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COAL-TO-NUCLEAR FOR POLAND
SUPPORT MECHANISMS

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Sobieski Institute
ul. Lipowa 1a lok. 20
00-316 Warsaw
sobieski@sobieski.org.pl www.sobieski.org.pl

sobieski@sobieski.org.pl
www.sobieski.org.pl

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REPORT

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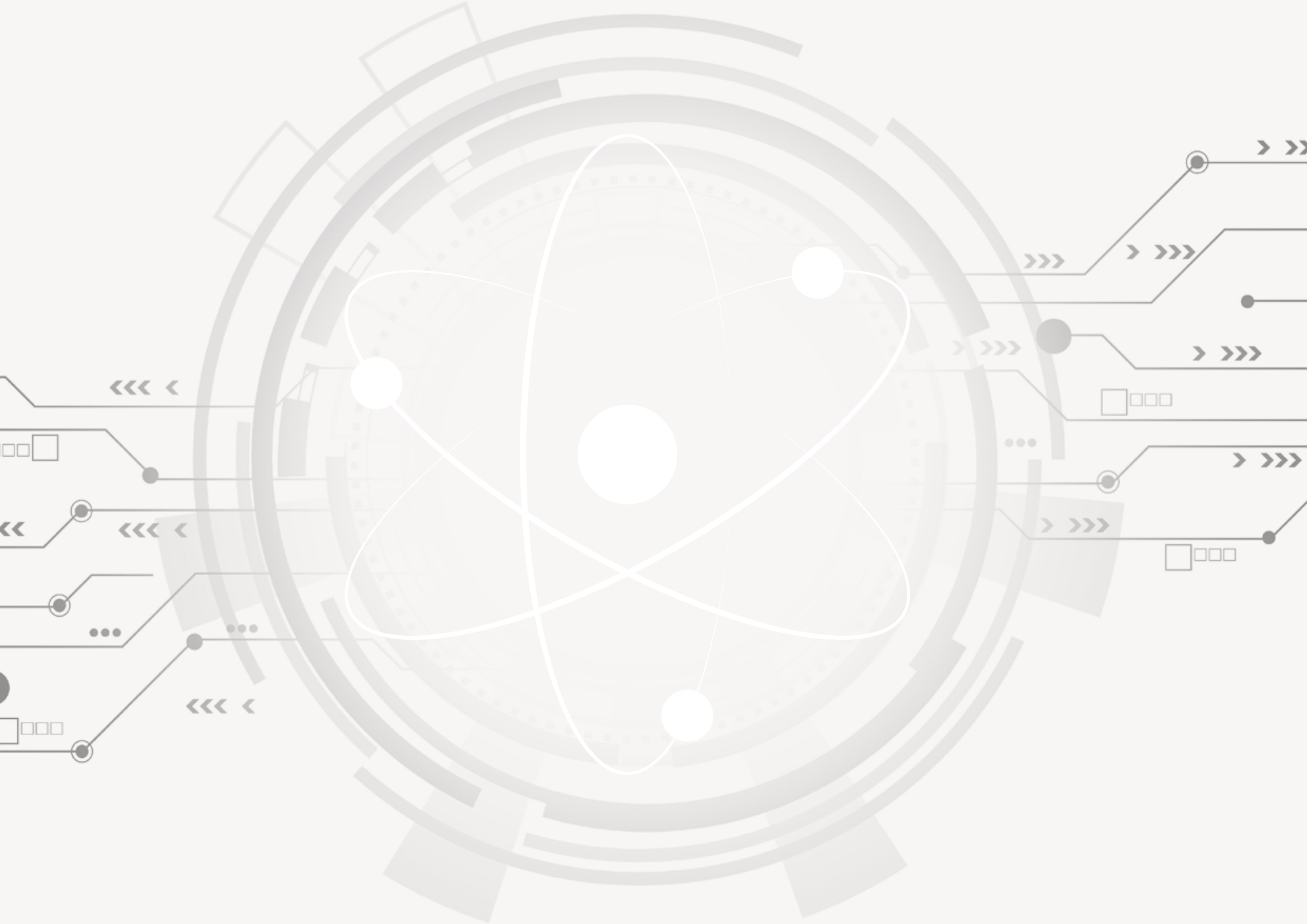
EXECUTIVE SUMMARY



COHERENT POLICY

- The success of nuclear projects depends on stable political support and clear regulatory frameworks. Given the multi-year timeline for constructing and operating nuclear power plants, establishing a long-term strategy and a consistent narrative, independent of electoral cycles, is crucial. Regulatory instability increases investment risk, hindering capital acquisition for nuclear energy development.

- Poland must accelerate its energy transition. Without nuclear power, the country faces risks of rising energy prices, supply shortages, and even blackouts. Leveraging existing conventional power infrastructure for nuclear development via the Coal-to-Nuclear pathway could significantly expedite the transition and lower its costs. Poland's 21st-century energy landscape requires not only nuclear reactors but also smart grids, energy storage, and the development of a hydrogen economy to meet growing energy demand and address climate change challenges.

THEORETICAL FRAMEWORK FOR INNOVATION IMPLEMENTATION

- Implementing technological innovations addresses societal needs but also encounters barriers arising from public concerns and misinformation. Theoretical models, such as the Technology-Organisation-Environment (TOE) framework or Everett Rogers' Diffusion of Innovations theory, help understand the technological and social challenges in the adoption process. A successful energy transition via the Coal-to-Nuclear pathway necessitates a combination of technology, education, and effective public policy to enhance innovation acceptance.

LEGAL AND REGULATORY ASPECTS

- Siting a nuclear power plant is a complex process requiring detailed environmental, geological, and demographic analyses. Polish regulations, rooted in the Atomic Law Act, impose stringent requirements designed to minimize risks to the public and the environment, adhering to the ALARA (As Low As Reasonably Achievable) principle. Current regulations do not fully address the specific characteristics of modern technologies like Small Modular Reactors (SMRs), often applying the same standards as for large-scale nuclear power plants.

- Significant siting exclusion factors include the presence of active tectonic faults and mining activities conducted within a 30 km radius during the past 60 years. In practice, this disqualifies large areas of Poland, including regions like Silesia, Małopolska, and Łódzkie, under current requirements. Meanwhile, countries such as Japan, the USA, and Turkey construct power plants in seismic zones using modern engineering solutions and safety measures. Therefore, revising the regulations is under consideration, potentially reducing the mining activity exclusion period from 60 to 20 years or introducing site-specific ground stability assessments instead of automatically excluding post-mining areas. Such amendments could enhance the feasibility of Coal-to-Nuclear projects in coal-dependent regions.

- Densely populated areas are also evaluated regarding safety and evacuation capabilities. Modern Generation III+ and Generation IV reactors, including SMRs with their advanced safety systems, can potentially be sited closer to urban centers. This approach could support local energy transitions and industrial decarbonization within the Coal-to-Nuclear framework.

- Aligning Polish regulations with international standards will be crucial. This would enable more flexible siting and construction of nuclear power plants while ensuring the highest safety levels and incorporating advancements in technology and international experience.

FINANCIAL ASPECTS

- Nuclear power, particularly in its conventional form (reactors around 1 GW capacity), is a capital-intensive, long-term undertaking demanding substantial financial investment and stable regulatory and political backing. Financing typically relies heavily on debt, with banks, financial institutions, and export credit agencies usually covering 60% to 75% of construction costs. High capital expenditure makes the Levelized Cost of Energy (LCOE) highly sensitive to interest rate fluctuations and supply chain price dynamics.

- Although renewable energy sources (RES) often appear cheaper based on LCOE compared to nuclear power, this metric overlooks full system costs, such as grid stabilization needs and transmission infrastructure expansion. Consequently, the actual cost differences between RES and nuclear power may be smaller than LCOE suggests. To better capture the true costs and value of different technologies, the International Energy Agency (IEA) introduced the Value-Adjusted LCOE (VALCOE) index, which considers factors like dispatchability and energy supply stability.

- A key challenge in financing nuclear power is the relatively long investment payback period, potentially extending 20–30 years. This underscores the necessity of government commitment, potentially through financial guarantees or energy price stabilization mechanisms. Smaller reactors, like SMRs or Generation IV designs, present an alternative. Although not yet widely deployed, they offer potential benefits such as shorter construction times, lower upfront capital costs, and suitability for more flexible financing models.

- Several proven support mechanisms exist for nuclear projects, including Contracts for Difference (CfD), Build-Operate-Transfer (BOT), Regulated Asset Base (RAB), the cooperative energy model (e.g., Mankala in Finland), and the Polish SaHo model (based on the cooperative concept). For Poland's first planned large nuclear power plant at the Lubiatowo-Kopalino site, the government selected the widely recognized CfD system, expecting this will expedite European Commission approval for state aid.

- The selection of support mechanisms for subsequent power plants, including those developed under the Coal-to-Nuclear pathway, should follow a thorough analysis. The government, in collaboration with experts, must develop an optimal support model for Polish nuclear energy, considering long-term strategic objectives. There is a recognized need to explore alternative support models beyond traditional CfD-style price regulation.

LESSONS FOR THE COAL-TO-NUCLEAR PATHWAY FROM THE RES EXPERIENCE

- Poland should advocate for a change in European Commission policy to ensure nuclear power is treated on par with renewable energy sources regarding European Union (EU) support funds, and that energy transition targets encompass all zero-emission sources.

- Challenges on the Coal-to-Nuclear pathway can be addressed by drawing lessons from the deployment of RES technologies, such as offshore wind farms. These large-scale projects, with significant costs and long lead times, highlight the critical role of regulatory support and incentive programs (e.g., subsidies, tax credits). The successes and setbacks of these investments offer valuable insights for developing nuclear reactors, particularly for first-of-a-kind technologies like Generation IV reactors.

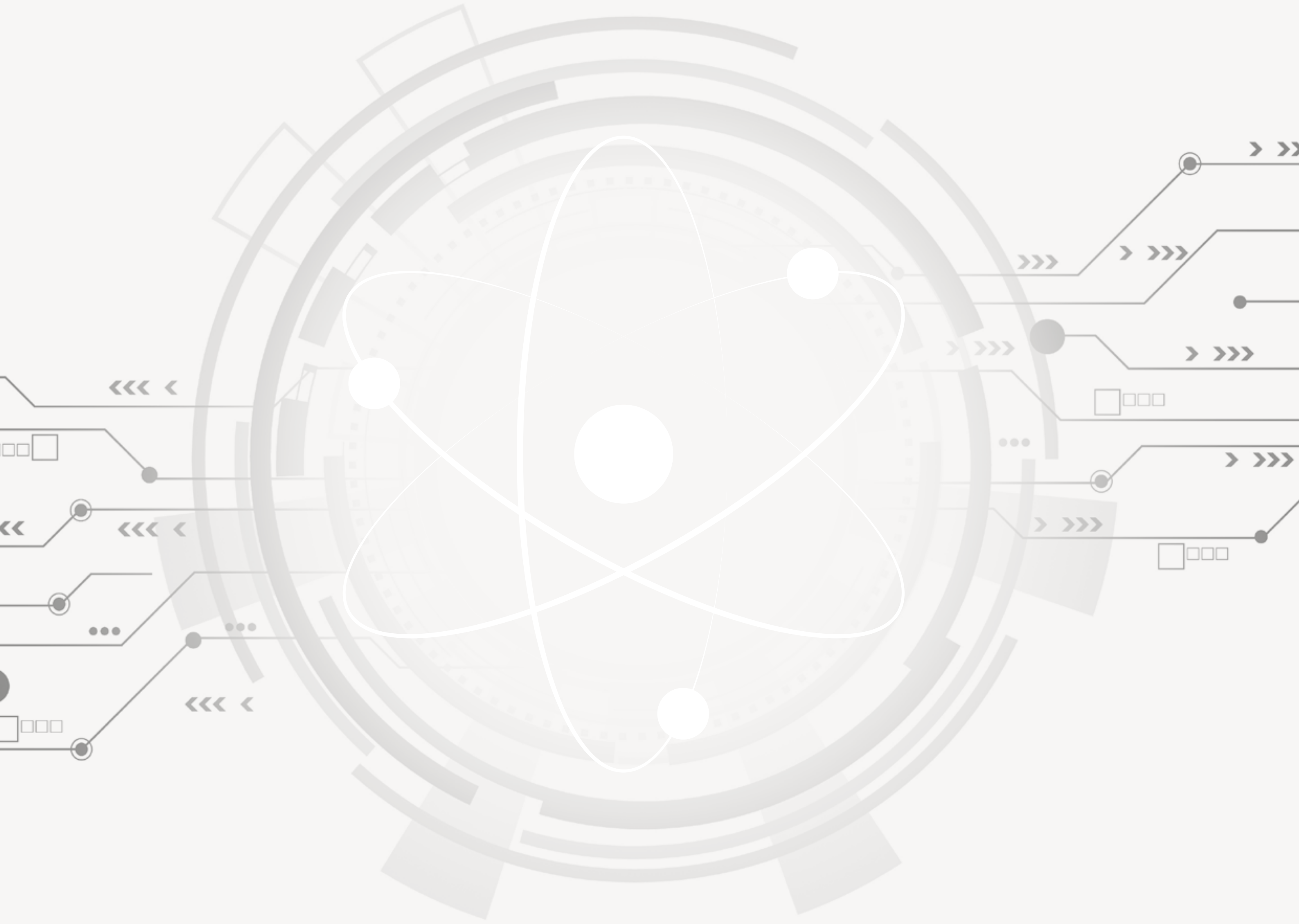
1. PURPOSE OF THE REPORT

The decarbonisation of Poland's utility-scale power sector represents one of the key challenges of the country's current energy policy. This issue was previously identified in the 2019 and 2020 reports ***SMR for Poland*** and ***Nuclear Power for Poland***, published by the Sobieski Institute (available in Polish on Sobieski Insitute's website). These reports concluded that Poland's decarbonisation and energy transition present a challenge for the coming decades, requiring a revised approach in numerous aspects: planning, corporate structures, securing funding for investments, and above all, a coherent and sustainable strategy aimed at building a modern, competitive, and climate-neutral economy. The Sobieski Institute's participation in the DEsire project and the preparation of thematic reports in the **'Coal-to-Nuclear for Poland'** series represent a continuation of this work.

The aim of this report is to present potential support mechanisms that can help accelerate the deployment of nuclear technologies within the Polish utility-scale power sector. Particular emphasis is placed on aspects related to the implementation of new technologies, alongside financial, regulatory, and organisational issues. The report discusses the main challenges and benefits associated with the Coal-to-Nuclear concept.

This document provides a comprehensive analysis intended to serve as a foundation for further legislative, investment, and organisational actions supporting Poland's energy transition towards a low-carbon, stable, and sustainable energy future.

2. A COHERENT STATE POLICY



A crucial element for any large-scale nuclear power plant project is support from the authorities of the country where it is planned. This stems from the high regulatory and political risks associated with such investments. The energy market, as well as the transport, handling, and storage of spent nuclear fuel, are subject to stringent regulations. Given the enormous costs borne by investors during both the multi-year construction phase and the subsequent operational phase, the clarity and predictability of regulations are paramount.

Nuclear projects often require a dedicated legal framework that accounts for their distinct scale and high level of risk – significantly greater than for projects like photovoltaic farms. This also applies to potential delays and cost overruns occurring even before the first fission reaction is initiated.

In the Polish context, where nuclear power could play a pivotal role in the energy transition, an active state policy is essential. Such policy should encourage the utilisation of existing infrastructure for new investments, potentially accelerating the implementation of nuclear projects significantly.

Poland's energy transition lags behind many other European countries. For decades, Poland relied almost exclusively on a single energy source: coal. Consequently, efforts to modernise transmission networks, increase energy storage capacity, and enhance power system flexibility were neglected for years. This resulted from the absence of a long-term strategy, leading to a situation where the transition must now proceed hastily and under considerable financial pressure.

Without a comprehensive energy transition, including the integration of nuclear power into the Polish energy mix as its foundation, the country will face serious consequences. The best-case scenario involves further energy price increases, burdening households and industry. **The worst-case scenario includes the risk of energy access restrictions**, the implementation of electricity rationing, **and even the threat of blackouts during peak demand periods**.

The energy transition demands modern and flexible solutions that address current challenges, such as energy supply instability, growing electricity demand, and the pursuit of environmental neutrality. While learning from past experience is valuable, relying solely on half-century-old technologies is insufficient, as these do not account for the depletion of domestic resources, dynamic climate change, the rise of renewable energy sources, or new geopolitical threats. Poland's 21st-century energy sector requires innovative solutions – including modern nuclear reactors, smart grids, energy storage technologies, and the development of a hydrogen economy – to meet growing energy demand reliably and securely.

Without investment in nuclear power, Poland risks not only stagnation and maintaining the status quo but also technological regression and a loss of competitiveness. Failure to adapt to the changing environment and delays in implementing modern energy solutions can weaken the economy and limit opportunities for further industrial development. Nuclear energy offers not only supply stability but also serves as a catalyst for developing modern technologies and building an innovation-based future.

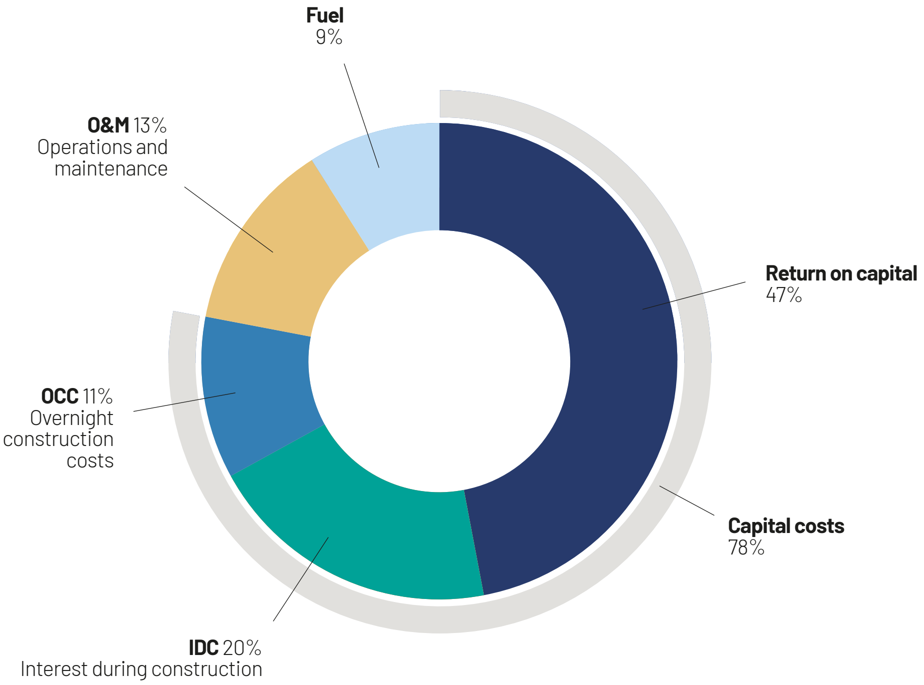
Effective implementation of long-term energy policies will not be possible unless decision-makers understand that the energy transition must leverage modern solutions, such as the Coal-to-Nuclear pathway. Relying solely on outdated energy models will lead to supply instability, rising costs, and dependence on external suppliers. **Only a deliberate and consistent modernisation of the energy sector can build a secure, sustainable, and competitive economy adapted to 21st-century challenges.**

Inappropriate decisions driven by short-term political gains rather than the country's long-term interests can exacerbate the effects of the energy crisis. Ignoring future challenges leads to an incoherent energy transition strategy, investment delays, and continued dependence on volatile energy sources. Persistent implementation of long-term policies can mitigate the crisis effects and ensure future energy security. Poland's future hinges on this consistency of action. **Projects based on nuclear technologies should be pursued across political divides and independently of election cycles.**

It must be recognized that **without investment in nuclear power, other large-scale projects**, such as the Central Communication Port (Centralny Port Komunikacyjny, CPK) or the development of high-speed rail, **will face significant implementation challenges**. All these undertakings require stable and predictable electricity supplies, which variable renewable sources alone cannot guarantee. **Without nuclear power as a baseload component and without pursuing the Coal-to-Nuclear pathway, Poland risks not only unreliable energy supplies for key economic sectors but also a slowdown in infrastructure modernisation, potentially weakening the country's international competitiveness**.

A coherent and consistent narrative regarding the energy transition, maintained irrespective of changing political parties, would send a strong, positive signal to investors. Political stability and regulatory predictability are crucial support mechanisms that reduce investment risk and encourage long-term capital commitment. Without stable and positive incentives to counteract the high investment risk, securing financing for nuclear power projects is extremely difficult. Banks and the broader capital market are hesitant to engage in projects with such high capital expenditure (CAPEX), which can constitute up to 78% of the total project lifecycle cost (covering planning, construction, and operation).

FIG. 1 **BREAKDOWN OF THE LEVELISED COST OF NUCLEAR POWER**[1]



SOURCE: World Nuclear Association

A lack of regulatory predictability and a long-term state strategy not only deters investors but also increases financial risk, potentially leading to delays or limiting the scale of implemented projects. From a financing perspective, this translates into reduced availability or higher costs of financial instruments, as lending institutions and investors demand a larger risk premium amidst an uncertain legislative and economic environment. Consequently, implementing strategic infrastructure projects like nuclear power becomes more difficult and costly, negatively impacting the pace of the energy transition[2].

