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Application of the United Nations Framework Classification for Resources and the United Nations Resource Management System: Use of Nuclear Fuel Resources for Sustainable Development – Entry Pathways

A report prepared by the Expert Group on Resource Management
Nuclear Fuel Resources Working Group

Geneva, 2021

Note

This report was prepared within the context of the work of the Expert Group on Resource Management (EGRM) of the United Nations Economic Commission for Europe (UNECE). The technical integrity of the report has been reviewed by experts at the International Atomic Energy Agency (IAEA), Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD-NEA) and World Nuclear Association (WNA).

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Preface

The 2030 Agenda for Sustainable Development (2030 Agenda), adopted by all United Nations Member States in 2015, provides a blueprint for peace and prosperity for people and the planet, now and into the future. While some progress is visible, overall action to meet the 2030 Agenda is not advancing at the speed or scale required. The world had agreed to make 2020 the year to usher in a decade of ambitious action to deliver the Sustainable Development Goals (SDGs) by 2030. Unfortunately, the end of 2019 brought a more urgent challenge in the form of the Covid-19 pandemic, which is not only causing substantial human suffering, but also is grinding the global economy to a halt.

With possible economic stress caused by the pandemic, there could be a push to adopt solutions that undermine sustainable development and aggravate the impacts of climate change. An essential understanding of the technologies that can lead towards a green recovery is needed. The context for such understanding can be provided by the United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS) that is being developed to complement UNFC. Both UNRMS and UNFC are offered as tools to support countries in meeting the SDGs, notably for affordable, clean energy and for climate action.

The focus of this report is on the need expressed by decision and policy makers in a number of countries worldwide who are exploring nuclear energy as part of a portfolio of options and including the utilization of local uranium resources in supporting sustainable development. Some countries choose to pursue nuclear energy with the view that it can play an important role in their energy mix, while other countries have decided not to depend on nuclear energy for a variety of reasons.

An earlier report, *Redesigning the Uranium Resource Pathway*[1], which was developed by the Nuclear Fuel Resources Working Group of the Expert Group on Resource Management and published by the United Nations Economic Commission for Europe in 2019, examined new approaches to uranium resource recovery and valorisation. The current report complements *Redesigning the Uranium Resource Pathway* and focuses on how best to use that resource, whether within the context of a national nuclear energy programme, or perhaps as part of regional cooperation for balanced, sustainable energy provision, or within the context of international initiatives for sustainable development and climate action.

It is hoped that this report would provide a touchstone for future United Nations projects on energy, such as the Carbon Neutrality Project. Successfully addressing climate change and other pressing environmental challenges while still achieving the economic growth necessary to improve the living standards of billions of people will require the use of all available low-carbon technologies, as well as technologies which have yet to be commercialized. This report can serve as a guide for the many countries that choose to deploy nuclear power as part of their sustainability pathway.

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[1] *Redesigning the Uranium Resource Pathway: Application of the United Nations Framework Classification for Resources for Planning and Implementing Sustainable Uranium Projects*, ECE Energy Series No. 57, United Nations Economic Commission for Europe (August 2019)

Acknowledgements

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Executive Summary

The world's energy sector is undergoing a profound transition. This transition is driven by the need to expand access to clean energy in support of socio-economic development, especially in emerging economies, while at the same time limiting the impacts of climate change, pollution and other unfolding global environmental crises. Fundamentally this transition requires a shift from the use of polluting energy sources towards the use of sustainable alternatives. The ongoing Covid-19 pandemic also reminds us of the importance of resilience in the energy system and is a profound motivation for countries to 'build back better'. There are many pathways to achieving this transition and each country will pursue its own route, taking into account its own endowment of natural resources as well as other local and regional factors. The UN's 2030 Agenda for Sustainable Development, distilled in the Sustainable Development Goals, has become an indispensable tool for decision makers concerned with navigating these difficult decisions.

This report explores the potential for nuclear energy as part of the energy portfolio and shows how the utilisation of local or regional uranium resources can provide a platform for sustainable development. Some countries have chosen to pursue nuclear energy with the understanding that it can play an important role in their energy mix, while other countries have yet to make a decision or currently have chosen not to depend on nuclear energy for a variety of reasons. This report meets a need expressed by global decision makers to better understand the role nuclear energy may play in the energy transition.

'Nuclear newcomers' are countries which are considering, planning for, or introducing nuclear energy into their energy mix. Around the world many nuclear newcomers are now making steady progress in their journeys to introduce nuclear energy while other countries are poised to embark upon that journey. This report illuminates some of the key options available to newcomers as well as some of the challenges. It also explores potential entry pathways in the context of local and regional factors, including the utilization of domestic uranium resources, which could facilitate nuclear energy and economic development by applying the United Nations Resource Management System (UNRMS). Key insights include:

- Nuclear energy is an indispensable tool for achieving the global sustainable development agenda. It has a crucial role in decarbonizing the energy sector, as well as eliminating poverty, achieving zero hunger, providing clean water, affordable energy, economic growth, and industry innovation. Improved government policy and public perception along with ongoing innovation will enable nuclear energy to overcome traditional barriers to deployment and expand into new markets.
- Nuclear energy entry pathways for newcomer countries align with the 2030 Agenda for Sustainable Development. Nuclear energy programmes, based on the IAEA's Milestones Approach, support national energy needs, socio-economic, and environmental goals, and can help countries meet international climate commitments.

- There are many sustainable options for implementing a nuclear fuel cycle and waste management strategy. Countries should adopt such strategies based on their needs (e.g. enhancing economic development and security of supply) as well as the presence of domestic mineral resources, technical capabilities, and the economic opportunities they see in the different fuel cycle options.
- Currently available nuclear reactor designs are based on mature and proven technologies that in some instances have been licensed to operate for 80 years. A range of designs are available, all of which offer high levels of safety and outstanding operating performance. They provide reliable, affordable and low-carbon electricity that will support a country in meeting its sustainable development goals.
- A wide range of small modular reactor and advanced reactor designs are currently under development, with some ready for near-term deployment. These offer enhanced flexibility and will be suitable for helping to decarbonize heat and transport as well as electricity – boosting sustainability even further.
- Nuclear innovation and the pursuit of so-called hybrid energy systems are the catalysts for integrated development and strengthening linkages between the nuclear sector and other clean energy technologies and non-energy sectors. Both current nuclear technologies and new reactor designs can provide high-quality heat for electricity, industry and transport cost-competitively with fossil fuel alternatives.
- There are many ways in which nuclear and renewable energy technologies complement each other for the common goal of delivering clean, affordable and reliable energy.
- For a nuclear programme to be successful, policy makers should prioritize: nuclear energy policy, electricity market design, international cooperation, regulatory harmonization, nuclear skills and supply chain development, project structuring and management, public engagement, and building diversity and inclusivity.

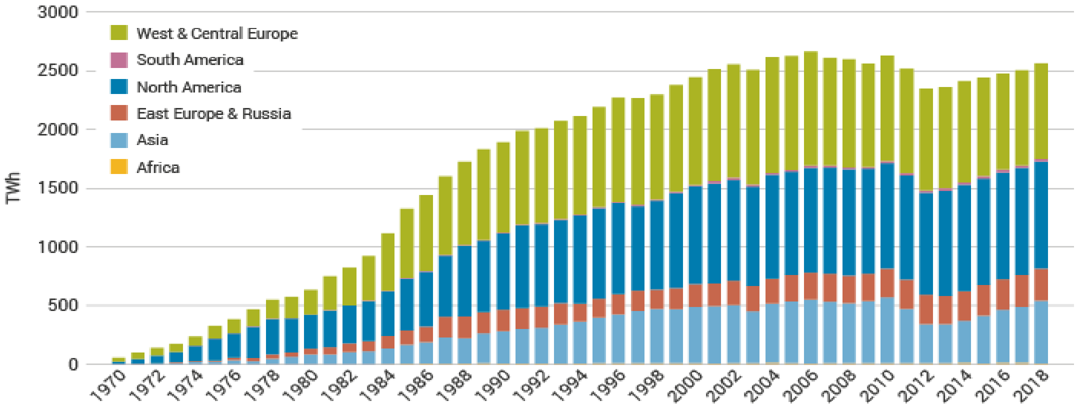
The UN Economic Commission For Europe (UNECE) has supported the region in developing its energy sources to aid economic recovery in the past. In the process, UNECE has developed numerous standards and best practices adopted by the region and beyond. The United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS) provide a crucial energy system management platform. They offer a framework for the assessment of the various factors related to nuclear energy and the development of its fuel resource. Sustainable pathways for nuclear development emerge as part of the full consideration of the regulatory, social, technical, environmental and economic aspects of programmes, as well as national capability and capacity.

Chapter 1 Introduction

Many countries embrace nuclear energy as a reliable, affordable and clean source of electricity that will play an increasingly important role in meeting the global energy and climate challenge. Other countries have decided not to depend on nuclear energy because of various considerations including cost and concerns over safety and radioactive waste management and disposal. Currently, there are about 440 nuclear power reactors operating in 32 countries that represent over 60 percent of the global population. A further 53 reactors are under construction in 19 countries.

There is wide variance in the outlook for nuclear energy development in different countries. In developed nations, nuclear energy is well-established and already makes a significant contribution to electricity supply (averaging roughly 20 percent of electricity supply across the OECD countries). The contribution of nuclear energy in these countries is relatively flat, with growth in some countries and withdrawal from nuclear energy in others. In developing countries and emerging economies nuclear energy represents less than 5 percent of electricity supply. Here interest in nuclear power is rising and deployment is accelerating, with several countries making rapid progress towards construction of their first nuclear power plants.

The term ‘nuclear newcomers’ refers to countries that are planning to introduce nuclear energy into their energy mix. Several of the newcomers are at an advanced stage and are making steady progress towards their infrastructure milestones, with firm intentions to build nuclear power plants in the future. An even greater number of countries can be described as ‘potential newcomers’ and are actively considering nuclear technology as a future solution to their energy challenges but have yet to make key decisions on whether to proceed. Roughly 28 newcomer countries are considering, planning or starting nuclear power programmes. The global outlook for nuclear energy depends on the progress of these newcomers, and especially those throughout Asia and Africa.



Source: World Nuclear Association and IAEA Power Reactor Information Service (PRIS)

Figure 1.1 Annual nuclear electricity production by region. Currently nuclear energy is heavily concentrated in Europe and North America but this is changing. Source: World Nuclear Association[2].

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[2] WNA, *World Nuclear Performance Report 2020* (data from IAEA PRIS database)

Interest in nuclear energy has grown in response to rising energy demand, the emerging climate crisis, and the global sustainable development agenda. The year 2015 proved to be a turning point for international action with the adoption of the Paris Agreement and the SDGs, helping to drive change throughout the global economy, and especially the energy sector. Some countries have specific motivations for pursuing nuclear energy, such as concerns over droughts and the future availability of hydro power, or strategies to exploit indigenous uranium resources. There are many drivers that influence the decision to introduce or expand nuclear energy, and each country's situation is unique. The choice to develop nuclear energy rests with sovereign countries, together with the responsibility to use it safely and securely.

Status of plans in nuclear newcomer countries

- Nuclear power plants under construction: Bangladesh, Belarus*, Turkey, United Arab Emirates*. (*First nuclear power reactor has now started operation.)
- Contracts signed, legal and regulatory infrastructure well-developed or developing: Egypt, Uzbekistan.
- Committed plans, legal and regulatory infrastructure developing: Ghana, Jordan, Nigeria, Poland, Saudi Arabia.
- Well-developed plans but commitment pending/deferred: Ethiopia, Indonesia, Kazakhstan, Lithuania (deferred), Malaysia (deferred), Philippines, Thailand (deferred), Vietnam (deferred).

Potential newcomers

- Developing plans: Algeria, Bolivia, Estonia, Kenya, Laos, Morocco, Rwanda, Sri Lanka, Sudan, Zambia.
- Discussion as policy option: Albania, Azerbaijan, Chile, Croatia, Cuba, Israel, Latvia, Libya, Mongolia, Namibia, Paraguay, Peru, Qatar, Serbia, Singapore, Syria, Tunisia, Venezuela.

Currently, available nuclear reactor designs are based on mature and proven technologies that in some instances have been licensed to operate for 80 years. They provide large amounts of dispatchable low-carbon electricity. Interest is growing in new smaller-scale reactor technologies that are under research, development, and in some instances, deployment (licensing and construction). These small modular reactor (SMR) technologies can enable deeper decarbonization by making nuclear suitable for smaller grids as well as cogeneration and non-electric applications.

Selecting reactor technologies (and technology partners) is only one of many factors nuclear newcomers must consider if they wish to maximize the sustainability benefits of their nuclear energy programme. Other important choices must be made in the development of infrastructure to support a nuclear programme – for example, whether to develop any domestic fuel cycle activities. For each country, the range of sustainable nuclear energy entry pathways will reflect its own unique situation and development requirements.

This report aims to inform sound policy formulation for countries considering nuclear energy programmes and to help them define locally relevant pathways to support sustainable development. Particular attention is given to newcomer countries and the deployment of SMRs. The report explores pathways in the context of local and regional factors, including the utilization of domestic uranium resources, that could facilitate nuclear energy and economic development.

This report is expected to contribute to optimal natural resource management, wherein certain fundamental principles of sustainable resource management can be used as guideposts. The United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS) support a refocus on the 2030 Agenda for Sustainable Development and action on climate change, notably SDG 7 (affordable and clean energy) and SDG 13 (climate action), to put natural resources on service for society. Many of the innovative approaches presented in this report are not only relevant to nuclear energy, they can be applied to other energy resources as well. The main chapters of the report include:

- **Chapter 2 Nuclear Energy and Sustainable Development.** How nuclear energy relates to the SDGs and its potential role in the future decarbonized energy mix.
- **Chapter 3 Nuclear Development Considerations.** Five common nuclear development factors include energy planning, socioeconomics, environment, legal and regulatory framework, and economics, which are key to making a decision on whether to pursue a nuclear energy programme and then making sure the programme remains aligned with principles of sustainable development.
- **Chapter 4 National and Regional Considerations.** The broader nuclear fuel cycle and the relative advantages of developing domestic facilities versus potential regional or international options, as well as strategies for radioactive waste management and disposal.
- **Chapter 5 Nuclear Technology Options.** The range of ‘gigawatt-scale’ nuclear technologies available today as well as SMRs, which are rapidly approaching commercialization. Analysis of their techno-economic performance and how they can help support future hybrid-energy systems, including low-carbon heat and hydrogen production in a high-renewables future mix.
- **Chapter 6 Nuclear Energy Entry Pathways.** The role of policy – how the existing policy framework can help a country make a decision on whether to pursue a nuclear energy programme, and the policy initiatives that can help to improve the economics of a programme and build public support for it once a decision is taken.

Chapter 2 Nuclear Energy and Sustainable Development

> *Nuclear energy is an indispensable tool for achieving the global sustainable development agenda. It has a key role to play in decarbonizing the energy sector but also supports the attainment of all the Sustainable Development Goals – including the elimination of poverty, zero hunger, clean water, affordable energy, economic growth and industry innovation. Improved government policy and public perception along with ongoing innovation will enable nuclear energy to overcome traditional barriers to deployment and expand into new markets.*

The Earth's land, oceans, atmosphere, biosphere and human societies form a dynamic system where changes in one element reverberate throughout the others. Many of the past mistakes, including the actions that are causing anthropogenic global warming, were committed by not understanding this system and its inherent latencies. Energy production and use lie at the centre of many of the problems we face today. Transitioning to low-carbon energy sources, such as renewables and nuclear, can mitigate most of these issues.

This chapter examines in detail how sustainable development and nuclear energy are intertwined. An understanding of these factors is very relevant to the application of the United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS) in a comprehensive resource management framework. Important factors to be considered include the establishment of national, and where appropriate, regional, nuclear energy competencies, through knowledge transfer, capacity building and context-sensitive policies for localization. These can also give rise to a range of benefits, such as public education and science awareness. These underpin the essential 'social licence to operate' (SLO) on which a successful entry programme will depend.

Several factors mentioned here highlight the integrated and indivisible nature of sustainable development. This interconnectedness highlights the important fact that the aspects discussed here do not just apply to nuclear energy, but could easily be transferred to other sectors within the green economy.

2.1 The environment, development and energy nexus

Human progress and economic development since the Industrial Revolution has helped billions to escape the comparative poverty of rural living. While this progress has been instrumental for humanity's development, as an unintended consequence it has also created certain conditions on Earth that have not been experienced for over 2.6 million years. It has pushed the warm interglacial climate towards one that could potentially melt both the ice-caps, raise the sea levels and even drive moisture out of much of our fertile soils. It has also dramatically impacted the natural world, with many ecosystems entirely lost in the ensuing 200 years and many more now seriously threatened. If the impacts of industrialization continue unabated, the Earth will experience significant species loss and may see many more precious ecosystems collapse entirely.

2.1.1 The emergence of sustainable development

Environmental discussions were elevated to new heights within the United Nations system with the publishing of the 1987 report, *Our Common Future*, also known as the Brundtland report in recognition of former Norwegian Prime Minister Gro Harlem Brundtland's role as Chair of the World Commission on Environment and Development (WCED)[3]. In addition to highlighting the impacts of runaway and unbalanced development on the environment as well as society, this report defined 'sustainable development' as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The Brundtland report recognized that the many crises facing the planet are all interlocking – separate elements of a much larger single crisis of the whole.

A surge of activity following the publication of the Brundtland report culminated in the adoption of the UN Millennium Development Goals (MDGs) in 2000. All of the UN member states committed themselves to achieving the eight developmental goals by 2015. The MDGs had a narrow focus on developing countries – encouraging them to eradicate extreme poverty and hunger, achieve universal primary education, promote gender equality, reduce child mortality, improve maternal health, combat lethal diseases, ensure environmental sustainability, and develop a global partnership for development.

Figure 2.1 The 17 Sustainable Development Goals.

Following on from the successful experience of rolling out and implementing MDGs, the UN Sustainable Development Goals (SDGs) were adopted in 2015. Seventeen goals and 169 targets were to be reached by the year 2030 (Figure 2.1). These were unanimously accepted by all the 193 UN member states in September 2015. In contrast to the MDGs, the SDGs apply to all countries, both developed and developing. The SDGs are described as "integrated and

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[3] Report of the World Commission on Environment and Development: *Our Common Future*, Transmitted to the General Assembly as an Annex to document A/42/427 – *Development and International Co-operation: Environment* (4 August 1987)

indivisible", which means they are not supposed to live in silos but rather relate to each other in myriad connections.

2.1.2 Climate change recognized as the most significant risk for life

While the possibility of anthropogenic climate change has been recognized since the 1960s, the Intergovernmental Panel on Climate Change (IPCC), the UN body for assessing the science related to climate change, provided the first consensus view on the subject in 1990. The IPCC *First Assessment Report* concluded that emissions resulting from human activities are substantially increasing the atmospheric concentrations of greenhouse gases, resulting in an additional warming of the Earth's surface.

The *First Assessment Report* served as the basis of the United Nations Framework Convention on Climate Change (UNFCCC), an international environmental treaty adopted on 9 May 1992, to achieve "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." The Kyoto Protocol adopted in 1997, committed many industrialized nations to reducing greenhouse gas emissions, based on the scientific consensus that global warming is occurring and that it is extremely likely that human-made carbon dioxide emissions are the dominant cause.

The IPCC *Fifth Assessment Report* published in 2014 suggested the possibility of an increase in global mean temperature in 2100 as high as 4.8 °C relative to pre-industrial levels – if there was a lack of any mitigating policies. This was the extreme case, but the report added that the current trajectory of global greenhouse gas emissions is not consistent with limiting global warming to below 2 °C, relative to pre-industrial levels.

In December 2015, 196 state parties adopted the Paris Agreement and at the time of publication 190 parties have ratified it. The Paris Agreement recognizes, amongst other things, that climate change is a common concern of humankind. Under this agreement, each country must determine, plan, and regularly report on the measures it undertakes to mitigate climate change. The Paris Agreement commits to holding the increase in the global average temperature to below 2 °C above pre-industrial levels.

On 8 October 2018 the IPCC published the Special Report on *Global Warming of 1.5°C*[4]. Its key finding is that meeting a 1.5 °C target is possible but would require deep emissions reductions and rapid, far-reaching and unprecedented changes in all aspects of society. Furthermore, the report finds that limiting global warming to 1.5 °C compared with 2 °C would reduce impacts on ecosystems, human health and well-being, whereas a 2 °C temperature increase would exacerbate extreme weather, rising sea levels and diminishing Arctic sea ice, coral bleaching, and loss of ecosystems – among other impacts.

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[4] *Global Warming of 1.5°C – An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, International Panel on Climate Change (2018)

The climate challenge is foremost an energy one, as indicated in Figure 2.2. While some greenhouse gas (GHG) emissions are associated with agriculture, land use and certain industrial processes (for example concrete and steel production), the majority of the emissions, about 70 percent, are associated with the production and consumption of energy. Energy production further impacts the climate by the emission of sulphate aerosols and black and organic carbon, which have positive and negative effects on radiative forcing. Energy, therefore, is the primary driver of climate change, which now affects every country on every continent. Climate change is already disrupting national economies and affecting lives – costing people, communities and countries dearly. The poorest and most vulnerable people are being affected the most.

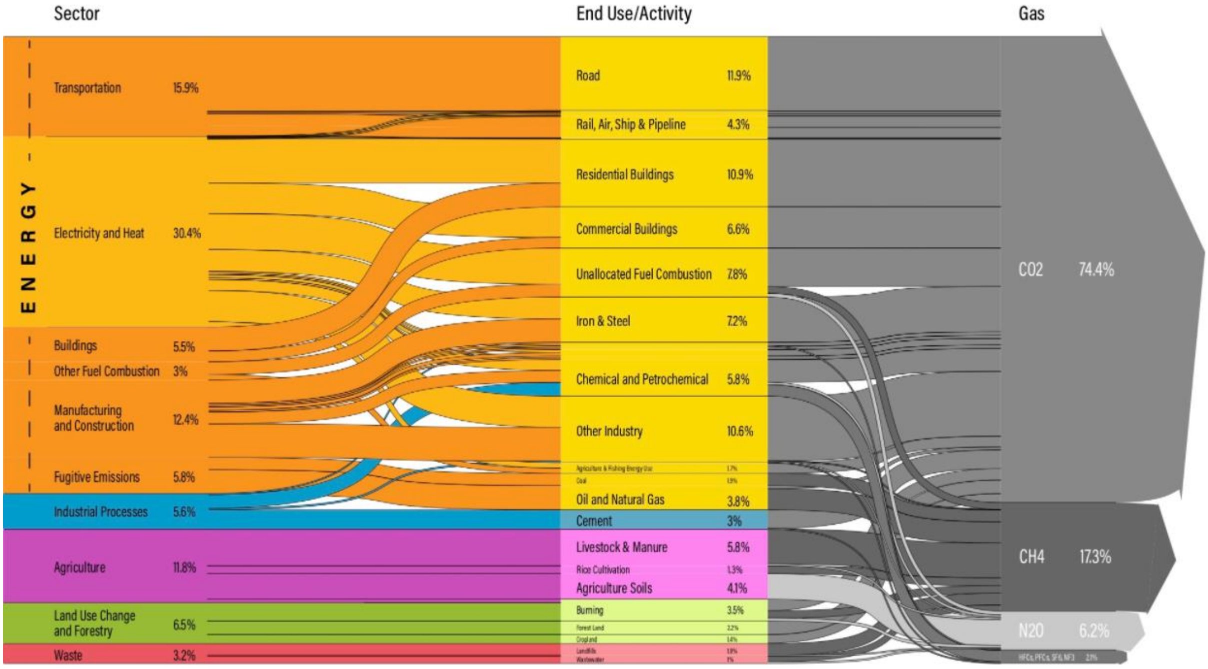

Figure 2.2 Global annual greenhouse gas emissions flows by economic sector (2016 data). Total emissions amounted to 49.4 gigatonnes of CO_2 (equivalent) Source: World Resources Institute[5].

According to the International Energy Agency (IEA), global energy-related carbon dioxide emissions continue to grow. They grew 1.7 percent in 2018 to reach an historic high of 33.1 gigatonnes. This was the highest rate of growth since 2013, and 70 percent higher than the average increase since 2010[6]. The main contributors to this trend were a higher energy demand associated with rapid economic growth and the associated increased use of fossil fuels. Oil demand grew by 1.3 percent, natural gas by 4.6 percent, and coal by 0.7 percent. The electricity sector accounted for nearly two-thirds of emissions growth. While the Covid-19 pandemic dampened global energy demand and associated emissions in 2020, there is no reason yet to believe this will continue in the years that follow[7].

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[5] *World Greenhouse Gas Emissions: 2016*, World Resources Institute

[6] *Global Energy & CO2 Status Report: The latest trends in energy and emissions in 2018*, International Energy Agency (March 2019)

[7] *Global Energy Review 2020: The impacts of the Covid-19 crisis on global energy demand and CO_2 emissions*, International Energy Agency (April 2020, revised July 2020)

Multiple options exist to reduce GHG emissions in energy production. These include energy efficiency improvements and reducing fugitive emissions from fossil fuel extraction, as well as replacing fossil fuels with low-GHG technologies such as renewable energy and nuclear power, along with increasing the electrification of heat and transport. In the future, carbon capture and storage technologies may be fitted to fossil plants that would capture most of their emissions. A range of energy options is needed and no single technology or even class of technologies is capable of successfully decarbonizing energy on its own. The stabilization of GHG concentrations at low levels requires a fundamental transformation of the energy supply system, including the long-term substitution of unabated fossil fuel technologies by a range of low-GHG alternatives.

2.1.3 The worsening biodiversity crisis

Life thrives on diversity. However, biodiversity is threatened by many factors including loss of forest cover, water stress and urbanization which are often exacerbated by human activities such as the increasing use of land, the production of untreated urban and rural waste, and pollution from industry, mining and agriculture. The use and production of energy also has impacts on biodiversity which attracts coordinated action in many countries.

The *Strategic Plan for Biodiversity 2011-2020, including Aichi Biodiversity Targets*[8], created in 2010 under the Convention on Biological Diversity (CBD), is a global initiative in support of sustainable development. A post-2020 global biodiversity framework is planned to be adopted during the 15th meeting of the Conference of the Parties to the CBD in 2021. As noted in the 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report on biodiversity, the Aichi Biodiversity Targets and the 2030 Agenda will not be achieved based on current trajectories. The IPBES report is a comprehensive report on biodiversity, which is comparable to the IPCC assessment reports on climate change. It concludes that human actions now threaten more species than ever before with global extinction and that around 1 million species already face extinction, many within decades. Across the world, local varieties and breeds of domesticated plants and animals are disappearing.

The IPBES reports notes that the harmful economic incentives and policies associated with unsustainable practices of fisheries, aquaculture, agriculture (including fertilizer and pesticide use), livestock, forestry, mining and energy (including fossil fuels and biofuels) often lead to overexploitation of natural resources, as well as inefficient production and waste management.

The conclusions of the IPBES report are alarming not just because of the loss of many species, but also because the whole natural world is threatened. Ecosystem functions once taken for granted are now deteriorating. The loss of diversity, including genetic diversity, poses a severe risk to global food security by undermining the resilience of many agricultural systems, making them vulnerable to threats such as pests, pathogens and climate change.

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[8] See brochure on *Strategic Plan for Biodiversity 2011–2020 and the Aichi Targets*, Secretariat of the Convention on Biological Diversity

2.1.4 Energy in "integrated and indivisible" sustainable development

As recognized explicitly in SDG 7, energy is "central to nearly every major challenge and opportunity the world faces today." Energy access supports all of the SDGs and is a key pillar of the UN sustainable development agenda. As the world becomes mostly urbanized and a greater number of countries enter the 'middle income' bracket[9], the aspirations of individuals will also increase. These aspirations include better education, stable jobs, nutritious diets, better healthcare and access to the cultural and leisure activities that enable a higher quality of living. Increasing energy access will be vital to meeting these aspirations, but this comes with potentially dangerous environmental costs if not managed carefully.

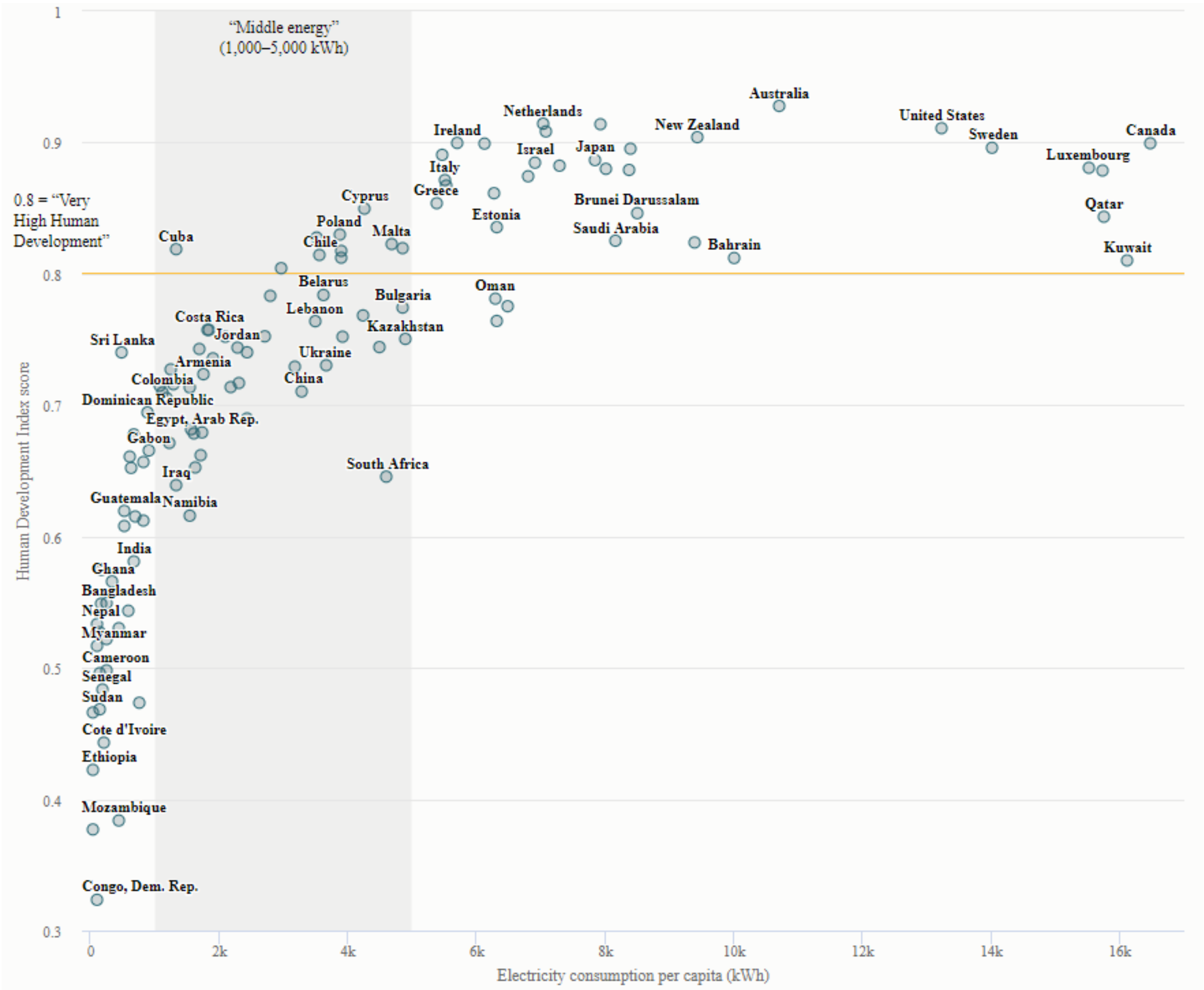

Figure 2.3 Relationship between annual electricity consumption and human development indicators. Source: Center For Global Development[10]. Data from UNDP and World Bank for 2013.

As the human population rises to around 10 billion by 2050, many questions will have to be answered, such as: how do we cope with food requirements, which are already under stress from diminishing freshwater resources, driven by a heating planet and accelerating soil loss of

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[9] See The World Bank webpage on The World Bank in Middle Income Countries

[10] *More than a Lightbulb Moment*, Center For Global Development (2016)

some 34 billion tonnes per year[11]? Adding to this is the rapid pace of urbanization. By 2050, about 70 percent of the world's population is expected to be living in cities. As the UN Food and Agriculture Organization describes it: "The water–energy–food nexus is about understanding and managing often-competing interests while ensuring the integrity of ecosystems."

At the same time, energy use contributes significantly to air pollution, which is a major cause of death and disease worldwide. The World Health Organization notes ambient air pollution is responsible for 4.2 million deaths every year while household pollution in the form of exposure to smoke in cooking fires causes 3.8 million deaths per year[12]. Women and children in the developing world bear a disproportionate share of this dismal situation.

Access to electricity in particular is closely linked to human development, as shown in Figure 2.3. Improvements to quality of life will be severely limited without a step-change in the power consumption. Currently, about 790 million people do not have any access to electricity; while over a billion more have only uncertain and intermittent access[13].

In the last three decades, the most substantial increase in electricity production has occurred in Asia (Figure 2.4). The impact can already be seen in the most populous countries, such as China and India. In nominal terms, China's economy has experienced exponential growth over the past few decades and is now worth $12 trillion (USD) – making it the second largest economy in the world today. To support its massive economy, China will remain the world's largest energy consumer and is projected to account for 22 percent of world energy consumption in 2040[14].

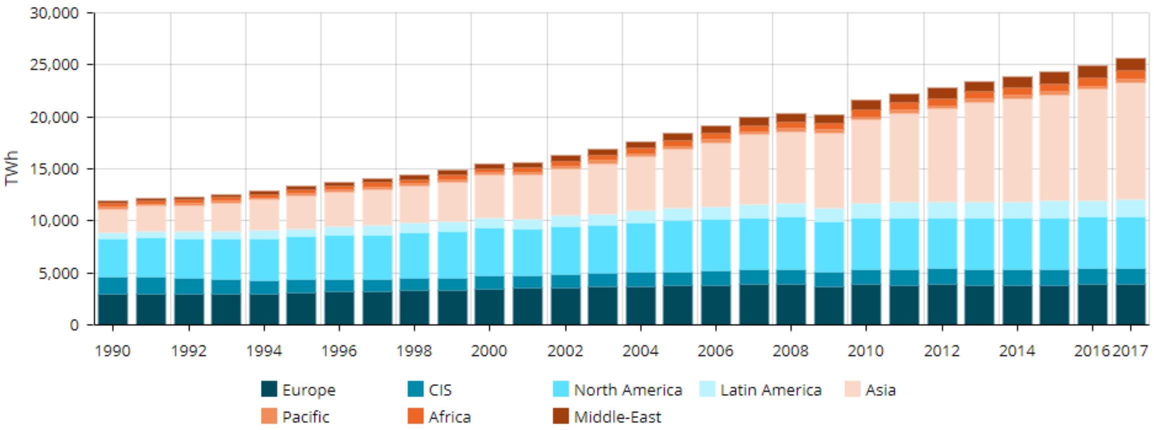

Figure 2.4 World electricity production by region. Electricity demand is growing fastest outside of Europe and North America. Source: BP.

In the five years between 2015 and 2019, the Indian economy has increased by $1 trillion to reach $2.6 trillion and lifted its position from the eleventh largest economy to fifth largest. In the next five years, India is targeting $5 trillion and expects to improve its position to third place

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[11] Pasquale Borrelli, David A. Robinson, Larissa R. Fleischer *et al.*, *An assessment of the global impact of 21st century land use change on soil erosion*, Nature Communications, 8, 2013 (December 2017).

[12] See World Health Organization webpage on air pollution

[13] See United Nations webpage on Sustainable Development Goal 7

[14] See *BP Energy Outlook – 2019: Insights from the Evolving transition scenario – China*

behind China and the USA. A recent IEA study concluded that if India can achieve consistent 9 percent economic growth for 20 years, it can bring all the low-income population out of poverty[15]. Crucial to achieving this 9 percent growth is a matching 7 percent growth in electricity production. In some scenarios, India is expected to account for over a quarter of incremental global primary energy demand growth up to 2040[16].

Africa will be the next Asia. The UN predicts Africa's population to increase from the current 1 billion to 3 billion by 2050[17], and the World Bank expects that most African countries will reach the equivalent of today's 'middle income' status by 2025[18]. Modern, affordable, reliable and sustainable electricity is critical for economic growth in Africa just as it is everywhere else.

The 'miracle on the Han River'

The role of energy in uplifting a country out of poverty can hardly be exemplified better than by South Korea. In the 1950s, South Korea had an underdeveloped, agrarian economy that depended heavily on foreign aid. In the 1960s South Korea embarked on a pragmatic and flexible journey to economic development resulting in what became known as the 'miracle on the Han River'. During the next three decades, the South Korean economy grew at an average annual rate of nearly 9 percent, and per capita income increased more than a hundredfold. South Korea was transformed into an industrial powerhouse with a highly skilled labour force. Energy availability per capita increased from 516 kg of oil equivalent in 1971 to 5,413 kg of oil equivalent in 2015. In 1961, the annual electricity production was 1,770 GWh, which increased to 73,992 GWh in 1987. The first commercial nuclear power plant came online in 1978, and today 24 reactors provide about one-third of South Korea's electricity. South Korean energy policy has long been driven by considerations of energy security and the need to minimize dependence on imported fuels. Nuclear power now provides the cheap and reliable energy required for supporting an industrialized economy.

The human development story and the intermingled 'revolutions' is also the story of energy. Most of the unintended consequences we face today are also linked to our energy choices. Solutions for some of the outstanding issues in sustainable development must, therefore, be searched for within the framework of access and use of energy.

2.2 Mapping nuclear technology to the Sustainable Development Goals

Today, there are about 440 nuclear power reactors operating in 32 countries providing about 10 percent of the world's electricity. Over the past 50 years, the use of nuclear power has reduced carbon dioxide emissions by over 60 gigatonnes, or nearly two years' worth of total

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[15] *India 2020: Energy Policy Review*, International Energy Agency (January 2020)

[16] See BP *Energy Outlook – 2019*

[17] *World Population Prospects 2019: Highlights*, United Nations, Department of Economic and Social Affairs, Population Division (2019)

[18] The World Bank classifies the world's economies into four income groups based on gross national income (GNI) per capita: high, upper-middle, lower-middle, and low. See World Bank Blogs webpage on New country classifications by income level: 2019-2020

global energy-related emissions, as shown in Figure 2.5. In addition to electricity generation, nuclear reactors can provide solutions to an even wider range of energy applications such as industrial process heat, and district heating. Nuclear energy can also be used to generate hydrogen and to create synthetic fuel.

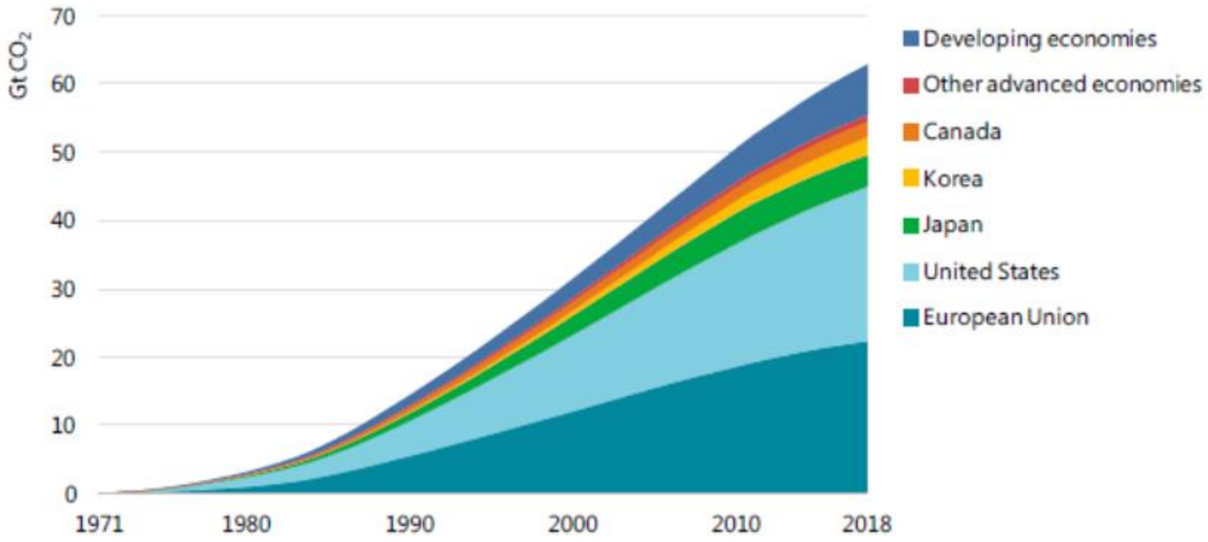

Figure 2.5 Cumulative CO_2 emissions avoided by nuclear power by region. Source: IEA[19].

Nuclear reactors are also used to create radioisotopes that are used in a number of medical, environmental and industrial applications all over the world. Generally these radioisotopes are made in special purpose reactors, but some power reactor designs can also produce useful isotopes. Every year, about 30 million people benefit from a diagnostic procedure or treatment by nuclear medicine and the numbers are steadily increasing. Radioisotopes and radiation used in food and agriculture are helping the fight against world hunger. Food irradiation exposes foodstuffs to gamma rays that kill bacteria that can cause food-borne disease, thus increasing shelf-life. Radiation is also used for agricultural pest control via the sterile insect technique, which reduces the use of pesticides, thus benefiting public health and the environment. Isotope hydrology techniques help tracing and measurement of the extent of underground water resources and any sources of contamination. They improve the management and conservation of existing supplies of water, and in the identification of new sources.

As shown below, nuclear energy has the potential to contribute to all of the SDGs (Figure 2.6). Many of these contributions are spelled out in greater detail in the chapters which follow. Nuclear energy has the most direct relevance to SDG7 and SDG 13[20], but increasing energy access enables economic growth, which is pivotal to many other SDGs. The nuclear sector is also a major industrial employer that demands high standards and competencies as well as international cooperation and a commitment to ongoing research and development.

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[19] *Nuclear Power In A Clean Energy System*, International Energy Agency (May 2019)

[20] *Nuclear Power for Sustainable Development*, International Atomic Energy Agency (September 2016)

There are opportunities to integrate the SDGs into core business activities of the nuclear sector, and nuclear energy companies can benefit from collaborating with stakeholders to broaden their impact and enhance their ability to leverage additional resources to achieve the SDGs. The SDGs are “interlinked and indivisible”, requiring approaches that promote synergies and manage trade-offs. Worldwide, countries are moving towards full alignment with SDGs and integrating them into policy. International, regional and national policies and plans, as well as business opportunities, will be shaped by maximizing alignment with them. Mapping nuclear technology to the SDGs can help the industry to:

- Understand current trends, challenges and opportunities in sustainable development.
- Define the business system interconnectedness and boundaries.
- Recognize the strengths of partnerships.

Road to development and carbon neutrality

Until the 1930s, Finland’s economy was predominantly agrarian and, as late as in the 1950s, more than half the population and 40 percent of output were still engaged in the primary sector. The 19th century saw the modest beginnings of industrialization and in the 20th century Finland came out of World War II with a severely crippled economy. Gradually the productive capacity was modernized, and the whole industry was reformed. To meet energy demand, Finland introduced nuclear energy in 1978. Finland today has four nuclear reactors providing about 30 percent of its electricity. A fifth reactor is under construction, and another is planned, to take the nuclear contribution to about 60 percent. Finland's four existing reactors (about 2700 MWe net total) are among the world's most efficient, with an average lifetime capacity factor of over 85 percent and average capacity factor over the last ten years of 95 percent. In June 2019, Finland announced a new energy policy to achieve carbon neutrality by 2035. The policy would see a complete phase-out of coal power by May 2029.

2.2.1 SDG 1 – No Poverty

Nuclear energy helps the economy by supporting direct, indirect and induced jobs during construction and operation of nuclear facilities. The cost-competitive and stable electricity supplied by nuclear power plants attracts energy-intensive industry, thus creating more jobs. Nuclear energy can power the development of local small and medium enterprises and support non-polluting e-connectivity for economic development. These enterprises also generate significant local economic activity in the form of jobs, revenues and local spending. As an energy technology that is almost entirely immune to fluctuations in the weather, nuclear also helps build climate resilience for the economy.

2.2.2 SDG 2 – Zero Hunger

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

2.2.3 SDG 3 – Good Health and Wellbeing

Nuclear contributes to a reliable and resilient energy supply that is needed to power modern health infrastructure. This is even more essential during a crisis such as the Covid-19 pandemic. Reliable energy also enables the automation of dangerous and unpleasant tasks. As a very low emissions technology, nuclear energy helps to ensure clean air, water and land thereby improving the health of communities.

Nuclear techniques play an essential role in diagnosing and treating various health conditions, in particular, non-communicable diseases such as cancer and cardiovascular diseases. Irradiation technologies can also be used to sterilize medical equipment. A nuclear-derived technique known as real time reverse transcription–polymerase chain reaction (RT-PCR) is being used to identify cases of the Covid-19 virus accurately within hours[21].

2.2.4 SDG 4 – Quality Education

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

2.2.5 SDG 5 – Gender Equality

In emerging countries increased access to cheap and reliable energy helps enhance labour emancipation and reduce jobs involving drudgery, which disproportionately affects women. The nuclear community, with the active participation of leading international agencies, is currently committed to attracting and retaining qualified women to the nuclear science and technology sector. As a traditional engineering field, men currently outnumber women in the nuclear industry, but many companies are now actively and publicly addressing the gender imbalance. As a result, the number of women in leadership and technical positions is increasing.

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[21] See International Atomic Energy Agency webpage on How is the COVID-19 Virus Detected using Real Time RT-PCR?

2.2.6 SDG 6 – Clean Water and Sanitation

Nuclear energy can be used to power desalination facilities and provide clean water to communities, helping to support energy-water-food nexus activities.

Various nuclear techniques help scientists to study the quality and quantity of water resources. Naturally occurring isotopes in water can be used to determine the water's origin, age, vulnerability to pollution, as well as how water resources move and interact with each other.

2.2.7 SDG 7 – Affordable and Clean Energy

Nuclear energy is complementary to renewable energy sources. When used together these technologies can help to achieve decarbonized electricity systems at low cost to consumers – as has been proven by France and Sweden. Nuclear power technology is evolving, and a range of new reactor technologies is being developed that offers greater flexibility and efficiency. These technologies can more readily contribute to energy services such as industrial heat, low-carbon hydrogen and synthetic fuel production.

