic, Iran and Ukraine, as well as Russia as of 2020 (IAEA PRIS).

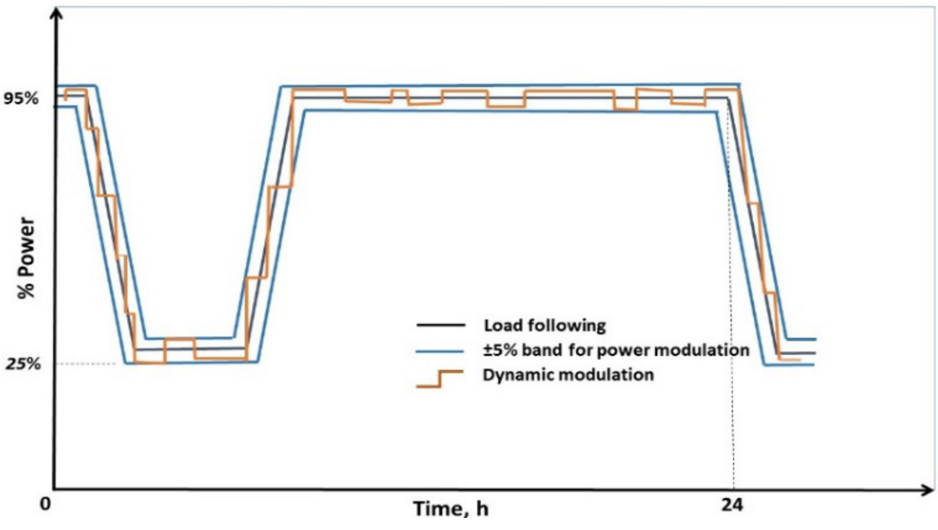
allow for pre-planned changes by a licensed reactor operator within safety limits. Current nuclear fleet experience is, therefore, limited to seasonal pre-planned power level changes (Carl and Fedor, 2017). The EPRI has a programme on flexible operations and is conducting studies to support US utilities, with assessment tools for transition from baseload to flexible power operation (Ziebell, 2017).

In recent years, recognising the need for increased flexibility for the integration of VRE sources, utilities in the United States and Europe have issued a new set of requirements for future, light water reactors (LWRs). The EPRI User Requirements Document also includes requirements for SMRs (EPRI, 2014). Most of the new reactors (Gen-III+) are compliant with the current utilities' requirements for the new nuclear plants. The IEA summarises European flexibility requirements for new, light water reactors as follows:

- The unit must be capable of continuous operation between 50% and 100% of its rated power (Pref), with a rate of change of electric output of 3-5% of Pref per minute.
- The standard plant design shall allow the implementation of scheduled and unscheduled load-following operation during 90% of the entire fuel cycle.
- The unit may be required to participate in emergency load variations, with a rate of change of 20% of Pref per minute (decreasing) and of 1-5% of Pref per minute (increasing).
- The unit shall be capable of taking part in the primary control of the grid, with a minimum range of ±2% of the rated power Pref, but values up to ±5% of Pref are recommended.
- The unit shall be able to contribute to grid restoration; and the unit should be capable of withstanding sudden load steps of up to 10% of Pref.
- The standard plant design shall allow the implementation of a secondary control (optional).
- The minimum control range for secondary control operation shall be ±10% of Pref, with a variation rate of 1% of Pref per minute. Higher values could be achieved, though not higher than 5% of Pref per minute (IEA, 2018).

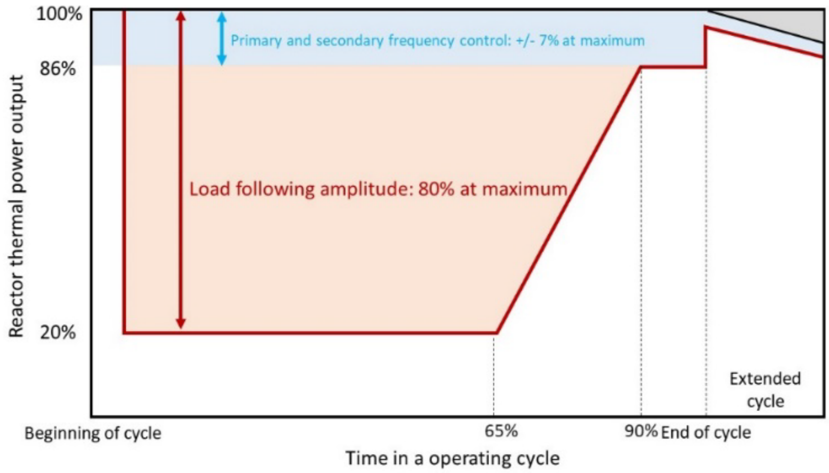
Most French reactors that provide flexibility services comply with the European utility flexibility requirements. A typical daily power output from a flexible reactor is depicted in Figure 4.2.1 below. It should be noted that during some plant events, such as after refuelling, core physical tests or extended life cycle operation, the plant will have limited load-following capacity or will need to stay at a stable power level.

Figure 4.2.1: Typical daily power variation of a flexible reactor



The ability of a LWR to provide flexibility services depends on the fuel condition. Typically, LWRs do not participate in ramping for a few days (depending on the reactor and fuel design) after refuelling until the fuel is conditioned. These reactors also do not operate in flexible mode towards the end of the fuel cycle. A typical French reactor's flexibility during the fuel cycle is illustrated in Figure 4.2.2 (IAEA, 2018). Reactors with continuous online fuelling, such as pebble-bed, high-temperature gas-cooled reactors or molten salt liquid fuel reactors, should not, in principle, be constrained by the fuel cycle.

