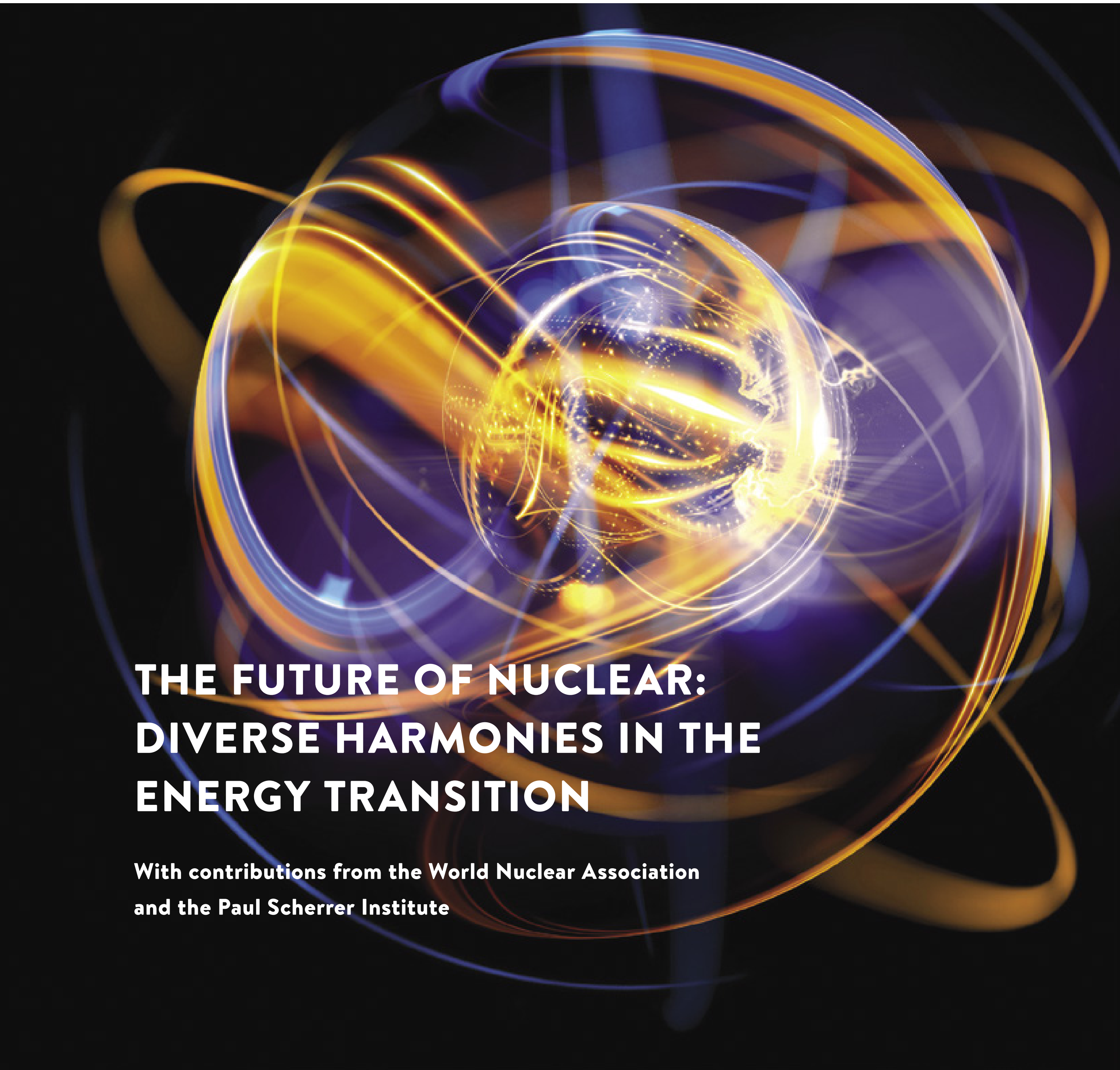
WORLD ENERGY COUNCIL

# World Energy Scenarios | 2019



## THE FUTURE OF NUCLEAR: DIVERSE HARMONIES IN THE ENERGY TRANSITION

With contributions from the World Nuclear Association and the Paul Scherrer Institute

## ABOUT THE WORLD ENERGY COUNCIL

The World Energy Council is the principal impartial network of energy leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all.

Formed in 1923, the Council is the UN-accredited global energy body, representing the entire energy spectrum, with over 3,000 member organisations in over 90 countries, drawn from governments, private and state corporations, academia, NGOs and energy stakeholders. We inform global, regional and national energy strategies by hosting high-level events including the World Energy Congress and publishing authoritative studies, and work through our extensive member network to facilitate the world's energy policy dialogue

Further details at www.worldenergy.org and @WECouncil

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## ABOUT THE REPORT

The "The Future of Nuclear: Diverse Harmonies in the Energy Transition" report provides a set of global scenarios describing alternative pathways for the nuclear energy industry to 2060. It is developed using the World Energy Scenarios archetypes framework – Modern Jazz, Unfinished Symphony and Hard Rock – and informed by insights from energy leaders.

This report aims at facilitating strategic sharing of knowledge between experts and promoting a better quality of strategic conversation among the Council's members, energy stakeholders and policy shapers.

**This report includes contributions from the World Nuclear Association.**

The Council's global scenarios framework used in this report is developed in 2016 in collaboration with Accenture Strategy and the Paul Scherrer Institute.

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# EXECUTIVE SUMMARY

**There is increasing and widespread recognition that nuclear energy will feature in the future global energy mix and make its contribution to sustainable development. The growth of nuclear energy and its role in the global energy transition will be influenced by a number of factors.**

The pace and direction of the global energy transition is part of a much wider set of global developments. The Grand Transition is under way and implies a fundamental socio-economic transition in response to the promise of a coming era of digital and ecological productivity. Within this broader context, the outlook for nuclear and other forms of energy is being shaped by a complex and unpredictable interplay of global drivers of change – including decentralisation, decarbonisation, digitalisation and evolving geopolitics. Multiple possible pathways are emerging for managing a successful global energy transition from hydrocarbon molecules to low-carbon energy.

Innovation will play a key role but not only through new and improved energy technologies. A broader and disruptive landscape of innovation has led to many new ways of producing, trading and using energy and electricity - such as in transport, buildings and industry.

Recognising the diversity of perspectives on nuclear energy, the World Energy Council (the Council), with contributions from the World Nuclear Association (the Association), has gathered insights from senior energy leaders on the future of the industry. This work has contributed to the Council's new global nuclear perspectives, which have been fed into an update of the Council's World Energy Scenarios.

In this report, the future of nuclear is described through the lens of the Council's World Energy Scenarios archetype framework – Modern Jazz, Unfinished Symphony and Hard Rock – in three plausible, alternative pathways for the future development of the sector. This report also describes implications for the role of nuclear energy in the global energy transition.

The Harmony programme, coordinated by the World Nuclear Association, sets out a vision for the future of electricity with the goal for nuclear to provide at least 25% of global electricity before 2050 as part of a clean and reliable low-carbon mix. The Harmony programme works with the whole energy community to get support from key stakeholders to ultimately deliver a low-carbon future in which nuclear fully contributes.

## NUCLEAR ENERGY GROWTH IN ALL THREE SCENARIOS WITH DIFFERENT IMPLICATIONS

Nuclear **energy will grow in all three scenarios** but could take three very different pathways:

**Modern Jazz** is a digitally disrupted, innovative, and globally market-driven world. In the Modern Jazz scenario, the nuclear industry has the potential to reinvent itself, from selling units to providing services, and to remain an energy source of choice as some of the major existing nuclear countries and emerging economies expand their nuclear fleets. In this scenario, nuclear accounts for 8.5% of electricity generation by 2060 compared with 11% in 2015. Installed nuclear generating capacity increases by 52% from 407 GW in 2015 to 620 GW in 2060.

**Unfinished Symphony** is a world in which more coordinated and sustainable economic growth models emerge with a global aspiration to a low-carbon future. This scenario sees nuclear energy widely accepted as part of a reliable and affordable response to the climate change emergency. In this scenario, the share of nuclear reaches 13.5% of total electricity generation by 2060 while its installed capacity almost triples to 1003 GW. In addition to new build and lifetime extension initiatives, new nuclear technologies – small modular reactors, floating units and Gen IV reactors – make a significant contribution to the global nuclear fleet.

**Hard Rock** explores the consequences of weaker and unsustainable global economic growth and inward-looking governments. In this scenario, nuclear power's share of global electricity generation reaches 12.5% by 2060, with installed capacity increasing by 70% to 696 GW in 2060. The main focus areas are new construction in emerging markets and lifetime extension initiatives in developed economies.

## REFLECTIONS FOR INDUSTRY LEADERS

### 1 INNOVATION IS IMPACTING THE ENTIRE VALUE CHAIN – HOW TO ACCELERATE THE RATE OF NUCLEAR LEARNING?

The accelerating pace of innovation, particularly in digitalisation, is blurring sector boundaries and enabling new, non-traditional players to enter the market. Looking to the future, digitalisation has the potential to improve the nuclear industry's performance and supporting it to allow better informed decisions on new build and lifetime extension. However, learning curves in other sectors will accelerate too– including renewable power, energy storage, and carbon capture and storage. The relative pace of learning across the nuclear sector can be increased through international coop-eration on harmonisation of regulatory processes, allowing reactor designs to be deployed globally with minimal design alterations. This would significantly reduce costs and project uncertainties.

Nuclear energy is one of the most cost-effective sources of electricity in many countries and the industry is actively improving project management. The industry must continue to ensure projects are delivered successfully, as shown by current programmes in Asia and elsewhere. These projects highlight the opportunity to accelerate innovation and take advantage of digitalisation and standard-isation to ensure the nuclear industry remains competitive.

## 2 MANAGING NEW TENSIONS BETWEEN STABILITY AND FLEXIBILITY – HOW CAN NUCLEAR ENABLE INTEGRATED, AGILE AND RESILIENT SYSTEMS?

Decarbonisation continues to be driven by electrification in all three scenarios. The scale up of intermittent renewable energy, however, is associated with system costs. In addition to providing clean and low-carbon energy, nuclear energy contributes to system stability and resilience attributes, which are not currently included in comparison of generation only costs. Small and medium reactor designs, which are being developed and some are under construction in some countries and are expected to be fully commercialised in the next 10-15 years, could provide new and significant opportunities for synergies in the development of nuclear-renewable hybrid energy systems. Reductions in the costs of nuclear-based electrolysis also present opportunities to help accelerate global trade in clean liquids, which depends in large part on global cooperation on new hydrogen pathways that might become economically feasible.

## 3 HOW CAN THE CO-BENEFITS AND SYNERGIES OFFERED BY NUCLEAR BE BETTER UNDERSTOOD AND RECOGNISED?

Despite increasing global awareness of climate change and of nuclear energy's status as a low-carbon energy source, greater support is needed from policymakers to establish a level playing field that compares the full costs offered by different technology pathways. In the public realm, improving awareness of the benefits of nuclear energy are starting points for clarifying the basis for inclusion of nuclear in green labelling initiatives.

Spent nuclear fuel and high-level radioactive waste remains an issue in all three scenarios. Both public and the industry work together on a final solution. Repositories for this purpose are currently in development and under construction in several countries and are expected to provide safe final disposal of the small volumes these materials represent.

Technology-neutral policies that enable all types of low carbon solutions to be considered, including nuclear power, will play a fundamental role in providing signal for investment and reducing the financing costs to deliver the best value to consumers.

**Looking across the scenarios, four critical challenges and opportunities faced by the global nuclear industry and energy leaders – faster learning, linking renewables and nuclear, leveraging benefits and leadership for the long-term – become clear and will define how nuclear energy fits in the future energy system. Implications are detailed in the main report.**

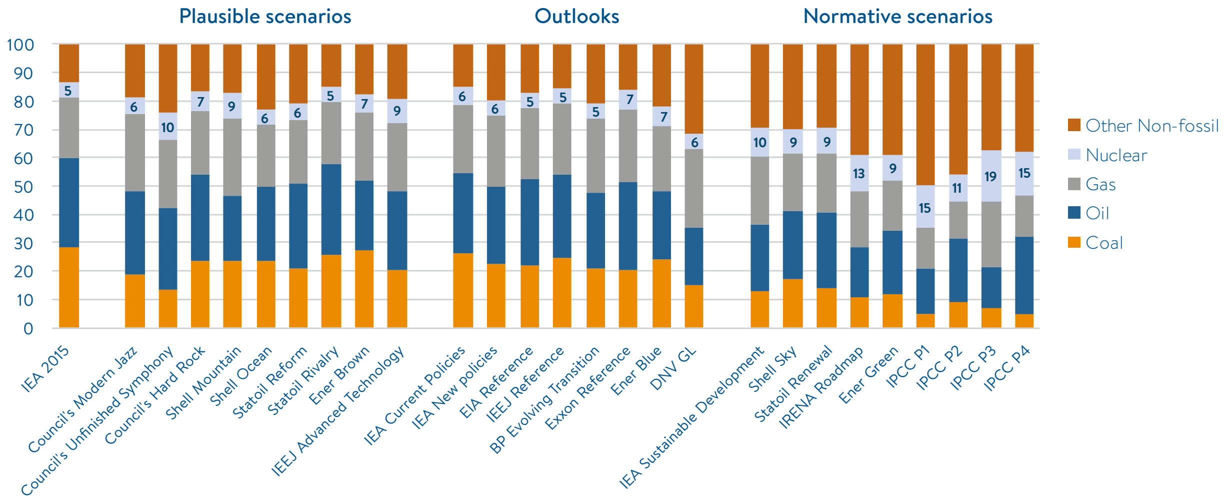
# Chapter one
# Introduction

# INTRODUCTION

Energy systems worldwide are undergoing rapid and fundamental changes as they are transformed by an accelerating pace of new technology developments and the interplay of wider shifts in society, geopolitics and the environment.

Nuclear energy will feature in the global energy mix for decades to come but its share in the mix and its rate of growth will depend on a number of factors. Some of these are largely determined by actions taken within the sector, e.g. speed of innovation in new nuclear technology and shaping policies on legacy waste management, whilst other factors such as energy policies, market design and financing structures are shaped and influenced by other stakeholders. In many normative goal-based energy scenarios nuclear is estimated to grow. For example in the IPCC special report on Global Warming of 1.5°C, nuclear contributes up to 19% to the electricity mix by 2040, an increase of nuclear capacity of three times compared to 2010, to help achieve the commitments of the UNFCCC Paris Agreement and the UN Sustainable Development Goals (Figure 1).

## Figure 1: Primary Energy Mix by 2040 and Share of Nuclear (%)




Source: Global Energy Scenarios Comparison Review (2019), World Energy Council

Due to the inherent complexities and deep uncertainties in play, a wide range of stories are emerging about the role nuclear might take in managing a successful global energy transition. As a technology- and geography-neutral platform, the World Energy Council (the Council), with contributions from the World Nuclear Association (the Association), has developed new insights into the future role of nuclear energy. These insights contributed to the development of the Council's new nuclear perspectives through the lens of the its three global archetype scenarios – Modern Jazz, Unfinished Symphony and Hard Rock. A plausible role for nuclear to 2060 is described in the context of each scenario. The three narratives are supported by illustrative quantification and highlight opportunities for collaborative action.

## THE WORLD ENERGY SCENARIOS

Since 2010, the Council has been developing World Energy Scenarios to help energy leaders manage the new realities emerging as the global energy system undergoes fundamental changes within the context of what is called 'The Grand Transition'.

In response to The Grand Transition, a number of energy pathways are emerging. In 2016, the Council presented three plausible pathways to 2060 to inform the conversation on climate change.

While all three scenarios reflect the same pre-determined factors, each individual scenario places a different emphasis on how four critical uncertainties might play out. Each storyline describes what might plausibly happen. The scenarios are not forecasts or visions and none advocates a preferred future vision.

**Modern Jazz** represents a digitally disrupted, innovative, and market-driven world. **Unfinished Symphony** is a world in which more coordinated and sustainable economic growth models emerge in a move towards a low-carbon future. **Hard Rock** explores the consequences of weaker and unsustainable global economic policies implemented by inward-looking governments.

In preparation for the 24th World Energy Congress, the Council tested the validity of the scenarios and decided to maintain its existing archetype framework. It has refreshed and refocused the World Energy Scenarios narratives, using a time horizon of 2040 to explore the fast shifting landscape of innovation. The aim is to support energy leaders as they grapple with the phenomenon of disruptive innovation and the implications of the transition to low-carbon and sustainable energy sources.

## THE ADDED VALUE OF USING SCENARIOS

The value to energy leaders of using multiple scenarios to support decision making is threefold:

- Scenarios are an opportunity to engage constructively with deep uncertainty and to clarify complexity;
- They open a safe space for disagreement and, thus, encourage new learning;
- They avoid the trap of forecasting and prepare contingencies for possible future developments, whether or not decision makers want or expect them to happen.

Two different ways to use the Global Nuclear Perspective scenarios are presented in this section.

### 1. Platform for better quality dialogue – levelling the playing field

One of the most profound uses of scenarios is as a stage for dialogue on extremely complex and contentious issues. Where there is deep disagreement, a wide-ranging, open and honest discussion is almost impossible under normal circumstances. Champions of one side or another must constantly argue their strongest position, for example, and often it is politically dangerous to step into the shoes of an opponent and explore how the issue might appear from another point of view. In such politically charged situations, discussions could quickly become arguments; or, if the atmosphere is congenial, the 'elephants in the room' might be politely ignored.

In such a situation, a team composed of people from different perspectives may be able to create scenarios together even when they cannot agree on policy positions. After all, scenarios are only stories of what might happen, not what should or will happen.

Often in the process of creating a story, those who hold opposing positions begin to understand the other point of view and to see possible opportunities for collaboration. A different kind of listening occurs, and shared understanding often emerges.