2.2.8 SDG 8 – Decent Work and Economic Growth

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

2.2.9 SDG 9 – Industry, Innovation, and Infrastructure

In simple terms, a nuclear power plant is major infrastructure development. With maintenance and periodic upgrades, a nuclear power plant can operate for 60 years or even longer, thereby reducing the volumes of new materials needed for energy production. Innovation is integral to achieving this longevity and enabling plants to operate at ever greater performance levels. Nuclear innovation is also resulting in spin-off technologies that can be used in other fields such as material research and structural mechanics. Nuclear energy is not yet widely deployed in the least developed countries and there is vast potential for increased international outreach to help introduce the technology in these countries. As a dispatchable and reliable low-carbon electricity source with low operating costs, nuclear is a perfect fit for data centres and other technology industries.

Radioisotope techniques can help make products safer and improve their quality. These techniques can also make industrial processes more efficient, environmentally friendly, and cost-effective.

2.2.10 SDG 10 – Reduced Inequalities

Nuclear project developers must typically engage stakeholders in extensive consultation before beginning construction, making sure that different voices get their say, including indigenous and marginalized groups. As a centralized form of electricity generation run by large companies with a culture of regulatory compliance, it should be easier to enforce anti-discrimination policies within a nuclear workforce than in some others. Universal access to low-cost clean electricity will help reduce socio-economic inequalities.

2.2.11 SDG 11 – Sustainable Cities and Communities

Nuclear energy can support urban development. Nuclear plants provide affordable reliable electricity which is well-suited to supplying cities where there is constant energy demand. Nuclear energy assists in the electrification of public transport, and especially rail networks, without contributing to air pollution. It supports municipal waste management and recycling. Since nuclear facilities are mostly located in rural communities, but headquarters and governments are based in cities, the nuclear industry creates links to different regions within a country. In addition, nuclear projects will result in significant economic development for the rural communities in which they are sited. Small modular reactors (SMRs) and microreactors are promising potential sources of electricity, district heating or desalination for off-grid remote communities.

2.2.12 SDG 12 – Responsible Consumption and Production

Nuclear energy generally requires fewer mineral inputs than other energy sources, including critical raw materials. Its primary ongoing mineral input is uranium; however, there are no primary competing peaceful uses for this. The uranium resource is ample and distributed widely across the globe, and its mining and processing are subjected to high standards. Nuclear energy does produce waste – notably high-level radioactive waste – but the volumes are small. They need to be responsibly managed before final disposal. Most of the materials and components of a plant are suitable for release based on nuclear regulatory control and therefore available for reuse or recycling. Only a small percentage of the total mass of a plant needs to be disposed of. Innovations such as new fuel designs can increase the efficiency of nuclear power plants, reducing materials requirements even further.

2.2.13 SDG 13 – Climate Action

Nuclear energy is the world's second-largest source of low-carbon electricity behind hydropower and it displaces fossil fuel sources that would produce about two gigatonnes of carbon dioxide every year. Nuclear energy can be scaled up in a country quickly compared to other low-carbon technologies, and including it in future energy pathways will help to reduce the time, costs, and risks of decarbonization. Nuclear plants can be engineered with a high degree of climate resilience and are less prone to many climate/weather disruptions than other low-carbon energy forms. Future reactors will be able to supply industrial heat and assist the production of synthetic fuels for transport applications, thereby further reducing carbon emissions from these sectors.

2.2.14 SDG 14 – Life Below Water

Nuclear energy does not produce carbon dioxide emissions which contribute to ocean acidification or other chemical emissions that pollute waterways. Scientists are using nuclear techniques to monitor and studying ocean acidification and understand how it affects marine life and ecosystems, and identify ways to protect the ocean and coastal communities.

2.2.15 SDG 15 – Life on Land

Nuclear energy has a very high energy density, and facilities take up minimal land. Plant boundaries are often set quite large for safety and security purposes, and within these, wildlife habitats are often found. Often plant operators support conservation activities which help to protect local species.

Nuclear techniques can be used to assess soil quality and to study how crops take up nutrients, as well as how soil moves. This can also be used to combat desertification.

2.2.16 SDG 16 – Peace Justice and Strong Institutions

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

2.2.17 SDG 17 – Partnerships for the Goals

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

With a ‘foot on the first rung of the ladder of development’

At the time of its independence in 1971, the vast majority of Bangladesh’s population of 75 million lived in poverty and depended on subsistence agriculture. By 2018 Bangladesh had emerged as one of the fastest-growing economies in the world. The country has undergone some structural transformation over the past four decades, where the share of agriculture in GDP declined from around 60 percent in the early 1970s to 15 percent in 2016. The structural transformation through an emphasis on manufacturing requires energy. Bangladesh started construction of its first nuclear power reactor in November 2017. Commissioning is expected in 2023. Construction of a second unit commenced in July 2018, with commissioning planned in 2024. More reactors are proposed, which will propel Bangladesh forward as a prosperous country in the next couple of decades.

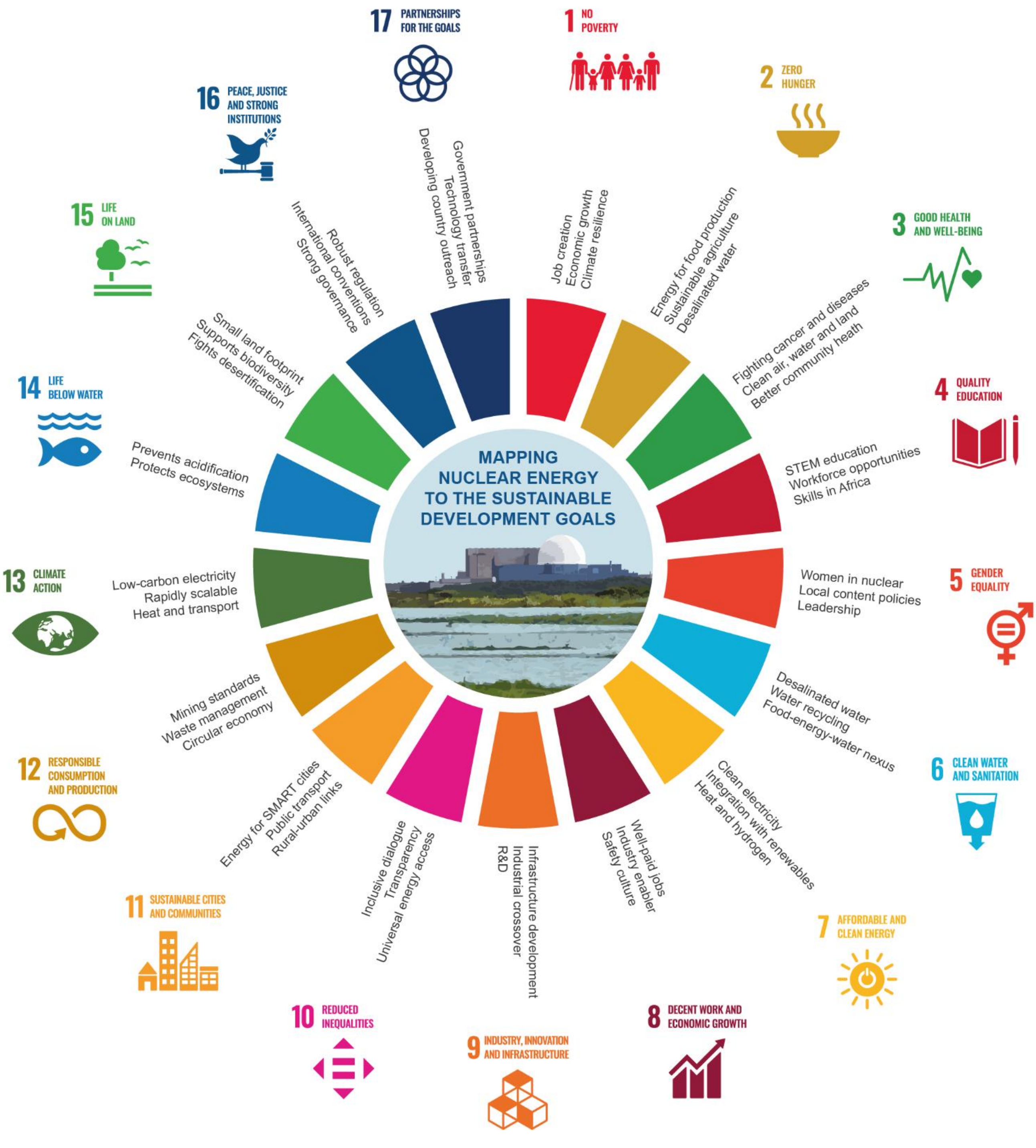

Figure 2.6 Nuclear energy and technology contributes to all of the UN SDGs.

2.3 Nuclear energy in the future sustainable energy mix

For some countries nuclear energy has a role to play in the future energy mix. While a few existing nuclear countries have decided not to retain the technology, most remain committed to it and many plan to expand it. In addition, a growing number of countries are turning to it to meet their clean development needs. Countries are also facing up to the challenge of transitioning to a deeply decarbonized energy system and finding through their climate-energy modelling that technology pathways that exclude dispatchable low-carbon options – such as nuclear – put the goal all but out of reach. While much is made of developments in wind, solar and battery technologies it should be noted that innovation is reshaping the nuclear sector too, and opening up greater opportunities for it to help decarbonize electricity and other sectors in the future.

2.3.1 What the energy models say

There are two main types of energy scenarios – those that are based upon current trends, and those that start with an end goal and work backwards to determine how that goal can be achieved, based on a range of assumptions. It is the latter which is essential when seeking to determine how the world can effectively avoid the worst impacts of climate change and meet the Paris Agreement goal. Many of the energy models from eminent international bodies have relied upon a significant contribution from nuclear energy – alongside renewables and CCS – to meet emissions targets. There are many such models, but here the role of nuclear energy is examined in the IEA's 2°C Scenario, the IPCC's Special Report on *Global Warming of 1.5°C*, the Deep Decarbonization Pathways initiative and UNECE's Pathways to Sustainable Energy project.

The IEA's 2°C Scenario was the main climate scenario in the *Energy Technology Perspectives* publication series for many years and widely used by policy makers and business leaders to assess their climate strategies. It set out an energy system pathway and a carbon emissions trajectory consistent with at least a 50 percent chance of limiting the average global temperature increase to 2 °C by 2100. By 2050, it projected nuclear energy to be one of the largest low-carbon electricity sources, accounting for up to 17 percent of global electricity demand (2015 edition) as shown in Figure 2.7.

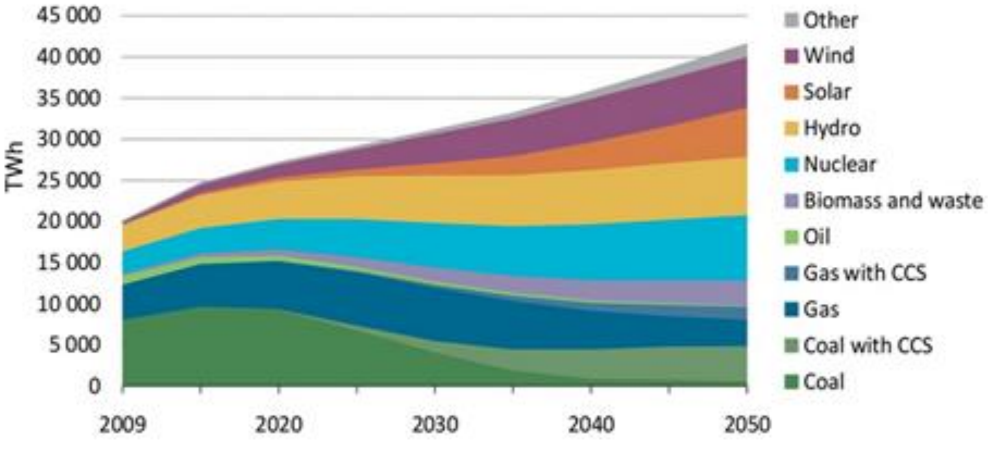

Figure 2.7 Global electricity by a source in IEA's 2°C Scenario. Source: IEA *Energy Technologies Perspectives 2015.*

The IPCC *Global Warming of 1.5°C* report published late in 2018 was intended to consider the impacts of global warming of 1.5 °C above pre-industrial levels and indicate pathways by which the greenhouse gas emissions could be avoided. According to the *Summary for Policymakers* document: "Some 1.5-degree pathways no longer see a role for nuclear fission by the end of the century, while others project over 200 exajoules per year of nuclear power in 2100." For context, nuclear energy currently produces just over nine exajoules (2500 terawatt hours) worth of electricity per year. While there are substantial differences between models and across the IPCC pathways, on average nuclear generation increases by around three times by 2050 from today's level in the 89 mitigation scenarios that are considered. In addition, the 'middle-of-the-road' illustrative scenario – in which social, economic, and technological trends follow current patterns and anticipates no major changes to, for example, diet and travel habits – sees the need for nuclear increase by six times globally by 2050.

The Deep Decarbonization Pathways initiative was a global collaboration of energy research teams that charted a practical pathway to profoundly reducing greenhouse gas emissions in their own countries in line with a 2 °C global target. The interim report was presented to UN Secretary-General and to the host of the 2015 UNFCCC climate conference. The project comprised 16 countries, representing 74 percent of global GHG emissions. In this pathway, nuclear energy grows by 1053 gigawatts to produce 8665 terawatt hours per year and supply 21 percent of electricity by 2050.

The UNECE Pathways to Sustainable Energy project explores pathways by which the UNECE region (consisting of North America, Europe and parts of central Asia) can achieve both the goals of the Paris Agreement and the Sustainable Development Goals (SDGs). The P2C scenario is a techno-economic scenario, where regional carbon dioxide emissions are assumed to continue reducing beyond 2030 and the world stays below 2 °C of warming by 2100. It is the only scenario developed by the programme which achieves the two-degree target. The scenario implies a high degree of diversification with fast uptake of low-carbon emitting technologies, including nuclear energy. Increasing nuclear and hydro capacities supplement dispatchable power from coal and gas which it assumes will be fitted with carbon capture and storage.[22]

A new nuclear powerhouse emerges.

A rapid expansion of nuclear energy is under way in China. Over the last five years one new reactor was put online every 65 days on average. In contrast, the first commercial reactor in China started operating in 1991 and until early 2002, China had only three reactors. The recent rapid expansion has resulted in a total of 49 reactors providing 47.5 GWe power today. As of writing, 16 units representing 17 GWe are under construction. Also, around 40 units representing 40 GWe are planned. Currently proposals are for an additional 170 power reactors (200 GWe) beyond this. China is currently on track to overtake the USA and become the country with the largest installed nuclear capacity base in the late 2020s.

2.3.2 New frontiers in nuclear energy

It is clear that the existing nuclear fleet plays a significant role in mitigating climate change today and that many models call for this role to increase if the worst impacts of climate change are to be avoided in the future. However, it is also evident that nuclear energy is not currently growing rapidly enough to help meet future targets. The global nuclear community is well

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[22] *Pathways to Sustainable Energy – Accelerating Energy Transition in the UNECE Region*, UNECE (December 2019)

aware of this fact and is unified in its commitment to boost deployment rates. To achieve this it is vitally important it embraces innovation and works with newcomers in emerging economies.

While some developed countries have been able to decouple their economies from energy consumption, they have largely done so by outsourcing their energy-intensive industries (and emissions) to emerging economies and importing products instead. It is simply not a realistic expectation for less developed countries to achieve a similar level of energy decoupling. If wealthy nations are serious about reducing their emissions, including the embedded ones, then they need to focus more on assisting the development of clean energy sources – including nuclear energy – in developing countries and emerging economies.

Developing countries do not always follow the same pathways by which developed ones have introduced life-improving technologies. There is a clear incentive to skip stages of development and go straight for the latest and most easily implementable option. In some ways, this is an enviable position to be in, but there is no technologically advanced future in which a dramatically expanded energy supply does not play an underpinning role. These countries may not be able to wait for new technologies to be proven before making necessary investments – nor can they afford to take large risks with unproven energy systems. The allure of innovation needs to be tempered with considerations of what has been proven to work.

It is likely that electricity systems of the future will look substantially different from today – driven by innovation in areas such as smart-grid technologies, demand-side management, energy storage, interconnectors and a host of new digital uses. However, the final shape and extent of this transition is not foreseeable, and it is possible that certain future technologies will simply not live up to expectations. It is important that countries are flexible regarding developments, and that they do not rule out any low-carbon energy technologies at this stage.

Innovation is reshaping the nuclear sector too. The pathways by which nuclear newcomer countries may choose to introduce nuclear energy are multiplying, with many new reactor technology options rapidly becoming available and new nuclear energy applications opening up. These developments (explained further in chapter 5) promise to increase the efficiency and flexibility of nuclear technology while also, potentially, drive down costs. Countries should be aware of these new reactor technologies while also not ignoring the current technologies which have made such remarkable contributions to sustainable development to date, and which also continue to improve with experience and innovation. For most countries a complementary mix of mature large reactors and novel SMR technologies will offer a low-risk and future-proof pathway.

What is known as the ‘fourth industrial revolution’ is under way now, driven by the confluence of many emerging and diverse technologies – artificial intelligence (AI), robotics, the Internet of things, autonomous vehicles, 3D printing, nanotechnology, biotechnology, advanced materials science, and many others. These technologies will both boost energy demand and have important ramifications for the development of energy systems. It is likely that they will soon have a huge and positive impact on the nuclear sector, which has been slow to uptake digital innovation to date and therefore still has a lot to gain as regulatory approval is obtained to employ technologies that are already established in other sectors.

A handshake with the future

The World Economic Forum report *Top 10 Emerging Technologies 2019* includes safer, efficient and flexible nuclear reactors as one of the technologies of the future. Generation IV reactors, the latest in nuclear technologies, incorporate passive safety systems, as well as fuel recycling to improve efficacy and reduce radioactive waste. Advanced reactors could also have their fuel in liquid form, dissolved in molten salt, which can remove fission products and be replenished with fresh fuel while in operation. Reactors could become more flexible, small and 'invisible', i.e., buried underground. They could extract more energy from fuel and reduce the volumes and lifetimes of radioactive waste. Some of these technologies are not new but tested since at least the 1960s. They experienced challenges in the past, which new approaches and breakthroughs are promising to overcome. Entrepreneurial focus on nuclear technology has recently surged, with over 75 projects on advanced nuclear designs reported in North America alone.

New technology by itself will not be enough to put the nuclear industry on track. The *Harmony* programme is a global initiative of the nuclear industry coordinated by World Nuclear Association that sets out a vision for the future of electricity to support efforts to transition towards a global low-carbon economy. Harmony sets a goal for nuclear energy to provide at least 25 percent of electricity globally by 2050 as part of a clean and reliable low-carbon mix.

The *Harmony* programme sets out three objectives:

- Establishing a level playing field in energy markets which drives investment in future clean energy, where nuclear energy is treated on equal terms with other low-carbon technologies and recognized for its value in a reliable low-carbon energy mix.
- Ensuring harmonized regulatory processes in order to provide a more internationally consistent, efficient and predictable nuclear licensing regime to facilitate significant growth of nuclear capacity and timely licensing of innovative designs.
- Creating an effective safety paradigm focusing on genuine public wellbeing, where the health, environmental and safety benefits of nuclear are better understood and valued when compared with other energy sources.

The *Harmony* goal is ambitious, but it is achievable as the new nuclear build rate required now has been achieved in the past. The main challenges are not project delivery— although significant strengthening of capability and capacity would be required— but in securing the necessary political support. In order to make progress it is vital that the industry, regulators, government and leading international bodies cooperate on the actions required for nuclear energy to integrate with other low-carbon energy sources and help meet the global energy challenge.

2.4 Sustainable resource management and nuclear energy

The United Nations Framework Classification for Resources (UNFC)[23] is a multi-axial resource classification and progression tool for the balanced, transparent and integrated management of all resources (Figure 2.8). UNFC currently applies to mineral, petroleum, nuclear fuel, renewable energy, anthropogenic resources and injection projects. UNFC application aligns resources to socio-economic, geological and techno-feasibility factors, together with the ability to manage and assess both uncertainties and sensitivities involved in the classification of those resources whether in a primary (first use) state or a secondary (second and subsequent – circular use) state. This capability supports a conventional 'resource progression' model – i.e. one that gives a degree of predictability and certainty to market access – but perhaps more significantly it enables full life cycle and materials flow modelling based on the premise that 'end-of-life' procedures for one cycle are simultaneously 'start-of-life' procedures for the next, even when the cycles may have a significant interval of inactivity between them. This recognition that in one sense all 'projects' are indefinite, but unpredictable in their cyclic periodicity, in and of itself makes space for non-resource-based factors to operate within the UNFC.

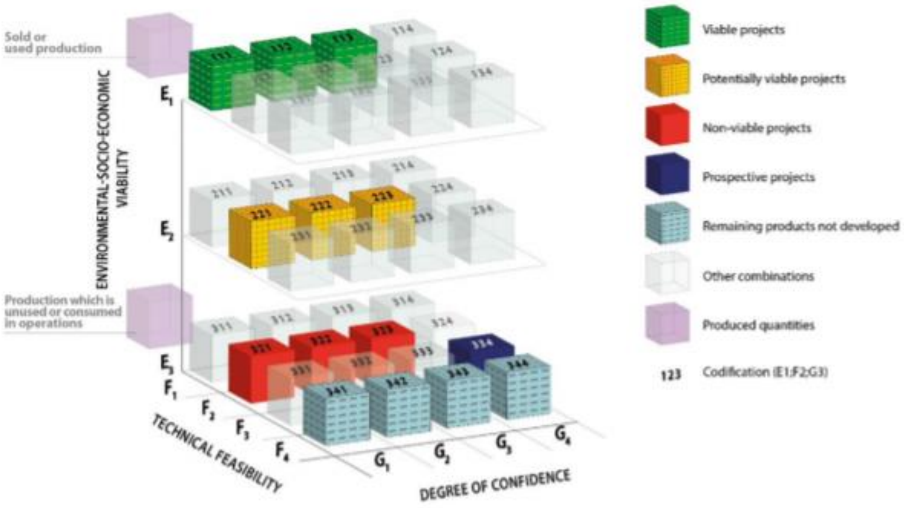

Figure 2.8 UNFC categories and example of classes.

The UNFC is currently being expanded into a resource management toolkit, the UN Resource Management System (UNRMS), which puts an even greater emphasis on accommodating social and environmental considerations at the centre of resource management. The purpose of the UNFC and UNRMS toolkit is first to provide decision and policy makers with the range of

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[23] See UNECE webpage on UNFC and Sustainable Resource Management

instruments, arguments and performance indicators that create the necessary and sufficient conditions for cost-beneficial, socially-accepted management of resources in general while meeting resource specific requirements.

UNECE's Expert Group on Resource Management (EGRM), which develops and maintains the UNFC, approved the nuclear fuel resources bridging document in April 2014[24]. It aligns the UNFC with other widely used resource classification systems for nuclear fuels, notably the '*Red Book*', co-published every two years since 1965 by the Nuclear Energy Agency of the Organisation for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA). UNFC guidelines for uranium projects provide additional support for holistic resource management, taking into consideration all specific aspects of uranium as an energy fuel, thus setting it apart from other mineral commodities[25].

While the energy markets are adapting to the requirements of the Paris Agreement and the SDGs, the role of nuclear energy remains crucial and controversial. The nuclear electricity sector has an opportunity to penetrate new markets with SMRs and with Generation IV technologies that are being designed to be more acceptable to the public and financiers, but it must fit into an energy-as-a-service model. Uranium-as-a-service should integrate into this new model[26]. This will require changing the narrative driver from 'commodity project' to 'energy policy' to pivot the uranium 'tale' from a 'push' to a 'pull' story where the policy landscape demands the inclusion of uranium in the set of energy resource options available to decision and policy makers facing multiple challenges: climate action; a public health crisis in the form of dangerous high levels of urban pollution and a related suburban, peri-urban and rural crisis of deforestation; the massive loss of fertile topsoil and desertification caused not by climate change but by bad farming and forestry practices, and wider natural resource management, notably use of water resources; and, the potential catastrophic loss of biodiversity resulting from land use conflicts related to energy and food security.

This by no means predicates a predetermined decision to proceed down the nuclear pathway. It simply says that if such a decision is taken, there are ways to implement it in a well-accepted, sustainable way, in combination with all other energy resources in the national portfolio.

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[24] *Application of the United Nations Framework Classification for Fossil Energy and Mineral Reserves and Resources 2009 to nuclear fuel resources*, ECE/ENERGY/2014/6, United Nations, Economic and Social Council (10 September 2014)

[25] *Guidelines for Application of the United Nations Framework Classification for Resources (UNFC) to Uranium and Thorium Resources*, Energy Series No. 55, United Nations Economic Commission for Europe (December 2017)

[26] *Redesigning the Uranium Resource Pathway: Application of the United Nations Framework Classification for Resources for Planning and Implementing Sustainable Uranium Projects*, ECE Energy Series No. 57, United Nations Economic Commission for Europe (August 2019)

Chapter 3 Nuclear Development Considerations

> *Nuclear energy entry pathways align with the 2030 Agenda for Sustainable Development. Nuclear energy programmes, based on a milestone approach, support national energy needs, socio-economic, and environmental goals, and can help countries meet international commitments. Detailed consideration of the whole nuclear life cycle to maximize the benefits to people, planet and prosperity ensures nuclear development aligns with the SDGs. UNFC and UNRMS provide a framework for assessment of the various factors related to nuclear energy and fuel resource development. Sustainable pathways for nuclear development emerge as part of the full consideration of the energy needs, regulatory, social, technical, environmental and economic aspects of the projects, as well as national capability and capacity.*

Introducing nuclear energy into a country is a major undertaking. This endeavour requires significant investment into building institutions, human resources, science and physical infrastructure as well as extensive cooperation with international partners and society. For a newcomer country it takes at least ten years of planning and commitment from when the decision to develop nuclear energy is made until the time when the first power reactor is generating electricity (subsequent reactor units can be deployed much faster). It requires working extensively with international partners to build up competencies to ensure that high standards are continuously met.

Developing a nuclear programme will engage local industry, government agencies and research centres and employ many specialists – including engineers and scientists as well as business professionals, lawyers, economists, accountants, financiers, project managers, communication experts to reach out to the public and ensure the social licence to operate, etc. Successfully establishing nuclear energy is a historic milestone in any country’s scientific and industrial progress. It brings international status and along with that, certain privileges and responsibilities. The nuclear industry is subject to governance at the international, regional and national level.

There is an internationally recognized process to assist countries in making the necessary preparations for a nuclear energy programme. The IAEA’s Milestones Approach [see box] is intended to offer guidance on how to create an enabling environment for introducing or expanding nuclear energy in a country’s energy mix. The approach lays a solid foundation for understanding and making a long term commitment to a safe, secure and sustainable nuclear programme. This report does not seek to repeat the Milestones Approach, but rather highlights five common nuclear development considerations which are readily aligned with sustainable development and often the subject of discussion in the global media as well as conferences and events. This includes:

- Energy system evaluation and planning.
- Socioeconomic development factors.

- Environmental factors.
- Regulatory and legal factors.
- Economics and project financing.

These considerations are likely to weigh heavily in the mind of nuclear newcomer countries as they evaluate nuclear energy pathways and consider which technologies to choose and whether also to develop local and regional approaches to uranium resources and the nuclear fuel cycle.

The IAEA Milestones Approach

The Milestones Approach identifies 19 infrastructure areas that are important for initiating and building a nuclear power programme. It provides a detailed description of the related activities and the expected level of achievement for each infrastructure issue. These activities are split into three progressive phases of development, leading to the achievement of the corresponding milestone:

- **Phase 1**: Considerations before a decision to launch a nuclear power programme (1-3 years).
- **Phase 2**: Preparatory work for the contracting and construction of a nuclear power plant after a policy decision has been taken (3-7 years).
- **Phase 3**: Activities to implement a first nuclear power plant (7-10 years).

The duration of these phases depends upon the degree of commitment, resources applied in the pursuant country, and the nuclear power plant design. A specific milestone at which the progress and success of the development effort can be assessed marks the completion of the infrastructure for each of these phases. The Milestones are therefore a set of conditions and do not necessarily have specific time-based implications:

- **Milestone 1**: Ready to make a knowledgeable commitment to a nuclear programme.
- **Milestone 2**: Ready to invite bids/negotiate a contract for the first nuclear power plant.
- **Milestone 3**: Ready to commission and operate the first nuclear power plant.

The three phases and the three milestones refer to the development of the national infrastructure needed to enable the nuclear power programme. (A programme refers to one or more nuclear power plants, and possible related projects, such as uranium exploration and fuel fabrication, and the supporting infrastructure.) As the programme develops, many specific activities will be undertaken to implement the first nuclear power plant project, and it is important that the distinction be clear. The infrastructure provides the processes and capabilities to enable the project activities and the subsequent operation of the nuclear power plant to be implemented safely, securely and sustainably.

Figure 3.1 Nuclear infrastructure issues in the IAEA Milestones Approach.

3.1 Energy system evaluation and planning

A large body of existing literature addresses energy planning and a great number of consultants and international organizations provide frameworks and advice for assessing the needs of energy systems. Most of these approaches have been based primarily on the evaluation of demand/supply of energy and electricity and only recently have the SDGs been taken into account.

Planning to meet growing energy demand is key for any developing country, not only to address the essential needs of the population - such as cooking and light - but also to unlock the potential for economic development and to fulfil the legitimate aspirations of people for greater comfort and access to modern-world standard of living. Increased energy availability will support economic growth in all sectors. International agencies such as IEA and UN bodies recognize that most of the growth in energy demand will occur in developing countries and are needed to secure basic access to energy while supporting future economic growth. By contrast, developed countries are seeing stabilization or reduction in their energy consumption, thanks to energy efficiency and outsourcing of their industry.

Many scenarios predict that developing countries will increase their current energy consumption four times over by 2050. It means that they will have to invest a huge amount of money in energy and electric system development. During the same period developed countries will need to invest heavily in decarbonizing their existing energy systems. It is of the utmost importance that all decision-makers make sure that wherever investments are made in the energy system, the life-cycle emissions of those investments are thoroughly considered. A holistic approach to energy cost and financing has to be part of strategies to reduce emissions and environmental impacts.

In this context it is essential that international financing agencies as well as lending institutions in developed countries seek ways to encourage developing countries to make decisions about their future energy systems which positively contribute to sustainable development and decarbonization. These institutions play a very significant role in determining whether countries have access to the energy sources they required to meet the SDGs.

Currently it is the case that many international organizations promote the development of renewable energy sources – notably hydropower to the extent possible as well as variable wind and solar – with a complement of gas as an idealized clean energy system. Some also include less mature technologies such as fossil fuel plants with the addition of carbon capture and storage and electricity storage options such as batteries. However most of these organizations, notably the World Bank, currently exclude nuclear energy, despite the fact that many countries have identified it as a proven, clean, reliable and affordable technology and are seeking to introduce it into their mix.

Betting the development of future energy systems on weather-dependent sources and immature technologies, without full consideration of proven technologies for an optimum mix, creates huge risk. It could lead to significant losses in time and money, as well as create barriers to economic growth and emissions reduction. Developed countries might be able to accept these risks and experiment with such an approach as they benefit from strong existing energy infrastructure and can afford to support ongoing R&D and build up the required industrial potential. Developing countries, however, will need to be more wary of these risks. They are likely to be influenced towards a conventional energy system which makes use of proven and off-the-shelf technologies.

Therefore, comprehensive energy system evaluation and planning should take into consideration the following points with the greatest care. It must address:

- The full spectrum of low-carbon energy sources and enabling technologies
    - All low -carbon energy technologies should be considered and supported– hydropower, nuclear, renewables, coal/gas with carbon capture/storage, etc.
- Security of supply
    - Higher weightage should be given to proven technologies, with a track record in cost, efficiency and SDGs contributions.
    - Intermittent energy sources should be backed-up by sufficient storage or reliable power sources.
    - Security of access to fuel, where appropriate, has to be looked at over the long term.
    - Resilience to system shocks as might be brought about by a pandemic, cyber-attack or extreme weather event.
- Localization

  - An essential component of the energy system evaluation is its contribution to the industrial growth of the country. Many countries have local content policies that aim to maximize contributions from the domestic suppliers.
- Life Cycle Assessment (LCA) and technology specific consideration
  - Reducing life-cycle emissions of key pollutants (CO_2, NOx, CH_4, etc.) are vital for mitigating climate change and environmental concerns.
  - Other impacts on human health and the environment from the cradle to the grave – particulate matter pollution, radiation, resources usage, land use, waste, biodiversity, etc.
  - Unique risks which may not be well covered by general assessments, such as proliferation and safeguards for nuclear, droughts on hydro-power and the consequences of accidents for all energy sources.
- Total costs of an energy system
  - Most evaluation will consider the levelized cost of energy/electricity (LCOE). LCOE allows comparison of the present cost per unit of electricity of a given technology at the point of generation but does not take into account the positive and negative externalities it may create. Nor does it consider the system costs associated with a technology – the need for backup, storage and grid enhancements. (MIT[27] and OECD[28] have issued important descriptive studies on those system costs, which are especially relevant to green-field projects in developing countries.)
  - Carbon price: In most cases a carbon price will be required to help internalize the climate impacts of fossil fuels and encourage the transition to low-carbon alternatives.
- Financing
  - The structuring and financing of investments have a very large impact on the overall cost of energy development. Governments have a role to play in facilitating access to low-cost financing that will secure the lowest rate of return and cost of capital.
- Regional considerations
  - Natural resources are usually taken into consideration, as will the existing and potential for domestic industry contribution as well.
  - Within the framework of a national energy system evaluation, it will be necessary to consider all regional approaches that may mutually benefit the region including resources, industries, grid interconnection, skills, etc.

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[27] Nestor A. Sepulveda, *Decarbonization of power systems: analyzing different technological pathways*, Massachusetts Institute of Technology (September 2016)

[28] *The Full Costs of Electricity Provision*, OECD Nuclear Energy Agency (2018)

Methodologies for energy planning and nuclear energy system sustainability assessment

The IAEA supports interested member states through a comprehensive capacity building program for energy system assessment. The IAEA has its own suite of energy system assessment tools and methodologies covering various phases of the energy planning process. The capacity building programme encompasses tools development, maintenance, and transfer of tools to users through provision of various types of training, support, information dissemination and technical assistance for energy studies. The IAEA assists member states in reinforcing national capabilities to conduct energy system analysis, so that countries independently can assess options and develop their own sustainable energy strategies and support national decision and policymaking.

The IAEA also offers the possibility to analyze nuclear energy in a more in-depth manner with a focus on sustainability, following INPRO methodology which contains over 100 assessment criteria in the areas of safety of reactors, safety of nuclear fuel cycles, economics, proliferation resistance, waste management, environment (stressors, depletions of resources), and infrastructure (including security). Additional studies can also be performed to look at various options to enhance nuclear energy sustainability through innovations in nuclear energy technology and collaboration (nuclear trade) among countries. The IAEA has also developed an analytical framework to simulate, analyze and compare nuclear energy systems and scenarios with different reactor and fuel cycle options in various countries allowing them to consider collaboration including nuclear trade among countries in any front-end or back-end fuel cycle stages.

The OECD Nuclear Energy Agency offers customized system cost analyses to its Member countries. As the penetration of variable renewable energy generation increases, the LCOE no longer provides sufficient information to design reliable, resilient and cost-effective electricity systems. NEA offers to perform in-depth country-specific system modelling to evaluate the true electricity cost and value of a postulated system with a given generation mix, taking into account not only LCOE but also system costs.

3.2 Socioeconomic development factors

The socioeconomic benefits of nuclear energy (alluded to in chapter 2) need to be fully weighed by potential countries and balanced against the potential impacts as part of a broader assessment of available energy technologies. Many countries have concluded that the net benefits from nuclear energy significantly outweigh the potential impacts.

3.2.1 Human health and well-being

An important item in the SDG concerning healthy lives and well-being is the reduction of deaths and illnesses from hazardous chemicals and air, water and soil pollution. Environmental emissions from power generation technologies affect human health in various ways. The most important emissions with negative implications for health include oxides of sulphur and nitrogen (SO2, NO_x) particulates, non-methane volatile organic compounds and ammonia. According to the World Health Organization (WHO) there is increasing scientific evidence of a causal link between exposure to ambient air pollution and cardiovascular diseases, especially ischemic heart diseases and strokes, and even between air pollution and cancer[29]. Additional implications of air pollution on human health include health disorders from respiratory diseases, both chronic and acute, including asthma.

WHO estimated in 2016 that outdoor air pollution is responsible for 3 million deaths annually. The global distribution of these fatalities is as follows:

- About 16 percent lung cancer deaths.
- About 25 percent chronic obstructive pulmonary disease (COPD) deaths.
- About 17 percent of ischemic heart disease and stroke.
- About 26 percent of respiratory infection deaths.

The highest numbers of deaths attributable to air pollution are in the Western Pacific region and Southeast Asia.

Nuclear power plants emit virtually no air pollutants during their operation, and their air emissions are very low over their entire life cycle. The emissions from nuclear plants are comparable to those of clean, renewable technologies such as wind and solar energy on a life cycle basis. It follows that nuclear power can contribute to reducing human health impacts from the energy sector.

Quantitative comparative assessments confirm the above observations. A study for the European Commission (New Energy Externalities Development – NEEDS) assessed human health impacts from a wide range of pollutant emissions from various electricity generation technologies. The researchers converted the various health effects into external costs and measured them in financial terms, (i.e. euro cents per kilowatt-hour). By adding up these costs, the total health effects are obtained for each technology. The results are shown in Figure 3.2[30]

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[29] 7 million premature deaths annually linked to air pollution, World Health Organization news release (25 March 2014)

[30] *External costs from emerging electricity generation technologies*, Deliverable No. 6.1 – RS1a, New Energy Externalities Developments for Sustainability, Project No. 502687 (March 2009)

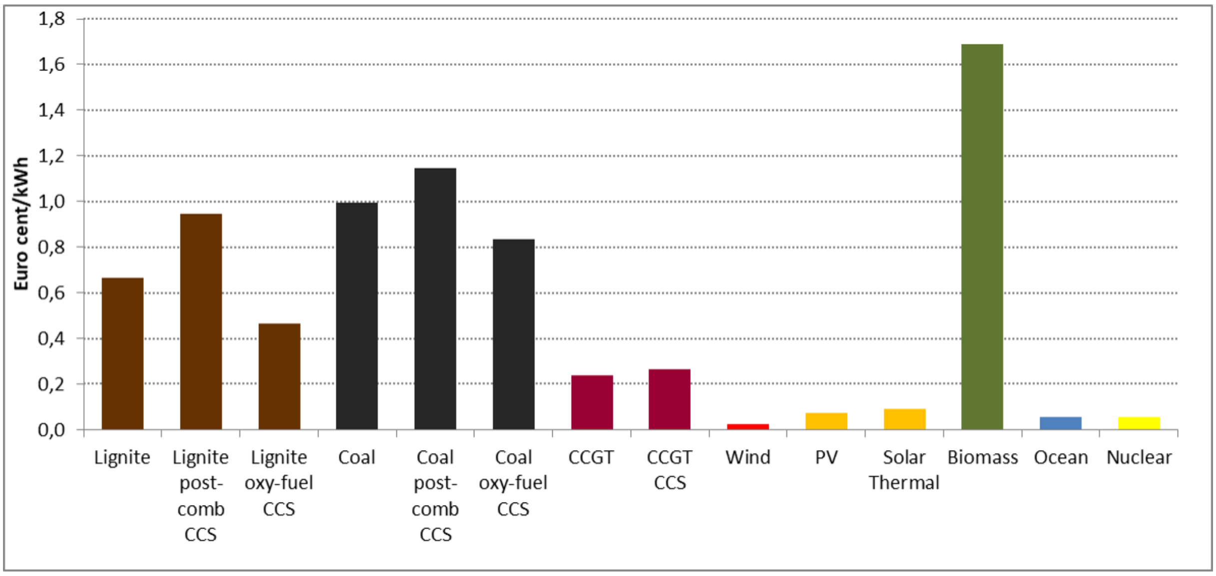

Figure 3.2 Health effects, measured by their external costs, for 14 technologies as they are expected to perform in 2025 based on the NEEDS (2009) study. Note: Post-comb: post-combustion; CCS: carbon capture and storage; CCGT: combined cycle gas turbine; PV: photovoltaics.

A joint study[31] by the National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies and Columbia University's Earth Institute investigated both the historical and potential future role of nuclear power in preventing mortality related to air pollution. The study estimates that globally nuclear power has prevented over 1.8 million air pollution-related deaths that would have resulted from fossil fuel burning between 1971 and 2009. The largest shares of prevented fatalities are estimated for the OECD member states in Europe and the USA. The overall conclusion of the study emphasizes the importance of retaining and expanding the role of nuclear power in the near term global energy supply. These assessments show that the large-scale deployment of nuclear power can make a higher contribution to reducing air pollution-related deaths in the future.

This conclusion holds even when accounting for the effects of nuclear accidents. During normal operations, nuclear power plants do not emit significant amounts of radioactive materials and worker exposure to radiation is kept within very conservative limits. Preventing radiological health and environmental impacts is the primary safety focus of nuclear operators and regulators, and significant resources are dedicated to this. At certain times, controlled releases of radioactive materials do take place, typically tritium, carbon 14, and noble gases, which are hard to filter, but the dose received by the nearby public will be over a thousand times less than that caused by natural background sources.

It is, however, possible for an accident situation to develop. The International Nuclear and Radiological Event Scale (INES) is a tool for communicating the safety significance of nuclear and radiological events; with a scale from 1 to 7. Major accidents – those that score 7 on the

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[31] Pushker A. Kharecha and James E. Hansen, *Response to Comment on "Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power"*, Environmental Science & Technology, 47, 12, 6718–6719 (22 May 2013)

INES scale – involve a large release of radioactive material and contamination of the local environment. These events are rare, and only two such major events have occurred in the history of civil nuclear energy – the accidents at Fukushima Daiichi and Chernobyl nuclear power plants. While both these events are deeply ingrained in the public consciousness, their direct health consequences are significantly lower than is often portrayed, especially when compared with the impacts from other industrial accidents.

UNSCEAR is the UN scientific committee which is charged with studying the impacts of radiation. It has published multiple reports on the accidents[32] with the main findings summarized in table 3.1.

Table 3.1 Radiological consequences of the Chernobyl and Fukushima nuclear accidents.

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

The deaths directly attributable to nuclear energy, including its accidents, are very low compared to other energy sources. So low in fact that on a deaths-per-kilowatt-hour basis, nuclear measures up as one of the safest of all energy technologies as indicated in Figure 3.2. It is the other consequences of accidents – the psychological and social damages such as resettlement – which have proven to be the greatest long-term impacts. Those consequences can be mitigated by improving public education on radiation, building trust in regulators, and

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[32] For Chernobyl accident, see *Sources and Effects of Ionizing Radiation, Volume II: Effects*, United Nations Scientific Committee on the Effects of Atomic Radiation (2008)*;* and *Evaluation Of Data On Thyroid Cancer In Regions Affected By The Chernobyl Accident*, UNSCEAR (2018).
For the Fukushima accident, see *Sources, Effects and Risks of Ionizing Radiation, Volume I*, UNSCEAR (2013)

having governments adopt "all-hazards" emergency response guidelines and commit to clearer science-based communication and policy making.

Even so, nuclear operators worldwide have cooperated to learn from these accidents and improve safety at their plants. There is a well-established culture of sharing safety information in the nuclear industry which is facilitated by multiple international bodies including notably the IAEA and the World Association of Nuclear Operators (WANO). Nuclear newcomer countries will therefore benefit from this learning and also the fact that modern reactor designs are safer than older ones, making both the likelihood and the impacts of any future accidents even smaller.

3.2.2 Education and learning

The SDG targets on education include increasing the number of people with technical and vocational training to foster their employment in decent jobs. The construction and operation of nuclear power plants requires a high level of technical skills in several disciplines ranging from civil and electric engineering to machine and control engineering. With the need for highly educated and trained employees, a national nuclear power programme boosts a country’s human capital and provides additional motivation for establishing and extending technical education, which increases the pool of highly skilled workers which other economic sectors will benefit from as well. Staff engaged in the nuclear power sector have strong long-term job prospects and comparative job stability.

Supporting the safe, secure and sustainable management of nuclear power programmes requires the availability of competent human resources. This requires long-term investments in human capital that can also induce additional economic growth via higher productivity in the electric power sector and beyond. Improved human capital in the nuclear power industry and connected sectors increases labour productivity in these sectors. Similarly to most other sectors of the economy, higher skills improve employment rates as well as earnings as they enable the operation of more sophisticated technologies and increase the output per unit of labour input.

A key element in ensuring a sustainable supply of suitably qualified human resources is capacity building. According to IAEA, the capacity building includes four key elements:

- Human resource development.
- Education and training.
- Knowledge management.
- Knowledge networks at the national, regional and international level.

Of these four elements, the first two have important linkages to the overall higher education and vocational training in countries operating nuclear power plants or planning to start a national nuclear energy programme.

Banks at al.[33] explored human resource development in three new nuclear energy states in the Middle East: the United Arab Emirates (UAE), Jordan and Turkey. Despite the different national conditions and education systems, they found a rich diversity of linkages between the education and training of nuclear personnel and the national higher education systems. The capacity building process for a nuclear energy program also promotes capacity building in other fields related to nuclear science – such as health and agriculture.

A noteworthy trend in the last decade or so is that the barriers between nuclear and non-nuclear professions have diminished. Professionals outside the nuclear sector, such as in governmental organizations, local authorities and private companies increasingly benefit from having basic knowledge in various aspects of nuclear technologies, resulting from targeted training and communication. These can take the form of specialized courses at national universities, including new multidisciplinary curricula and the collaboration of pertinent institutions, programmes offered by specialized national agencies (e.g. the Japan Nuclear Human Resource Development Network or the Nuclear Power Institute in the USA), bilateral and multilateral education, and training programmes arranged by national governmental institutions, and multinational corporations, especially nuclear power technology vendors. In turn, nuclear professionals increasingly obtain additional qualifications in non-nuclear subjects such as economics, management, social sciences, law and public administration.