Figure 4.2.2: Flexible operation of LWRs during the fuel cycle



Source: Feutry, S. (2018), "Flexible nuclear and renewables alliance for low carbon electricity generation", EDF.

4.2.1.1 Economic impact of load following

The flexible operation of a nuclear power plant could have adverse economic consequences. Nuclear power plants are capital intensive and have lower operating costs compared to fossil-fuelled plants (EIA, 2020). They are thus more economical when operated at full power output rather than modulated output. Reduced load factors due to flexible operation would increase the average electricity production cost, in particular if there is no fuel saving during load following. There could be opportunities for additional revenue from ancillary services (load following, frequency control) offered by the nuclear power plant depending on the terms of the power system operator and these additional revenues should be weighed against the lost production. Flexible operation of the nuclear power plant could also reduce the time it has to sell electricity below its variable cost. Non-electric applications and energy storage could improve the overall load factor and thus the economic viability of flexible nuclear power plants, both of which are discussed further in this chapter. If not already built in at the design stage, incorporating flexibility in an existing plant could require additional investment. The advanced Gen-IV reactor systems being developed would have this built-in flexibility.

Flexibility requirements are being considered in the development of the Gen-IV systems so as to avoid the limitations of some of the current generation of reactors.

Box 3: Cost-effective, flexible operation in France

French nuclear power plants were originally designed for baseload operation. In the early 1980s, in order to better respond to consumer demands on a daily or weekly basis, a decision was taken to improve nuclear power plant load following capabilities, leading to studies, modifications and administrative authorisations. Since then, flexible operation has been successfully implemented at nuclear power plants in France over the past 35 years. It is today considered as a standard design feature of French reactors. Électricité de France (EDF) currently operates 58 nuclear units in France, based on the pressurised water reactor (PWR) design technology. These units are spread over 19 sites, with an average age of 32 years and a total installed capacity of 63 GW.

Most French nuclear reactors can reduce their power twice a day, down to 20% of nominal power, in half an hour, when operating in load-following mode. They reduce their power when renewable generation is high, and they go back to full power when the sun sets or the wind weakens.

A cost-effective flexible operation

When it is possible, a nuclear power plant should be operated at full power, but flexible operation is possible and can be cost effective. When a great deal of renewable energy is available, electricity prices are low. It can be useful therefore to reduce nuclear power at this time because the quantity of unused fuel will be available at later time, when the market will need it, and at a higher price. Thanks to its large fleet, EDF is able to choose the reactors that need to be flexible, and those that can be operated at full power.

If a nuclear power plant, or a nuclear fleet, is required to be flexible because of very low consumption or high renewable generation, but it cannot, two solutions are available. The first is to curtail renewable generation, which can have a cost. The second is to shut down one or more reactors for a day or more. But market spot prices are determined on an hourly basis. While it can be cost effective to reduce power for a few hours, this is not the case for an entire day. A shutdown is a more complex operation than a short-term power reduction.

Nuclear safety

Nuclear safety is the overriding priority, and the operator should ensure that flexible operation sustains safety rules. Safety studies are undertaken to determine under which conditions the reactor can be operated. Those limits provide a dedicated domain, which is part of safety operating specifications.

Environment

When the nuclear fleet is able to “modulate” generation, it can serve as a low-carbon alternative to the fossil-fired capacity that is widely employed around the world. Fossil-fired plants can also adapt production, but they emit large volumes of carbon dioxide (CO_2). The SMR is also an alternative to the massive use of energy storage, but it has not yet reached technological maturity.

Liquid and gaseous waste generated during operation have been widely reduced since the 1980s. EDF studies have shown that additional activity released into the environment because of flexible operation is unnoticeable. Only a small increase in the volume of water or gas being released is of any notice.

Consequences on the primary and secondary circuits

No consequences have been observed on the primary circuit, because of the lack of variation in pressure, and temperature variations are small. There is thus no impact on the plant lifetime.

On the secondary part of the plant, where the turbine is located, and which is very much like a conventional plant, variations in temperature and pressure in the steam or water circuits are much higher, which can lead to unplanned unavailability. Experience from feedback on the EDF PWR fleet has nonetheless shown no significant additional costs.

To summarise, the flexible operation of nuclear plants has been practiced in France by 58 EDF reactors for 35 years, according to safety rules and without any noticeable or unmanageable impacts. It is cost effective and allows France to have one of the lowest levels of CO_2 emissions in the world for electricity generation.

4.2.2 Other attributes of flexible operation

In addition to manoeuvrability, the EPRI has introduced (2017) three additional attributes of operational flexibility for advanced nuclear reactors, as discussed below.

4.2.2.1 Compatibility with hybrid systems

Hybrid energy systems are proposed as a means to integrate VRE sources with nuclear reactors as new outlets to compensate for low load factors. A hybrid energy system may be broadly defined as a single facility (Ruth et al., 2014) or as a co-operatively controlled system (Bragg-Sitton et al., 2016) that integrates two or more energy inputs and produces one or more products. Hybrid energy systems can be configured in different ways and could include one or more energy storage systems, and one or more production facilities using thermal and/or electrical energies. The nuclear reactor must be compatible with energy storage and the intended production facilities in the hybrid system. For example, hydrogen production using thermo-chemical water splitting would require a reactor with high outlet temperatures, between 550 and 850°C. In fact, there are two intrinsic reactor characteristics that could enable or limit the synergy of reactors with hydrogen production: the reactor outlet temperature and the power rating (EPRI, 2016).

