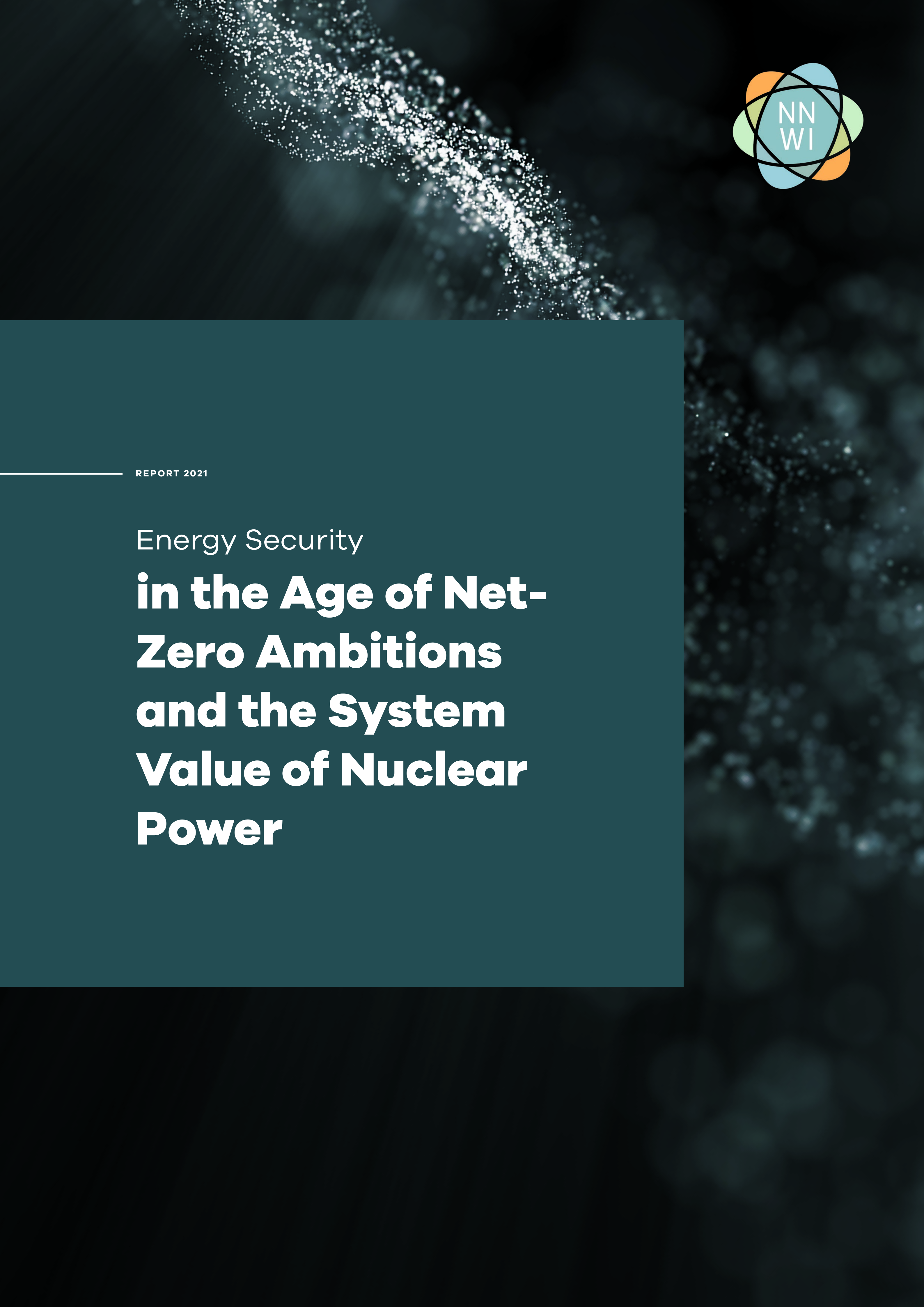

REPORT 2021

# Energy Security
# in the Age of Net-Zero Ambitions and the System Value of Nuclear Power

# Executive Summary

**This report focuses on the issue of energy security and the important contributions that nuclear power can make towards maintaining and strengthening it as energy systems decarbonise, both along the various transition pathways that energy systems have started upon and at their eventual low-carbon endpoint.**

It begins with an overview of how thinking about energy security has evolved over the last century, before analysing how current trends in the electricity sector may affect security up to 2030 and the ways in which the characteristics of different sources of power determine their security value in responding to those trends. Finally, the report presents an explanation of the potential energy security risks that lie along the nuclear supply chain, assesses their relative strength, and suggests ways in which they can be managed.

Energy security is often the overlooked and underappreciated component of the energy trilemma, the term used to describe the balancing act required when attempting to secure universal access to energy, deliver on the urgent need to tackle climate change, and protect and enhance the security of energy supplies. The central aim of COP26, the focal point of energy decision making in 2021, is to secure more stringent emission reduction plans from signatories to the Paris Agreement. Meanwhile, the importance of ensuring energy access for all has been enshrined in the Sustainable Development Goals (SDGs) of the United Nations, with SDG7 targeting "universal access to affordable, reliable, and modern energy services[1]" by 2030, contributing in part to a concrete improvement in global electricity access, which reached 90% in 2019.

However, the importance of energy security in the success of the two other parts of the energy trilemma cannot be understated. In fact, the preservation of energy security and the management and mitigation of energy security risks stands as a necessary condition to balancing it. Expanding the provision of energy and electricity to the nearly eight billion inhabitants of the world cannot succeed unless supplies sufficient to meet demand and energy systems resilient to both failure and disruption are coherently designed and operated. Equally, the increasing reliance of a variety of modern systems on the continuous supply of energy, whether it be the healthcare, transport, or financial system, implies that the decarbonisation transition, in particular its implications for the energy and electricity generation mix, may be compromised if the security of energy is not preserved in the decades to come.

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[1] https://sdgs.un.org/goals/goal7

# A Thinking about Energy Security

**The study of energy security is heterogenous and fragmented, characterised by a diverse range of analytical fields, various quantitative and qualitative measurement frameworks, and a disparate body of policy prescriptions. As a result, there is no single, universally accepted definition of energy security that provides a positive, meaningful understanding of the term, in part a reflection of the fact that developments in the study have often been prompted by categorically different historical events or processes, thus necessitating a new analytical viewpoint each time.**

However, three broad strands of thinking about energy security can be drawn out of its intellectual history, the perspectives of sovereignty, robustness, and resilience[2], which are now described in brief:

## 1. Sovereignty

Control over energy sources, either directly or via cooperation in multinational organisations, stands as the key determinant of security and methods to minimise the risk and severity of supply disruption, such as developing indigenous resources or diversifying the supplier base, are to be encouraged – although the oldest of the three strands, the use of rare earth metals in the production of renewable energy technologies represents a modern illustration.

## 2. Robustness

The vulnerability of energy systems is not thought to lie primarily in the geopolitical or strategic realm but in the limits of the technical and natural sciences – the former focuses on the ability of systems such as the power sector to withstand the failure of individual parts or sections while the latter initially focused on the impact of finite fossil fuel reserves on security while now assessing the likely effect of greenhouse gas emissions on the function of energy systems and the environmental conditions in which they operate.

## 3. Resilience

The principal threats to energy security are no longer certain in nature but arise unpredictably from the increasingly complex nature of modern energy systems, in which interconnectedness, feedback loops, and non-linearity leads to an ontological risk profile – as threats cannot be quantified in a meaningful way, the practice of energy security is concerned with designing well-diversified systems that are able to absorb stresses and strains and to return to normal function following a disruption in an acceptable time frame.

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[2] A. Cherp & J. Jewell, The Three Perspectives on Energy Security: Intellectual History, Disciplinary Roots and the Potential for Integration, Current Opinion in Environmental Sustainability, (September 2011)

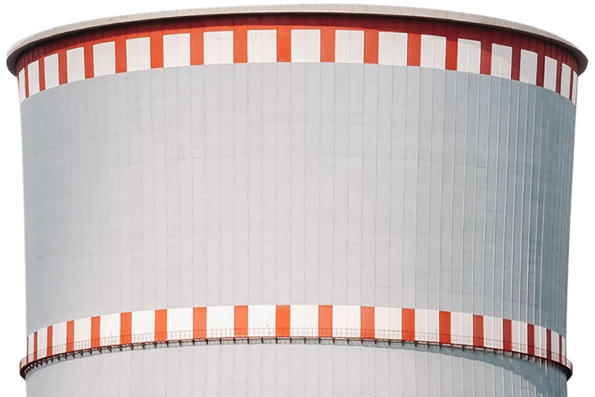
# B. The Potential Energy Security Threats of Sector Developments and the Security Value of Different Sources of Electricity

**The need to rapidly decarbonise modern energy systems requires a fundamental revolution in both their structure and their function, resulting in a state of flux characterised by a variety of sometimes contradictory sectoral challenges. As a physical product, electricity is homogenous but the sources from and the process by which it is generated are highly varied, meaning that the security value of different sources is not constant over different trends.**

Although a larger number of trends are considered in the main body of the report, the three principal challenges, although interrelated in nature, are:

## 1. The Growing Stringency of Climate and Environmental Legislation

The need to reduce greenhouse gas emissions at a faster rate than is currently being observed has stimulated legislation across the world intended to accelerate decarbonisation – the acceptability of carbon intensive products and processes, such as coal-fired power generation or use of the internal combustion engine, is falling and so energy systems must be reorientated to both supply the low-carbon energy required but also to adapt to the different use patterns, geographically as well as temporally, of final consumers without compromising security. In addition, the electrification of new sectors, the implied power demand growth of which is a separate trend in its own right, and the development of new energy subsectors, such as the hydrogen system, requires a highly integrated, long-term planning outlook if discontinuities in the future are to be avoided.

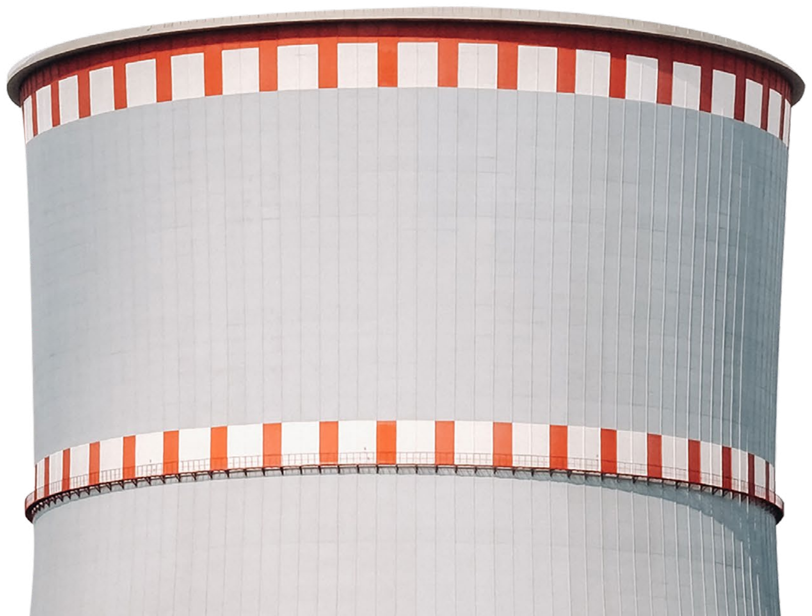


## 2. The Increasing Share of Variable Renewable Energy (VRE) Sources in Power Generation

Driven by a virtuous circle of declining installation costs, improved operational performance, and active policy support, the rapidly increasing growth of installed wind and solar capacity has played a significant and valuable role in bring down the carbon intensity of the electricity generation mix. The characteristic properties of VREs, primarily their intermittency and uncertainty that result in elevated system costs, require that power grids adapt to an increasing role for fluctuating supply by increasing their operational flexibility and back-up capacities, including interconnectors, storage, and gas-fired capacity, if energy security is to be maintained – the severity of these challenges is set to increase, potentially in non-linear manner, as the absolute share of generation met by VREs rises.

## 3. The Decline or Stagnation in Nuclear Power Capacity

In Europe and in the United States of America, in contrast to China for example, the average age of nuclear fleets is rising as new grid connections remain infrequent, with investment largely limited to the lifetime extension of existing plants, and as some countries implement nuclear phase-outs. This represents a decrease in generation from one of the few commercially mature, large-scale sources of firm, low-carbon electricity and so augments the volatility of supply caused by the growth of VREs and adds further stress to the maintenance of system adequacy - in turn, raising the exposure of preserving energy security to the successful development of storage and other technologies that are yet to be proved at scale.



# C Nuclear Power and Supply Chain Risks for Energy Security

**The potential role of nuclear power in facilitating a safe, cost-effective decarbonisation has been well covered but can only be realised by an ambitious increase in installed capacity, all the more ambitious when compared to capacity growth in certain regions of the world over the last decade and more. Such an increase in capacity, in relation to existing nuclear nations but more acutely to potential nuclear newcomers, can only be met by a significant increase in export activity.**

The decline in prominence of the traditional exporters in the nuclear industry, namely the United States of American, Europe, and Japan, and the rise of Russia as a leading exporter, not to mention the high ambitions of China, has led some to voice concern about the energy security risks of cooperating with state-supported nuclear vendors, principally driven by the supposed threat of dependency – in spite of the long-lasting reputational, and subsequently commercial, damage that an attempt to use an export project as a means of influence would embody.

However, these concerns are often voiced in broad terms without specific reference to points along the nuclear supply chain at which host nations may be exposed to a higher or lower level of risk and often conflate nuclear power with other sources of energy that may be more susceptible to unilateral disruption, such as the supply of natural gas.

The entire length of the nuclear supply chain is considered in the body of the report, but the points at which the risk influence stands more prominently are described below along with the potential means by which risks can be mitigated where possible:

## 1. Before Construction [Medium]

After the completion of business negotiations and the signing of the licensing and other project contracts, the host faces the risk of the vendor unilaterally cancelling the contract at which point the administrative costs of negotiation are rendered lost. The cost to the host nation at this stage is not negligible, while potentially greater for newcomer nations if the vendor had committed to a wider involvement in the development of the nuclear industry of the host, but the vendor itself also faces a cost in terms of negating the preparatory work done in directing and adapting its production capacities to the specificities of the contracted location and project size.

However, the host is able to mitigate to a certain extent the aforementioned risks via the use of a competitive vendor selection process, whether structured as a tender or otherwise, that requires participating vendors, neutrally selected, to negotiate favourable terms with the host. Moreover, the bargaining position of the host country may be further strengthened by the availability of other sources of low-carbon power and so have a credible reason to abandon the negotiation process while remaining committed to some degree of decarbonisation.

## 2. During Construction [Low/Medium]

Should the vendor halt construction of a nuclear power plant prior to completion, the host faces the difficulty and cost of sourcing an alternative vendor and the subsequent reworking of the plant and site design – however, the degree of risk exposure taken on by the host nation can be modulated according to the structure of the project, with the Build-Own-Operate model transferring almost the entire risk of non-completion to the vendor via the requirement for it to take an equity stake and potential operational responsibility of the plant and both the Engineering, Procurement, and Construction and the Nuclear Steam Supply System models restricting the host's risk to individual stages of the construction process.

It should be noted that the cancellation of a new nuclear build project by a vendor during this stage of the nuclear supply chain is an unlikely scenario with the 1979 cancellation of the Bushehr nuclear power plant by German vendors in the aftermath of the Islamic Revolution representing the only historical precedent. The project was later taken over and completed by Russia, with construction resuming in the late 1990s. Overcapacity in the global nuclear industry, in terms of the construction capacity of vendors versus their orderbooks, suggests that even if such an event were to occur again, the project would likely be taken over by a competing vendor, perhaps in conjunction with a vendor-arranged financing scheme to reduce the host's cost of switching. As a result, the hypothetical use of the threat of cancellation after the start of construction does not represent an effective tool of geopolitical influence.