3.2.3 Economic growth and employment

SDG 8 on economic growth aims for sustained growth, increasing productivity driven by, among others, technological innovation and decent job creation as key objectives. Sustained economic growth requires investments in productive assets for which a key precondition is a stable and secure supply of energy in general and electricity in particular. Energy security is a central policy objective in most, if not all, countries. This covers a variety of concerns ranging from the reliability of primary energy resource supplies to the absence of physical interruptions due to natural or technological causes, volatility in the price of primary and secondary energy, and the dependability of energy supply to end-users.

As opposed to oil and natural gas, for which huge reserves are concentrated in a few politically sensitive regions and need to be transported through possibly vulnerable sea transport corridors, uranium resources are widely distributed across five continents and can be transported via different routes. This makes nuclear energy less vulnerable to disruptions in primary fuel supply.

The cost structure of nuclear energy practically prevents large fluctuations in the cost of nuclear-generated electricity. The overwhelming share of its costs is the upfront capital costs while operating costs amount to only a small portion. Within the latter, the share of uranium

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[33] John Banks, Kevin Massy, Charles Ebinger (Ed.), *Human Resource Development in New Nuclear Energy States: Case Studies from the Middle East*, Policy Brief 12-02, The Brookings Institution (November 2012)

fuel cost is even smaller and comes to only about 7-10 percent of the total cost. This makes total generating costs, and thus the price of nuclear electricity, stable and predictable for decades.

Investments in nuclear energy trigger increases in economic activities, hence value-added and economic growth in other sectors such as construction, manufacturing and various service branches. During the construction phase, the construction industry and the manufacturing of machinery and equipment are the main beneficiaries of nuclear investment. Depending on the construction arrangements (fully domestic endeavour or involvement of foreign suppliers), indirect growth may arise in the supply chain. During the operations phase, additional turnover will be generated in the wholesale and retail trade, other commercial services, transport, education, etc., that results in additional economic growth. Not only are there direct jobs in all phases, but also indirect jobs are created in the domestic supply chain and supporting services.

Both direct and indirect jobs induce further employment as a result of their expenditures in the local economy – education, housing etc. Those impacts are well described in a joint IAEA/OECD-NEA report[34]. The higher than average pay rate within the nuclear industry helps to support many induced jobs. For each direct job in nuclear energy, about 2.5 to 3.5 indirect and induced jobs are created.

The high level of incomes in the nuclear industry is well illustrated by Figure 3.3, which shows that average salary for US nuclear worker salary is significantly higher than for either renewables or fossil fuels. Additional direct employment is established in related areas, including design, siting, licensing and supervising at the front end and during operation, and in waste management and decommissioning at the back end of the nuclear fuel cycle.

Apergis and Payne[35] conducted a large-scale panel study on the economic growth effects of nuclear energy consumption over the period 1980-2005 in 16 countries. They found that, on average, a 1 percent increase in nuclear energy consumption would increase the gross domestic product (GDP) by 0.32 percent. In comparison, the same increase in the economy-wide real gross fixed capital increases real GDP by only 0.17 percent. The study also found that a 1 percent increase in the nuclear labour force triggers an average increase in real GDP by 0.76 percent, but that the actual GDP impacts could vary significantly depending on the differences in the size of the economy and the magnitude of the nuclear energy programme. For example, in the USA each dollar spent by an average nuclear power plant during one year of operation is estimated to trigger an additional $1.04 of output in the regional economy, $1.18 in the State and $1.87 at the national economy level[36]. A study for Jordan estimates that one dollar spent in

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[34] *Measuring Employment Generated by the Nuclear Power Sector*, OECD Nuclear Energy Agency and International Atomic Energy Agency (2018)

[35] Nicholas Apergis and James E. Payne, *A panel study of nuclear energy consumption and economic growth*, Energy Economics, 32, 545-549 (May 2010)

[36] *Nuclear Energy's Economic Benefits — Current and Future*, Nuclear Energy Institute (April 2014)

the construction of a nuclear power plant will generate an additional output of $3.30 across all sectors of the national economy[37].

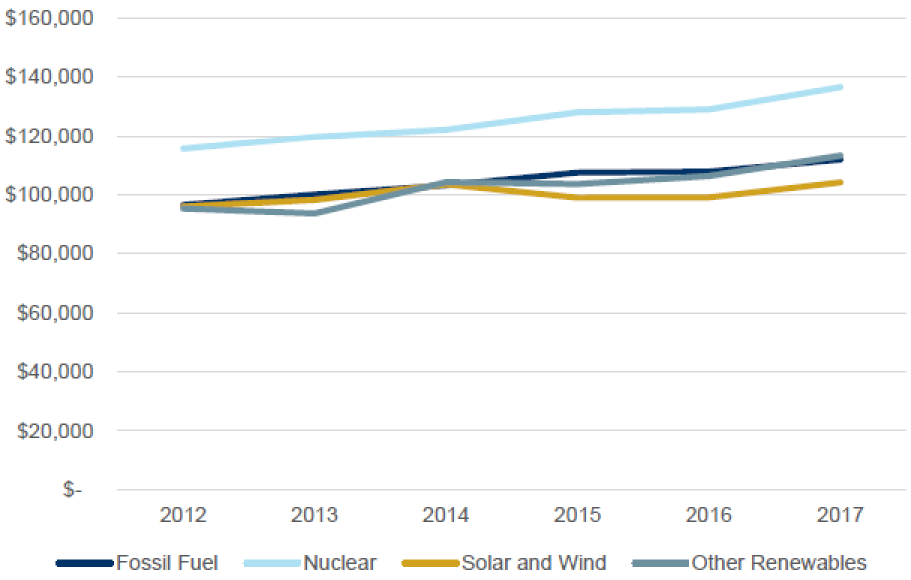

Figure 3.3 Average salary of a US energy worker. Source: Oxford Economics[38].

A recent Foratom[39] study assesses the annual economic benefits of using nuclear energy in the European Union (EU) over the period 2020–2050 for three scenarios. The number of nuclear-related direct and indirect jobs amounted to 1,129,900 in 2019 for an industry which provides about 25 percent of the electricity in the EU. Keeping the same share of nuclear energy in the total power generation over the next three decades would require an increase in nuclear capacity to 150 GW and comprise total employment of 1,321,600 people. The medium (103 GW) and the low (36 GW) scenarios involve declines in nuclear-related employment relative to 2019 to 1,000,600 and 650,400 jobs, respectively.

3.2.4 Infrastructure, industry and innovation

The SDG on resilient infrastructure, sustainable industrialization and innovation implies key prerequisites for sustainable development. These include well-developed and properly functioning infrastructure of various sorts, industrialization based on a country's natural resource and human capital endowments, and sustained investments in innovation and technological development. A national nuclear energy programme can support the fulfilment of these requirements rather well.

The proper functioning of infrastructure facilities in various domains such as transport, water, housing and communication requires a stable and reliable provision of energy, in particular

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[37] *White Paper on Nuclear Energy in Jordan "Final Report"*, Jordan Atomic Energy Commission, WorleyParsons (September 2011)

[38] *Nuclear Power Pays: Assessing the Trends in Electric Power Generation Employment and Wages*, Oxford Economics (April 2019)

[39] *Economic and Social Impact Report*, Foratom, Deloitte (25 April 2019)

electricity. Sufficient and reliable energy supply is also a precondition for industrial development. As opposed to intermittent power generation technologies, nuclear energy provides a flexible and reliable source of electricity. The availability factor (i.e. the percentage of the time it can produce electricity) for nuclear power plants is very high, on the order of 90 percent. Nuclear energy is a dispatchable generation source, capable of generating electricity 24/7, regardless of the weather. The occasional shutdowns for maintenance and refueling are planned well in advance, and in most cases can be scheduled for periods of low electricity demand. Unplanned interruptions can occur in the operation of all power generation technologies for various reasons but nuclear power plants perform better than all other energy technologies[40].

Many developing countries are endowed with mineral deposits and other natural resources that could support a sustainable industrialization process. The further the processing of such resources is pursued, the more value can be created for the national economy. Yet, some industrial processes are highly energy-intensive and hence their sustainability requires the supply of reliable, low-cost, low-carbon energy.

Approximately half of the total energy used in the global industry is used in five sectors: chemical and petrochemical branches, iron and steel, cement, pulp and paper, and the aluminium production chain. Demand for outputs of these sectors is likely to continue to increase in the future. In some parts of these sectors, the massive fossil energy requirements are not yet practical to replace with low-carbon energy sources. However, there is a considerable potential to replace carbon-intensive energy sources and especially fossil-based electricity in the iron, steel and aluminium industries, in cement production, and pulp and paper production. Thus, a national nuclear energy programme could reduce the climate footprints of these industries and, in turn, these sectors could ensure a stable demand for nuclear electricity.

The scientific research requirements and innovation processes associated with a nuclear power programme are likely to produce results that spill over to other industries and improve their technological capabilities, as well as to other domains of the society. In healthcare, for example, nuclear medicine is extensively used in both diagnosis and treatment of a wide range of diseases. Domestic production of radiopharmaceuticals is another example. In food and agriculture, nuclear techniques help mitigating soil erosion, eradicating tsetse flies and fruit flies, and are also used in plant mutation to increase yields. In water management, nuclear techniques are used to measure moisture levels in soils and plants, allowing experts to determine the timing and the exact amount of water and nutrients to use in water-saving drip irrigation. Isotope hydrology is an indispensable tool for exploring key characteristics (age, origin, evolution, contamination sources, etc.) of aquifers to foster their sustainable

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[40] *Performance of Generating Plant: New Metrics for Industry in Transition*, World Energy Council (2010)

management (IAEA, 2015). Skilled labour for all these applications and further research and development could be trained alongside the national nuclear energy programme.

In summary, new or extended national nuclear energy programmes have significant potentials to foster the implementation of SDGs in the four socioeconomic development domains reviewed in this section: improving human health by reducing air pollution, enhancing education and training by employing highly skilled labour, generating economic growth and employment beyond the nuclear industry, and supporting infrastructure development and operation, industrialization, and innovation and technological development in various sectors of the national economy.

3.3 Environmental factors

Like every form of energy production, nuclear energy causes environmental impacts and the technology needs to be subjected to monitoring and regulation to make sure these impacts are minimised and do not cause substantial harm. This section describes the main ways that nuclear energy affects the environment, both energy generation and uranium mining, as well as how the environment can impact the construction and operation of nuclear facilities. It reveals a perhaps surprising fact – that nuclear energy has one of the smallest environmental footprints of any energy generating technology.

3.3.1 Nuclear energy life-cycle assessments

Life-cycle assessments (LCAs) attempt to capture all the environmental impacts of a product across each stage of its life. For energy technologies this should include any associated mining, transport, fuel processing facilities, power plant construction, operation, maintenance and decommissioning activities. Potential impact categories for energy technologies are varied and include those that can affect human health and ecosystems as indicated in table 3.2.

Table 3.2 Example LCA impact categories applicable to different energy sources. Source: Gibon *et al.*[41]

Group	Environmental mechanism	Endpoint
Land occupation, transformation	Agricultural land occupation, land transformation potential, urban land occupation potential	Ecosystem quality
Toxicity	Freshwater ecotoxicity potential, human toxicity potential, marine ecotoxicity potential, terrestrial ecotoxicity potential	Human health, ecosystem quality
Air Pollution	Ozone depletion potential,	Human health
Greenhouse gases	Global warming potential	Human health, ecosystem quality
Eutrophication/acidification	Freshwater eutrophication potential, terrestrial acidification potential	Ecosystem quality
Ionizing radiation	Ionising radiation potential	Ecosystem quality

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[41] Thomas Gibon *et al.*, *Health benefits, ecological threats of low-carbon electricity*, Environmental Research Letters, 12, 034023 (March 2017)

Nuclear energy boasts two distinctive features that work to reduce its overall footprint compared to other energy sources. First, nuclear plants generate heat but without producing significant levels of environmental emissions. In contrast to the combustion of hydro-carbons (coal, gas. oil and biomass) the nuclear fission process keeps hazardous materials locked up inside the fuel. Almost all emissions from nuclear energy are in fact attributable to the use of fossil fuels throughout its life-cycle. This is small compared to the amount of energy generated and will likely reduce further in the future as non-emitting fuel sources replace high emission alternatives. In terms of climate change, the IPCC recognizes that the whole life cycle greenhouse gas emissions of nuclear energy are at a similar level to renewable energy sources and that it is, without question, a low-carbon energy source[42].

The second remarkable feature of nuclear is the energy density of nuclear fuel. On a per-unit weight basis, natural uranium contains over 10,000 times the amount of energy of chemical fuels. The volumes of material required and associated environmental impacts are correspondingly much lower for nuclear than for other fuel-based energy sources. This energy density means that nuclear boasts one of the smallest land and mineral resource requirements of any energy source – a fact that should be kept in mind in light of the recent IPBES Global Assessment which found that changes in land and sea use were the most important direct driver impacting biodiversity worldwide[43].

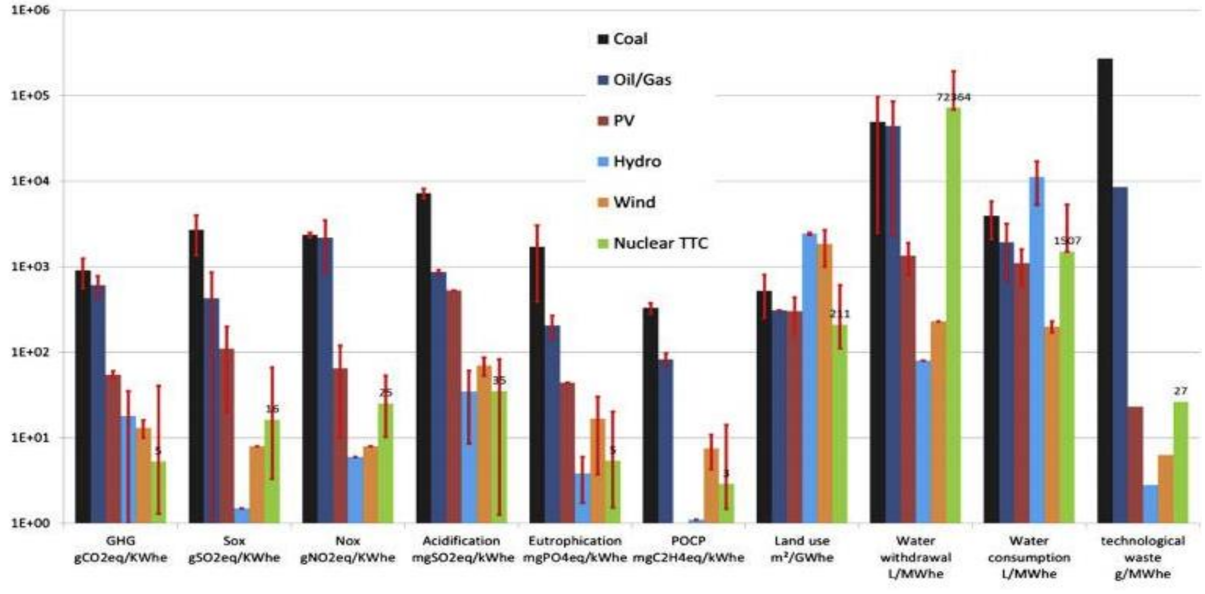

Figure 3.4 Results of a comparative life-cycle assessment of different energy sources in France (assumes one time recycling of fuel). The Y-axis is a log scale meaning that each additional graph unit represents a ten-fold increase of emissions or impact. Source: Poinssot *et al.*[44]

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[42] See for example *AR5 Climate Change 2014: Mitigation of Climate Change, Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, *Chapter 7 Energy Systems*, IPCC (2014)

[43] E. S. Brondizio, J. Settele, S. Díaz, and H. T. Ngo (editors), *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*, IPBES (2019)

[44] Poinssot *et al.*, *Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles*, Energy, 69, 199-211 (1 May 2014) Note that the French nuclear fleet recycles its fuel which should improve nuclear performance on some metrics.

The main perceived environmental drawback of nuclear power plants is the creation of long-lived highly-radioactive materials, which are, for the most part, treated as waste. These are potentially dangerous and require special shielding and remote handling to manage safely. However, the production of potentially hazardous waste is common to all energy sources. What matters from an environmental perspective is how well those wastes are managed, whether they are contained or dispersed into the environment and whether they can be reduced, reused or safely disposed of. High-level radioactive wastes from nuclear facilities are i) created in small volumes; ii) subject to very high standards of management and disposal iii); contained without dispersion into the environment; and iv) potentially recyclable. Management and disposal options for radioactive wastes are covered in chapter 4.

Another potential impact of nuclear power plants is their effect on the aquatic environment. Nuclear power plants require large amounts of water for cooling purposes just like other thermal energy sources such as coal, gas and biomass. The thermal efficiency of a nuclear plant varies according to reactor design and the environmental conditions of where it is located, but a typical value for one of today's operating plant is 33 percent. This means that 66 percent is released back into the environment as heat. Cooling water must be extracted from a local water body and in most cases returned to it in a process which heats and consumes water and that can negatively affect local species. However, whether this adds significantly to ecosystem stress levels depends heavily on the local aquatic context. Water withdrawal and consumption is not an important metric if water availability is not an issue. Careful plant siting goes a long way to reduce most potential aquatic impacts while there are measures that can be taken to mitigate aquatic stress if it develops. Some measures, such as cooling canals, may even result in nuclear plants acting as havens for certain species (such as crocodiles at the Turkey Point nuclear plant in the USA). Nuclear plants which are adapted for cogeneration can increase their thermal efficiencies and thereby reduce their aquatic impacts.

LCAs are an important tool for determining sustainability but they are not perfect. Results will vary depending on the methodology employed and the inputs used. It is therefore important to adopt an internationally recognised standardized, such as ISO 14040, to ensure robustness and comparability. With this acknowledged, it is still clear (see figure 3.4) that nuclear energy impacts remain low over all categories.

3.3.2 Nuclear plant siting and resistance to environmental threats

One of the most important decisions taken at the early stage of a nuclear power programme is site selection. From a nuclear industry viewpoint, a potential nuclear plant site needs to have three key things – access to water for cooling, stable bedrock free from geological faults and landslides, and reasonable proximity to a grid connection and load centre. For most countries there will not be a shortage of potentially suitable sites, but some sites will be considerably better than others. It is possible to engineer away some shortfalls in a potential site – for example by building a longer transmission link or cooling towers where water availability is a concern – but this will add to costs. Before a site selection can be finalized there will need to be a series of detailed environmental studies to make sure the facility does not do undue harm to local ecosystems. The final ingredient every nuclear project site needs is a supportive local public. Trust will need to be earned in many cases and this is a key element of a public consultation carried out during the environmental assessment.

In addition to considering the effects of nuclear power plants on the environment, it is also important to consider the potential impacts of the environment on nuclear power plants. This is especially true in a world where the climate is changing and certain extreme weather events may be increasing in frequency and magnitude.

Ideally, the site will be an area which does not experience significant seismic activity. Nuclear plants are engineered to be resistant to earthquakes, but additional protection measures in a more seismically active region adds more cost. An earthquake can also disrupt the grid or access to the nuclear facility, which calls for additional safety preparations. However, some regions are simply more seismically active than others, and so it becomes a question of relative degrees – making sure that nuclear facilities are sufficiently prepared for an earthquake and any effects on supporting infrastructure.

Operators of coastal nuclear plants need to protect against possible tsunamis. A massive tsunami disabled the diesel generators at the Fukushima Daiichi nuclear plant and was the direct cause of the accident there. Following the Fukushima Daiichi accident operators worldwide reviewed and improved protection against all external hazards and emergency response arrangements. Nuclear newcomer countries will benefit from the experience of the established nuclear countries.

While nuclear power plants are a key tool for preventing climate change, they must also adapt to become better prepared to withstand its impacts. Among the possible impacts of climate change are floods, droughts and unusual weather events.

There have been occasions where inland nuclear plants have been subjected to floods, but none have resulted in an accident situation (INES level 4 or above). With adequate preparation the build-up of water is slow enough to allow plant personnel time to respond and protect key systems. The same will also be true for nuclear plants based on the coast concerning projected sea-level rise. The risk must be taken seriously, but it is manageable.

Nuclear plants are occasionally idled due to hot weather. There have been several such occurrences recently in France where a large number of reactors are based adjacent to rivers, and water temperatures went beyond regulatory limits[45]. To date, the amount of nuclear generation lost to these events has not been particularly significant – and is less in fact than experienced for renewable energy systems[46]. The adaptation challenge is hardly unique to nuclear plants and all energy generation forms will face similar limitations. Nevertheless, it

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[45] *France's EDF halts four nuclear reactors due to heatwave*, Reuters (4 August 2018)

[46] Staffan Qvist, *Curtailment of Nuclear Power Output During Extreme Heatwaves: The European Case*, Energy For Humanity (August 2019)

should be considered carefully for inland nuclear sites with studies carried out on the local water bodies to determine how they are expected to evolve. Regulators should also take the changing ambient temperature conditions of the waterbody into account. It is possible to reinforce nuclear plants to minimize vulnerability to drought impacts – for example, by adding air conditioners to protect key equipment and increasing the capacity of heat exchangers – although it may not be practical to try to avoid all hot-weather-related outages.

On the other end of the weather spectrum, nuclear plants have proven to be highly resilient to cold spells. During the recent polar vortex and bomb cyclone events in the USA, almost every affected nuclear power plant stayed online[47] at a time when coal piles were freezing, and natural gas was prioritized for heating. In addition to this, some nuclear plants operating today even supply heat for district heating schemes, and there is increasing awareness of this application for small modular reactors in countries like Finland[48].

3.3.3 Uranium mining

Like all other mining activities, uranium mining can generate environmental impacts on local ecosystems, which need to be carefully managed. This includes impacts on air, land, water quality or health of workers and local communities. However, it is possible to minimize impacts by consistently applying best practices, using the latest technology and, above all, by strictly following relevant standards. Modern uranium mining practices are outlined in an important OECD NEA publication which forms the basis of much of this section[49]. Major considerations are shown in Figure 3.5.

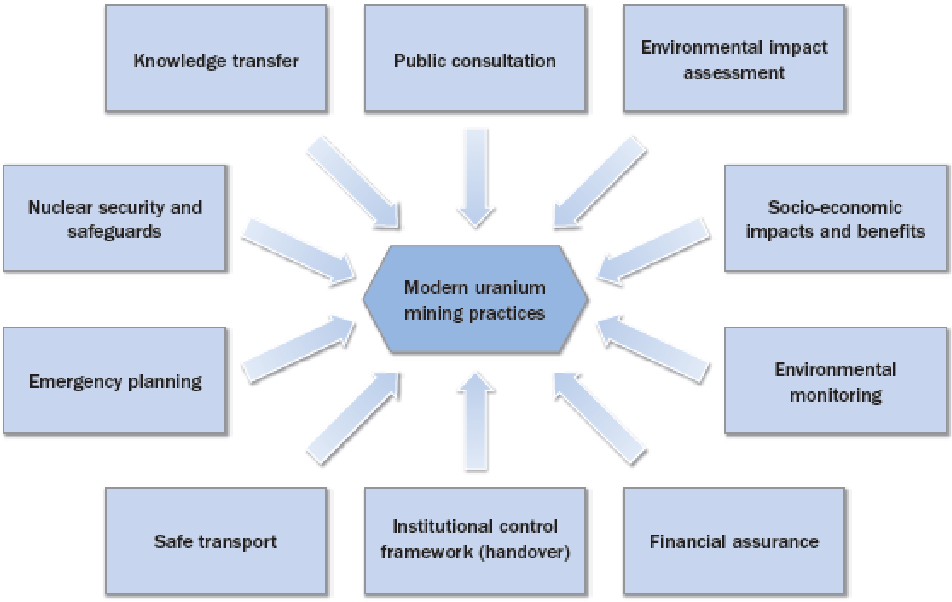

Figure 3.5. Modern uranium mining practises embrace a holistic approach to managing environmental risks and stakeholder expectations.

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[47] See *US nuclear plants operate through polar vortex*, World Nuclear News (4 Feb 2019)
[48] See VTT, 2017 District Heating With Small Modular Reactors
[49] *Managing Environmental and Health Impacts of Uranium Mining* OECD NEA (2014)

The key to sustainable environmental management lies in the development of a plan that takes into account the entire life cycle of a uranium operation and how it interacts with the environment[50]. The cost of environmental remediation at the end of the life cycle is generally greater than the cost of a planned reclamation during operational and mine closure phases, further reinforcing the importance of preventing environmental legacies.

The phases of a uranium mining/milling project are similar to those of other metal mines, beginning with exploration for viable ore bodies and concluding with site reclamation. As each phase involves different types of activities, environmental impacts can vary amongst the phases. The full mine life cycle can be partitioned into four phases, as shown in figure 3.6: the exploration and feasibility phase, the planning and construction phase, the mine operations phase and the mine closure phase.

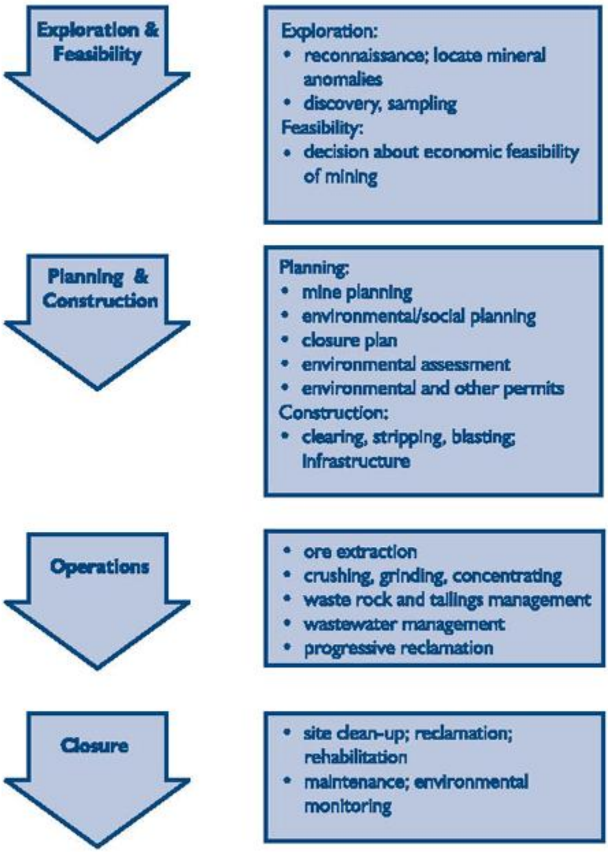

Figure 3.6 Activities of the mine life cycle.

Unlike siting a nuclear power plant, a host nation has no control over the site of a uranium deposit, as the presence of economic concentrations of uranium is dictated by geological events that occurred millions of year ago. Accordingly, from an environmental and human health perspective, the pre-production (site design and construction) is a key phase of the uranium mining life-cycle. Planning at this stage can ensure that environmental and human health protection is designed into the project from the beginning. It also provides the opportunity to reject those projects where risks outweigh benefits before significant investment. Typically, this phase will involve completion by the project developer of an environmental impact assessment (EIA) under the auspices of a certified external expert, stakeholder participation and a regulatory decision as to the acceptability of the project prior to receiving approval to commence construction of surface facilities.

Uranium mining methods can be broadly categorized into two types:

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[50] *Establishment of Uranium Mining and Processing Operations in the Context of Sustainable Development*, Nuclear Energy Series No. NF-T1.1, IAEA (2009)

1. Conventional mining and milling
    a) Open-pit
    b) Underground
2. In-situ recovery (ISR)

Open-pit mining is generally suitable for orebodies located at shallow depths with underground mining used for deeper and often richer ore deposits. Large, low grade and disseminated ore bodies are often preferentially mined using open-pit methods. Open-pit mining involves the removal of significant volumes of overburden and waste rock to access the ore grade material beneath. The orebody is mined from the top down. Beyond a certain depth, it becomes more economical to move to underground mining methods.

Ore from open-pit or underground mines is transferred to a mill for processing to form a uranium concentrate product referred to as “yellowcake” which is fit for transport to the next stage of the nuclear fuel cycle. Conventional milling usually involves acid or alkaline leaching of ore after crushing and grinding. Conventional milling requires the management of significant volumes of tailings. These tailings, consisting of the unrecoverable and uneconomic metals and minerals, chemicals, organics, and process water are discharged to a storage area referred to as tailings management facility. These management facilities must be engineered to ensure that they don’t leak and contaminate the local environment.

ISR is suitable for low grade ore bodies adequately placed between impervious stratigraphic layers. It involves direct injection of leaching solution – acid or alkaline - into the uranium-bearing formation. The leach solution is collected from extraction wells and sent to a central processing plant for yellowcake production. The in-situ leaching process eliminates the need for management of waste rock and large tailings management facilities.

The environmental impacts from ISR operations are substantially different from those of conventional mining and milling. The impacts on the surface and subsurface are significantly smaller as no material is physically removed save for the cuttings of the drillings; therefore, no mine pit is created, and no mill tailings requiring long term waste management are generated. The impacts to groundwater, however, have to be well monitored compared to other uranium recovery methods because of the number of drills that will bore through aquifers before reaching the ore body. In addition, the ore zone groundwater chemistry is altered by the release of minerals and metals present in the uranium ore during the leaching process. If not controlled, these constituents in ISR extraction and waste fluids can contaminate surrounding groundwater.

At the end of its productive life a uranium mine needs to be decommissioned and the landscape rehabilitated. There are numerous former mines in the World, both conventional and ISR, which have been fully remediated, for example in Czech Republic, France, USA, Canada, etc. The most important considerations are to make sure that the EIA describes upfront the remediation process that will be set in the future and then to set up the appropriate fund collection for the remediation works.

Australian uranium mining remediation success stories

Mary Kathleen in Queensland was the site of Australia's first major rehabilitation project of a uranium mine. It involved the plant site, a 28 hectare tailings dam, and a 60 ha evaporation pond area. All this has now returned to being a cattle station, with unrestricted access. The rehabilitation project was completed at the end of 1985 at a cost of about $19 million, and won an award for engineering excellence. The Nabarlek uranium mine in the Northern Territory was the first of the "new generation" of uranium mines to commence operations and the first to be rehabilitated. Environmental protection was stressed at Nabarlek since before mining commenced, and everything proceeded with eventual rehabilitation very much in mind. During the life of the operation the company worked together with government agencies, the Northern Land Council (NLC) and Aboriginal land owners to ensure a high standard of environmental management, culminating in its decommissioning and successful rehabilitation.

A final important point to underline is that modern uranium mining is highly regulated and distinct from mining practices employed in the past. Today, mine and mill workers are trained and protected from exposure to radiation through a combination of safe working practices which are sufficient to keep exposures well below regulatory limits as evidenced in Figure 3.7. Environmental planning and monitoring throughout the life cycle of the mine ensures that the planned performance is achieved from exploration to post-decommissioning stage, minimizing the environmental effects to meet acceptable standards and avoiding impacts to local populations.

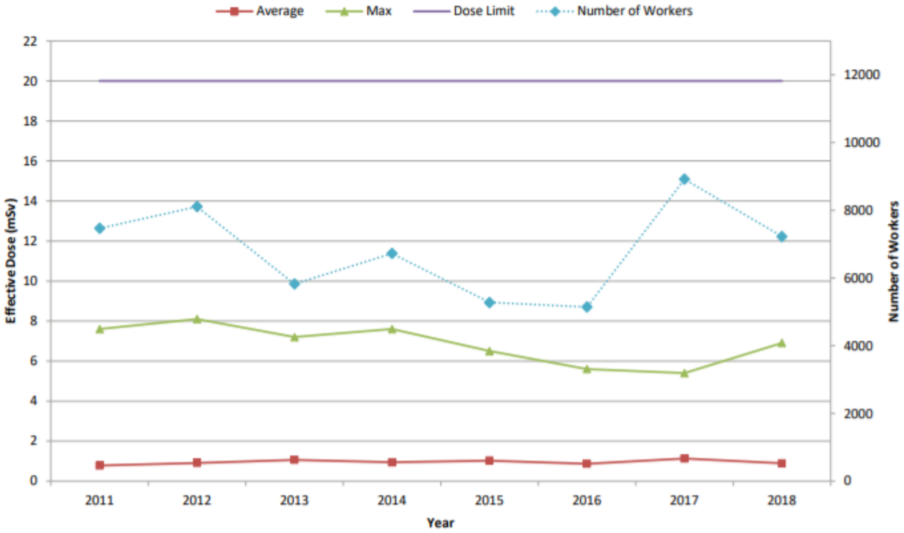

Figure 3.7: Australian uranium industry average and maximum effective doses with workforce numbers (2011–18). All workers record doses well below the regulatory limit. Source: ARPANSA[51].

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[51] *Australian Nuclear Radiation Dose Register in Review*, Australian Radiation Protection and Nuclear Safety Agency (2019)

It should be noted that radiological impacts are not limited only to mining for nuclear energy, given that rare earth elements (a critical input into wind and solar power) almost always geologically/mineralogically occur in the same ore bodies as uranium and thorium which are usually discarded as waste products. In some instances coal deposits also occur with uranium, for example the Springbok Flats in South Africa, and the uranium must either be recovered or discarded.

This was only a small part of the very broad theme of the environmental impact of uranium mining and its evaluation. This issue is dealt with in more detail by other publications, including those produced by OECD NEA, the IAEA [52] [53] and other authorities.

3.4 Establishing the legal and regulatory framework

Developing an effective nuclear legal and regulatory framework is critical to the success of any emerging civilian nuclear power program as it directly impacts the structure and trajectory of that program. An effective regime will ensure nuclear activities are conducted in accordance with the highest standards of safety and security, thereby providing assurance to the international community and supporting public confidence in the role of nuclear power as a sustainable addition to the energy mix. An effective regime should also be tailored to the particular goals and needs of the emerging nuclear state - ensuring the observance of the highest safety, security and safeguards standards while instilling efficiency in the nuclear power plant development, licensing and oversight process.

There are several key actions that an emerging nuclear state must make in establishing an effective nuclear legal and regulatory regime:

- **Government support.** Ensure that government institutions involved in the decision-making process understand the necessity and importance of the establishment of a nuclear legal and regulatory framework as part and parcel of the development of the state’s nuclear power program. Frequently institutions will need to be restructured to be able to perform their duties in a competent manner. For example, the nuclear regulator may need to be expanded and availed of more resources.
- **International treaties/conventions.** Understand the scope of international nuclear safety, security, safeguards and liability conventions and any obligation under them. Establish a plan and a timeline to adhere to these conventions.
- **Bilateral treaties.** Negotiate and enter into bilateral cooperation agreements with potential fuel and technology supplier states.

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[52] *Lessons Learned from Environmental Remediation Programmes*, Nuclear Energy Series No. NW-T-3.6, IAEA (2014)
[53] *Best Practice in Environmental Management of Uranium Mining*, Nuclear Energy Series No. NF-T-1.2, IAEA (2010)

- **Domestic law.** Pass a comprehensive law governing all aspects of regulatory control over the development and use of nuclear power, including establishing an independent regulatory body as well as implementing treaty obligations.
- **Regulatory framework.** Establish or reform the regulatory body and provide it with adequate resources to develop and implement the regulatory framework; including developing and promulgating a regulatory system for licensing, inspection and enforcement.

States embarking upon the development of a nuclear legal and regulatory framework have access to a significant number of resources to help guide them. For example, the IAEA has published handbooks on nuclear law with explanations and model provisions that provide guidance in the development of the necessary legal framework[54] [55]. They can also look to states with established nuclear programs as benchmarks for the best way to proceed.

Further, states can and should consider seeking outside assistance in this area. Nuclear law and regulation are highly specialized areas of expertise. There are complex obligations arising out of the adherence to international treaties, and there are many lessons learned from mature regimes with no “one size fits all” approach to developing and implementing a nuclear legal and regulatory framework. For these reasons, emerging nuclear nations should seek the input from legal, legislative and technical professionals in the areas of nuclear law and nuclear energy, including seasoned outside consultants where internal resources are not available.

Because of the complexity of the subject matter, rather than attempt to provide a comprehensive review of all major international legal instruments and aspects of a domestic regime; the following provides an overview of the major elements of the national legal framework and the major policy considerations a state must address in implementing an effective nuclear legal regime.

3.4.1 Description of major International legal instruments

One of the first steps in establishing its nuclear legal framework is for a state to take steps to become a party to certain international legal instruments that govern nuclear-related activities. Some of these instruments a state may already be adhering to, such as the Treaty on the Non-Proliferation of Nuclear Weapons. Others, like nuclear liability conventions, may require policy choices the state has not previously confronted. Adherence to key nuclear safety, security and liability conventions and the conclusion of safeguards agreements is crucial to the acceptance of a state’s nuclear power program by the global community, neighbouring states and its own institutions and citizens. Adherence to many of these treaties is also a prerequisite for an emerging nuclear country to secure a supply of nuclear material, equipment and technology from supplier countries. Detailed guidance on the development of the necessary legal

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[54] *Governmental, Legal and Regulatory Framework for Safety* IAEA (2016) https://www.iaea.org/publications/10883/governmental-legal-and-regulatory-framework-for-safety

[55] *Handbook on Nuclear Law: Implementing Legislation*, IAEA (2010)

framework are provided in IAEA publications. Some of the major international legal instruments are described below.

Convention on Nuclear Safety (CNS) (IAEA): The CNS, which was adopted in 1994 and entered into force in 1996, is the first legally binding and multilateral treaty to address the safety of nuclear installations. It aims to achieve a high level of nuclear safety worldwide by establishing and maintaining an effective defense against potential radiological hazards and accidents. The CNS applies to the safety of all nuclear installations with the exception of research reactors. Each contracting party to the CNS is required, inter alia, to: establish and maintain a legislative and regulatory framework, to ensure that on-site and off-site emergency plans are in place and routinely tested, and to ensure that siting, design, construction and operation of a nuclear installation are in accordance with certain obligations. In addition, the CNS establishes a "peer review mechanism", which means that each contracting party is required to submit a national report on the measures it has taken to implement its CNS obligations. Meetings are held for the purpose of reviewing national reports at least every three years.

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (IAEA)

The Joint Convention, which entered into force in 2001, is the only international legally binding instrument to address, on a global scale, the safety of spent fuel and radioactive waste management. The Joint Convention has a similar form and structure to the CNS, hence is sometimes referred to as its 'sister' convention. However, the scope of application of the Joint Convention is broader and applies to spent fuel from any nuclear reactor as well as radioactive waste from all civilian applications of nuclear energy – including radioisotope sources and certain discharges. The Joint Convention aims to ensure that the benefits created from using nuclear technologies today does not leave an unmanageable burden for future generations to deal with. Specific provisions cover transboundary movement and disused sealed sources. The Joint Convention also applies the same peer review mechanism as the CNS.

The Convention on Physical Protection of Nuclear Material (CPPNM) (IAEA): The original CPPNM, which entered into force in 1987, was a multilateral treaty that set levels of physical protection for nuclear material used in peaceful purposes during international transport and established a general framework for cooperation among parties in the protection, recovery, and return of unlawfully taken nuclear material. It also required parties to make punishable certain serious offences involving nuclear material and to either prosecute or extradite alleged offenders. An amendment to the CPPNM, which entered into force in May 2016, extends the scope of the original convention to cover physical protection of nuclear facilities and nuclear material used for peaceful purposes during use, storage and transport. It also adds criminal offenses related to the illicit trafficking of nuclear material and the sabotage of a nuclear facility, as well as providing strengthened international co-operation, such as assistance and information sharing in the case of sabotage.

Convention on Early Notification of Nuclear Accident (NOT) (IAEA): The NOT, which was adopted right after the Chernobyl accident in 1986, aims to strengthen the international response to nuclear accidents by providing a mechanism for rapid information exchange in order to minimize transboundary radiological consequences. The NOT applies in the event of any accident involving specified facilities or activities of a contracting party from which a release of radioactive material occurs, or is likely to occur, and which has resulted in or may result in an international transboundary release that could significantly affect another contracting party. In the event of such an accident, each contracting party is required to notify affected contracting parties as well as the IAEA, and to provide them with relevant information that could help minimize radiological consequences.

Convention on Assistance in the case of a Nuclear Accident or Radiological Emergency (ASSIST) (IAEA): ASSIST, which was also adopted in 1986, aims to strengthen the international response to nuclear accidents and radiological emergencies, including terrorist attacks or other malicious acts, by providing a mutual assistance mechanism with a view to minimizing consequences and protecting life, property and the environment from harmful effects. In the event of such an incident, a contracting party may request assistance from any other contracting party directly or through the IAEA and specify the type and scope of assistance needed. The IAEA has a key role regarding the facilitation of the requested assistance.

The Treaty on the Non-Proliferation of Nuclear Weapons (NPT): The NPT establishes a robust international legal regime aimed at preventing the spread of nuclear weapons, promoting nuclear cooperation, and furthering nuclear disarmament. Most relevant here, the NPT requires all non-nuclear weapon state parties to enter into a comprehensive safeguards agreement (CSA) with the IAEA which allow the IAEA to verify the state's compliance with their non-proliferation undertakings under the Treaty. States with minimal nuclear programs may enter into a Small Quantities Protocol (SQP), which holds in abeyance or suspends the implementation of several safeguards procedures for as long as the state meets certain eligibility criteria. Once a state ceases to meet the eligibility criteria (e.g. it decides to construct or to authorize the construction of a facility, or increases its holdings of nuclear material beyond specified quantities) the SQP will become non-operational and all safeguards procedures in the CSA will be implemented. The state will be also asked by the IAEA to rescind its SQP.

The Additional Protocol (AP) (IAEA): The AP provides the IAEA with greater access to information and locations inside states with CSAs. The measures provided for under the AP significantly increase the IAEA's ability to verify the peaceful use of all nuclear material. While states may decide voluntarily to conclude APs to their safeguards agreements, the AP is generally considered the current verification standard for non-weapon state parties to the NPT. In addition, some nuclear supplier states have called for the AP's universal adoption. Nuclear newcomers should therefore strongly consider whether to conclude an AP along with their

CSAs, as some nuclear supplier states may be less willing to engage in nuclear cooperation and trade with a state which has not done so.

Espoo Convention (UNECE): The UNECE Espoo (Environmental Impact Assessment) Convention sets out the obligations of Parties to assess the environmental impact of certain activities at an early stage of planning. It also lays down the general obligation of states to notify and consult each other on all major projects under consideration that are likely to have a significant adverse environmental impact across boundaries. The Convention was adopted in 1991 and entered into force on 10 September 1997.

Aarhus Convention (UNECE): The UNECE Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters was adopted on 25th June 1998 in the Danish city of Aarhus at the Fourth Ministerial Conference in the 'Environment for Europe' process. Together with its Protocol on Pollutant Release and Transfer Registers, it protects every person's right to live in an environment adequate to their health and well-being. They are the only global legally binding global instruments on environmental democracy that put Principle 10 of the Rio Declaration on Environment and Development in practice. The Convention grants the public rights and imposes on parties and public authorities obligations regarding access to information and public participation and access to justice.

Nuclear Liability Regime: The international nuclear liability regime consists of a number of multilateral treaties, including the Paris Convention on Third Party Liability in the Field of Nuclear Energy together with the supplementary Brussels Convention, the Vienna Convention on Civil Liability for Nuclear Damage and its 1998 amending Protocol, and the Convention on Supplementary Compensation for Nuclear Damage (CSC). The Paris Convention and the Vienna Convention are also linked through a Joint Protocol adopted in 1988 while the CSC aims at serving as an "umbrella" convention for states party to either the Paris or the Vienna Convention and States party to neither. The choice of which conventions to join is somewhat dependent on where a state is located and is influenced by certain other policy choices as well as the conventions its neighbours have joined. However, it is worth noting that, under the IAEA Action Plan on Nuclear Safety, the IAEA International Expert Group on Nuclear Liability (INLEX) has recommended that states with nuclear installations should "strive to establish treaty relations with as many states as practicable, with a view to achieving a global nuclear liability regime that establishes treaty relations among all states."

All of these conventions share the following basic principles:

- The operator of a nuclear installation is exclusively liable for nuclear damage.
- Strict (no fault) liability is imposed on the operator.
- Liability may be limited in amount and also time.

- Operators are required to maintain an adequate amount of insurance or other financial security;
- Beyond the operator’s liability coverage as provided by insurance or other financial security, additional compensation may be drawn from supplementary state contributions where available.
- Claims must be treated in a non-discriminatory manner, irrespective of the nationality, domicile or residence of the claimants.
- Exclusive jurisdiction is granted to the courts of one state party, to the exclusion of the courts in other states parties.

Joining and implementing one or more nuclear liability conventions is vital to the success of a state’s nuclear programme. One of the main functions of the international nuclear liability regime is to ensure legal certainty in the event of a nuclear incident and build confidence with the public and the international community. By ensuring that people injured by a nuclear incident will be compensated, a nuclear liability regime helps build public trust. Further, the liability conventions protect vendors of nuclear facilities by channelling liability to the operator and capping liability. Without such protection, the risk for any vendor would be too high, as even a supplier of a relatively minor component could, in the event of an accident, be subject to almost unlimited liability. Absent adequate liability laws, certain nuclear suppliers may refuse to do business with a state, thus hampering the program’s effectiveness. Due to the commercial importance of liability conventions, special attention should be given to their correct implementation within the state’s domestic legal order.

3.4.2 Bilateral Nuclear Cooperation Agreements

Bilateral agreements for peaceful nuclear cooperation (NCAs) are legally binding agreements between two states or a state and an international body (e.g. the EURATOM Supply Agency) that establish the conditions and outline the process for significant cooperation in the field of nuclear energy. Importantly, NCAs serve as part and parcel of the international nuclear non-proliferation and export control regime. Typically, NCAs will include provisions that follow the language or substance of the key tenets of the Nuclear Suppliers Group’s “Guidelines for Nuclear Transfers” (NSG Part 1 Guidelines), such as the prohibition on the manufacture of nuclear weapons or other nuclear explosive devices, physical protection requirements, safeguards and controls on retransfer, enrichment, reprocessing and other activities.

NCAs can play a significant role in shaping a new-build nuclear project in an emerging market. Many supplier states, such as the United States, Canada, Australia, and Japan, are required by their domestic legislation to have in place an NCA with the state receiving certain nuclear materials, reactors, and equipment from that supplier state before a regulator in the supplier state can issue a license to export or re-export it. Further, domestic legislation often requires the NCAs to include certain nonproliferation criteria, thereby limiting a government’s flexibility to negotiate NCA provisions. Other states may not have a legal requirement to enter into an NCA with a customer country but do so as a matter of policy.