4.2.2.2 Diversified fuel use

Diversified fuel use describes the ability of the advanced reactor system to operate using a variety of fuel designs, fuel structural materials (e.g. cladding) and fuel compositions (EPRI, 2016).

4.2.2.3 Island mode operation

Island mode operation describes a nuclear system’s ability to operate in isolation from local, regional or national electricity distribution networks, either on a routine or exceptional basis. Advanced small modular reactors are being considered for remote applications such as remote mining sites or remote communities that are not connected to a regional or national grid (CNA, 2018). Island mode operation may also be required for locations with poor reliability on an electricity grid, and unacceptable interruptions in off-site power supplies.

4.3 Flexible deployment

Deployment flexibility is the ability of an advanced nuclear reactor to be licensed, financed, sited and built under a range of external conditions. EPRI describes (2016) three attributes of deployment flexibility: scalability, siting and constructability.

4.3.1. Scalability

Scalability is the ability of an advanced reactor system to be sized to match energy demand, and to meet other local and regional requirements, or to have the ability to be resized to increase energy output as a means to meet changes and accommodate growth in demand. Essentially, this attribute addresses the extent to which there are technical limits on the minimum or maximum size of a particular reactor and fuel cycle technology. The modular designs of SMRs are conducive to expansion in capacity with the growing demand for energy for a particular application. For example, in situ bitumen extraction from oil sands is undertaken in phased expansion of the oil wells (PNNL, 2018) and would require modular type reactors to meet the increasing demand. EPRI suggests (2016) two aspects of scalability: modular design and the capability of the components to be updated to ensure that uprates can occur.

4.3.2 Siting

Siting flexibility is described as the compatibility of an advanced reactor system with a variety of host locations, environments and conditions. Land requirements for the emergency planning zone[2] (EPZ) is one important aspect of siting flexibility. One of the safety goals set by the Generation IV International Forum (GIF, 2014) for the development of Gen-IV systems is to eliminate the need for an off-site emergency response. Although the EPZ of each nuclear power plant is determined by local licensing requirements, the US NRC has agreed that, based on a detailed analysis of specific safety characteristics and accident impacts, the EPZ for a particular type of SMR can be scaled down, instead of applying the uniform EPZ size requirements that currently are applied to large, light water reactors (Charles, 2018). Depending on the intended use and location, other aspects of siting flexibility could include the ecological footprint, access to water, seismological requirements, access to transmission lines and proximity to population centres. SMRs have advantages in this regard, associated with their smaller size and lower electrical and heat outputs.

4.3.3. Constructability

Constructability is described as the relative ease of building an advanced reactor system on schedule and within budget. Experience with recent projects in Europe and the United States has shown low productivity at construction sites as one of the reasons for cost overruns and delays in new nuclear plant constructions (MIT, 2018). A shift away from, primarily, the field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardised plants was recommended in a recent study by the Massachusetts Institute of Technology (2018) to significantly reduce capital costs and shorten the construction schedule. This study recommended factory production of standardised systems and modular construction in factories to reduce on-site work. Most developers of advanced SMRs have proposed modular constructions, which could be an important consideration for remote locations with less developed industrial infrastructure. A fleet approach was also recommended to standardise SMRs for potential mining and remote community deployment in Canada (CNA, 2018).

A study by PNNL (2016) on the deployability of SMRs for oil sands extraction in northern Alberta, Canada evaluated 26 SMR designs using 13 criteria. Another study in the United Kingdom (ETI, 2015) explored siting criteria and siting constraints against the nuclear expansion programme.

4.4 Product flexibility

Product flexibility refers to the ability of advanced reactor systems to be used for multiple missions. Most of the current nuclear power plants produce electricity, although over 70 reactors worldwide have been used in cogeneration mode for various applications, including district heating, providing industrial steam and water desalination. Cogeneration is the term used for simultaneous production of electricity and thermal energy or heat; it is also called combined heat and power mode operation of a power plant. In the case of nuclear power plants, thermal energy use to date accounts for a small fraction (<1%) of the cumulative output of the nuclear power plants. The individual thermal energy applications varied nonetheless from 5 to 240 megawatts-thermal (MWth). It is also worth noting that the sodium cooled-fast reactor, a Gen-IV system, have has already been used for desalination of water and district heating (IAEA, 2017a).

4.4.1. Non-electric applications of nuclear energy

The non-electricity applications of nuclear energy have been studied extensively (IAEA, 2017a, 2017b, 2012, 2009; GIF, 2002). The type of potential applications depends on the temperature of the thermal energy delivered by the nuclear reactor. Past and current experience with nuclear cogeneration relates to lower-temperature applications such as district heating, sea-water desalination and process steam for industrial applications. The higher temperature advanced reactors could enable many more industrial applications, including hydrogen production and petroleum refineries.

2. An emergency planning zone is an area in which operations and protective measures may be needed in a nuclear emergency situation to protect public health, safety and the environment.

4.4.1.1. Low-temperature non-electric applications

Low-temperature, non-electric applications are typically those requiring thermal energy at less than 300°C, which can be supplied by most existing reactors and by Gen-III+ reactors.