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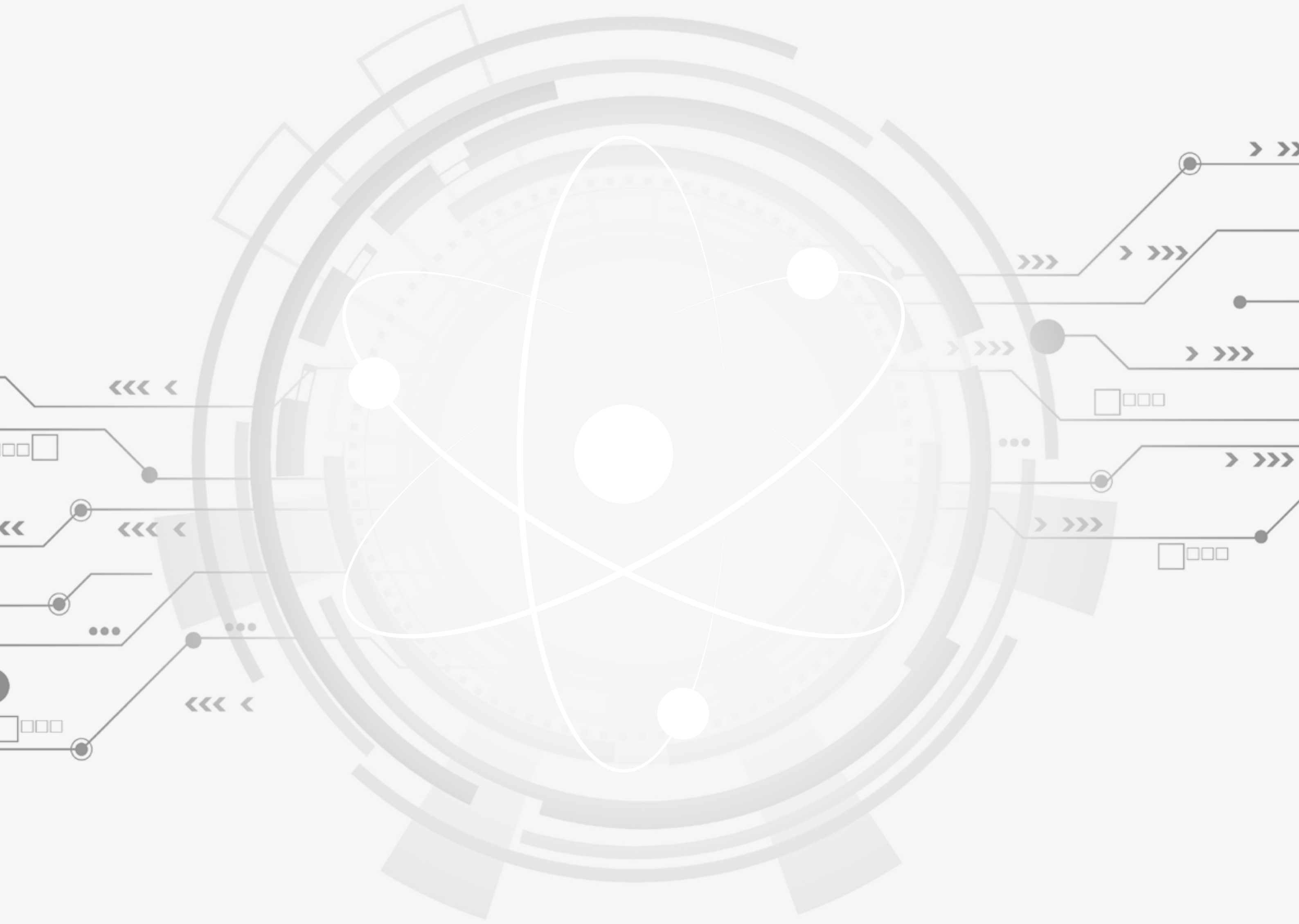
[1] S. Bilbao y Leon, *Financing nuclear power projects in the UNECE region*, World Nuclear Association, 2021, s. 4, https://unece.org/sites/default/files/2021-10/Sama-Bilbao-y-Leon-Financing_Oct_21.pdf.

[2] Economics of nuclear power, World Nuclear Association, 29.09.2023, https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.

3. THEORETICAL FRAMEWORKS FOR INNOVATION IMPLEMENTATION



3.1 INTRODUCING NEW SOLUTIONS TO THE MARKET - MOTIVATIONS FOR TECHNOLOGY DIFFUSION

Humans have always strived for innovation, seeking technologies to improve quality of life, enhance efficiency, and ensure safety. Each generation attempts to better living conditions, increase comfort, and improve efficiency in work and everyday tasks. While new technologies enable faster, easier, and more productive actions, they often evoke fear of the unknown. Incomplete knowledge about the long-term consequences of new inventions breeds anxiety and a perceived loss of control, exemplified by protests against the introduction of electricity in the 19th century. Evolutionarily, humans developed cautionary mechanisms towards the unknown, as novelty could once pose existential threats. Consequently, innovations requiring shifts in mindset and behaviour are challenging to introduce.

Over the past few decades, the world transitioned from analog communication to the Internet era, granting billions instant access to knowledge and real-time information exchange. This has dramatically accelerated innovation and the adoption of new solutions. Nevertheless, certain technological domains remain perceived as complex, shrouded in myth, and frequently misunderstood. Examples include genetic engineering, neuroscience, chaos theory, non-Euclidean geometry, the Internet of Things (IoT), blockchain, artificial intelligence (AI), and nuclear power. Fear of nuclear power often stems less from actual risks than from a lack of reliable information and negative historical associations. The pervasive issue of disinformation further complicates this. Public perception of inventions and new solutions is shaped by media, public opinion, and pop culture narratives, where sensationalized scenarios that fuel fear (driving engagement) often overshadow educational content. More on the public perception of energy can be found in Kevin Kelly's book, *The Inevitable: Understanding the 12 Technological Forces That Will Shape Our Future*[3].

Today's world, facing challenges like climate change, growing energy demand, and geopolitical instability, requires modern solutions. Technological progress is driven not only by curiosity and exploration but also by the need for greater independence, sustainability, and environmental protection. Energy generated by nuclear power has a low carbon footprint and represents a significant alternative to fossil fuels, while enhancing energy independence from external suppliers. This is particularly crucial for building energy security and economic resilience in Europe. However, nuclear technology continues to grapple with persistent myths.

Nuclear power is currently undergoing a significant phase of development. Next-generation reactors, including small modular reactors, are attracting increasing attention. Generation III+ and IV reactor designs offer higher efficiency and safety, and some can utilize portions of spent fuel, aligning with fuel recycling concepts. Nuclear technologies can be viewed as part of a larger, evolving system responding to societal needs.

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[3] K. Kelly, Nieuniknione. *Jak inteligentne technologie zmienią naszą przyszłość*, tłum. P. Cypryański, Poltext, Warszawa 2018.

Kevin Kelly, an American writer and futurist, analyzes technology's impact on society, the economy, and our future. His insights often focus on how technologies progressively expand access to resources and opportunities, transforming how we live and work. He is recognized for his deep, thoughtful perspectives on technological development. As co-chair of The Long Now Foundation, Kelly champions initiatives promoting long-term thinking and responsibility towards future generations. According to Kelly, technologies are tools that augment human capabilities, and technological progress inherently increases access to resources in previously impossible ways. Kelly posits that technological development trends towards greater accessibility. **Therefore, technological progress involves increasing access to more sophisticated forms of energy**[4].

From this perspective, nuclear power can be seen as part of technology's trajectory towards providing more complex yet efficient energy forms capable of meeting global needs. Nuclear power, particularly newer developments like SMRs and Generation IV reactors, fits within the concept of 'widening access' to advanced resources and technologies.

Kevin Kelly advocates the idea that technologies can evolve synergistically, complementing and propelling one another forward. This synergistic coupling of technology and digitalization is clearly evident in the renewable energy sources sector. The use of tools like the Internet of Things (IoT), Artificial Intelligence (AI), and advanced energy management systems enables efficient monitoring, control, and optimization of energy production and distribution. Smart grids, supported by demand response models, allow for real-time adaptation of supply to demand, which is critical given the variability of renewable sources.

In the nuclear power sector, digitalization progresses more slowly, primarily due to stringent safety requirements. Any new technology must undergo rigorous testing and meet strict regulatory standards, delaying its implementation compared to less demanding energy sectors. However, in the long term, integrating technologies like AI, IoT, and advanced energy management systems within the nuclear power industry promises significant benefits. It is important to note that in the nuclear sector, when procedures, technologies, or practices are proven effective in ensuring safety, they are frequently adopted as global standards. The nuclear industry's commitment to continuous improvement and global harmonization is relatively unique, paralleled by few industries, notably civil aviation.

Utilizing IoT for data collection across infrastructure elements and AI for predicting potential incidents and failures can enhance the safety and operational efficiency of nuclear reactors. While the nuclear industry already relies on probabilistic safety analysis, AI can be applied not only to analyze even more complex, multi-variant failure scenarios but also to optimize maintenance schedules, reducing downtime and operational costs. Digitalization facilitates real-time simulation and process modelling[5]. Although digitalization in nuclear power lags behind the RES sector, it will likely enable integrated control of grids relying predominantly on these two sources within the next decade.

During the energy transition and the search for low-carbon solutions, various theories and models emerge to help understand how new technologies are adopted by society and implemented on a large scale. Technological adoption models are theoretical analytical frameworks used in research on innovation implementation and diffusion. They are employed during the analysis and planning phases of innovation deployment, in designing public policies to promote new technologies, and by companies evaluating the applicability and implementation of innovations within their organizations. Prominent among these are

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[4] K. Kelly, Nieuniknione. *Jak inteligentne technologie zmienią naszą przyszłość,* tłum. P. Cypryański, Poltext, Warszawa 2018.

[5] N. Askwith, A. Saxena, GEH digital solutions for nuclear power plants, Hitachi, 2021, https://energiforsk.se/media/30579/6_geh_digital_solutions_for_nuclear_plants_final.pdf.

the Technology-Organisation-Environment (TOE) framework[6] and Everett Rogers' Diffusion of Innovations theory[7]. These provide tools to analyze key factors influencing technology adoption, such as compatibility with existing structures, perceived benefits (including environmental ones), and social acceptance.

Through these theories, we can better understand the transition to new technologies, such as nuclear power within a Coal-to-Nuclear strategy, and more effectively support their implementation. These models aim to identify and structure activities needed to create a supportive ecosystem for nuclear projects. They can serve as tools for governments, regulators, and standardization bodies to identify gaps and address them by developing appropriate policies and legal frameworks, including designing investment and operational support, strengthening the supply chain, and establishing a knowledge base for this new industry. For investors, these models help identify investment barriers, gauge potential user/customer acceptance of new strategies, and consequently, enable more effective planning of marketing and communication strategies.

The Technology-Organisation-Environment (TOE) framework is particularly relevant for identifying decarbonization challenges, as it addresses three key dimensions critical for technology implementation and supporting the energy transition: technological, organizational, and environmental context. In the Coal-to--Nuclear context, the TOE framework can help pinpoint the technological advantages of new reactors (e.g., energy stability, low emissions) and the organizational and environmental challenges of transitioning from coal to nuclear (e.g., the need for workforce adaptation and regulatory adjustments). Rogers' Diffusion of Innovations theory, conversely, focuses on the societal adoption process – relevant for both public policy and business strategies – by addressing the specific needs and concerns of different societal groups.

3.1.1 THE TECHNOLOGY-ORGANISATION-ENVIRONMENT (TOE) FRAMEWORK

The pillars of the TOE framework effectively capture the main aspects influencing the implementation of nuclear technologies and the Coal-to-Nuclear concept. This model identifies key factors that enable the adoption of a specific solution within companies, organizations, and the broader business environment. Technological factors relate to the characteristics of new solutions and technologies — such as compatibility, complexity, or competitive advantage — and how they influence adoption decisions. Organizational factors, like human resources, determine the capacity to accept and effectively implement new technologies. Finally, environmental factors pertain to the external context, including regulations, market competition, and trends of both local and global significance.

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[6] Technology-Organization-Environment Framework, 2024, https://open.ncl.ac.uk/academic-theories/23/technology-organization-environment-framework/.

[7] Diffusion of Innovations (DOI), 2024, https://open.ncl.ac.uk/theories/8/diffusion-of-innovations/.

PILLAR I: Technological factors[8]

Technological factors play a crucial role in deploying new, not-yet-commercially available nuclear technologies like small modular reactors and Generation IV reactors, especially within the context of energy transition and decarbonization. These modern solutions offer several unique advantages that make them potentially more attractive than traditional designs found in large-scale nuclear power plants.

One of the fundamental principles guiding the design of SMRs and Gen IV reactors is improved energy efficiency compared to established solutions. Using coolants such as gas, liquid metals, or molten salts allows for higher operating temperatures or reduced primary circuit pressure, leading to more efficient energy utilization. Modern nuclear reactor technologies are also being adapted for diverse industrial needs, making them versatile tools for the energy transition. Water-cooled SMRs can be suitable for applications like district heating, water desalination, or hydrogen production. In contrast, reactors cooled by gas, liquid metal, or molten salts, owing to their capacity to generate high-temperature process heat, are ideally suited for energy-intensive industrial processes like steel manufacturing, synthetic fuel production, and thermochemical hydrogen production. **This flexibility enables adaptation to varied industrial energy demands, particularly where both heat and electricity from nuclear plants can be utilized simultaneously through cogeneration. This approach can increase the overall plant energy efficiency to over 80%, compared to traditional nuclear power plants achieving around 33% efficiency when producing only electricity.** Cogeneration can also reduce capital investment by avoiding unnecessary energy conversion steps, enhance plant flexibility by allowing switching between heat and electricity production, and reduce heat losses and water consumption, thereby lowering the environmental footprint.

Modern reactor technologies enable more efficient utilization (higher burn-up) of nuclear fuel. For Gen IV reactors and advanced SMRs, using fuels like MOX (Mixed Oxide Fuel) is possible. This approach not only reduces the volume of high-level radioactive waste (HLW) but also decreases the demand for new uranium resources. **The fuel cycle strategies envisioned for these reactors often involve closing the fuel cycle, aligning with circular economy principles and contributing to global Sustainable Development Goals (SDGs).** Small SMRs (primarily Generation III+) draw upon operational experience from existing research reactors and nuclear power plants regarding fuel management, waste handling, and decommissioning procedures. However, **the choice of fuel cycle for nuclear reactors is often influenced by government policies, potentially limiting technological options**. Many SMR designs anticipate longer operating cycles between refuelling, which introduces challenges related to fuel performance, structural material integrity, and spent fuel management. **Early and comprehensive planning for the fuel cycle of SMRs and Gen IV reactors — including infrastructure and waste management strategies — is crucial for building stakeholder confidence. It also helps minimize potential technological, environmental, and financial issues**, which is fundamental to the success of modern nuclear reactors and the broader adoption of the Coal-to-Nuclear concept. This is particularly important for designs introducing innovative fuels like metallic, carbide, or nitride fuels, as their use necessitates establishing new industrial facilities for fuel fabrication, processing, and management.

In this context, developing new technologies for waste processing, transportation, etc., is essential. This requires intensive research, development, and demonstration (RD&D) efforts to support these industrial-scale solutions in the coming decades. Therefore, selecting a technology based on 'non-traditional' nuclear fuel necessitates concurrent planning for the associated spent fuel management infrastructure. Although

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[8] Small modular reactors. Advances in SMR Developments, IAEA, 2024, https://www-pub.iaea.org/MTCD/publications/PDF/p15790-PUB9062_web.pdf.

the concept of 'nuclear fuel leasing'[9] has been discussed for over 20 years, it remains largely conceptual and has not been implemented anywhere. Its potential advantages include reducing upfront investment costs and providing access to advanced technology for countries lacking developed nuclear fuel management infrastructure. However, this model raises significant questions regarding regulatory frameworks, long-term liability, and non-proliferation safeguards[10].

Both SMRs and Gen IV reactors are characterized by high levels of safety. These advanced reactors are designed with inherent safety features[11], meaning their physical properties and design intrinsically prevent or mitigate accidents without requiring active systems or human intervention. SMRs are generally designed not to need external power sources to maintain safety in accident scenarios. Nonetheless, power is typically still required for monitoring plant status during emergencies, such as a loss of offsite power, even for units employing advanced passive safety systems[12]. Examples of passive safety include using natural circulation for primary coolant flow, effectively removing decay heat without mechanical pumps. Gen IV reactors also incorporate advanced safety systems based on technological innovations. For instance, reactors might automatically reduce power or shut down in response to excessive temperature increases. Many Gen IV designs utilize innovative coolants like liquid metals (e.g., sodium, lead) or molten salts, which possess superior thermodynamic properties compared to traditional water coolants. This allows for more efficient heat removal from the reactor core, reducing the risk of overheating and fuel damage. Furthermore, the use of advanced structural materials enhances the reactor's resistance to corrosion, high temperatures, and radiation, potentially extending its operational lifetime and improving safety. **All these design philosophies aim not only to prevent accidents but also to minimize potential consequences for people and the environment if an event occurs. Their reliance on passive mechanisms tends to build greater public confidence by demonstrating the reactors' capability to respond automatically to potential hazards without human intervention.**

In summary, key technological factors likely influencing the acceptance of modern Generation III+ and IV nuclear reactors include potential for higher efficiency, enhanced safety features, and more efficient fuel utilization and waste management strategies compared to many currently operating large-scale nuclear reactors. Innovations in nuclear power are progressively addressing previous limitations, making the technology increasingly competitive and suited to contemporary energy needs.

PILLAR II: Organizational Factors

Implementing new technologies requires managing resources, developing infrastructure, and providing appropriate training to effectively harness the potential of modern Generation III+ and Generation IV nuclear reactor technologies. This process necessitates an integrated approach that combines investment strategy with operational planning and long-term life-cycle management of the nuclear facility. This coherent approach should be reflected in the regulatory and strategic frameworks at both governmental and corporate levels, facilitating access to diverse sources of investment and operational support and leveraging available financing mechanisms for projects utilizing the Coal-to-Nuclear concept.

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[9] D.L. Pentz, R. Stoll, Commercial Nuclear Fuel Leasing - The Relationships to Nonproliferation and Repository Site Performance, 2007.

[10] V.H. Reis i in., Nuclear fuel leasing, recycling and proliferation. Modeling a global view, March 2004, https://www.osti.gov/servlets/purl/15009811-OR9gV1/native/.

[11] Report applicability of the safety objectives to SMRs, WENRA RHWG, 12.01.2021, https://www.wenra.eu/sites/default/files/publications/WENRA_RHWG_Report_on_applicability_of_safety_objectivers_to_SMR.PDF.

[12] A. Strupczewski, Propozycje zmian w wymaganiach bezpieczeństwa MAEA dotyczące małych reaktorów modułowych (SMR), „Bezpieczeństwo Jądrowe i Ochrona Radiologiczna" 2023, nr 3.

One of the key challenges is ensuring access to adequate financial, human, and technological resources. Financing mechanisms are discussed further in Chapter 5 of this report. SMRs, due to their smaller investment scale compared to traditional nuclear power plants, could attract a wider range of investors, including private companies and local authorities. Investments could potentially be made through public-private partnerships (PPPs). **This opens possibilities for energy projects in regions with limited budgets or specific energy needs, for instance, where an urgent energy transition is required.**

Generation IV reactors still demand significant research and development (R&D) investment and international collaboration on technology development. Joint initiatives by European governments (e.g., EVOL, MYRRHA, ALLEGRO projects) can help accelerate the deployment of these technologies by sharing costs and risks among different entities. Such actions can strengthen the European economy by enhancing innovation in the energy sector, reducing dependence on external raw material suppliers, and supporting local companies (such as manufacturers of advanced materials or digital technologies) within the supply chain. **Creating stable, high-value jobs within this value chain will contribute to regional development and increase the competitiveness of the European economy on the global market.** Therefore, it is important to seek to locate the production of key components within the EU to the greatest extent possible. **Cooperation at the EU level could be key to building the necessary capacity for developing specialized facilities, such as advanced fuel fabrication and reprocessing plants or waste storage facilities, in the context of growing demand for low-carbon energy sources and the EU's energy security strategy. Joint action by Member States would enable cost optimization, technology transfer, and the accelerated implementation of innovative solutions for nuclear fuel cycle management and radioactive waste management. Integration of efforts within European R&D programs and financial support from EU funds could significantly enhance the competitiveness of the European nuclear sector globally.**

The development of SMRs and Generation IV reactors requires intensive investment in training specialized personnel for the nuclear industry. This requires a significantly greater effort than developing nuclear power based solely on a few large Generation III+ units. Experience from nuclear power implementation in the United Arab Emirates[13] indicates that inadequate workforce preparation can delay plant start-up, with responsibility resting with the investor, not the technology vendor. In new nuclear programs, ensuring the accountability of the supplier and general contractor throughout the project is crucial. It is also vital to emphasize safety aspects and engage local communities and the engineering sector. Quality and adherence to standards should be prioritized at every project stage. Education and training programs must be tailored to the specific characteristics of new technologies, including their modularity, passive safety systems, and more advanced fuels. **In Poland, TSOs (Technical Support Organizations) – entities providing technical and expert support to regulatory bodies – can play a key role.** For years, three institutes: the Institute of Nuclear Chemistry and Technology (Instytut Chemii i techniki Jądrowej), the National Centre for Nuclear Research (Narodowe Centrum Badań Jądrowych), and the Central Laboratory for Radiological Protection (Centalne Laboratorium Ochrony Radiologicznej), have expressed interest in cooperating as TSOs with the National Atomic Energy Agency (Państwowa Agencja Atomistyki, PAA) in supporting the implementation of the Polish Nuclear Power Programme (Program Polskiej Energetyki Jądrowej, PPEJ). In recent years, several institutions have received the National Atomic Energy Agency's authorization, attesting to the high quality of their work supporting nuclear safety[14]. Authorization from the National Atomic Energy Agency's President opens the way for interested research centers to apply for the role of a TSO for the Agency within the Polish Nuclear Energy Programme. Importantly, Poland has a limited number of institutions with finite personnel capacity eligible for authorization and capable of

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[13] UAE Announces Delay To Barakah-1 Commissioning, 5.05.2017, https://www.nucnet.org/news/uae-announces-delay-to-barakah-1-commissioning.

[14] Pięć instytucji eksperckich z autoryzacją Prezesa PAA, 11.08.2022, https://www.gov.pl/web/paa/piec-instytucji-eksperckich-z-autoryzacja-prezesa-paa.

providing TSO support services. This also poses a challenge regarding the availability of domestic expertise for work performed on behalf of the investor. Unbundling – the separation of regulatory, technical, and operational functions – is a key aspect in building an independent TSO system for nuclear power. For TSOs, this means organizations providing advisory, analytical, or particularly inspection/assessment services must operate independently of nuclear technology investors and vendors. Such separation is crucial to ensure objectivity and independence in assessing safety and the regulatory compliance of technologies. **Unbundling builds trust among regulators and the public by eliminating potential conflicts of interest between technical support bodies, investors, and technology vendors. Therefore, it is necessary to strengthen the personnel capacity of institutions aspiring to TSO or advisory roles, both in terms of the number of specialists and their expertise in modern nuclear technologies, safety regulations, and fuel cycle management.** Developing training and development programs to attract and retain highly qualified experts capable of supporting regulators and decision-makers in evaluating and implementing new nuclear projects is crucial. In the long term, the strategic strengthening of these institutions will enhance the independence of the national advisory and supervisory system, translating into more effective management of nuclear projects and better adaptation to dynamic changes in the nuclear power sector. The government's strategic documents should include various scenarios for nuclear energy development, including the Coal-to-Nuclear pathway. In this context, an immediate update of the 2023 Human Resources Development Plan for the Needs of Nuclear Power[15] is necessary. The current plan does not fully reflect the development of nuclear projects beyond Polish Nuclear Power Plants (Polskie Elektrownie Jądrowe), i.e., it does not envision scenarios where investments are implemented through public-private partnerships (as might be the case for SMRs) or are part of a broader energy transition than envisaged by the 2020 Polish Nuclear Power Programme.

In the nuclear sector, the separation of responsibilities among investors, regulators, and technical organizations can be modeled on unbundling in the power or railway sectors, where management and operational functions are clearly separated, and oversight is provided by independent bodies like the National Atomic Energy Agency. The Polish nuclear sector, drawing on these experiences, can build a TSO system based on transparency, safety, and compliance with international standards.