In today's global nuclear market, reactors, equipment and fuel (including various fuel components) may need to be sourced from suppliers in different countries. A host country's ability to exercise flexibility in its procurement strategy is in many ways dependent on whether it has in place NCAs with all of the key supplier states. Further, an NCA may support the export of nuclear technical assistance and services, such as engineering, project management and construction works. A host government may find that it is unable to source a critical component or secure assistance from top nuclear engineering firms without an NCA in place. Since NCAs may take months or even years to negotiate, planning ahead is key.

Accordingly, governments in newcomer countries should develop at the earliest stage of planning for their civilian nuclear power programme a matrix of all potential NCAs that may be required to achieve its program goals and a schedule to negotiate and execute those NCAs. Further, although many NCAs contain similar provisions, each NCA is different and is negotiated on a case-by-case basis. Since NCAs are long-term agreements (typically 20-30 years), these obligations can shape a nuclear program not only in the short term but for decades to come.

The most consequential obligations in NCAs are usually supplier state consent rights for activities such as retransfers of nuclear material, equipment and technology and fuel cycle activities. In negotiating and entering into NCAs, nuclear newcomer countries need to understand the obligations contained in the NCAs, the legal basis of these obligations (law or policy) and the consequences of accepting such obligations. An informed approach will allow for the host country to negotiate NCAs that support the key goals and objectives of its civilian nuclear power program.

3.4.3 Domestic law and policy considerations

A state's domestic nuclear legislation creates the framework in which a nascent nuclear industry will grow, and therefore impacts the viability of a state's nuclear program. For example, by defining the stages of the licensing process and what participatory rights the public may be afforded the legal framework will affect both the schedule of nuclear projects and public confidence in them. While there are benefits if a state can harmonize its nuclear laws to those of other countries, a state's nuclear law must fit within its overall legal structure, so there is no "one size fits all" approach.

The legal framework should both set out the internationally accepted principles of a civilian nuclear power program as well as provide the structure and responsibilities of an independent Nuclear Regulatory Body (NRB). Some states choose to adopt a single comprehensive nuclear law or act establishing the NRB and covering all relevant areas – including safety, security, safeguards and liability. Other states choose to adopt a separate nuclear liability law. Whichever approach is taken the NRB should be assigned clear legal authority and provided with adequate funding and staffing to carry out its responsibilities. A state must make sure that the NRB is functionally independent of other entities with stakes in the nuclear program. The possibility that these entities could influence the NRB's decisions can undermine public confidence in a nuclear energy program. The NRB should not itself be seen as promoting or advocating for the program, but instead as solely concerned with ensuring that the program is conducted in compliance with legislative and regulatory requirements.

In preparing such legislation, care should be taken to avoid any inconsistencies with existing laws. The legislation should be comprehensive; sections of the legislation should reference each other where appropriate, and also provide references to other legislation and international agreements, guidance, and codes. Also, any other legislation that affects the nuclear power programme should be assessed, and revised or adopted if necessary. This includes legislation in areas like protection of intellectual property, environment, foreign investment, procurement, etc. In general, the nuclear legislation should include all the elements indicated in the accompanying box.

The licensing process for a nuclear installation will normally include the following steps, depending on national legislation: siting and site evaluation, design, construction, commissioning, operation, decommissioning. Depending on the national legislative framework, each step of the licensing process may be divided into several sub-steps or may be merged or combined as appropriate to facilitate the regulatory process. Reactor technology licensing is discussed separately in chapter 6.

Site licensing processes utilized by regulatory authorities can be generally classified into two categories: the two-step process and the one-step process. It is important to note that both processes are viable options for a state and will yield similar results – the licensing of new nuclear power facilities through an internationally acceptable means.

The two-step licensing process involves a Construction Permit (CP) and an Operating License (OL). Under this process, the NRB initially reviews the safety of the preliminary plant design and the suitability of the prospective site and, if satisfied, issues a CP that allows the applicant to begin building the nuclear power plant. Once the applicant has the CP, it applies for an OL, which the regulatory authority issues only if all safety and environmental requirements are met. There are several benefits to utilizing this process. First, it allows for swift licensing of construction activities because operating issues such as training programs and operator qualification are not assessed at this stage. Second, it would allow the NRB more time to develop its licensing process. Finally, the process allows for review of designs that are not yet finalized. However, one disadvantage of two-step licensing is that the NRB's regulatory standards may evolve once the CL is granted, causing uncertainty for the applicant during the construction process and before the OL is issued. Another downside is that, by its nature, the two-step process is prolonged because it requires the NRB to conduct two separate, in-depth technical evaluations of the application.

What's in a nuclear energy act?

- Purpose and principles: The overarching purpose of the legislation is to provide a legal framework for conducting activities related to nuclear energy and ionizing radiation in a manner that adequately protects individuals, property and the environment. The legislation should uphold the following internationally accepted principles of nuclear law:
    - Nuclear safety: This principle promotes the exercise of caution and foresight to prevent nuclear and radiation incidents or limit their consequences.
    - Nuclear security. This principle addresses the need to account for and protect nuclear material and technologies in order to prevent their incidental or intentional diversion from legitimate uses.
    - Transparency. The agencies and organizations involved in the development, use, and regulation of nuclear energy should make public all relevant information about activities that could have an impact on public health, safety, and the environment.
    - Independence. The NRB must have the independence to make decisions on safety issues without the interference of entities, whether public or private, involved in the development or promotion of nuclear energy.
    - Operator responsibility. This is the notion that the operator or licensee should be primarily responsible for ensuring that its activities meet with applicable safety, security, and environmental protection requirements.
- Terminology: The legislation should adopt clear and consistent definitions and technical terminology commonly understood in the international nuclear energy community.
- Organization, responsibilities and tasks of the NRB: The legislation should clearly define the NRB's organization, chief responsibilities and tasks, including:
    - Authority to promulgate regulations and guidelines.
    - Authority to make regulatory decisions including licensing.
    - Provisions ensuring the independence of the NRB.
    - Authority of the NRB to establish and conduct a systematic inspection programme.
    - Authority to draft, issue, and enforce regulations, including the authority to levy fines and penalties for noncompliance.
    - Participation in the activities of IAEA and other international safety, safeguards or regulatory organizations.
- Implementation of international obligations: The legislation should implement the state's obligations under the international agreements discussed above.
- Licensing process requirements: The legislation should provide an overview of the requirements of the licensing process.

- Inspections and enforcement process requirements: The legislation should discuss the purpose and scope of inspections and enforcement activities and set out the operator or licensee responsibilities concerning these activities.
- Nuclear safety: The concept of nuclear safety has two chief goals: radiation protection and technical safety. The achievement of these goals in the design, site evaluation, construction and operation of nuclear power facilities should be discussed in the legislation. The legislation should discuss policy and practices for ensuring that all practicable measures are taken to prevent incidents and, if incidents occur, mitigate their consequences.
- Waste management and decommissioning: The legislation should set out a comprehensive policy for radioactive waste management.
- Transport: The legislation should provide for NRB to issue authorizations for the transport of radioactive material.
- Export and import controls: the export and import control provisions will be one of the most important aspects of the legislation, as their implementation will be under the scrutiny of international organizations, foreign governments, and the public in ensuring that nuclear material, equipment, and technology are not diverted to prohibited activities. The legislation should set out simple but comprehensive provisions on the licensing and control of nuclear material, equipment and technology, in keeping with international standards. In particular, the provisions should take into account the requirements established by the CPPNM and its amendment along with the Code of Conduct and the Guidelines, and the Zangger Committee and Nuclear Suppliers Group guidelines. The legislation should give the NRB the authority to create and develop an export control system and to define the authority of other ministerial/national agencies in the sphere of export controls. It should also generally define the items subject to export control and specifically state which nuclear items exported must be subject to IAEA safeguards in the importing state.
- Licensee responsibilities and obligations: The legislation should set out the general responsibilities and obligations of licensees with regard to: nuclear safety and security; non-proliferation; and management and disposal of spent fuel and radioactive waste and decommissioning of nuclear facilities, including coverage of future costs.

Finally, the two-step process allows for more potential delays due to the possibility of public hearings during each stage of the license approval.

The one-step process provides for the issuance by the regulatory authority of a combined Construction and Operating License (COL). A COL authorizes the construction and conditional operation of a nuclear power plant. Granting a COL signifies a resolution of all safety issues associated with the plant. This process developed along with the standardization of designs and is considered by many to represent an improved, more efficient, licensing structure. It is a process utilized by several regulatory authorities, such as the United States Nuclear Regulatory Commission (NRC), the Canadian Nuclear Safety Commission (CNSC), the United Kingdom's Office of Nuclear Regulation (ONR), and the Swiss Federal Office of Energy.

The one-step process has several advantages. First, it can potentially shorten the regulatory timeline by combining the two licenses into one. Second, it provides greater efficiency in the licensee's preparation and the regulator's review of the licensee's application by setting out from the beginning the rules and processes needed to obtain a license for a nuclear power plant. Third, the one-step process reduces the regulatory risk and affords certainty for the applicant by issuing the license before the major construction of the plant begins. Fourth, the process provides for further efficiency by allowing the applicant to resolve site-specific issues and to begin certain pre-construction activities prior to COL approval through the use of optional early site permit or limited work authorization processes.

On the other hand, the one-step process involves a prolonged period before the combined license can be issued. Further, changes in design during construction may be subject to license amendments and an additional review of the conformity of the unit to regulatory standards is required prior to the operating license being issued. Finally, choosing the one-step process gives NRBs in emerging countries less time to develop the licensing process and pass implementing regulations. Table 3.3 compares the two processes.

Table 3.3 Comparison of the one-step and two-step licensing process.

Process	Advantages	Disadvantages
Two-Step	• Allows for swift licensing of construction activities • Allows review of designs that are not finalized • Allows regulators in emerging countries more time to develop their licensing process	• May be prolonged because the regulator conducts two separate, in-depth technical evaluations of the application • More opportunities for a delay due to public hearings • For emerging countries, regulatory standards may evolve once CL is granted
One-Step	• Shortens regulatory timeline (in theory) • Most public hearings conducted before the start of construction • Greater efficiency and certainty -- sets out rules and processes needed to obtain a license for a nuclear power plant • Reduces regulatory risk for the applicant because license is issued before major construction of the plant begins	• Prolonged process for obtaining a license to commence construction • Changes in design during construction may be subject to license amendments • Additional review required prior to the operating license being issued • Not as well-tested as the two-step process • In emerging countries, regulators have less time to develop the licensing process

3.5 Economics and project financing

Despite the increased interest in nuclear, notably from China, India, Russia, South America, the Middle East and Africa, there remains a market challenge in getting technologies and projects to commercial delivery, and in particular in securing sufficient private sector financing for projects. This section explores how countries – particularly newcomers – can overcome this challenge and acquire new, low-carbon flexible nuclear power plants.

3.5.1 The nuclear project lifecycle

There are three distinct and different phases in taking a reactor technology concept through the design phase into manufacturing and ultimately selling the technology to an energy/ infrastructure project and having the technology commercially deployed. These are:

- Technology development: taking a concept, evaluating its feasibility and developing a product);
- Manufacturing development: building a supply chain and/or manufacturing facility to build the product;
- Nuclear project development: building a commercial nuclear power plant.

The main focus of this section is Nuclear Project Development. The company established to develop the nuclear power project and be the owner of the nuclear power project is often the key player. This entity is often established as a special purpose vehicle (SPV). The SPV will procure the technology (i.e. be the customer to the technology vendor), undertake development work such as obtaining permits and planning approvals and raise any finance required. This entity may also be the site licensee company (the holder of the nuclear license) and therefore also responsible for nuclear safety, security and safeguarding on the nuclear site. This entity may also be the operator of the nuclear facility once built. The IAEA provides more details of roles and responsibilities of different entities[56]

The lifecycle of a nuclear power project has four phases: development, construction, operation and decommissioning. Each of these presents different financing challenges, as described below.

Development

This is the period from project inception to financial close. During this time, the following major activities will be undertaken:

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[56] *Initiating Nuclear Power Programmes: Responsibilities and Capabilities of Owners and Operators*, IAEA (2020)

- The development organization will be established, design and recruitment will take place.
- Shareholders will be brought in to meet the development costs and the equity share of the construction and operation costs.
- The project will be structured, including establishing how nuclear regulatory obligations will be met during construction, operation and decommissioning.
- Technology will be chosen, a contractual matrix will be established, and all the major contracts such as the EPC, long term supply agreement, fuel supply agreement, operation and maintenance agreements etc. will be negotiated and finalized.
- Environmental impact assessments and other nuclear assessments will be undertaken.
- The required land will be acquired.
- Permits, planning permissions and licences (nuclear and other) will be applied for and secured.
- Operational processes and procedures will be determined.
- Front end engineering work and site assessments may be undertaken.
- Any off-take arrangements such as power purchase agreements, contracts for difference or regulated asset base agreements will be negotiated.
- Debt finance will be raised, secured and the agreements entered into.
- Works for additional infrastructure including roads, rail and grid connections, will be agreed.

The costs of developing a nuclear power project can be over one billion dollars and there is no guarantee that these projects will go ahead (compare with around 40 million dollars for a non-nuclear energy project). These development costs can be reduced with assistance from governments – for example by providing land for free and making regulation predictable and transparent. This is especially true for newcomer countries.

However, a developer can also bring down those costs by making sure they understand what is required at this stage and realizing that nuclear compliance is limited at this stage. Further, newcomer companies should develop an established technology with experienced companies. Developing a first-of-a-kind (FOAK) technology comes with additional risks which it would be best for newcomer companies to avoid. Even where a technology is established internationally, merely being the first example in a given country can add significant additional risk and be costly and therefore, assistance from the country of origin can be invaluable.

Due to the uncertainty, investors who come into a project at this stage tend to either be high net worth individuals (although few would support the full development costs of a project) or those who already understand the market and are happy to invest in the development and, probably, the construction phase, e.g. governments, utilities, corporates, technology vendors (if large enough). For newcomer countries, government involvement is unavoidable if the project is to happen.

Construction

Once the project structure is agreed, the land is acquired, permits and licenses are obtained, early engineering is completed (including the site design), the contracts are all signed and all the money is raised, a nuclear power project can move into the construction phase. Depending on the technology selected, the amount of on-site construction will vary. On-site construction brings with it increased risks of cost overruns and delays to the project.

The other inherent risk of any power project is around commissioning: will commissioning go according to plan and will the plant deliver the contracted volume of power as anticipated.

Equity can be particularly hard to find for the construction phase due to the large capex involved in classic nuclear projects. This is especially true for FOAK projects or FOAK-in-country projects where the risks are not yet fully understood. As such, there may be a role for the government in taking an equity stake to help build trust and confidence in the market and thereby de-risking projects, especially FOAK projects and those in newcomer countries. Debt may be able to be easier to secure depending on the project structure once the equity is secured. Export Credit Agencies may be brought in to support exports from other countries; however, this is often at odds with localization and domestic content. Different financial models are discussed in more detail further down.

Operation

Once the plant is operational the risk profile of the plant shifts dramatically and the project is far less risky, therefore opening up the options for refinancing, if needed.

At this stage most of the risks are held by the nuclear power company, the company that holds the nuclear license (this may be the owner or a separate company), the company that will operate the nuclear facility (this may be the owner, the company that holds the nuclear license or a separate company) and the supply chain. The interaction between the different companies will require specialist advice for each specific project. There is however a role for government to minimize risks associated with potential change of law and regulation, changes in international standards (within limits) and backstopping risk around third-party liability and waste management costs.

Once operational the financial challenges are severely reduced as the risks of costs overruns and delays are gone. At this stage the power project should be able to attract cheaper long-term financing. Refinancing should be much easier. However, if government support mechanisms have been used to assist with the construction, consideration will need to be given to how these should change if there is a refinancing. If governments have provided equity or debt for the construction phase, then they may want to exit on refinancing.

Decommissioning

The lessons that have been learnt from legacy plants in the USA, the UK and elsewhere is that the detailed plan for how to decommission the plant and to manage associated nuclear waste has to be in place before construction of a new plant starts. Further, there are benefits in building up, starting from the beginning of operations a decommissioning and waste management fund to meet those end-of-life liabilities. The costs of decommissioning and waste management can then be built into the electricity price rather than having to be found from elsewhere. The costs of decommissioning and waste management are small compared with the initial capital costs for a plant. Because of the effect of discounting, building those costs into the economics has very little impact on the total costs of generation. Decommissioning is discussed further in chapter 4.

3.5.2 Levelized costs of nuclear energy

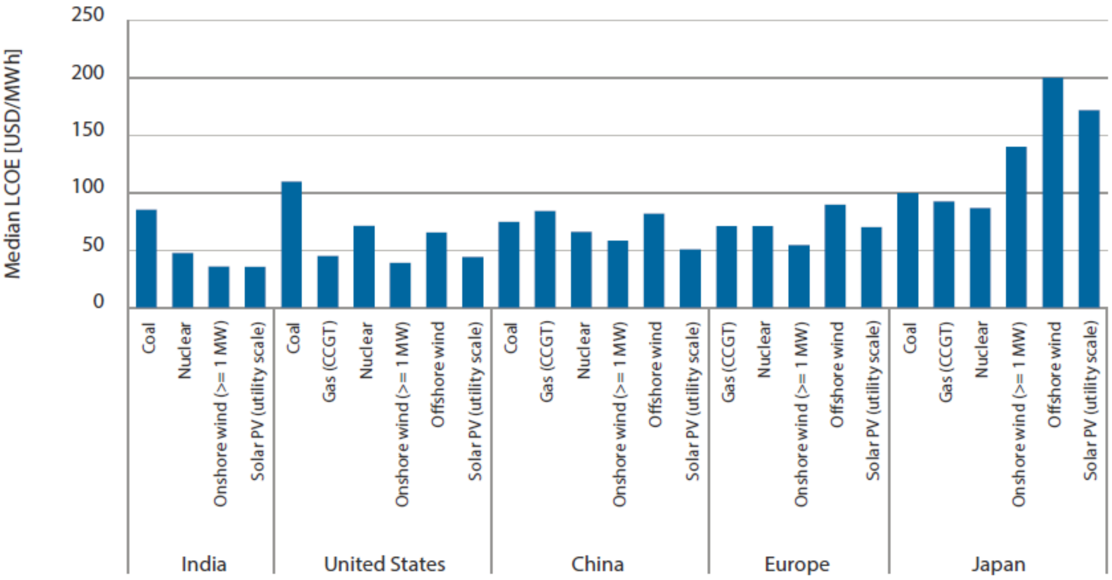
The costs of nuclear power projects development are very project-specific. Project development costs can vary widely due to a whole range of factors including the extent to which governments are involved, regulatory regimes both nuclear and non-nuclear, person-hour costs, fuel costs, reactor technology, overnight costs and cost of capital, risk allocation (between the vendor, investor, government) and also a country's credit rating. Many of these factors are country specific, meaning that nuclear project costs tend to vary significantly by country as shown in Figure 3.4. All development costs, construction costs, operating costs and decommissioning costs need to be included in any calculation to determine the full project costs and therefore, any reasonable price for the sale of electricity from the plant.

One way of assessing nuclear against other technologies is to consider the levelized cost of electricity (LCOE) in each country. This LCOE represents the cost per unit of energy production that would be required by a project developer/owner to recover all cost incurred during the lifetime of the plant (investment, operation, waste management and decommissioning). The LCOE is expressed as £/MWh or $/MWh etc., where megawatt-hours (MWh) is a common unit of electricity. The cost in the calculation includes the capex of a project as a whole, the cost of capital, fixed charges including tax and depreciation, operating and maintenance costs, decommissioning costs (which is often omitted for technologies other than nuclear) and fuel costs.

LCOE is calculated by summing all plant-level costs (investments, fuel, emissions, operation and maintenance, dismantling, etc.) and dividing them by the amount of electricity the plant will produce, after an appropriate discounting. The LCOE represents the average lifetime cost for providing a unit of output for a given capacity factor, often the average capacity factor achievable by the power plant.

The levelized cost estimates presented in figure 3.8 are based on a large nuclear plant utilizing currently available technology. There is insufficient data in the market available to confidently assess the LCOE of the small modular reactors (SMRs) that are being developed. However, the

Canadian government commissioned the Canadian Small Modular Reactor Roadmap[57]. This report contains the predictions of LCOE costs for SMRs against natural gas hydro and wind. As can be seen in Figure 3.9 the expectation is that small nuclear will be competitive against these technologies.



Note: Values at 7% discount rate.

Figure 3.8 Projected costs of energy technologies by country (2020). Data source IEA[58].

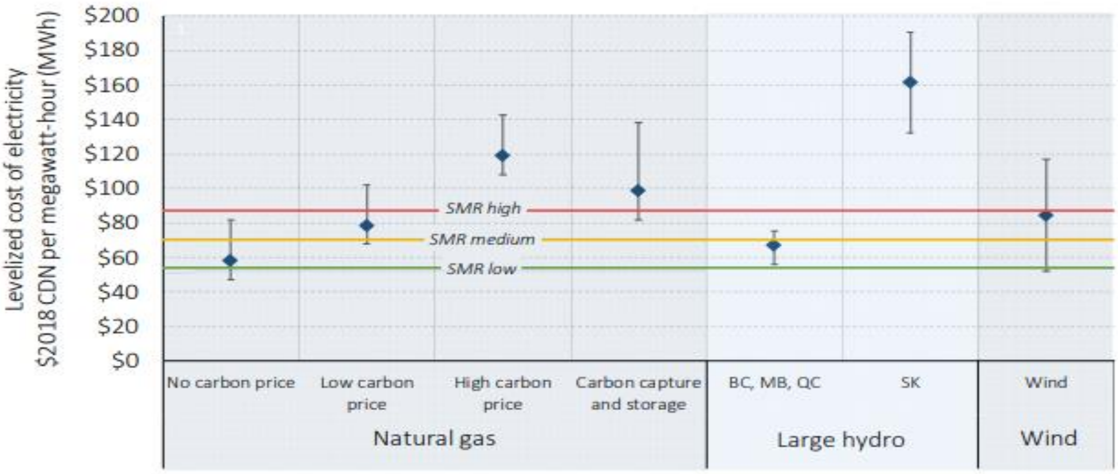


Figure 3.9 Projected LCOE costs (CDN) for SMRs compared to other options in Canada. This is considered the best case – with a 6 percent discount rate and the use of more innovative technology. Low, medium and high reflects the different capital. cost estimates. BC: British Columbia, MB: Manitoba, QC: Quebec, SK: Saskatchewan. Source: Canadian Small Modular Reactor Roadmap

While LCOE is a good way of assessing different technologies, it should not be the only assessment undertaken when either designing an energy system or considering the application of technologies. For example, when designing a power system a country also needs to consider

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[57] *A Call to Action: A Canadian Roadmap for Small Modular Reactors*, Natural Resources Canada (2018)

[58] *Projected Costs of Generating Electricity*, IEA and OECD NEA (2020)

the costs of firm power versus intermittent power, including additional costs that are incurred in balancing intermittent power sources and grid expansion. The effort required to ensure the necessary tight frequency stability of the system is often underestimated.

The Massachusetts Institute of Technology (MIT) has published comprehensive studies that analyze at a country level the costs implication for an electric system when looking at partial or complete decarbonization of the system[59]. More recently, OECD-NEA published a study on system costs, based on a greenfield approach which may prove of interest for developing countries[60]. These costs are difficult to allocate and have to be supported by energy consumers. When the share of intermittent renewable in a system increases above 30 percent of generation, the system costs will increase significantly.

Consideration also needs to be given to wider impacts for a country of low-carbon power development including social benefits of different technologies, the impact on wider policy objectives including climate change net-zero climate emissions, localization policies and industrial strategies. The LCOE of a particular technology may be less relevant if that technology allows industry to keep working and allows a country to meet its climate change objectives. In the last few years, there has been growing recognition among energy experts and policy makers of the need to move beyond LCOE calculations and to start looking at VALCOE – or the value adjusted levelized cost of energy – in order to deliver wider objectives such as decarbonization and the SDGs.

3.5.3 Financial models and funding support mechanisms

Historically governments funded a country's nuclear power programmes. However, with the evolution of markets, new entrants, constraints on governments' balance sheets, and policy decisions indicating the private sector should be responsible for new build and other developments, the nuclear industry has had to develop new ways of financing nuclear plants.

For the last ten years the nuclear community has been discussing the methods used around the world to finance new nuclear projects. These are discussed below. No matter which method or combination of methods is adopted, it is clear that government involvement - including funding and any financing support - is key to the success or failure of the project.

Government Financing

This structure is where a government finances a project (often providing 100 percent of the financing). This typically reduces the cost of capital compared to other financing options and can greatly reduce LCOE. China and Russia are two countries who continue to support government financing of new build. Some countries will not support this approach on policy grounds; others because the country's balance sheet can't support it.

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[59] Sepulveda, Nestor A, *Decarbonization of Power Systems: analyzing different technological pathways*, (2016)

[60] *The cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables*, OECD-NEA (2019)

Build, own and operate
In many respects, this is often another form of government financing but rather than the host government financing the project the technology provider’s government provides all or a substantial part of the financing. The technology provider will then assemble a consortium largely from its own country to build, own and operate the new nuclear plant and the host country will pay for the plant through power-purchase agreements or similar support mechanisms. This was the structure proposed on the Akkuyu project in Turkey. This is a good option for newcomer countries whose sole objective is the production of power as this model effectively cedes control of the project to another country.

Exceltium
This was a financing structure established between 2005 and 2010 in France whereby several industrial investors and banks formed a limited liability company – Exceltium – that entered into contractual arrangements with EDF to finance nuclear new build. The banks are paid back from by EDF (its portfolio rather than simply the new build project. The industrial investors are repaid in electricity, which they can either use or sell.

Mankala
This is the financing structure that is used in the Finnish electricity sector. The Mankala company is a limited liability company making zero-profits where every aspect – cost, risk, taxes etc. - of the project is shared proportionately between the owners. The shareholders in the Mankala are usually high energy users. They bring financing to the project (corporate or project) to cover CapEx and OpEx and in return, have the right to the electricity.

Corporate balance sheet financing (developer equity):
A large developed corporation with a strong balance sheet (historically a utility but this is no longer necessarily the case) is required which can raise funds on its balance sheet rather than funds being raised on a project finance basis purely for the nuclear project development. Financing a nuclear power plant from a company's own resources is only an option for the largest utilities and developers. The cost of a large plant - with two or three reactors - is usually around US $20 billion or more. For even the largest and most established company, it's a huge challenge to carry such a large capital commitment for an average construction period of five to seven years before the plant starts producing revenue. The Hinkley Point C project is being developed in the UK by EDF and CGN.

Vendor equity.
In the late 2000s, it was recognized that reactor technology vendors might be able to support new build projects financially as well as technologically. This realization gave rise to vendor equity, which helps to finance a project in return for the vendor's technology being deployed in the new facility. However, technology vendors do not have the balance sheets needed to allow them to invest in unlimited projects or to provide the contingent equity required to cover

changes and delays. The industry has seen companies such as Westinghouse and Hitachi struggling with trying to provide equity to nuclear power projects. Investing in projects is not what these companies were established to do and attempting to do so can put a severe strain on the company. In reality, they will only invest in the most advanced projects that are likely to succeed, or which will allow them to receive a return on their investment in the shortest possible time, and provide an option to exit the project at the earliest possible opportunity. In the UAE on the Barakah project, KEPCO provided equity to the project.

Quasi limited recourse project financing with Export Credit Agencies debt financing:
While a full non-recourse/limited recourse financing for nuclear projects, is still some way off, commercial banks are becoming less reluctant to lend to nuclear projects, and the support of a number of the Export Credit Agencies (ECAs) has helped this shift to happen. ECAs have provided the backbone of debt lending to a number of projects in recent years through either direct or guaranteed lending to projects. The ‘catch’ is that the lending is offered to support the export of goods or services from the ECA's home country. The nuclear project that has come closest to a project finance solution is the Barakah project in United Arab Emirates where it is reported that the financing comprises direct loans of $19.6bn with $16.2bn from the UAE government and another $2.5 billion from the Export-Import Bank of Korea (KEXIM), equity commitments from ENEC and KEPCO totaling $4.7bn as well as a $250m loan provided by National Bank of Abu Dhabi, First Gulf Bank, HSBC and Standard Chartered.

The form of financing that is yet to appear on this list is limited recourse/ non-recourse project finance. A limited recourse (or non-recourse) project financial structure is where project debt and equity used to finance a project is paid back from the cash flow (or revenue) generated by the nuclear power project. This allows an organization to raise funds for a project based on its feasibility and its ability to generate revenue at such a level to cover: construction and operational costs, interest from debt service and a return to investors. Lenders have recourse to the assets themselves and revenue streams, but there is no or only limited recourse to the shareholders/ parent companies. No nuclear power project has been progressed on non-recourse or limited recourse finance basis.

Non-limited (or recourse) project finance, by contrast, gives lenders to the project full recourse to the assets/revenue stream of the shareholders for repayment of the loan. The trust and confidence required to attract this level of financing are still missing from the nuclear industry.

The key to making any of these financing structures work is the national framework and mechanisms that support the project. The host government has a significant role to play, including:

- Providing the policy framework for new nuclear.
- Providing concession agreements where appropriate.
- Assisting with wider stakeholder management and public confidence.

- Assisting with siting and planning.
- Being an insurer of last resort.
- Providing a government guarantee.
- Providing a funding support mechanism such as a power purchase agreement or a contract for difference.
- Providing a guaranteed rate of return to attract private funding such as a regulated asset base model.

Only once nuclear projects have become more mainstream and they are built regularly to time and budget, or the nuclear industry introduces products based on a modular approach, will non-recourse or limited recourse financing become available. However, financial markets will become more accepting of lending to nuclear projects which demonstrate clear government support, more transparency and the reduction of risks and costs. It is believed that SMRs, once commercialized, will make it easier to attract private investment as less capital is required. However this will only be possible once reference plants are constructed and successfully demonstrated.

3.5.4 Risks mitigation and management

Risk, and the allocation of risks to the party best able to manage them, is fundamental to contracting and to raising finance from anyone, but particularly the private sector. Rating agencies will consider the risks being borne by a project company to consider what rating to apply. The rating that is given will determine whether a project company can raise capital at all and, if so, the cost of that capital. Anything below BBB+ and the project company may be unable to raise private finance. A higher rating helps to improve the chances of financing and the terms on which the financing can be raised (including the cost of capital).

While risks should be borne by the party best able to manage them (assuming the party can bear the consequences of the risk), under traditional contracting structures, risks are generally allocated between the parties on a fairly binary basis; allocating risks entirely to one party or the other together with all of the cost and financial consequences of the risk. There is also a focus on the end goal – meeting the particular completion date and performance requirements rather than considering how to make the project as a whole a success.

Allocating risks and responsibility remains the focus of contracting and creating the environment for private finance into nuclear projects. However, much has been learned across the construction industry of sharing the consequences of the risks and encouraging all participants to cooperate in managing and mitigating risks. Working collaboratively, communicating and developing behaviour across the contracting structure to manage the consequences of risks reduces the costs associated with these projects. This is particularly important in newcomer countries lacking the experience to develop nuclear projects.

Evidence from recent nuclear projects in China, Korea, Russia and UAE highlight nuclear power plants can be built on time and budget, and at lower cost. The evidence from these successful projects suggests that design standardization and commitment to a programme with multi-unit and serial construction are critical to project success. A systematic and programmatic approach enables capability building and learning from experience, leading to reduction in risks and costs. Conversely, embarking on new nuclear projects after long hiatuses, as has been the case in Europe and the US in recent years, is likely to result in difficulties due to an atrophy of critical skills and eroded supply chains.

These Western countries are now moving beyond the challenges faced by First-Of-A-Kind (FOAK) projects and their nuclear construction industries have, in large part, regained their capabilities. With timely decisions for future projects there is the opportunity for the continuation of the process of learning by doing and for large-scale cost reduction in existing nuclear technologies. In addition, SMRs and some Gen-IV reactor systems are making steady progress with demonstration projects. Irrespective of the nuclear technology, securing affordable financing is critical for timely and cost-effective deployment. Government policy and the setting of an appropriate energy market framework will be indispensable for unlocking investment in nuclear energy infrastructure projects.

3.5.5 The bottom line

Nuclear energy is accepted in many countries as part of the solution to meet the growing need for clean energy and to address climate change. As new nuclear becomes more widespread, and as the industry expands its experience in delivering nuclear projects that are cheaper, less complex and take less time to develop, it will become easier to privately finance nuclear projects. There will always be a role for government in financing, as there is in any large infrastructure project, but that role evolves over the life of the programme. As newcomers consider subsequent projects, the number of financing options should increase.

Chapter 4: National and regional considerations

> *There are specific national and regional considerations that should be addressed when considering the development of a nuclear energy programme. These relate primarily to the nuclear fuel cycle and life cycle. There are many sustainable options for implementing a nuclear fuel cycle and waste management strategy. Countries should adopt strategies based on their needs and requirements (e.g. enhancing economic development and security of supply) as well as the presence of domestic mineral resources and technical capabilities and the economic opportunities they see in the different fuel cycle options. Holistic consideration of the fuel cycle - from uranium mining, and nuclear power generation to spent fuel and waste management - is key to its sustainable management and addressing nuclear energy within the framework of SDGs. Tailoring decisions to national requirements and regional considerations, with a vision of "think globally, act locally", is at the core of the UNFC and UNRMS principles.*

Building and operating nuclear power plants is the main objective of a nuclear energy programme but this must be supported by a range of facilities and activities as well as specialized nuclear transport services which, taken together, constitute the nuclear fuel cycle. This includes:

Front end activities

- Mining and milling of uranium ore.
- Conversion of uranium compounds into different chemical forms.
- Enrichment of uranium to increase the isotopic concentration of U-235 relative to U-238.
- Fabrication of the fuel assemblies that are loaded in the reactors.

Back end activities

- Cooling of the discharged nuclear fuel.
- Packaging and Storage of discharged nuclear fuel.
- Used fuel reprocessing which separates reusable materials and waste.
- Conditioning of the final waste and emplacement in deep geological disposal.

For the front end of the fuel cycle, there is an existing and highly functional global market for each of these products and services already. Nuclear newcomers will generally find it easier and more cost-effective to rely on these markets than to try and develop their own facilities, although they may find in some cases that there are advantages to doing so. Most notably, countries blessed with a good uranium resource base may wish to exploit mining profits to help fund their nuclear power programme and will find other synergies here too. The barriers to establishing other facilities are higher, and tend to lend themselves to more experienced nuclear countries or those which are considering very sizable domestic reactor programmes.

Considering the back end of the fuel cycle, every nuclear country must take responsibility for the management of used nuclear fuel and disposal of nuclear waste. However here too options exist. Primary among these is whether countries choose to send their used fuel to be reprocessed in order to separate the uranium and plutonium for reuse as new fuels (reprocessed uranium based, mixed oxide MOX etc.). Whether they choose to or not, they will still need to develop plans for the management of radioactive material and the eventual disposal of high-level radioactive wastes. The universally agreed disposal method for this is isolation in deep geologic disposal facilities (GDFs[61]). Nuclear countries need to plan for developing their own national GDFs but the actual implementation of these plans will take time. There may be opportunities in the future to make use of shared or multi-national repositories.

At the end of their operating lifetimes nuclear facilities will need to be decommissioned and sites reclaimed for future uses or returned to a natural state if the sector is to be considered sustainable. This calls for a detailed decommissioning plan. There is a wealth of international experience to draw on – which newcomers should do at the earliest possible stage if they wish to avoid difficulties later on.

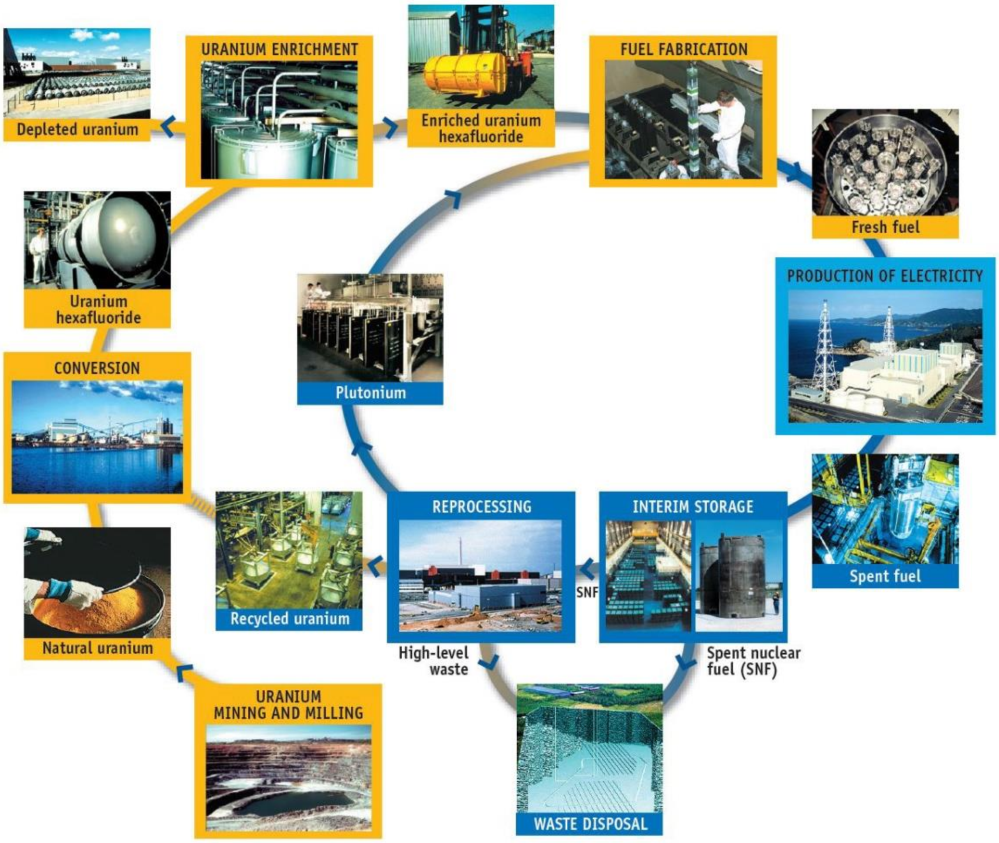

Figure 4.1 The nuclear fuel cycle. Source: OECD-NEA.

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[61] Also often referred to as deep geological repositories (DGRs)

Clearly these choices have local, regional and global considerations. While most countries desire energy independence there are arguably no advantages to be gained in ‘going it alone’ in setting up a nuclear programme. Regional and international cooperation is the key to a successful nuclear energy programme and grants access to important materials, technology trade and facilities. Important international conventions and arrangements must also be followed which control and safeguard nuclear materials and technologies to prevent potential misuse.

With the exception of uranium mines, most fuel cycle facilities need to be adapted for specific reactor technologies to an extent. This is another reason why newcomer countries need to be cautious about developing their own facilities. It also means that selecting a fuel cycle strategy for a country has important implications for a country’s nuclear future. These are detailed in the sections which follow.

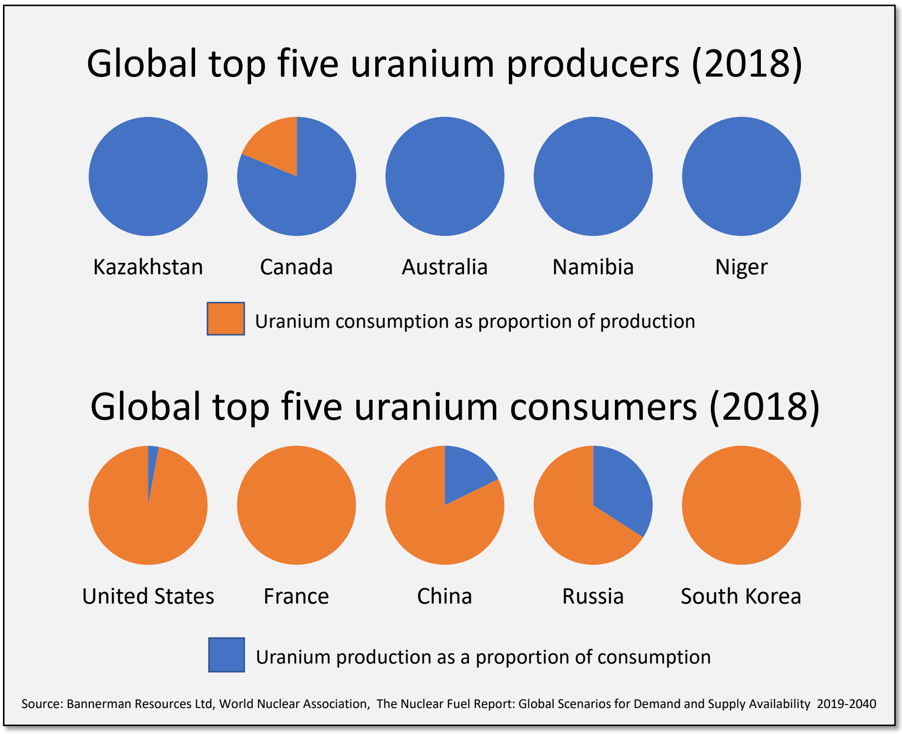
While the previous chapters have demonstrated that nuclear energy is in fact a highly sustainable activity that helps meet the United Nations 2030 Agenda, this chapter aims to highlight opportunities and challenges that the Sustainable Development Goals pose for the nuclear fuel cycle and its stakeholders, and how they might address them.

4.1 Utilizing local uranium resources

Prospective newcomer nations should consider what role existing or potential local uranium resources may play in their future nuclear energy plans.

Uranium – as the fuel source to reliable, low-carbon nuclear energy - can play a unique role in decarbonizing the world’s energy supply and is therefore critical to future prosperity and the environmental health of the planet. It is therefore important that it be understood as a clean energy material, rather than simply an industrial commodity. The benefits of responsible uranium extraction are felt at a local level, but also at an international level given uranium’s crucial role in the clean energy future of the planet. Governments have a responsibility to ensure that stakeholders are educated on uranium and its mining and, further, to provide conditions in which uranium can be extracted in an environmentally and socially acceptable way.

The uranium industry is characterized at present by the anomalous distribution of producers and consumers. With the exception of Canada and Russia, uranium is predominantly mined in countries that do not produce nuclear power. Further, the countries with the largest nuclear fleets do not mine substantive quantities of uranium. Accordingly, newcomer nuclear energy nations should consider the benefits and challenges of establishing their own domestic uranium production.



Source: Bannerman Resources Ltd, World Nuclear Association, The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2019-2040

Figure 4.2 The anomalous global distribution of uranium production and consumption.

4.1.1 Uranium as an energy source

Uranium is a naturally occurring heavy metal element found in the Earth's rock, soil, rivers and oceans. Its unique physical properties give it the potential to generate incredible amounts of energy, through the process of fission. This also gives uranium superior energy density to any other form of energy: a 10-gram uranium fuel pellet contains the equivalent energy to 1 ton of coal, 17,000 cubic feet of gas, or 149 gallons of oil[62].

Uranium mining and processing produces a high-purity uranium concentrate (U_3O_8 or UO_4), which is often referred to as yellowcake. Uranium concentrate is a fine powder that is packaged in steel drums and, whilst toxic, can be generally handled in the same way as other heavy metals, such as lead. Uranium concentrate is compact and stable, can be stored indefinitely and is readily transported. Natural uranium is only slightly radioactive and the radiation risks from uranium concentrate are relatively low and can be easily managed.

Naturally occurring uranium contains 0.7 percent U-235, which is the isotope of uranium that is fissile and can therefore be used as an energy source (the remainder is comprised of U-238). For most reactor types, uranium concentrate cannot itself be used as a nuclear fuel without enrichment and mining is therefore only the first step in the nuclear fuel cycle.

4.1.2 Uranium exploration, development and mining

As an element, uranium is common and geologically available throughout the world. Crustal abundance surveys average 0.0004 percent uranium by weight, ranging slightly higher and lower

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[62] see WNA website, Heat Values of Various Fuels

depending on the reporting source. It is a metal approximately as common as tin or zinc, and it is a constituent of most rocks and can even be found in the sea. Quantities of uranium mineral resources are therefore greater than commonly perceived however, as is the nature of mineral deposits, there are relatively few occurrences where uranium has been found in sufficient concentrations and quantities to have the potential to be an economically minable deposit. Many of the identified economic deposits have already been mined out and, further, there has been only limited economic or political incentive to explore for uranium in the past 30 years. Political and/or social restrictions on uranium mining have further restricted exploration in many parts of the world, including Australia, which hosts the largest uranium resources globally.

Current uranium mining activities are highly concentrated in a handful of geological provinces[63], largely due to the intrinsic concentration of uranium but also due to political restrictions or impediments. In 2018, more than 95 percent of the world's uranium production was from ten nations, with the top four nations, Kazakhstan, Canada, Australia and Namibia comprising 75 percent of global production[64]. In total, uranium was mined in 14 countries in 2018, including where it was produced as a by-product of other mining.

Over coming years, new discoveries will increase the number and distribution of potentially economic uranium deposits, including into newcomer nations, as a result of improving exploration technology and methods. There is a need, both for individual nations and the world at large, to attract early stage, generative exploration so that the next generation of uranium deposits can be identified.

4.1.3 Unique attributes of uranium mining

In many respects, the principles of uranium exploration and mining are identical to most other metals. However, uranium has a number of unique attributes – and challenges – that distinguish it from other commodities and justify different treatment at both at a governmental and societal level.

Uranium is a unique and essentially un-substitutable fuel for nuclear energy reactors. Every nuclear reactor in the world is currently fueled with uranium, in some cases supplemented with plutonium that is separated from uranium fuel that has previously been inside a reactor. While thorium is a potential fuel for certain advanced reactor concepts and has been investigated for use in some of today's reactor technologies there is currently no market for this fuel[65]. For this reason, uranium should be regarded (and regulated) as a clean energy material, rather than an industrial metal. Uranium is a strategic energy resource which can also potentially be diverted into nuclear weapons programmes, hence is subject to closer state and bi-lateral alignment than industrial metals.

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[63] *Uranium 2018: Resources, Production and Demand*, OECD-NEA & IAEA (2018)

[64] *The Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2019-2040*. World Nuclear Association (2019)

[65] See World Nuclear Association website, Thorium

Further, uranium’s role in generating very low-carbon energy generates strong net positive environmental and social impacts. When mined according to international best practice the environmental impacts are kept extremely low relative to other energy mineral extraction (as discussed in section 3.3). In this way, the net positive impacts of responsible uranium mining accrue to local communities, producing nations and the planet at large.