There is a notable fragmentation of perspectives about the role of nuclear energy in enabling affordable decarbonisation and globally inclusive prosperity. On the one hand, policy rhetoric increasingly recognises the role that nuclear energy can play in meeting the Paris Agreement goals and enabling new industrial development. On the other hand, discussion of policies that could enable new and better nuclear pathways is frequently overlooked or avoided. A scenario-based discussion can help identify policy-related challenges and offer new policy options.

### 2. Translating vision into action

A vision is a symbolic picture of the future that reflects shared values and is designed to motivate a change in action. To avoid unrealistic dreaming, it is necessary to tether a vision to reality. Translating a vision into action can be achieved through a process of back-casting from future to present to develop rational strategy and functional plans, with actionable milestones and budgets.

As well as creating a new shared vision, a set of scenarios can be used to stress-test an existing vision against different plausible future contexts to identify and address the gap between what we would prefer to happen and what we need to be prepared for.

#### WORLD NUCLEAR ASSOCIATION – THE HARMONY PROGRAMME

The global nuclear industry, in coordination with the World Nuclear Association, has developed the Harmony programme setting out a vision for the future of electricity to support the global effort to manage energy transition challenges. The goal is for nuclear to provide at least 25% of electricity before 2050 as part of a clean and reliable low-carbon mix. This would require building at least 1000 GWe of new nuclear capacity.

The Harmony programme sets out three objectives:

- Establish a level playing field in energy markets which drives investment in future clean energy, where nuclear energy is treated on an equal terms with other low-carbon technologies and recognised for its value in a reliable and robust low-carbon energy mix.
- Ensure harmonized regulatory processes 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.
- Create an effective safety paradigm focusing on genuine public wellbeing, where the health, environmental and safety benefits of nuclear are valued when compared with other energy sources.

Source: World Nuclear Association

# Chapter two

# The Shifting Nuclear Landscape

# 2. THE SHIFTING NUCLEAR LANDSCAPE

Historically, big changes in the nuclear landscape have occurred in timeframes of a decade or more, reflecting the reality that design, financing and construction take years. Scenario-based approaches, however, redirect leadership attention to changes beyond the sector that have yet to achieve full impact, and to new developments that are still emerging. This horizon scanning process is designed to offer alternative perspectives on the key drivers of change that will shape and impact the future of nuclear energy.

During 2019, the Council and the Association jointly conducted a series of 18 deep-dive interviews to explore the current state and future of nuclear with energy leaders from the nuclear sector and beyond. Interviewees were asked to define: the major changes in political, investor and public attitudes in the last three to five years; the major factors that will define the future development of nuclear; and the different stories emerging for nuclear over the next two decades.

Below box presents the top-line results of the synthesis of the deep-dive interviews, organised in terms of salience (low vs. high frequency of mentions) and level of agreement.

## CHORUS OF VOICES ANALYSIS – DEEP DIVE INTERVIEW SYNTHESIS

FREQUENCY OF MENTIONS: HIGH

**Statements that were mentioned the most, and had most disagreements in views**

- Is nuclear gaining more recognition as a main contributor to economic and climate change goals or does it face an existential crisis?
- Can nuclear be delivered in current liberalised markets or does it need more government participation and control?
- Are there synergies in opportunities for renewables and nuclear or the potential is slim?
- What will be the main technology choice – Gen III, or Gen III+, or Gen IV
- Who will be the main actor to drive change – industry, or governments or mix of industry, governments, and academia?

**Statements that were mentioned the most, and had most consensus**

- Public support for nuclear is location specific
- Innovative SMR development is under way and offers potential for non-power nuclear applications for decarbonising industry, heat, desalination, etc
- Longer term planning is essential
- High costs and poor performance of some recent projects discourage investors in some markets
- Innovation in licencing, construction and localised supply chain could reduce costs
- Good nuclear development in some countries (such as Russia and China) which continue to successfully develop and deploy nuclear.
- Nuclear has been successfully introduced into some new countries
- Need for clearer messages on nuclear benefits, not just safety
- Effective nuclear deployment benefit from fleet programme approaches
- Digitalisation is impacting across the whole value chain

FREQUENCY OF MENTIONS: LOW

**Statements that were mentioned less, and had disagreements in views**

- Will electricity storage development boost or limit nuclear developments?
- Waste issue – is it a challenge to the future of nuclear or effective implementation solution?

**Statements that were mentioned less, but had a consensus in views**

- Strict safety requirements are a cause of high nuclear costs
- Dispatchability and greater flexibility of power will be greatly valued
- Supply chains need to be integrated more into the project management of construction
- High level of regionalism

LOW — LEVEL OF AGREEMENT — HIGH

Source: Synthesis of series of interviews, World Energy Council, World Nuclear Association

The interviews throw light on the following realities:

- Discussions on the future of nuclear energy are fragmented and while there is no doubt as to the benefit of nuclear as a low-carbon energy source, there is no consensus on how the system benefits of nuclear, in maintaining energy security and reliability, will be valued and compensated in a liberalised market system. Collaborative innovation and hybrid systems may provide a solution.

- The nuclear energy industry faces two key questions: will construction times and costs of large reactors be brought under control in OECD markets; and will the industry succeed in bringing to market small medium reactors in time? The answers will be instrumental in determining who will be the future users of nuclear energy, and how they will use it. It is also important to continue to address the issues of nuclear waste, in particular, the disposal of spent fuel.

- New innovation opportunities – 'on demand' consumer logic, digitalisation of energy services, affordable decarbonisation, and flexible security (i.e. switching between supply and storage) present new opportunities in the development of the next generation of nuclear technologies.

- Opportunities for leveraging synergies and co-benefits: wherever nuclear energy is politically and socially included as part of the clean energy transition, the co-benefits include scaling up decentralised variable renewable sources, affordable and deeper decarbonisation, and broader economic and environmental benefits e.g. job creation and sustainable land use.

Other insights which have emerged from the interviews and wider horizon scanning are listed below.

## THE ROLE OF NUCLEAR IN THE ENERGY MIX

Nuclear power's high unit capacity and high reliability make it suitable for base-load power in the energy system. Compared to fossil fuels, nuclear has two distinct advantages. First is that it is a low-carbon energy source. Second is that it delivers predictable and relatively low-cost electricity: fuel cost per unit of power is marginal and does not fluctuate in price as much as fossil fuels. Current nuclear technologies can fit into the large power systems of industrialized economies. When commercially introduced, small and medium reactors (SMRs) are expected to be naturally compatible with relatively small power systems with low industrial consumption, where there are underdeveloped grids, or for decentralised power generation systems. SMR designs also promise to be more flexible in operation and siting and to supply other energy products, such as heat, as well as electricity.

## AN ACCELERATING PACE OF DIGITALISATION OF ENERGY

Some recent nuclear projects in OECD countries have resulted in cost overruns and project management delays, which had a negative impact on industry delivery capability. Many nuclear industry experts expect the digital revolution to transform business information management, improve project management and reduce build costs. Digital technologies are already having an impact on nuclear industry performance globally. In addition, digitalisation gains are expected with respect to lifetime extension or modernization and upgrades. Using digital technologies across the whole lifecycle of the nuclear power plant – from research and development through to construction and operation, refurbishment, upgrades and modernization – can help the industry to bring a step-change in performance and increase transparency with regulators.

## THE UN SUSTAINABLE DEVELOPMENT AGENDA

The UN Sustainable Development Goals, adopted in 2015, are guiding the direction of new global visions, reshaping international commitments and informing the development of national priorities. Nuclear power has a number of benefits across a range of social, environmental and economic indicators when compared with other energy sources. The development of nuclear energy and industry contributes to at least 10 of the 17 goals.

### NUCLEAR TECHNOLOGY CONTRIBUTION TO ACHIEVING UN SUSTAINABLE DEVELOPMENT GOALS

| | NATURAL GAS | RENEWABLES (wind and solar) | COAL | HYDROPOWER | NUCLEAR | |
|---|---|---|---|---|---|---|
| 1. No poverty | | | | | | |
| 2. Zero Hunger | | | | | ● | improves crop varieties and nutrition via radiation technologies - up to 20-25% of food losses can be avoided |
| 3. Good Health and Well-being | | | | | ● | by development of radio-medicine and radio-pharmaceuticals |
| 4. Quality Education | ● | ● | ● | ● | ● | education and training of highly qualified engineers and workers, esp. in the emerging economies |
| 5. Gender Equality | | | | | | |
| 6. Clean Water and Sanitation | | | | | ● | offers nuclear-based desalination technologies |
| 7: Affordable and Clean Energy | ● | ● | | ● | ● | reliable, affordable and low-carbon energy supply 24 hours a day |
| 8: Decent Work and Economic Growth | ● | ● | ● | ● | ● | a 2GW NPP creates 400,000 labour-years of employment |
| 9: Industry, Innovation and Infrastructure | ● | ● | ● | ● | ● | an innovation-driven industry; supports other industries' development, esp. for industrialising economies |
| 10: Reduced Inequality | | | | | | |
| 11: Sustainable Cities and Communities | | ● | | | | |
| 12: Responsible Consumption and Production | | ● | | | | |
| 13: Climate Action | ● | ● | | ● | ● | avoids contributing to climate change by generating low-carbon electricity (29 tonnes $CO_2e$ / GWh) |
| 14: Life Below Water | | | | | | |
| 15: Life on Land | | | | | ● | fights pests and diseases via radiation technologies; identifies soil erosion via radionuclides |
| 16: Peace and Justice Strong Institutions | | | | | | |
| 17: Partnerships to achieve the Goal | ● | ● | ● | ● | ● | partnering via supranational organisations to ensure industry's safe and reliable operations |

Source: World Energy Council analysis

## POTENTIAL SYNERGY WITH RENEWABLES

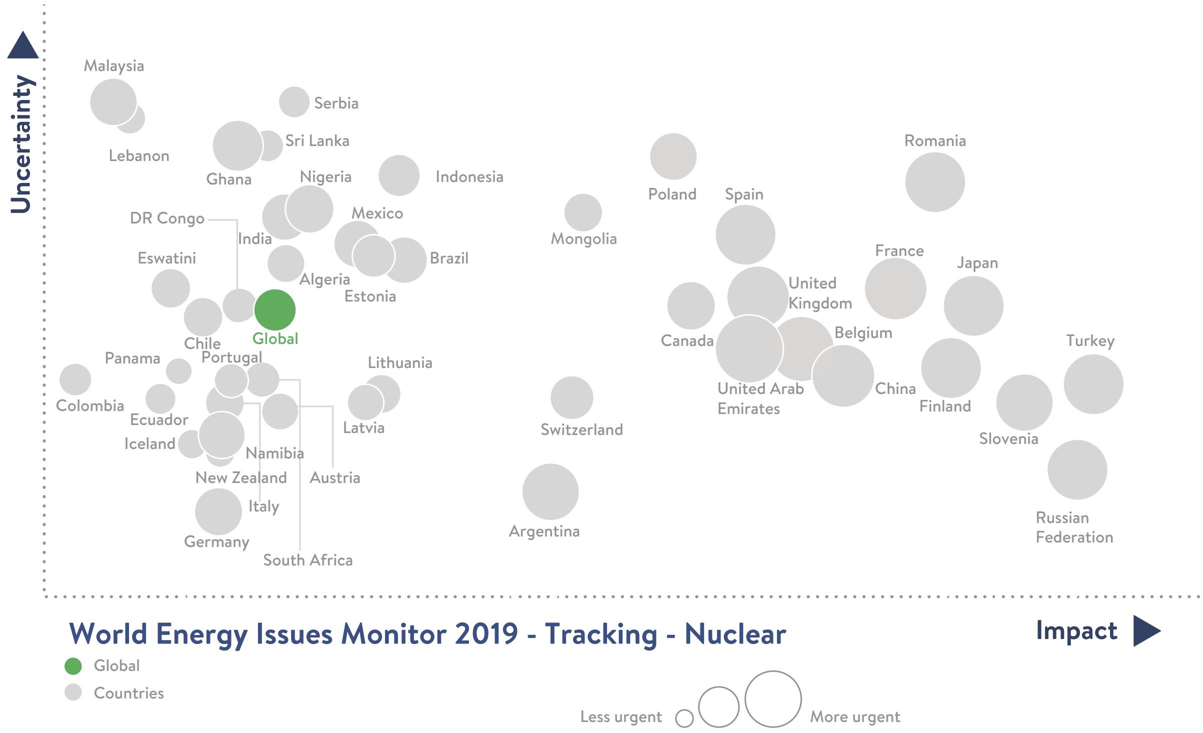
The intermittency of some renewable energy sources remains a challenge for the electricity system for it imposes the requirement of increasing flexibility and additional costs in the system through electricity storage, balancing and transmission. Nuclear power can provide reliable low-carbon electricity, which is critical to grid stability, while the flexibility of nuclear generating units has been well demonstrated in France and Germany and enables the integration and scale-up of intermittent renewable sources at lower cost. Nuclear power in this role reduces the need for more peaking power plants, such as gas fired power generation with CCUS technologies.

There is an opportunity to coordinate and integrated nuclear, renewable and storage systems, leading to the development of hybrid integrated low-carbon energy systems at national and international levels that can significantly reduce greenhouse gas emissions compared to fossil fuels. Co-location would improve the efficiency of the supporting workforce and infrastructure, including grid connections, and alleviate the social and economic cost of wind and solars significant land use. With the wider availability of renewables and an increasing need for a flexible and smart electricity grid, integrated energy systems could play a significant role and nuclear energy could be a component of such energy systems if it is allowed to compete on a level playing field.

## REGIONALISM AND DIVERSE NUCLEAR DEVELOPMENT STRATEGIES

While nuclear energy is used by 31 countries, full specialisation is limited to a small number.  This concentration reveals itself in many ways: from the current development of the national nuclear fleet to the national strategy toward nuclear development; to the localisation of specific assets and capabilities; and to public acceptance. The Council's Issues Monitor horizon scanning tool shows the great diversity of countries that consider nuclear in their priority action agenda.

### NUCLEAR TRACKING IN THE COUNCIL'S ISSUES MONITOR MAP (2019)




Source: World Energy Council analysis

There are about 450 operational power reactors in the world, roughly 70% of which are in OECD countries, providing on average 18% of their electricity needs. In the advanced economies as a group, nuclear power is the largest low-carbon source of electricity, providing 40% of all low-carbon generation. For non-OECD countries nuclear power plants contributed 4.6% of total gross electricity production for 2016. For comparison variable renewable energy (wind, solar, geothermal, tide, wave and other power facilities excluding hydro) provided 3.5% of total electricity production in non-OECD countries.

Looking more closely, however, there are other critical differences in national nuclear development strategies between OECD and non-OECD countries. European developments involve large scale nuclear power stations which are often built one-by-one in countries with different regulatory and licencing requirements. For OECD countries, nuclear is a significant source of reliable and affordable low-carbon base-load power in the energy system with limited risk from fuel price volatility compared to fossil-fuelled systems. At the same time, OECD countries are managing an aging fleet, nuclear legacy, including spent fuel and radioactive waste, and replacing low-carbon capacity with new nuclear units or other sources.

For a number of non-OECD countries, nuclear energy provides a solution to satisfying their growing energy demand and enabling industrial development without increasing their carbon footprint. Some are considering the construction of new fleets while others may opt for one or two additional units at existing plants.

## FLEET APPROACH

Nuclear electricity can be very cost competitive, with significant gains following construction of a standardised design, using modular components as far as possible, and establishing a fleet construction programme. This fleet approach, or serial construction, is the most efficient way to develop national nuclear capacity as it provides cost curve learning and economies of scale across the value chain. It usually leads to shorter construction periods and considerably lower unit costs. Recent programmes in countries such as Russia, China, South Korea, Japan and India have shown the benefits of a fleet construction programme. Other countries that have embarked on a fleet approach, or have expressed an intention to do so, are in the Middle East (such as the United Arab Emirates, Saudi Arabia, Iran, Turkey, and Egypt) while South Africa, Nigeria, and Brazil also include fleet options in their future thinking.

Growth in population, economic development and electricity demand are leading some developing countries to consider new nuclear technologies. The International Atomic Energy Agency reported that 28 countries, sometimes known as 'newcomers', are considering, planning or starting nuclear power programmes for the first time, while an additional 20 countries have expressed interest in nuclear power and are engaging in some nuclear infrastructure related activities. These developments mark a continued expansion eastward and southward for the nuclear sector.

Other signals of new and renewed interest in nuclear power development, within both OECD and non-OECD countries, are centered on innovation in next generation nuclear technology, including less capital intensive, modular-design SMR technologies and so-called micro-reactor power systems, which are suitable for remote communities with no access to central grid systems. See the Annex for further information on the different generations of existing nuclear technology and the outlook for new nuclear technologies.