4.4.1.1.1 Desalination

Sea-water desalination capacity around the world is increasing rapidly to meet the increasing demand for fresh water in both developed and developing countries. Most of the desalination plants depend on fossil fuel, and thus are subject to fuel price fluctuations and supply reliability, which could undermine its economic viability. Nuclear desalination has been demonstrated to be economically competitive, meeting product water quality through a properly designed coupling system between a nuclear reactor and a desalination plant, while providing this service with low-carbon emissions (NEA, forthcoming). Both thermal processes (multi-stage flash and multi-effect distillation) and membrane processes (reverse osmosis and electro-dialysis) are currently used for desalination. Thermal processes require saturated steam up to a maximum of 140°C, which can be supplied by the current generation of reactors. In Aktau, Kazakhstan, ten units of multi-effect distillation plants were coupled to a 1 000 MWth liquid, metal-cooled fast reactor (BN-350) to produce 14 500 m^3/d (IAEA, 2017a). The result was a very high-quality water for industrial and potable needs using multi-stage flash desalination units. Production ran for 26 years before shutting down in 1999. Advanced sodium-cooled fast reactors are being developed as generation IV reactors which could be used for several cogeneration applications including water desalination.

Although the current generation of reactors can meet energy demand and temperature requirements for all sea-water desalination technologies, some of the advanced reactors are also being proposed for this service. Some of the new integral SMR concepts, including SMART (IAEA, 2017a) and the NuScale integral pressurised water reactor (Ingersol et al., 2014) are being proposed for water desalination services. High-temperature, helium-cooled reactors, including the pebble-bed modular reactor and the Japanese concept gas turbine, high-temperature reactor, GTHTR300, have also been proposed for water desalination services as a lower-temperature cogeneration application (IAEA, 2017a, 2012). A comprehensive review of nuclear desalination is presented by Al-Othman et al. (2019), who estimated the cost of desalinated water to be between USD 0.4/m^3 and USD 1.8/m^3, depending on the reactor type and the desalination process.

4.4.1.1.2 District heating

District heating systems exist in many countries with harsh winters, for example in Europe and North America. Many of these are fossil-fuel systems. A gradual shift has also been seen to decentralised heating for individual houses or buildings because of low natural gas prices. District heating systems are usually based on either hot water or low-pressure steam, and they range in size from 600-1 200 MWth for large cities to 10-50 MWth for smaller communities. With increasing environmental concerns over the use of fossil fuels, nuclear-based district heating is being considered as a potential option. Total demand for district heating is significant and could require hundreds of nuclear reactors (IAEA, 2017a).

In 2019, a total of 68 commercial nuclear plants in 11 countries are being used, or have been used, for heating purposes, demonstrating safe and reliable operation with a heat output ranging between 5-240 MW (IAEA 2020, 2019). Over the years, several heating-reactor concepts have been proposed but very few have been implemented. Among these are one plant in Russia (Obninsk) and one in China (NHR-5) (IAEA, 2012). One example of a pressurised water reactor that is run in cogeneration mode for district heating is the Beznau plant in Switzerland. The Beznau plant began to supply nuclear district heating in the early 1980s and continues to do so today, serving a population of nearly 20 000. The peak district heat load is about 80 MWth (IAEA, 2017a). Experience in Switzerland has shown that nuclear-based district heating is economical, safe, reliable and acceptable to the public.

The transport of heat over long distances without significant losses has been underlined as a challenge that needs to be addressed. The transport and distribution of nuclear heat through existing district heating networks with high heat losses would involve extensive retrofit and investments. However, use of low-grade nuclear heat with adequate changes to the balance-of-plant is being studied extensively, partly as a result of environmental concerns. Feasibility studies on the use of existing nuclear power plants for district heating have been carried out for France, Finland, Hungary and Slovenia (NEA, 2021).

Although existing reactors and Gen-III/III+ designs could very well be used for district heating, some of the advanced reactor concepts are also being proposed as a possible option for district heating applications. The possibility of using low-temperature heat from the high-temperature pebble-bed modular reactor for district heating has also been investigated (IAEA, 2012).

4.4.1.1.3 Other low-temperature applications

Unlike desalination and district heating, limited use has been made of nuclear heat for industrial applications. The largest such application was carried out in Canada where medium-pressure steam from the Bruce nuclear power plant was used for heavy water production. The Bruce A nuclear power plant consists of four CANDU reactors operating in Ontario. It had the largest bulk steam system, with a capacity of 5 350 MWth, supplying ~750 MWth for heavy water production, 15 MWth for on-site building heating and about 72 MWth to an industrial park with food processing, ethanol and plastic film manufacturing plants until the mid-1990s (IAEA, 2017b).[3] The heavy water plants at the Bruce site were the largest ever built, using medium pressure steam from the Bruce plant to produce over 16 000 metric tonnes of heavy water between 1973 and 1997 (IAEA, 2017b). The production plant was located near the plant and was licensed by the national regulator. In Germany, the Stade nuclear power plant supplied 60 t/h of process steam at 0.8 MPa and at 270°C to a salt refinery between 1983 and 2003. In Switzerland, the Gosgen nuclear power plant supplies about 45 MWth thermal energy to a cardboard factory and a paper mill, using medium pressure steam (1.2-1.5 MPa) (IAEA, 2017b).

There is growing interest in using nuclear thermal energy to replace fossil fuel for industrial applications in order to combat climate change. Advanced reactors under development present additional opportunities for industrial applications because of higher outlet temperatures compared to existing reactors. In Europe, a comprehensive study of the European industrial heat market was undertaken in the context of the EU-supported EUROPAIRS (2009-2011) project (Bredimas, 2014). Although this study focused on the application of high temperature reactors for industrial cogeneration, it nonetheless identified significant thermal energy demand at temperatures below 300°C that can be provided by either currently operating reactors or by future Gen-III+ or advanced reactors. Cogeneration of an industrial product provides flexibility for nuclear power plant operation by allowing it to switch between electrical output and an industrial product that can be stored on-site.