## 3. Fuel Fabrication [Low/High]

The idiosyncrasies in the design of fuel assemblies, between competing vendors as well as across the product range of the vendors themselves, implies that a threat by the vendor to disrupt their supply could lead to either undue leverage or an energy security risk – this is certainly the case if provisions are not made for such an eventuality. However, encouraging greater diversity in supply of fuel assemblies, as has occurred in Ukraine, and the coordinated accrual of stockpiled fuel assemblies in volumes sufficient to cover the lead time needed for an alternative fuel manufacturer to start serial fabrication serves to limit the vulnerability of host to such behaviour. The extended fuel cycle of nuclear power plants, compared to other source of electricity, adds to the buffer in which alternative supply arrangements can be found.

# D. Policy Recommendations

## 1. Promote and Preserve a Diverse, Low-Carbon Generation Mix

The brittleness, or lack of resilience, of a given energy system is to a large extent determined by its reliance on a single or few energy sources, provided by a single or few suppliers and technologies, for the majority of its energy requirements. Given the complexity of modern energy systems and of the transition to decarbonisation, future disruptions to energy supply cannot be accurately predicted and so security can only be found in diversity of input. As a result, the often-political phase-out of nuclear power should be discouraged and instead the valuable characteristics of nuclear power in relation to the preservation of energy security must be both made clear and given proper place in policy discussions – debates as to the preferred course of the energy system can no longer be driven by unit cost estimates, sensitive as they are to input assumptions and other parameters, but must adopt a more holistic approach to energy supply, which includes security concerns, and the system level contributions that different sources of energy offer.

## 2. Ensure that Energy System Planning is Integrated, Long-Term, and System-Level

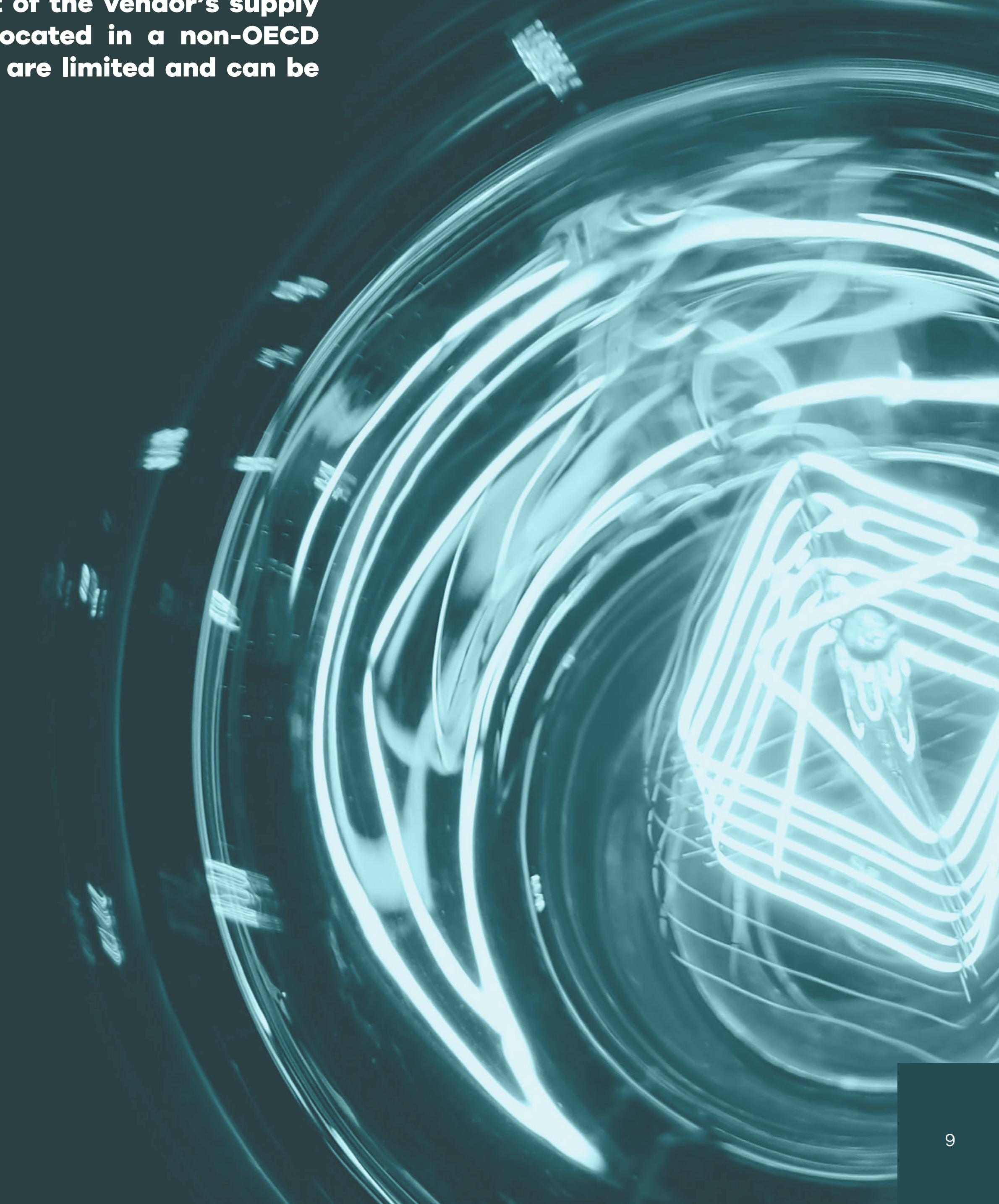
The introduction of interim climate targets, such as the target for the share of renewable generation adopted by the European Union, has to be compatible with the long-term transition to a decarbonised world. While the rapid increase in renewable generation over the last decade has certainly reduced the carbon intensity of many electricity grids, the longer-term energy security challenges faced by an increasingly weather-dependent grid are yet to be addressed in a meaningful manner and rely in some cases on the future commercialisation and large-scale deployment of unproven technologies, particularly those intended to increase system flexibility, or a long-term role for carbon-intensive, dispatchable gas-fired generation. The value, to energy security as well as decarbonisation, of firm, low-carbon power, as provided by nuclear plants as well as hydropower facilities, is not fully captured in markets for electricity at present.

## 3. Stimulate the Nuclear Export Market

As stated above, a key determinant of system resilience is diversity and so an increase in the diversity of participants in the nuclear export market ought to be encouraged, with the added benefit that doing so would likely benefit the vendor nation via the positive impact that nuclear development has on industrial strategy, in terms of jobs, economic multipliers, and so on. Alongside the GW-scale nuclear market, the prospect of the commercialisation of small modular reactor (SMR) designs could herald a more active and competitive export environment with the potential to contribute to energy security in certain ways more effectively than traditionally sized nuclear projects.

**The addition of new nuclear capacity is of clear benefit to the energy security of the host country, increasing both the robustness and the resilience of their energy systems and reducing fossil fuel imports. As this report has shown, the potential vulnerabilities of host countries to nuclear-specific supply chain risks – largely arising from scenarios in which the vendor or a large part of the vendor's supply chain is located in a non-OECD country – are limited and can be managed.**

Existing legal, regulatory, and market mechanisms – not least the negative reputational impact to the vendor that would follow untoward behaviour to a host country – serve to render new build nuclear projects effectively immune to energy security risks and the hypothetical abuse of market power for geopolitical ends, regardless of the identity of the individual vendor. Indeed, it could be argued that the ability to leverage influence in this way lies with the host nation – able to cancel or walk away from new build projects for bargaining or geopolitical purposes – resulting in continued import dependency, less resilient energy systems, and inefficient decarbonisation policies.



# Section 1

# Evolution of Energy Security Thinking

## Thinking about Energy Security

**Energy security is a concept that is infamously difficult to articulate – and to measure or quantify in a unified, comparative framework - in a concise and coherent manner due to the multifaceted nature of the term and the growing complexity and interconnected character of modern energy systems.**

The decision of Winston Churchill, then the First Lord of the Admiralty, in the run up to the First World War, to shift the fuel of the UK navy from coal to oil, from an indigenous fuel source to one requiring importation from abroad, is marked by studies of the historical development of the field as the point at which ensuring a secure supply of energy assumed a critical role in policymaking. At the time, it was resolved that the risk of a supply disruption would be mitigated by diversifying the supplier base, "[s]afety and certainty in oil", according to Churchill[3], "lie in variety and variety alone". It was evident that there was then a close relationship between securing ready access to oil and maintaining national security.

However, the study of energy security has advanced into new fields since then, prompted by specific energy events that have required the perspective and insight of academic and technical disciplines beyond that of national security – in this sense, the development of the field has often been responsive rather than proactive. The widening of the pool of viewpoints brought to bear on the field is a fundamental part of the reason why a unified definition of energy security remains elusive as the broad range of analytical and technical tools used by different disciplines to analyse it are often incompatible.

The context-dependency of the concept further complicates matters. In its most basic setting, this can be seen in what might constitute energy security for a net energy importer as opposed to a net exporter. The former may be concerned with diversifying its supplier base, as in the example above, or developing alternative indigenous sources of energy while the latter may focus on safeguarding demand and ensuring a reliable, stable revenue stream for its energy exports. This polysemic nature of energy security, its multidimensional nature allied to its capability of adopting local or national specificities, makes difficult any attempt at articulation of the concept[4].

In this light, three principal perspectives on energy security have developed over time, each prompted by a significant challenge at a particular time that threatened energy security that required a new mode of analysis to be developed and each with its own academic background, tools of analysis, and areas of focus.

**The three perspectives[5] are:**

- **sovereignty:** focusing on the threats to energy security posed by external actors.
- **robustness:** identifying the threats posed by physical and technical limits on energy systems.
- **resilience:** managing and/or limiting the negative impact of ontological risks on complex systems.

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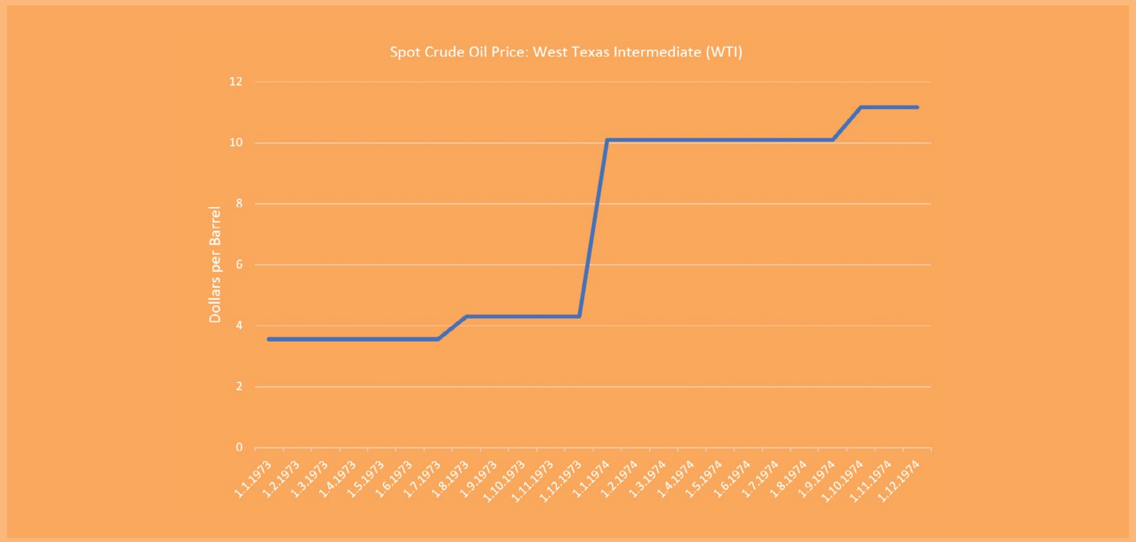
[3] D. Yergin, Ensuring Energy Security, (2006)
[4] L. Chester, Conceptualising Energy Security and Making Explicit its Polysemic Nature, (2010)
[5] A. Cherp & J. Jewell, The Three Perspectives on Energy Security: Intellectual History, Disciplinary Roots and the Potential for Integration, (2011)

## A. The Sovereignty Perspective

**The sovereignty perspective, the oldest of the three, finds its source in the actions of Winston Churchill described above and the broader need to secure supplies of fuel for the military during times of conflict. At its core lies the question of which actor or actors control access to energy sources and by what mechanisms do they do so. Implicit in this line of thinking is a belief in the threat of hostile action by an external actor that could serve destabilise the home nation and so it reflects the twentieth century concern with the international balance of power.**

In the post-war period, the sovereignty perspective retained its focus on the control of and access to fuel supplies but supplanted the need to ensure available supply for the military with the need to provide the fuel vital to newly industrialised societies, dependent as they were on oil for transport, heating, electricity generation and so on. An innate tension in this system was the fact that the majority of the industrialised nations were net importers of oil, thus often dependent on supply from developing nations who in turn were often dependent on oil export revenue to finance their own development and maintain political stability.

The fragility of this system was exposed on the 19th of October 1973 when the Organisation of Petroleum Exporting Nations (OPEC) instituted an oil embargo on the United States of America in retaliation to a request by President Nixon for Congress to make funds available for the support of Israel during the Yom Kippur War[6]. As a result, the spot price of WTI increased from $3.56 per barrel at the start of 1973 to $10.11 at the start of the following year, according to Federal Reserve Economics Data[7]. The militaristic origins of the sovereignty perspective were clear in contemporary analysis of the embargo, referring to the threat of the 'Arab Oil Weapon'[8], and more broadly in the risk mitigation techniques proposed by its adherents.



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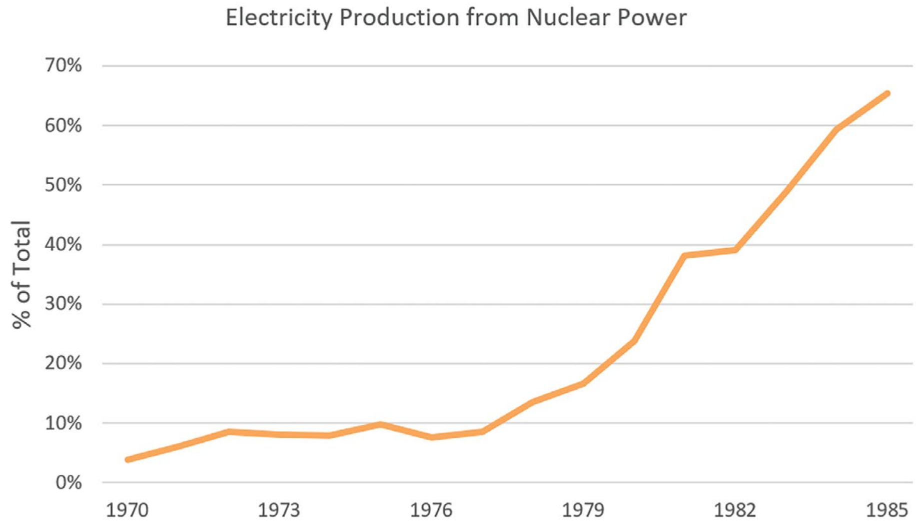
[6] https://www.federalreservehistory.org/essays/oil-shock-of-1973-74
[7] https://fred.stlouisfed.org/series/WTISPLC#0
[8] J. Paust & Albert Blaustein, The Arab Oil Weapon – A Threat to International Peace, (1974)

These mitigation techniques reflected the realpolitik of the Cold War era and focused on minimising disruptions to the supply of oil while reducing exposure to any single disruption. The pursuit of the former was often achieved through either the use or projection of military power while the latter was to be achieved by the development of a liquid and diversified global market for oil and oil products. This led to the immediate establishment of the International Energy Agency (IEA) in 1974[9], set the task of developing energy policy cooperation and ensuring the security of oil supply by monitoring the levels of strategic reserves held by its members, which remains a core responsibility of the organisation to this day[10]. Other supply risk mitigation techniques pursued in the wake of the oil embargo included developing previously unworked domestic oil reserves and switching to non-oil energy sources where available. In part, this spurred the growth in the use of nuclear power in some countries, as data from the World Bank for France, where the development of nuclear power in the 1970s was explicitly linked to energy security, illustrates[11].