## NUCLEAR INDUSTRY AND CAPABILITIES AS A DEVELOPMENTAL AGENDA

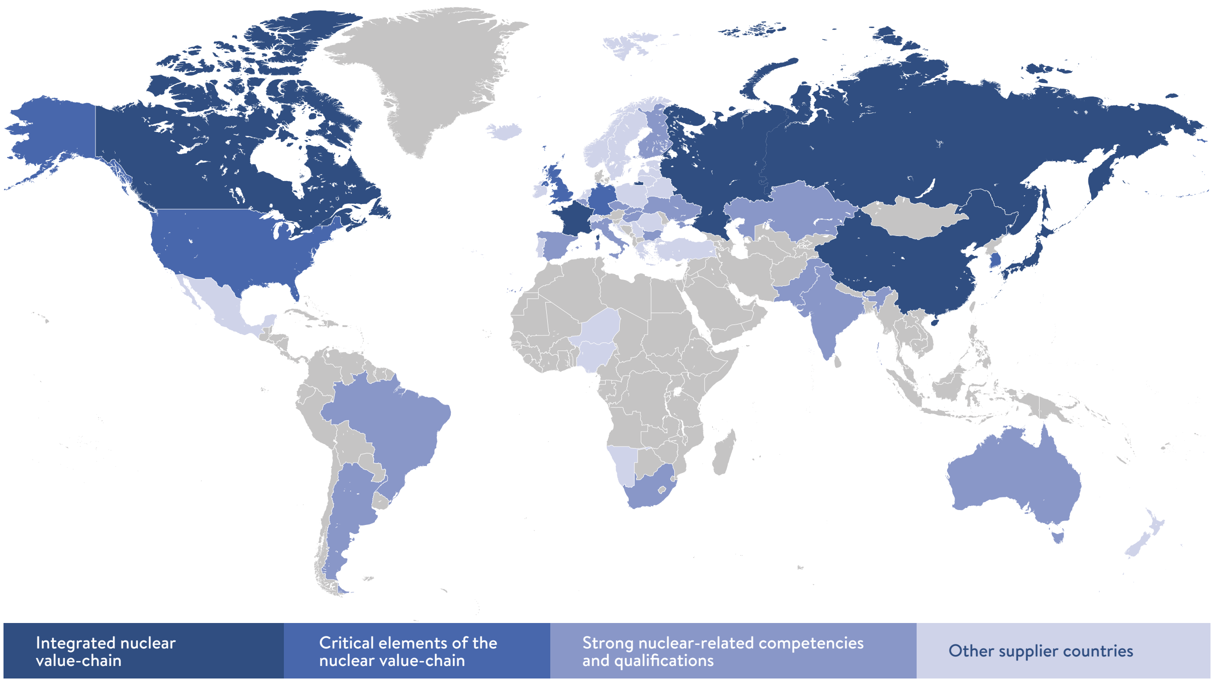
The choice between one-off construction and fleet-based strategies carries significant implications for investment in building skills and workforce capabilities.

The nuclear industry requires specialised skills, assets and knowledge, from academic qualifications and research to the ability to operate specialised manufacturing sites and nuclear facilities. There are millions of highly qualified people employed across the whole value chain all over the world. As of now, there are very few countries that provide the entire set of competences of the whole nuclear fuel cycle. A few more are moving toward developing their own competences across the whole value chain or some part of it.

At a national level, there are a number of countries with broad experience, qualifications, and capacity in nuclear energy. Today, the major nuclear reactor vendors are located in Canada, China, France, Japan, Korea, Russia and the US. There are also some advanced nuclear value chain elements available in Argentina, Brazil, India and the UK.

### NUCLEAR SKILLS AND CAPABILITIES MAP

There are different non-core nuclear-related competencies and qualifications in over 40 countries in all continents, spreading across the value chain from engineering, construction, and equipment manufacturing to operation and decommissioning, as well as across the nuclear fuel cycle from uranium mining to spent fuel and radioactive waste management.




Source: World Energy Council, analysis based on a Nuclear Suppliers Group data

For some countries nuclear development has been a strategic decision reflected in investment in integrated nuclear value chains, strong human capital development, incentivised industrial policy, and the creation of enabling institutions. Such considerations go far beyond nuclear energy and can involve the national agenda and the country's trajectory to reach the UN Sustainable Development Goals. The appropriate level of commitment to the sector is an important consideration for a national government making decisions about its future use of nuclear power. Looking to the future, the digitalisation of the sector and the rise in demand for energy-plus services will also require new skills to be developed.

## FRAGMENTED POLICY SUPPORT AND PUBLIC ACCEPTANCE

Policy support for nuclear energy varies widely by country and by region. Public acceptance is shaped by economic, social and cultural factors. Polling of public sentiment regularly shows that favourability towards nuclear energy is highest in areas that are in close proximity to a facility and where there is a concentration of knowledge about the sector. In areas further removed from nuclear facilities, polls show a less favourable opinion where large sections of communities are not familiar with nuclear operations and whose opinions are shaped largely by media.

Nuclear will remain an industrial and energy solution sensitive to the local political, social, and economic environment.

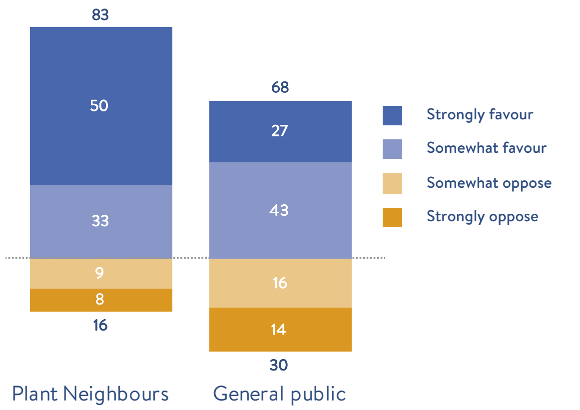
### FRAGMENTED PUBLIC ACCEPTANCE AND WORKING WITH COMMUNITIES

The highest acceptance rates are observed in countries where there is a considerable amount of energy being produced by nuclear power plants with certain exceptions, such as Germany and Japan. At the same time, there are also differences in public acceptance levels within larger countries.

Polling of public sentiment also regularly shows that favourability towards nuclear energy reaches the highest levels in areas proximal to a facility where there is more knowledge of the sector.

**Favourability of nuclear energy**

*"Overall, do you strongly favour, somewhat favour, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States?" (2015)*




Source: The Hill, 2015

Understanding major changes in a nuclear landscape and specifics of its development will help in charting the role of nuclear in new and emerging pathways to 2060.

# Chapter three

# The World To 2060

# 3. THE WORLD TO 2060

## WHAT IS PREDETERMINED – "THE GRAND TRANSITION"

Energy systems are in transition, shifting from an era of hydrocarbon molecule dominance to a promise of abundant affordable clean energy and universal access to electricity. New roles are emerging, and sector boundaries are blurring. The growing diversity of new clean energy sources is mirrored by an increasing diversity of energy system shapers and participants – within and beyond the energy sector.

The world is experiencing lower rates of growth in population and labour force, a higher level of penetration of new and powerful technologies, a greater appreciation of the planet's environmental boundaries, and a significant shift of economic and geopolitical power towards Asia.

All these factors collectively imply a fundamentally new context for the world energy system. The Council calls this journey "The Grand Transition".

## WHAT IS UNCERTAIN?

The outcome of the broad set of uncertainties will be critical in determining the course of the future world of energy. The Council recognises four critical uncertainties.

### What will be the pace of technological innovation and what will be the implications for productivity growth in an era of increasing automation and low labour force growth?

New technologies and digitalisation are impacting the whole value chain and providing the potential for huge improvements in energy efficiency within existing systems as well as for new energy sources and uses. Digitally empowered consumers are demanding "energy plus" services, while responsible consumerism is driving a circular and sharing economy. New accelerators of technology convergence and social change are leading to unexpected disruptions that are challenging traditional business models, government policies, and institutions. However, productivity gains are unevenly distributed – different future pathways may experience different paces of technology innovation with as-yet unforeseen implications for energy systems and players.

### How will international governance and geopolitics evolve?

The world is facing a shift in market power towards non-OECD countries, mainly in Asia, where India and China are the main economic engines of growth. Geopolitics is broadening beyond oil and gas to include technology, climate change and non-energy resources. Multilateralism is being weakened by new geostrategic competitions and a multipolar, regional order is emerging. Going forward, it is uncertain what form and focus state rivalry will take, and whether a collaborative international governance structure – a new global order – that serves the needs of all can be built.

### What priority will the public and governments assign to climate change and a wider range of environmental and sustainability issues?

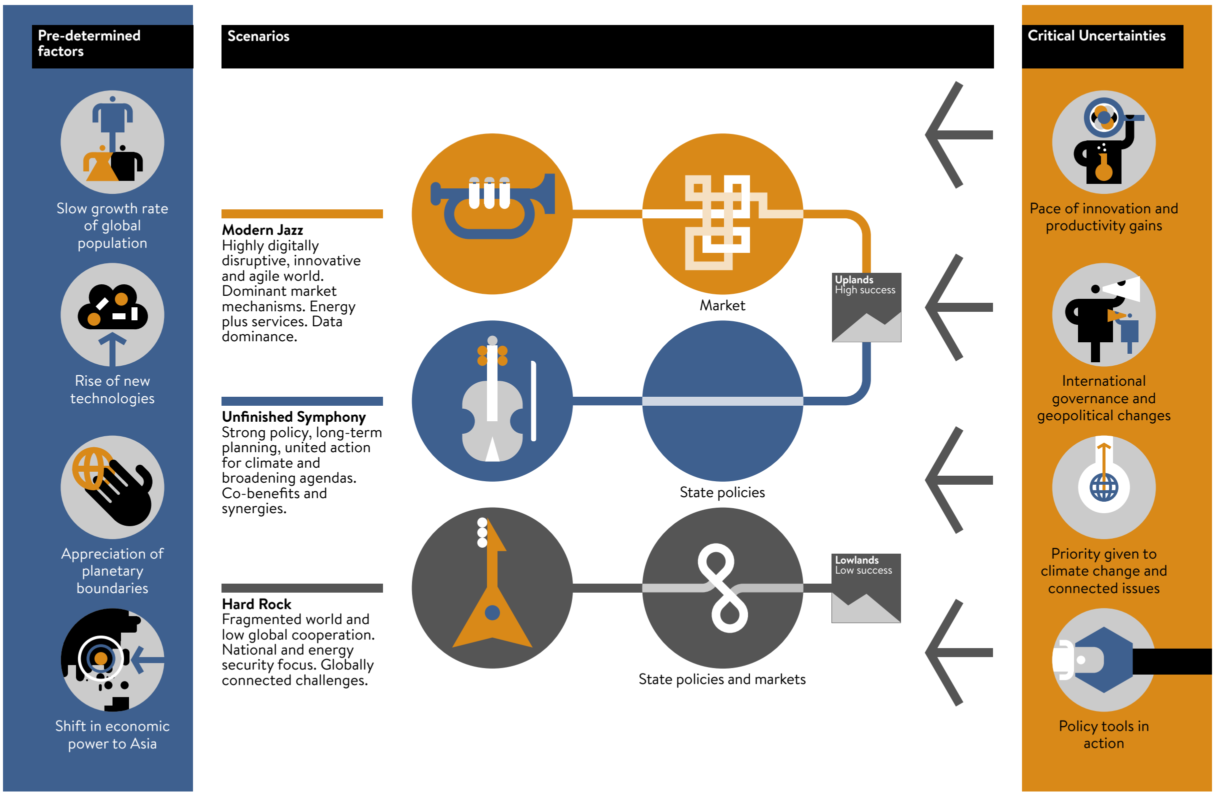
There is a growing diversity of views on the future roles of policy, finance and technology innovation in the energy transition. A growing convergence of agendas such as climate, wellbeing, air quality, and sustainability, is having the effect of pushing policy coherence and sector-coupling strategies. Adaptation has become an important part of the agenda in many countries, given the increasing number of extreme weather events that affect critical infrastructure. However, the priority that governments are likely to assign to a wide range of environmental, livelihood and sustainability issues is open to question and any policies would be subject to tests of public acceptance on the basis of their impact on affordability, way of life and land use among other things.

### What will be the preferred mode of managing the energy sector: state control, markets or a mixture?

The key tools for enabling change are state directives, market forces, and mixtures of both. Going forward, future developments will be defined by the selection of mechanisms used to drive investment in clean and sustainable energy developments and “affordability” of the whole energy system’s transition.

These four critical uncertainties interplay and create the underpinnings of the Council’s three unique scenarios to 2060 – Modern Jazz, Unfinished Symphony and Hard Rock. The four pre-determined factors and critical uncertainties, and the characteristics of the three scenarios are summarised in figure below.

## THE COUNCIL’S WORLD ENERGY SCENARIOS FRAMEWORK




Source: World Energy Council, Accenture Strategy, the Paul Scherrer Institute

## KEY NUCLEAR UNCERTAINTIES

Besides the wider set of uncertainties above, there are certain specific factors that will affect nuclear power's future and how much capacity is installed by 2060. Much will depend on reaching consensus on nuclear's role in the energy transition, lifetime extension and new build policy in developed and developing economies – issues which are intertwined with the pace of technological and institutional innovation.

## RECOGNITION OF NUCLEAR AND INSTITUTIONAL INNOVATION

Although nuclear has an obvious role in the low-carbon energy mix and is already one of the significant contributors to the UN Sustainable Development Goal agenda, there has been a continuous discussion at various policy platforms about nuclear energy's role in the green transition. The European Commission is in the process of developing a 'green taxonomy' – a classification of the energy sources that are eligible for an EU Green Label aimed at shifting financial flows towards decarbonization. There is ongoing debate of nuclear energy's position within the 'green taxonomy' but its inclusion remains uncertain. Nuclear power plant construction projects are also often excluded from the mandate of international development institutions such as the World Bank that support large infrastructure projects. Such debates on nuclear's position in green labeling will be one of the main uncertainties defining its future financing.

At the same time, there has been some progress in changing the perception of nuclear energy by the financial and investment community. Some financial analysts include nuclear projects in green and sustainable finance reviews. In 2018, the share of conditionally green projects in the nuclear sector accounted for USD 9.2 billion, compared to USD 5.2 billion in 2016. Such securities are issued, for example, by Finland and Switzerland. This is still only 3% of the total amount of green funding in the energy sector, and it remains unclear how this is going to progress in the coming years.

In reference to institutional innovations, the introduction of new innovative reactor designs, like Gen IV, SMRs and floating units, will provide an opportunity for greater international collaboration on regulation and licensing of new nuclear designs, materials and nuclear fuels, as well as their transport. The harmonisation and streamlining of regulatory processes would reduce costs and improve new build planning and performance.

## NATIONAL NUCLEAR STRATEGIES: LIFETIME EXTENSION AND NEW BUILD

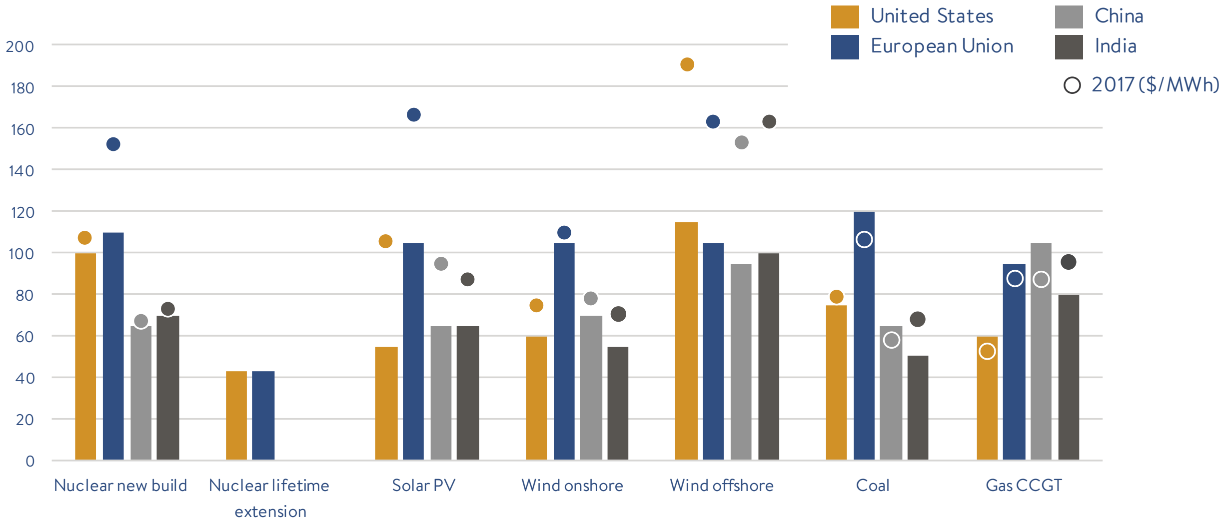
Nuclear energy is and can be one of the most cost-competitive low-carbon options for generating electricity. As an example, the cost of electricity in China from nuclear in 2017 was cheaper than other low-carbon sources. It is estimated that nuclear energy in China will remain one of the lowest cost forms of electricity in the timeframe to 2040, taking into account system value. Lifetime extension of existing reactors is one of the best power generation investments available in the market on the basis of the levelised cost of energy.

As for new build in the OECD, there are ongoing projects in France, Finland, Japan, Slovakia, Korea, Turkey, the UK and the USA. Some first-of-a-kind projects in countries that have not built nuclear plants for some time have resulted in cost and time overruns. The UK nuclear programme has plans for multiple nuclear plants and, despite delays, is now making good progress. The Czech Republic, Slovakia, Bulgaria, Hungary and Finland are among countries that have local supply chains and highly qualified human capital planning to build new nuclear power plants.

## COST COMPETITIVENESS OF DIFFERENT TECHNOLOGIES

Nuclear new build and lifetime extension of existing nuclear power plants can be competitive and cost-effective ways of providing low-carbon sources of electricity.