The energy transition brings numerous social challenges, including the need to restructure labor markets, diversify local communities' income sources, and adapt to new technologies. Closing coal-fired power plants often leads to socio-economic problems like job losses, reduced local tax revenues, and the degradation of infrastructure supporting the coal industry. **In regions where the coal industry has played a key role for decades, this can foster a sense of social marginalization and resistance to the transition. The Coal-to-Nuclear concept can help mitigate these negative effects.** Locally, workers from coal-fired power plants, particularly those involved in non-fuel handling operations (e.g., plant maintenance, logistics, ancillary services), can be retrained to work at the new nuclear facilities, minimizing regional unemployment risks. For example, engineers or technicians can successfully adapt their skills to the nuclear sector if appropriate retraining programs are established. However, the impetus for universities or vocational training institutions to create such educational projects must come from a clear state signal that this is a viable path for the socio-economic and workforce transition in regions historically tied to conventional fuels. **In this regard, the DEsire Energy Transformation Platform[16] can become a leading knowledge and education hub in Poland for decarbonization, integrating academic, industrial, and administrative activities to effectively support the energy transition.**

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[15] Krajowy „Plan rozwoju zasobów ludzkich na potrzeby energetyki jądrowej" zatwierdzony przez minister klimatu i środowiska, 8.12.2023, https://www.gov.pl/web/klimat/krajowy-plan-rozwoju-zasobow-ludzkich-na-potrzeby-energetyki-jadrowej-zatwierdzony-przez-minister-klimatu-i-srodowiska.

[16] Porozumienie założycielskie Platformy Transformacji Energetyki DEsire, https://projektdesire.pl/porozumienie-zalozycielskie-platformy-transformacji-energetyki-desire/.

In conclusion, implementing Generation III+ and IV reactors in Poland, including SMRs, requires a comprehensive organizational approach that considers resource management, infrastructure development, personnel training, and engagement with local factors. **This way, modern nuclear technologies can become the foundation of a sustainable, low-carbon energy future. Developing a plan and systematically implementing systemic solutions will foster innovation adoption and acceptance.**

PILLAR III: Environmental Factors

In the context of decarbonization, it is crucial that SMRs and Generation IV reactors are perceived as safe and effective ways to reduce emissions. The deployment of these technologies depends on government support, public acceptance, and appropriate regulations. SMRs, due to their lower power output, can better match local energy needs, enabling a more sustainable and regionally tailored approach to reducing emissions across different regions. It is therefore important to promote the Coal-to-Nuclear pathway not only because of the significant advantages of nuclear technology mentioned earlier, but also for its positive impact on the local and national economy.

Nuclear technologies generate stable, high-tech jobs, which can attract new investors to the region and support the development of local economies[17]. A nuclear power plant with the same capacity as the coal plant it replaces could employ more people and create additional long-term jobs. Nuclear retrofits also increase direct income (higher wages than in the conventional power sector) and indirect income (taxes) for the local community and region. As results from American studies show, the positive economic impacts of nuclear retrofits can be observed for any investment, regardless of its size[18]. It can be anticipated that in Poland, too, this would yield a noticeably positive effect, although it is currently difficult to measure due to the potential synergies arising from creating a new economic sector and jobs through the implementation of full-scale nuclear, SMR, and retrofit-oriented projects. (For more on the impact of nuclear projects on job creation, see the Sobieski Institute report Nuclear Power for Poland).

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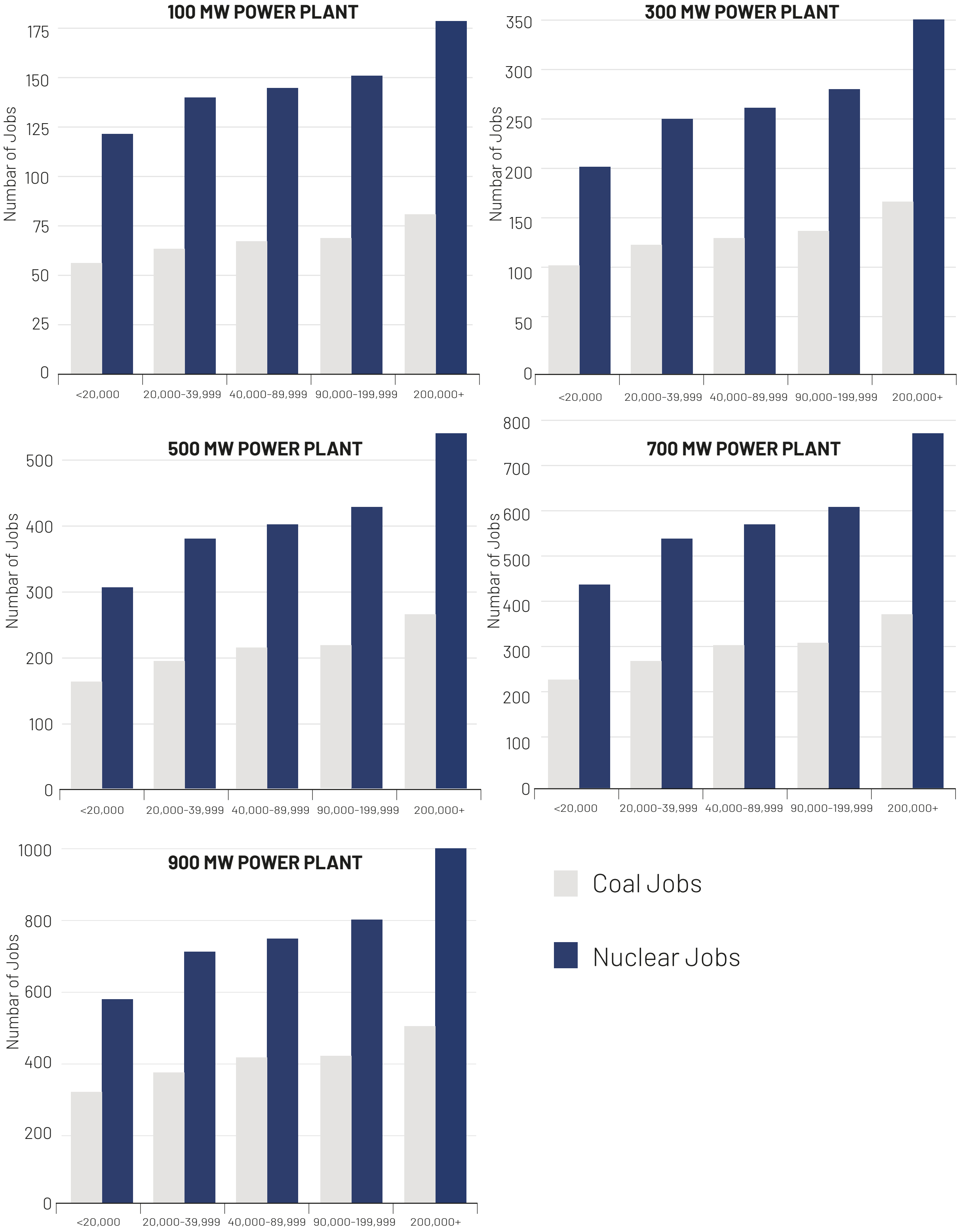
[17] Energetyka jądrowa dla Polski, Instytut Sobieskiego, 27.11.2020, https://sobieski.org.pl/energetyka-jadrowa-dla-polski/.

[18] Coal-to-Nuclear transitions. An information guide, U.S. Department of Energy, https://www.energy.gov/sites/default/files/2024-05/Coal-to-Nuclear%20Transitions%20An%20Information%20Guide.pdf.

FIG. 2 **LOCAL JOV GAINS BASED ON POPULATION SIZE AND POWER PLANT CAPACITY**[19]



SOURCE: U.S. Department of Energy

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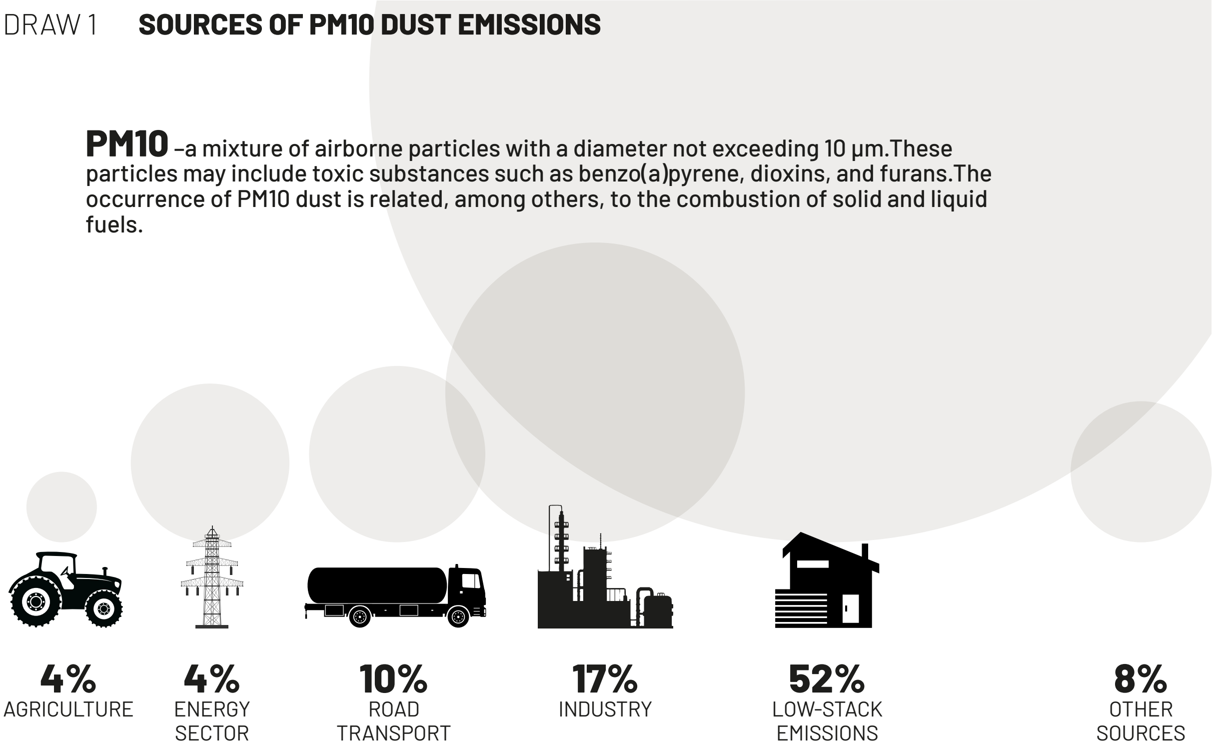
[19] Coal-to-Nuclear transitions. An information guide, U.S. Department of Energy, https://www.energy.gov/sites/default/files/2024-05/Coal-to-Nuclear%20Transitions%20An%20Information%20Guide.pdf.

Based on US projections of the impact of nuclear retrofits, it can be seen that the job creation advantage of nuclear power increases commensurately with plant capacity. In larger populations, more jobs are created, potentially due to greater local infrastructure needs and more complex ancillary services. Therefore, in regions with higher population density and a high degree of industrialisation, the transition to nuclear power could bring more noticeable benefits than in less developed areas, where nuclear power plants might become the starting point for establishing new communities and infrastructure[20].

In the long term, nuclear retrofits can contribute to an improved quality of life, not only by reducing air pollution in areas with power generation and industry, but also by encouraging the electrification of district heating, which will help reduce 'low-stack emissions' (local air pollution primarily from heating systems). This is crucial for the health of inhabitants in regions previously heavily dependent on the coal industry.

The Coal-to-Nuclear transformation should not be seen as a threat, but as an opportunity for development and modernisation. It should be promoted by the government as a truly just transition solution that can safeguard heavily industrialised regions from economic decline. The Coal-to-Nuclear pathway directly contributes to reducing pollutant emissions, which provides an incentive for using new technologies in highly urbanised regions that currently have significant environmental impacts. Nuclear energy is a driver for regional development and education. Better education, in turn, leads to further sustainable development.

DRAW 1 **SOURCES OF PM10 DUST EMISSIONS**



PM10 –a mixture of airborne particles with a diameter not exceeding 10 µm.These particles may include toxic substances such as benzo(a)pyrene, dioxins, and furans.The occurrence of PM10 dust is related, among others, to the combustion of solid and liquid fuels.

SOURCE: Author's analysis based on Polish Smog Alert data.

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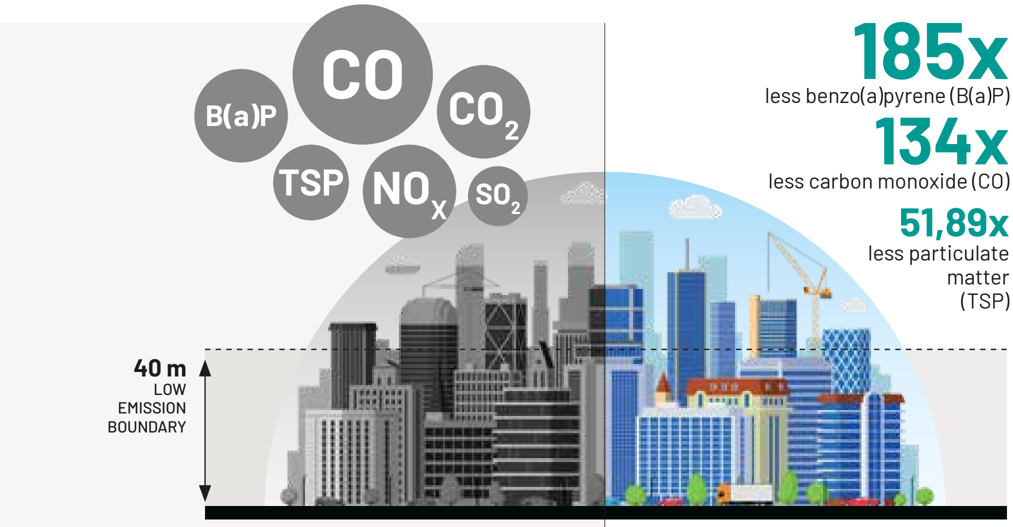
[20] Coal-to-Nuclear transitions. An information guide, U.S. Department of Energy, https://www.energy.gov/sites/default/files/2024-05/Coal-to-Nuclear%20Transitions%20An%20Information%20Guide.pdf.

DRAW 2 **DISTRICT HEATING REDUCES LOW EMISSIONS**



Low emissions refer to pollution released in the form of toxic smoke in the immediate surroundings of humans, at a height below 40 meters.

B(a)P - benzoalfapiren
TSP - pyły zawieszone
CO - tlenek węgla

DISTRICT HEATING
= CLEAN AIR
IN THE CITY

SOURCE: Own work based on Polski alarm smogowy

Another important factor inhibiting or accelerating innovation is the nature of regulations, including their flexibility and responsiveness to market demand and supply. We discuss this further in the next chapter of this report.

The model described above aims to identify key areas requiring strengthening for the introduction of the Coal-to-Nuclear pathway within the Polish energy transition. The model should be tailored to the needs of specific stakeholders, i.e., government bodies (creating national policies) or investors. Its application should aim to gain public support and foster a positive investment environment.

3.1.2 EVERETT ROGERS' DIFFUSION OF INNOVATIONS THEORY

Rogers' theory can describe the adoption of Generation III+ and Generation IV reactors, including SMRs as decarbonization tools, by different societal groups, considering five key attributes of innovation. The current state of public acceptance of nuclear power in Poland is presented in the report *Coal-to-Nuclear for Poland: Social Diagnosis*.

Attribute 1: Relative Advantage

Nuclear technologies can play an important role in decarbonization, especially if perceived as complementary or more efficient under specific conditions compared to other emission reduction methods, such as renewable energy sources. The relative advantage of nuclear power stems primarily from its ability to generate energy stably and continuously, independent of weather conditions, making it a potential key component of

DRAW 3 **EFFICIENCY AND FUEL CONSUMPTION IN DIFFERENT TYPES OF POWER PLANTS**

1 YEAR OF OPERATION OF A 1 GW POWER PLANT
WITH 90% CAPACITY UTILIZATION PER YEAR

NUCLEAR
POWER PLANT

REAL OPERATING TIME:
90-100%

GAS
POWER PLANT

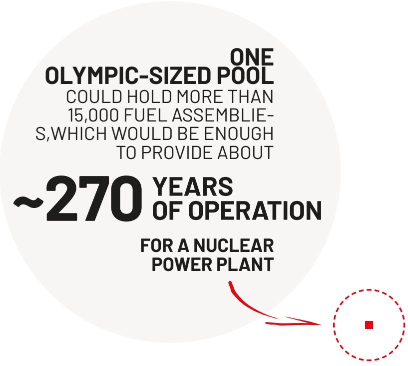
REAL OPERATING TIME:
40-60%

COAL
POWER PLANT

REAL OPERATING TIME:
30-50%

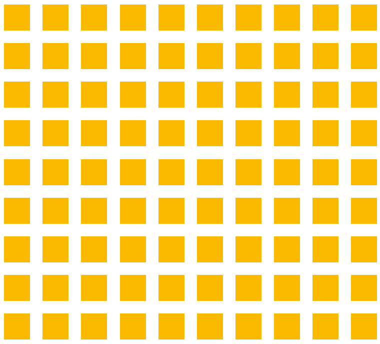
FUEL REQUIRED TO ENSURE POWER PLANT OPERATION

Modern nuclear reactors can operate continuously for 18-24 months on a single fuel load, and their lifespan is designed **for 60-80 years.**



ONE OLYMPIC-SIZED POOL COULD HOLD MORE THAN 15,000 FUEL ASSEMBLIE-S,WHICH WOULD BE ENOUGH TO PROVIDE ABOUT **~270 YEARS OF OPERATION FOR A NUCLEAR POWER PLANT**

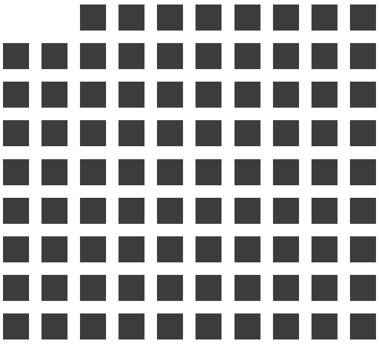
🟨 = **100 OLYMPIC-SIZED POOLS** FILLED WITH LNG



ANNUAL DEMAND:

1.35 BILLION M^3 OF GAS OR 2.25 MILLION M^3 OF LNG
900 OLYMPIC-SIZED POOLS FILLED WITH LNG

⬛ = **100 OLYMPIC-SIZED POOLS** FILLED WITH COAL



ANNUAL DEMAND:

2.9 MILLION TONS OF COAL
880 OLYMPIC-SIZED POOLS FILLED WITH COAL

SOURCE: Own work

the baseload power supply. Nuclear power guarantees high capacity factors (often exceeding 90% annually), enabling it to meet constant energy demand, which is essential for the economy, industry, and critical infrastructure. Unlike variable renewables, which require significant backup capacity or energy storage, nuclear power plants provide uninterrupted and predictable generation, enhancing power system stability and reducing the risk of energy shortages. Consequently, nuclear power as a foundation of the energy mix is less demanding in terms of requiring flexibility mechanisms. Modern nuclear reactors can operate continuously for 18–24 months on a single fuel load and are designed for operational lifetimes of 60–80 years.

Furthermore, the low-carbon nature of nuclear technologies is a key asset in the pursuit of climate neutrality – nuclear power generation involves a minimal carbon footprint per unit of energy, supporting global CO_2 reduction targets. This footprint is comparable to that generated by RES. The development of small modular reactors opens new opportunities for integrating nuclear power into various power system models, including at the local level.

Implementing modern nuclear technologies requires making the public and decision-makers aware of their environmental benefits (low emissions) and their positive impact on the power system and energy security.

Attribute 2: Compatibility

Adoption of nuclear technologies will increase if they align with societal needs, values, and expectations, particularly regarding safety and environmental concerns. In Poland, a country with high demand for clean energy and an urgent need to build new generation capacity, nuclear retrofits can be viewed as compatible with long-term transformation goals. However, implementing the Coal-to-Nuclear pathway requires full alignment with government strategic documents defining national energy policy, infrastructure development priorities, and funding mechanisms for nuclear projects. These include, among others, the Energy Policy of Poland, the National Energy and Climate Plan, and the Polish Nuclear Power Programme. Otherwise, such investments might be perceived as contrary to the interests of Polish citizens and burdened with high financial risk.

Attribute 3: Complexity

The simpler and easier an innovation is perceived to be to understand and use, the more readily it gains acceptance. SMRs are theoretically less complex to deploy and operate than traditional large nuclear power plants. This aspect will likely allow for faster and more flexible deployment, for example, in regions with urgent energy needs resulting from the transition.

A key message, highlighted in the Coal-to-Nuclear for Poland: Social Diagnosis report among others, is the need for transparent communication linguistically adapted to the target audience. **It is crucial to reduce the perception of nuclear technology as "incredibly complex and complicated" and instead present it positively – as user-friendly, intelligent, and manageable.** Technology demonstrations, educational site visits, seminars, and simulations can help overcome perceptions of technological complexity and increase public trust.

Attribute 4: Trialability

The possibility of testing the Coal-to-Nuclear concept and implementing it on a small scale could increase technology adoption and encourage investment in such projects. A current challenge is the inability to demonstrate a fully operational value chain and investment case. Therefore, **support from the government**

and European institutions is needed for pilot installations in specific regions, especially those requiring transformation or in communities seeking to transition to low-carbon energy sources. In this context, Poland could be positioned within the 'early majority' adopter category – representing countries or organizations interested in improving energy stability and reducing emissions, which are more cautious but recognize the potential of nuclear retrofits following successful pilot trials.

Attribute 5: Observability

The visibility of the benefits derived from Coal-to-Nuclear initiatives is crucial for widespread adoption. If communities and decision-makers can clearly see or quantify the positive effects of nuclear retrofits (e.g., job creation, reduced emissions, stable energy prices), they will be more inclined to accept the technology. Therefore, it is imperative to **support all Coal-to-Nuclear initiatives, from R&D projects like DEsire, through pilot plants, to fostering a favorable business environment based on investment and operational incentives.**

SUMMARY

Applying Rogers' model to the Coal-to-Nuclear pathway indicates that nuclear technology adoption is feasible but requires emphasizing its relative advantages, ensuring compatibility with government strategies, reducing perceived complexity, creating opportunities for trialability (pilot projects), and ensuring the observability of successes. A strategic approach to implementing this transition will increase its chances of success and facilitate the decarbonization process in Poland. Building public awareness through education and reliable information on the safety and long-term benefits of nuclear power will also be key. Support from international institutions and technology partners can further accelerate the implementation of the Coal-to-Nuclear pathway through knowledge transfer and the provision of stable financial frameworks. With appropriate legislative and investment mechanisms, Poland has the opportunity to become a leader in implementing the Coal-to-Nuclear transition in Europe, enhancing its energy independence and power system stability.

4. LEGAL AND REGULATORY ASPECTS

4.1 REQUIREMENTS FOR NUCLEAR FACILITIES: UNIFICATION AND STANDARDIZATION

Siting a nuclear power plant, regardless of its size, requires detailed investigations into tectonics, seismicity, hydrology, meteorology, demography, and the environment. This stems from the fundamental principle guiding the construction of nuclear facilities: striving to limit radiation doses absorbed by individuals and the general population, in accordance with the ALARA (As Low As Reasonably Achievable) principle. According to the current legal status (as of September 2024), this assessment is performed based on the Atomic Law Act (Journal of Laws 2024, item 1277)[21] and the Regulation of the Council of Ministers of 10 August 2012 regarding the detailed scope of site assessment for nuclear facilities, conditions precluding site suitability, and requirements for the site report for a nuclear facility (Journal of Laws 2012, item 1025)[22]. For the DEsire Phase A project, the siting analysis was based on the legal framework applicable in 2022[23], which does not differentiate based on the level of technological advancement, thus treating both large nuclear reactors and SMRs identically. Current Polish nuclear law is primarily based on the Atomic Law Act, originally enacted in 1986 and significantly updated in 2000 to reflect technological progress and international obligations. Its content has been supplemented by numerous amendments, including the most recent in 2023, and dozens of regulations detailing requirements for different life cycle stages of nuclear facilities, often with the implicit objective of facilitating the investment at the Lubiatowo-Kopalino site.