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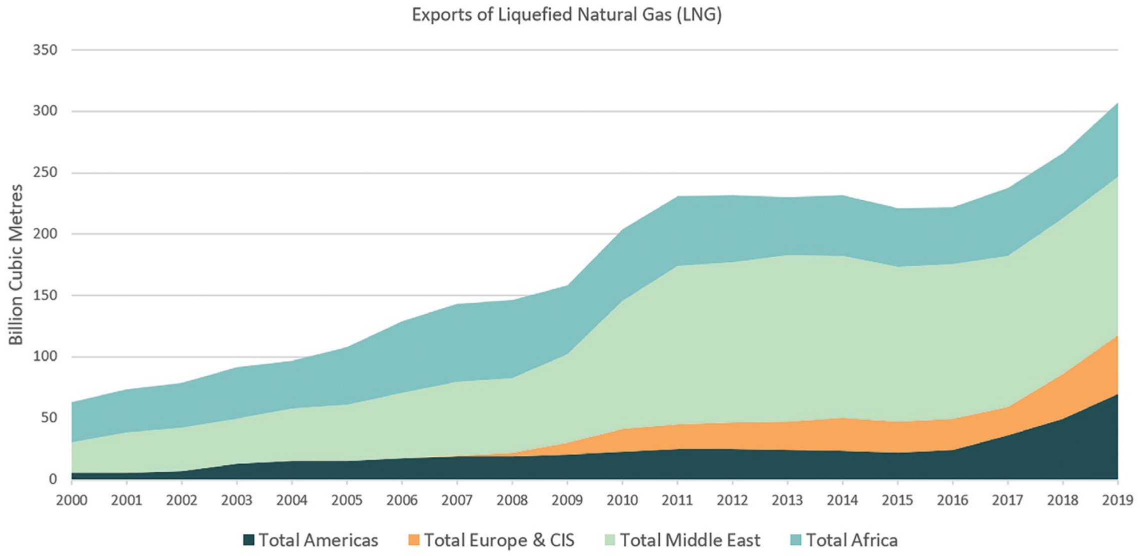
[9] https://www.iea.org/about/history
[10] https://www.iea.org/articles/oil-stocks-of-iea-countries
[11] https://data.worldbank.org/indicator/EG.ELC.NUCL.ZS?locations=FR

Contemporary analysis that adopts the sovereignty perspective, along with its roots in political science, international relations, and security studies, has expanded beyond oil and places a particular emphasis on natural gas. As before, there is a focus on diversifying the supplier base for net importers while net exporters are concerned with ensuring demand security – the two major and interrelated developments in this regard have been the growth of the market for liquefied natural gas (LNG), illustrated below based on BP's Statistical Review of World Energy[12], and the development of shale resources in the United States of America, which has turned the country into an exporter of fuels and fundamentally altered the global energy landscape[13]. However, the LNG market remains relatively small in comparison to the total gas market and so pipeline infrastructure remains a potential source of supply disruption if used as a 'choke point' by an external actor.



Another area of study to which the sovereignty perspective is now being applied is the degree to which the energy transition may reorganise geopolitics from an energy security perspective. The driving force in this regard is the level of mined natural resources – metals and minerals – that will be required by clean energy technologies, including renewable generation technologies as well as batteries and hydrogen-producing electrolysers, if the transition to a decarbonised energy system is to be achieved. As the spatial allocation of petroleum resources across the globe has characterised energy security relationships to date, a reorganisation of those relationships and power balances according to the spatial dispersion of required metals and minerals seems almost inevitable – a transition from OPEC to an Organisation of Mineral Exporting Countries (OMEC) has even been suggested[14]. The European Union has published four lists of 'critical raw materials' (CRM) since 2011, with the twin goals of identifying concentrations and dependencies, such as China providing 98% of its supply of rare earth elements[15], and stimulating the production and recycling of CRMs on a local basis[16].

The future development of the issue of access to the metals and minerals that are required to facilitate the energy transition can be explored through the sovereignty perspective in an either hawkish or dovish light – although, in reality, it will likely be a blend of the two. From the hawkish viewpoint, an explicitly geopolitical one, the challenge of securing access to metals and minerals resembles a zero-sum game, in which individual nations or alliances of nations compete to control resources at the expense of rival parties. In certain cases, it may even be preferrable to avoid the use of a particular transition technology – or to engineer an alternative that requires either less or none of the dependent metal or mineral – if doing so would disadvantage one's own energy security. Alternatively, the dovish viewpoint, built upon theories of global governance and multinationalism, focuses on the role of institutions and other non-state actors in managing the tensions of competing energy security desires, while stressing the realities of an interconnected world.

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[12] https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
[13] https://www.iea.org/news/the-us-shale-revolution-has-reshaped-the-energy-landscape-at-home-and-abroad-according-to-latest-iea-policy-review
[14] https://assets.kpmg/content/dam/kpmg/xx/pdf/2021/03/resourcing-the-energy-transition.pdf
[15] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN
[16] https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

# B. Robustness

**In contrast to the sovereignty perspective, the robustness perspective focuses on the vulnerability of energy systems to disruptions that are non-political in nature. Adopting the analytical framework of both the natural and the technical sciences, it seeks to identify objective and quantifiable threats to energy security, such as energy demand growth and the scarcity of finite natural resources, against a backdrop of energy systems whose technical complexity is ever growing and of modern societies and economies that are increasingly reliant on the ready generation of electricity for their smooth functioning.**

One of the first major works to consider the impact of natural resource constraints on the continued development of mankind – both demographically and economically – was 'Limits to Growth', published in 1972, which was commissioned by the Club of Rome, set up in 1968 to study "the present and future predicament of man"[17]. Its conclusions were stark, stating that "if the Present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years.[18]"The report described a world in 'overshoot', consuming resources at a faster rate than those resources could be restored, and concluded that, in the absence of any concerted effort to alter the growth trends above, society was headed for collapse, characterised by acute reductions in "both population and industrial capacity"[19].

Perhaps unsurprisingly, given the potentially apocalyptic nature of its conclusions, the publication of 'Limits to Growth' prompted a wave of criticism and its methods and findings are still debated. Even the presumably straightforward question of whether or not subsequently recorded data accords with its projections remains unclear, with some work indicating a close alignment with the forecasts of the 'business-as-usual' scenario[20] and other work contesting that claim, pointing to the claim that certain resources – still readily available – were predicted to be exhausted by now[21].

Putting aside the veracity or otherwise of the conclusions of 'Limits to Growth', its publication brought the notion of limited resources – and the implications of that fact – to the fore of energy security studies. The first manifestation of this development was to stimulate the theory of 'peak oil', first posited in 1956 by Marion Hubbert[22]. At the core of the theory is the assertion that the rate of oil production follows a bell-shaped curve over time, starting low, accelerating as the discovery rate rises and investment in supporting infrastructure improves the recovery rate, before subsiding in the face of oil depletion. As for 'Limits to Growth', the theory of 'peak oil' has also prompted much debate, particularly as to the timing of peak oil – still yet to take place[23] – and the role of unconventional oil supplies and demand-side factors as well as the actual shape of the production rate curve.

The thinking that underpins the notion of limited resources has also been applied to climate change, with focus being paid to the implicit cap on the emission of greenhouse gases if global warming is to be limited, as is the desired aim of the Paris Accord with its goal of limiting the rise in average temperature to below 2 degrees Celsius[24], preferably 1.5 degrees Celsius. To target a specific average rise in temperature allows for an assessment of a carbon budget understood as the remaining amount of cumulative carbon emissions permittable before the target is no longer achievable.[25]

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[17] D. Meadows et al, The Limits to Growth; a Report for the Club of Rome's Project on the Predicament of Mankind, (1972), p.9

[18] ibid., p.23

[19] ibid., p.24

[20] G. Turner, Is Global Collapse Imminent, (2014)

[21] https://foreignpolicy.com/2009/11/09/the-dustbin-of-history-limits-to-growth/

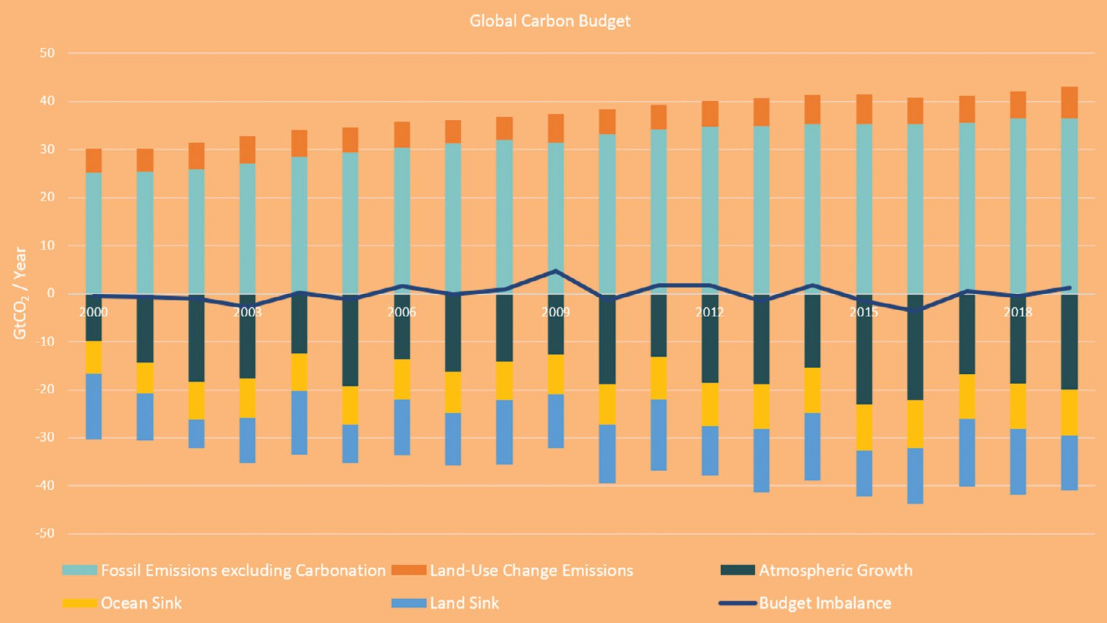
[22] M. Hubbert, Nuclear Energy and the Fossil Fuels, (1956)

[23] https://www.iea.org/reports/oil-2021

[24] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[25] https://www.carbonbrief.org/guest-post-a-new-approach-for-understanding-the-remaining-carbon-budget

The Global Carbon Project publishes an annual assessment of the carbon budget based on the emissions and removal – via carbon dioxide sinks on land and in the ocean – of carbon dioxide that are the direct and indirect of human activities[26], where 'atmospheric growth' the driver of growth in the atmospheric concentration of carbon dioxide. Data from 2000 to 2020 are presented in the accompanying graph[27].



In addition to assessing the implication of natural resources limits on energy security, the robustness perspective also focuses on the technical vulnerability of increasingly complex modern energy systems. The development of this focus was a natural response to the growing reliance of modern societies on the sustained functioning of the energy system that underpinned them.

This was nowhere more pronounced than the electricity sector, which is highly vulnerable to short-term disruptions due to the constant need to match supply and demand, in order to maintain a frequency equilibrium point, and the relatively restricted capacity to store electricity, in contrast to fossil fuels, for example, stockpiles of which can be raised as a buffer to manage temporary supply disruptions. This impact of a disruption to electricity supply will only gain in severity in the future as more sectors, such as transport and heating, are electrified.

The means of mitigating the risk of a technical failure in the electricity generation and transmission systems include reducing the reliance of any one electricity sector on the generation of a single or small number of power plants through a combination of installing sufficient backup capacity in the electricity grid and the implementation of either a fixed N-1 reliability criterion or a probabilistic energy criterion[28]. An N-1 criterion maintains that an electricity system ought to be able to operate at an acceptable level of reliability in the event of an unexpected failure of a single component at all times and thereby acts to prevent the concentration of load at any particular point, instead making clear the benefits of decentralisation. A probabilistic criterion seeks to evaluate both the cost of electricity grid disruptions, based on the likelihood of each system component failing and measured in terms of the Value of Lost Load (VoLL), and the cost of delivering varying levels of system reliability, including the cost of upgrading or replacing system infrastructure, in order to determine the cost-optimal level of grid reliability.

As has been shown, the primary concerns of the robustness perspective on energy security are for the most part predictable and based on recognised characteristics of the energy system and include the depletion of natural resources, the growth in electricity demand, and the occurrence of technical failures. As a result, the techniques used to manage energy security are less strategic, insofar as the need to respond to and prepare for the uncertain and hostile actions of an external actor is not of paramount importance, than those leading from the sovereignty perspective. Instead, the focus is on reducing and mitigating known risks using practical and non-political measures, such as switching consumption to more abundant resources when faced with the threat of resource depletion and maintaining the technical reliability of electricity grids by making prudent investments in infrastructure and limiting the threat posed by the failure of individual components by minimising the reliance of the system as a whole on any single unit.

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[26] http://www.globalcarbonatlas.org/en/content/global-carbon-budget

[27] P. Friedlingstein et al., Global Carbon Budget 2020, Earth System Science Data, (2020)

[28] M. Ovaere, Electricity Transmission Reliability Management, IAEE Energy Forum, (2016)

# C Resilience

**The third and most recent development in the way in which energy security is conceived of and analysed as a topic is the resilience perspective, which focuses on the ability of an energy system to withstand major disruptions within set degradation boundaries and to restore itself to proper function in a timely manner if those boundaries are exceeded. In contrast to both the sovereignty and robustness perspectives, the resilience viewpoint is relatively agnostic when it comes to threats and instead concentrates on the properties of an energy system itself and the ways in which its defining characteristics will determine its response to uncertain and unpredictable shocks and stresses.**

The prompt for the development of the resilience perspective occurred in the 1980s and 1990s in the face of the liberalisation of energy markets, with electricity markets a particular focus, in a number of countries in order to introduce a greater degree of economic competition in those markets and so, according to those in favour of the decision, bring about lower prices for both industrial and household consumers as well as greater levels of investment in energy infrastructure and market diversification through increased participation[29].

The intended aims of energy market liberalisation were primarily economic in their nature, concerned as they were with monopolistic behaviour, price levels and investment rates, which necessitated an economic appraisal of its outcomes and its impact on energy security, in contrast to the concerns of the two earlier energy security perspectives. As a result, while ensuring the uninterrupted supply of energy products retained its primacy as a metric of energy security success or failure, it was complemented with concerns as to the affordability and price stability of energy.

It should be noted that the deregulation of energy markets took on different forms in different countries and regions with distinct implications for energy security. For electricity markets, one profound difference is that between energy-only markets (EOM) and capacity markets, between markets that only compensate power that is actually produced and those that also remunerate power producers for their readiness to produce[30]. Proponents of the EOM model argue that the bringing to bear of the basic economic principle of supply and demand to the electricity market will result in an economically efficient matching process.