### Projected LCOE by technology, 2040




Source: IEA 2019

## ACCELERATING TECHNOLOGY LEARNING CURVES

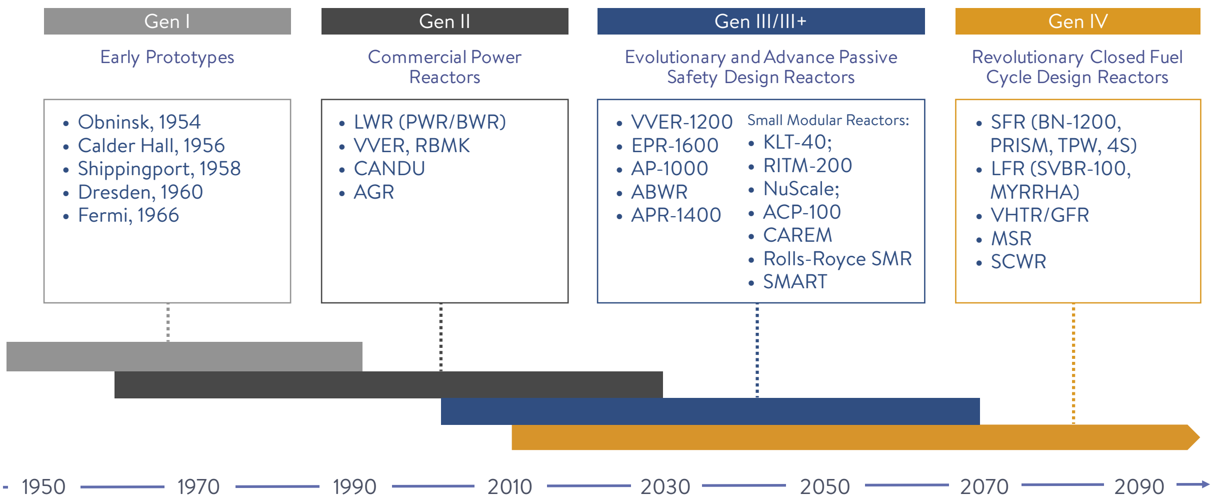
The nuclear industry has especially long investment and innovation cycles, as well as ultra-long operational cycles. It takes approximately six years to build a nuclear power plant that can operate for more than 60 years. Innovative reactors involve decades-long research and development programmes followed by years-long licensing procedures and first-of-a-kind construction and testing.

Looking at the time horizon to 2060, technological innovation that would have a major impact on the energy transition is focused primarily on SMRs. Russia has just completed its first floating barge SMR, designed to power remote locations. China is nearing completion of a small high-temperature gas-cooled reactor and has announced the launch of a project to build another SMR. Argentina is nearing completion of an SMR prototype. Several other existing nuclear energy countries such as Canada, Korea, the US and UK are actively supporting the development and deployment of advanced reactors and SMRs. The US and Canada are currently licensing a number of designs with the aim of first deployment in the 2020s.

SMRs are expected to have a number of additional applications beyond producing low-carbon energy, such as seawater desalination, hydrogen and synfuel production and heat supply to residential and industrial facilities. Beyond these reactor technology improvements are Gen IV systems which promise a further step change in ease of deployment and safety, as well as a closed fuel cycle.

Innovation in new nuclear technologies also includes accident-tolerant fuel for current reactors, advanced techniques to extend the service lives of major components, new ways to produce medical isotopes, borehole disposal of waste, as well as many less visible innovations that are driven by regulatory demands at existing operations – and of course the quest for fusion in the form of the ITER project. Many of these innovative developments have the potential to bear fruit within the next 10-15 years. It is anticipated that the major impact and contributions from SMRs will be from 2030 and beyond.

## ADVANCED REACTORS TIMELINE




Source: IAEA, World Energy Council, World Nuclear Association analysis

Different possible pathways for the future of nuclear emerge when all these factors - as well as wider critical uncertainties and uncertainties specific to nuclear – are mixed together.

# Chapter four
# Nuclear Narratives

# 4. NUCLEAR NARRATIVES

## MODERN JAZZ

*This is a consumer-driven, digitally transparent, and flexible world of much greater energy efficiency in which new investments in innovation are monetised quickly. An accelerated pace of innovation brings uneven but high productivity growth, and potential for new shocks. In this world clean energy abundance increases rapidly, and there is a faster-than-expected acceleration of end-use electrification. It is a story of exponential growth opportunities brought about by data-empowered consumers and falling energy prices.*

### The workhorse ploughs on

In the world of Modern Jazz, innovation takes place more rapidly in both energy supply and demand. The cost of renewable electricity generation falls significantly in the 2020s, which shifts energy supply from molecules to electrons. This, coupled with the development of storage solutions and a rise in demand for energy services, attracts investments in both centralised and decentralised hybrid infrastructure. In mature markets, automation, digitalisation, and artificial intelligence enable 'prosumerism' in which many consumers of energy also become producers, exporting electricity produced from their solar panels or held in storage, for example, back to the grid.

Nuclear grows at a slower pace than the other two scenarios in this new consumer-empowered and service economy. The rate of new nuclear construction in developed countries of Europe and North America slows down. Many markets do not value nuclear's contribution as a dispatchable source in electricity rooted in large-scale smart grids, decentralised generation, variability, and effective energy storage.

Despite the fact that lifetime extension of existing reactors is one of the best power generation investments available in the market from a levelised cost of electricity point of view, a number of EU countries and the US provide only limited support to nuclear energy. In leading-edge countries, stability is so reliant on demand-side flexibility and supply-side optimisation that 'old-world' capacity reserves no longer seem necessary.

Most older generation reactors in the US and EU are scheduled for retirement and decommissioning, which reduces nuclear baseload available to the grid by 2040. Among the many countries that opt not to extend the lifetime of their reactor fleet, some struggle to meet pressing carbon targets.

Growing demand for decommissioning and, to a much lesser extent, lifetime extension, transform the landscape of the nuclear industry in the developed world, where small, highly innovative engineering firms are using digital technologies on a large scale to analyse, design and run decommissioning projects. Large nuclear industry incumbents will be competing with these agile newcomers in a services-oriented market.

### Firmer foundations for new industrialising economies

In a Modern Jazz world, new build is largely driven by China, India and Russia in the period 2020-2030, and developing economies in the Middle East, like Iran, Turkey, Egypt, as well as Bangladesh and Indonesia in 2030-2040. These developments firmly place nuclear energy as a power source for emerging economies.

The core technology is the advanced large-scale Gen III and Gen III+ reactors for centralised power systems, mainly offered by Russia and China. Both countries incrementally improve Gen III+ reactors heavily involving digital technologies at all stages of the life cycle. There is a range of financial instruments, interstate purpose credits and financial support from vendor nations, balanced by power purchase agreements and 'build, own, operate' models.

The enabling factor throughout the highly volatile, innovative world of Modern Jazz is digital technology, which reshapes all energy sectors. Digitalisation productivity gains are high in nuclear too – digital technologies have helped vendors and operators to significantly improve lifecycle management, including construction project management, operations efficiency, as well as to learn some useful lessons for life extension projects, which have made a significant impact on the overall productivity of the nuclear industry. It all helps to reduce unit costs and improve overall performance that eventually leads to unchallenged customer trust in emerging economies after 2035. Nuclear becomes a major decarbonisation vehicle for emerging markets, gradually replacing coal.

## ROLE OF DIGITAL IN NUCLEAR

**Digital twins**

***By GE Digital***

**Digital Twin is an organised collection of physics-based methods and advanced analytics that is used to model the present state of every asset in a Digital Power Plant.**

**Digital Twin:**

- **allows 'what-if' scenarios to be tested against business objectives creating the most informed decisions possible**
- **monitors the integrity, efficiency or protection system performance of its high-risk systems, enabling the rapid prediction of future plant condition**
- **drives maintenance cost savings. e.g. a £3.7 billion saving could be made over the 60-year lifetime of a 16 GWe fleet**

**Multi-D technology**

***By Rosatom***

**The core of Multi-D technology is a Detailed Information Model that goes far beyond a usual 3-D model and serves as the centrepiece for the set of interconnected digital tools to address certain tasks in the context of different project management directions.**

**Multi-D:**

- **formalises business processes corresponding needs of the projects**
- **ensures operation within unified information space**
- **manages three main elements of project management activity: cost, time and quality**

Source: GE, State Atomic Energy Corporation Rosatom

## Islands of cheap, green energy

Japan and Korea are among countries scaling back nuclear energy research and development programmes between now and 2030 and reallocating resources to other energy areas, like digitalisation of the energy system, rolling out smart grids, installing storage, and building renewables. A number of other countries, like Russia, Canada and China, stay committed to developing new nuclear reactors and successfully debut both commercial Gen IV and SMR systems by 2035.

These new types of reactor are installed in a few locations by 2045, although their commercial efficiency is yet to be proven. SMRs have potential to gain greater recognition as developing economies and rural areas turn to decentralised electrification for their energy needs.

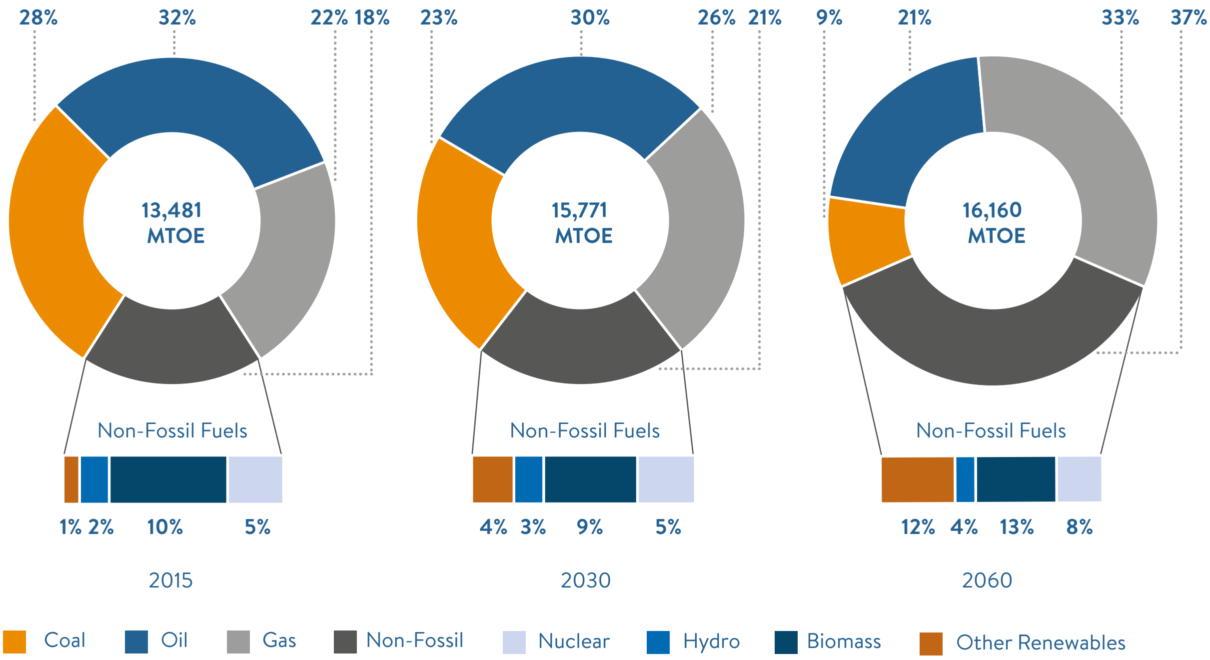
New reactor designs end up making only a marginal impact on the overall power system. Research and development, as well as installation of these reactors, is funded or guaranteed by governments.

While the world of Modern Jazz envisages a more vibrant, though somewhat volatile, digital energy sector, the lack of state-led, joined-up action results in significant unevenness in relative levels of progress against climate change at national levels.

In Modern Jazz, as a market driven world, investors prefer smaller projects with low capital requirements and relatively quick returns compared to larger projects that require governmental intervention and support or the build-up of institutional capacity.

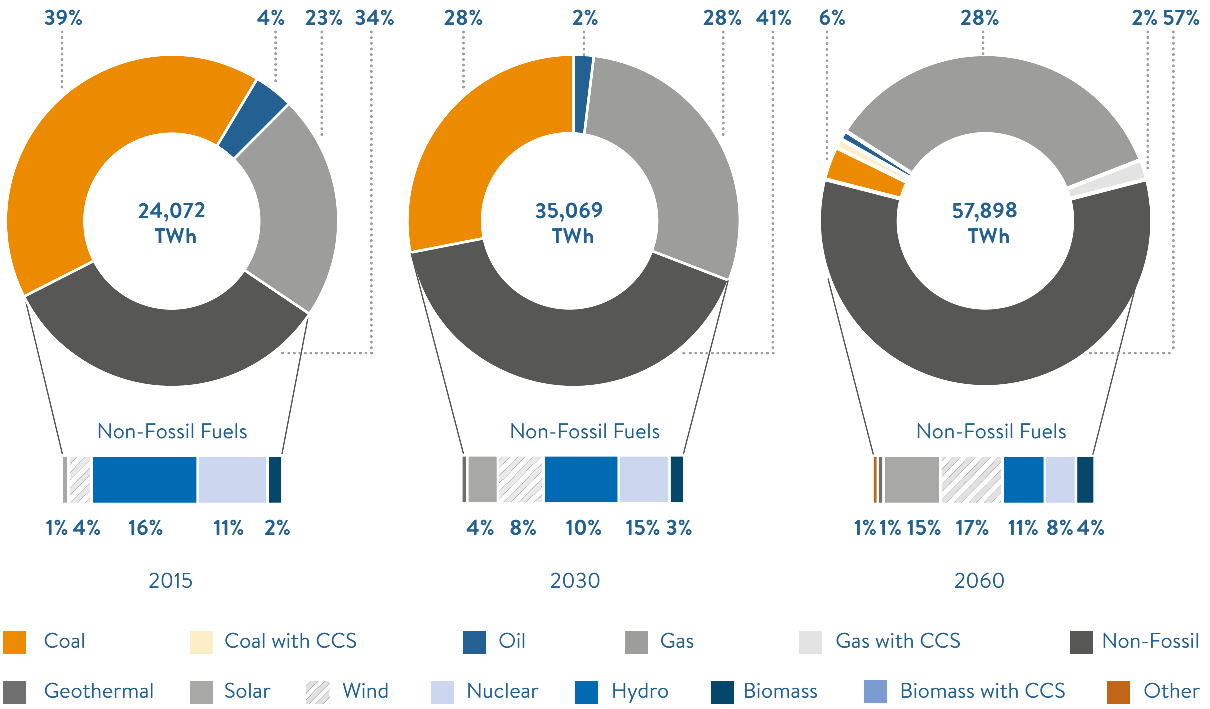
In this world the electricity generation sector undergoes a profound transformation towards low-carbon sources. The electrification rate (electricity in final energy consumption) doubles from 18% in 2015 to 37% by 2060. Because of the competition from other low-carbon sources, nuclear's share in electricity generation accounts for only 8.5% by 2060, compared to 11% in 2015. Nuclear installed capacity increases by around 52% from 407 GW in 2015 to 620 GW in 2060.

## Figure 2: Modern Jazz Primary Energy Supply (Mtoe) % Share




Source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy

## Figure 3: Modern Jazz Electricity Generation (TWh) % Share By Fuel Type




Source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy

## UNFINISHED SYMPHONY

*This is a world with a broadening agenda that goes beyond climate change and includes greater consideration of UN Sustainable Goals, water use, environmental health and livelihoods. A holistic approach drives international cooperation and the establishment of global frameworks and supranational policies. Industry regulation and policies are eventually synchronized globally to carefully manage a transition that delivers at the lowest overall cost, including externalities and considering what is the best fit for societies. While there is general agreement about what actions are needed to reach net-zero emissions, different regions follow their own pathways and develop their own energy portfolios to achieve these goals, recognizing that affordability, wellbeing and sustainability require subsidiarity as well as sector-coupling strategies.*

### The power of trust

Unfinished Symphony explores an integrated policy and strategy that encompasses an agenda of climate goals, environmental sustainability, affordability and wellbeing. Facilitated by governmental and citizen support for affordable deep decarbonisation pathways, public-private investment in a broad range of clean energy technologies decouples $CO_2$ emissions from economic growth.

After the initial few Western new build projects ran over schedule and budget in the 2010s, the nuclear industry learned and shared good practices from new build projects in Asia to significantly reinvent its approach to plant design and project management. It did so by incorporating a crucial role for digital technologies, which helped the industry to deliver projects consistently globally, helping to regain the trust and confidence of the market.

Better coordinated climate policies supported by new energy regulations and financing institutions encourage the European Union to review its position on the role of nuclear in tackling climate change in the 2020s and beyond. Digitally enabled nuclear new build is on a roll across the EU, especially the nuclear-accustomed markets of Bulgaria, the Czech Republic, Finland, Hungary, Slovakia, and the UK, perfectly fitting into the developing EU electricity grid and power market. South Korea reconsiders its no-nuclear decision in 2030 and renews its new build programme.

The major share of new nuclear capacity is rolled out using the fleet approach in China, India, Russia, and the Middle East in 2020-2030. In Africa, major nuclear construction programmes are started by South Africa, Nigeria, Tanzania and others to meet rising energy demand from rapid urbanisation. Power plants are built on time and budget, aided by the enhanced capability and capacity of the nuclear industry and facilitated by extensive use of digital technologies in the design, planning, and construction stages. Digital twins support safe, reliable and efficient plant operations.

Lifetime extension remains high on the nuclear agenda 2020-2030 both in the EU and in the US. Digital tools become significant for analysis and decision making. Most 'old world' reactors are put on lifetime extension programmes to keep them operational for another 20 years or more.

All Japanese reactors are upgraded and restarted. Japan also returns to the global nuclear technologies market as a strong nuclear exporter by 2035, building power plants in the EU, US, and the Middle East. South Korea's nuclear projects extend from the Middle East to the EU and Africa from 2040. There is growing global demand for nuclear power and competitive global supply chains from major reactor vendors in Russia, France, Japan, Korea, and China.

### The power of innovation

In a world where regional pathways diverge to progress to a net-zero carbon energy transition for the lowest cost and best fit to local needs, nuclear competes with other low-carbon baseload options like coal-fired power plants with CCS and hydropower. In many cases nuclear wins due to its efficiency, predictability, and small environmental footprint.

Innovations in Gen III+ reactors and nuclear power plant life-cycle management make it possible to regain customer trust in most nuclear technology markets in the period 2020-2030. Economies of scale and learning curve factors improve industry performance globally.

This bright future for the nuclear industry is driven by accelerated innovations such as Gen IV reactors and SMRs. Due to high demand and availability of new investment instruments, these reactors are commercially introduced by 2035-2040 and by 2060 they make up 25-30% of all new orders by capacity. The advanced reactor sector is the most intense area of competition between British, Canadian, Chinese, Japanese, Korean, Russian, and US vendors after 2040.