The presence of an active tectonic fault near a planned power plant site is an exclusion factor due to earthquake risk. The International Atomic Energy Agency (IAEA) clearly states in its guidelines (e.g., Safety Standards Series No. NS-R-3, Site Evaluation for Nuclear Installations) that locations near active faults should be rejected. This is also reflected in Polish law. Specifically, siting a nuclear power plant is prohibited if, within a 30 km radius of the location, mining activities, underground tankless storage of substances (or similar geological storage activities), underground waste disposal, or any other activity that could jeopardize the nuclear facility's safety by inducing seismic activity has occurred or is occurring within the last 60 years. This provision currently excludes large portions of the Śląskie (Silesian), Opolskie, Małopolskie, and Łódzkie Voivodships, areas with historical and ongoing mining activity. Rock bursts are dangerous phenomena that can occur after mine closure due to stress changes in the rock mass. Technologies are employed to reduce rock stress and ensure proper backfilling of mine workings to prevent this. Mine decommissioning and site remediation are long-term processes, often continuing

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[21] Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 10 lipca 2024 r. w sprawie ogłoszenia jednolitego tekstu ustawy – Prawo atomowe, Dz.U. 2024 poz. 1277, https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20240001277.

[22] Rozporządzenie Rady Ministrów z dnia 10 sierpnia 2012 r. w sprawie szczegółowego zakresu przeprowadzania oceny terenu przeznaczonego pod lokalizację obiektu jądrowego, przypadków wykluczających możliwość uznania terenu za spełniający wymogi lokalizacji obiektu jądrowego oraz w sprawie wymagań dotyczących raportu lokalizacyjnego dla obiektu jądrowego, Dz.U. 2012 poz. 1025, https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20120001025.

[23] A. Miśkiewicz, D. Chmielewska-Śmietanko, T. Smoliński, Dekarbonizacja energetyki opartej na węglu w Polsce poprzez zastosowanie modułowych reaktorów jądrowych, „Bezpieczeństwo Jądrowe i Ochrona Radiologiczna" 2023, nr 1.

for many years after exploitation ends, aimed at environmental protection and ensuring the safety of the population and infrastructure near the former mine. **Future mine closures, particularly in regions targeted for Coal-to-Nuclear implementation, will necessitate reclamation efforts allowing future industrial use while mitigating geological impacts (risk of induced seismicity) on the entire region.** Nuclear power plants are built worldwide, including in seismically active regions. Although seismic zones pose challenges, technologies used in these locations are designed to address earthquake-related hazards. Japan, situated in one of the world's most seismically active regions (the Pacific Ring of Fire), operates numerous nuclear power plants, including one of the world's largest, Kashiwazaki-Kariwa. Located about 300 km from Fukushima-Daiichi, it was undamaged by the 2011 earthquake; however, following a routine shutdown, local authorities have not yet permitted its restart. Over the past decade, the plant underwent upgrades and modernization to meet current, post-2011 tightened safety requirements[24]. The USA also has nuclear plants in areas with elevated seismic risk, notably in California, like the Diablo Canyon Power Plant near faults such as the San Andreas. Iran's Bushehr Nuclear Power Plant is located in an earthquake-prone region and was constructed using seismic-resistant technologies. Similarly, the Akkuyu nuclear power plant on Turkey's Mediterranean coast was built in an earthquake-prone region using modern construction technologies for seismic protection. These examples confirm that constructing nuclear power plants in seismically active areas is feasible, complies with international safety standards, and enables their safe, long-term operation. **Amendments to Polish law should allow the construction of a nuclear facility in a region where mining occurred less than 60 years ago, provided it can be demonstrated that technologies can effectively mitigate the effects of potential seismic activity. New regulations could draw upon solutions implemented in the USA, South Korea, and Japan, and should align with International Atomic Energy Agency guidelines.**

Easing regulations to allow greater siting flexibility while maintaining safety could involve:

Conditional Shortening of the Exclusion Period – Modifying regulations so the 60-year period could be shortened (e.g., to 20 years) if mining activities in the region did not significantly impact ground stability. This might apply, for example, to surface mines that have undergone reclamation or areas with only small-scale past mining.

OR

Case-by-Case Assessment – Introducing a mechanism for individual site evaluation. Instead of automatic exclusion due to mineral deposits or past mining, a detailed risk analysis would be conducted. If studies demonstrate the site is stable with no significant safety risk, the location could be approved.

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[24] Kashiwazaki-Kariwa to improve evacuation plan, 11.09.2024, https://www.neimagazine.com/news/kashiwazaki-kariwa-to-improve-evacuation-plan/.

Approving sites with potential seismic activity (natural or induced) should also be contingent upon the mandatory use of advanced technologies and engineering measures to enhance construction and operational safety, such as reinforcing reactor structures or implementing additional shutdown safety features.

Proximity to airports or location along the extended runway centerline is another significant siting barrier. IAEA guidelines require avoiding locations exposed to such hazards. This is reflected in Polish law (as of September 2024), which prohibits constructing a nuclear facility within 10 km of an airport. Currently, the Civil Aviation Authority's register lists approximately 230 civil and military facilities (airports, airstrips, road landing strips) with varying statuses (operational, disused, closed, disbanded, decommissioned). However, current Polish regulations do allow locating a nuclear plant near an airport if the probability of a large commercial aircraft impact is less than 10^{-7} per year (less than once in 10 million years). In practice, this restriction effectively applies to fewer than 20 airports in Poland currently capable of handling medium and large commercial aircraft. Therefore, these provisions do not represent a major obstacle to nuclear power development in Poland.

Hydrological and meteorological conditions, particularly location within **a floodplain or area at risk of flooding,** are also analyzed during the permitting process. Nuclear power plants must be built in locations free from such hazards. IAEA guidance on flood hazard assessment (e.g., ***Flood Hazard for Nuclear Power Plants on Coastal and River Sites***) specifies requirements. Polish regulations similarly mandate that such facilities must be located where the flood hazard frequency is less than once per thousand years (10^{-3} per year). Hydrological assessments must also consider risks from extreme weather events like intense rainfall or prolonged droughts. The resilience of nuclear facilities to climate change and weather anomalies should be a key aspect analyzed during siting decisions. **Consideration must extend beyond the facility's safety to its ability to ensure stable regional energy supply during weather events that might disrupt other energy sources.** Nuclear power plants are generally designed to be resilient to external conditions, enabling them to play a crucial role in stabilizing the power grid during crises. In this context, **during weather anomalies and natural disasters, continued energy supply** from nuclear plants can protect a region or country from the high costs associated with energy shortages. The Polish Economic Institute estimated in 2019 that a 12-hour blackout in Poland could generate losses of PLN 3.8 billion[25].

High population density may also be an exclusion factor due to challenges in evacuation and emergency management during an accident. The IAEA recommends avoiding construction in highly populated areas and provides guidance on establishing Emergency Planning Zones (EPZs), though specific requirements may vary. These recommendations often stem from operational experience with older (e.g., Generation II) large reactors. Generation III+ reactors and SMRs, due to their smaller size and enhanced safety features (with severe accident frequencies, e.g., for LOCA, comparable to or lower than Generation III+), require significantly smaller EPZs[26]. This makes them easier to site near cities, potentially supporting local energy transition, especially regarding district heating.

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[25] „Tygodnik Gospodarczy PIE" 2019, nr 49-50, https://pie.net.pl/wp-content/uploads/2018/07/Tygodnik_PIE_49-50-19.pdf.

[26] Ł. Koszuk, Ustanawianie stref planowania awaryjnego wokół elektrowni jądrowych: analiza praktyk w wybranych krajach i Polsce, „Bezpieczeństwo Jądrowe i Ochrona Radiologiczna" 2024, nr 3.

More flexible siting requirements also favor constructing SMRs near industrial plants, aiding the decarbonization of sectors like chemical manufacturing and refining. It should be noted that future pressure to extend EPZs beyond technically justified boundaries might arise purely from psychological factors rather than substantive safety analyses. Lack of public acceptance of safety assessment results, even if they indicate no need for off-site EPZs, could lead to excessively conservative regulations. **When making siting decisions, both the planned EPZs and site suitability criteria and the probability of severe accidents should be considered, potentially enabling non-electric applications of nuclear reactors or siting closer to populated areas.**

Construction of a nuclear power plant, like other major investments, is prohibited in nature protection areas or zones where construction could harm ecosystems. A detailed framework for the investment, including environmental impact, is established through the environmental impact assessment (EIA) decision.

Any of the above factors could render a site unsuitable for nuclear power plant construction. However, international guidelines, particularly for nuclear power, are regularly modified and adapted to technological advancements and evolving nuclear safety requirements.

Regarding siting requirements, SMRs potentially have less stringent needs than traditional large nuclear reactors, which is one of their main advantages. While large reactors could technologically perform the same functions, smaller units might require less land area and cooling water. In practice, however, some SMR designs might have greater specific requirements (per MW of capacity) for land or construction materials than large reactors. Verification of these design assumptions will only be possible after several units are built and operational.

4.2 LICENSING OF INNOVATIVE NUCLEAR REACTORS

It is important to remember that SMRs must meet the same safety standards as traditional large nuclear power plants and are subject to essentially identical licensing procedures. The assessment of SMR technologies also includes environmental impact, adding to the process's complexity. Governments often support SMR licensing, especially when domestic development is involved, for example, through project development grants. To expedite licensing, companies frequently utilize pre-licensing engagements, allowing regulators' recommendations to be identified and addressed earlier. Nevertheless, licensing a new nuclear technology typically takes at least three to five years for design certification or approval, followed by site-specific construction and operating license applications.

In Poland, the first SMRs might be built in the first half of the 2030s at the earliest, with subsequent units following later. The most advanced project, pursued by OSGE (Orlen Synthos Green Energy), is reportedly facing delays of 3 to 7 years, primarily attributed to the slow pace of pre-licensing and regulatory processes. The time required to prepare documentation for SMR licensing applications is often comparable to that for large reactors, although SMR construction times are expected to be shorter. Polish regulations are intended to be technologically neutral, balancing the interests of investors and the public.

Currently, constructing a nuclear power plant, whether based on a large reactor or an SMR, falls under the same overarching regulatory framework. Polish law does not formally favor specific technologies. Consequently, Decisions-in-Principle (DiP) have been issued for the following reactor designs: AP1000 (Westinghouse), VOYGR (NuScale Power), SMR-160 (Holtec), Rolls-Royce SMR, NUWARD (EDF), and BWRX-300 (GE Hitachi).

For nuclear technologies based on Generation IV reactors, regulatory adaptation efforts are at an earlier stage compared to SMRs, focusing on preparing relevant guidelines and legal frameworks. General nuclear safety guidance is provided by the IAEA through documents like the Fundamental Safety Principles and the Safety Standards Series. Generation IV reactors must comply with these fundamental standards, which address aspects like accident prevention and mitigation, radioactive waste management, cybersecurity, and minimizing risks to the public and environment. Specific guidelines are currently under development tailored to different advanced reactor technologies, recognizing that Gen IV reactors often use different fuels and coolants than commonly deployed Generation III/III+ reactors and the SMRs mentioned previously.

Currently, the licensing of Generation IV reactor technologies is primarily occurring in countries with extensive experience in nuclear power and established expertise in risk and safety assessment for innovative designs – notably the USA, Canada, the UK, France, and China.

The UK is developing regulations aimed at facilitating the deployment of advanced nuclear technologies[27], moving beyond regulations primarily tailored to light-water reactors (LWRs).

In Poland, the National Atomic Energy Agency, responsible for licensing and supervising reactor safety, currently focuses mainly on regulations pertaining to Generation III+ reactors (intended for large NPPs) and the future adaptation of regulations for SMRs also based on LWR technology. The National Atomic Energy Agency actively cooperates with the IAEA[28] and international nuclear regulatory bodies, signing numerous agreements to exchange information and collaborate on nuclear safety and radiological protection. These initiatives keep the Agency informed about global nuclear reactor licensing procedures and best practices[29].

The Generation IV technologies selected for decarbonization analysis under Phase A of the DEsire project are the Kairos Power Fluoride Salt-Cooled High-Temperature Reactor (KP-FHR), the ThorCon Molten Salt Reactor (MSC ThorCon), and the High-Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM). The latter two are currently undergoing licensing processes in other countries.

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[27] Advanced nuclear technologies, 6.12.2024, https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies.

[28] Przygotowania do licencjonowania z ekspertami MAEA – warsztaty w Państwowej Agencji Atomistyki, 20.01.2025, https://www.gov.pl/web/paa/przygotowania-do-licencjonowania-z-ekspertami-maea—warsztaty-w-panstwowej-agencji-atomistyki.

[29] USA-Polska. Porozumienie między Prezesem Państwowej Agencji Atomistyki Rzeczypospolitej Polskiej a Komisją Dozoru Jądrowego Stanów Zjednoczonych Ameryki o wymianie informacji technicznej i współpracy w dziedzinie bezpieczeństwa jądrowego, Rockville, 15.06.2023, https://www.prawo.pl/akty/m-p-2023-1018%2C21874649.html.

Kairos Power is developing the KP-FHR reactor, cooled by a fluoride salt mixture (Flibe) and using TRISO fuel. The company is constructing a non-electric demonstration reactor named Hermes in Oak Ridge, Tennessee. In December 2023, the U.S. Nuclear Regulatory Commission (NRC) issued a construction permit for Hermes following an expedited review facilitated by intensive pre-licensing interactions ongoing since 2018[30]. Construction began in June 2024, and construction of the fuel salt purification plant for this reactor started in October 2024[31].

ThorCon plans to build a 500 MWe molten salt cooled demonstration reactor integrated into a floating power plant barge. The reactor is intended for installation near Gelasa Island in Bangka-Belitung Province, Indonesia. The Indonesian regulatory process reportedly began in 2023[32].

In China, two demonstration HTR-PM units (totaling 250 MWe) have been in commercial operation since December 2023[33]. Project construction began in 2012, with the first reactor achieving criticality in September 2021. These reactors feature high levels of passive safety, confirmed by tests demonstrating their ability to cool down naturally during accident scenarios without active intervention or emergency systems. The Chinese government plans further commercial deployments and development of a larger HTR-PM600 version. The HTR-PM program is part of China's energy transition strategy.

All three technology developers are currently focused on deployment in their respective primary markets (USA, Indonesia, China). There are no immediate initiatives for licensing and introducing these specific Gen IV designs in Europe, including Poland. However, export potential exists, especially for regions and countries struggling with limited water resources or needing to reduce industrial emissions. Countries pursuing deep decarbonization may become future adopters if these projects reach sufficient commercial maturity for global expansion.

Licensing Generation III+ and IV reactors, including SMRs, as well as licensing non-electric applications of nuclear reactors, requires close cooperation with international institutions like the IAEA and adaptation of national regulations to new technologies. Harmonization and international agreement are undoubtedly necessary for these efforts[34]. The situation in Poland, similar to other European countries, shows that while advanced reactor technologies attract significant interest, their implementation is a lengthy process requiring thorough regulatory and technological preparation.

Poland, by pursuing the Coal-to-Nuclear pathway, will likely face challenges typical for countries adopting novel technologies – often referred to as 'teething problems'. This process requires building domestic competence and adapting regulations, often drawing upon theoretical guidelines and the experiences of other countries with large nuclear facilities, which may not always be directly transferable to Polish circumstances. However, the experience gained during this transition will be invaluable and could become a significant asset for Poland in the future.

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[30] Kairos Power begins construction on Hermes low-power demonstration reactor, 30.07.2024, https://kairospower.com/external_updates/kairos-power-begins-construction-on-hermes-low-power-demonstration-reactor/.

[31] Kairos Power breaks ground on salt production facility to make molten salt coolant for advanced reactors, 2.10.2024, https://kairospower.com/ external_updates/kairos-power-breaks-ground-on-salt-production-facility-to-make-molten-salt-coolant-for-advanced-reactors/.

[32] ThorCon begins pre-licensing consultation in Indonesia, 5.04.2023, https://world-nuclear-news.org/Articles/ThorCon-begins-pre-licensing-consultation-in-Indon.

[33] World's first commercial small modular reactor powers up 'brain' in China, 22.05.2024, https://news.cgtn.com/news/2024-05-22/World-s-first-commercial-small-modular-reactor-powers-up-in-China-1tOh34l59Sw/p.html.

[34] Benefits gained through international harmonization of nuclear safety standards for reactor designs, WNA Discussion Paper, https://staging.world-nuclear.org/uploadedFiles/org/WNA/Publications/Working_Group_Reports/ps-cordel.pdf.

Through such a transformation, Poland has the opportunity to become an expert in the 21st-century energy revolution, building a modern, nuclear-based energy mix. Although Poland may not become a primary developer of nuclear reactor technologies, it can specialize in their deployment, licensing process management, and integration into the national energy system. T**his acquired knowledge and practical experience could become an exportable commodity**, particularly valuable to countries only beginning to consider nuclear power investments, such as nations in Africa, Asia, and South America. Poland could play a role as an advisor and leader in energy transition, supporting nuclear development in emerging economies and **monetizing its know-how internationally**.

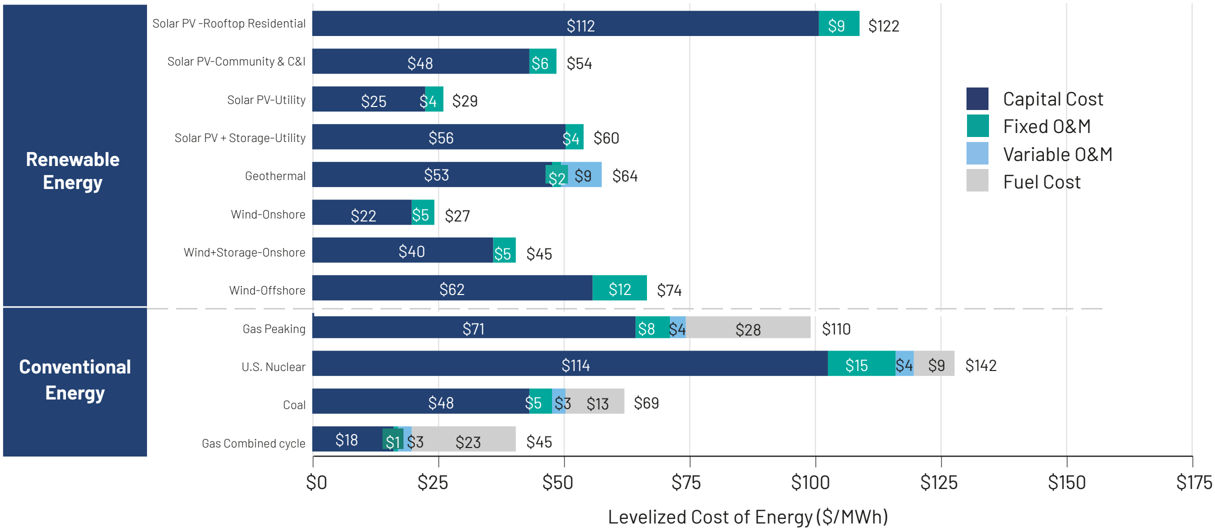
5. FINANCIAL ASPECTS

Conventional nuclear power projects (with reactor capacities around 1 GWe) are characterized not only by long design and construction timelines but also by immense capital intensity. Consequently, financing such projects requires utilizing appropriate instruments and support mechanisms.

5.1 THE LEVELIZED COST OF ENERGY (LCOE) INDICATOR AND CHOOSING FINANCING SOURCES

Typically, 60–80% of a nuclear power plant's construction cost is financed through debt instruments issued by private and state-owned banks, as well as specialized Export Credit Agencies (ECAs)[35]. The significant share of debt financing in nuclear investments (such as the EPR – European Pressurised Reactor) makes the unit cost of electricity generation **(LCOE) for nuclear projects highly sensitive to interest rate changes**. Significant capital expenditures (CAPEX) and keeping construction within budget also depend heavily on price dynamics within the supply chain.

FIG. 3 **LCOE COST COMPONENTS, BASED ON THE U.S. MARKET – LAZARD[36]**



SOURCE: Lazard

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[35] Walstra, J.G. Financing new nuclear, Governments paying the price?, 30.09.2024, https://wisenederland.nl/wp-content/uploads/2024/10/Financing-of-new-nuclear-Governments-paying-the-price-Profundo.pdf

[36] Lazard's LCOE+ 2024 Report, June 2024, https://www.lazard.com/research-insights/levelized-cost-of-energyplus/.

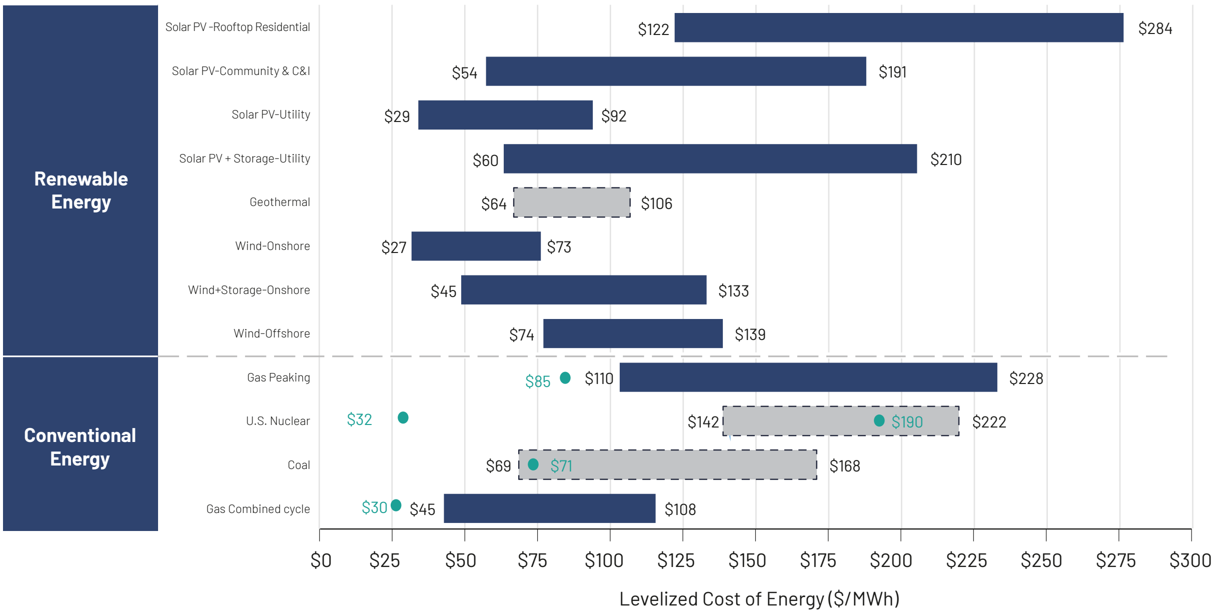
The Levelized Cost of Energy (LCOE) is widely regarded as a key metric in planning and developing energy projects, as it allows for a standardized comparison of energy production costs across different technologies, such as wind, solar, gas, nuclear, or coal[37].