4.4.1.2 High-temperature, non-electric applications

High-temperature, non-electric applications require a thermal energy supply at temperatures above 300°C, and they therefore are non-existent due to the limitations of the reactor outlet temperatures of existing reactors. The ongoing development of advanced reactors with significantly higher temperatures has created the possibility of using nuclear heat for additional industrial applications. The EUROPAIRS study (Bredimas, 2014) found that the most significant heat market is below 550°C and above 1 000°C, with very few processes, such as industrial gases and lime production, requiring energy in the temperature ranges of 550°C to 1 000°C.

4.4.1.2.1 Hydrogen production

As discussed in Chapter 2, hydrogen as an energy carrier has significant potential to contribute to global decarbonisation efforts. To be used as an energy carrier, hydrogen must be produced from water, using energy efficient processes and using a low-carbon energy source, such as nuclear energy. Therefore, high-temperature water-splitting processes for hydrogen are being developed alongside the development of high-temperature reactors. The Generation IV International Forum (GIF) has a special project for the development of high-temperature hydrogen production processes as part of the development of very high-temperature reactors

3. Although the Bruce A nuclear power plant is still operating for electricity generation in 2021, the bulk steam system was demolished in 2006 (IAEA, 2017b).

(VHTRs) (GIF, 2014). These high-temperature processes include thermo-chemical cycles (such as the sulphur-iodine cycle and copper-chlorine) and high-temperature water electrolysis (GIF, 2014; IAEA, 2012). The capacity of converting hydrogen back to electricity using fuel cells offers additional flexibility for nuclear plant operation as the hydrogen can be used both as energy storage and as a saleable product.

While there are technical challenges that are specific to coupling nuclear reactors with industrial facilities, such as prevention and mitigation of cross-contamination and impacts from accidents at industrial facilities (IAEA, 2019), research and development (R&D) activities are nevertheless being promoted by national programmes in some countries so as to address these challenges. The Japan Atomic Energy Agency (JAEA) has the High Temperature engineering Test Reactor (HTTR), a 30 MWth helium-cooled reactor, and has also developed a sulphur-iodine, thermo-chemical process for hydrogen production. A test plant for coupling the HTTR with the gas turbine and hydrogen production process has been planned in the late 2020s (Yan et al., 2018) to demonstrate the licensing ability of the JAEA's commercial reactor concept of gas turbine high-temperature reactor, the GTHTR300C, for electricity and hydrogen cogeneration. Korea also implemented a programme for the development of nuclear-hydrogen production using a high-temperature, gas-cooled reactor and the sulphur-iodine, thermo-chemical process (NEA, 2021). One of the main uses of hydrogen in Korea will be for steel making, using direct reduction of iron ore. At the Idaho National Laboratory of the US Department of Energy (DOE), a high-temperature steam electrolysis process is being developed for hydrogen production using a high-temperature reactor (O'Brien et al., 2010). Some studies have highlighted the technical feasibility and economics of certain types of ARSs for hydrogen production via high-temperature steam electrolysis (LucidCatalyst, 2020; NuScale, 2020). Much research has also been carried out exploring large-scale hydrogen storage in salt caverns.

In addition to activities being undertaken by research institutes, some industrial players have started developments for the commercial use of nuclear energy for hydrogen production. In November 2020, Synthos Green Energy, which belongs to Synthos S.A. Capital Group, including Synthos S.A., a leading chemical manufacturer based in Poland, announced a partnership with the Ultra Safe Nuclear Corporation for the development of an energy system using micro modular reactor technologies that will generate hydrogen at industrial scale as a part of an overall decarbonisation strategy (Synthos, 2020).

4.4.1.2.2 Other high-temperature applications

As discussed in Chapter 2, advanced reactor systems could make a contribution to high-temperature industrial heat supply, particularly with heat below 550°C. This market could be captured by a "plug-in" high-temperature reactor, replacing the existing fossil-fuel operations. One study underlined (Bredimas, 2014) the significant potential of the "extended" heat market that includes oil refining, iron and steel, and cement manufacturing, where heat is mostly provided by embedded boilers and burners. The EUROPAIRS study (Bredimas, 2014; Futterer et al., 2014) also looked at two sub-markets: polygeneration and pre-heating. The polygeneration sub-market involves the production of base raw materials such as industrial gases (hydrogen, nitrogen, oxygen) in addition to the cogeneration of heat and power. Polygeneration could provide additional flexibility for nuclear power plants and improve the economics, particularly for integration with VRE sources, while easing the siting restrictions for the plants. The second sub-market segment investigated was "pre-heating" for industrial steel and glass manufacturing, if nuclear thermal energy could be economically competitive. Use of high-temperature reactors for steam supply, for the in situ extraction of bitumen from oil sands, has also been investigated (PNNL, 2018, 2016). Various studies of the potential cogeneration of high-temperature reactors for petrochemical and steel sectors are also summarised in a report by the International Atomic Energy Agency (IAEA, 2017b).

Despite these diverse studies examining cogeneration possibilities for high-temperature reactors, challenges related to economic competitiveness, licensing for co-location and coupling of a nuclear power plant to a production plant, as well as public acceptance, have not been explored in any detail.

4.4.2 Hybrid energy system

Hybrid system concepts were proposed to integrate nuclear with VRE sources so as to improve both the reliability of power and the economics of an integrated system. A hybrid energy system may be broadly defined as a single facility or co-operatively controlled system that integrates two or more energy inputs, and produces one or more products, with an energy commodity such as electricity or transport fuel (Ruth et al., 2014). Hybrid energy systems – which have a common grid for both variable renewable and dispatchable sources, with storage possibilities to generate both heat and electricity – have been proposed as a means of better integrating renewables with nuclear energy reactors via new outlets that will compensate for lower load factors.