Institutional innovation supports technological advancements. New international frameworks and regulation on licensing to facilitate global deployment of SMRs and the use of new fuel materials are established in the 2030s.

A wide range of financial institutions extend conventional green bonds and new sustainable and social financing instruments to nuclear-related projects, including new build and lifetime extension. Finance institutions make decisions based on life-cycle digital models presented by vendors to ensure construction is on time and on budget, and that operations continue for more than 60 years at the highest levels of safety and performance.

### The power of synergies

In Unfinished Symphony governments emphasise the multiple links between jobs, health, wellbeing and sustainability. Similar integrated approaches become the basis for decisions by many countries to go into nuclear new build programmes that drive industrial growth and human capital considerations, on top of the energy and climate agenda.

The nuclear energy value chain spreads across the globe, involving new markets, new businesses, and creating highly qualified jobs. Overall, nuclear industry development in terms of both conventional and breakthrough technologies has accelerated the growth of adjacent nuclear applications, including medicine, agriculture, desalination, and others – crops in many regions are saved using radioisotope technologies; millions of people are treated for serious diseases with radiotherapy; nuclear-powered water desalination facilities produce fresh water for millions of people in water-deprived regions in the Middle East and Africa; and universities and technology startups attract the best talent to promote science and innovation in the nuclear industry. All these developments make the nuclear industry one of the most significant contributors to achieving the UN Sustainable Development Goals.

In Unfinished Symphony, new policy mandates and market designs attract public and private investment in hydrogen production pathways and clean energy trading. Nuclear is used to make hydrogen electrolytically, while high-temperature reactors are used to make it thermochemically.

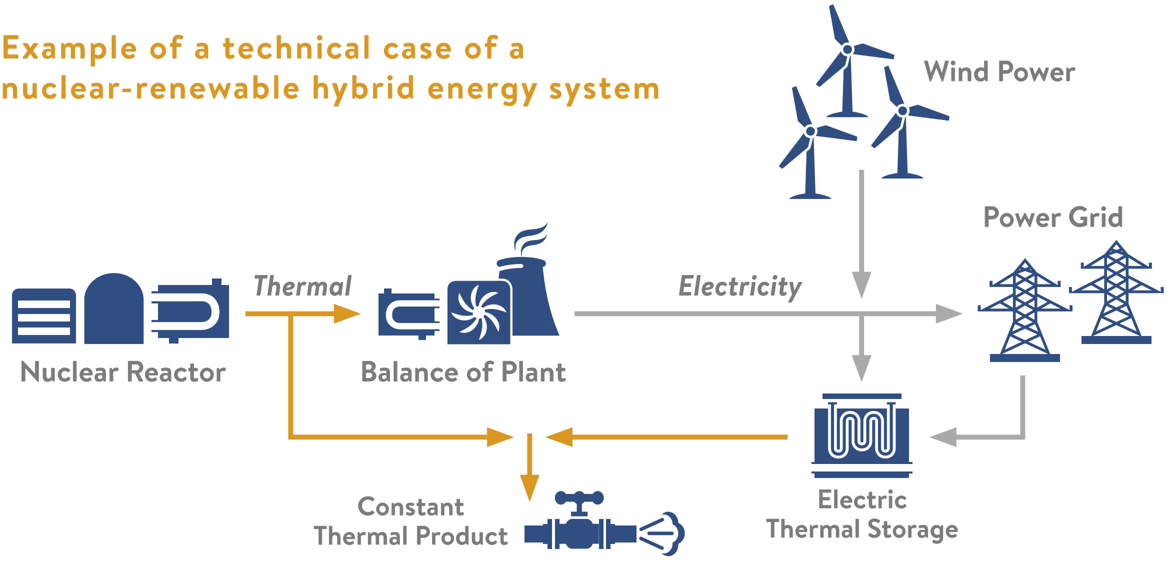
Businesses and governments realise the opportunity for strategically developing hybrid integrated low-carbon energy systems that include nuclear, renewables, and storage. Nuclear vendors merge and make alliances with renewable power project developers for coordinated low-carbon initiatives, such as building solar and wind farms in the proximity of nuclear power plants, both on- and off shore. This approach allows the use of land that has limited alternative use as well as more efficient use of grid connection infrastructure, construction equipment, workforce, and facilities. These low-carbon energy clusters prove to be the most sustainable and economically efficient way to develop low-carbon energy systems at the national level and to help address the need for grid flexibility, greenhouse gas emission reductions and optimal use of investment capital.

Hybrid energy systems also drive cogeneration for seawater desalination, hydrogen production, district heating, cooling and other industrial applications. SMRs are particularly well-suited to such fully integrated systems.

## SYNERGIES FOR A FLEXIBLE INTEGRATED GRID

**Nuclear-renewable hybrid energy systems are a potential technology that can generate dispatchable electricity and provide low-carbon thermal energy to industry at lower cost than alternatives. Such hybrid systems are defined as a co-managed and linked nuclear reactor that generates heat, a thermal power cycle for heat-to-electricity conversion, at least one renewable energy source, and an industrial process that uses thermal and/or electrical energy.**

### Example of a technical case of a nuclear-renewable hybrid energy system

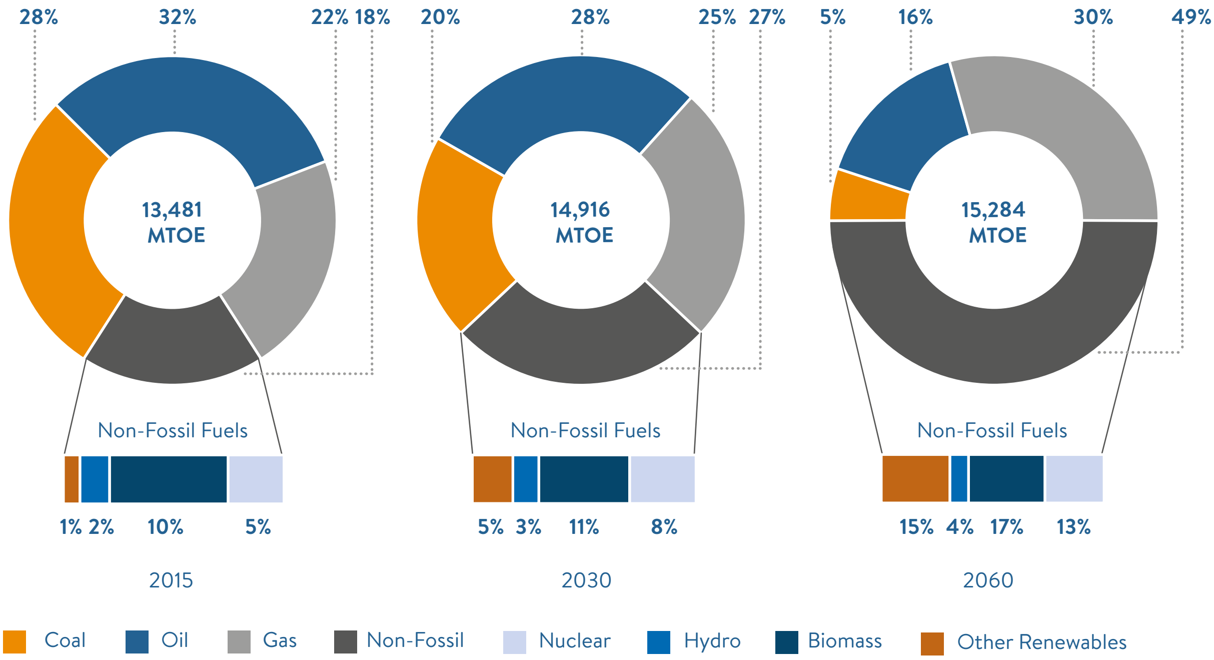



Orange arrows indicate flow of thermal energy and grey arrows indicate electricity

Source: The Joint Institute for Strategic Energy Analysis 2016

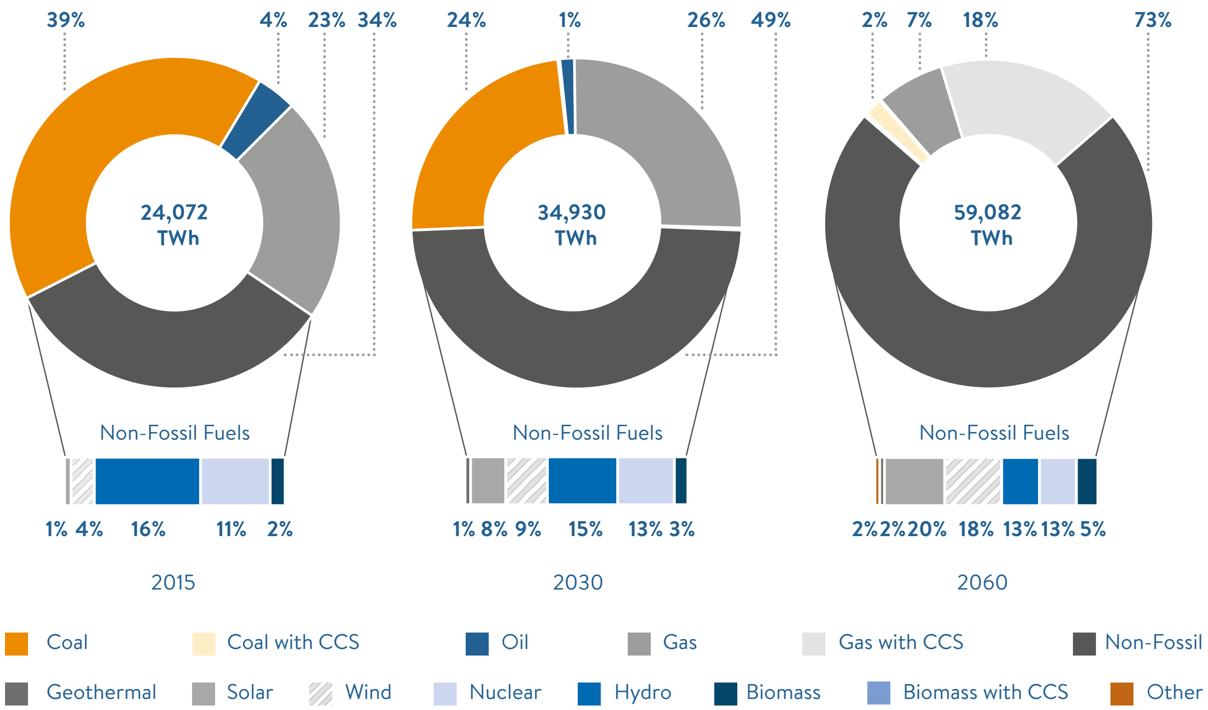
In Unfinished Symphony, electrification and efficiency are at the forefront of a deep and affordable decarbonisation pathway, supported by better systems integration, smart grids, and improved load management. Electricity in final energy consumption reaches 41% by 2060. Nuclear energy accounts for 13.5% of total electricity generation, while installed capacity increases almost by a factor of three from 407 GW in 2015 to 1003 GW in 2060.

## Figure 4: Unfinished Symphony Primary Energy Supply (Mtoe) % Share




Source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy

## Figure 5: Unfinished Symphony Electricity Generation (TWh) % Share By Fuel Type




Source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy

## HARD ROCK

*This is a fragmented world with low economic growth, increasing geopolitical tensions and low levels of cooperation between nations. National security, jobs, skills development and local environmental issues are top of national agendas. Affordable decarbonisation is a global norm as nations are not ready to sacrifice growth for climate considerations. The energy landscape is a reflection of the regionalism driven by geopolitical, economic and security factors. Industry regulation and policies remain weak and there is no global synchronisation.*

### State capitalism on the rise

With increasing geopolitical tensions and little international cooperation, flows of data, technology, and global capital become more constrained. Governments are forced to look at their own sources of strength – resource endowments, existing assets, automated systems integration, and demand-side measures – to achieve local energy security. Nations are much more concerned with jobs, health, and local environmental stresses than with global issues.

Nuclear new capacity is driven mainly by the fleet approach in China, India, Russia between 2020 and 2030 – countries that made a strategic bet on nuclear as a main source of energy and development. This is followed by new build programmes in 2030-2040 in the Middle East, including in Saudi Arabia, the United Arab Emirates, Iran, Turkey, Egypt, and others.

In these countries the core nuclear technology remains large-scale Gen III and Gen III+ reactors for centralised power systems. Incremental innovations and the use of digital technologies make Gen III+ a natural choice for all newcomers as it is a reliable, well-studied, serially built, and economically efficient nuclear solution.

### Discreet conservatism

In Hard Rock energy security drives efficiency, but a fragmented world with trade limits is a barrier to strong technological progress. While the Gen III and Gen III+ reactors have succeeded in supporting nuclear new build across emerging markets as well as in some developed economies, innovation has been relatively slow and poorly integrated.

Russia and China remain the dominant players in the nuclear technology market, and most of the funds for construction come from nation states and development institutions. New build is facilitated by financial instruments such as interstate purpose credits as well as ‘build, own, and operate’ models, power purchasing agreements and guarantees by national governments or affiliated institutions.

In 2030, Russia and China successfully debut both commercial Gen IV and SMRs. By 2045 Russian and Chinese Gen IV and SMRs have also been installed in a number of other locations around the world. Neither Gen IV nor SMR make any considerable impact on the overall energy system by 2060.

Closing the nuclear fuel cycle and enabling modular design remain top innovation priorities, mainly driven by state-funded research and development programmes in Russia and China that have been in place for decades.

While there is bilateral cooperation in dealing with legacy issues, many countries maintain the stance that nuclear waste must be dealt with within the country of origin.

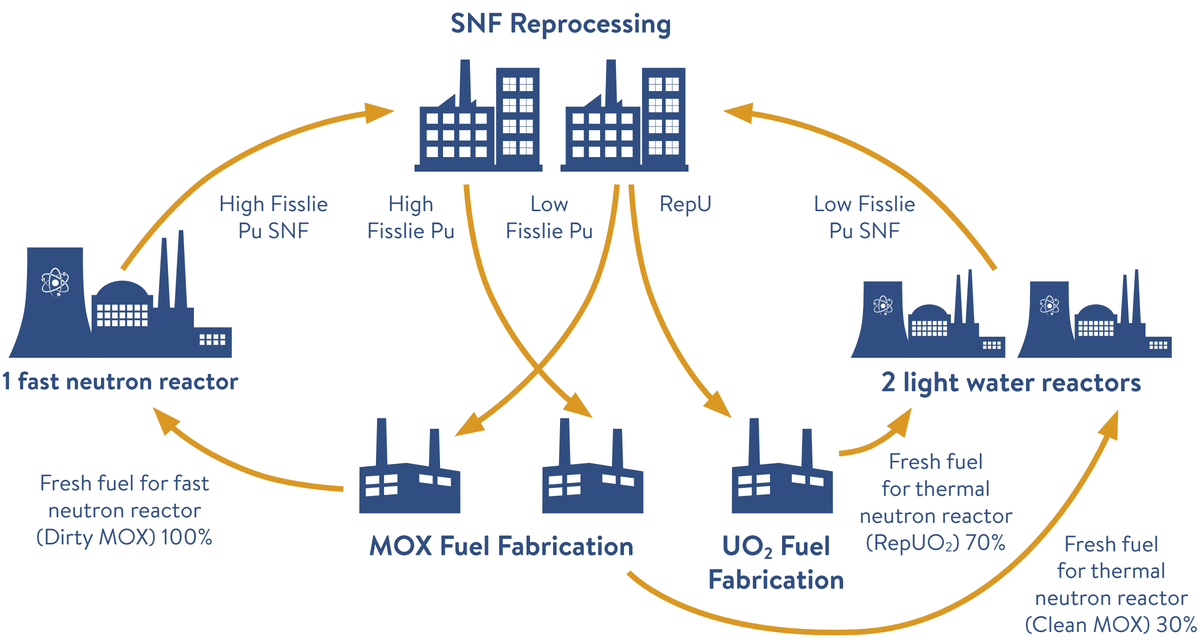
## INSTITUTIONAL INNOVATION TO IMPROVE SUSTAINABILITY OF NUCLEAR ENERGY

The use of fast reactors operated in a closed fuel cycle could increase uranium resource efficiency. Large scale deployment of fast reactors would essentially decouple nuclear energy from uranium resource availability. This would further enhance the sustainability of nuclear energy.

Creating a framework for international collaboration on technical issues such as radioactive waste disposal would initiate a well-funded global market and stimulate innovation.

### Dual-Component Nuclear Power System

Dual-Component Nuclear Power System (DCNPS) embodies both thermal neutron and fast neutron reactors. Nuclear Fuel Cycle in DCNPS is closed and self-sustained. Benefits of such system includes environmental (reduction of the natural uranium consumption, decrease of SNF amount), economical (cost reduction and effectiveness increase for the nuclear fuel cycle).




Source: The Joint Institute for Strategic Energy Analysis 2016

### Split in the West

In Hard Rock there is no unity within the OECD on a vision for further nuclear development. For some OECD countries nuclear is seen as a significant source of reliable and predictable low-carbon baseload power in the energy system with limited risk from fuel price volatility compared with fossil-fuelled systems. At the same time, there are a considerable number of reactors reaching the end of their designed lifetime. This raises questions at the national level regarding lifetime extension and decisions on whether to invest in new reactors or to replace the retiring capacity with low-carbon sources that can support climate commitments.

In the 2020s the EU and the US generally favoured policies that allowed lifetime extension of existing reactors, which is one of the best emissions-free power generation investments available in the market in terms of LCOE. In 2020-2030 most of the “old world” reactors in the US and the EU have been granted 20-year life extensions that will keep them operational beyond 2040-2050.