Because of the long construction and operating cycles of nuclear power plants, uranium is subject to price fluctuations on a longer cycle time – and often experiences cyclical price fluctuations at different times to industrial metals and other commodities. Thus, uranium mining can offer producing nations important diversity of economic and fiscal contributions during commodity cycle downswings.

4.1.4 Potential advantages of uranium mining to a nuclear power newcomer

The advantages of uranium mining to a nuclear power newcomer will differ based on whether that nation already has viable uranium deposits or production, or whether that nation is considering incentivizing exploration to potentially identify such deposits in the future. For this discussion, it is assumed that the newcomer does not have existing uranium production or advanced uranium development projects.

There are a number of synergies between developing domestic capability in uranium mining and developing nuclear power. For instance, stakeholder engagement on the domestic availability of uranium may assist with public perceptions around the role and benefits of nuclear power and the impetus for the nation to contribute positively to carbon reduction on a full cycle basis. Equally, the presence of (or intention to operate) nuclear power plants and the associated public debate may assist with public acceptance of uranium mining. Much of the public education required for the proposed introduction of nuclear power is applicable to public understanding of uranium mining, and vice versa.

The inclusion of nuclear energy in a broad energy mix will enhance a nation’s energy security. As a base-load power source, nuclear energy complements intermittent energy sources and reduces a nation’s exposure to disruptions in the availability of, or acceptability of utilizing, baseload fossil fuels. Some newcomer nations will see nuclear energy as a means of reducing reliance on imported power or, conversely, an opportunity to export excess power to neighbours. The energy security attributes of nuclear energy can be enhanced where a country has known, viable uranium deposits that are able to produce uranium in the future, enabling long term planning in a broad range of scenarios. It should be noted that uranium is readily stored and stockpiled, either through accumulating domestic production or purchasing from the world market, thereby buffering against temporary supply disruption or market price fluctuations.

It should be cautioned, however, that the integration of domestic uranium into nuclear energy production is not as simple as fossil fuels. For instance, domestically produced coal can be conveyed from a mine to a power plant in days and otherwise only requires road/rail transportation from mines to power plants. Moreover, domestic gas supplies only require pipelines to feed nearby power plants. Uranium, on the other hand, needs to be exported for conversion and enrichment and then requires fuel fabrication before it can be re-imported into a domestic reactor. Further, uranium concentrate is a homogenous product that has the same properties regardless of where it is produced. Given the need for export and transportation, there may be no benefits to a country utilizing its own uranium production for power, rather than selling its uranium production and purchasing its requirements on the world market. It should also be noted that several newcomer nations are considering nuclear power plant vendors that provide a bundled nuclear fuel supply, meaning that the newcomer does not need to establish fuel buying capacity and would be unable to directly utilize any domestically produced uranium.

There is an increasing dialogue within nations with mining industries that calls for downstream beneficiation, or value addition, to those minerals. Such debates regarding uranium have occurred, for example, in Namibia and Australia. An industrial metal such as copper has a multitude of downstream value addition opportunities, with varying technical complexity and capital intensity, which makes progress on such requirements achievable in degrees, even for a country without a substantial industrial complex. However, in the case of uranium, any further downstream step beyond producing high purity uranium concentrate is practically impossible for a newcomer nation. The immediate and only next step in uranium value addition is conversion from uranium concentrate to gaseous UF_6 (or conversion to UO_2 for Pressurised Heavy Water Reactors). Conversion is technically complex and capital intensive and has large incumbent facilities that have centralized the industry to only five countries. The next step in the fuel cycle after that, enrichment, has even greater barriers. Since 2011 both processes have been in global oversupply[66] which further reduces the incentive or viability of developing such facilities domestically.

Nonetheless, the benefits of mining uranium to the host community should be viewed in addition to the advantages of producing a unique clean energy material for the benefit of the world at large. Indeed, for newcomer nations, these benefits can further enhance the clean energy benefits of that nation’s nuclear power programme. Steps taken to ensure environmental and social best practice in the mining of uranium thus become extremely important[67].

4.1.5 Potential challenges for uranium mining in newcomer nations

The mining of uranium is subject to a range of challenges typical of any form of mining, including infrastructure availability, workforce capability, safety considerations, environmental or social impacts and transparency. These challenges may be greater in developing nations.

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[66] Although the placing of the Metropolis conversion plant into temporary care and maintenance has contributed to short term deficits in the conversion market.

[67] For a leading example of best practices in the mining industry, see: *Environmental Principles for Mining in Namibia. A Best Practice Guide*, Namibian Chamber of Environment et al, (2018)

In addition, there are several challenges that are unique to uranium, the best known of which is radiological safety. Radiation risk is not unique to mining uranium. In fact, radiation needs to be managed for the mining of coal, rare earth elements, rare metals, mineral sands and mining where uranium and/or thorium are geologically coincident with the targeted metal. Among energy minerals, coal miners may be exposed to significant doses of radiation. Rare earth minerals are commonly required in the construction of renewable energy technologies such as wind and solar and can also cause significant radiation doses to mine workers, according to the United Nations Scientific Committee on the Effects of Atomic Radiation.

Whilst modern uranium mining techniques entirely mitigate radiation safety risks, the public perception, and misunderstanding, of radiation risks continues to be a challenge for communities and governments. Misinformation on radiation risk is widespread, leading to unnecessary anxieties in host communities and political decisions that hamper the role uranium and nuclear power can play in decarbonizing the world’s energy. For example, governments in Sweden and Kyrgyzstan recently prohibited uranium mining. Accordingly, it is essential that host countries effectively regulate radiological safety and also educate the public so that host communities have an accurate understanding of radiation risk.

Political and social sensitivity are higher for uranium mining than many other forms of mining and predominantly relate to radiation concerns. Public attitudes are therefore highly variable from country to country and in many jurisdictions these concerns need to be weighed against development priorities and alternative availability of economic growth and employment. Similarly, interest groups play an enhanced role in opposing uranium mining. Anti-nuclear groups can be sophisticated and influential, often adopting unconventional techniques to achieve their outcomes that can present challenges for governments or project proponents. However, these groups generally gain less traction where there is accurate public education on the benefits and risks of nuclear power and uranium mining.

For nations that have brought into force the Additional Protocol to their comprehensive safeguards agreements under the Treaty on the Non-proliferation of Nuclear Weapons, naturally occurring uranium is subject to IAEA safeguards verification. All current uranium mining nations have implemented the Additional Protocol and new mining nations would be expected to do so by the international community. Accordingly, uranium mining within a newcomer nation will be subject to safeguards obligations, including information provision, IAEA inspections access and co-operation with IAEA verification activities[68]. Further, existing and proposed laws relating to mining, export and import controls and radiation protection will need to be reviewed to identify any necessary modifications to address obligations under the nation’s safeguards agreements.

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[68] See *Safeguards Implementation Practices Guide on Facilitating IAEA Verification Activities*, IAEA (2014). See also *Safeguards Implementation Practices Guide on Establishing and Maintaining State Safeguards Infrastructure*, IAEA (2018)

Similarly, maintaining the security of uranium during production, storage, transport and export is a vital responsibility that requires close co-operation between the mine, the state and the IAEA. The IAEA works with authorities to train personnel and help develop national safety and security regulations for transporting uranium. National regulations for the safety and security of radioactive material must meet international standards, covering the whole transport process from production and packaging to transit routes and delivery[69].

The transportation of uranium presents particular challenges, both within a country and across borders. In some instances unprocessed uranium ore will be transported in-country (for instance to a centralized processing plant) but in most cases processed uranium concentrate must be transported from the mine for export to conversion facilities, typically involving public roads/rail and shipping. As with any radioactive material, Class 7 shipping conventions must be observed which has implications for ports and rail operators. Some port operators around the world do not permit Class 7 shipments and recent consolidation within the global shipping industry has reduced the diversity and availability of Class 7 ships and routes. This concentration of Class 7 shipping will disproportionately affect newcomer uranium producers, compared with incumbent producers, and will have impacts on delivery consistency and working capital requirements for new mines. Although the nuclear industry has a long history of safely transporting radioactive materials, there remains public opinion considerations which can impact approvals and costs. For all the above reasons, newcomer nations will require government leadership to enable transport routes that can enable the export of uranium and import of nuclear fuels.

As a result of the foregoing, uranium mining requires enhanced regulatory oversight and public stakeholder engagement, in excess of the responsible and effective regulation of mining per se. Newcomer nations will thus need to invest in the capability to prescribe, monitor and enforce regulations relating to radiological safety, non-proliferation and security, which will have impacts on government departments relating to health, mining, policing and foreign affairs. For nations that do not have well developed mining and environmental laws, or are dealing with internal security issues, this challenge will be compounded.

Finally, the combination of the above factors results in long lead times from the discovery of a viable uranium deposit to the operation of a uranium mine, which can be heavily exacerbated where there is a lack of effective government support. This requires both project proponents and governments to manage the expectations of communities. The long lead time also allows extra time for newcomer nations to ensure their jurisdiction is relatively attractive to uranium explorers and producers.

4.1.6 Market-based exploration and development

Stock exchange funded exploration and development has been responsible for the large majority of mineral discoveries in the last 30 years. Mineral exploration is a very high risk

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[69] See *Nuclear Security in the Uranium Extraction Industry*, IAEA (2016)

business enterprise, with the vast majority of early-stage exploration investments failing to yield a discovery or any economic return. Nonetheless, such investments continue to be made into geologically prospective areas where private investors identify the possibility of making extremely high returns that justify this level of risk. Stock exchanges facilitate the distribution of this risk amongst many investors, who can in turn diversify their risk across many investments in the anticipation that extreme returns on successful exploration investments will outweigh the value loss across the majority of the portfolio. Accordingly, to attract private investment into mineral exploration, including for uranium, it is essential that governments recognize the profit motives driving investors and ensure that, should a mineral discovery result from the investment, investors are not prevented from achieving high returns.

The capital for investing in high-risk exploration is concentrated in several jurisdictions and stock-exchanges, notably North America, Australia and the United Kingdom, with Chinese risk capital playing an increasingly important role. Many host countries, particularly in the developing world, do not have significant private domestic capital that is available for such investment and hence rely on foreign direct investment.

Further, mineral investment capital is highly mobile between jurisdictions, given that geological and scientific expertise is not bound by political boundaries. Investors primarily consider geological prospectivity, which is weighed against a variety of factors such as political risk, security of tenure, policy certainty, taxes and royalties, infrastructure availability, ease of doing business, security and stability, legal restrictions and the availability of skilled workforce. Accordingly, competition between different nations is high and host governments ought to recognize the positive or negative effects of policy decisions on the relative attractiveness of their nation compared with peers.

Exploration and development timeframes are long in the mineral and energy sectors, with production from a mine often achieved 20 or 30 years after the first investment of exploration into the relevant area. For this reason, ensuring policy certainty over long investment cycles is important for attracting investors, in particular regarding the mineral rights and licensing regime, fiscal provisions and certainty of tenure/ownership.

Of course, it is also necessary for the state and its people to obtain appropriate benefits from mineral resource development and a balance needs to be achieved between private and state interests. In general, the mining industry will tolerate an equal sharing of financial returns between investors (in the form of net profit and dividends) and the state (in the form of income taxes, royalties, withholding taxes, value added taxes, customs duties, levies, profit sharing and all other state-imposed costs of doing business). The degree to which countries each achieve a balance is routinely ranked and proposals or laws to increase aggregated state returns will demote the attractiveness of that jurisdiction and its capacity to attract investment. Ultimately, as noted by mineral economist James Otto, countries that over-tax their mineral industries will reduce their tax base in the long run as investors will shy away from new investment.[70]

Uranium, as a strategic energy source, may justify additional state controls or more rigid selection of which private companies are permitted to explore and develop. However, achieving these aims without alienating private interests requires consultation and, preferably, implementation of such measures before investment commences.

The behaviour and values of private interests are very important for maintaining public support of uranium exploration and development and for ensuring maximum benefits to host communities. As far as possible, states should seek to attract private companies that demonstrate a commitment to best practice Environmental Social Governance (ESG) and Corporate Social Responsibility (CSR) principles. These principles primarily encompass environmental, health, safety, community, governance and transparency, but may extend to local employment and procurement practices. When there are opportunities to select partners for development, these matters should be given priority, recognizing also that foreign operators will be subject to varying behavioural constraints in their home jurisdictions, such as compliance with Foreign and Corrupt Practices legislation in the United States, United Kingdom, Australia and Canada.

It is crucial that regulators and administrators reward good behaviour and deter poor behaviour in the mining industry. Too often, particularly in the developing world, individuals or companies are given preferential treatment based on illegal behaviour or political connection, whilst foreign companies that demonstrate best practice social and developmental credentials are prevented or delayed from accessing exploration licences or administrative procedures. Enabling illegal behaviour or nepotism ultimately comes at a cost to a nation and its citizens, through slowing development or adding cost and/or risk to legitimate mineral explorers. The risks associated with illegal behaviour or politically exposed individuals are more acute in the uranium industry, because of the geo-politically sensitive nature of the nuclear energy industry.

4.1.7 State-based exploration and development

The state has an important direct role to play in supporting generative exploration programmes, primarily through undertaking broad reconnaissance work, coordinated geological mapping and through the effective operation of a geological survey department.

Broad-scale surveys, such as the nation-wide airborne geophysical surveys and regional geological mapping undertaken in Namibia, provide an overview of large scale geological structures and are an important dataset for the initiation of generative exploration. Further, in the case of uranium deposits that occur at surface, airborne radiometric surveys may identify the radiation signature of a deposit (as well as thorium and potassium that may be indicators

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[70] See James M Otto, *The taxation of extractive industries*, The United Nations University World Institute for Development Economics Research (2017)

for other minerals of interest). The Etango Project in Namibia is an example of a large-scale uranium deposit that was identified through a state sponsored airborne radiometric survey.

The availability of current and historical data (such as surveys, maps, reports, drill core, drilling results, soil sampling, etc.) is also a substantial incentive to commence exploration, as this data indicates what methods have been tried in the past and may be an indicator of future potential - particularly when these datasets are integrated using modern geospatial mineral prospectivity mapping techniques and/or quantitative assessment of undiscovered mineral resources approaches[71]. The collection, preservation and distribution of this data is an important function of an effective geological survey department.

In the last 30 years, the financing and operation of state exploration and mining companies has enjoyed limited success compared with enabling market-based exploration that is incentivized to be efficient and attract the best talent. State-sponsored mining has been effective in certain, limited situations. This is typically possible where there is a known resource inventory that is not already subject to private rights – in the uranium sector Kazatomprom JSC has successfully developed Kazakh uranium projects that were discovered by state programmes of the USSR.

Where licenses are already subject to private rights (such as exploration licenses issued to foreign companies), governments should be very cautious if considering any steps to alienate those rights in favour of state participation. Concerns about resources nationalization and/or nationalism are foremost risks for private investors and policies or actions that may result in appropriation of private rights are a disincentive to exploration for many years afterwards. Such steps may also impact on the perception of security of property rights beyond the resources sector, with implications for foreign direct investment and credit ratings across the entire economy. In contrast, the most recent trend worldwide has been to privatize state owned mines (for example in Malaysia, Peru, Poland and Russia).

4.1.8 Potential for vertical integration

Some nuclear power plant operators have developed or acquired uranium mines, thereby vertically integrating the production and consumption of uranium. Such integration provides nuclear power producers with some additional security of supply and also insulates uranium mines from volatile global uranium pricing. This model has been successfully applied to operate uranium mines for example by Rosatom (in Russia and in a joint venture in Kazakhstan), China General Nuclear Power Corporation (in Namibia), China National Nuclear Corporation (in Namibia) and INB (in Brazil). However the amount of uranium coming from these investments has changed over time and is not always a large fraction of the operator’s requirements.

The driver for a nuclear power operator to seek, to own, and operate uranium mines is to achieve the security of supply of uranium and thereby improve the risk profile of their power

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[71] *Quantitative and Spatial Evaluations of Undiscovered Uranium Resources*, TecDoc 1861, IAEA (2018).

production. Accordingly, a mine that is attractive for vertical integration typically has some or all of the following attributes:

- Technical reliability and resilience (low risk of under-producing).
- Remaining long operating life (to complement the long life of the nuclear power programme).
- Long term community and government support (to ensure stable long term export).
- Low environmental/social risks and strong government regulation (to protect the operator’s reputation).
- Limited risks associated with security and stability in the host community/nation.
- Strong bilateral relations and investment support such as treaty protection.

Mines operated in vertical integration are attractive to a host country. Uranium concentrate comprises a small minority of the total life cycle cost of producing nuclear power, with upfront capital being the largest cost. Accordingly, the economics of mining uranium in a vertically integrated structure are not as acutely important as for a commercial enterprise. Further, a nuclear operator can make long term price assumptions over the life of mine, thereby insulating the mine from market volatility and enabling a mine in some cases to continue operating during market downturns that might otherwise make the mine unprofitable. Further, nuclear power operators can access large scale low-cost financing, often in the form of sovereign debt, which means the upfront capital required to construct a uranium mine is likely to come at a lower capital cost and more quickly in a vertical integration than for commercially available finance. This lower cost of capital and assured customer off-take reduces uncertainty and economic hurdles to production, which would enable a mine to be sooner financed and operating.

The predominant challenge to be resolved for vertical integration is establishing a uranium price at which taxes and royalties can be levied and to avoid perceptions of inappropriate transfer pricing. This challenge has been overcome by, for instance, ensuring that a minor proportion of the uranium production is sold on the open market, generating a reference price for calculating income taxes and mining royalties.

Historically, such integration has commenced at early exploration or development. For instance, Japan’s JOGMEC and Russia’s ARMZ have partnered at the uranium exploration stage with exploration companies. However, more recently the trend has been for nuclear power operators to acquire uranium mines or developments from private interests who possess the specialist prospecting and development skills to progress the project through discovery to feasibility. This approach effectively allocates skills and capital to the most appropriate use and ensures a market-based incentive for the high-risk exploration and development phase of uranium mining.

4.1.9 Important policy considerations

The policy environment is paramount for attracting and regulating uranium exploration and mining. Best outcomes are achieved when government policy is transparent, clear and consistent over the investment cycle. Policy changes should be implemented in consultation with industry stakeholders and caution should be taken when implementing policies that negatively affect existing private rights or the perceived investment attraction of a jurisdiction. The assessment of this impact should be undertaken before implementing consultation, as the public proposal of negative policy changes can affect investor confidence, even where such changes are ultimately abandoned.

The strategic nature of uranium resources requires careful policy support that balances framework conditions by government and incentivized capability from private industry. Sound policies can ensure the management and stewardship of those resources whilst respecting the private sector's requirement for high returns to justify high risks.

4.1.10 Promotion of SDGs

The mining of uranium, and its role in producing clean, base-load nuclear power, strongly promotes SDG7 Affordable, Clean Energy, SDG11 Sustainable Cities, Communities and SDG 13 Climate Action. The advancement of those SDGs is experienced both within the newcomer nation and at a global scale, with significant public health benefits, particularly in heavily polluted urban areas. The mining industry generally has the potential and opportunity to contribute to all 17 SDGs[72], but uranium mining can promote the following SDGs in particular:

- Direct and indirect employment, in particular in developing nations where uranium mining provides highly paid jobs that have a multiplier effect in the local community (SDG1 Poverty Eradication and SDG2 Zero Hunger).

- Medical and radiation monitoring of employees and communities promotes greater medical awareness, particularly in developing nations (SDG3 Good Health and Well Being).

- Uranium mining and associated government and private capability development provides opportunities for highly skilled development and employment (SDG4 Quality Education and SDG8 Decent Work and Economic Growth). Uranium mining is a sophisticated enterprise that creates a significant number of well-paid jobs, high levels of workplace training and regular vocational health assessments.

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[72] See further *Mapping Mining to the Sustainable Development Goals: An Atlas*, (2016), a joint effort of the United Nations Development Programme, the World Economic Forum, the Columbia Center on Sustainable Investment and the Sustainable Development Solutions Network.

4.1.11 UNFC and UNRMS application for uranium

UNFC, and in future UNRMS, are tools that allow countries to manage their total resource base at the national level in a consistent, coherent and transparent manner. The long-term policy and strategic planning framework of a country may be based on UNFC data, which is disaggregated at a project level. For many prospective users of UNFC, realistic assumptions about the total resource base and its economically affordable supply over the medium- to long-term (say the next 25 years) can provide a well-considered basis for growing the domestic mining industry in a country, attracting the right mix of national and external investors (the Nash Stackelberg equilibrium approach) and implementing an appropriate local content policy, aligned to OECD guidelines. Within such a structure, companies, whether government or privately held, can use the same data for more nearer term planning, incorporating a blend of tested and new technologies and flexible business models[73].

4.2 Developing the nuclear fuel cycle

Establishing fuel cycle facilities beyond uranium mines is particularly difficult for most nuclear newcomer countries because it represents a huge additional investment in infrastructure, as well as an additional long-term investment in skills and training of the workforce. To be bankable, a fuel fabrication facility would have to service nuclear power plants with a combined minimum capacity of at least 12 gigawatts, while a reprocessing or enrichment facility would need to serve over 30 gigawatts. This is much larger than what most newcomers are aiming for. Presently, the existing global fuel supply chain and services already feeding utilities all over the world can easily accommodate the additional demand created by nuclear newcomer countries. Given the economic advantages of expanding an existing facility compared to starting from scratch, not to mention the technical challenges in establishing such facilities, the market incumbents find themselves in a strong position. Nuclear newcomers need to be aware of this and to consider carefully the advantages and disadvantages of developing their own fuel cycle facilities against those of relying on upon the international market.

This section addresses the available fuel cycle supply chain worldwide and outlines the decision drivers for consideration by newcomers in implementing a strategy for the front end and the back end of the nuclear fuel cycle.

4.2.1 Conversion

The uranium concentrate produced from a uranium mill requires further processing before the uranium can be used as a fuel for a nuclear reactor. The concentrate needs to be converted to uranium hexafluoride before undergoing enrichment and then being fabricated into physical fuel assemblies. Therefore, after the uranium ore concentrate is produced at the mill it is packaged in 55 gallon drums and sent to a uranium conversion plant. At the conversion facility, the concentrate undergoes a series of chemical transformations ending with the production of UF_6 which can then be shipped to an enrichment plant.

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[73] For more discussion see *Redesigning the Uranium Resource Pathway*, ECE ENERGY SERIES No. 57 (2019)

Current conversion capacities available around the world total 62,000 TU/y and are owned by five companies which service a broad range of countries. This global capacity is not currently fully utilized and can cover expected nuclear growth in the near term, although recently one plant in the US has been idled because of adverse market conditions (not shown in table 4.1).

Table 4.1 World conversion capacity.

Converter	Country	Nameplate capacity (tonnes of uranium)
Cameco	Canada	12,500
Orano	France	15,000
ConverDyn	USA	7,000
CNNC	China	15,000
Rosatom	Russia	12,500
Total		62,000

4.2.3 Enrichment

When uranium is mined, it consists of approximately 99.3 percent uranium-238, 0.7 percent uranium-235, and less than 0.01 percent uranium-234. Only the U-235 is 'fissile', or capable of undergoing fission, the process by which energy is produced in a nuclear reactor. For most kinds of reactors, the concentration of the fissile uranium-235 isotope needs to be increased – typically to between 3.5 percent and 5 percent U-235.

Enrichment is an isotope separation process which concentrates (‘enriches’) one isotope relative to others. On an atomic level, the size and weight of these isotopes are slightly different. With the right equipment and under the right conditions, the isotopes can be separated using physical processes. The enrichment process requires the uranium to be in a gaseous form. This is why the uranium oxide concentrate is first converted to UF_6, which becomes a gas at relatively low temperatures.

There are multiple enrichment technologies, but today gas centrifuges are the technology of choice, offering the best economics and lowest consumption of electricity. This technology has replaced the older method of gaseous diffusion and today provides the vast majority of global enrichment needs. A third technology, laser isotope separation remains in the R&D phase with companies pursuing commercialization.

The supply of enriched uranium is composed of primary supplies provided from commercial enrichment plants, as well as secondary supplies (for example inventories of previously produced enriched uranium or tails re-enrichment). Uranium enrichment technology is geo-politically sensitive and capital intensive, creating substantial barriers to entry for any new supplier. The safeguards process to put in place and non-proliferation controls are demanding and create an additional entry barrier for development by newcomer countries.

Hence, enrichment operations are centred on only a limited number of facilities worldwide. The uranium enrichment industry has three major producers today, namely Orano (France), Rosatom (Russia), and Urenco (USA and Europe). China National Nuclear Corporation (CNNC) is developing as a major domestic supplier and is pursuing export sales. In Japan and Brazil, the respective domestic fuel cycle companies continue to manage modest domestic supply capability. However non-safeguarded facilities elsewhere continue to be subject to significant international opposition. There are other small enriching countries with limited capacities having developed domestic centrifugation technologies, mainly for their internal needs (i.e. no exports): Argentina, India, Pakistan, and Iran.

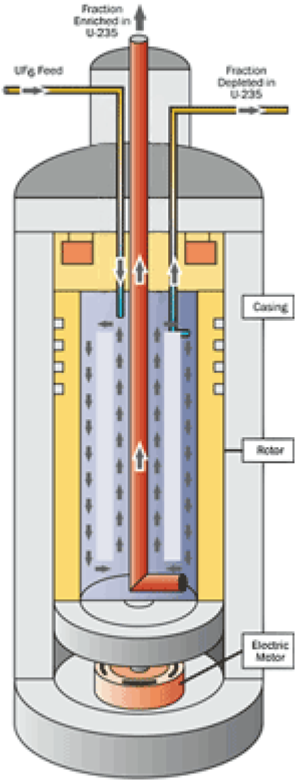

Figure 4.3 Schematic of a centrifuge.

The capacities of the main enrichers are presented in the table 4.2 with a growth perspective for 2030 according to World Nuclear Association 2019 Fuel Report[74]. The installed capacity is flexible and easily covers the current global reactor requirements.

Table 4.2. Capacity of the world's enrichers. (SWU equals separative work unit). Source WNA.

Capacity in million SWU	**2019**	**2030 target**
CNNC	6,75	≈ 20
Orano	7,5	7,5
Rosatom	≈ 28	25
Urenco	18,4	16,5
Other (INB,JNFL)	Very little	0,45
Total	60,6	69

4.2.3 Fuel fabrication

Fuel fabrication for light water reactors typically begins with the receipt of low-enriched uranium, in the chemical form of UF6, from an enrichment plant. The UF6 is heated to gaseous form, and then chemically processed to form uranium dioxide (UO2) powder. This powder is then pressed into pellets, sintered into ceramic form and loaded into zircaloy tubes which are then constructed into fuel assemblies. Depending on the type of reactor a fuel assembly may

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[74] *The Nuclear Fuel Report - Global Scenarios for Demand and Supply Availability 2019-2040,* WNA (2019)

contain up to 313 fuel rods and have cross-section dimensions of 30-40 centimetres by about 2.5 to 4.0 metres long. Fuel fabrication for light water reactors does not have to start with low-enriched uranium. It can also start with reprocessed uranium and plutonium as detailed in the next section.

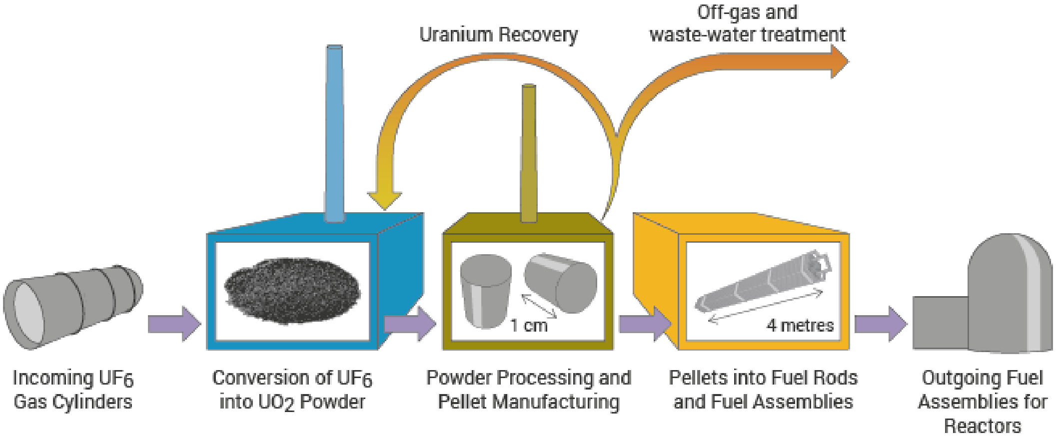

Figure 4.4. Simplified schematic of the nuclear fuel fabrication process. Key steps include creation of UO_2 powder, sintering into pellets and then loading pellets into physical assemblies. Source: WNA[75]

Fabricated nuclear fuel assemblies, as loaded into reactors, are a complex highly engineered products and vendors must undertake research and development activities. Fuel fabrication in fact requires two complementary skill sets: design and manufacturing. Designers are the owners of the fuel-related intellectual property and define the specifications for manufacturing their fuel design. Most designers are also manufacturers but there are some exceptions.

The fabrication of the fuel components demands the supply of zirconium, different types of steel and other metal products. Localization of the manufacturing of these components can be a consideration given the standard and common manufacturing processes involved. The barriers to fabrication are not as high as for either conversion or enrichment and therefore a fuel fabrication facility may be considered as an option by newcomer countries. However, the expertise and experience necessary to make such specialty products needs to be taken into account when considering localizing these value-added parts.

Improved moderation and reduced neutron absorption in fuel assemblies has led to improved uranium utilization, allowing more complete burn-up of the fuel in the assembly. Improvements have also taken place in in-core fuel management, notably the use of new loading patterns for fresh fuel in order to reduce neutron leakage. Some further reductions in uranium utilization should result in the next few years from continuing improvements in fuel design.

Table 4.3 gives an overview of the main fabricators of fuel assemblies for light water reactors (LWRs) in tons of uranium in the world. This class of reactors represents about 90 percent of global installed and operable nuclear capacity. There are many actors in this supply chain segment well spread over the world. Fabrication is more a regionally-driven industry than

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[75] See WNA website, Nuclear Fuel and its Fabrication

either conversion or enrichment. As the table shows capacity is broken down in 28 percent in Western Europe, 39 percent in the USA and 33 percent in Asia.

Table 4.3 Global fuel fabrication capacity for light water reactors. Source WNA[76]

Country	Fabricator	tonnes Heavy metal/y
Brazil	INB	400
China	CJNF	800
	CBNF	400
	CNNFC	200
France	Framatome-FBFC	1,400
Germany	Framatome-ANF	650
India	DAE Nuclear Fuel Complex	48
Japan	NFI (PWR)	284
	NFI (BWR)	250
	Mitsubishi Nuclear Fuel	440
	GNF-J	630
Kazakhstan	ULBA	0
South Korea	KEPCO NF	700
Russia	TVEL	1,500
Spain	ENUSA	500
Sweden	Westinghouse AB	600
UK	Westinghouse	860
USA	Framatome Inc.	1,200
	GNF	1,000
	Westinghouse	2,154
Total		15,276

Table 4.4 Global fuel fabrication capacity for pressurised heavy water reactors. Source: WNA[77]

Country	Fabricator	t Heavy metal/y
Argentina	Conuar	160
Canada	Cameco Fuel Manufacturing	1,500
	BWXT	1,500
China	CNNFC	246
India	Nuclear fuel Complex	1,000
South Korea	KEPCO NF	400
Pakistan	Chasma Fuel Fabrication Plant	20
Romania	SNN	250
Total		5,076

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[76] *The Nuclear Fuel Report - Global Scenarios for Demand and Supply Availability 2019-2040*, WNA (2019)

[77] ibid

Pressurized Heavy Water Reactors (PHWRs) are the next largest reactor class representing about 6 percent of global installed & operable capacity. The fuel supply is also diversified and located in countries operating PHWR type reactors. One notable feature of PHWRs is that they are capable of running on un-enriched or very lightly enriched uranium. This means that fuel assemblies are not as energy dense and that to produce the same amount of energy more fuel assemblies are required. Table 4.4 gives the capacities in assemblies par ton of heavy metal par year.

4.2.4 Reprocessing

After being used in a nuclear reactor, fuel assemblies are discharged from the core and cooled down in reactor spent fuel pools. Used nuclear fuel can then be reprocessed in order to recover the remaining uranium it contains – known as reprocessed uranium (RepU) – as well as the plutonium that has been generated during irradiation of the fuel in the reactor. Discharged nuclear fuel is typically composed of 94% uranium, 5% fission products, 0.8% Plutonium, 0.2% minor actinides as well as the cladding. Reprocessing is an optional step which countries may choose to adopt for their nuclear power programmes. It adds a short-to-medium term cost to the management of used fuel but it can save costs later on, as well as helping to preserve natural resources and reducing the environmental impacts of final waste disposal.

However, of all the fuel cycle facilities commercial reprocessing plants are arguably the most technically complex and costly to establish since they involve the handling of highly radioactive material which can only be carried out remotely. The costs of setting up such a facility run into the tens of billions of US dollars. Reprocessing is also a proliferation sensitive technology which is subject to stringent international safeguards and control. Setting up the required processes would pose additional challenges for newcomer countries. Developing domestic reprocessing capabilities is not something nuclear newcomers need to initially consider, although they may wish to keep the option in the future. Lack of economies of scale would amount to a severe financial challenges for smaller countries and newcomers. More immediately, they may wish to procure the services of international reprocessing service providers as is currently and routinely done by countries with small nuclear programmes.

There are currently two providers of international reprocessing services:

- France (La Hague, UP2 & UP3) 1,700 tonnes heavy metal (tHM) per year.
- Russian Federation (Chelyabinsk, RT-1 at the Mayak plant) 400 tHM per year.

India has 260 tHM per year reprocessing capacity solely for domestic used PHWR fuel. Another 250 tHM per year will be available after Russia finishes the construction of the Pilot Demonstration Reprocessing Plant at the Zheleznogorsk Mining and Chemical Combine (MCC), which is expected to be completed in 2020. World reprocessing capacity would increase by 800 tHM per year with the restart of the Japanese plant at Rokkasho-Mura, which is implementing safety upgrades following the March 2011 Fukushima accident. China also has a closed nuclear fuel cycle policy. Currently, China has 60tHM per year of recycling capacity available, which is not a commercial-scale facility. The construction of an indigenous recycling plant of 200 tHM/yr nameplate capacity is currently under discussion. In addition, a project for a commercial 800 tHM per year facility is being developed for start-up around 2030. If both projects are realized on schedule, China would have around 1,060 tHM/yr spent fuel recycling capacity available by 2030.

Currently about 10,000-13,000 tHM of used fuel are unloaded every year from nuclear power reactors worldwide. This annual discharge amount will evolve as new reactors enter commercial operation on the one hand and, on the other, as units that have reached the end of their operating lifetimes shut down.

Reprocessing takes used nuclear fuel and, after the valuable material are recovered, separates it into several different waste streams for conditioning. The most highly radioactive content of the spent fuel consists of fission products, activation products and minor actinides. These are concentrated and embedded in a glass matrix – a process known as vitrification – and poured into stainless steel canisters. Structural wastes from fuel assemblies are generally compacted and conditioned in the same type of canister along with technological wastes. These are intermediate level radioactive wastes containing long-lived elements. All the final conditioned wastes are then safely stored waiting for the final disposal in a repository.

Reusable materials such as plutonium and uranium are, in the majority of cases, the property of the owners of the used fuel. Mostly these are seeking to reuse these materials in their reactors. At the start of civil nuclear power development, recycling was selected by countries that wished to reuse valuable material in not yet commercialized fast reactor technologies. However since then recycled fuel has been used, in LWRs and PHWRs in many countries.

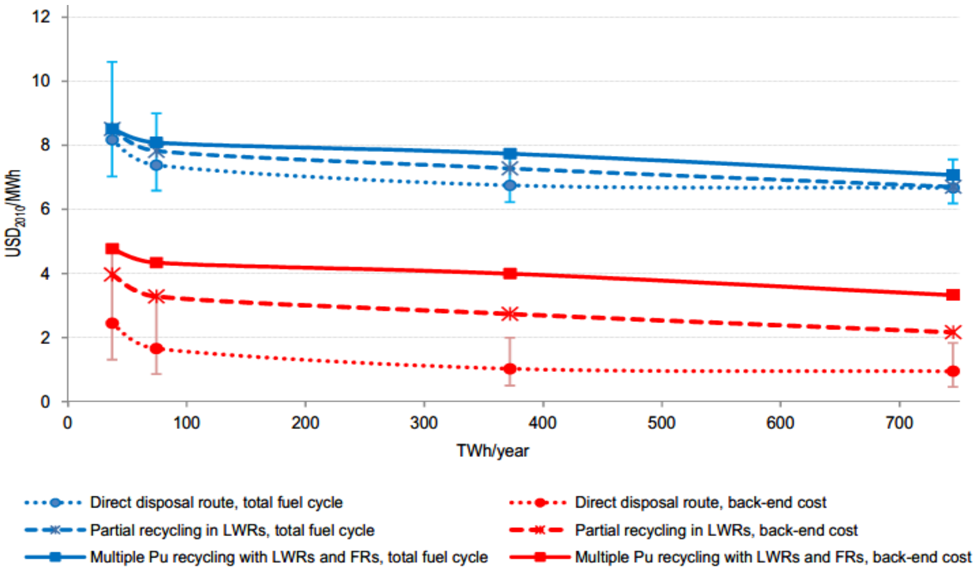
Reprocessed uranium can be re-enriched and capacities for this exist in the Russian Federation (Rosatom) and France (Orano), and in the Netherlands (Urenco). Fuel manufactured with reprocessed uranium has been already operated in a number of reactors. Plutonium is mainly recycled into Mixed Oxide (MOX) fuel and needs specialized fabrication plants. The main international MOX fuel fabrication facility, the Melox plant, is located in Marcoule, France and operated by Orano. In 2015, Rosatom’s Mining and Chemical Combine (MCC) in Zheleznogorsk, Russia officially started the commercial production of MOX fuel for the BN-800 fast reactor, and is also capable of producing MOX fuel for other reactors. Another MOX fuel fabrication plant, the JMOX plant, is currently under construction at Rokkasho-Mura in Japan. It is planned that the plant will enter operation around 2022.

What about the used nuclear fuel?

France had its first nuclear reactor operational in 1956, and following the “oil shock” in 1974, a decision was made to depend predominantly on nuclear power. Today, the country has 56 nuclear reactors providing around 70 percent of its electricity. Government policy plans to reduce this to 50 percent by 2035. However, what happens to the used nuclear fuel? France choses to reprocess used fuel to recover uranium and plutonium for re-use in its reactors. This recycling option allows up to 25 percent more energy to be extracted from the original natural uranium and reduces the waste volumes by five. Since beginning operations, France's La Hague reprocessing plant has processed over 36,000 tons of used fuel from various countries, including over 23,000 tons of French used fuel. The final waste products consist of structural wastes from compacted fuel assemblies and a highly stable vitrified glass that contains the most highly radioactive materials.

4.2.5 Choosing the open or closed fuel cycle

Nations are not aligned on the question of whether to recycle used nuclear fuel and hence close the nuclear fuel cycle. The countries which have opted to develop reprocessing are China, France, India, Japan, Russia, and originally the UK. The USA also previously developed the technology but has never commissioned a commercial reprocessing facility. Countries such as Belgium, Bulgaria, the Czech Republic, Germany, Italy, Japan, the Netherlands, Slovakia, Spain, Sweden and Switzerland have been able to utilize British, French and Russian facilities for reprocessing fuel. Some countries have decided on a ‘mixed’ approach where they reprocess some fuel and intend to directly dispose of the remainder.



* Uncertainty bands are only plotted for the direct disposal case. Similar bands apply to the other options.

Figure 4.5 Fuel cycle costs for direct disposal of spent nuclear fuel and using different reprocessing strategies including partial recycling into light water reactors and multiple recycling in fast reactors. Assumes 3% discount rate. Reprocessing adds to the near-term fuel cost but comes with multiple sustainability benefits. Source: OECD-NEA[78].

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[78] *The Economics of the Back End of the Nuclear Fuel Cycle*, OECD NEA (2013)

Closing the fuel cycle is likely to result in somewhat higher costs than for the open cycle, at least initially. But this extra cost is at least partly recovered as fuel is re-used and the volumes of wastes to be disposed of are reduced. This is indicated in Figure 4.5. The final cost of the fuel cycle option depends on many factors such as existing national infrastructure, details of contracts with service providers, etc., and therefore needs to be evaluated carefully by each country.

Regardless of the fuel cycle option selected, financial requirements for used nuclear fuel have to cover all operations up to and beyond the final disposal of radioactive waste. These requirements should encompass short-term stages but also the very long-term duration of the overall system or programme. Different options present different financial requirement profiles, but also present a different risk and uncertainty evolution over time.

Beyond economics, countries may still prefer this option for reasons of increased energy security, improved resource sustainability, as a hedge against future uranium cost increases or scarcity, to reduce demands for geological repository space, to decrease the environmental impact of long-lived radioactive waste, for the creation of new commercial capabilities to reprocess used fuel and fabricate MOX, or for other reasons. Recycling arguably increases the long-term sustainability of nuclear energy by:

- Enhancing the security of energy supply.
- Reducing the volumes of radioactive waste for disposal.
- Reducing the duration that waste stays radioactive and needs to be isolated for from millions year timeframe to thousands of year time frame.
- Simplifying the safety and security and safeguards assessment of the geological disposal facility because of the minimization of the amount of fissile content and thermal load (see below).
- Reducing the consumption of mined uranium while preventing the disposal of valuable material such as plutonium and uranium.
- Supporting ongoing scientific progress due to the continuous development of the recycling technologies.
- Providing rare and unique radio-isotopes recovered from reprocessing used nuclear fuel for further application in medicine, space industry, metallurgy etc.

It also allows for the potential separation of minor actinides which are long lived radioactive materials that can be transmuted in fast reactors. By recycling the uranium and plutonium, the radiotoxicity of final radioactive waste is decreased by a factor of 10 compared to the initial spent fuel. This means that the time frame to consider for the safety assessment of the final geological disposal is of the order of 10,000 years rather than 250 thousand years. This is shown in Figure 4.6.

In addition, recovery of plutonium will reduce by a factor of five the thermal load of the high-level radioactive waste: Thermal load is a key design parameter for the compactness (and so the cost) of interim storage solutions and the footprint of a geological disposal facility. It is also important to point out that site qualification is more complex when the volume of the geological barrier to investigate is large.

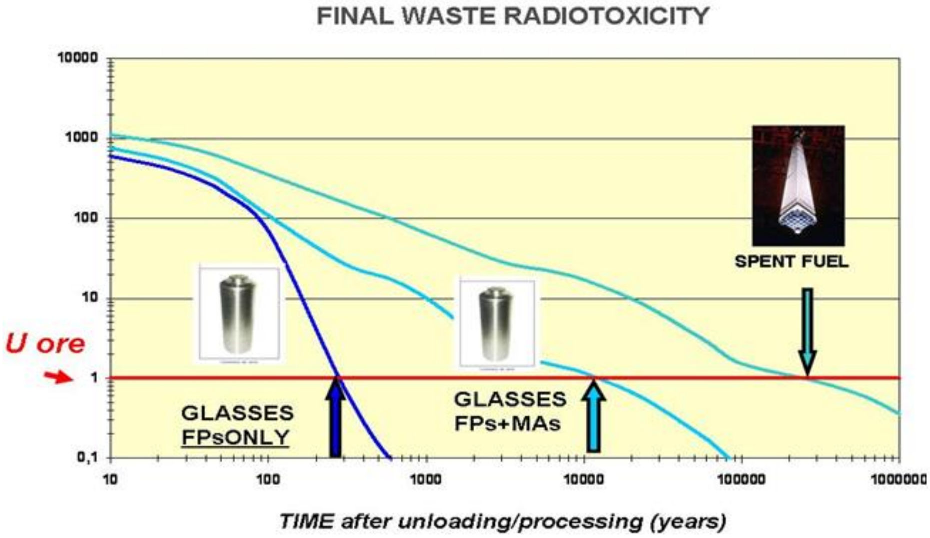

Figure 4.6 Graph showing how long high level radioactive waste stays radioactive. The y-axis measures how radioactive the waste is as multiples of the radioactivity of uranium ore. Without recycling spent fuel stays radiotoxic (i.e. more radioactive than mined uranium ore) for about 250 thousand years. If uranium and plutonium are recycled – leaving fission products (FP) and minor actinides (MA) – then waste stays radioactive for about ten thousand years. If minor actinides are removed then the vitrified fission products will stay radioactive for only about 200 years.

The eventual development of fast reactor technologies will increase the attractiveness of reprocessing even further. With the capability to increase by a factor of 50 to 100 the amount of energy output from a given amount of uranium, fast neutron reactors should dramatically improve the already impressive long-term sustainability of nuclear energy. Fast neutron reactors will also improve the high-level radioactive waste management with the deployment of advanced technologies which can partition and transmute minor actinides in spent fuel, such as americium, thereby further reducing the thermal load of waste and the length of time a repository must keep waste isolated. This makes the environmental assessment of a repository easier to handle since it reduces the inherent uncertainties in longer ‘geological’ time frames.

4.2.6 Nuclear materials licensing and safeguards

A nuclear fuel cycle facilities oversight programme includes inspections in the areas of safety, safeguards, and environmental protection. This oversight programme applies to all major commercial facilities processing highly enriched uranium, low-enriched uranium, natural uranium, depleted uranium, and/or plutonium.

The international non-proliferation regime seeks to prevent the diversion of sensitive materials and technologies from peaceful uses to the manufacture of nuclear weapons or other nuclear explosive devices. It includes measures and controls that can be summarized into three areas:

- Export and import controls – to increase the difficulty for a country to acquire sensitive materials and technologies.

- Nuclear security and information security – to prevent countries or terrorist groups from diverting or stealing nuclear materials or technologies.
- International safeguards (e.g., as implemented by the International Atomic Energy Agency, IAEA) – to verify that nuclear materials in states are being used for civil purposes.

The IAEA safeguards are designed to provide credible assurances about the exclusively peaceful use of nuclear materials and facilities. The Treaty on the Non-Proliferation of Nuclear Weapons (NPT) is the cornerstone of the global nuclear non-proliferation regime. The Treaty was extended indefinitely at the NPT Review and Extension Conference in 1995. Currently, there are 191 States Parties - 5 nuclear-weapon states and 186 non-nuclear-weapon states:

- **Nuclear-weapon states:** Those States who manufactured and tested a nuclear weapon or other nuclear explosive device before 1 January 1967 – USA, Soviet Union (now Russia), UK**,** France, and China.
- **Non-nuclear-weapon states**[79]: The remaining 186 States parties.
- **Non-signatories** of the NPT: India, Pakistan, Israel.