The LCOE calculation incorporates the major costs associated with building and operating an energy project, including:

- Capital Expenditures (CapEx): e.g., constructing a wind farm or gas-fired power plant.
- Operating Expenditures (OpEx): ongoing maintenance, repairs, labor costs.
- Corporate Income Tax (CIT).
- Fuel and Emissions Costs (if applicable to the technology).
- The expected operational lifetime of the facility and the total energy output anticipated during that period.

This allows, in theory, for the identification of the most cost-effective generation option for a given project scope.

FIG. 4 **LEVELIZED COST OF ENERGY COMPARISON – VERSION 17.0**[38]



SOURCE: Lazard

Investors and policymakers use LCOE to assess the potential return on investment for energy projects. A low LCOE suggests a project is more likely to generate competitively priced energy within the merit order dispatch system and yield higher returns for the investor[39].

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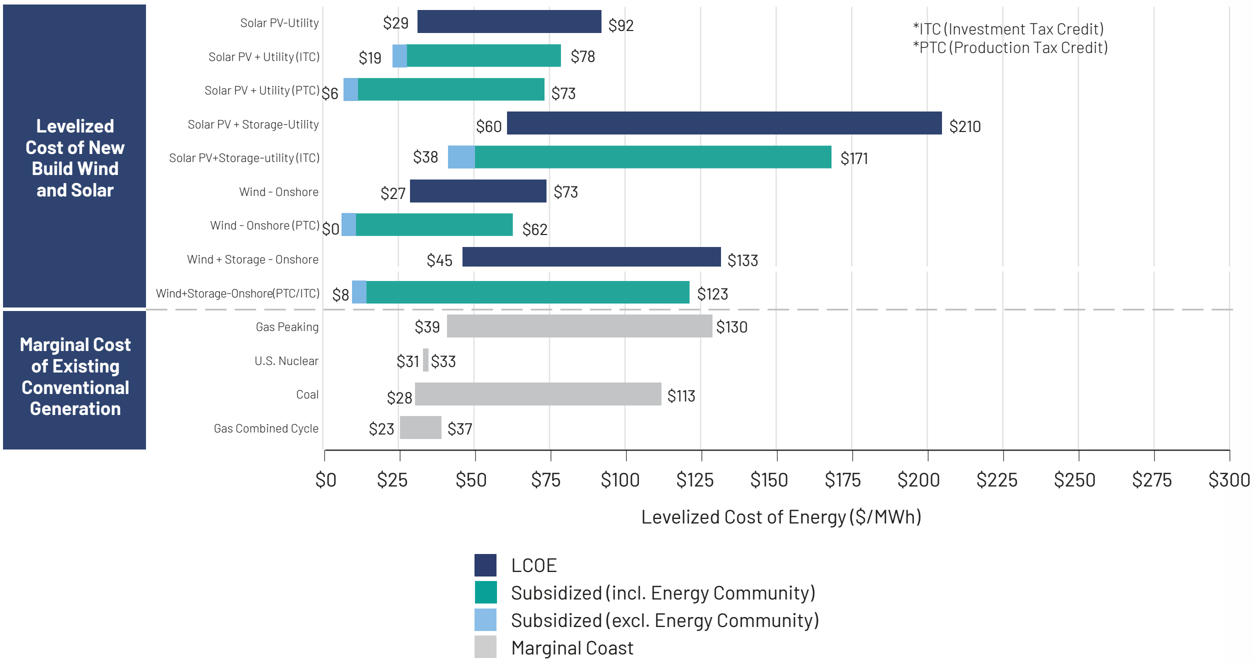
[37] With the proviso that LCOE is not the right indicator for the capacity market (e.g. peak gas capacities). When their use is low, LCOE will be high, but these are capacities necessary to balance the system with a large share of RES.

[38] Lazard's LCOE+ 2024 Report, June 2024.

[39] Again, with the proviso regarding the capacity market, within which gas units can only operate at times of peak demand for electricity and be remunerated for such a system balancing service under a separate agreement.

FIG. 5 LEVELIZED COST OF ENERGY COMPARISON – NEW BUILD RENEWABLE ENERGY VS. MARGINAL COST OF EXISTING CONVENTIONAL GENERATION[40]



SOURCE: Lazard

Nominally, renewable energy sources appear unbeatable in terms of LCOE. However, it is crucial to remember that this indicator overlooks significant differences between conventional power and RES, particularly regarding full system costs.

While **LCOE** is useful for assessing project profitability from a private sector perspective, it **neglects additional factors vital to the entire national power system. These include costs borne by transmission and distribution system operators (TSOs and DSOs – largely public sector entities) to provide adequate grid connection infrastructure and ensure system stability**. Integration costs for wind or solar power, especially for large-scale deployments, can be substantial, potentially exceeding 50% of the generation cost itself[41]. Thus, due to the exclusion of integration costs, LCOE does not accurately reflect the final cost of electricity delivered to consumers. **Furthermore, relying solely on LCOE might mislead policymakers into believing nuclear power becomes less competitive against RES as RES penetration increases, when in reality (due to the escalating system costs of integrating high levels of RES), the opposite might be true.**

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[40] Lazard's LCOE+ 2024 Report, June 2024.

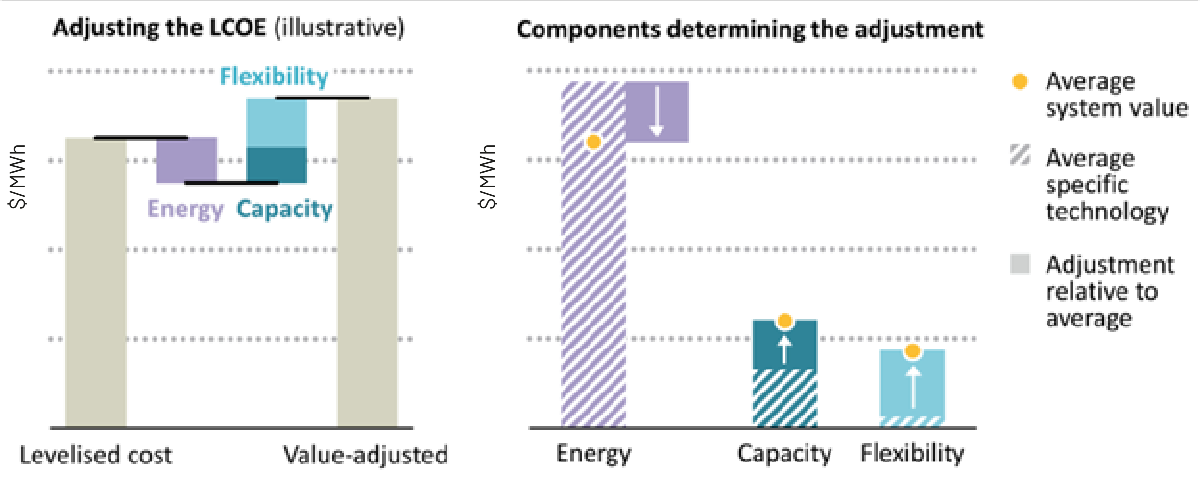
[41] A. Juszczak i in.,, What policies for a secure and competitive Europe? 10 ideas for the European Commission, Polish Economic Institute, Warsaw 2024, https://pie.net.pl/wp-content/uploads/2024/12/PIE_Policy-Paper_10-ideas-for-the-European-Commission.pdf.

Recognizing these limitations, the International Energy Agency (IEA) developed and utilizes t**he more comprehensive Value-Adjusted Levelized Cost of Electricity (VALCOE) indicator**. VALCOE considers not only the cost of generating electricity with a given technology but also its value to the power system. This indicator incorporates:

- **Energy Value** - the market price the generated electricity can achieve when it is needed.
- **Flexibility Value** - the ability of the source to provide system services, such as frequency regulation or capacity market contributions.
- **Capacity Value** - the ability to reliably generate power on demand, especially during peak load periods.

Weather-dependent RES, lacking these attributes inherently, must be complemented by additional technologies like energy storage, distributed energy resource management systems (DERMS, including Virtual Power Plants - VPPs), or pumped hydro storage. When these system-level factors and costs are considered, the cost gap between RES and nuclear power often narrows significantly (as conceptually illustrated by the VALCOE adjustments). This is because nuclear power plays a stabilizing role, capable of continuous baseload operation irrespective of external conditions. In contrast, RES generation capacity is weather-dependent, leading to variable availability. They are non-dispatchable (generation cannot be flexibly controlled on demand) and thus necessitate additional investments in infrastructure to enhance overall system flexibility.

FIG. 6 **ADJUSTMENT OF LCOE TO VALCOE**[42]



SOURCE: International Energy Agency

Expenditures not only on energy storage and gas peaking plants but also on digitalization, smart grids (SCADA, AI, IoT), Demand Side Management (DSM), and Demand Side Response (DSR) services will increase proportionally with the share of variable renewable energy sources in the energy mix[43].

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[42] Global energy and climate model, IEA, Paris 2024, https://www.iea.org/reports/global-energy-and-climate-model, Licence: CC BY 4.0.

[43] A. Rusin, A. Wojaczek, Inwestycje jądrowe, a bezpieczeństwo energetyczne kraju, referat seminarium „Zagadnienia organizacyjne ścieżki dekarbonizacji Coal-to-Nuclear", projekt DEsire, Gliwice, 23.01.2025.

While VALCOE rightly focuses on costs and system value (providing a more accurate comparison of nuclear versus RES or fossil fuels on these grounds), like LCOE, it does not explicitly account for energy security aspects. This omission is significant, as inadequate diversification can lead to over-reliance on imported fuels and expose a country to geopolitical risks.

Regardless of whether LCOE or VALCOE is used, financing a conventional large-scale nuclear power plant project typically exceeds the capacity and risk appetite of a single private investor. **Therefore, diversifying capital sources is essential.** Even within a consortium, investors often struggle to secure debt financing without concrete government support commitments – either participation in the multi-year construction costs or guarantees for the sale of generated electricity at a price ensuring return on investment (considering that the payback period for such projects can be 20–30 years[44]). Predictable cash flows, often backed by government guarantees, are crucial for obtaining debt financing, as banks and financial institutions base lending decisions on credible estimates of future electricity sales revenue.

Faced with the challenges encountered by large-scale nuclear projects in recent decades, many engineering firms have developed designs for smaller reactors, known as Small Modular Reactors (SMRs), with planned capacities typically ranging from 75–300 MWe. According to available studies, the unit cost of energy (per kilowatt-hour) produced by an SMR is projected to be comparable to that of a conventional large nuclear power plant[45]. This is attributed to the fact that the lack of economies of scale for SMRs is potentially offset by factors like simplified safety systems (often relying more on passive features), more compact infrastructure, potential for factory fabrication, and consequently, significantly shorter construction times. **Although no commercial SMR projects based on these new designs have yet been completed and operated, it is anticipated that such investments might be less prone to the schedule delays often seen with large units**. However, as highlighted in a Polityka Insight report: "SMRs are not yet commercially available, and realistic deployment timelines differ from the declarations of some investors. The possibility of starting construction of the first units in Poland might arise around 2030. It's possible some projects will never reach commercialization, or it will occur much later than the market expects"[46].

SMR technology potentially presents a different risk profile, suggesting that support mechanisms suitable for conventional large nuclear power may not be optimal for SMRs. It is highly probable that the first SMR investment in Poland would utilize technology from a foreign vendor, likely after a first-of-a-kind (FOAK) project is operational in the vendor's home country. Consequently, due to their smaller scale, the lower contribution of a single SMR unit to overall system capacity, and lower total capital costs per project, financing models for SMRs should arguably involve a more limited role for direct consumer funding (e.g., via surcharges on electricity bills) compared to large nuclear plants.

The lower upfront capital required for SMR projects may encourage investors to seek financing outside traditional large-scale nuclear support systems. The decentralization, modularity, and application flexibility of SMRs and Generation IV reactors, coupled with the energy transition imperative, create potential for distributed deployment in industrial sectors. **This could facilitate financing through 'new' public-private partnership models, green bonds, or long-term Power Purchase Agreements (PPAs) with large energy consumers (particularly relevant for energy-intensive data centers, where 'Big Tech' investors like Google, Amazon, or Microsoft might partially finance projects as equity partners or lenders).** Unlike large reactors typically requiring substantial state support, smaller reactors addressing local needs might

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[44] The path to a new era for nuclear energy, IEA 2025, s. 95, https://www.iea.org/reports/the-path-to-a-new-era-for-nuclear-energy.

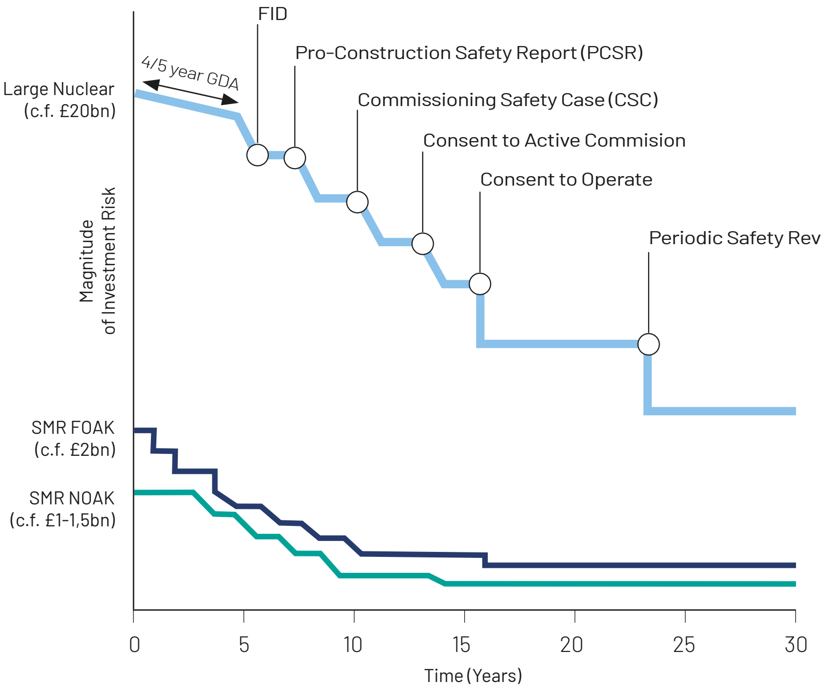
[45] A. Asuega, B.J. Limb, J.C. Quinn, Techno-economic analysis of advanced small modular nuclear reactors, „Applied Energy" 2023, vol. 334, https://www.sciencedirect.com/science/article/pii/S0306261923000338.

[46] D. Brodacki, J. Cydejko, Mały atom. Nadzieje kontra rzeczywistość, Polityka Insight, 2024, https://www.politykainsight.pl/bibliotekaraportow/2262361,maly-atom-nadzieje-kontra-rzeczywistosc.read.

develop in a more market-driven way, potentially reducing the financial burden on the general ratepayer base in the long run. Nonetheless, a key question remains: **as SMR technology matures, will a more conducive regulatory environment emerge in Poland and Europe (enabling streamlined, potentially standardized licensing and series production), or will each project require a separate, bespoke certification process (which could fundamentally limit the intended benefits of modularity).**

In the context of Coal-to-Nuclear investments, the ability to utilize existing infrastructure should partially mitigate risks that negatively impact project schedules and budgets. Therefore, **such investments will likely face different implementation challenges compared to constructing a large greenfield nuclear power plant.**

FIG. 7 **DISTINCT FINANCIAL RISK PROFILES FOR LARGE NUCLEAR POWER PLANTS AND SMRS**[47]



SOURCE: World Nuclear Association

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47 S. Bilbao y Leon, Financing nuclear power projects in the UNECE region, World Nuclear Association, 2021, https://unece.org/sites/default/files/2021-10/Sama-Bilbao-y-Leon-Financing_Oct_21.pdf.

5.2 AVAILABLE SUPPORT MECHANISMS FOR NUCLEAR PROJECTS

A range of support instruments exists for conventional nuclear projects. Securing at least some of these is often essential for investors to reach a Final Investment Decision (FID).

Over recent decades, countries incorporating nuclear power into their energy mix have developed various mechanisms to support these projects. A common feature is the presence of direct government-level support (e.g., through a stable regulatory environment). A model that has recently gained prominence for large-scale nuclear projects is the Contract for Difference (CfD), partly due to the European Commission's favorable stance towards it.

Other mechanisms, either previously tested or currently proposed as alternatives addressing CfD's limitations, include Build-Operate-Transfer (BOT) and the Regulated Asset Base (RAB) model. A distinct approach, successfully implemented in Finland among others, is the cooperative energy model (e.g., Mankala); this concept has been adapted to Polish conditions by domestic experts within the SaHo Model.

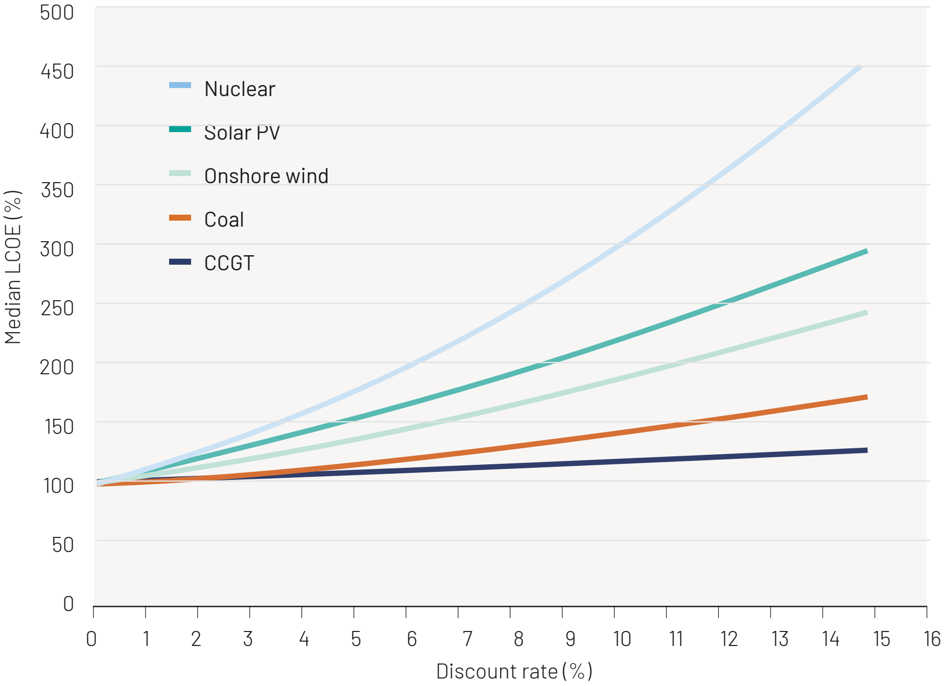
These mechanisms warrant closer examination and assessment in the context of Polish investments in large-scale nuclear power or SMRs, including those pursued via the Coal-to-Nuclear pathway.

5.2.1 CONTRACT FOR DIFFERENCE (CFD)

This model has long been used outside the nuclear sector for projects relying on project finance, such as renewable energy farms (wind and photovoltaic) and, in the UK, gas-fired combined heat and power (CHP) projects. A CfD entails the project developer being responsible for covering construction costs in return for a guarantee to sell the generated electricity at a pre-agreed fixed price (strike price) for a specified duration (typically 15–35 years for renewables, potentially longer, e.g., up to 60 years, for nuclear, depending on the plant's expected lifetime and specific contract terms).

In the UK, the Hinkley Point C nuclear power station project, with EDF as the lead investor, is financed using this model. **The construction risk is borne primarily by the developer. Ultimately, however, consumers bear the cost through adjustments to their bills reflecting the difference between the wholesale market reference price and the agreed *strike price*.** If the market price is below the strike price, consumers cover the difference; if above, they receive the difference back. This cost/benefit is typically realized on consumer bills only after the power plant becomes operational.

FIG. 8 **FIGURE 8. IMPACT OF DISCOUNT RATE ON LCOE FOR VARIOUS TECHNOLOGIES (EXAMPLE)**[48]



SOURCE: OECD Nuclear Energy Agency

It must be emphasized that the final capital expenditure of a nuclear project is significantly influenced by the prevailing economic conditions. Rising inflation, leading to higher interest rates and discount rates, increases the cost of capital. **The cost of capital profoundly impacts the project's business model: a higher cost necessitates a higher electricity sale price to ensure an adequate Return on Investment (ROI)**[49]. In the case of Hinkley Point C, construction delays (and the resulting enormous cost overruns)[50] directly impacted the interest accrued under loan agreements throughout the prolonged construction period. **A higher cost of capital inflates the total CAPEX, potentially meaning that an investor (without additional support) might never achieve the expected return on their investment.**

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48 Economics of nuclear power, 29.09.2024.

49 Ibidem.

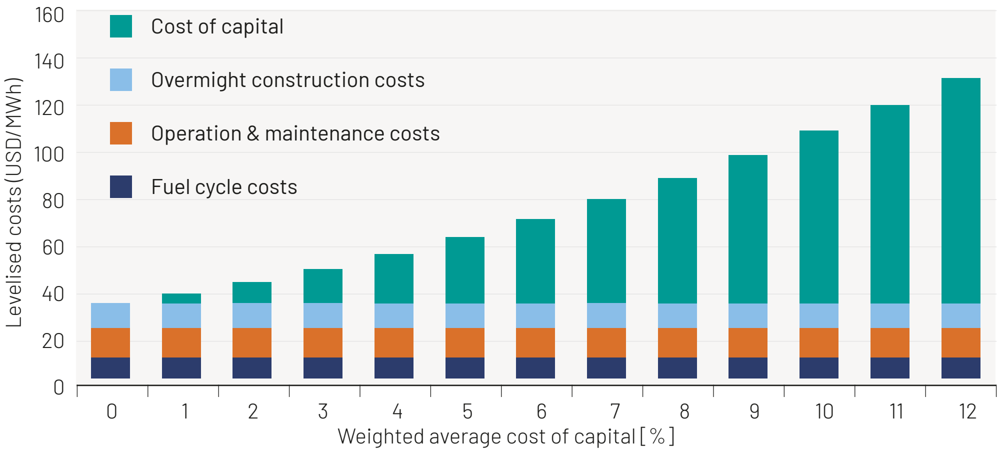
50 Hinkley Point C was originally scheduled to open in 2025 at a budget of £18 billion. The first reactor is now expected to open in 2029, with a budget of £46 billion.

TAB. 1 ESTIMATED LCOE FOR NTH-OF-A-KIND (NOAK) NUCLEAR PROJECTS (USD/MWH) BY COUNTRY[51]

COUNTRY	At a discount rate of 3%	At a discount rate of 7%	At a discount rate of 10%
France	45,3	71,1	96,9
Japan	61,2	86,7	112,1
South Korea	39,4	53,3	67,2
Slovakia	57,6	53,3	67,2
USA	43,9	71,3	98,6
China	49,9	66,0	82,1
Russia	27,4	42,0	56,6
India	48,2	66,0	83,9

SOURCE: OECD IEA&NEA.