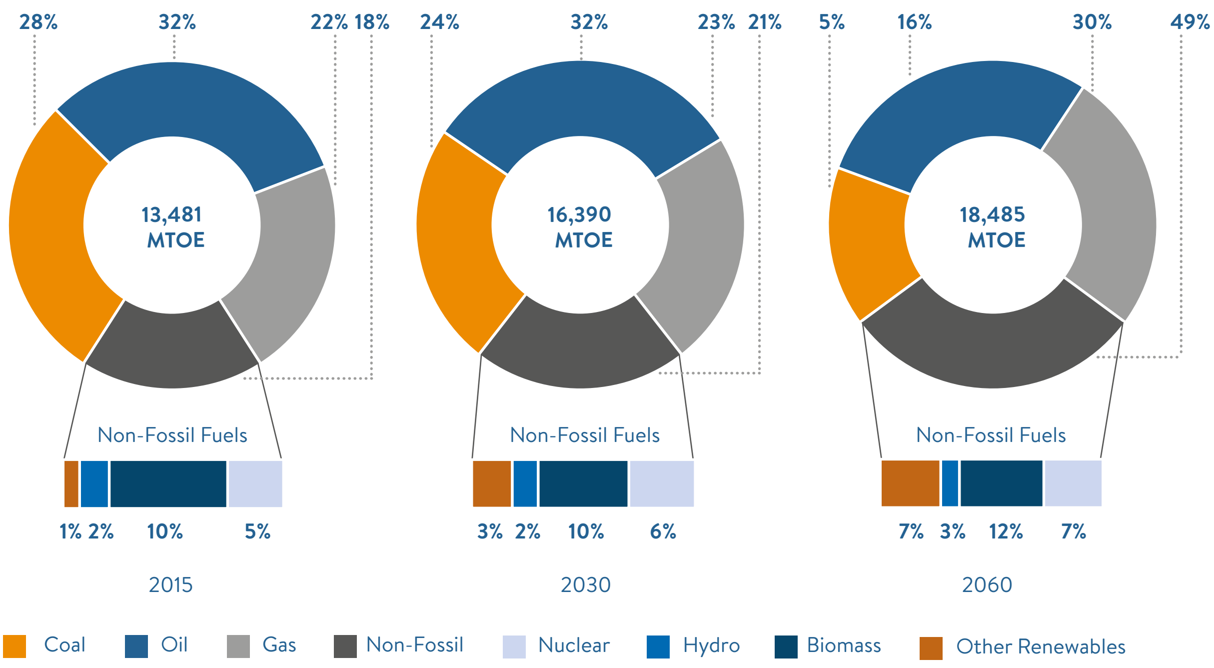
However, between 2035 and 2040 when lifetime extension is no longer an option for a large part of the existing fleets in the EU and the US, there is a heated debate on how to replace this considerable low-carbon capacity. Some previously reluctant countries drift gradually towards nuclear new build options, supported by the evidential success of nuclear in the developed economies that did not stop their programmes. However, there are a few others who decide to opt out of nuclear.

In this scenario, the US and most EU countries are reluctant to proceed with nuclear new build from 2020-2030, in some cases due to low public acceptance and in others due to unclear economic viability. However, others go in the opposite direction. The Czech Republic, Hungary, Slovakia, and Bulgaria decide to extend their nuclear development programmes for 2030-2040. This provides them not only with energy solutions and an ability to advance their local environmental agenda, but it also supports economic growth and human capital development. Some of these projects have taught hard lessons to all parties involved: cost and schedule overruns made industry players and decision makers rethink their approaches to plant design and project management.

Globally by 2060, some countries are significantly less carbon intense than others. The effects of extreme weather, water stress, and climate change are increasingly felt on an uneven basis. This forces collaboration on a sub-regional level in order to create technological and economic solutions for accelerating climate change adaptation.

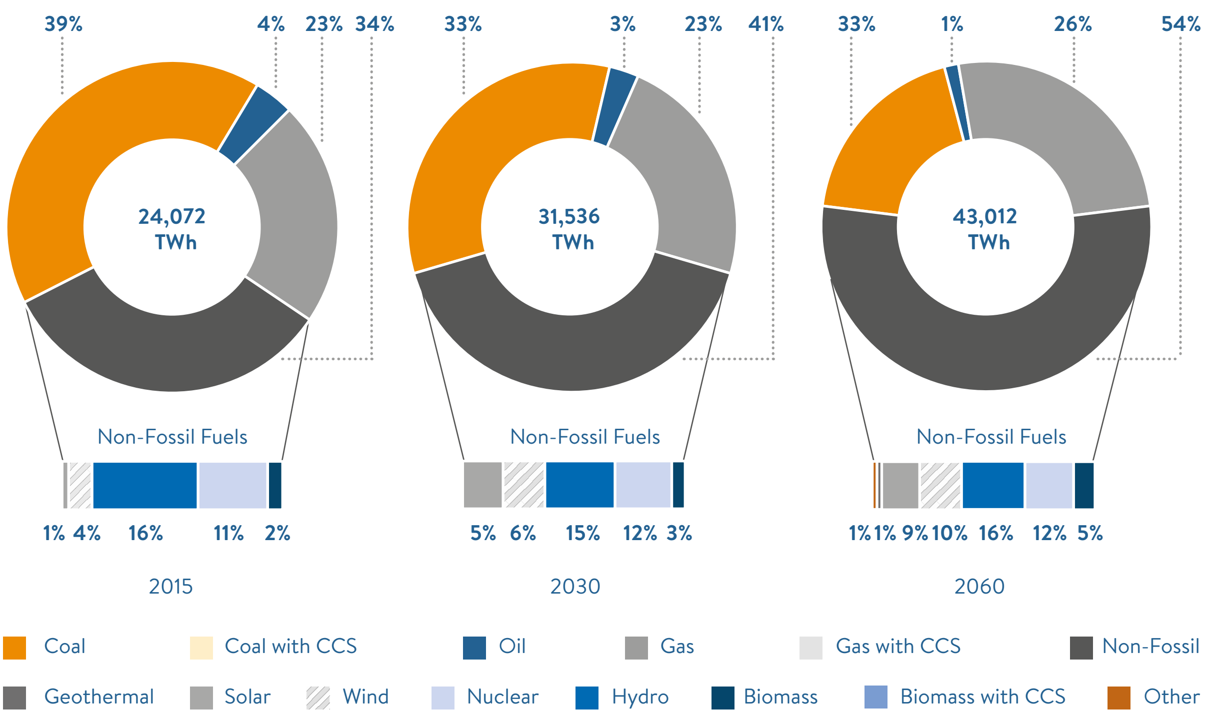
In Hard Rock the electricity generation sector accounts for 23% of final energy consumption in 2060, when the energy mix remains dominated by fossil fuels, although to a lesser degree than today. Nuclear’s share in electricity generation reaches 12.5% by 2060 compared with 11% in 2015. Installed nuclear capacity increases three quarters from 407 GW in 2015 to 696 GW in 2060.

## Figure 6: Hark Rock Primary Energy Supply (Mtoe) % Share




Source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy

## Figure 7: Hark Rock Electricity Generation (TWh) % Share By Fuel Type




Source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy

# Chapter five

# New Imperatives For Collaborative Action

# 5. NEW IMPERATIVES FOR COLLABORATIVE ACTION

Nuclear energy will be part of the global energy mix up to 2060 and beyond, but the rate of growth and pattern of developments over the next 40 years cannot be reliably predicted. A scenario-based approach can help energy leaders engage constructively with unpredictable uncertainties and better prepare for new and faster emerging opportunities. A set of scenarios explores what might happen – not what will or what should happen – to redirect energy leaders' attention to the unexpected, the unfamiliar and thus often the unwanted and difficult-to-discuss new realities.

This report describes the outlook for nuclear energy development through the lens of the Council's three world energy scenarios. The growth of nuclear energy is greatest in Unfinished Symphony, a scenario that assumes stronger global cooperation, policy-led innovation and proactively addresses integration and reliability challenges while recognising co-benefits in the drive to affordable, deeper and socially just (net zero carbon) energy transition pathways. In the two other scenarios, entrepreneurial Modern Jazz and inward-looking Hard Rock, the growth of nuclear is more constrained for different reasons.

Looking across the scenarios, four critical challenges and opportunities faced by the global nuclear industry – learning, linking, leveraging and leadership – become clearer and will define how nuclear energy fits in the future energy system.

## ACCELERATING LEARNING CURVES

The research, development, deployment and diffusion of centralised, capital intensive nuclear energy technologies involves government support and takes many years, even with the emergence of SMRs. This contrasts with faster learning curves in other energy sectors, including oil and gas, renewables and transport, which are driven by a combination of global competitive markets and policy support. Sharing and learning good new build and construction practice (in particular from Russia and Asia) will benefit those countries that consider fleet approaches as part of their strategy. Digitalisation is assumed to play a greater role in improving nuclear industry performance in all three scenarios but with different implications and outcomes due to other factors.

- In **Modern Jazz** – modular factory construction of large reactor sections and entire SMRs enables components to be built and assembled in controlled environments. This improves quality, lowers cost and accelerates schedules. It leads to better built structures and superior quality standards. In this scenario, taking full advantage of digital and information technology enables effective collaborative working and management of asset performance.

- In **Unfinished Symphony** – regulatory harmonization to enable standardization of reactor designs that can be adopted globally will be critical to reduce cost and project risks. This would also cut development time and increase supply chain competition. Regulatory harmonization would be facilitated by coordinated efforts by governments, multilateral agencies and national regulators.

- In **Hard Rock** – a faster learning curve is achieved with a fleet approach and a long-term programme to build and maintain supply chain capability. Cost reduction is achieved through serial production and learning-by-doing.

## LINKING SYSTEM INTEGRATION OPPORTUNITIES

There is growing recognition that significant amounts of fluctuating electricity at low/zero marginal cost pricing presents both reliability and economic challenges associated with the scale-up of renewable energy. The total cost of electricity supply increases significantly due to the cost of additional infrastructure for balancing, flexibility, transmission and distribution, as the share of variable renewable sources rises. There are many different models of hybrid grid development and an ongoing search for flexible security and new storage solutions, which include switching between supply and storage. It is also envisaged that clean electricity and clean liquid fuels will be used in tandem to balance fluctuations in demand and supply. While current large nuclear plants have proved themselves an essential part of centralised energy systems, there will be greater roles for renewables, flexible and smart electricity grids, integrated energy systems, hybrid opportunities and new nuclear technologies such as SMRs.

- In **Modern Jazz** – as digitalisation continues to impact the whole energy landscape, value is migrating to consumer-centric energy systems and services. The nuclear industry will need to respond to new opportunities for consumer-centric services.

- In **Unfinished Symphony** – a combination of today's large reactors with SMRs and advanced reactors enables nuclear energy to decarbonise industry by replacing fossil fuels with high temperature reactors, enables the production of synthetic fuel and hydrogen, and provides energy for remote communities and decentralised grids. The opportunity for developing hybrid integrated low-carbon energy systems that include nuclear, renewable, and storage will need to be realised.

- In **Hard Rock** – nuclear will play an essential role in centralised systems providing energy reliability and resilience as well as energy security, while integration with renewables in hybrid arrangements will enable more flexible integrated systems.

## LEVERAGING CO-BENEFITS

Access to useful, clean, affordable and reliable modern forms of energy is the key to an era of digital prosperity and environmentally sustainable development that allows society to flourish.

End-users value the attributes of energy, whether in the form of electrical power, heat or liquid fuel. Digitalisation accelerates across the energy landscape, migrating along the value chain towards aggregators of demand and shaped by new consumer logic.  Energy-plus services open up new opportunities for economic value creation and growth.

In all three scenarios nuclear will provide a number of benefits including industrial development, human health, food production, water management and environmental protection. Financial innovation will play a critical role in unlocking new opportunities for nuclear.

## LEADERSHIP FOR THE LONG TERM

National governments and international agencies have crucial roles in influencing the direction and pace of the energy transition by setting energy policy, market design and sustainable development frameworks. This is particularly important for nuclear projects, considering their high capital cost and long investment cycles. Governmental policy support is essential to secure investment in new nuclear plants.

- In **Modern Jazz** – developing countries experiencing population growth, urbanisation and economic development are concerned about meeting energy demand and focus on long-term planning of the energy system.
- In **Unfinished Symphony** – increasing global awareness of still-rising carbon emissions and the need for urgent action to address climate change results in coordinated policy support for all low-carbon technologies, investment in infrastructure, and the unlocking of green financing for nuclear. Governments and intergovernmental organisations have important roles to play in the development of policies to support the role of nuclear energy in clean energy systems.
- In **Hard Rock** – countries become increasingly concerned about energy security and ensure a mix of energy sources, including nuclear, to guarantee adequate supply.

The future of nuclear energy will be impacted by actions from the industry, policy makers and energy leaders. The insights from this report can play an important role in facilitating dialogue between the industry and keys stakeholders on addressing the challenges and opportunities.  These scenarios, along with the Harmony programme, show the potential pathways for nuclear energy development and help to translate vision into action.

# Annex

# NUCLEAR TECHNOLOGIES DESCRIPTIONS

The Generation IV International Forum (GIF), representing governments from 14 countries, defined six general reactor technologies which its members believe represent the future shape of nuclear energy. Those concepts include the Gas-cooled Fast Reactor (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 represent significant advances in sustainability, economics, safety, reliability and proliferation-resistance for nuclear technology.

## Generation IV reactor designs

| | Neutron spectrum (fast/ thermal | Coolant | Temperature (°C) | Pressure* | Fuel | Fuel cycle | Size (MWe) | Use |
|---|---|---|---|---|---|---|---|---|
| **Gas-cooled fast reactors** | fast | helium | 850 | high | U-238 + | closed, on site | 1200 | Electricity & hydrogen |
| **Lead-cooled fast reactors** | fast | lead or Pb-Bi | 480-570 | low | U-238 + | closed, regional | 20-180**<br>300-1200<br>600-1000 | Electricity & hydrogen |
| **Molten salt fast reactors** | fast | fluoride salts | 700-800 | low | UF in salt | closed | 1000 | Electricity & hydrogen |
| **Molten salt reactor -advanced high-temperature reactors** | thermal | fluoride salts | 750-1000 | | $UO_2$ particles in prism | open | 1000-1500 | hydrogen |
| **Sodium-cooled fast reactors** | fast | sodium | 500-550 | low | U-238 & MOX | closed | 50-150<br>600-1500 | electricity |
| **Supercritical water-cooled reactors** | thermal or fast | water | 510-625 | very high | $UO_2$ | open (thermal) closed (fast) | 300-700<br>1000-1500 | electricity |
| **Very high temperature gas reactors** | thermal | helium | 900-1000 | high | $UO_2$ prism or pebbles | open | 250-300 | Hydrogen & electricity |

Source: World Nuclear Association

There were originally six technologies chosen, but development on one has gone in two directions, so seven technologies are described.

*Gas-cooled fast reactor (GFR).* Like other helium-cooled reactors which have operated or are under development, GFRs will be high-temperature units – 850°C. They employ similar reactor technology to the VHTR, suitable for power generation, thermochemical hydrogen production or other process heat. The reference GFR unit is 2400 MWt/1200 MWe, large enough for breakeven breeding, with thick steel reactor pressure vessel and three 800 MWt loops. For electricity, an indirect cycle with helium will be on the primary circuit, in the secondary circuit the helium gas will directly drive a gas turbine (Brayton cycle), and a steam cycle will comprise the tertiary circuit. The used fuel would be reprocessed onsite and all the actinides recycled repeatedly to minimise production of long-lived radioactive waste.

*Lead-cooled fast reactor* (LFR). The LFR is a flexible fast neutron reactor which can use depleted uranium or thorium fuel matrices, and burn actinides from LWR fuel. Liquid metal (Pb or Pb-Bi eutectic) cooling is at atmospheric pressure by natural convection (at least for decay heat removal). Fuel is metal or nitride, with full actinide recycle from regional or central reprocessing plants. A wide range of unit sizes is envisaged, from factory-built "battery" with 15-20 year life for small grids or developing countries, to modular 300-400 MWe units and large single plants of 1400 MWe. Operating temperature of 550°C is readily achievable but 800°C is envisaged with advanced materials to provide lead corrosion resistance at high temperatures which would enable thermochemical hydrogen production. A two-stage development programme leading to industrial deployment is envisaged: by 2025 for reactors operating with relatively low temperature and power density, and by 2040 for more advanced higher-temperature designs.

*Molten salt reactor* (MSR) (now two variants): one a fast reactor with fissile material dissolved in the circulation fuel salt; the other with solid particle fuel in graphite and the salt functioning only as coolant.

In what is considered to be a normal MSR, the uranium fuel is dissolved in the fluoride salt coolant which circulates through graphite core channels to achieve some moderation and an epithermal neutron spectrum. The reference plant is up to 1000 MWe. Fission products are removed continuously and the actinides are fully recycled, while plutonium and other actinides can be added along with U-238, without the need for fuel fabrication. Coolant temperature is 700°C at very low pressure, with 800°C envisaged. A secondary coolant system is used for electricity generation, and thermochemical hydrogen production is also feasible.

Compared with solid-fuelled reactors, MSR systems have lower fissile inventories, no radiation damage constraint on fuel burn-up, no requirement to fabricate and handle solid fuel or solid used fuel, and a homogeneous isotopic composition of fuel in the reactor. These and other characteristics may enable MSRs to have unique capabilities and competitive economics for actinide burning and extending fuel resources.

*Sodium-cooled fast reactor* (SFR). The SFR uses liquid sodium as the reactor coolant, allowing high power density with low coolant volume, at low pressure. It builds on some 390 reactor-years experienced with sodium-cooled fast neutron reactors over five decades and in eight countries, and was initially the main technology of interest in GIF, and remains at the forefront despite needing a sealed coolant system.