However, its sceptics counter that investment in capacity required to meet peak load will be insufficient as, without additional compensation for readiness, the financial return on such reserve capacity will be unattractive, which is known as the 'missing money' problem. While there are means by which electricity supply can be guaranteed in an EOM, such as the role of the control reserve market in Germany[31], the vulnerabilities of the model to supply disruption were evident during the electricity crisis in Texas, which operates an EOM, in February 2021[32].

The concern that market incentives alone may not be always relied upon to deliver optimal capacity investments is echoed in concerns as to their ability to uphold and improve energy security. Markets reward efficiency in production and those producers that are able to minimise or even eliminate waste will create an enduring competitive advantage for themselves that will lead to greater market concentration over time as less efficient producers are forced to exit the market on economic grounds[33]. While this mechanism can to some degree be tempered by market regulation, such as the implementation of capacity markets already described, there remains a tension between market efficiency and energy security insofar as the latter is determined by factors beyond waste minimisation and may in fact be undermined by the homogenisation brought about by maximising efficiency as opposed to resiliency.

Indeed, the homogenisation of energy systems that may result from a single focus on efficiency was further criticised as both an inappropriate policy to apply to increasingly complex and interrelated systems and based upon a mischaracterisation of the main risks to energy security. The inherent uncertainty of the risks facing the energy system implied that traditional, probabilistic risk management frameworks were ill suited to questions of energy security and that widespread diversification, not solely of fuel sources but also partners, technologies, infrastructures and so on, should be pursued ahead of market efficiency[34]. In this sense, expenditure on the research and development of innovative energy technologies can be thought of as contributing to energy security by treating such spending as a real option that may deliver a means by which to increase energy diversification in the future.

Implicit in the rise in the importance of resilience as opposed to efficiency were the methods and conclusions of complex systems theory, the study of which had been accelerated by the founding of the Santa Fe Institute in 1984[35]. Complex systems are "systems where the collective behavior of their parts entails emergence of properties that can hardly, if not at all, be inferred from properties of the parts[36]" and are composed of interacting agents, objects, and the environment in which they are located.

**The Main Characteristics of Complex Systems and their Application to Energy Systems**

Summarised from C. Bale et al.[35]

| Term | Definition | Energy System Example |
|---|---|---|
| Agents | individuals or organisations that act and interact in the system and adapt to, learn from, and influence the actions of other agents | households, governments, producers, operators, utilities, regulators, investors |
| Networks | physical and social structures by which agents interact, defined by directionality and tightness | gas and electricity infrastructures, social networks between consumers and utility companies |
| Dynamics | complex systems are fluid and fluctuate in non-equilibrium, driven in part by feedback loops | technological advances, population growth, lifestyle practices, production costs |
| Self-Organisation | adaption is autonomous and system organisation develops despite no single agent having total control | decisions are taken at multiple levels, agents respond to the changes in their environment |
| Path Dependency | current state of the system is a result of past actions and decisions that render each system unique | fossil fuel lock-in, infrastructure decisions, previous policy choices, state of the housing stock |
| Emergence | macro behaviour arises from interactions of agents and cannot be predicted based on an understanding of all the constituent system parts | inability to accurately predict future energy demand based on historical data and knowledge of individual agents due to future interactions and alterations in behaviour |
| Coevolution | systems coexist with other systems as do sub-systems within the system which co-evolve due to interdependencies | sub-systems in the energy system include power generation and transport which coevolve, interdependencies with water and food production systems |
| Learning and Adaption | systems employ experimentation and novelty to maintain or improve their functionality in the face of changes to their environment | consumer behaviour adapts due to demand-side management (DSM) methods, particular energy technologies adapt to technological and political changes |

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[29] https://ec.europa.eu/energy/content/liberalisation-energy-market-electricity-and-gas_en
[30] https://www.next-kraftwerke.com/knowledge/energy-only-market
[31] https://static.agora-energiewende.de/fileadmin/Projekte/2019/Liberalisation_Power_Market/Liberalisation_Electricity_Markets_Germany_V1-0.pdf
[32] https://insights.som.yale.edu/insights/why-the-texas-power-market-failed
[33] https://hbr.org/2019/01/the-high-price-of-efficiency

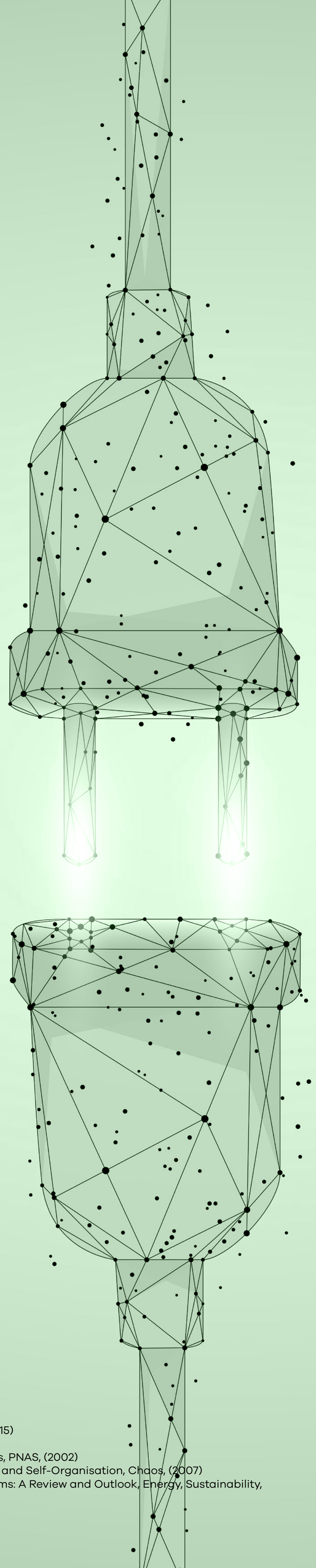
[34] A. Stirling, Diversity and Ignorance in Electricity Supply Investment: Addressing the Solution rather than the Problem, Energy Policy, (1994)
[35] https://www.santafe.edu/about/history
[36] https://cssociety.org/about-us/what-are-cs

The methods used to model and analyse complex systems, particularly in terms of the manner in which they are affected by feedback loops and respond to external shocks, differ from standard, equation-based techno-economic ones and allows for a greater understanding of desirable system qualities, such as resilience which can in turn be construed as a combination of adaptability and flexibility, and the means by which they may be realised[37].

Resilience “determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters and still persist[38]” and so, with the question of energy security in mind, can be thought of as the ability of a given energy system to return to proper function following either a short-term shock or a longer-term stress to its typical pattern of energy supply and use, with an example of the former being the technical failure of particular generation, transmission, or distribution unit and the latter the ongoing transition to decarbonisation.

An agent-based model, one such alternative method used to analyse complex systems, is constituted of a system of heterogenous agents and the relationships between them and is able to capture emergent behaviours and trends that result from repeated interactions between them[39]. Another alternative method, network theory, perceives a complex system as a series of nodes, representing the system agents, some of which are connected via edges of varying closeness and directionality and so can be used to analyse how behaviours and shocks at certain points in the network may reverberate around the wider system. One application of network theory to power generation has been to model how the cascading failure of individual generators or sections of transmission infrastructure at system critical points leads to system blackouts and how the evolution of a given power system may increase or decrease the likelihood of such events[40].

One of the key insights of complex systems theory therefore for considerations of energy security is that the unpredictability of the functional form of such shocks and stresses combined with the inherent uncertainty of the future behaviour or an energy system, in part caused by the potential for emergent behaviour and non-liner relationships, is that resilience is a valuable trait to establish. It can be thought of in terms of both adaptability – the capacity to manage change in an orderly fashion – and transformability – the capacity for a system to reorientate itself in a fundamental manner – and both can be developed by encouraging both diversity and connectivity within a system[41].



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[37] C. Bale, L. Varga, and T. Foxon, Energy and Complexity: New Ways Forward, Applied Energy (2015)
[38] C. Holling, Resilience and Stability of Ecological Systems, p.19, (1973)
[39] E. Bonabeau, Agent-based Modelling: Methods and Techniques for Simulating Human Systems, PNAS, (2002)
[40] I. Dobson, Complex Systems Analysis of Series of Blackouts: Cascading Failure, Critical Points, and Self-Organisation, Chaos, (2007)
[41] B. Jesse, H. Heinrichs, and W. Kuckshinrichs, Adapting the Theory of Resilience to Energy Systems: A Review and Outlook, Energy, Sustainability, and Society, (2019

# Section 2

# Potential Threats and the Security Value of Different Sources of Electricity

## Today’s Energy Sector Developments and their Impact on Electricity Security

**As the previous section has described, the development of thinking about energy security and the policies by which attempts to maintain and improve it have often been a direct response to the contemporary challenges of the time. At present, a number of fundamental trends and tendencies that characterise most modern energy systems also pose a potential threat to security, particularly that of electricity generation, and so ought to be managed and mitigated where possible. It should also be noted that the impact of some of the trends – or the impact of component parts of certain trends – may indeed prove to be a net positive for security and that many of the trends, along with their implications and consequences, are closely interrelated.**

In this section of the report, these developments will be considered and their potential impact on the security of power generation will be discussed. As noted earlier in the report, the concept of energy security is inherently context-dependent and so the descriptions and conclusions to be made here ought to be thought of in relation to an abstract electricity sector resembling the type found in many developed economies. This is taken here to imply that the electricity sector stands as the early stages of the decarbonisation transition, characterised by a growing share of renewable electricity or the gradual phasing out of coal-fired power generation or both, with limited indigenous natural gas reserves and system adequacy.

Alongside the exposition of the aforementioned potential threats, the related advantages and disadvantages of different sources of electricity will be considered. While, from a physical point of view, electricity is a homogenous product, the varying technologies by which it is generated are a heterogenous group and the differences, such as dispatchability and required fuel source, between them have a direct impact on the security of electricity supply. Moreover, the diversity of both the type and the nature of the potential threats means that what may be considered an advantage of one particular source of electricity in one situation is rendered a disadvantage in different circumstances.

Given that the framework for this analysis, as outline above, is to be an electricity sector of the type found in developed countries, the principal sources of electricity under consideration are coal, hydropower, natural gas, nuclear power, solar power, and wind power. Although either only indirect sources of electricity or technologies whose deployment remains in its infancy, references to hydrogen, interconnectors, and various forms of energy storage will also be made.

# A. Advancing Electricity Grid Decentralisation, in Terms of Generation, Storage, and Demand-Side Management

**Historically, the generation of power has been dominated by large-scale, conventional power plants, typically coal-fired or powered by either nuclear fission or hydropower, and the transmission and distribution of electricity has been managed by a small number of large utility companies. This state of affairs was driven by the logic of the economies resulting from scale and reflects the legacy of either state control or ownership of national electricity sectors.**

In recent times, the model of the centralised electricity sector has been increasingly challenged by the growth of decentralised generation, which refers to power that is generated away from the main grid and often consumed at or in close proximity to the generation site. This growth has been driven by a number of factors, which are societal, political, technological, or market-based in nature and include: the steep decrease in the cost of renewable generation, regulatory acceptance and the issuance of formal guidelines and frameworks, changes in customer behaviour and a desire to realise alternative revenue streams, and the extension of public financing mechanisms including subsidies and other incentives[42].

In terms of the security of electricity supply, a decentralised generation model has two clear benefits insofar as the siting of power generation in the vicinity of its final consumption serves to reduce or even eliminate any losses that may occur along the transmission network and the presence of a greater number of generation facilities across the grid, whether renewable-based or combined heat and power (CHP) units, lowers the exposure of the power system as a whole to the failure of a single, large plant[43].

However, the trend towards greater decentralisation also presents a number of challenges to the maintenance of electricity security, not least that the combination of an increasingly fragmented market and a growing reliance on decentralised intermittent technologies, such as residential solar panels, may complicate the balancing of an electricity grid at the aggregate level if implemented at large scale. This complication arises from the heightened difficulty of forecasting future levels of supply and demand that this combination of factors entails and may require higher reserve and flexibility requirements than does a centralised system[44].

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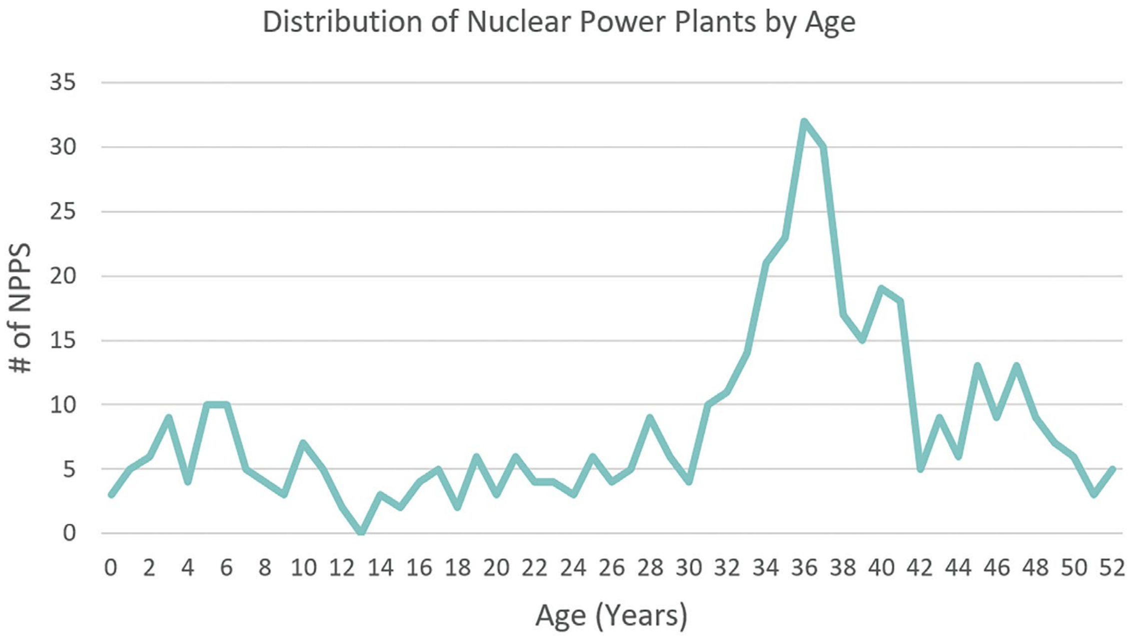
[42] https://assets.kpmg/content/dam/kpmg/pdf/2015/06/decentralised-energy-industry.pdf
[43] https://www.therma-mech.co.uk/what-is-decentralised-energy-and-why-is-it-important/
[44] https://www.europarl.europa.eu/document/activities/cont/201106/20110629ATT22897/20110629ATT22897EN.pdf

# B. Declining Nuclear Capacity Brought About by National Phase-Outs or Limiting Investment to Lifetime Extensions of Existing Plants or Both

**At the global level, the average number of years for which an operational nuclear reactor has been running stands at thirty-one, according to data from the International Atomic Energy Agency[45] (IAEA) displayed in the accompanying graph. On a regional level, the fact that forty new nuclear power plants have been installed in China since 2010 indicates that the average age of operational reactors in other parts of the world, particularly Europe and the United States of America, has been rising throughout this period as new grid connections have become gradually more infrequent.** .