Hybrid energy systems are comprised of multiple sub-systems, which may or may not be geographically co-located (Bragg-Sitton et al., 2016):

- nuclear heat generation source;
- a turbine for the conversion of thermal energy to electricity;
- at least one VRE source;
- an industrial process that uses heat and/or power from energy sources to produce commercial-scale products;
- energy storage (thermal and/or electrical).

Hybrid energy systems can be configured in various ways, for instance as a "tightly coupled" system that acts as a single financial entity where nuclear generation, VRE sources and industrial production are controlled upstream of a single connection point to meet flexible demand from the grid, while operating the nuclear plant at capacity.

The key benefits of hybrid energy systems are that they:

- provide dispatchable, flexible and carbon-free electricity generation;
- provide synchronous electro-mechanical inertia to the grid (frequency control);
- reduce the carbon footprint of industrial production;
- stabilise energy costs;
- reduce the energy system impact on water resources.

The United States DOE programme for hybrid systems has sets out a plan for R&D requirements that integrates renewable sources with nuclear reactors in an energy system (Bragg-Sitton et al., 2016). The focus of this R&D plan is on reaching the demonstration stage for a nuclear-renewable hybrid energy system by 2030. As such, the key areas of research are on "integration technologies, communications, and system control versus development of novel subsystem technologies" (Bragg-Sitton et al., 2016). Although fully integrated hybrid systems have not yet been demonstrated, the component technologies are mature. Industrial-scale energy storage would be required for hybrid energy systems. Thermal energy storage is considered to be the most economical (Forsberg et al., 2017). Heat storage technologies can be coupled to nuclear reactors, which may enable these nuclear reactors to provide economic energy storage in order to provide reliable dispatchable electricity and ensure the economic integration of VRE sources.

Hybrid systems are promising to provide the required flexibility for the integration of nuclear energy with renewable energy, but its viability will depend both on the geographical location and the business model.

4.5 Summary

The increasing share of VRE sources on the grid requires additional flexibility on the part of dispatchable energy sources to meet the variable and, at times, unpredictable residual load demand. Nuclear generation is typically characterised by high capital cost and low variable cost, and it is therefore economically attractive if operated at high-capacity factor rather than in a varying output mode. Nonetheless, most nuclear power plants are capable of flexible operation, and plants in France and Germany have, to a certain extent, been operating in flexible mode. Utilities require new build nuclear power plants to provide flexibility services to the grid. However, to be economically viable, the nuclear plants will require alternate energy products and/or large-scale energy storage to achieve high-capacity factors, in addition to providing flexibility services to the grid. EPRI has proposed expanding criteria for the flexibility of advanced reactors, which extends beyond operational flexibility and includes other aspects such as deployment flexibility and product flexibility.

Advanced reactors that are under development promise to have better flexibility compared to existing reactors, as stipulated by utility requirements for new nuclear power plants. Some of the existing reactors are known to suffer from higher maintenance costs, longer outages and unplanned shutdowns due to thermomechanical stresses induced by power ramping and load following. Existing, light water reactors are capable of providing full flexibility services for about two-thirds of the fuel cycle, with limited or no flexibility at the beginning or near the end of the fuel cycle. In the case of gas-cooled advanced reactors, thermal fluctuations can be avoided by controlling the coolant flow with the required power fluctuations, thus preventing ageing of components due to thermomechanical stresses. Reactor developers are already taking into consideration these flexible operation requirements during the design and development phase. Many advanced reactor concepts are also being developed as small modular reactors that have the potential for improved constructability and deployability compared to the current generation of reactors.

Although many nuclear reactors have been used for low-temperature cogeneration applications, such as district heating, water desalination and process steam, such applications account for a small fraction of the cumulative energy output of nuclear power plants. The EUROPAIRS study (Bredimas, 2014) found that the most significant heat market is below 550°C and above 1 000°C, with very few processes requiring energy in the temperature range of 550°C to 1 000°C. Existing nuclear power plants can provide thermal energy at temperatures below 300°C. ARSs will be more suited for cogeneration applications at temperatures above 300°C because of higher outlet temperatures that would be able to replace fossil fuel with thermal energy in many process industries. Simultaneous development of high-temperature, water-splitting processes presents opportunities for more economical hydrogen production using high-temperature advanced reactors to enable hydrogen as an energy carrier. Despite these diverse studies examining cogeneration possibilities for high-temperature reactors, challenges related to economic competitiveness, licensing for co-location and coupling of a nuclear power plant to a production plant, as well as public acceptance, have not been explored in any detail. ARSs, together with large-scale energy storage technologies, will also be more suited to the hybrid energy systems that will be proposed to improve the reliability and economics of integrated nuclear-VRE systems.

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5. Conclusions

Over the last two decades, significant efforts have been undertaken in many countries to expand the role of low-carbon energy sources. We have nonetheless witnessed a steady rise in global carbon dioxide (CO_2) emissions, since demand for energy has outstripped global efforts to decarbonise the energy system. While it is clear that nuclear power can continue to meet this increasing demand for electricity, the interest in how advanced nuclear reactor systems might address decarbonisation of the future energy system has nevertheless been growing, not only for the electricity sector but also for other parts of the energy sector. The key findings and recommendations for future action outlined below describe what this future energy market could resemble.