The SFR utilises depleted uranium as the fuel matrix and has a coolant temperature of 500-550°C enabling electricity generation via a secondary sodium circuit, the primary one being at near atmospheric pressure. Three variants are proposed: a 50-150 MWe modular type with actinides incorporated into a U-Pu metal fuel requiring electrometallurgical processing (pyroprocessing) integrated on site; a 300-1500 MWe pool-type version of this; and a 600-1500 MWe loop-type with conventional MOX fuel, potentially with minor actinides, and advanced aqueous reprocessing in central facilities elsewhere.

Two significant large SFRs are starting up: the BN-800 at Beloyarsk in Russia (started in 2014) and the Kalpakkam PFBR of 500 MWe in India (expected in 2018). The BN-800 is largely an experimental reactor for fast reactor fuels. GIF observes that the technology is “deployable in the very near-term for actinide management.” Much of the ongoing R&D focus will be on fuels.

*Supercritical water-cooled reactor* (SCWR). This is a very high-pressure water-cooled reactor which operates above the thermodynamic critical point of water (374°C, 22 MPa) to give a thermal efficiency about one-third higher than today’s light water reactors from which the design evolves. The supercritical water (25 MPa and 510-550°C) directly drives the turbine, without any secondary steam system, simplifying the plant. Two design options are considered: pressure vessel and pressure tube. Passive safety features are similar to those of simplified boiling water reactors. Fuel is uranium oxide, enriched in the case of the open fuel cycle option. The core may use thermal neutron spectrum with light or heavy water moderation, or be a fast reactor with full actinide recycle based on conventional reprocessing. Since the SCWR builds both on much BWR experience and that from hundreds of fossil-fired power plants operated with supercritical water, it can readily be developed, and the operation of a 30 to 150 MWe technology demonstration reactor is targeted for 2022.

*Very high-temperature gas reactor* (VHTR). These are graphite-moderated, helium-cooled reactors, based on substantial experience.

The core can be built of prismatic blocks such as the Japanese HTTR and General Atomics’ earlier GTMHR design and others in Russia, or it may be pebble bed such as the Chinese HTR-10 or HTR-PM and the PBMR formerly under development in South Africa. Outlet temperature of over 900°C and aiming for 1000°C enables thermochemical hydrogen production via an intermediate heat exchanger, with electricity cogeneration, or direct high-efficiency driving of a gas turbine (Brayton cycle). At lower outlet temperatures, the Rankine steam cycle may be used for electricity generation, and this is the focus for demonstration projects. Modules of 600 MW thermal are envisaged.

The 2014 GIF Roadmap indicates that a 600 MWt VHTR dedicated to hydrogen production could yield over two million normal cubic metres per day. An R&D priority is qualification of TRISO fuel for operation up to 1250°C and 200 GWd/t burn-up, though US development has attained this, and also its robustness for hundreds of hours at 1,600, 1,700 and 1,800°C. However, in the short term, electricity production and industrial processes based on high temperature steam that require outlet temperatures of (700-850°C) hold most potential.

The HTR-PM demonstration unit in China is under construction at Shidaowan, and will pave the way for a commercial version of the VHTR.

## SMALL AND MEDIUM REACTORS

Global interest and development in small and medium sized or modular reactors has been increasing due to their lower investment risk, reduced cost, faster construction time, greater compatibility with a flexible electricity network and wider range of energy applications.

*Small modular reactors* (SMRs) are defined as nuclear reactors generally 300MWe equivalent or less, designed with modular technology using module factory fabrication, pursuing economies of series production and short construction times.

Currently, there are around 20 primary SMR designs under development in 10 countries (Argentina, China, France, India, Italy, Japan, Korea, Russia, South Africa, and the US) for domestic energy production and, in the case of some designs, for commercial export.

The US Department of Energy has strongly supported the development of SMR technologies to capture a slice of the nuclear technology market. It issued a multi-year cost-shared funding opportunity to support the development of existing, new and next-generation reactor designs including SMR technologies. In January 2012 the DOE called for applications from industry to support the development of US light-water reactor designs. Four applications were made, from Westinghouse, Babcock & Wilcox, Holtec, and NuScale Power, the units ranging from 225 down to 45 MWe. NuScale's SMR design is undergo regulatory licensing and plans a 12-module SMR plant in Idaho slated for operation by the mid-2020s.

The UK has a strong industry government program supporting SMR development, as part of the national nuclear "Sector Deal". Tthe Department for Business, Energy & Industrial Strategy (BEIS), announced in September 2018 eight organisations were awarded contracts to produce feasibility studies for the first phase of the Advanced Modular Reactor (AMR) Feasibility and Development (F&D) project: Advanced Reactor Concepts (ARC-100); DBD (representing China's Institute of Nuclear and New Energy Technology's HTR-PM); LeadCold (SEALER-UK); Moltex Energy (Stable Salt Reactor); Tokamak Energy (compact spherical modular fusion reactor); U-Battery Developments (U-Battery); Ultra Safe Nuclear (Micro-Modular Reactor); and Westinghouse (Westinghouse LFR). In July 2019 UK government has committed £18m to support the development of SMR design led by Rolls-Royce as part of the Industrial Strategy Challenge Fund

Canada is also keen to support the development of SMR technology. Natural Resources Canada published a "Canadian Small Modular Reactor Roadmap" in 2018 and provided a concrete set of recommendations across four thematic pillars to guide future actions needed by governments, industry, and other nuclear stakeholders. In April 2019, the Canadian Nuclear Safety Commission received the first licence application for a small modular reactor from Global First Power, with support from Ontario Power Generation and Ultra Safe Nuclear Corporation. This application is a proposal to deploy a Micro Modular Reactor plant at Chalk River in Ontario.

Russia has developed and deployed many SMR over several decades. Russia has developed and operated civilian nuclear-powered vessels since 1957, with the icebreaker NS Lenin. The current Arktika-class icebreakers uses two OK-900A Reactors generating 171 megawatt each. Taymyr-class icebreakers or use in shallow waters such as estuaries and rivers is fitted with one KLT-40M reactor producing 135 MW. Future icebreakers are plan with new reactors RITM-200 reactors of 175 MWt each and RITM-400 reactors of 315 MWt. In addition, a range of small VVER are being developed including OKBM Afrikantov's VBER-300 PWR unit with 325 MWe output, The VK-300 boiling water reactor is being developed by the Research & Development Institute of Power Engineering (NIKIET) for both power (250 MWe) and cogeneration with desalination etc.  As well as other The BREST-300 lead-cooled fast reactor.

## FLOATING NUCLEAR POWER PLANT

Floating nuclear power plants are a technology that has been used since the late 1950s in icebreaker when a barge-mounted reactor provided power to the Panama Canal Zone.

The floating system offered by Russia's Rosatom is a coupling of modern light water reactors used previously on icebreakers and floating platforms similar to those used in offshore oil and gas operations. Nowadays, there are well established technologies and procedures which should enable relatively short assembly and deployment periods for floating nuclear power plants.

The reactors for floating nuclear power plants are designed to generate energy continuously for three to five years without the need to be refuelled, which reduces overall electricity generation cost for industrial consumers as well as for end-users. The concept also lowers barriers to entry for consumers, who for example do not need to make a 60 year commitment to nuclear energy.

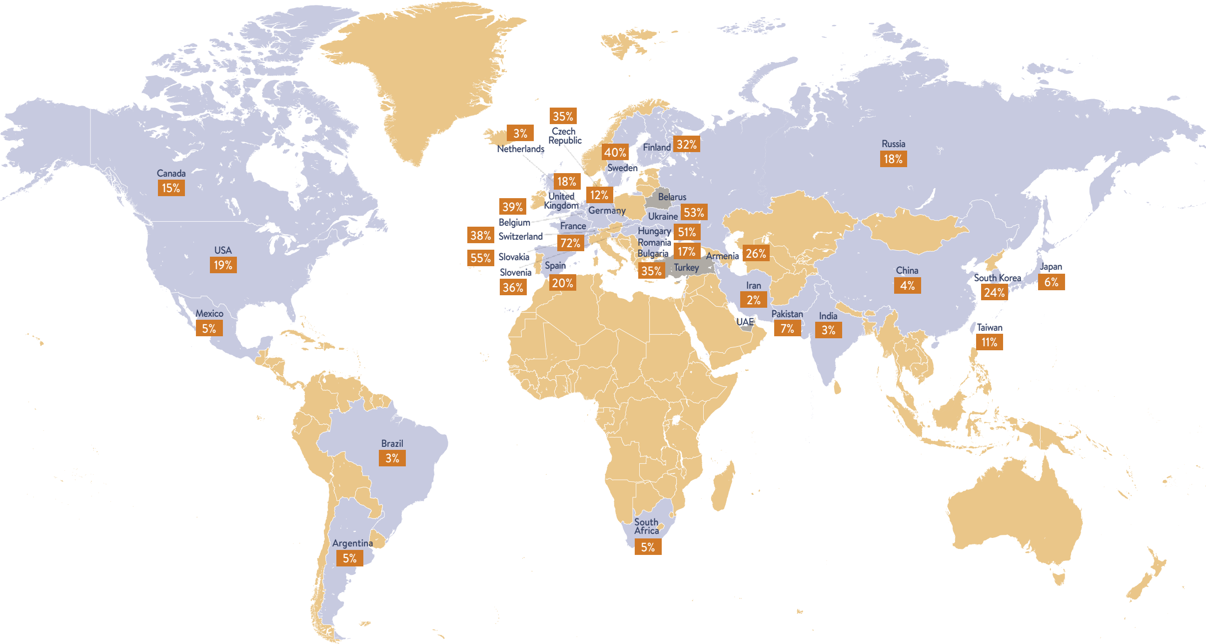
Another advantage is mobility. Floating units can be manufactured in one country and exported internationally, providing flexible energy generation to back up wind and solar in heavily dependent locations as well as distant regions entirely relying on ship-delivered fossil.

As of 2019, Rosatom stays globally at the forefront in FNNP development and construction, being the only global company to commission the first floating nuclear unit Akademik Lomonosov in 2019 with an estimated energy reactors capacity of 70 MWe, which is enough to maintain a city of 100,000 population. It will be sited in Pevek.

In July 2017 Rosatom announced the second generation of FNPPs, now called Optimised Floating Power Units (OFPUs), would use two RITM-200M reactors derived from those for the latest ice-breakers. These are more powerful than the KLT-40S reactors, at 50 MWe each, have fuel enriched to almost 20%, need refueling only every 10-12 years at a service base, so no onboard used fuel storage is required.

In parallel, a number of Chinese corporations are working towards 2020 deployment of equivalent technologies, while US scientists made some advanced researches promoting economic feasibility of this energy generation technology in their country. At the same time, French company 'Naval Group' has presented its Flexblue reactor, which would not floated but be submerged on the sea floor.

## Share of Nuclear Power in Total Electricity Generation 2018




| Countries with operating nuclear power plants | New nuclear countries with nuclear power plants under construction | Countries without nuclear power plants | World: 10.5 % |
|---|---|---|---|

Source: World Energy Council based on data of World Nuclear Association

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# METHODOLOGY


### The global multi-regional markal model – an overview

The scenarios were quantified using the Global Multi-Regional MARKAL Model (GMM). GMM is a tool used to quantify and enrich the scenario storylines developed by the World Energy Council. GMM's detailed technology representation enables the model to provide a consistent and integrated representation of the global energy system, accounting for technical and economic factors in the quantification of long-term energy transitions.

The model is driven by input assumptions reflecting the scenario storylines and applies an optimisation algorithm to determine the least-cost, long-term configuration of the global energy system from the perspective of a social planner with perfect foresight. GMM belongs to the family of MARKAL (MARKet ALlocation) type of models, where the emphasis is on a detailed representation of energy supply, conversion and energy end-use technologies (a so-called 'bottom-up' model).

GMM is a technologically detailed cost-optimisation model that has been developed by the Energy Economics Group at the Paul Scherrer Institute (PSI) over a number of years (Rafaj, 2005; Gül et al., 2009; Densing et al., 2012, Turton et al, 2013, Panos et al. 2015, Panos et al. 2016, Volkart et al. 2018, Kober et al. 2018). The World Energy Council joined as a model partner to support continued development and dissemination of the model with the goal of improving transparency, accessibility and credibility of global energy scenario modelling. In this regard, the Council and PSI have developed GMM into a fully open source model available to all Council members (subject to licensing). Such tools do not seek to model directly the economy outside of the energy sector, which is represented as a set of exogenous inputs to the model based on a coherent scenario storyline. GMM is applied to identify the least-cost combination of technology and fuel options to supply energy services using a market-clearing optimisation algorithm. This algorithm simultaneously determines equipment investment and operating decisions, and primary energy supply decisions for each region represented in the model to establish equilibrium between the cost of each energy carrier, the quantity supplied by producers, and the quantity demanded by consumers. Additional information about the model and its methodology can be found at the Paul Scherrer Institute's website[1].

## Geographies

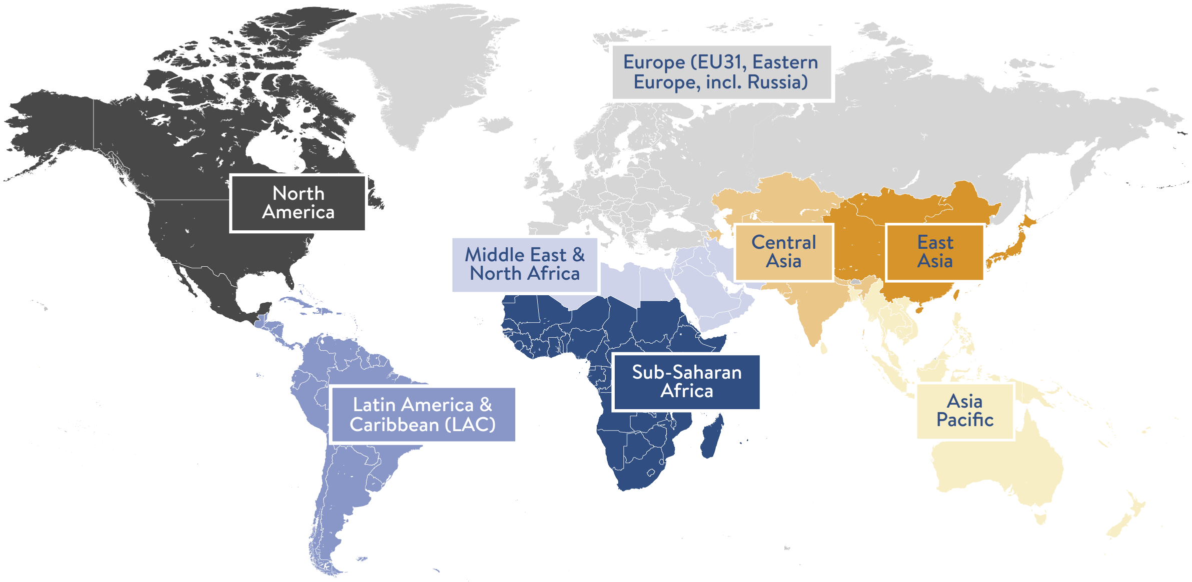
PSI's model contains 17 world regions. For the purpose of this report, the World Energy Council highlights eight world regions that have the most significant impact on the energy sector, shown in the figure below. Major countries are modelled as separate regions: Brazil, China, the European Union[2], India, Russia and the US. Aggregated regions include: Eastern Europe[3]; South and Central Asia (excluding India); the developed far East (Japan, Korea and Taiwan); Australia and New Zealand; Latin America together with the Caribbean (excluding Brazil and Mexico); the Gulf Cooperation Countries; other Middle Eastern countries; North African countries; Canada together with Mexico; Sub-Saharan Africa; and Southeast Asia and the Pacific (excluding Australia and New Zealand).
For each region, scenario assumptions influence the dynamics of demand and supply technologies (cost, efficiencies and availability). The regional and technology differentiation leads to a large-scale optimisation model, which represents in detail the energy system of each region from resource extraction and imports to energy conversion, use and exports. Trade among the regions, based on bilateral trade links and global markets, is also endogenously represented in the model.

1. PSI provides a fundamental view on methodology used and tools on their website: www.psi.ch/eem/methods-and-tools

2. Including Norway, Switzerland and Iceland.

3. Albania, Armenia, Belarus, Bosnia and Herzegovina, Georgia, North Macedonia, Moldavia, Serbia, Turkey, Ukraine, Kosovo and Montenegro.

## Regional break-down for modelling




### Calibration of energy demands, technologies and energy resource potentials

The GMM model is calibrated to recently published statistics for the year 2010. This calibration covers current demands for each energy subsector, the technology and fuel shares, and estimates of current costs and efficiencies of technologies. A primary source used for much of the calibration of fuel production and consumption is the IEA's Energy Balances (IEA 2015a). To ensure a better representation of developments since 2010 (up to the year 2015), the model uses additional statistics for recent years for which reliable data are available (EIA, 2015; BGR, 2016; IEA, 2015b; see Turton et al., 2013 for further references). For the near-term calibration until 2020, national and regional outlooks are also taken into account (e.g., AEO 2018 for the US, EU-Trends 2016 for the EU31, China's five-year national plan, India's five-year national plan, and several others).