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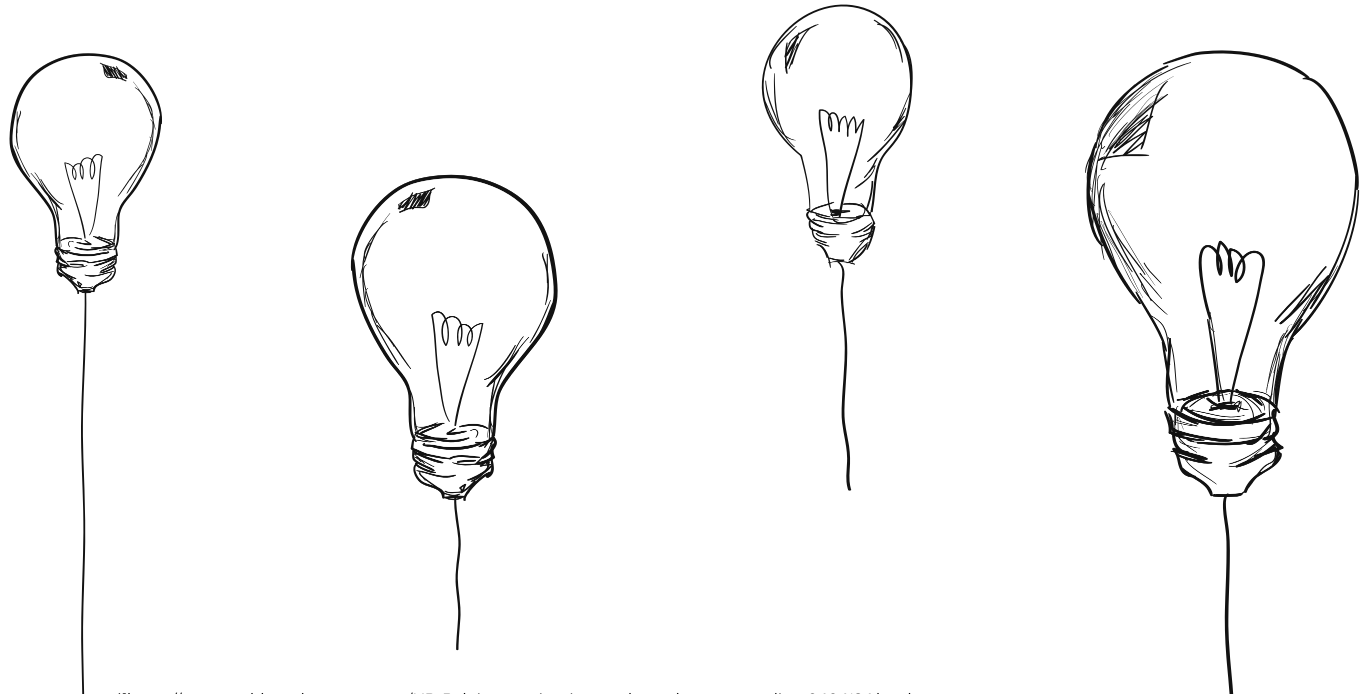
[45] https://pris.iaea.org/PRIS/WorldStatistics/OperationalByAge.aspx

In addition, the implementation of nuclear phase-outs, whether whole as in the cases of Germany and Belgium or as yet partial as in the case of Japan, in response to the Fukushima Daiichi accident in March 2011 has added an active impetus to the decrease in nuclear capacity beyond the passive absence of significant investment in new projects in many nuclear nations. The latter, it should be noted, is not solely the result of safety concerns following 2011 but also a reflection of the difficulties, in both time and cost, that some ongoing projects have faced in Europe and elsewhere.

In abstract terms, a decline in nuclear capacity represents a decline in baseload or firm generation capacity, which is capacity that can be relied upon to deliver electricity to the grid at a high capacity factor at all times. As a result, the removal of such capacity poses a clear threat to the price stability of electricity supply in the short-term as well as the adequacy of the power sector in the long-term unless it is replaced by either an alternative source of baseload power or a technology or set of technologies by which to balance non-firm sources of electricity to ensure that load is constantly met. This task is further complicated by the ongoing phase-out of coal-fired generation in a number of countries in line with their decarbonisation commitments, the spatial constraints involved in siting large hydropower facilities, and the limited availability of energy storage technologies able to balance seasonal variations in the supply and demand of power.

The case of the nuclear phase-out in Belgium is instructive in making clear the potential threat to electricity security that such a course of action may incur as well as its implication for decarbonisation. After a series of deadlines for the phase-out had been missed or delayed, the Belgian government agreed in 2018 to uphold a previous policy that committed the country to a phase-out of a nuclear power by 2025[46], a position that was maintained by the governing coalition in 2020[47] In 2019, Elia, the Belgian grid operator warned of serious power shortages unless alternative energy sources were rapidly expanded and sited the phase-out from coal in neighbouring countries as a potential restriction on Belgium's ability to import power[48]. In April 2021, it was announced that the Belgian reserve capacity mechanism would auction 2.3 GW of new natural gas capacity by the end of the year to increase the flexibility of the national power sector and maintain security of supply[49].

The potential limitation on Belgium's ability to import electricity via interconnectors from neighbouring countries, a result of their decisions to phase out coal-fired generation, is worthy of further comment as the expansion of interconnectors is often a proposed measure by which the intermittency of the growing share of electricity generation provided by renewables, chiefly solar and wind power, can be managed. The logic underlying the proposal is that the correlation between weather systems falls as the geographical area under consideration increases in area and so low levels of renewable generation in one location can be balanced by importing renewable electricity from an area in which the weather conditions are favourable. However, the apprehension demonstrated by Elia illustrates that this conclusion is not necessarily always given, particularly when the deployment of large-scale, seasonal energy storage is limited, and that there remains a valuable role for sources of firm power as far as electricity security is concerned.



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[46] https://www.world-nuclear-news.org/NP-Belgium-maintains-nuclear-phase-out-policy-0404184.html

[47] https://www.nucnet.org/news/new-government-stands-by-phaseout-plans-but-calls-for-report-on-security-of-supply-10-4-2020

[48] https://www.reuters.com/article/us-belgium-nuclearpower-idUSKCN1TT233

[49] https://www.brusselstimes.com/news/belgium-all-news/167347/belgium-council-of-ministers-approves-auction-of-two-to-three-gas-fired-power-plants-tinne-van-der-straeten-crm-bill-nuclear-phaseout/

## C

## Geopolitical Tension(s) that Result in Unilateral Action Intended to Cause Interruptions to Cross-Border Flows of Electricity or Natural Gas or Both

**At the outset of this subsection, it should be made clear that geopolitical tension and subsequent unilateral action of the type concerned here is neither a trend nor a tendency in the same sense as the other potential threats to energy security included in this section. Instead, it ought to be understood as both idiosyncratic and binary, and so best analysed using a scenario framework rather than at an average value. It is also the phenomenon most directly linked to but one of the three perspectives on energy security discussed in the previous section, that of sovereignty, although a resilient system would be one with the capacity to return to normal function following a unilateral disruption of energy flows in a timely manner.**

This being the case, the techniques by which this risk can be managed are couched in the language of geopolitical and international strategy, namely, to diversify supply where possible, including of supplier as well as supply infrastructure, and to engage with multinational institutions and other similar organisations to establish an environment in which disagreements can be mediated in an structured manner and in which stockpiles of reserves can be coordinated, and in which disruptive unilateral actions can disincentivised.

Finally, a distinction should be drawn between the threat of unilateral disruption to the cross-border flow of natural gas and that of electricity. If it is to be assumed that the implementation – or even threat – of actions intended to disrupt cross-border energy flows is based on a judgement by the supplier of the energy flow that such a course of action can be used to exert leverage over or simply harm either a transit or delivery country, then it follows that the potential impact of disrupting natural gas supply is likely to be far greater than disrupting the international flow of electricity.

This is largely a feature of the infrastructure underlying the respective energy flows with the gas network exhibiting a much higher frequency of vulnerable choke points and bottlenecks and being relatively sparse, with less diverse connectivity and fewer alternative routes, compared to cross-border transmission lines. The development of a broad-based, liquid natural gas (LNG) market would serve to reduce this discrepancy between the vulnerability of electricity and natural gas flows[50].

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[50] https://hir.harvard.edu/evolving-markets-lng-and-energy-security-in-europe/

# D. Growing Demand for Electricity Brought About by the Electrification of New Sectors (Transport, Heating, etc.)

**The electrification of historically fossil fuel reliant sectors, including transportation and heating, is a required step towards in the transition towards the decarbonisation of energy systems as a whole and will necessitate a not insignificant increase in generation capacity, if system adequacy is to be preserved, efforts to improve the efficiency of energy use notwithstanding. This increase in generation capacity will also be required to align with broader commitments to reducing the carbon intensity of the electricity sector and so occur alongside the retirement or phasing out of fossil fuel-fired power plants. In addition, the use of power in previously unelectrified sectors may fundamentally alter the pattern of consumption, in terms of both timing and location, thus also requiring an increase in both system flexibility and balancing capacity[51].**

To illustrate the implications of the electrification of new components of the energy system, the output relating to electricity demand of the 'Future Energy Scenarios 2021' report published by National Grid ESO, the electricity system operator for Great Britain, is presented in the accompanying graph[52]. The scenarios model different transition pathways for the electricity sector of Great Britain on its path to net zero with 'Leading the Way' achieving net zero at the earliest date, in 2047, and, along with 'Consumer Transformation', also meeting the requirements of the Sixth Carbon Budget[53], released by the UK's Climate Change Committee (CCC).

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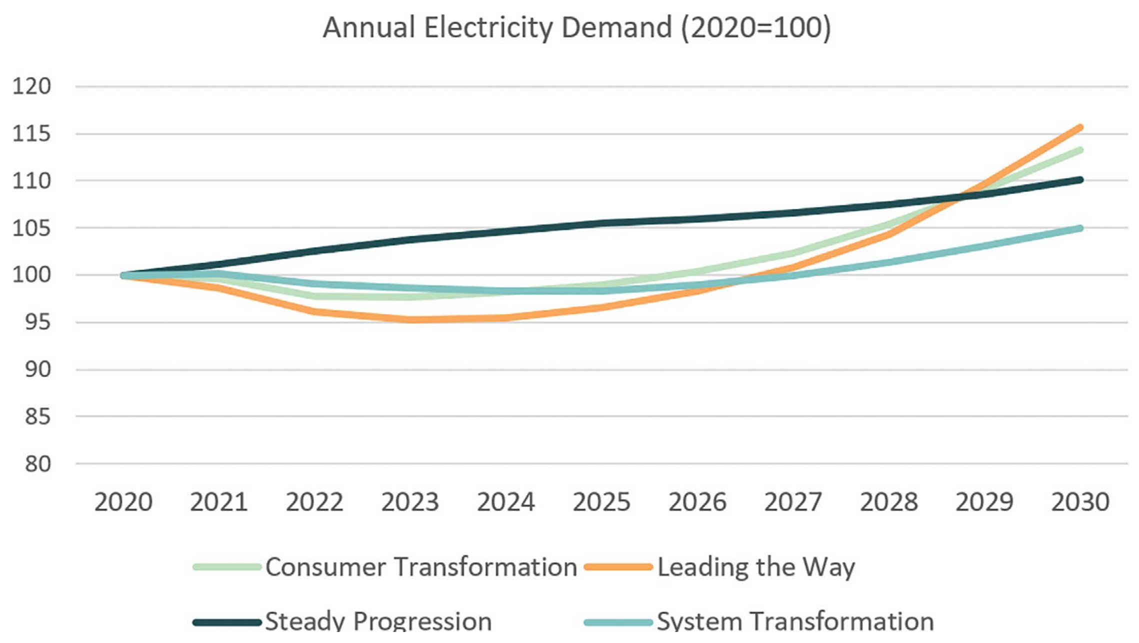
[51] https://iea.blob.core.windows.net/assets/ed98d01e-dbe7-47c6-897e- feb27877bd59/Secure_energy_transitions_in_the_power_sector.pdf

[52] https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021

[53] https://www.theccc.org.uk/publication/sixth-carbon-budget/



Beyond the increase in electricity demand up to 2030, and indeed continuing up to 2050, that is presented in all four scenarios, the evolution in the underlying composition of the electricity sector is also relevant. While electricity demand rises by between 5% and 16% over the period depending on the scenario assumptions, total installed capacity, measured in gigawatts (GWs), rises by significantly more, by between 52% to 92%. This is due to a large expansion in carbon-free wind and solar capacity, from 36 GW in 2020 to between 70 GW and 113 GW in 2030, which typically operates at a much lower capacity factor than baseload power plants. As a result, the share of total installed capacity that is accounted for by renewable technologies rises from 35% to an average of 52% across the four scenarios in 2030.

With regards to the security of energy supply, the electrification of new sectors, as illustrated using the example of the 'Future Energy Scenarios 2021', presents a clear challenge to the adequacy of energy systems and one that is further complicated by the necessity of increasing power generation while the phasing out of carbon-intensive generation, particularly coal-based but also in the lack of reinvestment in nuclear capacity described in the subsection above, takes place. Another significant development is that the electricity sector will become increasingly driven by supply as the share of weather-dependent capacity in the system increases. In turn, this will require a concurrent increase in the flexibility of the system if the grid is to be kept balanced, delivered by significant investment in flexible technologies, including interconnectors, demand-side management (DSM), and energy storage as well as electrolysers used to produce hydrogen. In the 'Leading the Way' scenario, for example, interconnector capacity rises from 4.75 GW in 2020 to 21.55 GW in 2030[54].

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[54] National Grid ESO, Future Energy Scenarios 2021, Data Workbook accessible here: https://www.nationalgrideso.com/future-energy/future-energy-scenarios/fes-2021/documents

# E. Heightened Stringency and Burden of Environmental and Climate Legislation, Implemented to Bring About Decarbonisation

**The 26th United Nations Climate Change Conference, also known as COP26 (Conference of the Parties), will take place in Glasgow in November 2021 and will aim to build upon the achievements and implementation of the Paris Agreement, signed at COP21 in 2015, the legally binding international treaty the signatories of which are committed to limiting global warming to well below 2 degrees Celsius with a target of 1.5 degrees[55]. At COP26, under the provisions of the Paris Agreement, countries will be required to present an updated version of its emission reduction plan, known as a Nationally Determined Contribution (NDC), to indicate the extent to which it is able to increase its level of emission reduction ambition.**

This process, know colloquially as the 'ratchet mechanism', exists to increase the effectiveness of climate change mitigation, which is required as the raft of national current pledges and targets made thus far submitted to the United Nations Framework Convention on Climate Change (UNFCCC), taken as a single package, imply an estimated 2.4 degrees Celsius rise in global average temperatures[56]. Moreover, the 2030 emissions gap, the amount by which predicted emissions in 2030 exceed the level compatible with a 1.5 degree temperature rise, ranges between 20 and 23 gigatonnes (Gt) of carbon dioxide equivalent.

The European Green Deal, a set of proposals first presented by the European Commission in December 2019 and followed up with a number of further policies such as sector-specific decarbonisation strategies, lies at the heart of the European Union's effort to limit global warming. Although not yet European law, the European Green Deal seeks to bring about a reduction in greenhouse gas emissions, compared to 1990 levels, of 55% by 2030, an increase to the previous target of 40%, and to position the European Union to achieve net zero, or climate neutrality, by 2050. In July 2021, the European Commission released a package of new proposals to this effect including: raising the target of renewable energy sources to 40% of the energy mix by 2030, implementing a 55% reduction in emissions from passenger vehicles by 2030 and a total elimination of emissions from new cars by 2035, the introduction of a carbon border tariff that will require importers to pay for the carbon emissions embodied in their products, reducing the number of permits issued under the European Emissions Trading System (ETS) and creating a second ETS to cover new sectors, and setting a goal of 49% renewable energy use in buildings by 2030[57].