5.1 Key findings

5.1.1 Increasing needs for flexible power operation

The need for flexible power operation from power plants, covering both shorter-term and longer-term flexibility, are expanding as variable renewable energy sources are being increasingly deployed in electricity grids. Nuclear power plants not only provide large quantities of reliable, low-carbon electricity, but they also have the capability to provide important ancillary services to ensure the security and stability of the electricity distribution system via frequency response and inertia. Current generation III and III+ (Gen-III/III+) reactor technologies are already compliant with the latest utility requirements as of 2020. Future advanced reactor concepts, including small modular reactors and generation IV reactors (Gen-IV) reactors, have different characteristics (advantages and challenges) for flexible operation, and flexibility requirements should therefore be considered by developers (see Chapters 2, 3 and 4).

5.1.2 The diverse role of nuclear power in the electricity system

The future electricity system is likely to look quite different from today's system in the event that governments continue to propose incentives and policies to address climate change, including those to increase the adoption of variable renewable energy sources and electric vehicles. The potential for widespread adoption of electric vehicles in the future, for example, creates a mechanism for demand-side management at large scales, via the timing of a significant proportion of electricity demand on intra-day timescales. Various storage technologies can mitigate the inconsistency of the power supply, with demand side management technologies also being developed. These technologies can not only help mitigate some of the issues associated with the high deployment of variable renewable energy sources, but they can also allow conventional plants, including nuclear power plants, to operate at high-capacity factors even under scenarios with significant variable renewable energy deployment. Given that advanced reactor systems can provide not only a firm capacity to help the electricity system ensure a sufficient amount of supply and system stability (e.g. inertia) but also a certain manoeuvrability over a wide range of timescales – from very-short-term (frequency response) to seasonal dispatchability – these advanced systems will therefore be in a position to provide different values to the electricity system according to their characteristics (see Chapters 2 and 4).

5.1.3 *Decarbonisation and the potential contribution of advanced reactors to the heat sector*

Heat accounts for a considerable proportion of global energy consumption and for global carbon dioxide (CO_2) emissions. This report finds that advanced reactor systems have a great potential to help decarbonise this sector, by providing low-temperature heat (<300°C) for district heating, seawater desalination and some industrial process heat. Higher temperature heat (up to 550°C) can potentially be supplied by many Gen-IV reactors that are currently under development. The heat demand in this temperature range accounts for a large part of global heat demand, and therefore the heat application of advanced reactors has considerable potential to contribute towards the decarbonisation of this sector. Small modular reactor systems also aim to achieve higher deployment flexibility, which may more readily enable co-location of these systems near industrial sites (see Chapters 2 and 4).

5.1.4 *Potential contribution from hydrogen production via advanced reactor systems*

Decarbonisation of large-scale hydrogen production is another area where advanced reactor systems can play an important role. Hydrogen has long been expected to contribute to the decarbonisation of various sectors, including heat supply, chemical-feedstock and fuel for transport, under the condition that it is produced through low-carbon energy sources. All advanced reactors concepts can produce hydrogen using the existing low-temperature electrolysis technology, and some concepts have been suggested to be technically and economically feasible for high-temperature electrolysis. The very high-temperature reactor can potentially produce hydrogen with even higher efficiency through water-splitting processes. Along with infrastructure development for hydrogen use currently ongoing around the world, hydrogen production by advanced reactor systems can greatly contribute to global decarbonisation (see Chapters 2 and 4).

5.1.5 *Higher temperature Gen-IV reactors*

Historically, the focus has been on the deployment of Gen-IV systems, and particularly liquid metal-cooled fast reactors, to close the fuel cycle. The benefits of a closed fuel cycle are numerous and invaluable over the longer term, and include minimising radioactive waste and enhancing resource use. Given the current availability of uranium and relatively small inventories of spent fuel and high-level radioactive waste, the other potential benefits of Gen-IV reactors in addition to the closed fuel cycle are its higher temperatures, which may prove to be strong motivation for deploying these systems in the short to medium term. For certain Gen-IV systems that can demonstrate high levels of passive safety over conventional reactor systems, this may also ease co-location on certain industrial facilities (see Chapters 3 and 4).

5.2 Recommendations

5.2.1 *The potential of advanced reactor systems as low-carbon, cost-effective means to support country policies with respect to low-carbon emission targets and variable renewable energy deployment should be recognised*

Further, drastic decarbonisation is needed in the electricity system to help countries on their way to achieving carbon-neutral targets. Over the last few years, renewable energy has accounted for the largest proportion of investment in the power sector at more than seven times the size of nuclear energy investment, and this trend is expected to continue for a few decades (IEA, 2020, 2021). However, further increases in the penetration of variable renewable energy sources will inevitably give rise to power system reliability issues. As shown in this report, advanced reactor systems could offer a solution with their stability and manoeuvrability over broader timescales. In terms of cost effectiveness, the Nuclear Energy Agency has suggested that the cost of building an electricity system that could achieve very low CO_2 emission rates would increase dramatically as the share of variable renewable energy sources increase, and would lower as the share of nuclear energy increases (NEA, 2019). Although the strategies of each country or region for carbon neutrality can be diverse, reflecting the characteristics and needs of individual energy markets as discussed in the previous sections, policymakers should nonetheless recognise that advanced reactor systems are a potential option to help achieve both low-carbon and reliable energy systems.

5.2.2 Non-electric applications involving advanced reactor systems should be included in policymaking considerations

Despite the great potential for CO_2 reductions from non-electric applications of advanced reactor systems, they are not often included in policy discussions. The reason could be related to their complete absence from internationally referenced decarbonisation scenarios, such as the International Energy Agency Sustainable Development Scenario (IEA, 2021). Given that they are widely applicable to sectors where other low-carbon energy sources may be difficult to apply, the non-electrical applications of advanced reactor systems are worth considering as important options for decarbonisation policies. It should be noted in particular that nuclear hydrogen production has enormous potential for decarbonisation when combined with the development of a hydrogen infrastructure, and that international co-operation or initiatives, such as the Generation IV International Forum and the Nuclear Innovation: Clean Energy Future Initiative, can help with the effective promotion and development of these technologies.