FIG. 9 LCOE OF A NEW NUCLEAR POWER PLANT PROJECT DEPENDING ON CAPITAL COSTS[52]



Note: MWh = megawatt hour. Calculations based on OCC of USD 4500 per kilowatt of electrical capacity (/kWe), a load factor of 85%, 60-Year lifetime and 7-year construction time

SOURCE: NEA

The fact that under the CfD model, the developer bears the full construction risk has contributed to the cancellation of other planned UK nuclear projects in recent years – Hitachi's Wylfa Newydd in Wales and Toshiba's Moorside in Cumbria. Consequently, another EDF project, Sizewell C, is planned to be financed using the RAB model instead.

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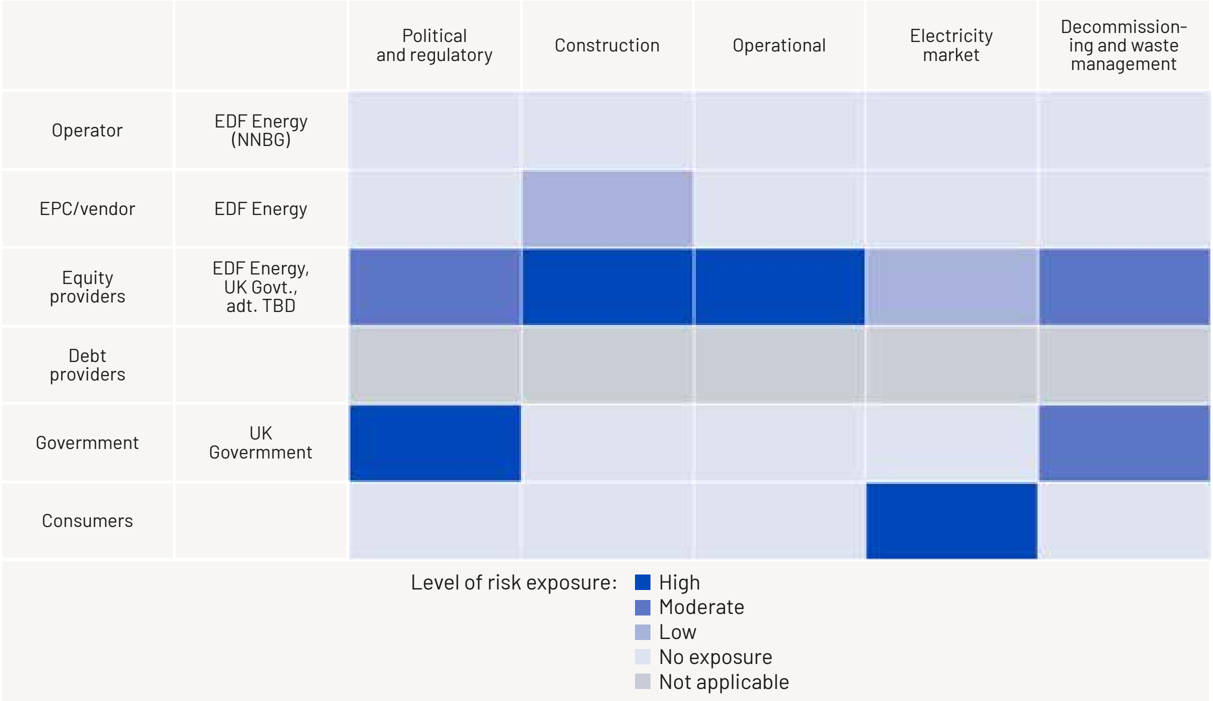
[51] Projected costs of generating electricity, 85% współczynnik wydajności, wartość dolara z 2018 r., OECD IEA & NEA, 2020, https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.

[52] Unlocking reductions in the construction costs of nuclear, NEA, OECD Publishing, Paris 2020, https://www.oecd-nea.org/jcms/pl_30653/unlocking-reductions-in-the-construction-costs-of-nuclear.

TAB. 2 **ALLOCATION OF KEY RISKS ASSOCIATED WITH THE HINKLEY POINT C PROJECT WITHIN THE CFD MECHANISM**[53]



		Political and regulatory	Construction	Operational	Electricity market	Decommissioning and waste management
Operator	EDF Energy (NNBG)	□	□	□	□	□
EPC/vendor	EDF Energy	□	▧	□	□	□
Equity providers	EDF Energy, UK Govt., adt. TBD	▨	■	■	▧	▨
Debt providers		░	░	░	░	░
Govermment	UK Govermment	■	□	□	□	▨
Consumers		□	□	□	■	□

Level of risk exposure:
■ High
▨ Moderate
▧ Low
□ No exposure
░ Not applicable

SOURCE: Clean Air Task Force

Meanwhile, at the EU level, the Council of the European Union approved an electricity market reform in 2024 that identified two-way Contracts for Difference (or equivalent direct price support schemes) as the preferred mechanism for new investments in low-carbon electricity generation[54]. Around the same time (30 April 2024), **the European Commission issued a positive decision regarding the Czech Republic's application of a CfD mechanism for the Dukovany II nuclear power plant project**[55].

As part of this decision, the Commission outlined several conditions for this form of state aid:

- The CfD will be in force for 40 years (instead of the 60 years proposed by the Czech Republic).
- Electricity generation levels should respond to market signals and price fluctuations. The Commission stated that **the absence of special protection from market mechanisms would prevent distortions of competition and the displacement of RES, benefiting the electricity system and the decarbonization process**[56].

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[53] Financing nuclear energy in Poland, 9.12.2024, https://www.catf.us/resource/financing-nuclear-energy-poland/

[54] Reforma rynku energii elektrycznej: Rada zatwierdza zaktualizowane przepisy, 21.05.2024, https://www.consilium.europa.eu/pl/press/press-releases/2024/05/21/electricity-market-reform-council-signs-off-on-updated-rules/; Tekst rozporządzenia: https://data.consilium.europa.eu/doc/document/PE-1-2024-INIT/pl/pdf.

[55] European Commission Decision on the measure State aid SA.58207 (2021/N) which Czechia is planning to implement to support the construction and operation of a new nuclear power plant at the Dukovany site, 30.04.2024, https://ec.europa.eu/competition/state_aid/cases1/202511/SA_58207_572.pdf

[56] Commission approves State aid to support construction of nuclear power plant in Czechia, 30.04.2024, https://ec.europa.eu/commission/presscorner/detail/en/ip_24_2366.

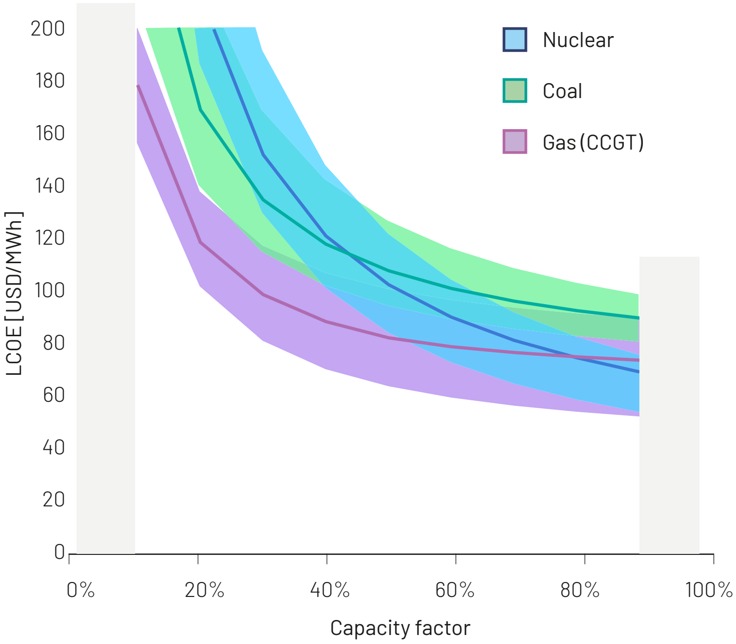
Throughout the plant's operational life, **at least 70% of the electricity generated by Dukovany II must be sold on the open power exchange** (e.g., day-ahead, intraday, or futures markets). The remaining maximum 30% can be sold through objective, transparent, and non-discriminatory auctions, allowing winners to conclude Power Purchase Agreements (PPAs). These conditions aim to prevent market concentration and the risk that the CfD might unduly favor specific electricity consumers.

According to some experts, the logical consequence of these conditions is **that the Dukovany II plant might be forced to operate more like a peak-load or mid-merit plant, serving effectively as a backup for variable RES, rather than as a traditional baseload generator**[57]. Such an operating model contradicts the typical role of nuclear power, which relies on continuous, stable generation due to its inherent characteristics and limited operational flexibility (regarding frequent shutdowns and startups).

Operating at a lower capacity factor would naturally lead to an increase in the LCOE and, consequently, a potentially wider spread between the strike price and the market reference price, increasing the subsidy amount due to the investor per MWh produced. Furthermore, under such an operational regime (regardless of the reactor's technical flexibility), the plant would generate fewer megawatt-hours overall, potentially creating cash flow challenges for the investor and hindering their ability to achieve the expected return on investment.

Additionally, the requirement to sell a maximum of 30% of generation through bilateral long-term contracts with buyers selected under market conditions limits the investor's flexibility in securing strategic partners (and offtakers) for the project[58].

FIG. 10 **LCOE OF NUCLEAR, GAS, AND COAL PROJECTS DEPENDING ON CAPACITY FACTOR**[59]



SOURCE:

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[57] B. Horbaczewska, Pierwsza polska elektrownia jądrowa, 10.12.2024, https://gazeta.sgh.waw.pl/meritum/pierwsza-polska-elektrownia-jadrowa.

[58] Ibidem.

[59] Projected costs of generating electricity 2020, IEA, Paris 2020,. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, Licence: CC BY 4.0.

Given these conditions imposed on the Dukovany II project and the Commission's analysis during its assessment, it is reasonable to anticipate **that similar stipulations might apply to Poland's first planned nuclear power plant in the Lubiatowo-Kopalino area**, where the investor also intends to use a CfD support mechanism (notification has already been submitted to the European Commission).

This situation raises legitimate concerns about whether CfD is indeed the optimal mechanism for subsequent Polish nuclear projects, including those following the Coal-to-Nuclear (CtN) pathway.

Based on the Dukovany II decision, it can be inferred that **the European Commission holds a specific view on the role of nuclear power within the electricity systems of Member States opting for new nuclear builds**. Following the reasoning of the Directorate-General for Competition (DG COMP), nuclear power should arguably be subordinate to the primacy of RES, potentially even at the expense of consumers and taxpayers. **This apparent dogma of preferential treatment for RES and the effective prohibition against their displacement by other low-carbon technologies (like nuclear power plants) seemingly disregards the VALCOE perspective – the total system cost of an RES-dominated energy transition, including the necessity for large-scale energy storage and significantly higher grid expenditure.**

Therefore, the European Commission appears to have established a specific interpretation regarding CfDs for nuclear power. This, combined with the aforementioned risk of sharp increases in the cost of capital due to construction delays, **underscores the need to consider support mechanisms other than 'direct price support' for future Polish nuclear projects, including Coal-to-Nuclear initiatives.**

Advantages: CfDs undoubtedly provide investors with revenue stability for a portion of their output over a long period (e.g., 20–40 years), provided the plant operates and sells into the market. Such guarantees are often essential (especially for large-scale investments) to secure debt financing for construction. CfDs have proven successful in the UK for deploying offshore wind capacity and, to a lesser extent, for CHP projects[60]. It is a widely used support mechanism in the power sector.

Disadvantages: The success of a CfD-based project is highly dependent on the economic climate, particularly the cost of capital, leading up to the FID. A guaranteed price agreed upon earlier with the government might become insufficient for debt servicing if financing costs rise significantly, potentially hindering project finance feasibility. Furthermore, if FID is reached but construction delays occur, accrued interest costs will increase the overall project cost, which may ultimately translate into higher costs for end consumers. Within the EU context, the European Commission's current state aid policy interpretation (evident in the Dukovany II decision) potentially significantly limits the perceived benefits of using CfDs for baseload nuclear power.

Application for Coal-to-Nuclear pathway

Contracts for Difference could be an effective support mechanism for both SMRs and Coal-to-Nuclear investments, provided these generation assets are intended and allowed to operate as baseload power sources. In both cases, revenue stability can facilitate financing and accelerate technology deployment. However, the CfD model would likely need tailoring to the specifics of these technologies, perhaps by differentiating strike prices for subsequent units based on deployment year, location, or additional functionalities provided (e.g., heat for industry or district heating).

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[60] Kent heat and power plant becomes UK's first energy-from-waste CfD facility, 14.08.2020, https://www.businessgreen.com/news/4019013/kent-heat-power-plant-uk-energy-waste-cfd-facility.

5.2.2 REGULATED ASSET BASE (RAB)

This is a financing model proven in the UK for large-scale infrastructure projects involving airports, water and sewage systems, gas pipelines, and electricity transmission networks.

In 2022, the UK government under Rishi Sunak passed the Nuclear Energy (Financing) Act, **enabling the application of this model to new nuclear projects in Great Britain.**

Under the RAB model, the investor receives a license from the regulator allowing them to charge consumers a **regulated amount during the construction phase, which contributes towards financing the project**. In return, the investor commits to completing the investment and commissioning the power plant, subject to certain exemptions for defined high-impact, low-probability events. Thus, end consumers participate in financing the plant's construction and eventual operation from the outset. The investor does not bear the full construction risk alone; the model typically includes government support mechanisms or guarantees that may activate under specific circumstances or above certain cost thresholds. **The costs recovered through consumer charges during construction are reflected in end-user bills before the plant generates electricity.** This approach aims to avoid the significant accumulation of interest during construction (IDC) associated with traditional debt financing, which ultimately inflates the total costs recovered from consumers post-commissioning.

According to analysis commissioned by the UK government, **the RAB model is projected to deliver lower overall costs to consumers, potentially saving up to GBP 30 billion over the project's lifetime compared to the CfD model used for Hinkley Point C. This is achieved while maintaining appropriate incentives for the investor to minimize delays and budget overruns**[61]. The model assumes the government can effectively assess and allocate risks before investment begins and implement incentives that motivate the investor to prevent major delays and cost escalations.

However, it is undeniable that the RAB system shifts a significant portion of the construction risk to consumers before they receive any direct benefit (electricity) from the investment. **Critics argue it exemplifies the socialization of costs and risks while allowing the investor to retain the primary benefits (profits)**. On one hand, consumers effectively provide zero-interest financing through surcharges; on the other, taxpayers may ultimately provide a backstop guarantee if unforeseen events halt construction.

Furthermore, it remains an open question **whether RAB is the most suitable support scheme for modular SMR projects.** For SMRs, the risk of construction delays and cost escalation is potentially lower due to their smaller scale, and securing offtake contracts (e.g., via power purchase agreements) for the entire plant output might be easier. For such projects, financing through the investor's own balance sheet, green bonds[62], or traditional project finance debt might be relatively more feasible due to the lower overall CAPEX required per project compared to large NPPs.

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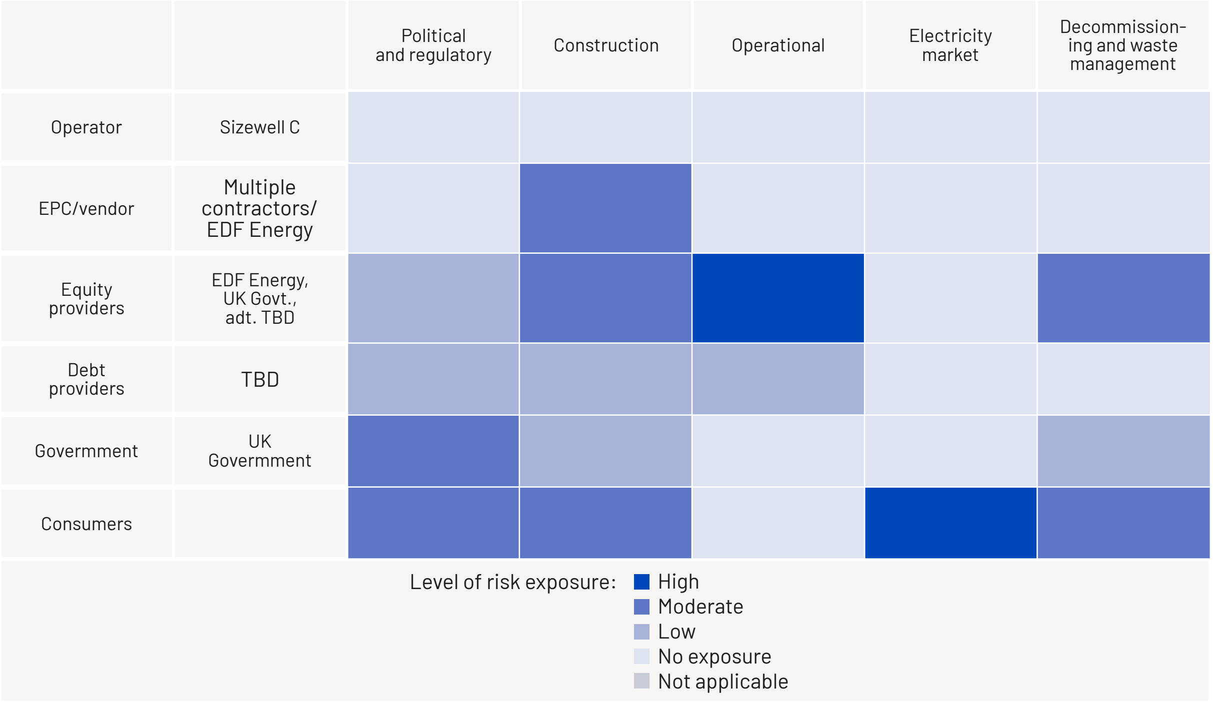
[61] New finance model to cut cost of new nuclear power stations, 26.10.2021, https://www.gov.uk/government/news/new-finance-model-to-cut-cost-of-new-nuclear-power-stations.

[62] OPG expands green financing to include new nuclear, 26.06.2024.

TAB. 3 **EXPECTED ALLOCATION OF KEY RISKS ASSOCIATED WITH THE SIZEWELL C PROJECT WITHIN THE RAB MECHANISM**[63]



		Political and regulatory	Construction	Operational	Electricity market	Decommissioning and waste management
Operator	Sizewell C	░	░	░	░	░
EPC/vendor	Multiple contractors/ EDF Energy	░	▓	░	░	░
Equity providers	EDF Energy, UK Govt., adt. TBD	▒	▓	█	░	▓
Debt providers	TBD	▒	▒	▒	░	░
Govermment	UK Govermment	▓	▒	░	░	▒
Consumers		▓	▓	░	█	▓

Level of risk exposure:
█ High
▓ Moderate
▒ Low
░ No exposure
□ Not applicable

SOURCE: Clean Air Task Force

Researchers from the University of Cambridge calculated[64] that **financing construction costs through an additional consumer charge (under specific assumptions, including a 2% discount rate) could potentially lower the project's LCOE to GBP 50/MWh (approx. PLN 250/MWh)**. The estimated additional cost per UK household (based on 27 million households) was GBP 4 per year during construction. However, it is crucial to note **these calculations were performed in 2019, before the recent inflationary period and significant interest rate hikes, and thus may not fully reflect currently required CAPEX levels**[65].

Advantages: The proposal to use the RAB model for nuclear projects is an attempt to address issues encountered with the CfD-financed Hinkley Point C project in the UK. By establishing a clear regulatory framework and oversight mechanism, the government aims to provide transparency and financial predictability, enhancing investment credibility. The RAB model mitigates the risk of escalating financing costs due to construction delays by allowing approved costs to be progressively recovered from consumers. The investor is shielded from accumulating excessive interest during construction through the regulated consumer charge, meaning cost recovery begins in real-time, not just post-commissioning. This structure theoretically reduces project risk, potentially lowering the cost of capital (access to cheaper debt).

Disadvantages: The RAB model faces criticism for potentially privatizing profits while socializing costs, as it shifts significant construction risk to consumers to protect the investor's ROI. This could encounter

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[63] Financing nuclear energy in Poland, 9.12.2024, https://www.catf.us/resource/financing-nuclear-energy-poland/.

[64] D. Newbery i in., Financing low-carbon generation in the UK: The hybrid RAB model, EPRG Working Paper no. 1926, Cambridge University, 2019, https://www.jbs.cam.ac.uk/wp-content/uploads/2023/12/eprg-wp1926.pdf.

[65] New Perspectives for Financing Nuclear New Build, OECD, NEA, 2022, https://www.oecd-nea.org/upload/docs/application/pdf/2022-12/7632_nea_financing_report.pdf; D. Newbery i in., Financing low-carbon generation in the UK: The hybrid RAB model.

social and political resistance, particularly if delays occur. It might also make abandoning a project more difficult, even if market conditions or project economics deteriorate significantly.

Application for Coal-to-Nuclear pathway

The RAB model could potentially be used to finance investments based on the Coal-to-Nuclear concept, but likely only if these investments result from a strong socio-political consensus. This consensus would need to affirm that a specific project in a specific location serves clear energy transition and national energy security goals, with tangible and quantifiable benefits. Developing the detailed assumptions for long-term RAB support would be challenging in the Polish context, requiring resilience against shifting political interests across successive governments.

5.2.3 BUILD-OPERATE-TRANSFER (BOT)

This model typically involves foreign investors who receive a concession to build and operate a facility (like a power plant) for a specified period. After this period expires, they are required to transfer ownership and operation of the infrastructure to the host government or a designated state-owned entity. The mechanism aims to attract foreign capital when there is a shortage of suitable domestic investors or insufficient capacity in the domestic financial market. It is a form of Public-Private Partnership. Key elements defined within a BOT model include the concession duration, financial terms, and facility management arrangements. Examples of BOT usage outside the energy sector include investments in transport infrastructure like highways and airports.

One nuclear power project initially planned under this framework was **the Sinop power plant on Turkey's Black Sea coast**. The Turkish government signed an agreement with a consortium comprising Mitsubishi Heavy Industries (MHI) and EDF, supported by the Japanese government and the Japanese conglomerate Itochu. However, the agreement was ultimately terminated in 2018 due to significant construction cost escalations (linked to required safety upgrades following the Fukushima accident, as Sinop is in a seismically active zone) and the devaluation of the Turkish lira.

Using this model (e.g., potentially combined with long-term PPAs, as reportedly planned for Sinop) in the Polish market for large-scale power plants would likely be problematic. **Infrastructure of that scale is considered strategic, necessitating state control.**

However, BOT or similar structures might be attractive to large IT companies (like Google or Amazon) seeking to power their own data centers with a reliable, dedicated energy source, potentially utilizing SMRs.

Advantages: BOT can be a suitable solution when the host country lacks the technological know-how or domestic entities willing and able to undertake the project risk. The private investor has a strong incentive to ensure project profitability during the concession period, potentially leading to efficient energy sales management and cost optimization. This model might also be viable when a foreign investor plans to build a smaller-scale plant primarily to supply its own facilities (e.g., a data center).