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[55] https://ukcop26.org/uk-presidency/what-is-a-cop/

[56] https://climateactiontracker.org/publications/global-update-climate-summit-momentum/

[57] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

Taken as a whole, the European Green Deal proposals, along with similar policy initiatives across the world, represent a radical restructuring of modern energy systems with the electricity sector adopting an increasingly integral role in their proper functioning, as explored in part in the previous subsection. With regards to energy security, it should be noted that potential threats arise not just in the proposed reconfiguration of energy systems but also along the implied transition pathways. From the resilience perspective presented in the first section of this report, the extent of the changes proposed to the numerous subsectors of the energy system and the interrelated nature of those subsections, set to only increase as electrification accelerates, implies vulnerabilities in the system may arise in an unpredictable manner. As a result, diversity in the system, although constrained by climate targets, should be promoted to reduce exposure to individual shocks.

Another aspect of the European Green Deal that relates to electricity security is its aim of developing an interconnected internal energy market, "across multiple energy carriers, infrastructures, and consumption sectors[58]", which will require both the modernisation of existing subsystems as well as significant investment in new infrastructure capacities and energy technologies. The successful development of such a market will require both planning and implementation of a highly integrated nature to ensure that the transition does not become disjointed, which could expose individual subsystems or the system at large to disruption. For example, the proposed increase in renewable capacity, which is discussed in greater detail in the following subsection, must be coincident with a coordinated development and expansion of the associated transmission infrastructure, including the regulations required for managing issues such as the compensation for loop flows[59], if intermittency is to be managed securely.

Furthermore, the proposed development of a hydrogen ecosystem in Europe, as a means to decarbonise certain subsectors of the heating sector and to provide a storage option for excess renewable electricity produced at times of high generation[60], will require that the infrastructure development of the electricity sector be closely linked to the development of the required hydrogen generation, storage, and transmission infrastructure. The pace of the development of one of these will act to some extent as a limiting factor on the development of the other and a disconnection between the two would stand as a vulnerability to the proper function of the system as a whole.

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[58] European Commission, Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration, p.1, (2020)

[59] https://fsr.eui.eu/paradigm-shift-in-energy-security-agenda/

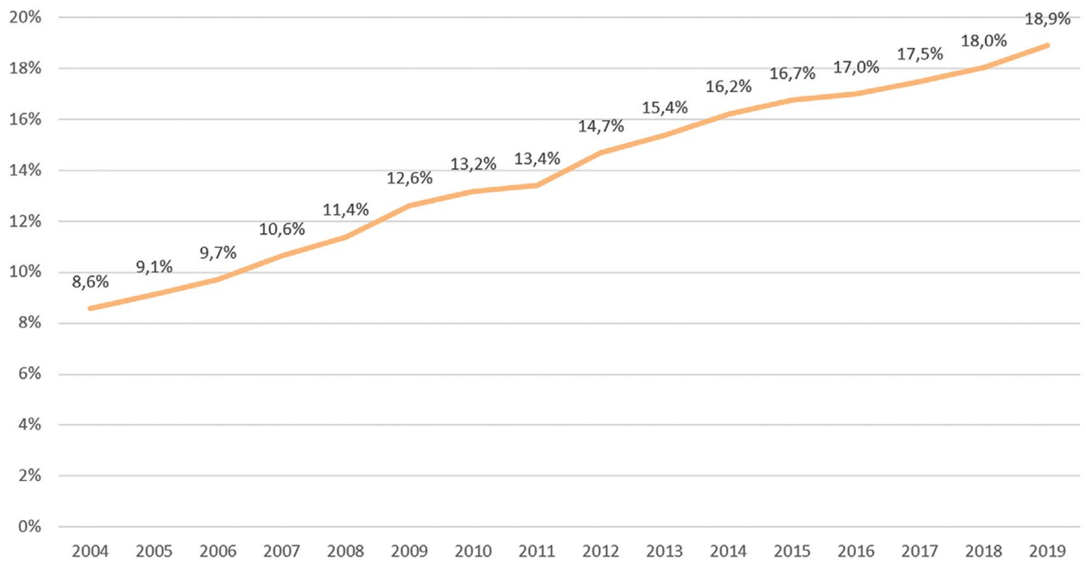
[60] European Commission, A Hydrogen Strategy for a Climate-Neutral Europe, (2020)

# F. Increasing Share of Intermittent, Weather-Dependent Renewables in Total Electricity Generation, mainly Generated using Wind and Solar Power

**As the example of Europe in the previous subsection illustrates, the implementation of a target share for renewable energy has become a regular centrepiece in climate and environmental legislation. As a result, the installed capacity of both wind and solar generation technologies has rapidly increased. In the European Union, according to Eurostat[61], wind capacity grew from 84 GW in 2010 to 191 GW in 2019 and solar capacity increased from 31 GW to 134 GW over the same period, at an annual average rate of 9.5% for the former and 17.8% for the latter.**

In addition to the policy support given to renewable energy deployment, the expansion in capacity was also driven by a notable decrease in the cost of renewable energy, driven by higher levels of installation as well as technological advances in both production and operation.

EU-28 Renewable Share in Gross Final Energy Consumption[59]



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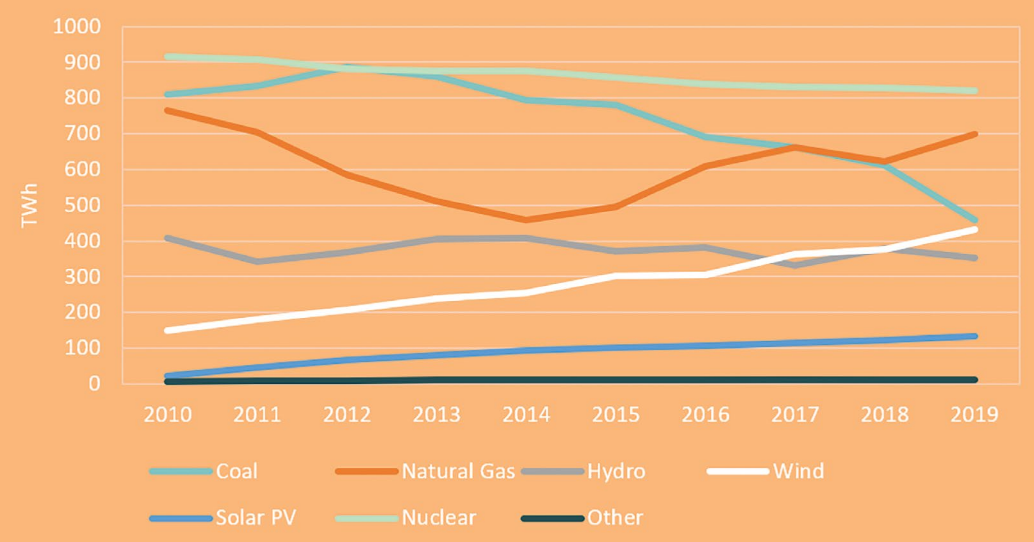
[61] https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epcrw/default/table?lang=en

Alongside this expansion of wind and solar installed capacity, the share of electricity generation accounted for by conventional baseload power plants has fallen, from 69% in 2010 to 56% in 2019, according to Eurostat data[62], while the share accounted for by natural gas has been rising since 2014, from 16% to 24% in 2019. These trends are set to continue as the phase-out of coal-fired generation and the stagnation of nuclear capacity, discussed in detail in a previous subsection, continue and natural gas is increasingly relied upon as a dispatchable form of power production at times of low renewable generation. As a result, the electricity sector in Europe is becoming increasingly weather-dependent, notwithstanding the greater deployment of energy storage technologies at commercial scale that is also targeted.

EU-28 Electricity Generation by Source[60]



With regards to energy security, wind and solar power have contributed in a positive way to the diversity of electricity generation and are indigenous resources meaning that fuel importing countries can deploy renewable technologies as a means to increase their self-sufficiency and to reduce their vulnerability to fuel price volatility and fuel supply disruption. Moreover, renewable technologies are able to contribute to a faster post-blackout recovery then larger thermal power plants, which require larger sections of the system to be restored before being able to operate, and so bolster the resilience of the electricity system[63].

However, as renewable generation continues to increase and conventional power plants are phased out, whether actively or passively, it appears probable that diversity in electricity generation will decrease, requiring measures to ensure that security is not compromised. The growing capacity of renewables may also pose a threat to renewable operators too as the correlation in time of weather-dependent generation reduces the value of renewable electricity in the absence of large-scale energy storage. Moreover, this correlation may also imply increased volatility in the price of electricity as market supply is increasingly driven by the prevailing weather conditions. The variability and uncertainty of renewable generation necessitates greater flexibility, whether provided by gas-fired generation or an expansion in the interconnector network or energy storage technologies, or a combination of all three, if the reliability of the electricity sector is to be preserved. Indeed, a reliance on gas-fired capacity as a source of flexibility and a means to guarantee system adequacy could have the effect of increasing the vulnerability of an importing region, such as Europe, to supply disruptions even as total generation from the fuel decreases.

It should be noted that the challenges posed by the increasing share of intermittent, weather-dependent renewable generation technologies will depend on the absolute value of the share itself. At low levels of generation, the impact of renewable technologies will likely be unnoticed but as the share grows the issues relating to correlation, volatility, and flexibility discussed above will grow in stature and begin to challenge security. A renewable integration phase categorisation, presented in the IEA's Status of Power System Transformation 2018 report, is summarised below in order to demonstrate how the potential threats to electricity security may evolve; Europe, where the combined generation of wind and solar power is approaching 20% of electricity generation, can be thought of as in phase three.

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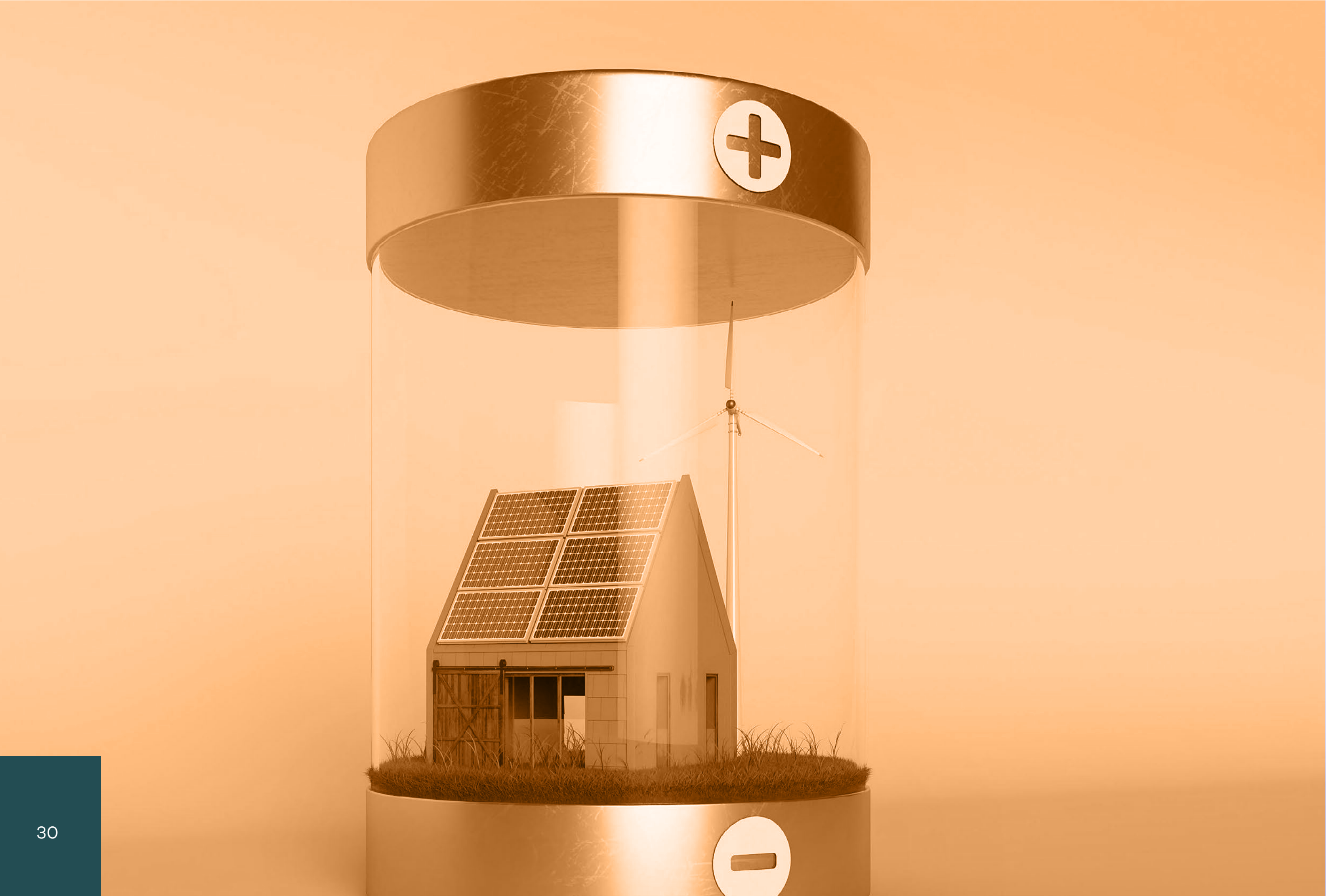
[62] https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_PEH__custom_1152087/default/table?lang=en
[63] IEA, Power Systems in Transition: Challenges and Opportunities Ahead for Electricity Security, (2020), p.23

| | Impact of Renewable Share | Challenges and Threats |
|---|---|---|
| **Phase One** | no noticeable impact | |
| **Phase Two** | minor to moderate impact on system operation | changes to typical patterns of operation, changes in load and net load become noticeable |
| **Phase Three** | determines the operation pattern of the system | larger swings in the balance of supply and demand require structural increase in power system flexibility beyond that supplied by existing assets |
| **Phase Four** | constitutes almost the entirety of total generation at times | unexpected disruptions in either supply or demand may threaten system stability, renewable technologies may be required to provide frequency response services |
| **Phase Five** | increasing amounts of surplus renewable generation | curtailment of renewable generation will occur with growing frequency unless demand can be time-shifted, interconnector capacity exploited, or energy stored |
| **Phase Six** | seasonal surpluses and deficits of renewable generation | seasonal storage will be required to balance the electricity market across the year |



# G

# Climate Trends and More Frequent Extreme Weather Events Caused by Climate Change (e.g. Flooding, Heatwaves and Droughts, Thunderstorms, Blizzards)

**The impact of climate change on the energy system is already being felt, whether in terms of the changing patterns of rainfall, increasing demand for colling in the face of rising temperatures, or the growing frequency of extreme weather events. In February 2021, repeated severe winter storms and low temperatures caused the electricity system in Texas to fail as a large proportion of its generation technologies and gas transmission infrastructure was not winterised[64].**

Both conventional thermal and renewable generation technologies are affected by climate change, with the operational efficiency and required maintenance of the former negatively impacted by rising temperatures and the production potential and pattern of the latter affected by the changes to ambient conditions and weather systems. Extreme weather events pose a threat not to generation technologies alone but also the transmission and distributions systems, the efficiency of which also falls as ambient temperatures rise and the electrical current that flows through them has to be reduced to prevent overheating[65]. The operation of nuclear power plants is also complicated by climate change as water shortages may prevent freshwater facilities from operating at full capacity[66], also a potential threat for hydropower facilities, and those sited in coastal regions could be vulnerable to flooding and rising sea levels[67].