## SUPPLEMENTARY DATA TABLES

(All below tables data source: The World Energy Council, Paul Scherrer Institute, Accenture Strategy)

### Table 1. Modern Jazz Economic Indicators

| Indicator | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Population (million)** | 7,372 | 8,163 | 8,541 | 9,200 | 9,762 | 10,213 | 0.7% |
| **GDP** (trillion USD2010 MER) | 76 | 105 | 124 | 171 | 229 | 300 | 3.1% |
| **GDP per capita** (USD2010 MER) | 10,263 | 12,920 | 14,467 | 18,555 | 23,489 | 29,355 | 2.4% |
| **Car ownership** (cars/1000 people) | NA | NA | 168 | 198 | 238 | 264 | NA |
| **Primary Energy Intensity** (toe/Million USD2010 MER) | 178 | 145 | 128 | 95 | 71 | 54 | -2.6% |
| **Final Energy Intensity** (toe/ Million USD2010 MER) | 129 | 103 | 91 | 68 | 52 | 40 | -2.6% |

### Table 2. Modern Jazz Primary Energy Supply (Mtoe)

| Primary Energy Supply (MTOE) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 13,481 | 15,309 | 15,771 | 16,251 | 16,297 | 16,160 | 0.4% |
| **Coal** | 3,826 | 3,796 | 3,618 | 2,918 | 1,730 | 1,433 | -2.2% |
| **Oil** | 4,272 | 4,695 | 4,666 | 4,191 | 3,902 | 3,433 | -0.5% |
| **Gas** | 2,937 | 3,798 | 4,168 | 5,087 | 5,660 | 5,325 | 1.3% |
| **Nuclear** | 616 | 788 | 850 | 977 | 1,156 | 1,241 | 1.6% |
| **Biomass** | 1,310 | 1,372 | 1,417 | 1,597 | 1,859 | 2,173 | 1.1% |
| **Hydro** | 327 | 404 | 421 | 472 | 523 | 562 | 1.2% |
| **Other renewables** | 193 | 458 | 630 | 1,010 | 1,466 | 1,993 | 5.3% |

### Table 3. Modern Jazz Nuclear in Primary Energy by Region (Mtoe)

| Primary Energy by Region (Mtoe) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 616 | 788 | 850 | 977 | 1,156 | 1,241 | 1.6% |
| **Sub-Saharan Africa** | 3 | 3 | 2 | 3 | 3 | 5 | 0.8% |
| **Middle East & North Africa** | 1 | 4 | 4 | 4 | 8 | 37 | 9.0% |
| **Latin America & the Caribbean** | 6 | 8 | 9 | 8 | 7 | 7 | 0.6% |
| **North America** | 246 | 226 | 225 | 225 | 224 | 226 | -0.2% |
| **Europe** | 305 | 276 | 273 | 263 | 263 | 254 | -0.4% |
| **Central Asia** | 11 | 35 | 52 | 83 | 116 | 127 | 5.5% |
| **East Asia** | 45 | 234 | 282 | 387 | 529 | 577 | 5.9% |
| **Asia Pacific** | - | 1 | 2 | 4 | 6 | 8 | NA |

## Table 4. Modern Jazz Power by Fuel Source (TWh)

| Fuel Source (TWh) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 24,072 | 31,898 | 35,069 | 44,085 | 51,493 | 57,898 | 2.0% |
| **Coal** | 9,341 | 10,457 | 10,050 | 7,741 | 2,886 | 2,139 | -3.2% |
| **Coal (with CCS)** | - | - | - | 34 | 105 | 264 | NA |
| **Oil** | 990 | 897 | 819 | 669 | 597 | 526 | -1.4% |
| **Gas** | 5,561 | 8,247 | 9,849 | 15,650 | 20,561 | 20,257 | 2.9% |
| **Gas (with CCS)** | - | - | - | 68 | 296 | 1,115 | NA |
| **Nuclear** | 2,571 | 3,055 | 3,294 | 3,787 | 4,484 | 4,811 | 1.4% |
| **Hydro** | 3,903 | 4,695 | 4,900 | 5,488 | 6,085 | 6,540 | 1.2% |
| **Biomass** | 527 | 833 | 923 | 1,401 | 1,998 | 2,567 | 3.6% |
| **Biomass (with CCS)** | - | - | - | - | - | - | NA |
| **Wind** | 840 | 2,187 | 2,968 | 4,991 | 6,964 | 9,523 | 5.5% |
| **Solar** | 256 | 1,345 | 2,000 | 3,643 | 6,195 | 8,821 | 8.2% |
| **Geothermal** | 80 | 146 | 192 | 307 | 466 | 599 | 4.6% |
| **Other** | 2 | 37 | 75 | 306 | 856 | 736 | 14.7% |

## Table 5. Modern Jazz Carbon Emissions

| Carbon Emissions | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **$CO_2$ emissions** (GtCO2/yr) | 31 | 35 | 35 | 33 | 28 | 22 | -0.7% |
| **$CO_2$ capture** (GtCO2) | 0 | 0 | 0 | 0 | 1 | 2 | NA |
| **$CO_2$ per capita** (tCO2) | 4 | 4 | 4 | 4 | 3 | 2 | -1.4% |
| **$CO_2$ intensity** (kgCO2/USD2010) | 0 | 0 | 0 | 0 | 0 | 0 | -3.7% |

## Table 6. Modern Jazz Installed Nuclear Generation Capacity (GW) by Region

| Nuclear Generation Capacity (GW) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 407 | 436 | 443 | 499 | 580 | 620 | 0.9% |
| **Sub-Saharan Africa** | 2 | 2 | 1 | 1 | 2 | 2 | 0.4% |
| **Middle East & North Africa** | 2 | 2 | 2 | 2 | 4 | 19 | 5.1% |
| **Latin America & the Caribbean** | 4 | 4 | 5 | 4 | 4 | 4 | -0.1% |
| **North America** | 121 | 115 | 114 | 114 | 113 | 115 | -0.1% |
| **Europe** | 171 | 158 | 147 | 141 | 139 | 134 | -0.5% |
| **Central Asia** | 6 | 18 | 26 | 41 | 57 | 63 | 5.2% |
| **East Asia** | 101 | 137 | 147 | 193 | 257 | 280 | 2.3% |
| **Asia Pacific** | 0 | 1 | 1 | 2 | 3 | 4 | NA |

## Table 7. Unfinished Symphony Economic Indicators

| Indicator | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Population (million)** | 7,372 | 8,163 | 8,541 | 9,200 | 9,762 | 10,213 | 0.7% |
| **GDP** (trillion USD2010 MER) | 76 | 101 | 116 | 153 | 198 | 249 | 2.7% |
| **GDP per capita** (USD2010 MER) | 10,263 | 12,376 | 13,533 | 16,624 | 20,240 | 24,407 | 1.9% |
| **Car ownership** (cars/1000 people) | NA | NA | 160 | 188 | 225 | 272 | NA |
| **Primary Energy Intensity** (toe/Million USD2010 MER) | 178 | 147 | 129 | 98 | 77 | 61 | -2.3% |
| **Final Energy Intensity** (toe/Million USD2010 MER) | 129 | 104 | 92 | 71 | 55 | 43 | -2.4% |

## Table 8. Unfinished Symphony Primary Energy (Mtoe)

| Primary Energy Supply (MTOE) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 13,481 | 14,863 | 14,916 | 15,009 | 15,116 | 15,284 | 0.3% |
| **Coal** | 3,826 | 3,425 | 3,023 | 2,114 | 1,083 | 785 | -3.5% |
| **Oil** | 4,272 | 4,480 | 4,237 | 3,430 | 2,859 | 2,382 | -1.3% |
| **Gas** | 2,937 | 3,611 | 3,780 | 4,390 | 4,820 | 4,498 | 1.0% |
| **Nuclear** | 616 | 955 | 1,147 | 1,471 | 1,754 | 2,016 | 2.7% |
| **Biomass** | 1,310 | 1,467 | 1,570 | 1,832 | 2,196 | 2,623 | 1.6% |
| **Hydro** | 327 | 431 | 463 | 527 | 615 | 658 | 1.6% |
| **Other renewables** | 193 | 493 | 696 | 1,245 | 1,789 | 2,320 | 5.7% |

## Table 9. Unfinished Symphony Nuclear in Primary Energy by Region (Mtoe)

| Primary Energy by Region (Mtoe) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 616 | 955 | 1,147 | 1,471 | 1,754 | 2,016 | 2.7% |
| **Sub-Saharan Africa** | 3 | 5 | 6 | 10 | 17 | 28 | 4.9% |
| **Middle East & North Africa** | 1 | 13 | 17 | 31 | 58 | 76 | 10.8% |
| **Latin America & the Caribbean** | 6 | 9 | 11 | 13 | 18 | 21 | 3.0% |
| **North America** | 246 | 229 | 229 | 237 | 247 | 265 | 0.2% |
| **Europe** | 305 | 295 | 284 | 312 | 309 | 366 | 0.4% |
| **Central Asia** | 11 | 54 | 83 | 177 | 274 | 313 | 7.7% |
| **East Asia** | 45 | 346 | 510 | 678 | 812 | 921 | 7.0% |
| **Asia Pacific** | - | 3 | 6 | 13 | 19 | 26 | NA |

## Table 10. Unfinished Symphony Power by Fuel Source (TWh)

| Fuel Source (TWh) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 24,072 | 31,817 | 34,930 | 45,519 | 52,698 | 59,082 | 2.0% |
| **Coal** | 9,341 | 9,468 | 8,326 | 5,167 | 579 | 166 | -8.6% |
| **Coal (with CCS)** | - | 35 | 71 | 371 | 1,045 | 1,053 | NA |
| **Oil** | 990 | 771 | 493 | 264 | 162 | 92 | -5.1% |
| **Gas** | 5,561 | 7,727 | 8,953 | 13,611 | 10,728 | 3,956 | -0.8% |
| **Gas (with CCS)** | - | 38 | 77 | 547 | 5,437 | 10,793 | NA |
| **Nuclear** | 2,571 | 3,701 | 4,448 | 5,704 | 6,802 | 7,818 | 2.5% |
| **Hydro** | 3,903 | 5,019 | 5,388 | 6,131 | 7,153 | 7,660 | 1.5% |
| **Biomass** | 527 | 848 | 1,004 | 1,438 | 2,099 | 2,700 | 3.7% |
| **Biomass (with CCS)** | - | - | - | 24 | 74 | 172 | NA |
| **Wind** | 840 | 2,335 | 3,236 | 5,602 | 8,275 | 10,786 | 5.8% |
| **Solar** | 256 | 1,700 | 2,684 | 6,038 | 8,970 | 11,773 | 8.9% |
| **Geothermal** | 80 | 138 | 180 | 330 | 559 | 859 | 5.4% |
| **Other** | 2 | 35 | 70 | 290 | 815 | 1,253 | 16.1% |

## Table 11. Unfinished Symphony Carbon Emissions

| Carbon Emissions | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **$CO_2$ emissions** (GtCO2/yr) | 31 | 33 | 31 | 25 | 17 | 11 | -2.3% |
| **$CO_2$ capture** (GtCO2) | 0 | 0 | 0 | 1 | 4 | 7 | NA |
| **$CO_2$ per capita** (tCO2) | 4 | 4 | 4 | 3 | 2 | 1 | -3.0% |
| **$CO_2$ intensity** (kgCO2/USD2010) | 0 | 0 | 0 | 0 | 0 | 0 | -4.8% |

## Table 12. Unfinished Symphony Installed Nuclear Generation Capacity (GW) by Region

| Nuclear Generation Capacity (GW) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 407 | 511 | 581 | 739 | 875 | 1003 | 2.0% |
| **Sub-Saharan Africa** | 2 | 3 | 3 | 5 | 9 | 14 | 4.4% |
| **Middle East & North Africa** | 2 | 7 | 9 | 16 | 30 | 39 | 6.8% |
| **Latin America & the Caribbean** | 4 | 5 | 6 | 7 | 9 | 11 | 2.2% |
| **North America** | 121 | 116 | 116 | 120 | 125 | 134 | 0.2% |
| **Europe** | 171 | 161 | 153 | 167 | 163 | 191 | 0.3% |
| **Central Asia** | 6 | 27 | 41 | 88 | 135 | 154 | 7.3% |
| **East Asia** | 101 | 192 | 248 | 330 | 394 | 447 | 3.4% |
| **Asia Pacific** | 0 | 2 | 3 | 6 | 10 | 13 | NA |

## Table 13. Hard Rock Economic Indicators

| Indicator | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Population (million)** | 7,372 | 8,163 | 8,541 | 9,200 | 9,762 | 10,213 | 0.7% |
| **GDP** (trillion USD2010 MER) | 76 | 98 | 110 | 138 | 168 | 200 | 2.2% |
| **GDP per capita** (USD2010 MER) | 10,263 | 12,005 | 12,911 | 14,970 | 17,191 | 19,591 | 1.4% |
| **Car ownership** (cars/1000 people) | NA | NA | 183 | 213 | 248 | 284 | NA |
| **Primary Energy Intensity** (toe/Million USD2010 MER) | 178 | 160 | 149 | 126 | 107 | 92 | -1.4% |
| **Final Energy Intensity** (toe/ Million USD2010 MER) | 129 | 115 | 108 | 94 | 81 | 71 | -1.3% |

## Table 14. Hard Rock Primary Energy (Mtoe)

| Primary Energy Supply (MTOE) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 13,481 | 15,704 | 16,390 | 17,411 | 17,880 | 18,485 | 0.7% |
| **Coal** | 3,826 | 4,009 | 3,926 | 3,917 | 3,267 | 2,905 | -0.6% |
| **Oil** | 4,272 | 5,007 | 5,214 | 5,350 | 5,381 | 5,300 | 0.5% |
| **Gas** | 2,937 | 3,547 | 3,791 | 4,123 | 4,516 | 4,770 | 1.1% |
| **Nuclear** | 616 | 862 | 982 | 1,124 | 1,266 | 1,391 | 1.8% |
| **Biomass** | 1,310 | 1,485 | 1,558 | 1,681 | 1,891 | 2,193 | 1.2% |
| **Hydro** | 327 | 398 | 403 | 454 | 521 | 583 | 1.3% |
| **Other renewables** | 193 | 396 | 517 | 762 | 1,038 | 1,342 | 4.4% |

## Table 15. Hard Rock Nuclear in Primary Energy by Region (Mtoe)

| Primary Energy by Region (Mtoe) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 616 | 862 | 982 | 1,124 | 1,266 | 1,391 | 1.8% |
| **Sub-Saharan Africa** | 3 | 3 | 2 | 2 | 2 | 3 | -0.4% |
| **Middle East & North Africa** | 1 | 6 | 8 | 11 | 15 | 33 | 8.7% |
| **Latin America & the Caribbean** | 6 | 9 | 10 | 10 | 9 | 14 | 2.0% |
| **North America** | 246 | 225 | 224 | 227 | 228 | 236 | -0.1% |
| **Europe** | 305 | 288 | 273 | 266 | 276 | 309 | 0.0% |
| **Central Asia** | 11 | 33 | 47 | 83 | 121 | 174 | 6.3% |
| **East Asia** | 45 | 298 | 416 | 519 | 608 | 612 | 6.0% |
| **Asia Pacific** | - | 1 | 2 | 4 | 7 | 10 | NA |

## Table 16. Hard Rock Power by Fuel Source (TWh)

| Fuel Source (TWh) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 24,072 | 29,927 | 31,536 | 35,722 | 39,593 | 43,012 | 1.3% |
| **Coal** | 9,341 | 10,708 | 10,465 | 10,548 | 8,704 | 8,137 | -0.3% |
| **Coal (with CCS)** | - | - | - | - | - | - | NA |
| **Oil** | 990 | 1,046 | 912 | 741 | 646 | 594 | -1.1% |
| **Gas** | 5,561 | 6,635 | 7,245 | 8,376 | 10,605 | 11,070 | 1.5% |
| **Gas (with CCS)** | - | - | - | - | - | - | NA |
| **Nuclear** | 2,571 | 3,342 | 3,808 | 4,357 | 4,910 | 5,394 | 1.7% |
| **Hydro** | 3,903 | 4,627 | 4,686 | 5,286 | 6,063 | 6,786 | 1.2% |
| **Biomass** | 527 | 793 | 912 | 1,136 | 1,610 | 2,017 | 3.0% |
| **Biomass (with CCS)** | - | - | - | - | - | - | NA |
| **Wind** | 840 | 1,592 | 1,897 | 2,720 | 3,480 | 4,443 | 3.8% |
| **Solar** | 256 | 1,076 | 1,477 | 2,328 | 3,150 | 3,943 | 6.3% |
| **Geothermal** | 80 | 100 | 119 | 169 | 272 | 365 | 3.4% |
| **Other** | 2 | 7 | 14 | 60 | 153 | 265 | 12.2% |

## Table17. Hard Rock Carbon Emissions

| Carbon Emissions | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **$CO_2$ emissions** (GtCO2/yr) | 31 | 36 | 37 | 38 | 36 | 34 | 0.2% |
| **$CO_2$ capture** (GtCO2) | 0 | 0 | 0 | 0 | 0 | 0 | NA |
| **$CO_2$ per capita** (tCO2) | 4 | 4 | 4 | 4 | 4 | 3 | -0.5% |
| **$CO_2$ intensity** (kgCO2/USD2010) | 0 | 0 | 0 | 0 | 0 | 0 | -1.9% |

## Table 18. Hard Rock Installed Nuclear Generation Capacity (GW) by Region

| Nuclear Generation Capacity (GW) | 2015 | 2025 | 2030 | 2040 | 2050 | 2060 | % CAGR 2015-2060 |
|---|---|---|---|---|---|---|---|
| **Total** | 407 | 466 | 498 | 565 | 634 | 696 | 1.2% |
| **Sub-Saharan Africa** | 2 | 1 | 1 | 1 | 1 | 1 | -0.8% |
| **Middle East & North Africa** | 2 | 3 | 4 | 6 | 8 | 17 | 4.9% |
| **Latin America & the Caribbean** | 4 | 5 | 5 | 5 | 5 | 7 | 1.3% |
| **North America** | 121 | 114 | 114 | 115 | 115 | 120 | 0.0% |
| **Europe** | 171 | 157 | 148 | 143 | 146 | 163 | -0.1% |
| **Central Asia** | 6 | 17 | 23 | 41 | 60 | 86 | 5.9% |
| **East Asia** | 101 | 168 | 202 | 252 | 295 | 297 | 2.4% |
| **Asia Pacific** | 0 | 1 | 1 | 2 | 4 | 5 | NA |

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