Disadvantages: BOT projects typically require long operational periods or the ability to charge high fees/tariffs for the investor to recoup their substantial upfront investment. Over-reliance on BOT for critical infrastructure could generate national security risks. If the private investor encounters financial difficulties, the host government might be forced to renegotiate the investment agreement, potentially incurring additional public costs.

Application for Coal-to-Nuclear pathway

For projects of strategic national importance, such as those envisioned under the Coal-to-Nuclear concept, leaving the decision to proceed or abandon the investment solely in the hands of a foreign investor (responsible for both technology and capital) is likely not optimal from the host country's perspective. Furthermore, nuclear power plants receive special scrutiny due to the global consensus on non-proliferation of fissile materials. Perhaps, with the dynamic development of the SMR segment and associated advancements in safety and security, opportunities may arise in the future to discuss alternative ownership models, potentially including greater private sector participation, even for these types of investments.

5.2.4 THE SAHO MODEL

The alternative SaHo model was developed by Dr. Bożena Horbaczewska of the SGH Warsaw School of Economics and Łukasz Sawicki, a nuclear industry analyst. **It is based on the cooperative model that has proven successful in Finland (the Mankala model).**

According to the model's authors, SaHo's primary distinguishing feature is **its objective: to deliver electricity to end-users at the lowest possible cost, rather than (as with CfD) generating an acceptable return on investment for the project developer/investor.** In other words, under SaHo, the Special Purpose Vehicle (SPV) established for the project is not profit-oriented; the electricity generated by the nuclear power plant is intended to be sold at cost to its owners (shareholders).

In this model, the 'primary investor' (which, depending on the specific SaHo variant, could be the state or an equivalent entity[66]) establishes a joint-stock company (the SPV) to build and operate the power plant. The primary investor thus assumes most of the investment risk during the initial project phases, including political, regulatory, and economic risks. Subsequently, shares in the SPV are sold to end-users of the energy (referred to as 'end-investors' – potentially encompassing industrial companies, municipalities, or even households) at any point during construction as the project progresses**. These sales are conducted on market principles, potentially via auctions. Shareholders acquire both the right and the obligation to offtake electricity at the cost of generation, proportionally to their ownership stake.** The authors describe this as "a state-initiated (and possibly state-controlled) para-cooperative of energy end-users"[67]. Given the structure of the Polish power sector (with a significant presence of State Treasury Companies[68]), it is difficult to envision the SaHo Model being implemented at this stage without state participation as the primary investor (either directly or, perhaps for smaller projects, through a state-controlled utility). Therefore, for this chapter, we assume the Polish state would act as the primary investor.

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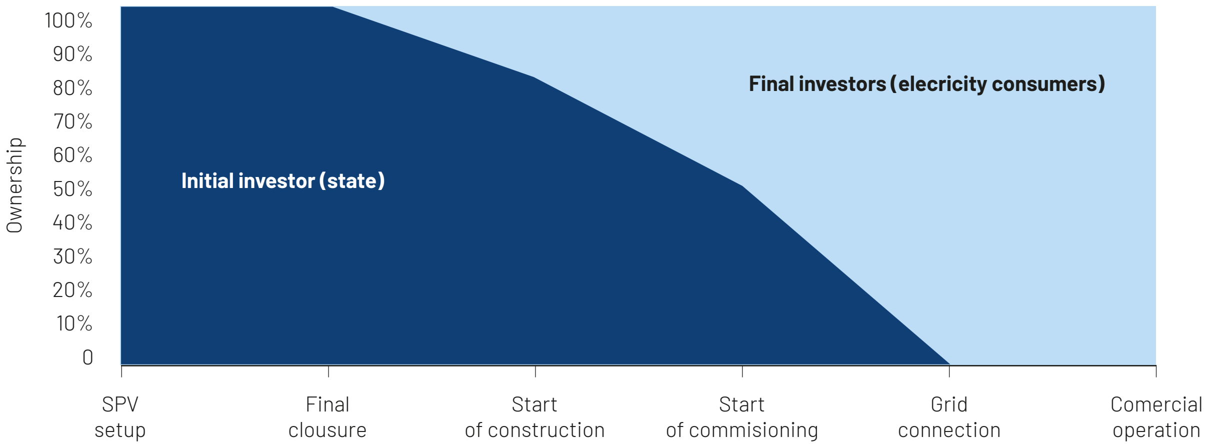
[66] In both the initial and basic versions, the authors indicated the state as the primary investor. Model versions were also developed where the second (next to the state) or the only primary investor is a private entity that meets certain conditions: (a) is able to take on the risk of the construction period, (b) guarantees the completion of the project, (c) has access to cheap capital, (d) its goal is to sell shares to final investors before the nuclear power plant is launched. An experienced technology supplier associated with large financial institutions is cited as an example of such an investor. Source: https://sahomodel.pl/o-modelu/.

[67] Czym jest Model SaHo?, https://sahomodel.pl/o-modelu/.

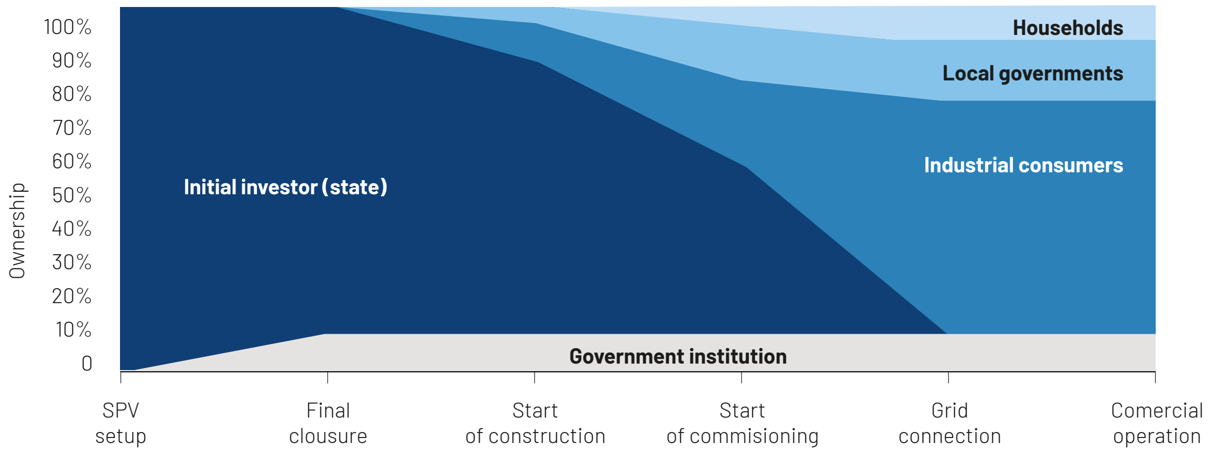
[68] Spółki Skarbu Państwa gwarantem bezpieczeństwa energetycznego Polski, 12.10.2022, https://www.gov.pl/web/aktywa-panstwowe/spolki-skarbu-panstwa-gwarantem-bezpieczenstwa-energetycznego-polski.

FIG. 11 **SAHO MODEL – BASIC VERSION**[69]



SOURCE: sahomodel.pl

FIG. 12 **SAHO MODEL – VERSION WITH DIFFERENT TYPES OF FINAL INVESTORS**[70]



SOURCE: sahomodel.pl

Under current regulations, selling electricity from a nuclear power plant on the open energy market faces uncertainty because RES generation has priority access[71], not only for grid connection but also for dispatch under the merit order system. **SaHo is therefore conceived as a model operating largely outside the fully deregulated energy market,** where variable purchase prices create revenue uncertainty.

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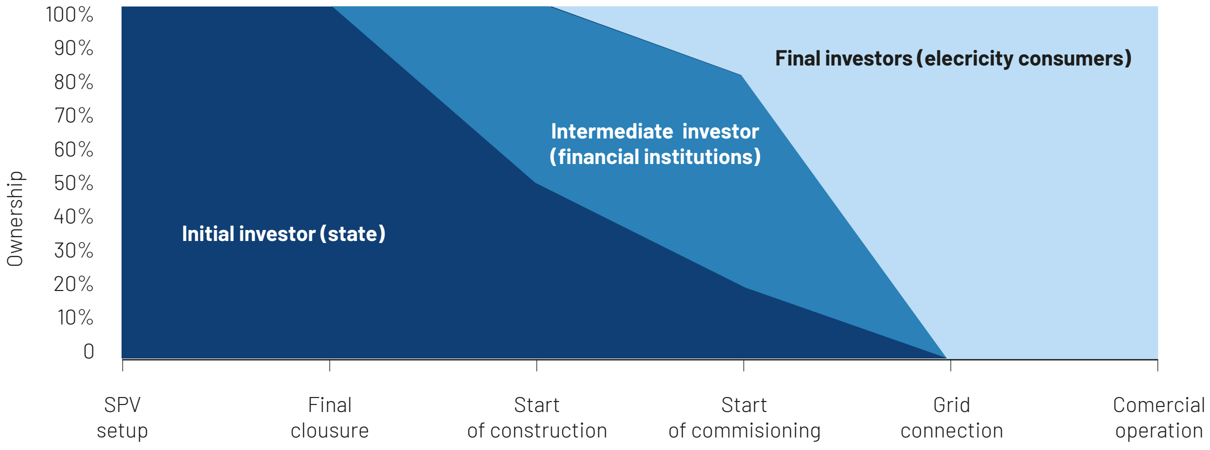
[69] Czym jest Model SaHo?, https://sahomodel.pl/o-modelu/.

[70] *Ibidem.*

[71] For example, the latest nuclear power plant in the Czech Republic cannot compete with renewable energy sources (displace them from the market). Therefore, CfDs must compensate for the risk of not selling energy.

FIG. 13 **SAHO MODEL - VERSION WITH INTERMEDIATE INVESTOR(S)**[72]



SOURCE: sahomodel.pl

Within this model, there is also the possibility of trading SPV shares during construction, which might attract financial investors (e.g., mezzanine funds) due to the potential for high returns upon successful project completion and share resale to end-investors.

Advantages: The state (assuming a state entity is the primary investor in Poland) can potentially finance construction at a lower cost of capital due to its low insolvency risk and access to preferential financing compared to private developers. For end-investors, shares acquired under the SaHo model could be viewed as a safe investment and a hedge against inflation, as their implicit value would likely rise alongside open market energy prices. **Owner-consumers purchase electricity (proportional to ownership) from "their own" plant at generation cost, without profit margins or intermediaries.** This avoids financing the project through tariff surcharges on general consumers (unlike RAB). Importantly, the Finnish Mankala model and the proposed Polish SaHo model **are argued to be compliant with EU regulations – they are not direct price support mechanisms but are based on self-consumption and energy community principles, aligning with EC guidelines on energy market development**. SaHo could be particularly relevant for industrial clusters with numerous energy-intensive companies, where individual firms might purchase shares proportional to their energy needs. Another potential advantage is an inherent "money recycling" mechanism: funds raised from selling shares in the first completed plant/unit could finance subsequent nuclear investments, enabling the construction of multiple units with lower net public outlay over time.

Disadvantages: The SaHo model (and its various versions, numbering eight at the time of writing) is currently conceptual. Thus, discussing disadvantages based on practical implementation experience is impossible. However, drawing on historical experience in the energy sector and international financial markets, potential challenges for the 'initial' or 'basic' SaHo versions (considered most likely for Poland) can be identified.

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[72] Czym jest Model SaHo?, https://sahomodel.pl/o-modelu/.

In the Polish context, lacking a well-developed energy cooperative tradition like Finland's[73], a state entity would likely need to initiate construction and then sell shares to interested energy-intensive buyers. The initial/basic SaHo versions require significant state commitment and upfront expenditure (e.g., from the state budget) during the high-risk early development and construction phases. In an era of increased fiscal discipline (following years of low interest rates) and pressure to leave project risk assessment and financing to the private market, a government opting for SaHo[74] (or any state-led mechanism) would likely face criticism regarding the efficient use of public funds, at least until shares are successfully sold. Capital-intensive projects in highly politicized environments face significant systemic risks, including unstable political support, reduced implementation efficiency, and lack of transparency, especially across government changes. In the SaHo context, this could deter end-investors from committing capital, potentially leading to the state failing to divest the intended shareholding[75]. Early dialogue with potential end-investors to understand expectations and manage risks would be crucial. However, even with preliminary agreements, **end-investors would not be bound by final contracts imposing obligations and risks comparable to those borne by developers under other support mechanisms until much later in the process.**

Determining the share sale price also presents a challenge. Post-construction, the price must be attractive to end-investors (considering the risk profile and long-term nature) but cannot expose the primary investor (State Treasury) to losses or accusations of mismanagement. While one might argue the "market" will set the price, it would likely be a thin market (limited to entities prepared to be long-term end-users/offtakers, unlike Mankala which includes traders) with limited liquidity. The "security" traded would be shares in a specific power plant, without (unlike Mankala) the ability to easily resell unused energy on the spot market[76]. Building a liquid secondary market for these shares, comparable to, say, the market for Guarantees of Origin, would be challenging.

Therefore, while SaHo theoretically allows end-investors to buy/sell shares at any time[77], trading would likely be subject to restrictions (e.g., pre-emption rights for existing shareholders, lists of ineligible buyers). This could make SaHo less attractive to energy-intensive end-investors needing flexibility to adjust energy offtake in response to economic cycles (affecting demand for their products). Such investors would likely demand a purchase price reflecting this inflexibility risk (akin to the commitment of a 'take-or-pay' PPA clause but with limited resale options for the underlying 'asset' – the shares). Consequently, there is no guarantee the price end-investors are willing to pay would allow the primary investor (the state) to break even or achieve a positive return on its initial investment.

Creating a strategy to involve municipalities (partially considered in SaHo's extended version C) and enabling share transfers within local government structures could be a partial solution, but a coherent framework for such joint energy financing by municipalities does not currently exist in Poland.

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[73] This fact was one of the key premises for the authors indicating the need to develop an alternative para-cooperative model.

[74] As the authors themselves admit, the initial variant would also be adequate for FOAK technologies such as SMR; source: https://sahomodel.pl/o-modelu/.

[75] In the case of the SaHo model, there is a risk that the investment could be criticised on the grounds that the state is supporting specific end investors rather than 'ordinary citizens'. Whereas in the case of the CfD mechanism, the equivalent of an 'end investor' is not strictly defined, so it is potentially easier to argue in public debate that a 1 GW+ nuclear power plant will serve the general public.

[76] Investors in the Mankala cooperative model have the option of reselling surplus energy on the NordPool market.

[77] https://sahomodel.pl/korzysci/.

Application for Coal-to-Nuclear pathway

The SaHo model is evolving and holds potential (especially for industrial clusters), seemingly aligning with the principle of meeting local demand, which is relevant for Coal-to-Nuclear projects potentially based on SMRs. SMRs can be built incrementally, fitting the concept of gradual share acquisition by investors. However, it must be stressed that all SaHo model versions remain conceptual and untested in any real-world nuclear power plant investment[78]. As Coal-to-Nuclear projects themselves are novel, comparative data on the model's suitability for such investments is unavailable. If SaHo were effectively adapted, a major advantage would be the ability to reinvest funds from share sales into subsequent Coal-to-Nuclear projects, facilitating further sector transformation.

5.3 PREFERRED FINANCIAL MODELS FOR NUCLEAR PROJECTS IN POLAND

For Poland's first planned nuclear power plant at the Lubiatowo-Kopalino site, the Polish government selected the CfD support system. A likely motivation for this decision was the desire **to obtain a positive state aid decision from the European Commission as quickly as possible**. However, considering international experiences (including the UK's), it is pertinent to question whether CfD is the most appropriate model for deploying a program of large-scale nuclear power plants. **If the primary objective is ensuring the affordability of electricity generated – thereby supporting the competitiveness of the Polish economy and fostering public acceptance – it is worth considering whether this goal could be achieved more effectively using an alternative model.**

Given that the choice of support system profoundly impacts project success, decisions regarding subsequent nuclear investments should be preceded by in-depth analysis. The government, in collaboration with experts, must develop an optimal, long-term support framework for Polish nuclear energy.

Mario Draghi's widely discussed report on European competitiveness (or lack thereof) identifies nuclear power as a vital component of the European energy mix. However, this perspective does not seem to be shared by the European Commission's Directorate-General for Competition (DG COMP).

Therefore, in the context of its national nuclear program, including potential Coal-to-Nuclear (CtN) projects, the Polish state should develop a 'Plan B'. This is necessary in case the conditions imposed by the European Commission on the CfD for the Lubiatowo plant undermine the rationale for using this mechanism for future investments from the outset. **Poland cannot afford to implement a coal-to-nuclear transition strategy only to find itself unable to operate these nuclear assets efficiently as baseload power sources.** As previously outlined, CAPEX constitutes the vast majority of a nuclear project's lifetime cost, with fuel costs being relatively minor. **Operating a nuclear plant in a peak-following or reserve mode defeats its economic purpose and hinders the ability to achieve a return on investment** (especially considering the negative impact of higher interest rates, and thus a higher cost of capital, on nuclear project profitability).

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[78] While the energy cooperative model was the starting point for SaHo, it has features (necessary due to Polish conditions) that differ significantly from, for example, the Finnish Mankali, which has been operating successfully for decades.

Consequently, an alternative support model, not relying on a conventional CfD-type price regulation mechanism, should be developed and proposed for future projects. Given that the Mankala model (Finland's cooperative approach) has precedents accepted by the Commission, and the SaHo Model was specifically designed with the Polish energy sector in mind, **establishing an inter-ministerial team to conduct a comprehensive analysis of nuclear financing models is recommended. This team's task would be to determine the optimal risk allocation between public entities (the state) and the private sector under Polish conditions**. The analysis should aim to identify a mechanism for subsequent projects (including Coal-to--Nuclear) **that maximizes the chances of successfully implementing these strategic investments (by appropriately allocating associated risks) while simultaneously fostering public acceptance** (e.g., through cost-effectiveness leading to lower electricity costs for consumers). The analysis should therefore also **consider derivative or hybrid models beyond those presented in this report**, as support mechanisms should evolve alongside the maturation of Poland's nuclear energy market.

DRAW. 4 **SPECTRUM OF SUPPORT MECHANISMS BASED ON RISK ALLOCATION BETWEEN THE STATE AND PRIVATE INVESTORS**

State Owned
Significant state control through entire project lifecycle with majority or significant State ownership.

SaHo model
The State as initial investor takes risk up to grid connection, with final investors obligated to purchase 'power at cost'.

Regulated Asset Base (RAB)*
A licensee nuclear company delivers the project, with investor return set by a regulator into perpetuity.

Contracts for Difference*
Contract between generator and state backed counterparty provides price certainty over contract period.

Power Purchase Agreements (EU)
Long-term offtake agreements with private sector to buy output per a revenue formulae.

Mankala Model
Cooperative ownership model, with investors obligated to purchase 'power at cost' from the project company.

* In extreme situations (high impact events), the government may be forced to take over responsibility for the project.

SOURCE: Own work (based on KPMG data).

Concurrently, the Polish government should actively advocate for translating the energy-related theses of the Draghi report into European Commission policy. Key priorities include integrating nuclear energy into EU support funds currently reserved primarily for RES, and broadening the scope of binding energy transition targets for Member States from solely renewable sources to encompass all zero-emission sources. Our perspective on this aligns with that of the Polish Economic Institute[79].

Now that many RES projects have achieved full commercial viability, the preferential treatment afforded to renewable sources by the European Commission may no longer meet the proportionality criteria often cited by DG COMP. It is high time for EU policy in this area to change, moving away from discrimination against other zero-emission sources and restoring nuclear energy to its foundational role recognized since the inception of the EU (vide the Euratom Treaty).

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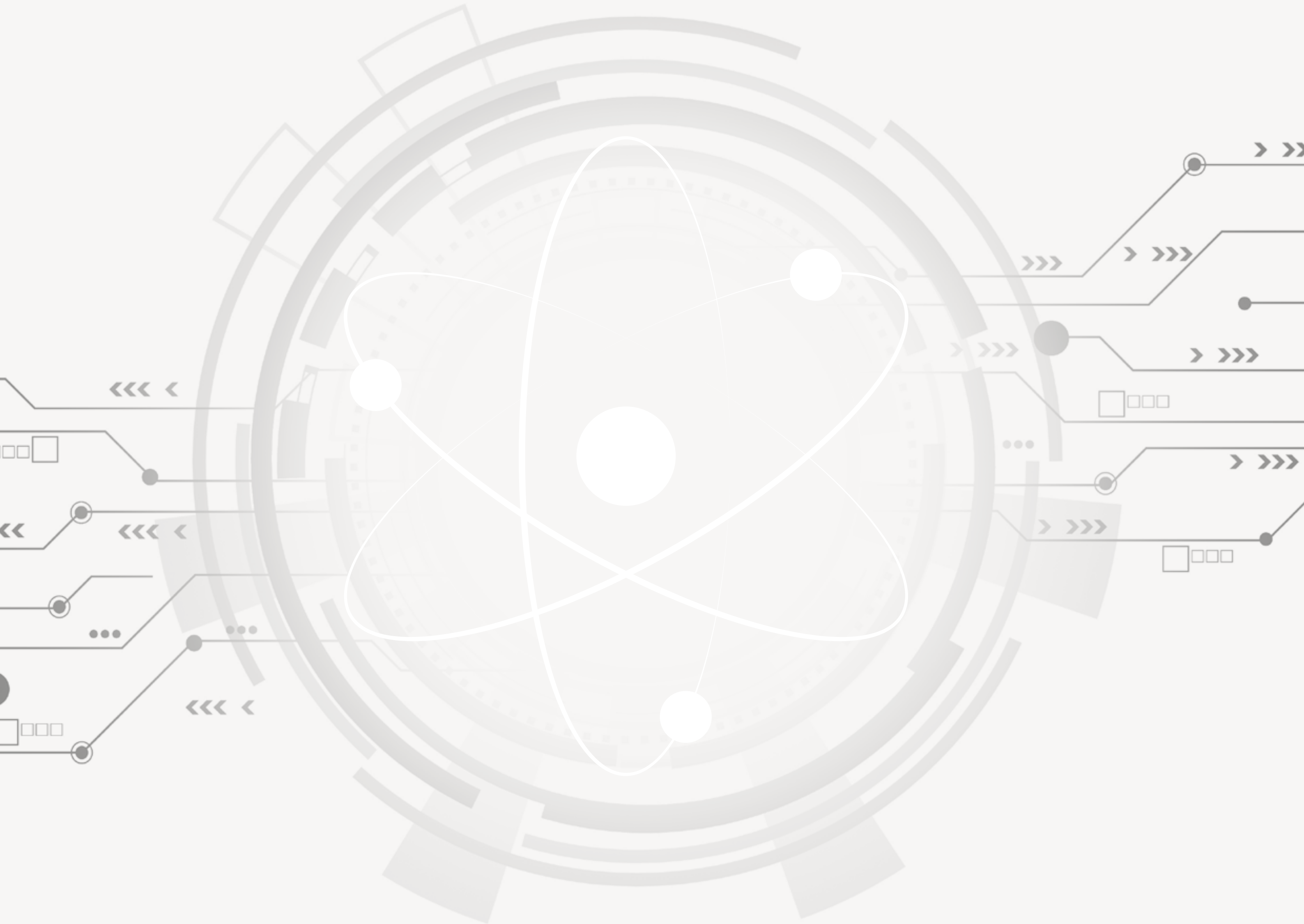
[79] A. Juszczak i in., What policies for a secure and competitive Europe? 10 ideas for the European Commission.