Ensuring the security of electricity supply in the face of climate change requires a resilient power system, one that is able to endure fluctuating weather and ambient conditions, to maintain function during extreme weather events, and to restore full operation following a climate-related disruption in a timely manner.

The first can be achieved by pre-empting and proactively defending against the consequences of climate trends by, for example, winterising equipment and installing all or critical parts of the transmission and distribution network underground. Protecting the function of the electricity system during an extreme weather event can be made easier by diversity in the generation mix as different generation technologies will be affected to varying degrees of severity by different weather events. The presence of spare or excess capacity in the system will also reduce its vulnerability to the failure of other generation units. Finally, the recovery of the system will prove to be easier if system planning has been conducted in an integrated manner, as discussed in a previous section, so as to ensure any response is coordinated.

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[64] https://www.theguardian.com/us-news/2021/feb/20/texas-power-grid-explainer-winter-weather

[65] https://climate-adapt.eea.europa.eu/metadata/adaptation-options/adaptation-options-for-electricity-transmission-and-distribution-networks-and-infrastructure

[66] https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/climate-change-poses-big-water-risks-for-nuclear-fossil-fueled-plants-60669992

[67] https://www.scientificamerican.com/article/mounting-climate-impacts-threaten-u-s-nuclear-reactors/

# H.

# Targeted and Ever More Sophisticated Cyberattacks in Conjunction with the Growing Digitalisation of the Energy Sector

**In May 2021, the Colonial Pipeline, the largest pipeline for refined oil production in the United States of America and responsible for transporting almost half of the fuel supplies used along the east coast, halted operations in order to contain a cyberattack on its systems, which involved ransomware, and remained shut down for almost one week, causing a fuel shortage[68]. The incident highlighted both the risk inherent to energy systems that depend on unique critical components to function and the difficulty of protecting legacy systems, to which a digital function or digital components have been added after their construction, from cyberattacks. It also drew attention to the limited extent to which cybersecurity has been considered in relation to energy security to date.**

The cyberattack surface of the electricity system, the sum of the different points at which an unauthorised agent can enter, operate, and extract data from the system, is expanding as the system becomes more and more digitalised. It is not just the generation, transmission, and distribution infrastructure that are vulnerable in this regard but increasingly end-users are exposed to malicious cyber activity due to the proliferation of networked digital devices such as smart thermostats, residential demand management systems, and electric vehicles. The interdependency and connectedness of modern electricity systems also means that cyberattacks can spread throughout the system once entry has been gained at an individual point.

In terms of security, managing the threat of cyberattacks on the electricity system resembles the techniques outlined in the previous subsection. Regardless of whether or could be made impregnable the cost of doing so would likely be prohibitive and so electricity systems ought to be equipped with a high degree of cybersecurity as well as the ability to function to an acceptable level during a cyberattack and to return to full function following one in as short a time as possible. The example of the Colonial Pipeline hack illustrates that cybersecurity efforts need to take into account the criticality of individual energy system components and to adjust relative levels of security accordingly as well as installing back-up systems in order to limit the disruption to proper function of the system should a critical infrastructure be brought down.

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[68] https://www.spglobal.com/platts/en/market-insights/latest-news/oil/050821-colonial-pipeline-confirms-cybersecurity-attack-temporarily-halts-operations

# Section 3

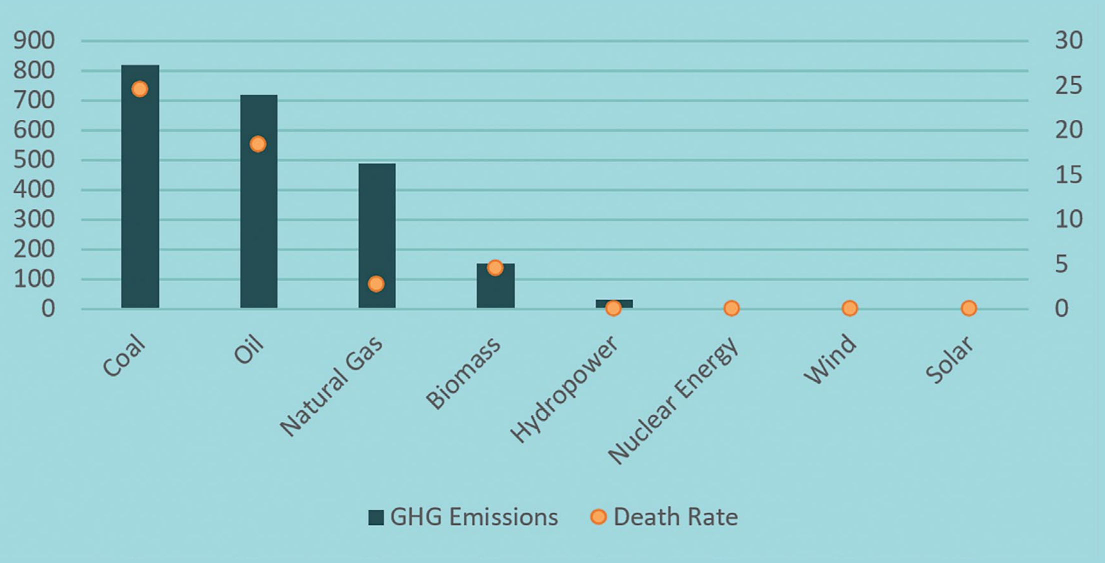
# Focus on Nuclear Power and Nuclear Supply Chain Risks

## Nuclear Power and Energy Security

### The Valuable Role of Nuclear Power in Meeting Climate Targets

If a successful transition to a decarbonised energy system is to be achieved without compromising energy security, it is clear that there are many strong arguments to support the inclusion and further deployment of nuclear power in the generation mix. In this regard, it is important to note that the exclusion of nuclear power is most commonly a political decision, rather than one supported by either energy system studies or the historical safety record of nuclear power relative to other sources of electricity.

As the accompanying graph, based on data taken from Our World in Data[69], illustrates, nuclear power represents a low-carbon, measured in carbon dioxide equivalent per gigawatt-hour of power generated over the lifecycle of the plant, highly safe, measured in terms of deaths from accidents and air pollution per terawatt-hour of generation, source of electricity.



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[69] https://ourworldindata.org/safest-sources-of-energy

There is no single technology that will deliver decarbonisation while maintaining energy security and the systems best-placed to achieve an efficient and successful transition will be those that contain a diverse array of low-carbon generation options. However, the particular benefits of nuclear power in the context of transition are of notable value. The low system costs associated with nuclear energy, in contrast to renewable technologies, implies that the most cost-effective option to achieve strict grid carbon intensity targets relies primarily on nuclear power[70]. Similarly, the firm nature of nuclear power supply, the ability of nuclear power plants to meet demand when needed across a given year and over sustained periods of time, has also been shown to lower the cost of decarbonised electricity generation[71].

## Energy Security Concerns

In this section of the report, a detailed assessment of nuclear power in terms of its contributions towards and potential weaknesses with regards to energy security will be presented, with analysis at each stage of the nuclear supply chain. If the valuable contribution to decarbonisation that nuclear power has the potential to deliver is to be realised, the installed capacity of nuclear power will necessarily have to rise. In the 'Sustainable Development Scenario' (SDS) presented by the International Energy Agency in the World Energy Outlook 2020 report, for instance, 140 GW of new nuclear capacity is built by 2030, rising to 180 GW in the 'Net Zero Emissions by 2050' (NZE2050), while total global capacity rises by roughly 50% to 600 GW[72].

This expansion in installed capacity, encompassing existing nuclear nations as well as nuclear newcomers, can only be achieved via a significant level of export in the nuclear industry due to the relatively limited number of practicable suppliers. Of late, the leading exporter of nuclear technologies has been Russia, following a decline in the export activity of American, European, and Japanese nuclear vendors, while China is making concerted efforts to take on a larger role in the market[73].

This implies that any sizeable increase in nuclear power up to 2030 and beyond, notwithstanding the possibility of a revival in the export activity of the traditional technology providers, is likely to be met in no small part by the exports of state-supported vendors, whether Rosatom, or the China National Nuclear Corporation, or the China General Nuclear Power Group, or a combination thereof. Indeed, the period up to 2030, as opposed to the period afterwards, may see a relatively higher level of activity from such state-supported vendors, due to the significant time required by other suppliers to build up their production capacity.

To some, such a scenario represents a direct threat to energy security due to their view of the extent to which the export of nuclear technologies and related services could be used by state-adjacent actors to establish a unidirectional dependency between vendor and host that could in turn be used to manipulate, control, or exert leverage over the latter. This dependency is understood varying as being strictly commercial and anti-competitive in nature or more broadly in geopolitical terms or as lying somewhere between the two. Therefore, this section of the report will seek to analyse the dependency hypothesis, identify stages of the nuclear supply chain at which vulnerabilities to energy security may arise from dependency, and to suggest means by which such risks can be managed and mitigated.

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[70] OECD-NEA, The cost of Decarbonisation: System Costs with High Shares of Nuclear and Renewables, (2019), p.25
[71] N. Sepulveda et al., The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonisation of Power Generation, Joule, (November 2018)
[72] https://www.iea.org/reports/world-energy-outlook-2020
[73] J. Nakano, The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China, CSIS, (2020)

# A Commercial Dependency

**The breadth of nuclear technologies and services offered by state-supported vendors, coupled with the relative concentration of the new nuclear build export market, although less apparent in downstream market subsectors, ought to be understood in both the context of the historical development of the international civic nuclear industry as well as the particular economic factors that drive its competitive environment and growth.**

The size of the average nuclear project, in terms of installed capacity but of financial investment in particular, combined with the potential cost cutting effect of repeat or fleet construction, the result of realising economies of scale in production as the first-of-a-kind to nth-of -a-kind transition is made, implies that the competitive position of a given national nuclear industry will depend to a large extent on the reliability and consistency at which it delivers new build orders. In the absence of such a level of activity, economies of scale cannot be realised, production capacity will decline, and inefficiencies will enter the supply chain as technical skills and experience of production atrophy.

It is precisely this scenario which has led to the decline in the nuclear industries of the traditional nuclear nations as, following the Chernobyl disaster in 1986, nuclear new build in those nations was considerably slowed. In France, for example, the operable capacity of nuclear power increased by 15 GW in the decade following 1986 having risen by 42 GW in the preceding ten-year period[74]. A similar slowdown was evident in the United States of America, with operable capacity increasing by 17 GW in the post-Chernobyl decade after growing by 40 GW in the preceding one[75]. As a result, the competitiveness of the nuclear industries in the aforementioned countries began to decline.

In contrast, the Russian and Chinese nuclear industries are today both characterised by a high level of activity and continued innovation. Since the post-Chernobyl nuclear slowdown, Russia has made a conscious pivot towards an export orientated strategy, based upon flexible business models, capacity building of host nations, and the extension of financing schemes[76]. In fact, Russia has installed a larger number of nuclear power plants abroad than it has on a domestic basis during this period. Meanwhile, the Chinese nuclear industry, a relative newcomer compared to its Russian counterpart, has focused its activities at home in the face of rapidly increasing electricity demand caused by economic and demographic growth. Installed operable capacity in the country rose from 12 GW in 2011 to 50 GW in 2021[77]. The focus of the Chinese nuclear industry on its home market as a means by which to gain experience in the construction and operation of its specific technologies has not led to the development of the export-orientated capabilities of the Russian industry and so it stands today as an emerging force in the export market. Overall, then, the relative concentration of nuclear export activity ought not to be viewed as the result of deliberately anti-competitive action but the predictable evolution of a high-entry, high-fixed cost industry in which repeat, reliable sales are a core driver of industrial competitiveness.

Whilst new nuclear build has and continues to be perceived by some as a tool by which geopolitical and other malicious influences can be levied, there is little evidence to suggest that either nuclear energy projects or the supply of nuclear-related supplies have ever been used in this manner. On the contrary, the operation of new nuclear build in a host country, regardless of the identity of the vendor, represents a clear means by which it can reduce its external energy dependency by lowering the reliance of its generation mix on imported fossil fuel. The historical and present support for export activity by vendor countries is more plausibly explained by considerations of industrial strategy than geopolitical considerations – the depth and breadth of the nuclear supply chains stands as a means by which vendor countries can create demand for high value-added and R&D intensive sectors as well as large numbers of high-skilled, well-remunerated jobs.

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[74] https://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx
[75] https://world-nuclear.org/information-library/country-profiles/countries-t-z/usa-nuclear-power.aspx
[76] hN. Schepers, Russia's Nuclear Energy Exports: Status, Prospects and Implications, Non-Proliferation and Disarmament Papers, No. 61, (February 2019
[77] https://world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx

The case of Russia also illustrates the ways in which domestic social policy considerations can encourage the promotion of nuclear technology and related exports. As a legacy of the Cold War, nuclear supply chain facilities in Russia are concentrated in areas previously characterised by heavy travel restrictions and company towns – known as ‘monotowns’. As a result, these regions are almost entirely dependent on a single industry and so a decline in activity would result in highly detrimental social outcomes. Therefore, while the ability to wield geopolitical influence is difficult to prove theoretically or in practice, there is a clear benefit to Russia in terms of social stability and livelihoods in fostering sustained nuclear export activity.

If the structure of the nuclear market itself is not indicative of a potential commercial dependency, but instead the result of economic forces, it has been argued that its concentration could be leveraged by suppliers to develop such a dependency as in a market of few vendors, a nuclear newcomer faces a limited choice of supplier. Indeed, wider geopolitical or strategic issues of a non-nuclear nature could further restrict the list of plausible suppliers to an even narrower pool. It is suggested that, as a result, host nations could theoretically be vulnerable to the use of nuclear projects as a means of geopolitical leverage by the vendor, such as the threat of the latter reneging on a commercial contract to influence or apply pressure to the behaviour of the former, in the context of a seller’s market.