The most relevant articles of NPT which set out the rights and requirements of states are indicated in the accompanying box. It is worth noting that while there is nothing in the NPT which forbids a non-nuclear-weapon- state from developing enrichment and reprocessing technologies – which are considered sensitive technologies – any state that chooses to develop such technologies can expect to be the subject of significant international attention and possibly subject to economic and trade restrictions. Furthermore, some countries may seek to make it a condition of nuclear trade and cooperation agreements that a newcomer country legally forgo its right to develop these technologies and facilities.

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[79] The Democratic People's Republic of Korea – joined the NPT in 1985. It announced its decision to withdraw from the NPT in 1993 and 2003.

The main articles of the NPT

Article I – Each nuclear weapons states shall not transfer nuclear weapons or control over such weapons.

Article II – Each non-nuclear weapons states shall not receive the transfer or manufacture nuclear weapons.

Article III – Each non-nuclear weapons states shall accept IAEA safeguards on all special fissionable and source materials in all peaceful nuclear activities in the territory of the state, under its jurisdiction or control and conclude comprehensive safeguards agreements with the IAEA.

Article IV – All States parties have ‘inalienable rights’ to develop, produce & use nuclear energy for peaceful purposes, in conformity with Articles I and II of Treaty.

Article VI – All States parties shall pursue negotiations in good faith on effective measures relating to cessation of the arms race and to nuclear disarmament

Article X – Each State party shall have the right to withdraw from Treaty if it decides that extraordinary events, related to the subject matter of the Treaty, have jeopardized the supreme interests of its country.

4.3 Sustainable management of radioactive materials and waste

Radioactive materials and wastes are produced during the commissioning, operating and decommissioning phases of nuclear power plants, uranium mines and other fuel cycle facilities. These demand sustainable management practices which protect workers and the environment. With an increasing number of countries beginning nuclear power programmes, as well as an increasing number of nuclear power plants reaching the end of their operating lives, ensuring the sustainable management of these materials remains a topic of great interest. This has naturally encouraged international cooperation and led to the sharing of experiences based on lessons-learned, joint research and development, and even some shared waste treatment facilities.

Radioactive waste and spent fuel management practices continue to evolve, benefitting from the continuous integration of the most recent findings and experience. This knowledge is disseminated worldwide through established channels that seek to ensure a responsible and internationally harmonized approach. Cooperation is facilitated by organizations such as IAEA, OECD-NEA, WNA and the Electric Power Research Institute (EPRI). Their recommendations cover all relevant aspects for dealing with radioactive materials and waste.

By taking advantage of the most recent international guidelines and recommendations, nuclear newcomer countries can benefit significantly from the experience of established nuclear countries. They should implement this knowledge in the early stages of their nuclear programmes and thereby reduce the future amount of waste generated and the cost and difficulty of its management and eventual disposal. They can also benefit from current global developments such as the increasing preference for recycling and reuse of materials, as well as innovations in technology such as robotics and automation.

4.3.1 Classes of radioactive waste

Radioactive materials are created in the nuclear power sector both directly as a result of the fission process, and indirectly when non-radioactive materials come into contact with radioactive ones. Most materials used in the generation of nuclear electricity can be recycled and reused, provided that they do not become overly contaminated and difficult to treat. Even spent nuclear fuel cannot automatically be considered to be a waste, since the opportunity exists to recycle it after reprocessing (as discussed in section 4.2). The term ‘radioactive waste’ therefore only applies to radioactive materials for which it is considered impractical to reuse or recycle, and which are destined for disposal. Choosing not to reprocess spent nuclear fuel therefore means that it becomes waste, even though it still contains valuable material.

Radioactive waste occurs in a variety of forms, including:

- Vitrified high-level waste from reprocessing used fuel or entire spent fuel assemblies.
- Solid waste, including:
    - Activated/contaminated concrete.
    - Compactable (including activated metals).
    - Incinerable (paper, plastics, gloves, protective clothing, filters, etc.).
- Aqueous effluents, such as decontamination solutions and those from laboratory drains.
- Ion exchange resins.
- Gaseous radioactive waste (e.g. fission and activation gases that are generated during nuclear power plant operation, or gases created by waste treatment facilities such as incineration). Gaseous radioactive wastes are usually retained in specific waste systems (e.g. pressurized tanks for storage, absorbent charcoal beds).

These all need to be treated, conditioned, packaged and disposed of in specific repositories. Despite a common misconception, only 10 percent of the waste material generated from nuclear energy is classed as radioactive waste while the remaining 90 percent is essentially non-radioactive or has a level of radioactivity sufficiently low to be mostly reused and recycled. This category includes most of the concrete and metals used on nuclear power plant sites. The choice of whether to give them a ‘second use' depends on the analysis of various economic, legal, technical, environmental and time considerations, and is integral to sustainable waste management.

Radioactive wastes are categorized according to the level of radioactivity present as well as the amount of time they stay radioactive, this latter being determined by the half-lives of the radioisotopes present. The IAEA provides the following classification[80]:

- Very low-level waste (VLLW) and low-level (LLW) wastes are wastes that are suitable for disposal in near surface landfill type facilities.
- Intermediate-level waste (ILW) and high-level waste (HLW) require underground disposal. ILW and HLW contain long-lived radionuclides which require disposal depths of the order of 10s to 100s of metres. HLW also contains large amounts of long lived radionuclides or activity levels high enough to generate significant quantities of heat.

The overall aim of waste management is to reduce the potential hazard of the waste stream and isolate materials from the biosphere, environment, and society for as long as they remain hazardous. Where the activity levels of materials are below exemption levels, they can be cleared from regulatory control and treated as non-radioactive waste in accordance with the relevant national regulations. Since radioactivity naturally decays over time, some wastes which are in storage for long enough may change categories. Despite the small volumes, radioactive wastes are managed very carefully by the plant operators and are subject to strict oversight from regulators.

It needs to be emphasized that about 97 percent of the radioactive waste by volume generated by the nuclear industry is, after radiochemical characterization, classified as either LLW or VLLW[81]. HLW, which consists mostly of used nuclear fuel and vitrified remnants, makes up the smallest fraction in terms of volumes (less than 0.1 percent), but accounts for about 95 percent of the total radioactivity. Since the 1950's, the consensus adopted by the international nuclear community in relation to the final step in the management of HLW entails its disposition in a geologic disposal facility (see section 4.5)[82].

4.3.2 Integrated approach to radioactive materials and waste management

In order to improve their sustainability, nuclear operators need to adopt an 'integrated approach' to the management of back-end activities. An integrated approach covers the management of conventional materials, declassified waste, different classes of radioactive waste, spent fuel. It integrates all processing steps from sorting, reuse, treatment and conditioning, onsite and off-site storage, transport up to disposal of ultimate waste. It incorporates principles of environmental protection and public consultation, as well as seeking to constantly improve safety, reduce costs and increase efficiency. It will also clearly define the

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[80] *Classification of Nuclear Waste*, General Safety Guide, No. GSG-1, IAEA (2009)

[81] *Status and Trends in Spent Fuel and Radioactive Waste Management*, IAEA (2018)

[82] *Disposal of Radioactive Waste on Land*, US National Academy of Sciences (1957),

assignment of responsibilities amongst the organizations involved, and implement a specific legal and regulatory framework at an early stage. These integrated approaches appear to be particularly relevant for newcomers during the early phase of their nuclear programmes, and countries that are considering small modular reactors[83].

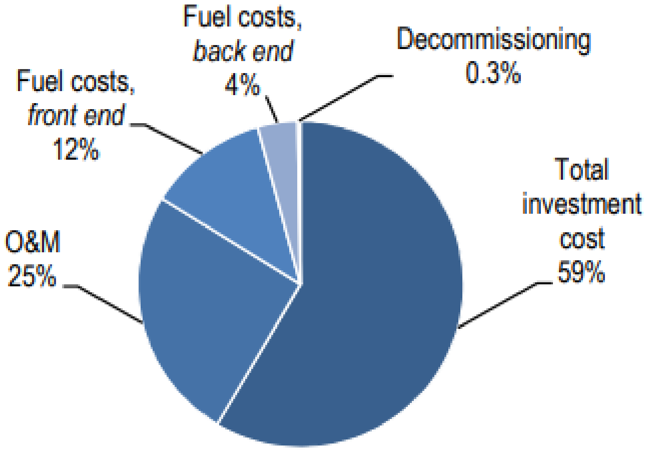

Figure 4.7 Structure of nuclear electricity generation cost, at a 5 percent discount rate. Source: OECD-NEA.

Another fundamental component of an integrated approach is the establishment of a suitable spent fuel and waste management funding mechanism in national policy. A detailed analysis conducted by the OECD Nuclear Energy Agency[84] reveals that the costs associated with back-end activities and decommissioning represent a relatively small fraction of the total levelized cost of electricity generation for a nuclear power plant, as shown in Figure 4.7. These costs occur in the future and are therefore discounted compared to what they would cost today.

While these costs are not prohibitive, and funds can readily be collected either as a tax or a required amount that operators set aside as part of their fuel and operating/decommissioning costs, it is important that funds are available on time for key expenditures. Also, overall costs are subject to change and need to be re-evaluated periodically. One of the biggest risks of funding shortfall is if plants are retired prematurely. This results in less funds being collected and expenditures being brought forward.

Strategic considerations in spent fuel and radioactive waste management and decommissioning also have to take into account effective stakeholder engagement. The IAEA has published several comprehensive technical documents on this[85,86,87] and the OECD Nuclear Energy Agency has established the Forum on Stakeholder Confidence to foster learning about stakeholder dialogue

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[83] I. Gordon, S. Monti, *Considerations in Radioactive Waste Management for SMRs – The Role of The IAEA*

[84] *The Economics of the Back End of the Nuclear Fuel Cycle*, OECD NEA, (2013)

[85] *An Overview of Stakeholder Involvement in Decommissioning*, IAEA (2009)

[86] *Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities*, IAEA (2011)

[87] IAEA, 2014, Communication and Stakeholder Involvement in Environmental Remediation Projects

and ways to develop shared confidence, informed consent and acceptance of radioactive waste management solutions[88].

4.3.3 Current trends and influencing factors

Nuclear back-end practices continue to improve as a result of innovation with a number of topics addressed through international cooperation and exchange between various research programmes. The IAEA has made a variety of valuable resources available on its Nucleus website[89] which have been created by its professional networks, including: the International Predisposal Network (IPN), the International Network of Laboratories for Nuclear Waste Characterization, International Low Level Waste Disposal Network – DISPONET, International Network on Spent Fuel Management (SFM Net), Underground Research Facilities Network for Geological Disposal (URF) and the International Decommissioning Network (IDN). Several proposed European initiatives are noteworthy in this regard too. The EURAD programme seeks to coordinate activities on common priorities identified by European waste management organisations, technical support organisations and research institutes, while the PREDIS project targets the development and implementation of activities for pre-disposal treatment of radioactive waste streams other than nuclear fuel and high-level radioactive waste.

Important recent examples of innovation include automation and robotics that can accelerate the completion of decommissioning projects while reducing the exposure of workers to radiation. Ongoing innovation will also help to further reduce environmental impacts and costs. Operator skills, techniques and training competencies will have to adapt in order to keep pace. Other industries will also be able to benefit from new technologies originally developed for nuclear material and waste management. For example, exo-skeletons originally developed for the nuclear industry could be adapted to assist people that suffer from reduced mobility.

However, challenges are not limited to those of a technical nature and there are various factors that may influence spent fuel and waste management strategies over time. Seeking regulatory alignment is one such factor. National waste regulations vary from country to country as international principles are adapted to meet local considerations and national policies objectives. Such differences between neighbouring countries may lead to public confusion and loss of confidence in nuclear operations.

Aligning national regulatory practices with internationally approved standards and directives will anchor the role of intergovernmental authorities in back-end practices. It should also increase the confidence of nuclear project stakeholders that the best available materials management techniques are being employed. The resulting harmonization of practices, and especially between neighboring countries, should boost credibility for the project and enable

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[88] See OECD NEA website, Forum on Stakeholder Confidence

[89] See IAEA Nucleus website

project developers to focus on improving the sustainability of a project, rather than having to continually provide fundamental justification.

The alignment of national policies to existing and already approved international directives by the various countries would also assist the incorporation of lessons learned from one country to another. This would allow benchmarking and comparison on a common basis, as well as helping to identify new areas for R&D to target ongoing improvement and innovation. It should also ease the qualification of decommissioning operators and foster the sharing of experience and global cooperation.

4.3.4 Examples of good practice

Some recommendations and good practices have been developed based on the international experience acquired by the operators involved in radioactive waste management and decommissioning projects. These are presented below and can serve as a basis for developing new integrated approaches for new facilities. Nuclear operators and regulators should:

- Conduct continuous characterization of radionuclide inventories, starting from the design phase and site selection, and pursue this all along the decades of operation until decommissioning.
- Use best available techniques/technologies (BAT) whenever possible to reduce the volume of radioactive waste generated and destined to be disposed of.
- Implement a 'circular economy' – reuse and recycling materials should be implemented wherever practical[90] in order to support sustainability of nuclear power generation.
- Make use of dedicated facilities (for instance, demonstrators) and existing infrastructure for training and education of operators.
- Secure funds for back-end management and guarantee their availability, on time, based on well-established spent fuel and radioactive waste management and decommissioning programmes and associated roadmaps.
- Foster experience-sharing and international cooperation for the decommissioning of nuclear facilities and the management of spent fuel and radioactive waste, along with sharing the necessary scientific and technical knowledge of best practices and the solutions available for emerging issues as well as technology development and R&D.
- Whenever possible, align and harmonize the application of the internationally agreed regulatory basis to readily incorporate lessons learned from one country to another.

4.3.5 Summary

The global nuclear industry has dedicated considerable efforts over the decades to developing the necessary technologies and international frameworks for safely managing radioactive waste and spent fuel. Recommendations and lessons learned have been thoroughly captured which

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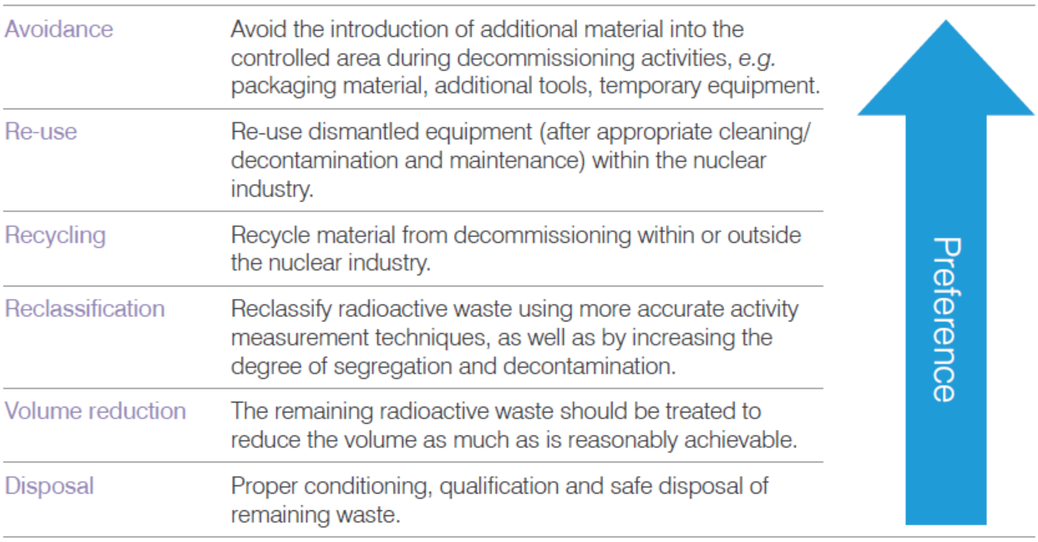
[90] See Pieraccini et al, *A nuclear owner/operator perspective on ways and means for joint programming on predisposal activities,* European Physics Journal on Nuclear (5 May 2020), 190064

now help to ensure the successful implementation of these programmes in many countries. There are a number of mature techniques available which can mitigate all serious environmental impacts of radioactive waste management and disposal. This needs to be recognized by potential newcomer countries as they consider whether to begin a nuclear energy programme. They should seek to build them into their waste management programme in simple, effective steps at an early stage, as outlined in international best practice recommendations.

The growing inventories of spent fuel and radioactive waste present a global challenge, but also provide a solid opportunity to transfer knowledge between countries. It has already led to increasing the sharing of experience and personnel, thanks to common training and globally recognized qualifications and degrees. Industrial means and capacities will increasingly be shared between countries as will be the use of some facilities. To make this easier, regulatory alignment between countries should be fostered, building on existing international recommendations and directives already approved by most countries.

4.4 Focus on decommissioning

During the decommissioning of nuclear facilities, significant quantities of radioactive materials and waste will be generated in a relatively short time period. The waste hierarchy establishes the priority order for managing this in the most sustainable manner possible. In brief, the aim is to move up the chart – i.e. avoid producing waste wherever possible, and to capitalize on all opportunities to safely reuse or recycle materials in order to minimize the volume for final disposal. Figure 4.4.1 defines the significance of each step.



Avoidance	Avoid the introduction of additional material into the controlled area during decommissioning activities, *e.g.* packaging material, additional tools, temporary equipment.
Re-use	Re-use dismantled equipment (after appropriate cleaning/ decontamination and maintenance) within the nuclear industry.
Recycling	Recycle material from decommissioning within or outside the nuclear industry.
Reclassification	Reclassify radioactive waste using more accurate activity measurement techniques, as well as by increasing the degree of segregation and decontamination.
Volume reduction	The remaining radioactive waste should be treated to reduce the volume as much as is reasonably achievable.
Disposal	Proper conditioning, qualification and safe disposal of remaining waste.

Figure 4.8 The radioactive waste hierarchy. Source: WNA[91].

The application of the principle of "waste hierarchy" encourages recycling and thus the minimization of waste to be disposed of. Despite different regulations in different countries, some actions can be applied by all to support the achievement of the aims of the waste hierarchy, and assist the development of a sustainable decommissioning strategy. To this end a

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[91] *Methodology to Manage Material and Waste from Nuclear Decommissioning*, WNA (2019)

set of observations and recommendations has been prepared by the World Nuclear Association Waste Management and Decommissioning Working Group, as shown in the accompanying box.

Recommendations and observations for effective decommissioning

Recommendations on ‘end states’ definition and associated decommissioning strategy**:**

- Decommissioning strategy selection must consider of a wide range of influences including national policy, space requirements, funding, waste disposal availability, nuclear power plant fleet closure programmes, future use including re-use for nuclear and more; hence, the strategy may not be selected on technical attributes or operational priorities. Currently, significant drivers to selection are economic and waste management availability which normally supports the ‘Deferred Decommissioning’ option.
- Definition of end state (the future use of the nuclear site after decommissioning process has been completed) and associated strategy (either if deferred or immediate) has to be established, ideally in the planning phase of the nuclear decommissioning project.
- The selection of a particular decommissioning strategy has a more significant impact on the selection of appropriate methodologies for waste processing than ‘end state’ influences, especially for managing hazards from the ILW and LLW radioactive inventories.
- The selection and application of a decommissioning strategy will influence the quantity and category of radioactive waste generated during decommissioning, influencing the complexity of processing methodologies and the provision of suitable handling, transport and storage facilities.
- End state objectives are normally determined outside the control of the nuclear power plant operator by a combination of applicable national goals, policies and regulations developed to satisfy a complex mix of strategic, economic and technical criteria. As a consequence, any decommissioning plan will need to understand both the goal (end point) and how achieving that goal would be validated.
- National approaches to End States normally have goals but are not prescriptive on how this is demonstrated or achieved. It is important that the nuclear power plant operators define the processes to be deployed and validate approaches prior to commencing decommissioning in order to ensure these are optimized.
- Strategy and End State definition have a direct impact on decommissioning planning and estimating criteria. The earlier in the facility lifecycle that the decommissioning requirements and objectives are identified then the earlier they can be defined, allowing the associated finances to be available in line with the proposed project schedule and activities.

Recommendations on establishment of reliable detailed Inventories taking into account the history of the nuclear facility since its siting.

- In order to perform an efficient decommissioning, a complete inventory or radioactive material and waste is needed, as the volume of radioactive waste is one of the main factors affecting the costs.
- Proper characterization of physical and radiological inventories to assess the type, nature and amounts of waste needs to be undertaken in order to adequately prepare the waste routes and management steps, including treatment capabilities. Inventory records need to be maintained throughout the operation of the plant and a thorough assessment needs to be made at the beginning of a decommissioning project.
- All information about modifications, systems, accidents and their consequences will be logged, documented and stored in a nuclear power plant operations database.
- Every single facility would normally require an independent calculation of the induced activity levels and shielding materials by the time of its decommissioning.

Recommendations on the identification of available waste routes and definition of decommissioning scenarios (including both dismantling, suitable, environmental sustainable treatment options):

- In order to reduce the waste volume, it is necessary to sort the actual radioactive waste to be disposed of and to separate them from other materials that could be recycled.
- The principle of recycle and reuse of radioactive materials should be pursued wherever possible (in terms of techniques and processes available, routes developed and cost efficiency) with materials sorted accordingly.
- The selection of suitable treatment technologies for radioactive waste has to be done in accordance with the respective Waste Acceptance Criteria (WAC). Where WAC are not available yet, the chosen treatment technologies should generate inert, water free matrixes.
- Treatment, conditioning and transport of radioactive waste will be conducted such as to minimize the final volume of waste while ensuring safe handling in line with the ALARA principle of radiological protection. Wherever economical, use of Best Available Technology is encouraged for this.
- The variety of amounts of materials, waste routes and waste management strategies requires a range of treatment processes that are commonly used throughout industry.
- Disposal of waste should be achieved in dedicated repositories according to the hazard presented by the waste, national regulations and other factors. These range from surface or near-surface facilities for LLW and some ILW, to deep geological repositories for other ILW and HLW, including spent nuclear fuel.

International feedback survey and incentivization of innovation:

- A variety of waste routes should be kept open for each category of radioactive material whenever reasonable to ensure that waste handling and treatment never become bottle necks.

Funds mechanisms:

- At all steps, financial provisions have to allow the availability of funds, on time, when needed, incorporating also the necessary pragmatic R&D.

Education and training:

- Countries should make better use of dedicated facilities (for instance, demonstrators) and existing infrastructure for training and education of operators.

Taking account of lessons learned.

- Gathering feedback acquired on worksite and sharing knowledge is important to implement experiences in future projects to improving future designs, environmental preservation, and technical and financial mastery as well as to encourage public acceptance and nuclear industry credibility and sustainability.

As a consequence of the growing number of nuclear facilities entering decommissioning worldwide the associated waste management challenge is also growing. Many of the older nuclear facilities were not fully designed with decommissioning in mind. However, nowadays new nuclear technologies and projects should incorporate dismantling and waste management considerations from their earliest stages. Therefore, nuclear decommissioning projects in the future should be easier.

Over the last few decades, the nuclear industry has been expected to continuously improve its performance regarding its societal and environmental impact. In contrast to the early years of the industry – when military or energy security concerns were prioritized – increasingly stringent standards have been introduced which industry must conform with. In order to maintain stakeholder confidence and public acceptance, nuclear operators have to provide assurance not only of their ability to carry out decommissioning in a safe and effective manner, but also of their competence in technical, financial, environmental and societal areas. The nuclear community therefore continues to carry out research to identify ways of enhancing existing decommissioning and waste management processes.

Decommissioning and associated waste management should not be seen as separate from the operation of a nuclear facility, but simply, as the last of the three normal phases of its life-cycle, after construction and operation. Implementing solutions to the financial and technical challenges of decommissioning management is simply a part of ensuring that nuclear power is a sustainable option. Handling the radioactive materials and waste produced during decommissioning is a complex multidisciplinary task that requires case-by-case attention. However it can be done, and is being done in a safe and effective manner by organizations in many different countries. Newcomers should expect no less.

4.5 Disposal of high-level waste

A key aspect of improving the sustainability of nuclear energy is ensuring a route to the disposal of the resulting radioactive wastes. Today, many near surface disposal facilities for VLLW and LLW are being operated worldwide and several underground disposal facilities for LLW and ILW exist as well. The recognized practicable solution for final disposal of HLW is emplacement in deep geological formations that have been stable for timescales far beyond the active lifetime of even very long-lived radionuclides. Following decades of R&D, scientifically and technologically mature disposal concepts for HLW exist and several countries are making sustained progress towards the operation of a Geological Disposal Facility (GDF).

Implementation of a GDF is expensive in absolute terms; current national cost estimates range from a few to tens of billions of US dollars. However, for a nuclear-power programme of significant size, the disposal costs represent a relatively minor part of all the cost of generating electricity – and, importantly, the forecasted necessary funds can be accumulated by only a small surcharge on the electricity produced (as discussed in section 4.3). For small nuclear power programmes with only one or a few nuclear reactors, on the other hand, financing a national GDF represents one of the more serious challenges they face. Certain countries may also face challenges in identifying geographical regions and geological environments that are suitable for a GDF. Key documents such as the IAEA Joint Convention on Spent Fuel and Radioactive Wastes management[92] or the Spent Fuel and Waste management Directive of the European Commission[93] state that while the ultimate responsibility for the management of radioactive waste lies with the generating country, they accept that, in certain circumstances, safe and efficient management of spent nuclear fuel and radioactive waste might be fostered through agreement among countries to use shared facilities including a GDF. Accordingly, as described below, agreements between sovereign states might eventually lead to development of a multinational repository.

What are the back-end options open to any country which has, or which plans to introduce, nuclear energy into its national energy strategy? The resulting HLW can be safely stored at the surface for many decades – but this is not a permanent solution and disposal will ultimately be necessary. Broad approaches towards implementing the required disposal facilities have been documented in a number of publications. They are summarized below.

4.5.1 Developing a national geological disposal facility

From a technical standpoint any nuclear waste disposal facility needs to accomplish three things[94]:

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[92] *Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management*, INFCIRC/546, IAEA, Vienna (1997),

[93] *Council Directive 2011/70/Euratom of 19 July 2011 Establishing a Community Framework for the Responsible and Safe Management of Spent Fuel and Radioactive Waste*, European Commission (2 August 2011),

[94] Juhani Vira (Posiva), *Concepts Developed for disposal of HLW and/or SNF* (2014)

- Isolate the waste from the biosphere and substantially reduce the likelihood of inadvertent human intrusion into the waste.
- Contain the waste until most of the radioactivity has decayed.
- Delay migration of radionuclides to the biosphere.

For HLW, a GDF needs to be capable of meeting these requirements for on the order of several 100,000 years. In order to achieve this, multiple barriers need to be placed between the waste and the biosphere. HLW first needs to be immobilized in an insoluble matrix, then sealed in a corrosion resistant canister and finally placed several hundred metres underground in a suitably stable rock structure. Designing such a facility poses a complex environmental engineering and cost optimization challenge which requires careful research and development. Each potential site will be different and so will each concept, requiring solutions which are designed accordingly. Promising geological media include crystalline rock, sedimentary rock and salt formations, but each needs to be matched with additional engineered barriers.

Nevertheless, the constantly improving scientific knowledge of geology, materials and how radioisotopes move through different media, as well as advances in mining technology and practices, provide very high levels of confidence that such facilities can be successfully constructed. In fact no other type of human waste is subjected to such high standards and rigorous research and development. By seeking to make absolutely certain that waste produced today does not become a burden for future generations the nuclear industry demonstrates strong alignment with principles of sustainable development.

Arguably harder than demonstrating technical feasibility of GDF concepts has been building and maintaining the necessary public support for such facilities. There are understandable fears about nuclear waste amongst the general public which makes it hard to find willing host communities – and harder still to maintain political support over the long project development timeline. Several countries have apparently achieved success through consultation based on voluntary approaches. In Sweden two communities vied to host the national GDF with a victor, Forsmark, selected in 2009. In other countries progress on GDFs has stalled. The USA, for example, spent billions of dollars characterizing Yucca Mountain after designating it the site of a national repository in 1987 – only to have the government cancel the decision in 2009 as result of political opposition.

Nuclear newcomer countries are encouraged to learn from international experience and to adopt a consultation based approach suitable to their culture. Effective stakeholder engagement is crucial when developing and implementing a disposal programme[95,96].

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[95] *Communication and Stakeholder Involvement in Radioactive Waste Disposal*, IAEA (2020).

[96] *Stakeholder involvement throughout the life cycle of nuclear facilities*, IAEA (2011).

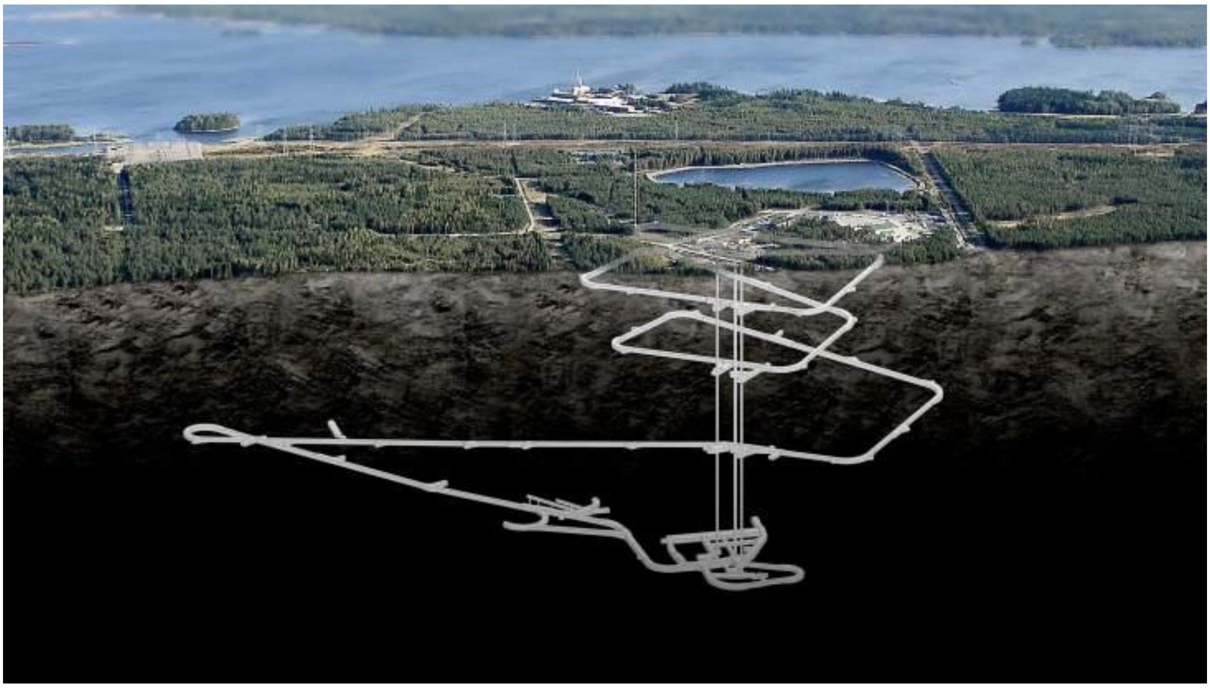

Figure 4.9 Artist's impression of the planned Onkalo repository in Finland. Tunnels from the surface extend for many kilometres before reaching the chambers where canisters are emplaced. Source: Posiva.

As stated above GDFs represent large capital investments, but the major financial outlays necessary do not arise until some long time after nuclear power production has started. This allows funds to be gradually accumulated via payments which amount to only a very small fraction of the revenue of a nuclear plant. Spent fuel emerging from a reactor (and also high-level radioactive wastes from reprocessing) need to have an extended cooling period before being emplaced in deep underground so that a GDF will only be required to operate decades after initial nuclear power production. However, the evidence from national disposal programmes indicate that to progress from the initial choice of disposal concept, through facility design, site selection and characterization, to repository construction and operation, currently takes longer than 20 years. Therefore establishing a management and disposal strategy is something that should begin at the early stage in a nuclear power programme.

Building the necessary technical competences, establishing an effective regulatory system and mechanisms to accumulate the funds required for later construction and operation of the repository are all critical activities that should have commenced by the time a nuclear power programme starts generating electricity. In typical spend profiles based on repository planning, costs remain modest in the planning phase, rise significantly when comprehensive site characterization tasks are undertaken, peaks during the construction phase and continue at a significant level through the operational phase, which can last for several decades up to the closure. Costs must be also considered for GDF post-closure monitoring.

International progress towards GDFs

Finland’s national spent nuclear fuel repository Onkalo is presently being built into the granite bedrock at Eurajoki (the site of the Olkiluoto nuclear power facility) by Posiva. A very thorough site selection process began in 1983. It involved four prospective sites and took into account geological and environmental factors- as well as democratic and local opinion - before the Finnish government made its decision. The construction of Onkalo is well under way and Posiva expects commercial operations expected by 2023.

In Sweden, R&D also work began in the 1980’s with multiple candidate sites leading up to Sweden selecting the Forsmark site in 2009. On January 23, 2018, the Swedish Radiation Safety Authority, SSM, completed its review of SKB’s application for permission to construct a repository for spent nuclear fuel and recommended that the government issue such a permit. This approval of SKB’s license application was a fundamental step towards the establishment of a Swedish final repository. Some details are still being challenged but currently Forsmark, another repository for spent nuclear fuel, is also expected to become operational in the 2020s.

Responsibility for the development and operation of a final disposal facility for radioactive waste in France lies with the National Radioactive Waste Management Agency (Andra). Work already began in 1988 for the purpose of identifying a suitable site for a high-level radioactive waste repository. Authorization for an underground laboratory in the Bure municipality in France was granted in 1999, with construction beginning soon after. In 2012 Bure was officially proposed as the site for a national repository. A government decision on whether to proceed with the construction and operation of a reversible deep geological repository is expected soon.

The site selection process for a GDF in Russia started in Russia in the 1980s. Having evaluated various options, in 2008 the government made the decision in favour of the Nizhnekansy massif in the Krasnoyarsk region. A responsible body, National Operator for RW management, was established in 2011, and its funding mechanism and the main principles were recorded in the national law. The first stage of repository development is an Undeground Research Laboratory, designed and approved in 2016 with construction works starting in 2018. It is expected that in approximately 2035 all the required R&D will be complete and GDF construction will begin.

4.5.2 Examining alternative technologies

For countries that have small nuclear programmes and correspondingly small radioactive waste inventories, there will be considerable interest in developing approaches that promise to be more cost efficient than implementation of a conventional GDF, which consist of mined tunnels and caverns at depths of hundreds of metres. One potentially practicable option being developed is deep borehole disposal. Disposing of highly active wastes in boreholes drilled to depths of a few kilometers has been discussed at various times over the past decades, however the restrictions on feasible hole diameters restrict the types of waste packages that can be emplaced, and, for large spent fuel inventories, the numbers of required boreholes make the concept unattractive[97]. However some recent early stage US studies indicate that, with modern drilling technology which allows long horizontal boreholes to be drilled at great depths, the potential feasibility of this option could be enhanced[98].

Another solution that has been proposed as a possible approach to reducing quantities of wastes that need to go to a GDF is chemical partitioning of the high level waste with further transmutation of the long-term lived fraction with the help of the special techniques like Fast Neutron Reactors or Accelerator Driven Systems. Some technologies for HLW partitioning and minor actinides transmutation are at an advanced level of R&D study today but the feasibility and the costs of treating large spent fuel inventories are open questions. As the technology matures, these costs would need to be considered in relation to any savings on the development of a GDF.

4.5.3 Explore multinational and regional approaches as part of a dual track

A key characteristic of a GDF programme is that the fixed costs (i.e. all steps leading up through siting to construction of access shafts or tunnels) constitute a relatively large part of the total costs and are independent of waste inventories. Variable costs that are proportional to inventory include those for excavation of disposal tunnels or caverns, and encapsulation of wastes and waste emplacement operations. Sharing the fixed costs between a number of partners may result in economies of scale. The benefits that a multi-national repository (MNR) could bring are wider than the purely economic – but there are also significant hurdles, as described below.

While currently there are no MNRs planned or in operation, there are various ways in which the development of MNRs have been approached and might come to exist in the future.

- *Sharing with other small programmes*. In this approach a group of countries with small HLW inventories agree to set up a shared facility, establishing joint management and pooling funds.
- *Using or offering a commercial disposal service*. This is a variation on the above where differences relate mostly to the process for initiating the development of the MNR and to the final relationships between service provider and users. In the commercial case, the potential profits would be the prime incentive for undertaking the project.
- *Take-back or take-away by a supplier of a broader nuclear service such as power plant construction, reactor fuel fabrication or reprocessing*. A logical solution to the spent fuel

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[97] Chapman, N. A., *Who might be interested in a deep borehole disposal facility for their radioactive waste?*, Energies, 12, 1542; doi:10.3390/en12081542 (2019)

[98] Muller R.A. et al, *Disposal of High-Level Nuclear Waste in Deep, Horizontal Drillholes*, Energies, 12, 2052; doi:10.3390/en12112052 (2019)

disposal challenge of small or nuclear newcomer programmes would be that the supplier of such services agree to take back spent fuel and manages them along with the much larger inventory from its own program and from other take-back users.

- *"Add-on" by a country already organizing a large scale GDF.* This is a potential advantage to 'first mover' countries which develop their repository before others. They have the option to offer such a service in the future, most likely on a commercial basis.
- *A supranational solution*. The concept of a supranational solution, i.e. a GDF controlled by an international organization has previously been suggested. However, no serious attempts have been made to further this option.

A longer discussion of the approach that would be needed to develop a multinational repository as well as the legal, contractual and institutional arrangements are covered in an IAEA report[99].

The most obvious benefits of MNRs are economic. The users can expect unit disposal costs below these that would arise from implementing a small scale national GDF. The provider of an MNR could also enjoy economic benefits. A multi-year GDF project could bring in a very large revenue stream that could be used to benefit not only the GDF operator but also the host region and country in which the facility is sited. But the benefits are not only purely economic, there are also potential socio-economic, environmental and geo-political benefits. Socio-economic benefits include additional jobs, spin off industries and infrastructure development needed to transport and manage the waste inventories. Environmental benefits stem from reducing the number of sites for HLW disposal. Geo-political benefits result as the host nation becomes more influential within the global nuclear community.

Of course, initiatives to establish an MNR also face significant challenges. Given that many national GDF programmes have experienced immense difficulties and major setbacks while trying to identify willing host communities and regions, this risk is likely to be greater for a MNR programme which can clearly be implemented only on a voluntary basis. The issue of importing radioactive waste also remains very sensitive, and even forbidden by law in several countries. Therefore newcomer countries cannot depend on such a solution being available in the future.

It should be noted that for any country, the options listed are not mutually exclusive and a decision on a final repository option can be kept open. The long development time for a disposal solution implies that premature choices need not be locked-in. In particular, it has been emphasized by international bodies that countries should not rely on hopes that one of the options in the multinational category will definitely be available. A national programme including competence building and funding accrual should be commenced in any case. Running this along with keeping multinational options open has been described as a "dual track strategy".

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[99] *Framework And Challenges For Initiating Multinational Cooperation For The Development Of A Radioactive Waste Repository,* IAEA (2016)

4.5.4 The relevance of waste disposal to the sustainability of nuclear power

There is an ongoing debate on whether the issue of the final disposal of the wastes from reactors impact upon the assessment of nuclear power as a sustainable energy source. The following points can be made in this context.

- Existing scientific, technical and financial approaches can ensure that radioactive wastes are safely and securely disposed of using current technologies. It can also be claimed with confidence that treatment and disposal technologies will continuously improve as a result of ongoing R&D.

- For any given nuclear power programme to be judged as sustainable there must be an acceptable, safe and secure plan for disposing of the radioactive wastes that are produced. This plan may include several options to be decided upon at a later stage.

- Existing technologies allow for nuclear waste to be safely stored on the surface for decades if not hundreds of years. The long development time for a disposal solution implies that final choices need not be locked-in prematurely.

- Disposal in a deep GDF is currently the internationally recognized and practicable approach for the sustainable disposal of HLW. Therefore every country has a responsibility for ensuring that a GDF will be available for their HLW in the future. This GDF can be a national repository exclusively for wastes from the producing country or a multinational repository that accepts wastes from a number of countries.

- A successful MNR project with a willing host country and is carried out in compliance with all relevant laws could result in significant benefits; however, newcomer countries cannot depend in such an option being available in the future and should also start development on a national GDF as part of a ‘dual track’ strategy.

- By seeking to make absolutely certain that waste produced today does not become a burden for future generations the nuclear industry demonstrates strong alignment with principles of sustainable development.

Chapter 5 Nuclear Technology Options

> *Currently available nuclear reactor designs are based on mature and proven technologies that in some instances have been licensed to operate for 80 years. A range of options are available, all of which offer high levels of safety and outstanding operating performance. They provide reliable, affordable and low-carbon electricity to support a country in meeting its sustainable development goals. In addition, a wide range of small modular reactors and advanced reactors are currently under development, with some ready for near-term deployment. These offer enhanced flexibility and will be suitable for helping to decarbonizing heat and transport as well as electricity – potentially boosting sustainability even further. Nuclear innovation and the pursuit of so-called hybrid energy systems are the catalysts for integrated development and strengthening linkages between the nuclear sector and other clean energy technologies and non-energy sectors. The UNFC and UNRMS frameworks enable consideration of technologies at different levels of maturity to optimize the development of resources with positive impacts on the society, environment, local economies and employment.*

Selecting reactor technologies and technology partners is one of the most critical decisions facing a nuclear newcomer country, and indeed any country looking to start a new reactor build programme. There are many mature and proven nuclear technologies available today. The 44 reactors that were connected to the grid in the five years from 2015 to 2020 consist of 19 different designs – these are all evolutionary upgrades of existing technologies and offer exceptional safety and reliability as well as low fuel and operating costs. They have typically large power outputs – of the order of a gigawatt – and are sold by large and experienced international nuclear vendors, which are also national champions of their countries of origin. A history of nuclear technology development and an overview of the currently available technologies is provided in section 5.1.

However, the international reactor market is changing quickly and a range of new designs will become available in the coming years. Among these, what are known as small modular reactors (SMRs) have gained the most attention, with about 70 designs now in R&D; some are undergoing licensing and others are being constructed. In fact, an SMR nuclear plant – the *Akademik Lomonosov* consisting of two small reactors on a floating barge – began operation off the coast of Russia at the end of 2019, while a high temperature gas-cooled reactor is expected to start operation in China in 2021. Many SMRs are expected to have a first-of-a-kind (FOAK) plant in operation before 2030. Some SMRs are based on today's nuclear technologies but others are more exotic and, if commercialized, will bring significant diversification to the global nuclear sector. They are being developed by the established nuclear vendors, but also by a number of what are essentially start-up technology companies. The common feature of all SMRs is that they are less than 300 MWe in size, can be factory assembled, and are deployable in multi-module plants. More information on SMRs is provided in section 5.2.

Receiving less attention, but clearly developing quickly, are the so-called microreactor technologies. While not yet officially defined, these reactors are expected to produce between 1 – 20 megawatts (thermal), exhibit some self-regulating features and are designed to be transported as a fully contained power plant. Early designs are being tailored for off-grid applications and defence installations, or can simply be plugged into existing power networks. Some microreactor designs may be available in Western countries soon, as they could be commercially viable without any reforms in the niche markets they are targeting (mostly competing with diesel generators in remote communities or facilities).

The selection of nuclear power plant technologies and technology partners has important implications for the whole nuclear programme. Therefore, the selection should be considered as part a comprehensive strategy, rather than based on technical performance considerations alone. Many of the relevant considerations have already been covered in chapters 3 and 4. In section 5.3 the relationships between technology choice and these considerations will be explored further. For example, certain fuel cycle and waste policy decisions will exclude some reactor technologies from being options.

While traditionally nuclear reactors have provided electricity, there is growing interest in their 'non-electric' capabilities. Already today there are operating reactors which provide district heating and desalination and some are being used to trial the production of clean hydrogen. Advanced nuclear technologies offer even more promising potential in this regard, and newcomer countries may wish to factor them into their long-term energy planning as tools that can aid decarbonization beyond the electricity sector. This topic is explored in more detail in section 5.4.

Any nuclear reactor technology selected will be capable of supplying reliable low-carbon energy and will help nations to meet their sustainable development goals. However, in order to maximize the sustainability benefits, governments will need to carefully assess their own national situation. There is no 'one-size-fits-all' technology.

5.1 Nuclear reactor technologies

In order to understand current developments in nuclear technology it is worth briefly summarizing its history. Soon after the discovery of nuclear fission in 1938, scientists started investigating potential applications. In 1942, Enrico Fermi and Leo Szilard achieved criticality (a sustained nuclear reaction) at the first reactor, known as Chicago Pile 1, which was built in secret as part of the Manhattan Project to develop nuclear weapons during World War II. Early reactor research and development subsequently proceeded throughout the late 1940s and early 1950s in the USA, UK, Canada, and USSR, with a broad range of technology prototypes trialled.

Electricity was generated for the first time by a nuclear reactor on 20 December 1951, at the Experimental Breeder Reactor I (EBR-I) in Idaho, USA, which initially produced about 100 kW.

Active research was also carried out on nuclear marine propulsion, with a test reactor being developed by 1953. The first nuclear submarine, the *USS Nautilus*, launched in 1955. In 1953, US President Dwight Eisenhower gave his famous 'Atoms for Peace' speech at the United Nations, emphasizing the need to develop peaceful uses of nuclear technology. In 1954, amendments to the Atomic Energy Act allowed rapid declassification of US reactor technology and encouraged development by the private sector. The pioneering nuclear nations soon deployed the first generation of nuclear power plants. On 27 June 1954, a 5 MW reactor in Obninsk, Russia became the world's first nuclear power plant when it connected to the grid. The world's first commercial-scale nuclear power plant, Calder Hall at Windscale, England, was opened in 1956 with an initial capacity of 60 MW for the first unit, which was later expanded to 240 MW. The Shippingport Atomic Power Station in Pennsylvania started operation in 1957 and became the first commercial power reactor in the USA.