5.2.3 Governments and industry should work together to demonstrate the current capabilities of advanced reactor systems in target markets

While some applications, such as flexible operation and low-temperature heat supply, have already been technically proven in some regions, the nature of nuclear new build projects depends not only on geographical characteristics but also on market conditions. Demonstration projects in particular play an important role in confirming the technical and institutional feasibility of these projects in target regions and in attracting investments for further development. Given the uncertainty resulting from the limited experience of these new applications in actual markets, the high capital costs associated with nuclear new build projects, and the longevity of these assets, early government commitment and political consensus on the role of nuclear energy in long-term energy strategies is essential for involving private sector investment in these projects. In addition to building proper regulatory frameworks and market systems that could provide long-term price signals and business predictability, governments can support private business in securing funding for new nuclear build projects via a variety of mechanisms, for example through direct financial support, power purchase agreements and regulated asset base arrangements (NEA, 2020). The feasibility and effectiveness of government support depends largely on the political and social conditions of a country, as well as the characteristics of the project. Close communication and co-operation between government and industry is therefore essential to create the effective project environment to develop the new nuclear applications. Countries such as Canada, the United Kingdom and the United States have been implementing national programmes to promote research and development (R&D) of advanced reactor systems and to incentivise private investment.[1] In these countries, public-private partnerships contribute to developing innovative reactor concepts and streamlining regulatory frameworks, which could ultimately lead to several new demonstration projects.

5.2.4 International collaboration should be promoted to improve the economic viability of advanced reactor system development

Future nuclear power plant developments will be more adapted to the needs and characteristics of the regions of interest. The target market will be more segmented and less likely to benefit from economies of scale, despite high costs for the development and demonstration of advanced reactor concepts and related technologies (e.g. coupling to hydrogen production). R&D collaboration between countries that share similar market needs or geographical conditions

1. For example, the SMR Roadmap Project in Canada, the BEIS Energy Innovation Programme (EIP) in the United Kingdom, and the Gateway for Accelerated Innovation in Nuclear (GAIN) in the United States.

should provide numerous benefits, such as reducing the study duration, sharing experience, decreasing R&D costs and facilitating access to investment sources. Sharing existing research infrastructure is a widely used approach to optimise research, development and deployment (RD&D) costs. Existing frameworks, such as the Generation IV International Forum and the Nuclear Innovation: Clean Energy Future Initiative, could continue to play an important role in promoting international collaboration.

Harmonising industrial codes and standards, as well as regulatory frameworks across different countries, could reduce the technical barriers between markets in different countries and help business entities to gain economies of scale. Of the activities currently underway for this purpose, the World Nuclear Association industry sponsored group, Cooperation in Reactor Design Evaluation and Licensing (CORDEL), is carrying out studies related to the harmonisation of codes and standards for nuclear facilities (WNA, 2019). It is also working on the harmonisation of licensing, including for new nuclear plant designs such as small nuclear reactors (WNA, 2019). Countries taking part in the NEA Multinational Design Evaluation Programme are interested in specific reactor designs (e.g. EPR, AP1000), share information and co-operate on evaluations, construction, commissioning and the early phase operation of specific reactor designs to explore opportunities for the harmonisation of regulatory practices.[2]

5.2.5 Public understanding for advanced reactor systems should be continuously fostered

Public anxiety around nuclear energy continues to exist, in particular in relation to the safety and environmental impact of radioactive waste. In order to gain public support for the development of advanced reactor systems, it will be important to respond to these public concerns. Advanced reactor systems have many favourable features to help address public perception issues, including improved safety and the better management of spent fuel via a closed fuel cycle operation. The shared understanding of the features and benefits of advanced reactor systems among nuclear experts and the public could improve public perception around advanced reactor systems. It is also important that governments support communication initiatives to help address public perceptions of the challenges.

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2. More information on MDEP is available at www.oecd-nea.org/mdep/.

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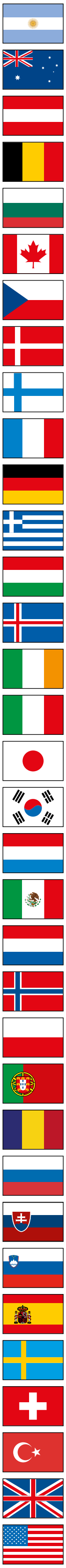

Advanced Nuclear Reactor Systems and Future Energy Market Needs

Energy markets will be significantly different in the future. The electricity generation system is becoming more diverse with the development of energy-related technologies including renewable energy sources, storage technologies and demand-side management. Beyond the electricity sector, various low-carbon energy technologies are being developed to respond to the need to decarbonise hard-to-abate sectors such as heavy industry and long-distance transportation.

In this report the NEA investigates the changing needs of energy markets and the potential role of nuclear technologies as low-carbon energy sources. Focusing on the technical characteristics of advanced nuclear reactor systems, including Generation III/III+ reactors, small modular reactors and Generation IV reactors, it explores the ways these advanced nuclear technologies could address the future energy market needs. The conclusion is that advanced nuclear reactor systems, while complying with the flexibility requirements of the electricity grid and supporting system reliability, have a large potential as alternative low-carbon energy sources for residential and industrial heat supply and hydrogen production.

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