To assess this risk, the potential vulnerability of the energy security of the host nation at each point along the nuclear supply chain is presented in the table below along with explanations of the vulnerability and, where available, details of relevant historical case studies. It should be noted that the degree of vulnerability at each stage is in part a function of the cost faced by the host nation when switching to a new vendor as a high switching cost may prove to be prohibitive for the host nation, thus tying it closer to the initial vendor and reducing its bargaining power in ongoing or future negotiations.

| Stage | Level of Risk | Detail/Case Study |
|---|---|---|
| Before Construction | Medium | at this stage, prior to the commencement of any construction activities but following the negotiation and signing of the licensing and other project contracts, the host is vulnerable to the extent that the commitment of the vendor remains limited, perhaps to the adapting of its production capacities to the specificities of the specific location and project size, and so facing few sunk or unrecoverable costs should it follow through on a threat to walk away from the deal<br>the commitment of a nuclear newcomer host to the vendor may exceed the cost of negotiating and signing the project contract if the vendor nation has been involved in the broader development of its nuclear industry, such as providing training to local technicians or contributing to the implementation of nuclear industry regulations.<br>equally, the availability of non-nuclear low-carbon energy sources with shorter lead times in terms of deployment would bolster the bargaining power of the host insofar as delaying or cancelling a new build project of the abuse of market power by the vendor is suspected. |
| During Construction | Low/Medium | after construction has started it is preferable for the host nation that the vendor completes the contracted nuclear power plant due to the cost of reworking the particular plant design should a different vendor be required to complete the project<br>precedent of the reworking of a part-constructed nuclear plant can be found in Temelín Nuclear Power Station, in the Czech Republic, the construction of which was halted by the Czech government following the Velvet Revolution in 1990 to be restarted later in the decade following safety and other design upgrades carried out by Westinghouse[78]<br>the vendor itself is exposed to project risk during this phase of the nuclear project lifecycle that varies with the contractual model agreed upon, at the high vendor risk end of the spectrum the Build-Own-Operate (BOO) model transfers the project risk to the vendor in its entirety, with the Engineering, Procurement, and Construction (EPC) and Nuclear Steam Supply System (NSSS) representing less risky models for the vendor – under the structure of the latter two models, the host is contracted to purchase under a ‘pay-as-you-go’ model and so the total vendor risk is limited to the risk at each individual stage of supply during construction |
| Operational Phase | Low | at this stage in the nuclear project lifecycle, the impact of vendor action and so the vulnerability of the host nation is low, although it would increase relative to the nuclear experience of the host nation and the extent to which the operation of the nuclear plant remains reliant on the expertise of vendor staff<br>a notable example of the host-vendor relationship terminating during the operational phase of the project concerns India, where the first pressurised heavy water reactors (PHWRs) and boiling water reactors (BWRs) were built in the 1960s with Canadian and American assistance respectively – the provision of assistance by the vendors was terminated in the light of the refusal of India to sign the Non-Proliferation Treaty and subsequent weapons test, from which time the Indian nuclear industry developed on indigenous, isolated terms[79] |
| Uranium Supply | Low | uranium reserves are well distributed at the global level as week as the commercial level and do not exhibit the spatial concentrations of fossil fuel resources<br>the structure of the market is international in nature and the combined use of long-term supply contracts and periodic entries into the often-oversupplied spot market serves to reduce the exposure of the host nation to disruptions in supply and vulnerability to threats of non-supply by individual actors |
| Uranium Conversion /Enrichment | Low | as for the market for uranium, the market for conversion and enrichment services is diversified and broad-based and so any one actor has minimal leverage over another<br>both the supply of uranium (one row above) and its subsequent conversion and enrichment account for a relatively minor amount of the final output cost and so should a disruption arise a shift to a higher cost provider would have a limited impact on the affordability of the generated power |
| Fuel Fabrication | Low/High | the intricacies of the design of a nuclear power plant are reflected in the design of its fuel assemblies, which differ between vendors and are neither technically straightforward nor inexpensive to replicate via backward engineering or other methods and so the host nation is potentially highly vulnerable to a supply refusal or disruption on the part of the vendor |

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[78] https://www.cez.cz/en/energy-generation/nuclear-power-plants/temelin

[79] https://world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx

| Stage | Level of Risk | Detail/Case Study |
|---|---|---|
| Fuel Fabrication | Low/High | the key factor that determines the vulnerability of the host to a disruption in fuel assembly supply is the length of the lead-time as the risk of disruption can be managed if reserve assembly stock has been accrued and so existing inventory can be used while the idiosyncrasies of the particular fuel assembly are reworked – the European Supply of Safe Nuclear Fuel (ESSANUF), for example, was a European Commission project tasked with increasing the security of supply of European reactors to the supply of Russian fuel assemblies, allowing for alternative stockpiles to be built up[80]<br>Ukraine provides a recent example of a host nation switching fuel assembly supply, with Westinghouse contracted to supply assemblies for Russian-designed VVER-1000 and VVER-440 reactors[81] |
| Services /Maintenance /Decommission | Low | the market for ancillary services is liquid and flexible, including not only established nuclear vendors but also the subsidiaries of international engineering companies as well as numerous specialised engineering firms based in both nuclear and non-nuclear countries<br>decommissioning is an innovative and international market that receives funding from experienced decommissioning authorities |

Furthermore, the use of a nuclear project for leverage by a vendor would likely have a deleterious impact on its commercial reputation and so the short-term gain delivered by such a unilateral action would have to be compared to a sustained, long-term threat to its ability to raise export business. The nuclear export market is relatively small in terms of the number of signed or completed projects per year and so the value in contracting new customers as well as securing repeat sales is high, thus elevating corporate reputation and trust to the levels of a commercial advantage.

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[80] https://cordis.europa.eu/project/id/671546
[81] https://www.reuters.com/article/us-ukraine-energy-westinghouse-idUSKBN26L25B

# B. Geopolitical Dependency

**The construction of a nuclear power plant, especially for a host state new to the use of nuclear power, represents a significant commitment not only in terms of financial investment but also of time. Before the construction of a new build project starts, the host state will have undergone a lengthy preparatory phase, according to the IAEA the time from initial consideration of a first nuclear power plant to its eventual operation takes 10-15 years[82]. If this preparatory phase is added to the typical operational life of a nuclear power plant and the option of granting the facility a Long-Term Operation (LTO) license, a nuclear project may run for a century.**

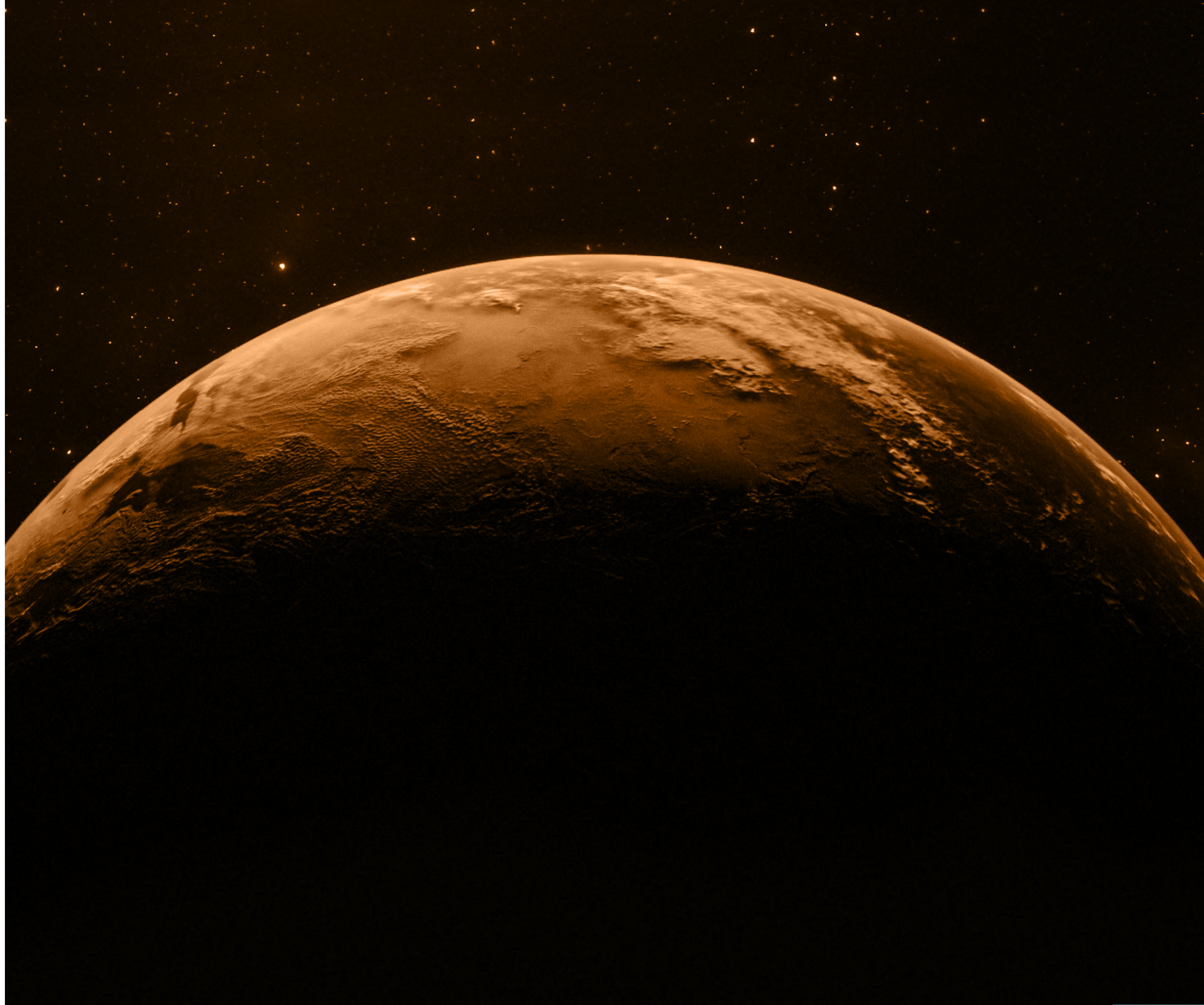
As a result, the relationship between the vendor and host is often understandably close before construction starts, indeed a close relationship may even be considered a prerequisite to a successful one. While the previous section viewed vulnerabilities from the perspective of the host nation, the vendor nation may also be seen to be vulnerable in some regards and so incentivised to work towards a close relationship. For example, the vendor nation is vulnerable to a unilateral decision by the host country to cancel a project on the grounds that the introduction of nuclear power is no longer acceptable, as has occurred in the Philippines[83]. Equally, the strategy of a vendor when contracting a first project with a country may rely on repeat custom if decreasing series production costs allow for the earning of a higher return on subsequent units.

The choice of a particular nuclear vendor could well be related to broader geopolitical signalling or the completion of a broader economic package, although as suggested in the previous paragraph both factors are indicative of a pre-existing closeness between two countries, but it should be noted that nuclear new build projects, in addition to fuel supply agreements, have a low degree of correlation with geopolitical tightening on a historical basis. The initial deployment of the French nuclear industry on Westinghouse-supplied pressurised water reactors (PWRs) did not lead to either technological dependency on the United States of America nor a lockstep agreement between the two nations as to foreign policy during the Cold War or in later periods.

Similarly, despite the presence of Russian nuclear reactors in the former Eastern Bloc has not prevented those nations, albeit to contrasting grades, pivoting towards the West or the European Union or both. Moreover, despite heightened tensions between the two nations, Russia is yet to disrupt or cancel supplies or uranium or fuel assemblies to Ukraine, in contrast to natural gas flows which the former has used to exert leverage on the latter. Not only does this illustrate the limited geopolitical capital that can be extracted using the nuclear supply chain but also a commercial realism that acknowledges that rival firms have the capacity to reproduce the fuel assembly design of other vendors but also that the fluctuations in the price of nuclear fuel, perhaps caused by having to find an alternative supplier, have a minimal impact of the final output price of nuclear-produced energy, thus limiting the potential energy security risk.

Finally, it has been argued that vendor-arranged project finance leading to the growth of the debt of the host country could be exploited by the country of the vendor – usually the lender in these scenarios – as a long-term tool of geopolitical leverage. Such concerns have been voiced in relation to a broad range of vendor-constructed infrastructure projects, particularly in Africa[84]. The risk of a geopolitical 'debt trap' arising if the foreign debt of the host country in question is excessively exposed a single lender notwithstanding, the risk of financially driven dependency resulting from new nuclear build projects is relatively low.

Firstly, the finance related to a new nuclear build project is unlikely to represent a significant proportion of the foreign debt of the host country and is therefore unlikely to cause the overall position of its foreign debt to shift from sustainable to unsustainable or an overexposure to a single lender. Secondly, the prevailing form of financing extended in such scenarios is a direct credit line, which typically offers an interest rate favourable to the market cost of debt. Thirdly, both macroeconomic and microeconomic perspectives on new build nuclear projects suggest that they can be a source of sustained value creation for the host country, thus providing a means to reduce indebtedness in the long-term. After the initial payback period for the upfront capital is completed, a nuclear plant tends to operate at high margins that can be used to stimulate economic activity and create value as the host sees fit and proper. In particular the multiplier effects from both the job creation and stimulus to downstream industries, such as construction, required to construct and then operate a plant over its extended lifetime should allow for the reduction of the debt-to-GDP of the host over time.



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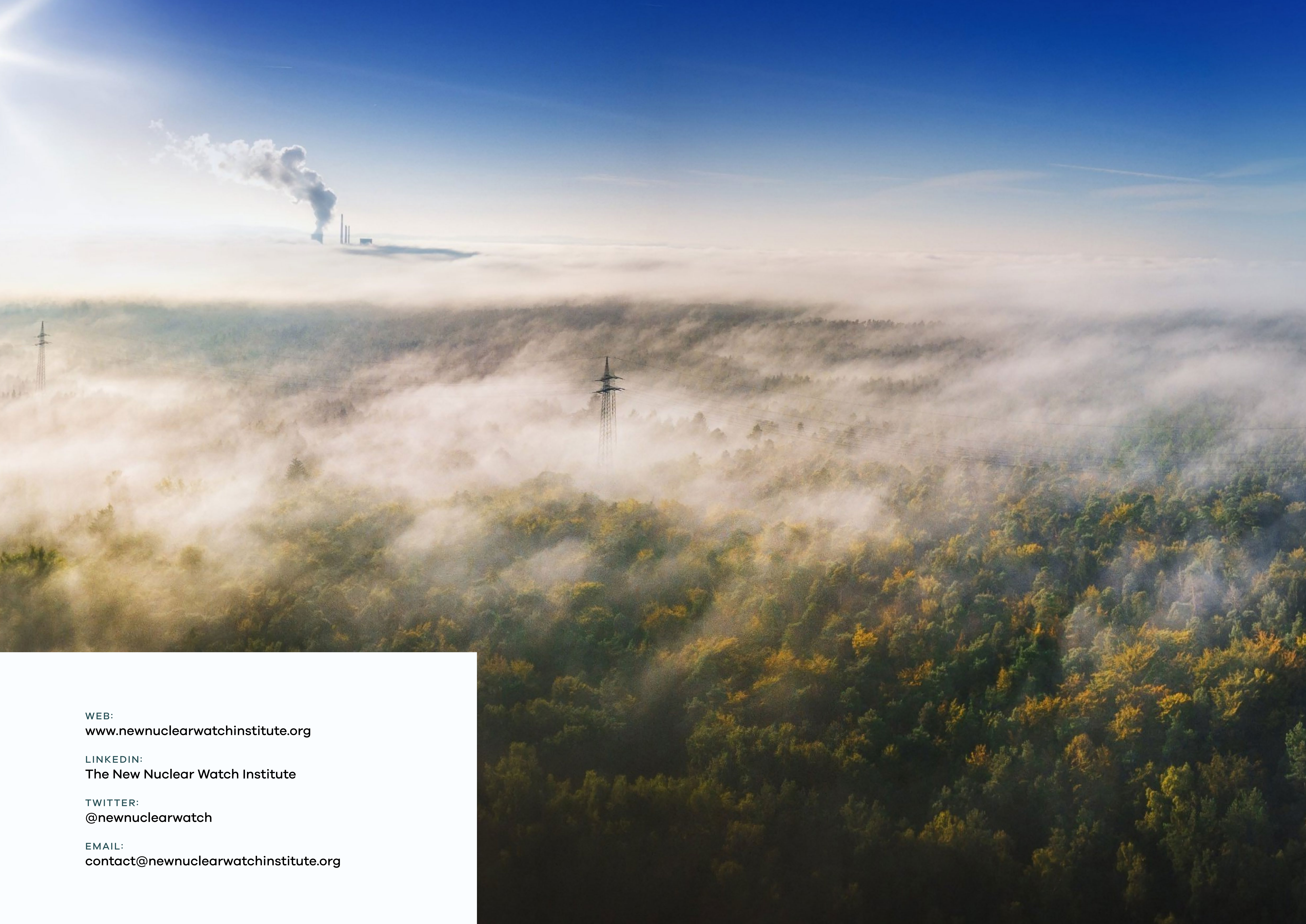
[82] IAEA, IAEA Milestones Approach: Developing the National Infrastructure for Nuclear Power
[83] https://www.neimagazine.com/news/newsphilippines-considers-reviving-bataan-nuclear-power-project-8164700
[84] https://www.ispionline.it/en/pubblicazione/africas-debt-whats-debate-27061



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