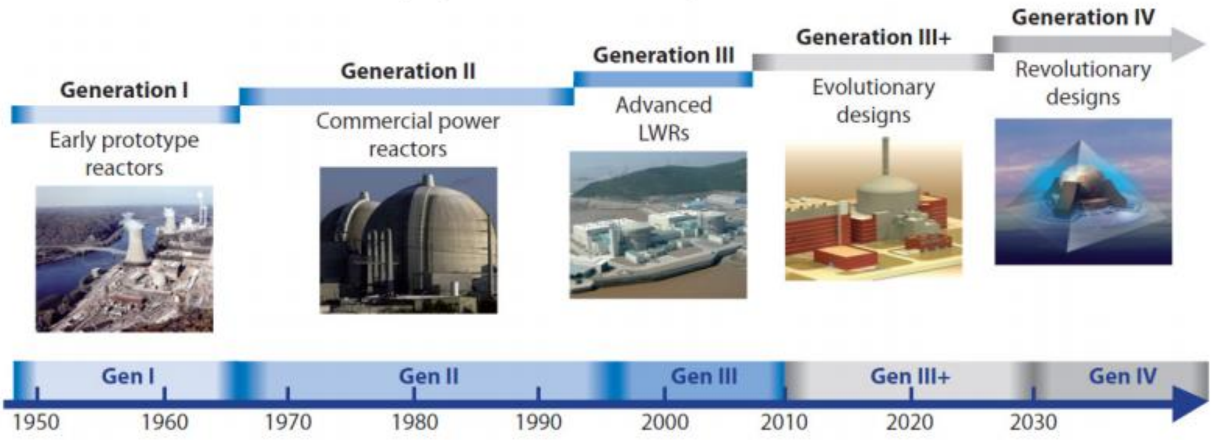

Figure 5.1 Timeline of nuclear power plant generations. Time ranges correspond to the design and the first deployments of different generations of reactors. Source: Generation IV International Forum[100].

The history of nuclear power plants is often divided into four generations, as presented in figure 5.1. The first generation (Generation I) of nuclear power plants was made up of design prototypes. The lessons learned from the construction and operation of these enabled reactor designers to improve their designs, leading to the second generation of nuclear power plants (Generation II), which still make up most of the global nuclear fleet today. During the 1980s, some Western countries started to liberalize their electricity markets and private organizations began to play a greater role in designing, developing and operating nuclear power plants. Vendor nations also adopted more of a commercial approach to their nuclear sectors and actively sought out opportunities export these technologies to newcomer countries, thereby leading to the first true round of globalization of the nuclear industry. The commercialization and globalization of the nuclear enterprise created competition between what by then were the proven and dominant nuclear technology types:

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[100] *Technology Roadmap Update for Generation IV Nuclear Energy Systems*, OECD Nuclear Energy Agency on behalf of the Generation IV International Forum (January 2014)

- Pressurised water reactor (PWR).
- Boiling water reactor (BWR).
- Pressurized heavy water reactor (PHWR).
- Gas-cooled reactor (GCR).
- Light water cooled graphite moderated reactor (LWGR, better-known as the RBMK, *reaktor bolshoy moshchnosti kanalnyy*).

The main technical difference between these technology types, as indicated by the name, involves the choice of reactor coolant – which extracts heat from the nuclear fuel – and moderator – which serves to slow neutrons down so that the fission process can continue. In PWRs, BWRs and PHWRs the coolant and moderator is water, although it is 'heavy' (deuterated) water in the case of the PHWR. The GCR uses carbon dioxide as a coolant and graphite as a moderator, while the LWGR is water-cooled and graphite moderated.

Today's fleet of nuclear power plants largely consists of Generation II designs but some Generation III designs are also operating. Currently, the vast majority of nuclear power plants are light water reactors – which includes both PWRs and BWRs – as presented in table 5.1. PHWRs can also be found in several countries around the world while the GCRs and LWGRs are now to be found operating only in the UK and Russia respectively.

Table 5.1 Operational reactors as of August 2020[101].

Reactor Type	Number of Reactors	Total Net Electrical Capacity (MW)
PWR	299	283,798
BWR	65	65,604
PHWR	48	23,875
GCR	14	7,725
LWGR	13	9,283
FNR*	3	1,400
Total	442	391,685

*Fast neutron reactor

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[101] International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) page on *Operational & Long-Term Shutdown Reactors*

Light water reactor technologies

The pressurized water reactor (PWR) is the most common nuclear power reactor technology in the world today. A PWR comprises two internal cooling circuits containing water. The water in the respective circuits is separated by physical barriers that prevent radioactivity transfer. The primary circuit is maintained at high pressure to prevent the water boiling at the reactor operating temperatures (typically ~325 ^{O}C). Water is circulated inside the reactor vessel and used to extract heat from nuclear fuel. From there it goes to a steam generator where the heat is transferred to the water in the secondary circuit. This water is allowed to boil and expand, with this steam pressure used to turn turbines for electricity generation. After this, steam is converted back to water in the condenser and then pumped back to the steam generator to close the Rankine cycle. The cooling of the condenser is provided either by an external water body (e.g. seawater, lake or river), or the atmosphere (using cooling towers that release steam into the air).

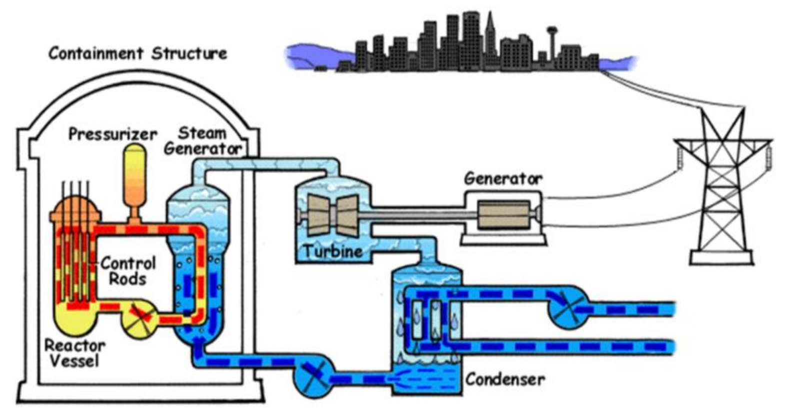

Figure 5.2 Schematic of a pressurized water reactor.

The boiling water reactor (BWR) is the second most common nuclear power plant technology. It contains one internal cooling circuit, which integrates the functions provided by the primary and secondary circuits in PWRs. In a BWR, the water is heated by the fuel and boils in the upper section of the reactor vessel. The steam produced is then sent to the turbine generator to generate electricity. The water is cooled down in the condenser, similar to a PWR.

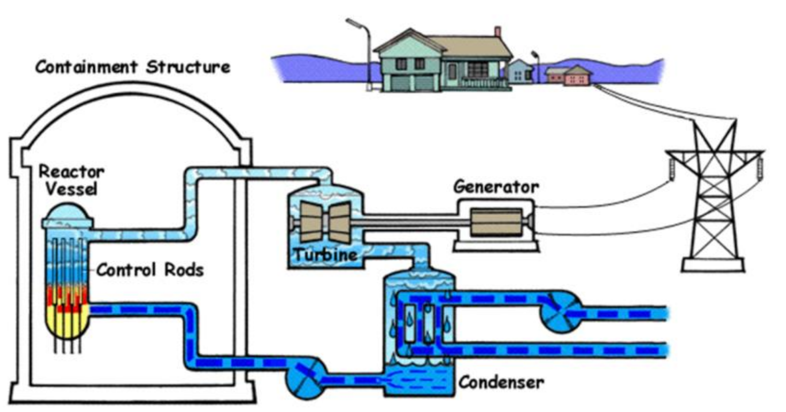

Figure 5.3 Schematic of a boiling water reactor.

5.1.1 Today's reactor technologies

Lessons learned from years of experience with Generation II nuclear power plants enabled the development of the third generation of nuclear reactors. These are all standardized designs and evolutionary improvements on the established Generation II technologies. Generation III designs have incorporated the lessons learned from major nuclear accidents, including Three Mile Island in 1979, and Chernobyl in 1986. They offer enhanced safety features, plus improved techno-economic performance. Some vendors later introduced a further subcategory – the so-called Generation III+ designs – which incorporated further safety and operational improvements.

Table 5.2 Reactors under construction as of August 2020[102].

Reactor Type	**Number of Reactors**	**Total Net Electrical Capacity (MW)**
PWR	43	47,767
BWR	4	5,253
PHWR	4	2,520
FNR	1	470
HTGR	1	200
Total	53	56,210

A range of commercially available Generation III designs are now being deployed in many countries. These are mostly PWR, BWR and PHWRs as shown in table 5.2. Note also two new reactor technologies – the fast neutron reactor (FNR) and high temperature gas-cooled reactor (HTGR) – which are generally considered to be Generation IV (see section on advanced reactors below). These are essentially demonstration units.

While there are many important differences between Generation III designs, they have the following in common:

- Large rated capacities. Typically in excess of a gigawatt, these designs are suitable for powering industrializing economies with growing electricity demand.
- High plant availability. Plants are typically available more than 90 percent of the time making nuclear energy one of the most reliable of all forms of energy generation.
- Long asset lifetimes. Modern plant designs will be expected to operate for a minimum of 60 years.
- Comparatively low and stable fuel and operating costs. This compensates for the high capital costs of nuclear power plants, and makes nuclear energy a superior option for countries seeking to improve energy security.
- A host of sustainable development benefits, including very low environmental life-cycle impacts on most indicators.

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[102] IAEA PRIS page on *Under Construction Reactors*

- Production of long-lived highly radioactive waste that needs to be managed responsibly and eventually disposed of.

Table 5.3 Currently available gigawatt-scale reactor technologies[103].

Vendor	Design	Type	Capacity (MW)
CNNC/CGN	Hualong One	PWR	1000
EDF/Framatome	EPR	PWR	1770
	Kerena	BWR	1300
EDF/Framatome and Mitsubishi	Atmea1	PWR	1100
GE Hitachi (Hitachi-GE in Japan)	ABWR	BWR	1400-1700
	ESBWR	BWR	1600
KHNP	APR1400	PWR	1400
Rosatom	VVER-1000	PWR	1000
	VVER-1200	PWR	1200
SNC-Lavalin	EC6	PHWR	750
SNPTC	CAP1400	PWR	1500
Westinghouse	AP1000	PWR	1200

The major nuclear accidents to date have impacted both the institutional and regulatory framework (nationally and internationally) as well as public opinion. Regulators implemented stricter requirements which affected the development of nuclear power plants in many countries. As a result, the safety of nuclear energy improved but the cost of some projects under way at the time also increased as regulators insisted work was repeated to meet the new standards. Moreover, the complexity of nuclear plant designs increased and more safety systems were introduced to meet new regulatory requirements. Designers generally responded to this by increasing the rated capacities of new designs in order to keep them cost-effective.

Unfortunately, the cumulative impacts of added regulation, increased complexity, and public acceptance issues have led to an escalation in the costs and schedule of some nuclear energy projects. This has been particularly evident in recent FOAK projects in the USA and Europe – regions which experienced long hiatuses in nuclear construction and loss of skills and competencies as a result. Driving nuclear capital costs down has become an urgent industry imperative and the subject of multiple international forums.

5.1.2 Advanced reactors

The fourth generation of nuclear power plants (Generation IV) is currently under research and development. This was given a boost in the year 2000 when a collaborative international initiative – the Generation IV International Forum (GIF) – was launched to study the feasibility and performance capabilities of six advanced nuclear systems: the gas-cooled fast reactor

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[103] Most information sourced from the Inernational Atomic Energy Agency's Advanced Reactors Information System (ARIS)

(GFR), lead-cooled fast reactor (LFR), molten salt reactor (MSR), supercritical water-cooled reactor (SCWR), sodium-cooled fast reactor (SFR) and very high temperature reactor (VHTR). These are not entirely new technologies, as many have been pursued in the past, but they represent the consensus view of the GIF participants as the most likely options to improve upon the environmental sustainability, economics, safety and reliability, as well as proliferation resistance and security of existing nuclear reactor technologies. They offer great potential for not only for improving the efficiency of nuclear power systems but also non-power applications such as high temperature cogeneration, waste management and hydrogen production (see section 5.4).

Some of the Generation IV nuclear power plant designs are only expected to be widely available about 20 years from now or even further in the future, although GIF has pointed out: “Some of these reactor designs could be demonstrated within the next decade, with commercial deployment beginning in 2030.” The era of advanced nuclear reactors is approaching more rapidly than many realize. However, it is important to note that most of the Generation IV systems are still in the concept phase and require substantial research and development. It is not yet known for certain which reactor technologies will succeed in meeting the expectations placed upon them. Enthusiasm for these technologies should be tempered with some caution.

5.2 Small modular reactors

The International Atomic Energy Agency defines small modular reactors (SMRs) as:[104] “Newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises. Most of the SMR designs adopt advanced or even inherent safety features and are deployable either as a single or multi-module plant….. The key driving forces of SMR development are fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil-fired units, enhancing safety performance, and offering better economic affordability.” The term SMR does not refer to either a generation of reactors or a subset of technology types (there are both Generation III and Generation IV SMR technologies), but rather applies to the rated capacity of a given reactor design and how it is to be constructed.

SMRs are suitable for electricity production but many designs are also particularly suitable for district heating, desalination, and hydrogen production. Detailed load following studies of SMRs for cogeneration of hydrogen have shown this to be feasible[105] . Other studies have investigated the coupling of SMRs with different desalination technologies[106]. SMRs and

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[104] *Advances in Small Modular Reactor Technology Developments – A Supplement to: IAEA Advanced Reactors Information System (ARIS), 2018 Edition*, International Atomic Energy Agency (September 2018)

[105] Giorgio Locatelli *et al.*, Load following of Small Modular Reactors (SMR) by cogeneration of hydrogen: A techno-economic analysis, *Energy*, 148, 494-505 (1 April 2018)

[106] D.T. Ingersoll *et al.*, Integration of NuScale SMR With Desalination Technologies, *Proceedings of the ASME 2014 Small Modular Reactors Symposium*, V001T01A009 (15-17 April 2014)

microreactors are also more appropriately sized for industrial applications than larger reactors. If these reactor designs, delivering high quality heat and power, can be built economically at small sizes they could decarbonize certain industrial facilities. Another place where SMRs may find a niche is in remote communities or small power grids that do not have the electricity demand to support a large nuclear power plant. SMRs are small enough to be transportable by ship, rail or even by truck to the point of demand. The small capacities, range of applications, and ease of siting of SMRs make it possible to rapidly expand the current global reactor fleet, from less than 500 operating units, to the many thousands of units required to power a broad range of human activities worldwide.

The rapid emergence of microreactors

Recent years have seen a growing interest in the potential of microreactors and a rapid acceleration in their design and licensing activities. In July 2019, the Canadian government issued notice of commencement of an environmental assessment for a 15 MW thermal (5 MW electrical) high temperature gas-cooled reactor project proposed by Global First Power.

In March 2020, the US Department of Defense awarded contracts to three nuclear companies to each begin design work on a mobile nuclear reactor prototype. The engineering design phase of the projects will last up to two years, after which one of the three teams may be selected to build and demonstrate a prototype reactor.

Also in March 2020, California-based company Oklo submitted a combined licence application for its 4 MW thermal (1.5 MW electrical) heatpipe fast reactor design to the US Nuclear Regulatory Commission. This was the first such licensing proposal to be submitted using a new application structure for advanced fission technologies and the first privately funded application for a commercial advanced reactor.

5.2.1 Economics and cost drivers

Economies of scale have traditionally been employed to drive down the generation costs of conventional large nuclear power plants. This, together with the deployment of standarized fleets and hosting multiple units on a single site have enabled existing nuclear power plants to achieve low cost. This is illustrated in Figure 5.4. At this stage the exact cost of SMRs and their economic benefits are yet to be demonstrated. However, SMRs adopt a different approach to large reactors in attempting to reduce cost and maxmize economic benefits. The most important factors are[107] :

- Reduction of capital cost employed for a single unit. This makes the investment more scalable and 'bankable', meaning it should easier to source the necessary financing –

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[107] B. Mignacca and G. Locatelli, Economics and finance of Small Modular Reactors: A systematic review and research agenda, *Renewable and Sustainable Energy Reviews*, 118, 109519 (February 2020, published online 1 November 2019).

including private financing. Financing options and associated challenges are described in section 3.5.

- Modularization. The process of converting the design and onsite construction of a typical nuclear plant to factory fabrication of modules for shipment and installation in the field. Factory fabrication is cheaper than onsite construction and it should be easier to control quality, although this benefit may be limited by the availability of cheap transport. SMRs have a distinct advantage over large reactors since it is possible to have a higher percentage of factory-made components.
- Multiple units at a single site. If needed, SMRs allow investors to make smaller incremental capacity additions to a pre-existing nuclear site. This leads to co-siting economies, i.e. the setup activities related to siting (e.g. acquisition of land rights, connection to the transmission network) have already been carried out. Certain fixed indivisible costs can be saved when installing the second and subsequent units. The greater the number of co-sited units, the smaller the total investment costs for each unit. In addition, revenue from the first unit(s) can be used to finance the construction of further units. This is true for both large and small reactors, however it is possible to add more SMRs before other site limits come into play[108].
- Learning and mass production economies. It is likely that more units of a given SMR design will be produced than for a given large reactor design. Therefore it is possible to have a large bulk ordering process of components. This allows SMRs to exploit economies of mass production and benefit from a more standardized procurement process. Completing the installation of a larger number of units should improve the learning rates as well[109].
- Portfolio considerations. The smaller the size, the easier it should be to diversify a generating portfolio[110].
- Many SMR designs are expected to be simpler than today’s large designs. By relying on natural physical principles to maintain safety, reducing the need for multiple active engineered safety systems, they should reduce complexity and associated costs.

In addition to the above, the construction of SMRs is expected to be shorter than for large reactors. This is important since the construction schedule has a major impact on nuclear power construction economics in two ways. Firstly, it will lower the fixed daily cost. On a nuclear construction site, where there are thousands of people working and expensive equipment (e.g. cranes) is in use, the fixed daily costs are considerable. Secondly, it will bring

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[108] S. Boarin, G. Locatelli, M. Mancini, and M. E. Ricottia, “Financial case studies on small- and medium-size modular reactors,” *Nucl. Technol.*, vol. 178, no. 2, pp. 218–232, 2012.

[109] M. D. Carelli *et al.*, “Economic features of integral, modular, small-to-medium size reactors,” *Prog. Nucl. Energy*, vol. 52, no. 4, 2010.

[110] G. Locatelli and M. Mancini, “Large and small baseload power plants: Drivers to define the optimal portfolios,” *Energy Policy*, vol. 39, no. 12, pp. 7762–7775, 2011.

forward project revenue. The shorter construction times of SMRs mean that electricity – and revenue – is generated sooner than for a larger project.

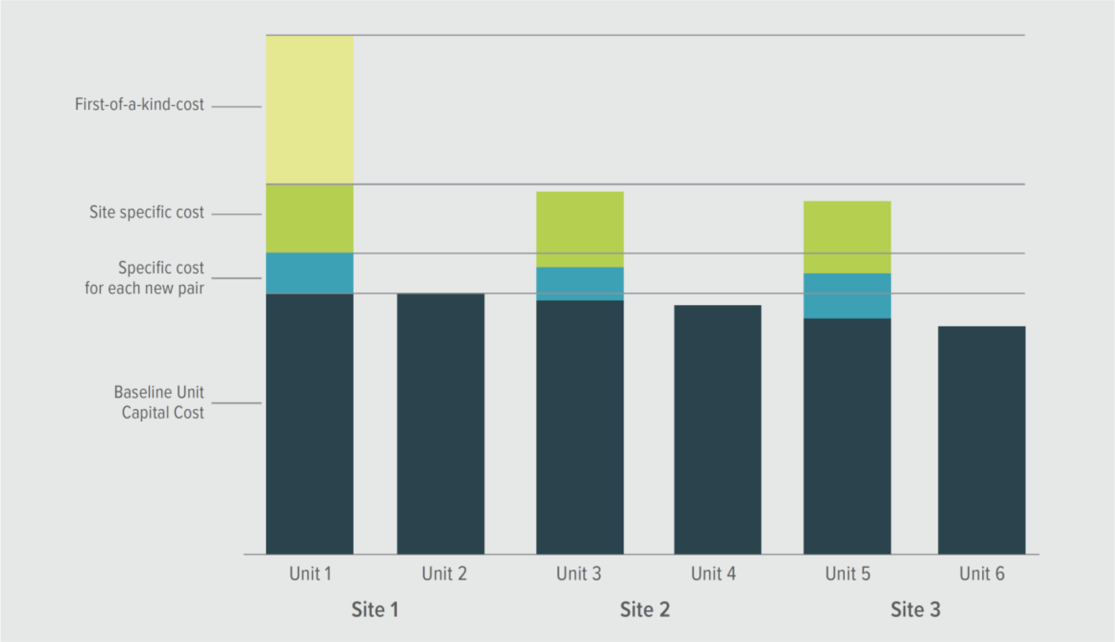

Figure 5.4 Cost reduction due to series and site effects. Source: NIRAB [111]

Experience with large nuclear plant construction has shown that three elements especially are critical to reducing construction schedules and cost, namely: (i) continuous construction activities over an extended period to maintain a qualified and experienced workforce; (ii) series build of the same design; and (iii) multiple units on the same site. It is clear that SMRs can also benefit from all these aspects as more units need to be built and these will probably be spread over a longer time.

Both large reactors and SMRs have a role in providing low-carbon energy to a future sustainable mix. A range of technologies will be required to meet the wide needs of energy users and applications.

5.2.2 Importance of reactor licensing

Licensing is one of the most important factors affecting the investment appraisal and viability of nuclear power plant projects[112] . Existing licensing processes have over time been adapted to suit the design and site approval of large reactor designs. Changes to the licensing process could enable more of the techno-economic advantages of SMRs to be realized. For example, a reduction in the size of the regulatory required emergency planning zone (EPZ) would facilitate the co-siting of SMRs with other industrial activities. A reduction in licensing duration, and

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[111] *Achieving Net Zero: The role of Nuclear Energy in Decarbonisation, A Report for the Department for Business, Energy and Industrial Strategy (BEIS)*, Nuclear Innovation and Research Advisory Board (April 2020)

[112] T. Sainati, G. Locatelli, and N. Smith, “Project financing in nuclear new build, why not? The legal and regulatory barriers,” Energy Policy, vol. 129, pp. 111–119, Jun. 2019.

better flexibility to accommodate ad hoc assessments, such as in-factory certifications, should directly help to reduce construction costs[113].

Another relevant licensing challenge is the variation between national reactor technology licensing regimes of difference countries. A design licence obtained in one country is only valid for that country. A licensing process can take years and cost hundreds of millions of dollars with all costs incurred before there is even a possibility a project will go ahead. The licensing process is therefore a risky undertaking for the stakeholders paying for it, and even more so where the investments to be made are smaller, as is more likely to be the case with SMRs.

The licensing of SMRs does not only need to take the smaller size of reactors into account, but also the different design approach and non-water cooled technologies. For a long time it has been acknowledged that different requirements are needed for non-water cooled technologies, and in the USA these efforts led to the release of its *Guidance for Developing Principal Design Criteria for Non-Light-Water Reactors* in 2018. These include concepts such as 'functional containment', and a move away from the traditional emphasis on loss of coolant accidents.

The SMR Regulators' Forum, hosted by the International Atomic Energy Agency (IAEA), was created as a pilot project in March 2015 to identify, understand and address key challenges that may emerge in future SMR regulatory discussions. The Forum members are regulators and technical support organizations of those IAEA member states with experience and some activities related to SMR licensing. They include Canada, China, Finland, France, Korea, Russian Federation, Saudi Arabia, the UK and USA. Countries considering introducing SMRs are encouraged to join and learn more about these evolving issues.

5.3 Selection of nuclear power plant technology

Nuclear power projects and their applications are diversifying. Historically, large power reactors were used for on-grid applications whereas small research reactors were used not only for research and development but also for the production of radioisotopes for medicine and industries, silicon doping and other commercial applications. However smaller reactors open up so many more opportunities, as shown in table 5.4. The first step in selecting nuclear technology (and technology partner) is determining what energy need it is intended to fulfil.

The selection of a nuclear power plant technology and technology partner has critical implications for the whole nuclear programme, including:

- Implications for the fuel cycle and the associated infrastructure, including enrichment facilities, fuel fabrication and reprocessing.
- The amount of financing required, and the sources available for it.

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[113] T. Sainati, G. Locatelli, and N. Brookes, "Small Modular Reactors: Licensing constraints and the way forward," *Energy*, vol. 82. pp. 1092–1095, 2015.

- Waste management strategy and associated infrastructure.
- Implications for the stability and reliability of the energy grid.
- Which entities will own and/or operate the nuclear plant.
- Technical capabilities required by the operator of the nuclear reactor and the regulatory body.
- Technology transfer and local content expectations.
- Trade policy with third countries associated with the nuclear programme, in particular the provisions with the technology provider and critical suppliers.

Table 5.4 Nuclear power reactor applications

Size	Likely setting	Applications
Microreactors <20 MW (thermal)	Off-grid Industrial facility Mining operations Remote communities Oil and gas platforms Off-grid agriculture	Electricity Heat
SMRs 20-300 MW (electric)	On or off-grid Large developed grids Small or non-developed grids Industrial processing, e.g. data centres Off-grid agriculture	Electricity Hydrogen production Desalination District and industrial heating
Medium to Large Reactors >300 MW (electric)	On-grid (large developed)	Electricity Hydrogen production Desalination District heating

Technology selection is influenced by many factors, each with multiple possible inputs, and consequences of varying importance. To solve such a multidimensional problem, a methodology or framework is needed that compares technical and economic specifications against national objectives.

Many methodologies have been developed over the years as countries made the decision to pursue nuclear energy. In the past they may have been limited in scope as political and policy considerations have traditionally dominated decision making. More recently, with the growing number of designs and the increasing globalization of the industry, efforts have been made to develop systematic, technology neutral frameworks to facilitate more objective decision making.

The systems decision process (SDP) used in systems engineering has been proposed. It is a structured, comprehensive and proven decision making aid that includes integrated qualitative and quantitative analyses. SDP has also been applied in a limited case study[114]. Another paper proposes the use of Multi Criteria Decision Making (MCDM) methods and defines a two-step framework to choose the best nuclear reactor at the pre-feasibility study phase[115]. As might be expected, these evaluations include economics and financial indicators (e.g. Net Present Value) but also non-financial aspects (e.g. employment creation), both of which are intrinsically uncertain. Figure 5.5 summarizes all the relevant aspects included into a single framework.

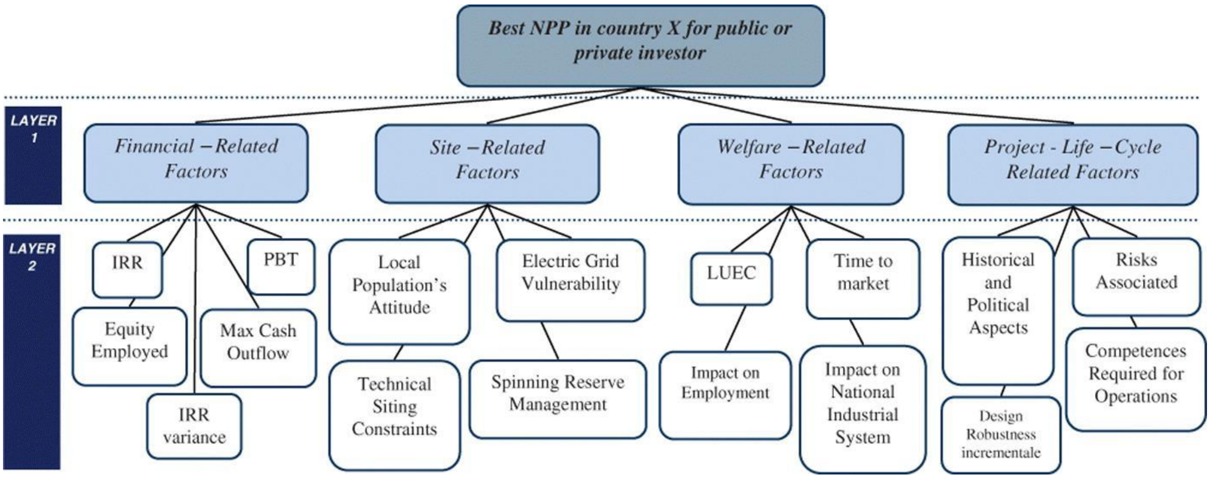

Figure 5.5 Framework for the selection of nuclear technologies[116]

The financial indicators relate to the cost of a nuclear technology. The levelized unit of electricity cost (LUEC) or levelized cost of electricity (LCOE) is one of the main indicators for policy makers. This indicator accounts for all the life cycle costs and is expressed in terms of energy currency, typically in $/kWh. The net present value (NPV) measures the absolute profitability (in $) and uses a discount factor to weight 'present cost' versus the 'future revenue'. The discount factor depends on the source of financing and for many practical applications can be interpreted as the weighted average cost of capital (WACC). A low WACC gives similar weighting to present cost and future revenue (promoting capital-intensive plants, like nuclear power plants), while high WACC is weighted more towards the present cost in respect to future revenues (promoting low capital cost solutions like gas plants). The internal rate of return (IRR) is a 'specific dimensionless indicator', i.e. the value of WACC that brings the NPV to zero. The greater the IRR, the higher the profitability of the investment. Other financial indicators include the pay back time (PBT), the money employed by the investors (equity employed) and the maximum amount of money at stake in the project (maximum cash outflow).

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[114] Muhammed Zulfakar Zolkaffly and Ki-In Han, Reactor technology assessment and selection utilizing systems engineering approach, *AIP Conference Proceedings*, 1584, 22 (2014)

[115] G. Locatelli and M. Mancini, A framework for the selection of the right nuclear power plant, *International Journal of Production Research*, 50, 17, 4753-4766 (1 September 2012)

[116] Ibid.

IAEA methodology for nuclear power plant technology assessment

The International Atomic Energy Agency has developed processes that can be used in the evaluation of technology performance, including the ‘Milestones Approach’ infrastructure milestone development programme, intended for nuclear power programme development in newcomers, and the reactor technology assessment (RTA) methodology. The RTA considers the whole nuclear power plant and facilitates the evaluation, selection and deployment of the most suitable technology to meet the objectives of a nuclear power programme in the context of the national energy policy.

The first publication detailing the RTA methodology was released in 2013 and used for training courses worldwide at the national and interregional level. The feedback received during the training courses, and some national implementations of the RTA methodology, pointed to the need to refine it to include recent developments in the nuclear industry – such as new builds of large commercial nuclear plants in newcomer countries, new innovative reactor designs, technology transfer from established to embarking nuclear countries, life extensions and mid-life refurbishment projects, SMRs, non-electric applications, and tightly coupled nuclear-renewable energy systems.

The RTA methodology results in a decision/selection matrix for the assessment of each technology option against key elements. Every key element is further defined by its components, called a key topic. Not every key element is defined by the same number of key topics, nor does each of them have the same importance.

This methodology requires that an importance percentage weight is assigned to each key element and topic and the nuclear designs under assessment are scored or ranked on a comparative or absolute performance basis. The final results provide an overall score and ranking of the assessed technologies. The RTA methodology assesses safety, safeguards, technical performance, technology readiness, economy, and environmental impacts, while the key topics address more specific aspects of a nuclear power plant technology to lead to an objective and unbiased scoring. An ‘RTA toolkit’ has been developed in parallel to facilitate the application of the RTA methodology.

The non-financial aspects become relevant when the consequences of the selection affect many stakeholders, as is always the case with a nuclear power project. In the framework shown in figure 5.5 they are grouped under site-, welfare- and project-related factors. The importance of these aspects has grown through the years, especially in the evaluation of policies and technologies for electricity generation. For instance, choosing technology ‘A’ instead of technology ‘B’ could promote the development of national industries, increase job positions or reduce some risks. So, even if some of the economics and financial indicators of plant ‘B’ are slightly better than those of plant ‘A’, it may be preferable to choose plant ‘A’.

Although most key indicators[117] or external factors are not expected to be influenced by the size of a design (large reactors compared to SMRs), a few can be. These include[118] :

- The need for more potential reactor sites.
- Time to the market.
- Benefit for national industries.
- Additional costs in terms of the required grid back-up (spinning reserves).

The importance assigned to the different indicators by individual countries may also differ.

5.4 Nuclear innovation and hybrid energy systems

Innovation is vital to the long-term survival of any industry. The nuclear industry is no exception. The problem faced today is that the world demands low-cost, low-emission energy in immense quantities and very rapidly. To date, fossil fuels have been able to deliver all the modalities of energy that the world needs. However, nuclear innovators are seeking to further improve upon the economics and versatility of their reactor designs so that they can substitute for fossil fuels in a greater number of applications. They seek to deliver nuclear power systems that are cheaper and easy to license and build, and which are rapidly deployable. These technologies could help decarbonize not only electricity, which accounts for roughly 30 percent of total global greenhouse gas emissions, but also industry and transport, which together account for most of the balance.

New nuclear technologies will increasingly need to function in a future grid with a high level of variable renewables. A concept which has gained considerable traction in recent years is that of an ‘integrated hybrid energy system’, in which nuclear and renewable sources are tightly coupled in a way that optimizes their output for a combination of electricity production and other applications[119]. Such a system would be capable of apportioning resources to first meet grid demand and then utilize excess thermal and, in some cases, electrical energy to drive a process that results in an additional product.

5.4.1 An innovation industry

For most of its history, reactor development has been carried out by large national laboratories and a handful of established international technology vendors. The typical timeline for new reactor RD&D has been decades. In the last decade, however, there has been a significant increase in the number of private sector concerns seeking to commercialize advanced reactor designs, particularly in North America and Europe. US think tank Third Way counted 48 such North American-based companies in 2015, and the number has grown since then. Many of

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[117] *Deployment Indicators for Small Modular Reactors – Methodology, Analysis of Key Factors and Case Studies*, IAEA-TECDOC-1854, International Atomic Energy Agency (September 2018)

[118] G. Locatelli and M. Mancini, The role of the reactor size for an investment in the nuclear sector: An evaluation of not-financial parameters, *Progress in Nuclear Energy*, 53, 2, 212-222, (March 2011)

[119] S.M. Bragg-Sitton *et al.*, *Rethinking the Future Grid: Integrated Nuclear Renewable Energy Systems*, NREL/CP-6A20-63207, National Renewable Energy Laboratory (January 2015)

these companies have secured venture capital and are seeking to develop a commercial product as quickly as possible – with expected commercialization in the 2020s, and ready for rapid global deployment in the 2030s. Technologies being developed include many in the Generation IV category: MSRs, GFRs, LFRs and SFRs. The race is now on to see which technologies will be commercialized and by when.

Recent developments show that support for the advanced nuclear sector continues to grow. In July 2019, the US Senate passed the Nuclear Energy Leadership Act, which directs the US Department of Energy (US DOE) to help demonstrate advanced nuclear reactor concepts and make an initial supply of high-assay low-enriched uranium fuel available, which is required by many technologies. In August 2019, the US DOE submitted an environmental impact assessment for the construction of the Versatile Test Reactor – a facility which can test materials that will be used in a number of different designs. The Canadian government launched the SMR Roadmap in 2017 and 10 designs are currently being reviewed by the Canadian Nuclear Safety Commission as part of a pre-licensing process.

In Russia and China, government support for advanced nuclear has been continuous, with R&D carried out by large state-owned enterprises. While Western countries are still talking about development and demonstration, China has almost completed building the HTR-PM, a demonstration high temperature gas-cooled reactor. Meanwhile Russia is currently the only country in world operating commercial fast reactors, with two sodium-cooled reactors (the BN-600 and BN-800), and is about to start construction on a lead-cooled prototype as part of the 'Proryv', or Breakthrough, project to enable a closed nuclear fuel cycle.

What is driving all this interest? Advanced nuclear technologies promise the following unique set of attributes that can help achieve deep decarbonization across all modalities of energy:

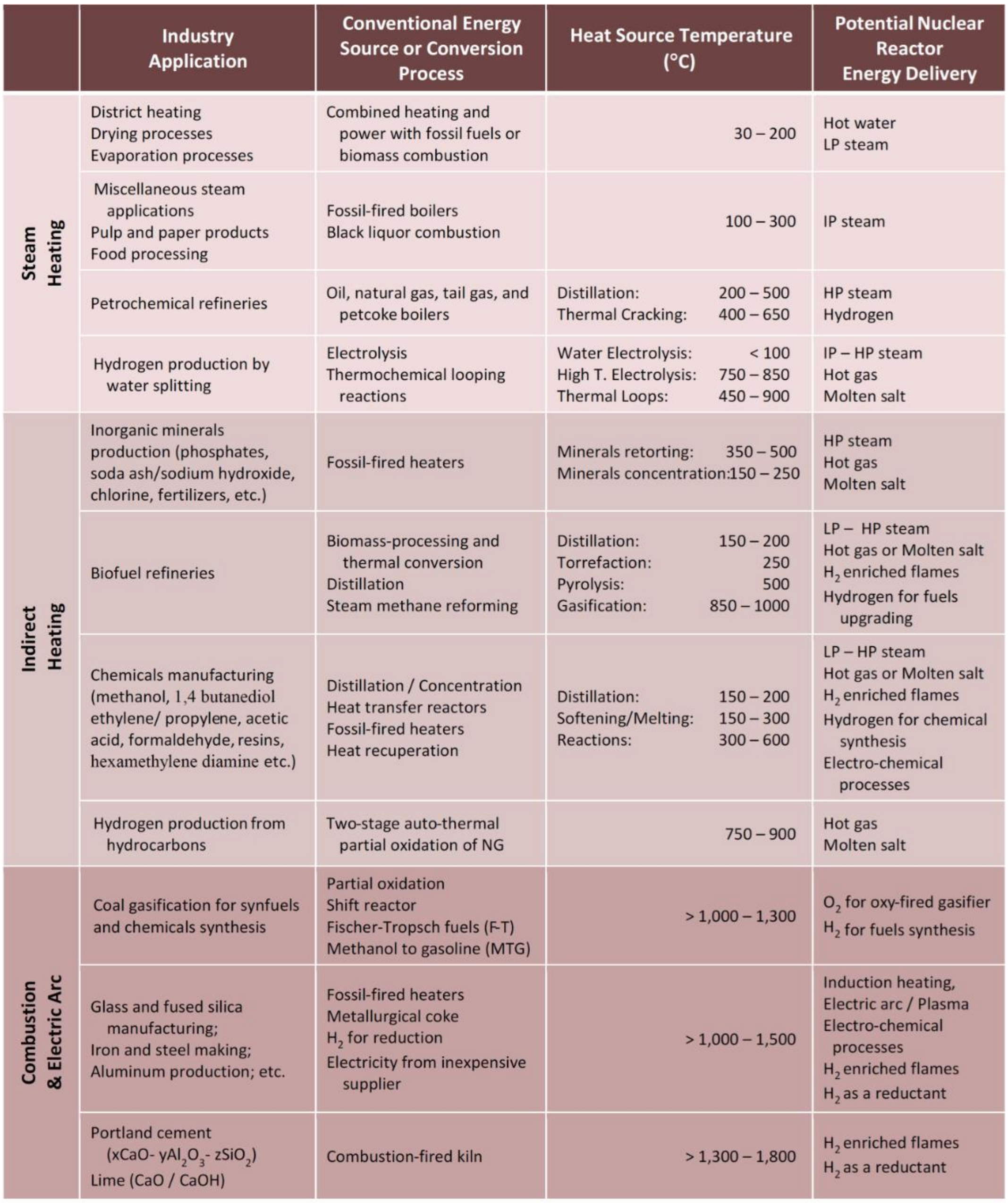
- Lower costs, specifically reduced capital cost.
- Small and flexible (in the case of SMRs) designs, suitable for a greater range of settings and providing a greater number of grid services – such as load following, black start capability and islanding mode.
- High-temperature output suitable for a greater range of industrial applications.
- Increased efficiency, reducing the resource requirements and the production of radioactive wastes.
- They are geographically unconstrained. Reduced water requirements for cooling coupled with inherent safety and reduced proliferation risk, removes some of the trade and siting restrictions.

It is worth examining some of these attributes further – exploring how innovation enables the integration of nuclear energy with renewables and how it can help decarbonize not just electricity, but also industrial and transport energy requirements as well.

5.4.2 Nuclear industrial heat and hydrogen

A high-temperature low-carbon technology is important for decarbonizing industrial heat supply. This is because the electrification of heat, in most cases, is thermally inefficient. If a thermal power plant is used to produce electricity then between half and two-thirds of the available energy is effectively wasted in the conversion, and more will be lost in the transport and distribution. Even if wind and solar are at similar prices to fossil electricity sources, they would need to be over half as cheap again to compete with thermal sources.

Table 5.5 Breakdown of the principal manufacturing industries, including the conventional energy source and the approximate thermal range of heat transfer. LP – low pressure steam (< 1 MPa), IP – intermediate pressure steam (1-10 MPa), and HP – high pressure steam (> 10 MPa)[120]



	Industry Application	Conventional Energy Source or Conversion Process	Heat Source Temperature (°C)	Potential Nuclear Reactor Energy Delivery
Steam Heating	District heating Drying processes Evaporation processes	Combined heating and power with fossil fuels or biomass combustion	30 – 200	Hot water LP steam
	Miscellaneous steam applications Pulp and paper products Food processing	Fossil-fired boilers Black liquor combustion	100 – 300	IP steam
	Petrochemical refineries	Oil, natural gas, tail gas, and petcoke boilers	Distillation: 200 – 500 Thermal Cracking: 400 – 650	HP steam Hydrogen
	Hydrogen production by water splitting	Electrolysis Thermochemical looping reactions	Water Electrolysis: < 100 High T. Electrolysis: 750 – 850 Thermal Loops: 450 – 900	IP – HP steam Hot gas Molten salt
Indirect Heating	Inorganic minerals production (phosphates, soda ash/sodium hydroxide, chlorine, fertilizers, etc.)	Fossil-fired heaters	Minerals retorting: 350 – 500 Minerals concentration:150 – 250	HP steam Hot gas Molten salt
	Biofuel refineries	Biomass-processing and thermal conversion Distillation Steam methane reforming	Distillation: 150 – 200 Torrefaction: 250 Pyrolysis: 500 Gasification: 850 – 1000	LP – HP steam Hot gas or Molten salt H_2 enriched flames Hydrogen for fuels upgrading
	Chemicals manufacturing (methanol, 1,4 butanediol ethylene/ propylene, acetic acid, formaldehyde, resins, hexamethylene diamine etc.)	Distillation / Concentration Heat transfer reactors Fossil-fired heaters Heat recuperation	Distillation: 150 – 200 Softening/Melting: 150 – 300 Reactions: 300 – 600	LP – HP steam Hot gas or Molten salt H_2 enriched flames Hydrogen for chemical synthesis Electro-chemical processes
	Hydrogen production from hydrocarbons	Two-stage auto-thermal partial oxidation of NG	750 – 900	Hot gas Molten salt
Combustion & Electric Arc	Coal gasification for synfuels and chemicals synthesis	Partial oxidation Shift reactor Fischer-Tropsch fuels (F-T) Methanol to gasoline (MTG)	> 1,000 – 1,300	O_2 for oxy-fired gasifier H_2 for fuels synthesis
	Glass and fused silica manufacturing; Iron and steel making; Aluminum production; etc.	Fossil-fired heaters Metallurgical coke H_2 for reduction Electricity from inexpensive supplier	> 1,000 – 1,500	Induction heating, Electric arc / Plasma Electro-chemical processes H_2 enriched flames H_2 as a reductant
	Portland cement ($xCaO$- yAl_2O_3- $zSiO_2$) Lime (CaO / CaOH)	Combustion-fired kiln	> 1,300 – 1,800	H_2 enriched flames H_2 as a reductant

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[120] Shannon M. Bragg-Sitton *et al*., Nuclear-Renewable Hybrid Energy Systems: 2016 Technology Development Program Plan, INL/EXT-16-38165, Idaho National Laboratory (March 2016)

As of 2010, the USA alone had approximately 2,000 industrial facilities in operation. These facilities rely on electric power, direct heat, and steam which is powered by heat. Over 99 percent of the latter two categories are generated by fossil fuel power. The industrial sector in the US is responsible for about 25 percent of the country's total greenhouse gas emissions. Most industrial facilities have heat duties of between 60 and 150 MW thermal.

High thermal ranges are also required for most industrial applications. Advanced nuclear technologies that use coolants other than water have the capability of delivering high-quality, high-temperature power, which is perfectly substitutable for the heat that is provided by natural gas, coal or coke. Industry requires heat ranging from 60 ˚C up to 1600 ˚C. Hence, a small nuclear system that can scale from 50 MWth to 600 MWth, and that can deliver up to 800 ˚C heat to an industrial process has the potential to decarbonize a considerable fraction of global industrial heat requirements, as indicated in table 5.5. It is important that the final heat is delivered at a lower cost than its fossil fuel alternative. Small high-temperature reactors have the potential to satisfy this economic requirement, owing to the unusually high thermal efficiency inherent in a high-temperature system.

Hydrogen Economic Evaluation Programme

The IAEA's Hydrogen Economic Evaluation Programme (HEEP), was developed to assess the economics of large-scale nuclear hydrogen production. HEEP evaluates the economics of some of the promising new processes for hydrogen production along with the conventional ones. This tool facilitates conducting comparative studies considering different nuclear technologies, as well as fossil fuels, as sources of input energy. The IAEA successfully conducted benchmarking of HEEP through a collaborative research project involving several nuclear and non-nuclear countries.

High-temperature reactor systems would be ideal for the production of clean, cost-competitive industrial hydrogen, principally via high-temperature electrolysis, using both heat and electric power generated by the reactor system. Clean, low-cost hydrogen would have an immense impact on industry. It could conceivably enable the use of hydrogen in applications such as direct reduction of iron for large-scale steel production, or for ammonia production, or for synthetic fuels.

5.4.3 Nuclear innovation applied to the transport sector

An expansion of the nuclear power plant fleet using existing nuclear technology can immediately deliver electricity for clean charging of electric vehicles. In fact it could be a key technology for this purpose if consumer behaviour results in the charging of electric vehicles taking place mainly at night, when solar energy is not available. It is even conceivable that remote charging stations could be powered by small reactor technologies sized particularly for such a purpose.

As illustrated above, small, scalable, high-temperature power technologies that are low-cost and low-emissions have the capability of decarbonizing industry in a non-incremental way. It could do likewise for the transport sector. Nuclear power technologies, and especially new advanced reactor technologies, have all the features required to drive large-scale production of synthetic transport fuels, including gasoline, diesel and aviation fuel. These fuels could be produced with a total absence of petroleum, and could be seamlessly substituted for petroleum-based fuels. The only inputs required are: carbon from air, hydrogen from water, and closed-loop chemistries.

It was explained in the previous section how nuclear reactors may be the ideal power source to drive large-scale, clean, affordable hydrogen via electrolysis, or some other closed-loop chemistry. Likewise, an advanced reactor system may prove to be useful in carbon capture systems. If a direct air carbon capture system has as its object the production of industrial carbon, considerable power is required, including heat to drive chemical processing. Hence, a high-temperature nuclear system could drive industrial carbon production.

Carbon and hydrogen can be chemically transmuted into liquid hydrocarbon fuels, using the well-established Fischer-Tropsch chemical process. This process has been in use for many decades for the liquefaction of coal and natural gas. It requires heat power and pressurization, which an advanced reactor system is capable of delivering in large quantities.

The technological readiness of such a synthetic fuel production system is extremely high, with hydrogen production, carbon capture and Fischer-Tropsch processes all being technically feasible, but in many cases, not ecologically feasible, and/or not economically-feasible. The missing ingredient is low-cost, low-emissions, high-temperature power.

Synthetic fuels produced in this way would create a closed-loop carbon cycle. Carbon is captured from the atmosphere, processed into fuel, combusted and released back to the atmosphere for recapture. These fuels are net-zero carbon. Moreover, the emissions during the pre-operating phase of these fuels are reduced by an estimated 35 grams CO_2/kWh. Synthetic fuels would have an exceedingly high purity. They would not, for example, produce sulfur oxide or particulate matter. These are impurities that come only from petroleum.

Finally and remarkably, because the inputs of these fuels are not commoditized, the price of fuels would cease to be volatile. The value of this cannot be overstated. Volatility in transport fuel price injects massive risk into the global economic system, felt at every level of society.

These fuels could seamlessly be used to power the global aviation, shipping, rail and automobile industries. Furthermore, synthetic diesel could be used to fuel small electricity generators, such as those used in small industrial facilities or in remote communities.

5.4.4 Nuclear-renewable integrated energy systems

Nuclear power is often referred to as a base-load electricity generation source although today some large nuclear power plants do already perform load-following operations, notably in France and Germany. Many advanced nuclear technologies can quickly and easily decrease power output if required by the electricity transmission system, even to the point of zero output. They can also just as easily increase power output, even from a zero output position. These increases or decreases must take place within minutes to effectively stabilize the grid.

Traditionally, fossil fuel power plants have performed this function in many markets, typically at greater cost than when providing base-load energy.

Load-following becomes increasingly important in an electricity grid with growing contributions from variable renewable energy. Since the power output of wind and solar energy can change very quickly, it is important to have energy readily available to deliver generation to the grid system. Conversely, it may become necessary to remove excess base-load generation when solar and wind energy capacity resumes generation.

Since the capital cost of nuclear remains the largest contributor to the LCOE/LUEC, with the fuel and operations costs relatively low, operators will always wish to maximize generation and run the plant as close to full power as possible. So unless the market design provides incentives for load-following (as is the case in the markets where this take place) full power operation remains the optimum operating mode. This is true for both large reactors and SMRs. As mentioned, many advanced reactors and SMRs are designed to have enhanced load follow capabilities, but to achieve better economics a potential alternative is load-following by cogeneration; i.e., diverting the excess power, in respect to the electricity demand, to an auxiliary system.

Advanced reactors and SMRs are potentially more suitable for cogeneration than existing large reactors. It is possible to design and license them to be more flexible to load follow, or to switch some of the units at a multi-unit site to perform cogeneration. Consequently, a plant with multiple SMRs can run at the full nominal power and maximum conversion efficiency[121] .

Cogeneration introduces new challenges in design, licensing and operation but also offers additional opportunities as other income streams can be explored. There are numerous non-incremental ways in which nuclear innovation can integrate with renewable power systems, enabling further deployment of these clean energy technologies globally. Two such pathways are explored below.

High-temperature technologies that use coolants other than water or steam to transfer heat have the potential to provide heat storage solutions. A popular medium is molten salt. Molten salt is already broadly used in concentrated solar power to store heat generated during sunny periods, and then discharged during overcast periods, or on demand. The salt used is generally potassium nitrate, a common and inexpensive material that is available in industrial quantities.

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[121] G. Locatelli *et al.*, Load following by cogeneration: options for small modular reactors, Gen IV reactor and traditional large plants, *Proceedings of the 2017 25th International Conference on Nuclear Engineering* (July 2017)

Nuclear desalination

Nuclear energy is also an option for countries pursuing desalination; the IAEA has developed the Desalination Economic Evaluation Program (DEEP) and the Desalination Thermodynamic Optimization Programme (DE-TOP). DEEP enables its users to conduct performance assessment and cost evaluation of different power and seawater desalination cogeneration configurations. It is suitable for performing comparative analysis among different power plant types (e.g. steam, gas, combined cycle and heat only plants), different fuels, and various desalination technologies including multi-effect distillation (MED), multi-stage flash (MSF), reverse osmosis (RO) and hybrid options. It includes formulation of different alternatives such as different turbine configurations, backup heat, intermediate loop, water transport costs and carbon tax. The other tool, DE-TOP, which is equipped with an intuitive graphical user interface and provides flexible selection of different coupling arrangements between the power plant and non-electric application. It models the steam power cycle of different water-cooled reactors or fossil plants, and the coupling with any other non-electrical applications.

Thermal storage technologies are commonly becoming recognized as complementary to lithium ion battery storage technologies, and appear to be far superior as well. These hot molten salts, when stored in insulated tanks onsite, can trap heat with a very low heat dissipation rate, thereby making the energy storage durable and grid-scale in nature, which lithium ion batteries are not. At least one of the advanced nuclear technologies described above use molten salt as its heat transfer medium. It is therefore possible to store excess heat generated by the system inexpensively in an onsite tank farm, and discharge that energy for various purposes – such as for electricity generation during periods of high power demand; or to drive industrial processes (e.g. hydrogen production) during periods of low demand.

In the short term, the most relevant cogeneration applications are concerned with district heating, where the residual heat in the turbine circuit of a nuclear plant is fed to heat exchangers in order to produce hot water/steam, which is delivered to consumers. Heat transportation pipelines are installed either above or below ground. Co-generation plants, when forming part of large industrial complexes, can be readily integrated into an electrical grid system. In turn, they serve as a backup for providing energy security and a high degree of flexibility.

Thanks to innovation, nuclear energy can contribute to global energy in ways not previously envisaged. Both current nuclear technologies and innovative new reactor designs can provide high-quality heat power for electricity, industry and transport, cost-competitively with the fossil fuel alternatives. There are myriad ways in which nuclear and renewable energy technologies can complement each other for the common goal of delivering clean affordable energy the world over.

Chapter 6 Nuclear Energy Entry Pathways

> *Nuclear energy supports the realization of a number of national policy goals, including: affordable and clean energy provision; mitigating climate change; enhancing energy resilience; and development of industry and infrastructure. For a nuclear programme to be successful governments should prioritize attention in some key areas: nuclear energy policy; electricity market; international cooperation; regulatory harmonization; nuclear skills and supply chain development; project structure and management; public engagement; and building diversity. All these aspects could be assessed with the United Nations Framework Classification for Resources (UNFC) and the United Nations Resource Management System (UNRMS), which would help countries to gain useful insights into the appropriate pathways for nuclear deployment.*

The choice of nuclear energy entry pathway does not exist in a policy vacuum. In fact, nuclear energy intersects with a broad range of policy areas and supports the realization of multiple policy objectives. This chapter considers the role of existing policy in facilitating the introduction of nuclear energy into the energy mix, as well as policies that support implementation of a nuclear energy programme once a decision is taken to proceed.

6.1 Making a decision – existing policies that support nuclear energy

Introducing nuclear energy can help to meet a number of broader policy and planning goals, including meeting future energy demand, mitigating climate change, and enhancing energy security. Therefore, the presence of sound and coordinated policies in support of these goals often contributes to the case for nuclear energy in a country. Such policies include:

- Policies that support sustainable development.
- Policies for implementing a low-carbon energy transition.
- Energy market reforms that support long term strategic investment.
- Policies for improving energy security and resilience.
- An industrial development strategy.

These are explored in more detail below.

6.1.1 A roadmap to sustainable development

In September 2019, the UN Secretary-General called on all sectors of society to mobilize for a decade of action on three levels. First was global action to secure greater leadership, more resources and smarter solutions for the Sustainable Development Goals (SDGs). Second was local action embedding the needed transitions in the policies, budgets, institutions and regulatory frameworks of cities and local authorities. Third was action by people, including civil society, the media, the private sector, unions, academia and other stakeholders, to create a social movement for change.

Beyond 2030 the sustainable development agenda will no doubt evolve, but it will also continue to be a priority that is increasingly integrated into national policy objectives. Countries which proactively introduce policies to support realization of the SDGs should increasingly find themselves drawn towards nuclear as an energy option for the reasons outlined in chapter 2. There is also a growing civil society movement that recognizes that value of nuclear energy and wants to see it expand, with prominent proponents such as Stephen Pinker [122], James Hansen and Bill Gates[123]. Increasingly, nuclear energy is being embraced as part of the social movement for an energy transition.

> *"Nuclear is ideal for dealing with climate change, because it is the only carbon-free, scalable energy source that's available 24 hours a day."*– Bill Gates

In addition to energy production, there are nuclear technologies that improve the health, research, agriculture and manufacturing sectors of a country and which are of tangible benefit to its people. Building up a nuclear sector should be considered as one of the more promising pathways to scientific and sustainable development. Sustainable development policy is incomplete without evidence-based and impartial consideration of nuclear energy and radioisotope technologies.

6.1.2 Policies for transitioning to a low-carbon economy

The need to decarbonize is now almost universally recognized, with 195 countries signatory to the Paris Agreement. However, the level of commitment to climate action from individual countries varies. Some – such as Sweden, the UK, France, Denmark and New Zealand[124] – have set legal targets of achieving net zero greenhouse gas emissions by 2050, while most others are still assessing the practicalities of this in relationship to their other development objectives.

As noted in chapter 2, the decarbonization challenge is foremost an energy one. While some emissions are associated with agriculture, land use and certain industrial processes (for example concrete and steel production) the majority, about 70 percent, are associated with the production and consumption of energy that takes place throughout these sectors. Most leading climate and energy organizations are now calling for an increase in electrification and, simultaneously, its total decarbonization as one of the most urgent and achievable steps for reducing global climate emissions. While some organizations see more potential for energy efficiency than others, there is a consensus on strong growth of the electricity sector: global demand is expected to at least double between 2018 and 2050.

> *"Electricity demand grows strongly as the world uses more and more electricity and the digitalization becomes a major driver, and, therefore, the electrification of the energy world, our societies, our economies, will shape the future."*
> – Fatih Birol, Executive Director, International Energy Agency

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[122] Joshua S. Goldstein, Staffan A. Qvist and Steven Pinker, Nuclear Power Can Save The World, New York Times (6 April 2019)

[123] Kelly McPharlin, Why We Should Listen to Bill Gates on Nuclear Energy, Nuclear Energy Institute (4 February 2019),

[124] Energy & Climate intelligence Unit, Net Zero Emissions Race 2020 Scorecard

Today, fossil fuels – a combination of coal, gas and oil – currently account for about 80 percent of global energy needs. Despite three decades of global climate action, this share is almost exactly the same as in 1990[125]. The relative contributions of different energy technologies to primary energy supply are indicated in figure 6.1. While some observers criticize a lack of political will for this apparent lack of progress, it is also testament to the versatility, reliability and cost-effectiveness of these energy sources – they are hard to substitute while maintaining the same level of energy service. Nuclear plants offer advantages here, since they provide a similar role to coal or gas plant in the electricity mix.

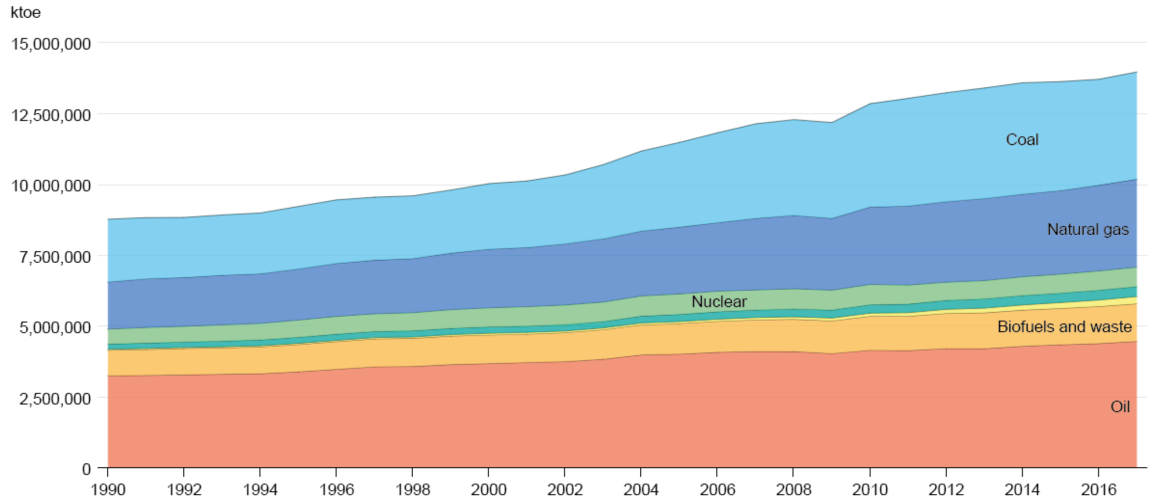

Figure 6.1 Total primary energy supply by source. Source: IEA[126]

As countries commit to ever stricter climate targets they invariably start re-evaluating energy options. Countries that previously discounted nuclear energy or were not yet ready for it are beginning to acknowledge it as an essential tool for combating climate change. For example, a recent review by an Australia parliamentary committee has recommended a partial lifting of the moratorium there[127]. Policies that either seek to shut down high emissions power plants or which support low-carbon energy growth can also support the development of nuclear energy and the long-term operation of existing nuclear plants, unless it is explicitly excluded. Such policies include:

- Deep decarbonization or net-zero carbon target.
- Technology-neutral low-carbon energy portfolio standards.
- Coal/fossil fuel phase-outs.
- Policies that aim to increase electrification of heat and transport.
- Policies for decarbonization and modernization of energy-intensive industries.

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[125] See: The World Bank webpage on Fossil fuel energy consumption

[126] International Energy Agency, Data and statistics

[127] *Not without your approval: a way forward for nuclear technology in Australia*, House of Representatives Standing Committee on the Environment and Energy, The Parliament of the Commonwealth of Australia (13 December 2019),

6.1.3 Electricity market design

One of the key policy levers for influencing the make-up of the electricity mix is the market design. How generators get paid has a significant impact on which electricity technologies end up being built. The prevailing electricity market designs in developed countries favour incumbent generators wherever investment decisions depend on a long-term vision for capital expenditure and fuel prices. New technologies such as wind and solar would not have been able to overcome barriers to entry without the support of off-market subsidies and other policies. Nuclear energy is no exception and newcomer countries will need to design their energy market structures to facilitate investment.

Some general features of the existing market structure will make the choice to introduce nuclear energy much easier. Nuclear energy is favoured by market designs that, among other things:[128]

- Ensure price transparency and a predictable pricing environment that enables investment in large capital-intensive and long-lived energy assets.
- Take a comprehensive approach to reducing greenhouse gases via effective pricing mechanisms which may include a carbon tax, carbon trading scheme or a binding requirement to lower greenhouse gas emissions.
- Value energy reliability and resilience – specifically, the need for certain technologies to provide secure, reliable and dispatchable generation to support the integration of variable renewables.
- Value non-power (socio-economic) benefits and seek to fulfil multiple and sometimes competing policy goals.

Many policy makers are increasingly looking beyond the levelized costs of energy for a generating technology, and instead are considering its role in reducing the costs of the overall electricity system as well as reducing environmental and social externalities. A report from the OECD-NEA recently concluded that all low-carbon technologies have a role to play in reducing the full costs of electricity, but that for a generalized country "a mix relying primarily on nuclear energy is the most cost-effective option to achieve the decarbonization target of 50 gCO_2 per kWh."[129] Even in a case with ultra-low-cost wind and solar PV – which is increasingly a reality – reaching such an aggressive decarbonization target would require that "a larger share of 40-60 percent provided by dispatchable low-carbon technologies such as nuclear or, perhaps one day, fossil-fuelled plants with carbon capture, utilization and storage."

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[128] This is a selection of recommendations presented in *Nuclear Power In a Clean Energy System*, International Energy Agency (May 2019)

[129] *The Costs of Decarbonisation:* System Costs with High Shares of Nuclear and Renewables, OECD Nuclear Energy Agency (2019)

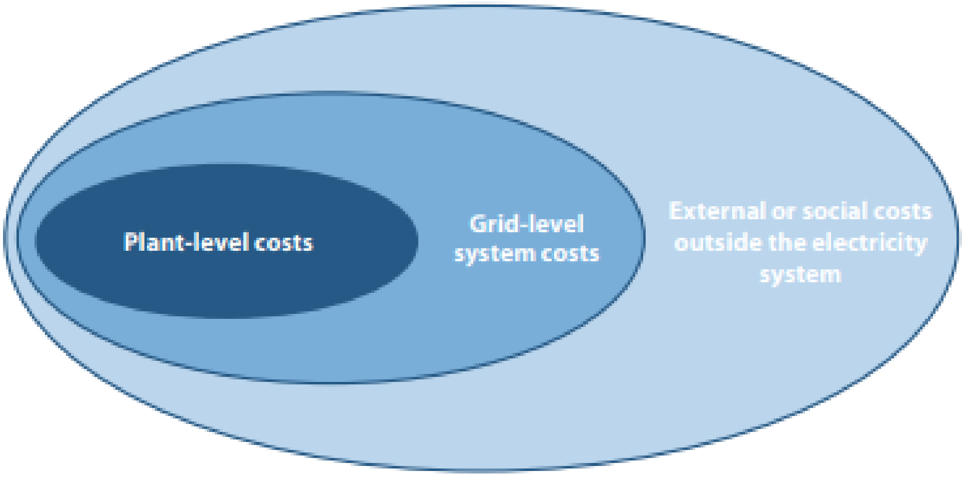

Figure 6.2 Different cost categories composing the full costs of electricity generation. Increasingly the focus of policy makers is moving beyond plant-level costs to include system costs and environmental and societal costs. Source OECD-NEA

6.1.4 Policies for improving energy security and resilience

All countries aim to ensure energy security and promote energy self-sufficiency. The oil crises of the 1970s and ’80s had a profound impact on energy policy globally and led to the near-total phasing out of oil as an electricity source. Europeans will also remember a dispute over gas supplies between Russia and Ukraine in 2009 that led to a disruption in gas supplies across much of the continent and sudden price escalations. Energy systems need to be more resilient to political turmoil and be able to ensure supply, including in times of crisis.

The Covid-19 pandemic has demonstrated the importance of having a reliable electricity supply as more than ever hospitals and other critical civil infrastructure need to keep operating under very challenging conditions. The economic impacts of the virus will also turn out to be severe, but they would be greater still if power disruptions were to hit the millions of people now working from home. A reliable supply of electricity is the lifeblood of modern society.

Nuclear energy has long been considered an important tool for countries keen to lessen their dependence on volatile fossil fuel imports and protect themselves against possible disruptions in fuel supply. The high energy density of nuclear fuel makes it possible to store several years’ worth of fuel at a nuclear power plant, and many nuclear operators do this. The oil crises were a direct driver for the French nuclear energy programme – which now supplies 70 percent of that country’s electricity. Prior to 2011 Japan was building up nuclear energy in order to reduce imports of coal and gas, as the country lacks domestic resources. South Korea has until recently pursued nuclear energy for a similar reason.

The physical security and structural requirements of nuclear power plants, along with the fact that they are not dependent on daily fuel transports means that they also offer increased resilience to some external threats such as extreme weather events as well as cyber and physical attacks. Countries that are developing policies to boost energy security and resilience will find that nuclear power plants are a valuable asset.

6.1.5 Integrated industrial development

The level of energy-intensive industry within a country will play a significant role in determining its level of base-load energy demand. Nuclear plants can be operated flexibly, but they are also the quintessential base-load energy source and will naturally be looked at by industrializing countries experiencing rapid economic growth. Nuclear plants provide large amounts of reliable energy at low and stable productiom costs – which is needed by heavy industry.

Along with aerospace engineering, nuclear is an exemplar of highly advanced technology, and requires demanding technical standards and continuous R&D and innovation. Countries which have set policies that seek to build up a scientific and engineering base will find that nuclear energy is a major asset.

Considering also the availability of domestic energy mineral resources, policies that support the mining and beneficiation of local mineral resources to support low-carbon goals will also make it easier for countries to introduce nuclear energy. For some countries this is about their domestic uranium resource. How uranium mining can support the development of a domestic nuclear energy programme is discussed in section 4.1. For other countries there is the potential to sell more oil and gas in valuable export markets if they offset local electricity demand with low-cost alternatives like nuclear energy. Russia has pursued nuclear energy for this reason, and the UAE and Saudi Arabia have similar ambitions. Proceeds from the international sale of these commodities can help to implement the local energy transition.

Figure 6.3 The four-unit Barakah nuclear power plant in the UAE. Image courtesy of Emirates Nuclear Energy Corporation

6.2 After the decision – policies that facilitate a nuclear programme

Establishing and successfully maintaining a nuclear energy programme will be a lot easier if newcomers manage to avoid the pitfalls that some established nuclear countries have fallen into. There have been several instances where nuclear countries have run into serious difficulties – most notably in terms of costs overruns and delays on new build projects, but also with operating facilities losing their social licence to operate. While there are many contributing factors to these predicaments they are specific to the individual countries and a full discussion is beyond the scope of this report. Instead, some high-level guidance is provided that should help ensure success in all countries.

The IAEA's 'Milestones Approach' (described in chapter 3) lays out all of the national infrastructure areas (covering governmental and institutional, legal and regulatory, managerial and technological, human resource, industrial and stakeholder requirements) which countries need to develop and the key milestones they need to achieve on their journey to introducing nuclear energy. The information provided here is complementary and highlights steps that can be taken to reduce the costs and risks of a nuclear energy programme, as well as policies that help to improve socio-economic benefits and improve public support:

- International cooperation.
- Regulatory harmonization.
- Developing indigenous capabilities.
- Delivering projects on time and on budget.
- Proactively engaging stakeholders.
- Encouraging diversity in the nuclear sector.

These are explored further below.

6.2.1 International cooperation

While a newcomer is likely to choose only one, or at most a few, main nuclear technology partners, there is a wealth of experience to be found in all established nuclear countries which newcomers should seek to learn from. Most formal intergovernmental exchanges in nuclear matters require high-level cooperation agreements, which newcomers should pursue with a number of strategic countries. Newcomers will also need to ratify the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), become members of the IAEA and agree to safeguards before they will be able to trade in nuclear materials (as described in section 3.4). This is essentially a pre-condition of embarking on a nuclear programme.

In addition, there are various international forums for regulatory and governmental exchange which address all aspects of nuclear energy. Most notable are those hosted by the International Atomic Energy Agency and the OECD Nuclear Energy Agency, but there are also some regional forums such as the African Commission on Nuclear Energy (AFCONE) and the Arab Atomic Energy Agency (AAEA), as well as forums dedicated to specific topics such as the development of advanced nuclear technologies (for example the Generation IV International Forum). At the level of industry, the World Nuclear Association provides forums for improving the uranium fuel cycle, plant performance, transport, economics and the international harmonization of reactor design, evaluation and licensing. Newcomer governments should make sure they are active participants in those forums and working groups where they have a particular need or interest. They should also prioritise their resources carefully, with an initial focus on getting their nuclear programmes up and running.

IAEA assistance to countries embarking on nuclear power

Introducing nuclear power into the national energy mix is a sovereign decision of each country. Developing the required institutional, legal and regulatory infrastructure for nuclear power is a responsibility that rests with the national government. The aim of IAEA assistance to newcomer countries is to enable them to understand the commitments and obligations associated with developing a safe, secure and sustainable programme. The support is comprehensive and integrated to involve all IAEA departments. It is based on the Milestones Approach, and the phase of development of the country's nuclear infrastructure. The IAEA support can be categorized in two areas: 'Assessment' and 'Assistance'.

Assessment

Since 2009, the IAEA has offered the Integrated Nuclear Infrastructure Review (INIR) service to support countries in assessing the overall status of development of their national nuclear power programme. The IAEA provides guidance that enables countries to conduct a self-evaluation and develop an initial national action plan. The self-evaluation and the initial national action plan are enhanced through the conducting of an INIR mission. These can be carried out in each of the three phases of programme development. To date, 30 INIR missions have been conducted at the request of 21 member states.

Countries also benefit from infrastructure issue-specific IAEA peer review missions and advisory services, for example in the fields of site survey and selection (Site and External Events Design Review Service, SEED), developing a regulatory framework and establishing the nuclear regulatory body (Integrated Regulatory Review Service, IRRS), establishing or enhancing the safeguards system (State Systems of Accounting for and Control of Nuclear Material mission, ISSAS), nuclear security system (International Physical Protection Advisory Service, IPPAS) and nuclear emergency planning and response system (Emergency Preparedness Review EPREV). Operating organizations also benefit from safety reviews of their readiness to start operation (pre-OSART (Operation Safety Review Team) and World Association of Nuclear Operators (WANO) prestart review).

Assistance

The technical departments of the IAEA develop and/or update standards and guidance publications related to nuclear energy through processes that involve experts from member states. The Nuclear Infrastructure Bibliography on the IAEA website identifies key publications for each of the 19 infrastructure areas, including relevant safety and security standards and guidelines, as well as current best practices and guidance. An extract of competencies needed throughout the different phases of the programme in all key organizations, i.e. the government, the regulatory body and the operating organization involved, is presented in the web-database Nuclear Infrastructure Competency Framework. The Nuclear Power Human Resource (NPHR) model assists countries in examining their infrastructure development workforce plans covering the entire nuclear programme life-cycle from early planning through construction, commissioning and operation.

The IAEA Integrated Nuclear Infrastructure Training initiative, offers inter-regional, regional or national capacity building workshops on the development of nuclear infrastructure as well as on issue-specific topics to increase competence in newcomer countries. This programme is supported by web-based e-learning modules covering various aspects of nuclear power programme development. Between 2016 and 2019, the programme supported 50 member states and 1250 participants through 78 training sessions.

The IAEA departments and its Office of Legal Affairs host technical meetings on the development of nuclear infrastructure as well as on issue-specific topics. These meetings provide a forum for countries to share information and lessons learned and to provide comments and input for the development or revision of related publications.

Ensuring the safe operation of nuclear facilities is of paramount importance to the entire global nuclear industry and newcomers will be expected by the international community to adopt the IAEA safety standards. These provide the fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment. Advice and support in developing a strong level of nuclear safety is available from multiple sources, including the forums listed above. In addition, the mission of the World Association of Nuclear Operators (WANO) is: “To maximise the safety and reliability of nuclear power plants worldwide by working together to assess, benchmark and improve performance through mutual support, exchange of information, and emulation of best practices.” WANO counts all nuclear facility operators amongst its members and a number of technology vendors as well. Newcomers should make sure that their national operators are members. This will help make facilities safer and build public confidence in a national nuclear programme.

Newcomers should also be aware of the Electric Power Research Institute (EPRI), which conducts research to improve the performance of existing nuclear assets and support the deployment of new technologies. It is based in the USA but maintains global collaboration with nuclear power plant operators, regulatory agencies, and other research organizations.

6.2.2 Pursuing regulatory harmonization

Within the global nuclear industry there is a large push towards greater international harmonization of codes and standards, licensing and regulation. It is believed that harmonization will, on balance, improve the regulation of nuclear power plants while also strengthening the global supply chain – granting access to a deeper pool of qualified vendors and workers.

The ‘holy grail’ of these efforts is to deploy standardized, or near identical, nuclear power plant designs in different countries. At the moment it is often the case that significant changes need to be made to nuclear power plant designs in order for them to comply with the regulatory requirements of different countries. This adds cost and complexity – and introduces significant risk for project developers. Standardized designs would not need to be significantly altered to meet local requirements, beyond adjusting the non-nuclear part of the plant to account for local environmental factors. This reduces the overall engineering and construction time and cost compared to the non-standardized approach. It can moreover increase predictability of construction, thereby improving the economics and investment case of nuclear new build.

These standardized reactors could, theoretically, be subject to some kind of regional or international licensing process. Currently reactor design certification is considered strictly a national responsibility and must be carried out by the national regulators of each country where a particular design is intended to be built. A regional or international design certification should significantly reduce the costs and risks of nuclear projects, but is perceived by some as potentially conflicting with national rights and responsibilities set out in high-level treaties. Despite this, progress towards international licensing is taking place; for example, regulators in the USA and Canada have agreed to carry out a joint review of Terrestrial Energy's 195 MWe Integral Molten Salt Reactor (IMSR) design[130].

While there is a significant divergence in requirements between established nuclear countries, newcomer countries that are developing their licensing processes can achieve harmonization at an early stage. They can enjoy the benefits of standardized nuclear power plants by simply adopting as much as possible of the licensing requirements from their vendor country, as well as its quality codes and standards. In the past, several newcomers have taken this option – including the UAE with South Korea (the UAE regulator reviewed only the site-specific impacts and post-Fukushima studies), and South Africa with France. Newcomers can also join the regional and international forums pursuing harmonization.

International regulatory cooperation is coordinated, notably, through the Multinational Design Evaluation Programme (MDEP), as well as regional forums such as the Western European Nuclear Regulators Association (WENRA). These have all shown that collaboration between regulators, including constructive exchanges with the industry, can be transparent. They are forums that facilitate voluntary cooperation between different regulators, rather than being international institutions. One notable example is the Forum of Nuclear Regulatory Bodies in Africa (FNRBA), which has 34 African countries as members. For the last year 10 years it has been working towards the enhancement, strengthening and harmonization of the radiation protection, nuclear safety and security regulatory infrastructure and framework between its members.

Reactor standardization and some kind of streamlined licensing approach are considered particularly important for the development of SMRs. The licensing cost is proportionally higher where less capacity is planned, which is likely to be the case for SMR projects. In addition, most

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[130] *US and Canadian regulators select SMR for joint review*, World Nuclear News (6 December 2019)

fabrication will be built into an optimized factory process making deviations from a standard potentially costly and difficult. They face other unique licensing challenges as well. The SMR Regulators' Forum and the IAEA Technical Working Group on SMRs are coordinating international efforts to address these challenges.

6.2.3 Developing skills and a local supply chain

Many newcomer countries will want to attract investment into their country[131]. This can be done by introducing policies that facilitate the international financing of nuclear infrastructure (a range of financing options are discussed in section 3.5). Beyond just power plant financing, newcomers may wish to introduce policies that encourage overseas investors to develop a local supply chain and skills base in order to enhance the socio-economic benefits from the investment.

Nuclear systems and components are challenging to manufacture and are subject to demanding standards. They are produced by specialist vendors most of which supply globally and which are well placed to expand their production. However, the 'nuclear island' makes up only a fraction of a nuclear power plant. Most of the capital costs of a nuclear power plant (when measured by either labour activity or materials) consist of turbine island, balance of plant and general supporting structures – i.e. the non-nuclear structures. This is indicated in tables 6.1 and 6.2[132]. There are significant opportunities for a local supply chain to service a nuclear build programme, given adequate support by government.

Even after a plant is constructed there will need to be ongoing operations and maintenance which will require a steady stream of materials and equipment as well as specialized maintenance and services. It is usually better for these to be available locally rather than be dependent on imports.

Table 6.1 Nuclear plant capital costs by activity.

Design, architecture, engineering and licensing	5 %
Project engineering, procurement and construction management	7 %
Construction and installation works:	
- Nuclear island	28 %
- Conventional island	15 %
- Balance of plant	18 %
Site development and civil works	20 %
Transportation	2 %
Commissioning and first fuel loading	5 %

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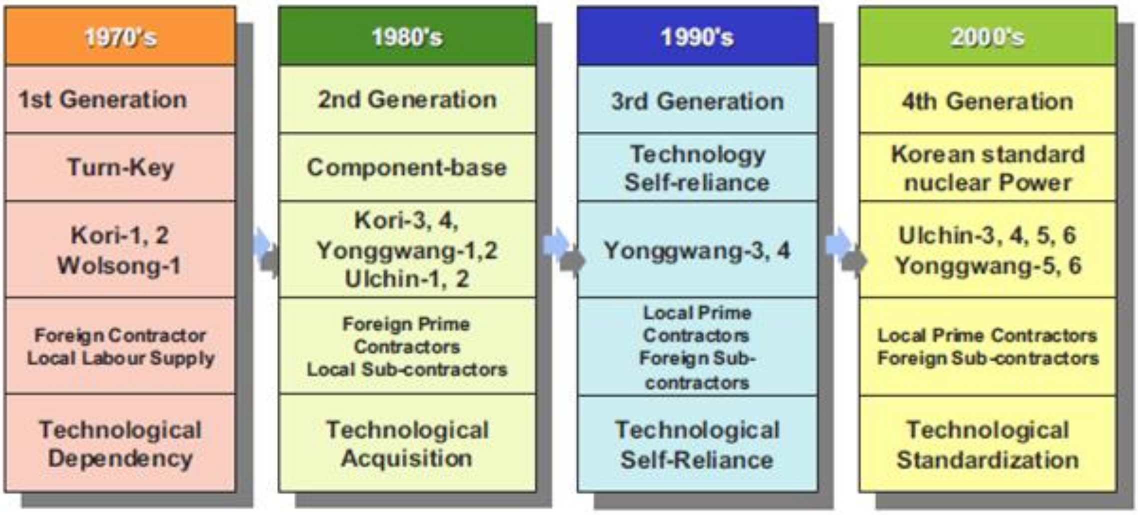
[131] *Industrial Involvement to Support a National Nuclear Power Programme*, IAEA Nuclear Energy Series No. NG-T-3.4, International Atomic Energy Agency (December 2016)

[132] Source: *The World Nuclear Supply Chain – Outlook 2035*, World Nuclear Association (September 2016)

Table 6.2 Nuclear plant capital costs by labour, goods and materials

Equipment	
- Nuclear steam supply system	12 %
- Electrical and generating equipment	12 %
- Mechanical equipment	16 %
- Instrumentation and control system (including software)	8 %
Construction materials	12 %
Labour onsite	25 %
Project management services	10 %
Other services	2 %
First fuel load	3 %

Policies to promote the involvement of local industry need to be developed that give careful consideration to a country's industrial capability and worker capacity to support a nuclear programme. Capability can be built up over time, as at set intervals larger components will need to be replaced. Those countries intending to install large fleets may wish to progressively increase the level of localisation for subsequent reactors. Both South Korea and China have done this, developing to the point now where they are capable of designing and fully supplying their own indigenous reactor designs. Figure 6.4 shows the progressive localisation of the South Korea nuclear energy programme. Furthermore, a nuclear programme requires a qualified skills base. Policies that promote specialist education and training will be the key to enabling the introduction of nuclear energy[133].



1970's	1980's	1990's	2000's
1st Generation	2nd Generation	3rd Generation	4th Generation
Turn-Key	Component-base	Technology Self-reliance	Korean standard nuclear Power
Kori-1, 2 Wolsong-1	Kori-3, 4, Yonggwang-1,2 Ulchin-1, 2	Yonggwang-3, 4	Ulchin-3, 4, 5, 6 Yonggwang-5, 6
Foreign Contractor Local Labour Supply	Foreign Prime Contractors Local Sub-contractors	Local Prime Contractors Foreign Sub-contractors	Local Prime Contractors Foreign Sub-contractors
Technological Dependency	Technological Acquisition	Technological Self-Reliance	Technological Standardization

Figure 6.4 Progressive localization of the South Korea nuclear programme. Generation refers to South Korean reactor projects and not reactor technology. Source: IAEA[134]

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[133] *Workforce Planning for New Nuclear Power Programmes*, IAEA Nuclear Energy Series No. NG-T-3.10, International Atomic Energy Agency, (February 2011)

[134] *Nuclear Technology And Economic Development In The Republic of Korea*, IAEA (2009)

6.2.4 Delivering on time and on budget

For a nuclear programme to maintain public and political backing it's important to deliver projects on time and budget. Nuclear plants (and most notably those employing large reactor designs) are classified as megaprojects. Megaproject construction is by its nature extraordinarily complex, which creates many pitfalls but also numerous opportunities for optimization. There are some common high-level recommendations which can help to achieve success. For the most part, these recommendations are independent of the specific reactor technology chosen. They include:

- Selecting a 'proven' design. For newcomers it is important that a reference plant is operating in an established nuclear country.
- Using experienced engineering, procurement and construction (EPC) contractors.
- Making use of a reliable supply chain. Emphasize component quality considerations over cost in procurement.
- Establishing effective project management processes.
- Not beginning construction until after a detailed plant-level design is completed.
- Selecting a suitable contract structure. For newcomers this is usually a 'turnkey contract' as they are unlikely to be able to manage the interfaces.
- Establishing clear regulatory processes and close cooperation between the vendor country regulatory body and that of the recipient country.
- Government commitment and consistent long-term policy support.

In order to dramatically improve chances for success it is necessary for all the parties involved in construction – utilities, vendors and contractors – to learn the lessons from previous projects. Information on this is available in a range of reports.[135] [136] [137]

Innovation should help significantly drive down nuclear construction costs and schedules. Policies and regulations that seek to promote key enabling technologies at an early stage can help newcomers to overtake existing nuclear countries. Notable innovations include:

- Digitalization/digital twinning (creating a full digital replica of a nuclear plant). This can assist with design change/knowledge management activities.
- Additive manufacturing (3D printing). This can ensure the ready availability of some bespoke components.
- Automation and sensor technologies. Plant telemetry will facilitate better system health monitoring and maintenance regimes, prolonging the life of critical components.

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[135] *Lesson-learning in Nuclear Construction Projects*, World Nuclear Association (April 2018)

[136] *The ETI Nuclear Cost Drivers Project: Summary Report*, Energy Technologies Institute (April 2018)

[137] *Project Management in Nuclear Power Plant Construction: Guidelines and Experience*, IAEA Nuclear Energy Series No. NP-T-2.7, International Atomic Energy Agency (February 2012)

- Artificial intelligence. This can help to improve project scheduling thereby reducing the cost, time and risks of outages and upgrades.
- Robotics. New robots are increasingly finding applications in difficult to access and high radiation environments, allowing tricky maintenance tasks to be carried out remotely.

6.2.5 Proactively engaging stakeholders

The levels of public support for nuclear varies substantially between different countries. In some places nuclear energy faces stiff opposition and governments have implemented early phase out policies which will shut reactors down well ahead of their technical lifetimes – notable examples include Germany and Taiwan (China). Some other countries currently maintain prohibitions against the technology – for example, Austria, Australia and Ireland. However, in many other countries public attitudes are a lot more supportive towards nuclear energy. This diversity of opinion can be seen in Figure 6.5, which shows the results of a global survey carried out just after the Fukushima Daiichi nuclear accident. Public support was negatively affected shortly after the accident but subsequent national surveys show that in several countries (such as the UK) it recovered within a few years to pre-accident levels[138]. More recently it seems that public attitudes are improving globally in response to the twin challenges of addressing climate change and meeting sustainable development goals.

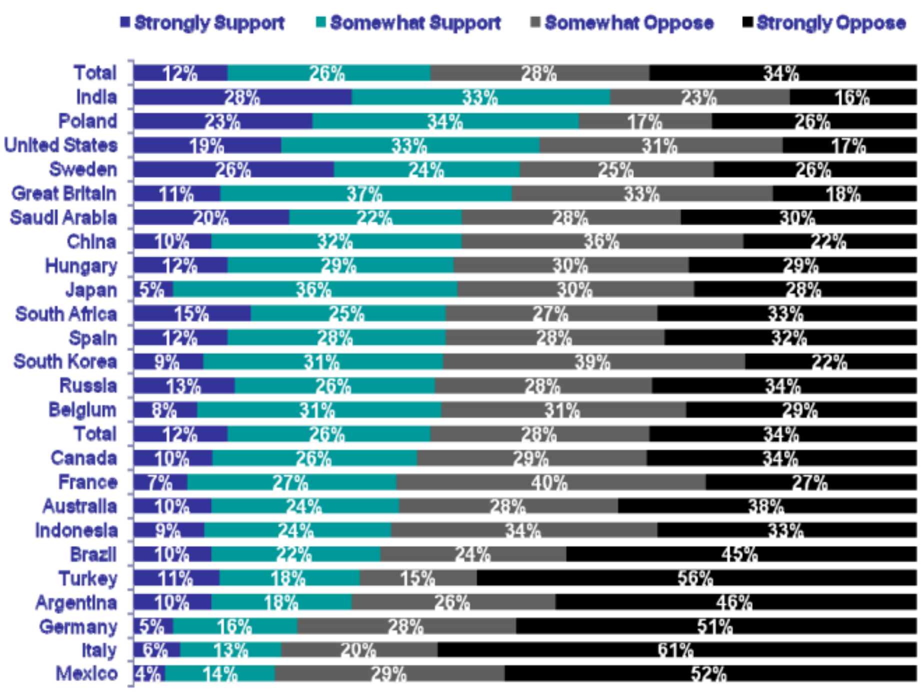

Figure 6.5 Results of a 2011 poll carried out by Ipsos MORI to assess views on different energy sources. Respondents were asked: "Please indicate whether you strongly support, somewhat support, somewhat oppose or strongly oppose each way of producing electricity (nuclear)."[139]

Public acceptance is absolutely vital to nuclear energy. As a minimum requirement a 'social licence' needs to be earned before facilities are constructed and this must be maintained if they

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[138] *What People Really Think About Nuclear Energy*, Foratom (January 2017)

[139] *Global Citizen Reaction to the Fukushima Nuclear Plant Disaster*, IPSOS (June 2011),

are to operate for the long term. However broader and stronger public support helps key enabling decisions and policies to be enacted in the future. It takes time and effort to build up public support for a nuclear energy programme and policy makers cannot afford to leave it to chance. Rather, they need to build awareness of the technology and consult with key stakeholders on important policy decisions. This is especially important at the early stages of a programme, before construction begins[140].

Where the public feels informed about nuclear, support levels tend to be high. The results of recent surveys in the EU demonstrate this[141]. On average EU citizens do not feel well-informed about nuclear issues and radioactive waste in particular. However, in countries where the public considers their level of knowledge to be greater like Sweden (knowledge: 47 percent; acceptance: 62 percent), Finland (51 percent, 61 percent), Netherlands (44 percent, 55 percent) and Czech Republic (41 percent, 64 percent), public opinion is also more favourable towards nuclear energy. General education and awareness building is a key step. It is not surprising that communities near to nuclear facilities also tend to exhibit the highest levels of support.

Many countries have witnessed steep declines in trust levels for public institutions in recent years – a result of complex underlying socio-economic factors[142]. It has grown harder to implement major infrastructure projects as a result. There is no shortage of action groups and intervenors that will oppose almost any industrial development, with the 'not-in-my-back-yard' (NIMBY) syndrome describing a common reaction experienced when locals are confronted with the prospect of such a project. As a result, in many countries governments and industry have shifted from announcing decisions to consulting on them, engaging in processes that listen to stakeholders and incorporate their views into the development, in order to gain much-needed public support. Often these processes highlight the need for additional measures to protect the environment or to enhance public benefits to compensate for any negative impacts caused.

The IAEA acknowledges stakeholder involvement in nuclear projects as crucial to their success, noting that consultation is important for "openness and transparency, and understanding that the purpose of stakeholder involvement isn't always about gaining complete public acceptance. Rather, its aim is to help people understand the rationale behind the competent authorities' decisions." [143] The key point is that trust has to be earned and then maintained. The process is more like relationship building than educating in an attempt to fill a knowledge deficit. The IAEA offers a range of tools and peer review services that can support in carrying out engagement exercises.

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[140] *Stakeholder Involvement Throughout the Life Cycle of Nuclear Facilities*, IAEA Nuclear Energy Series No. NG-T-1.4, International Atomic Energy Agency (July 2011)

[141] Eurobarometer surveys presented in *What People Really Think About Nuclear Energy*, Foratom (January 2017)

[142] *Edelman Trust Barometer 2020*, Edelman (January 2020)

[143] *Building Public Trust in Nuclear Power*, IAEA Bulletin, 54-1 (March 2013)

6.2.6 Encouraging diversity in the nuclear sector

As is typical for engineering fields and the energy sector generally, the nuclear industry is currently male-dominated. For example, in the UK, currently only about 20 percent of nuclear industry workers are women[144]. This has prompted the UK sector to set a target of 40 percent by the year 2030.[145]

With strong established regulatory and training frameworks, as well as a culture that openly embraces principles of leadership, the global nuclear industry is well-placed to take a prominent role in addressing the deeply ingrained stereotypes that has led to the current lack of gender diversity in science, technology, engineering, and mathematics (STEM) fields. Society is evolving and in most countries it is no longer acceptable for women not to be given the same opportunities as men.

It is vital to its own future success that the nuclear industry does embrace a leading role here. One of the most prominent splits in public acceptance of nuclear is along gender lines, with males being on average 15 percent more supportive of nuclear energy than females. Improving gender diversity in the workforce should therefore help to improve public support. It should also help to improve the financial performance of companies. According to a report by McKinsey: “Companies in the top quartile for gender diversity are 15 percent more likely to have financial returns above their respective national industry medians.” Simply put, bridging the gender divide is one of the biggest challenges that the global industry faces.

It is clear that in recent decades the industry has started rising to this challenge. Women in Nuclear is a global network with chapters in many established nuclear countries which aims to promote interest in nuclear engineering, science and other nuclear-related professions, especially among women and young people. The current heads of the US Nuclear Energy Institute (the largest nuclear trade association in the world) and the World Nuclear Association are both women. However, there is still much more work to do not only in increasing gender diversity but improving inclusivity across the spectrum of race, religion and sexuality. Newcomers can use their nuclear programmes to address existing social inequities, making sure inclusivity is factored in at the very beginning.

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[144] *Nuclear Sector Gender Roadmap – A journey to a diverse and inclusive sector*, Nuclear Skills Strategy Group (2017)

[145] *Industrial Strategy: Nuclear Sector Deal*, UK Department for Busines, Energy and Industrial Strategy (27 June 2018)