6. LESSONS FOR THE COAL-TO-NUCLEAR PATHWAY FROM THE RES EXPERIENCE



New approaches in nuclear power, such as the Coal-to-Nuclear pathway or the deployment of SMRs, introduce innovative solutions requiring appropriate infrastructure and coherent regulatory policies – much like any novel energy technology. Energy transition plans envisioning transmission and distribution systems based on smart grids connecting weather-dependent sources with energy storage still require significant development and support. Integrating Generation IV reactors or Small Modular Reactors (SMRs) into this evolving system necessitates their inclusion now in long-term grid development plans prepared years, or even decades, in advance. However, planning at the Transmission System Operator (TSO) and Distribution System Operator (DSO) level is insufficient on its own. Creating a supportive business environment is crucial, and here we can draw lessons from the market introduction of other low-carbon, previously unconventional energy sources (namely RES). Yet, it is vital to maintain 'technological co-evolution', recognizing that different energy technologies are interdependent and should ideally develop synergistically, rather than hindering each other due to excessive favoritism towards one, which could ultimately destabilize the power system. The ambition to change the energy mix to diversify domestic energy sources is always positive, regardless of the initial motivation – whether technological progress, enhanced energy security, climate policies, or energy price stabilization. However, good intentions alone may not suffice to create an enabling investment environment.

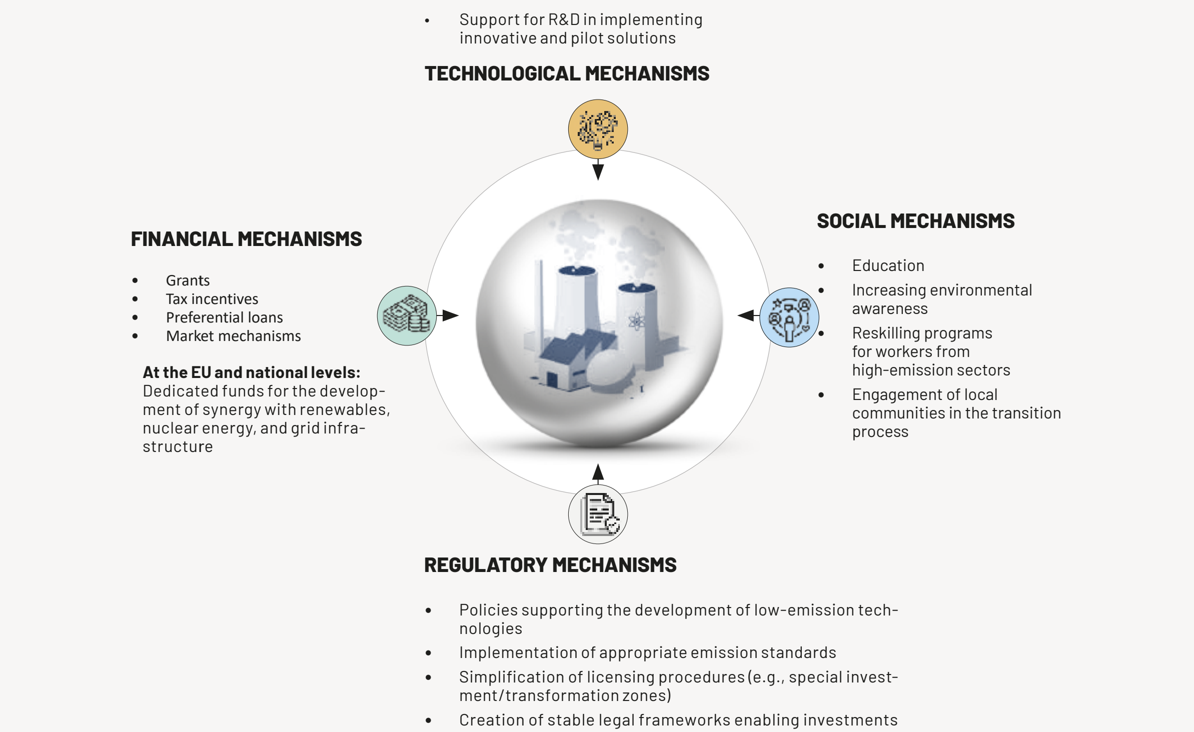
Policies and regulations play a key role in promoting new technological solutions that accelerate decarbonization in the energy, transport, and agriculture sectors. Over the past decade, the European Union extensively supported RES development, facilitated by a stable legislative framework, access to funding, and cooperation among Member States. The adoption of the Clean Energy for All Europeans package initiated new regulations like the Renewable Energy Directive (RED II, RED III) and the broader Fit for 55 package. Funding for RES investments is provided through mechanisms like the Cohesion Fund and the European Regional Development Fund (ERDF). The LIFE programme supports environmental and climate projects, while the Connecting Europe Facility (CEF) finances energy infrastructure, including RES projects. However, RES subsidization in the EU has evolved significantly, moving from direct feed-in tariffs towards more complex market-based and regulatory mechanisms. Current support often targets 'third-generation' RES installations, which offer more than just standalone generation; they focus on improved efficiency, scalability, reduced environmental impact, and better grid integration through hybrid installations (often including storage), Power-to-X applications (frequently involving hydrogen), or harnessing more predictable renewable sources like ocean energy, advanced biofuels, or offshore wind. Due to varying levels of technological maturity and relative novelty, many still require support. This path towards climate neutrality demands continued investment, innovation, and engagement from all economic sectors.

The European Union's Fit for 55 framework nominally adopts the principle of technology neutrality. This implies Member States can choose technologies best suited to their needs and capabilities, provided they contribute to the 2030 emissions reduction target (-55%) and the 2050 climate neutrality goal. The European Commission has recognized certain natural gas and nuclear energy activities – albeit under strict conditions (as outlined in the EU Taxonomy Climate Delegated Act) – as compatible with EU climate and environmental objectives, intended to accelerate the transition away from more carbon-intensive fossil fuels[80]. The European Parliament has acknowledged that nuclear energy is a low-carbon alternative to fossil fuels, accounting for nearly 26% of EU electricity production[81]. Therefore, for Poland, nuclear power can certainly complement the growing share of RES in the power system. However, this complementarity should be viewed ambitiously, pursuing decarbonization via the Coal-to-Nuclear pathway.

The Coal-to-Nuclear pathway faces numerous challenges, which can potentially be addressed by drawing on experiences from deploying the aforementioned RES technologies. The deployment of offshore wind farms (including floating wind), given their project scale – capital intensity, lengthy preparation and implementation times – highlights the critical importance of regulatory support and assistance programs, such as subsidies or tax incentives. The successes and failures of these large-scale RES investments offer valuable lessons for developing nuclear reactors, particularly for first-of-a-kind (FOAK) applications, encompassing both novel reactor technologies themselves (like Generation IV) and new applications for existing or modified designs (like SMRs for industrial heat or replacing coal plants).

The sustained development and commercialization of Generation IV reactors or SMRs will be more likely if – mirroring past efforts to promote RES – public awareness of their benefits is actively built. This can foster societal acceptance for creating synergies between infrastructural, regulatory, and financial support for the Coal-to-Nuclear pathway, which is crucial for the future of Poland's energy sector. There is a significant opportunity for Poland's energy transition to occur not through disruptive upheaval but in an evolutionary manner, taking into account existing, functional system elements and infrastructure, socio-economic realities, and energy security needs.

DRAW 5 **TYPES OF MECHANISMS SUPPORTING THE COAL-TO-NUCLEAR TRANSITION**



- Support for R&D in implementing innovative and pilot solutions

TECHNOLOGICAL MECHANISMS

FINANCIAL MECHANISMS

- Grants
- Tax incentives
- Preferential loans
- Market mechanisms

At the EU and national levels: Dedicated funds for the development of synergy with renewables, nuclear energy, and grid infrastructure

SOCIAL MECHANISMS

- Education
- Increasing environmental awareness
- Reskilling programs for workers from high-emission sectors
- Engagement of local communities in the transition process

REGULATORY MECHANISMS

- Policies supporting the development of low-emission technologies
- Implementation of appropriate emission standards
- Simplification of licensing procedures (e.g., special investment/transformation zones)
- Creation of stable legal frameworks enabling investments in energy transformation

SOURCE: Own work

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[80] Gaz i atom w taksonomii, 2.02.2022, https://poland.representation.ec.europa.eu/news/gaz-i-atom-w-taksonomii-2022-02-02_pl.

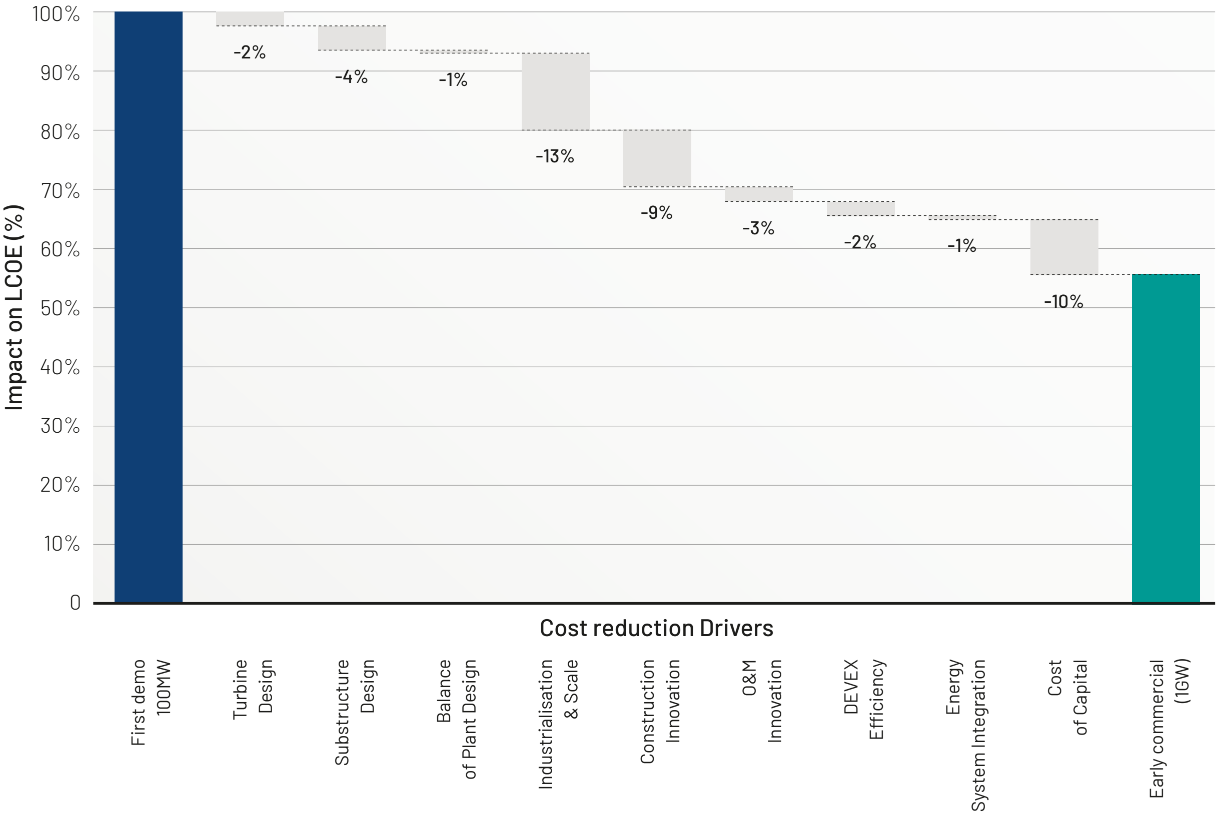
[81] C. Cordina, Energia jądrowa, maj 2024, https://www.europarl.europa.eu/factsheets/pl/sheet/62/energia-jadrowa.

6.1 PILOT PROJECTS AND PROOF OF TECHNOLOGY FEASIBILITY

Lesson learned. Floating wind farm projects such as Hywind Scotland[82] have highlighted the need for pilot schemes to demonstrate feasibility, build confidence and refine designs before scaling up. This aspect is addressed in the section of the report on theories of acceptance and introduction of new technologies.

While the LCOE[83] for the Hywind Scotland FOW, which opened in 2017, is €245/MWh and would not be commercially viable on its own, its construction and operation allowed Equinor to refine its architectural design and technology and thus enable the development of another farm with similar parameters (Hywind Tampen) at a lower cost. The same pattern can be seen with FOW projects based on a different technology of floating platform (floater design) and anchoring systems (mooring & anchoring system).

FIG. 14 **LCOE REDUCTION PROFILE OF FLOATING WIND FARMS BASED ON MAIN COST FACTORS[84]**



SOURCE: FOW Cost Reduction Pathways, 2024,

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[82] Investor: Equinor; production capacity: 30 MW; investment value: GBP 210 million.

[83] Levelized Cost of Electricity (discussed in more detail in section 5.1).

[84] Floating Offshore Wind Centre of Excellence, FOW Cost Reduction Pathways, 2024, https://fowcoe.co.uk/wp-content/uploads/2024/10/FOW-CoE-FOW-Cost-Reduction-Pathways-Public-Report.pdf

Application to Nuclear Technologies. Pilot projects of SMRs, Generation IV reactors and Coal-to-Nuclear adaptations are highly useful to demonstrate their technical feasibility, safety and operational efficiency. This approach builds confidence in the technology, reduces perceived risk, attracts diverse investors and manages the expectations of relevant stakeholders as well as the public.

The Polish State, through the National Centre for Nuclear Research (NCBJ), is already involved in a fourth-generation reactor pilot project, i.e. the ALLEGRO reactor[85], which is one of three projects under the aegis of the European Commission under the European Sustainable Nuclear Industrial Initiative (ESNII) programme[86]. The ALLEGRO reactor project was initiated in 2005 by the French Atomic Energy Commission (CEA) as a demonstrator of helium-cooled fast reactor technology[87] (Gas Fast Reactor, GFR). In 2010, the project management was taken over by the V4G4 Centre of Excellence (Visegrad 4 for Generation 4 reactors) consortium[88], bringing together institutions from Hungary, Poland, the Czech Republic and Slovakia (it brings together research institutes from the Visegrad Group countries - ÚJV Řež from the Czech Republic, MTA EK from Hungary, VUJE a.s from Slovakia and NCBJ from Poland). The National Centre for Nuclear Research (NCBJ) joined the project in June 2012.

ALLEGRO aims to develop reactor technology operating on fast neutrons (those with higher energy than the neutrons on which light-water reactors operate - thermal). In reactors operating on such neutrons, it is possible for them to be captured by non-fissile uranium-238 and then converted into fissile plutonium-239, which is also used in MOX fuel. As an alternative to uranium-238, thorium-232 can be used. A fast neutron reactor is capable of producing its own fuel - it is a fuel-bearing reactor, as confirmed by experiments at the Superphenix reactor in France. The advantage of fast neutron reactors is that they can use some of the spent fuel from Generation II and III reactors operating on thermal reactors, not only by 'consuming' plutonium, but also by fissioning actinides into isotopes with shorter lifetimes and lower activity.

The ALLEGRO reactor demonstrator, with a capacity of about 75 MWt, has been under development for more than a decade with dedicated projects focusing on specific aspects of the prototype (fuel cycle, safety). Key decisions on the future of the prototype, i.e. moving from the feasibility study phase to the construction preparation phase of the demonstrator, including its siting, are expected to be taken between 2025 and 2026.

The example of the ALLEGRO reactor, as a demonstration initiative for Generation IV reactor technology, shows that it is crucial for countries interested in new nuclear technology to have their own research resources, simulation and experimentation capabilities and experienced scientific staff. In this context, it will also be essential for the Coal-to-Nuclear pathway to demonstrate practical solutions. Building demonstrators minimises the risks associated with innovation, while presenting evidence of its effectiveness and cost-effectiveness. In some cases, especially when the technology is well known and proven, building a demonstrator may not be necessary and can be replaced by in-depth analysis. In the case of the Coal-to-Nuclear pathway, such a solution is likely to be the appropriate choice for greenfield sites and using Generation III and III+ light-water reactor technologies. For deeper applications using existing infrastructure and Generation IV reactor technologies, the Coal-to-Nuclear pathway will at least require a nuclear technology demonstration.

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[85] ALLEGRO, https://allegroreactor.cz/#pll_switcher; NCBJ, news, 7.06.2023,. https://www.ncbj.gov.pl/aktualnosci/male-kroki-ku-wielkiemu-celowi-spotkania-grup-zaangazowanych-w-badania-nadreaktorami.

[86] ESNII Vision Report No. 1, 8.04.2022, https://snetp.eu/wp-content/uploads/2023/09/ESNII_Vision_Paper_2022.pdf.

[87] The other two projects concerning the development of G4 reactors are being carried out by teams led by France (sodium-cooled reactor) and Belgium and Romania (lead-bismuth-cooled reactors).

[88] V4G4 Centre of Excellence, https://allegroreactor.cz/projects/.

6.2 STANDARDIZATION AND MODULARITY

Lesson learned. Standardization and modular designs in the bottom-fixed offshore wind sector helped reduce costs, streamline production, and facilitated the gradual deployment of more efficient turbines. Currently, in the floating offshore wind (FOW) sector, which has yet to reach commercial scale, over 100 different platform designs are being tested. Those already successfully deployed through pilot projects have a significant advantage and are more likely to become leading technologies during the commercialization phase.

Application to nuclear technologies. For SMR projects, technology fragmentation remains prevalent, with numerous companies developing distinct designs[89]. The vast majority have not yet reached the pilot or demonstration stage (a notable exception being China's ACP100, which is under construction[90]). As the market matures, technology consolidation will likely be necessary to achieve economies of scale and enable the commissioning of subsequent power plants at lower costs. Focusing on standardizing reactor designs and adopting modular construction methods can reduce costs, accelerate deployment, and simplify regulatory processes. These approaches are considered key potential advantages of SMRs but require consistent implementation to deliver the intended benefits[91]. Standardization can also bring significant benefits to the Coal-to-Nuclear concept, for instance, by speeding up the design and construction process. A systematic approach, facilitated by identifying key aspects for feasibility studies when considering the decarbonization of coal plant sites (potentially reusing some infrastructure), can accelerate the investment planning phase, even while maintaining neutrality towards specific nuclear technology vendors. In this context, the DEsire Energy Transformation Platform can play a crucial role by supporting these efforts and contributing to Poland's rapid energy transition.

6.3 STREAMLINED REGULATORY FRAMEWORKS

Lesson learned. Early wind farm projects encountered regulatory hurdles, eventually leading to the development of more technology-specific frameworks that streamlined permitting processes.

Application to nuclear technologies. Early engagement with regulatory authorities is crucial to establish clear, efficient, and technology-appropriate licensing frameworks for advanced reactors like SMRs. Harmonizing international regulations for new nuclear reactor designs would facilitate international collaboration and technology exports.

In the context of SMR development in Europe, a supportive regulatory environment within the EU and Euratom is vital. Therefore, the formation of the European Industrial Alliance on SMRs, in cooperation with the European Commission, is a noteworthy development[92]. Its inaugural plenary meeting was held in May 2024, with one objective being to enhance information exchange among SMR project developers, EU nuclear safety institutions, and national regulators in Member States. (Further details on unifying the regulatory framework for nuclear projects can be found in Chapter 4 of this report).

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[89] Łańcuch wartości energetyki jądrowej w Polsce, Instytut Energetyki – Państwowy Instytut Badawczy, 2023, https://ien.com.pl/baza-wiedzy/materialy-informacyjne/lancuch-wartosci-energii-jadrowej-w-polsce.

[90] ACP100, China's first modular reactor for sustainable nuclear energy, 17.09.2024, https://energynews.pro/en/acp100-chinas-first-modular-reactor-for-sustainable-nuclear-energy/#google_vignette.

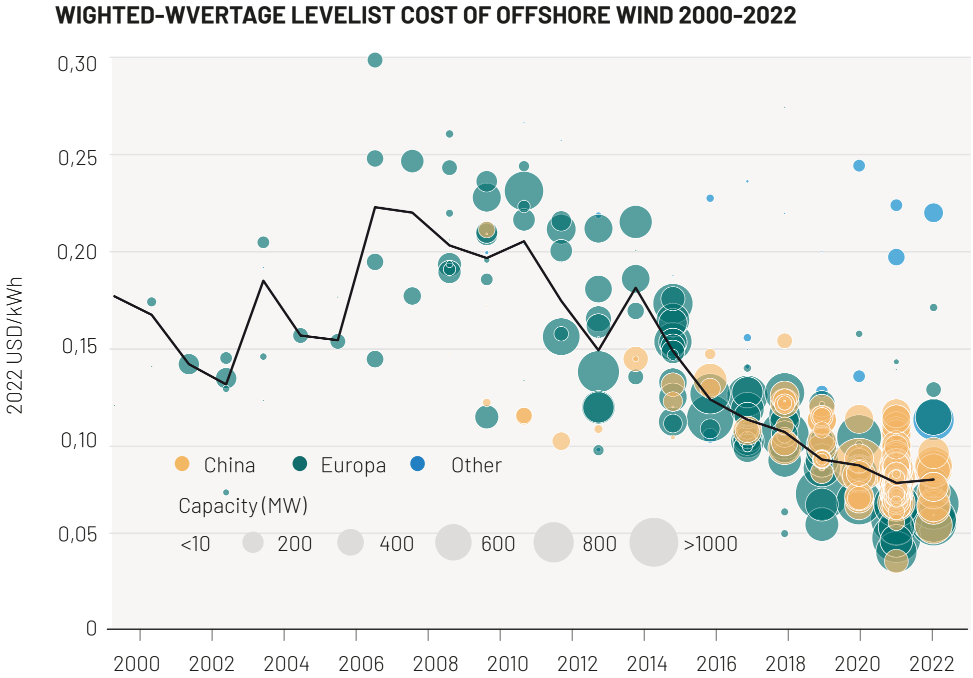
[91] C.A. Lloyd, T. Roulstone, R.E. Lyons, Transport, constructability, and economic advantages of SMR modularization, „Progress in Nuclear Energy" 2021, vol. 134, https://www.sciencedirect.com/science/article/abs/pii/S0149197021000433?via%3Dihub.

[92] European Industrial Alliance on SMRs,. https://single-market-economy.ec.europa.eu/industry/industrial-alliances/european-industrial-alliance-small-modular-reactors_en?prefLang=pl.

6.4 COST REDUCTION THROUGH LEARNING CURVES

Lesson learned. Wind farms achieved significant cost reductions through operational experience, economies of scale, and technological innovation across successive installations.

FIG. 15 **LCOE OF OFFSHORE WIND FARM PROJECTS IN DIFFERENT REGIONS OVER THE YEARS**[93]



SOURCE: IRENA

A key factor that undoubtedly helped reduce wind power costs was technology refinement leading to increased capacity factors per MW of installed capacity.

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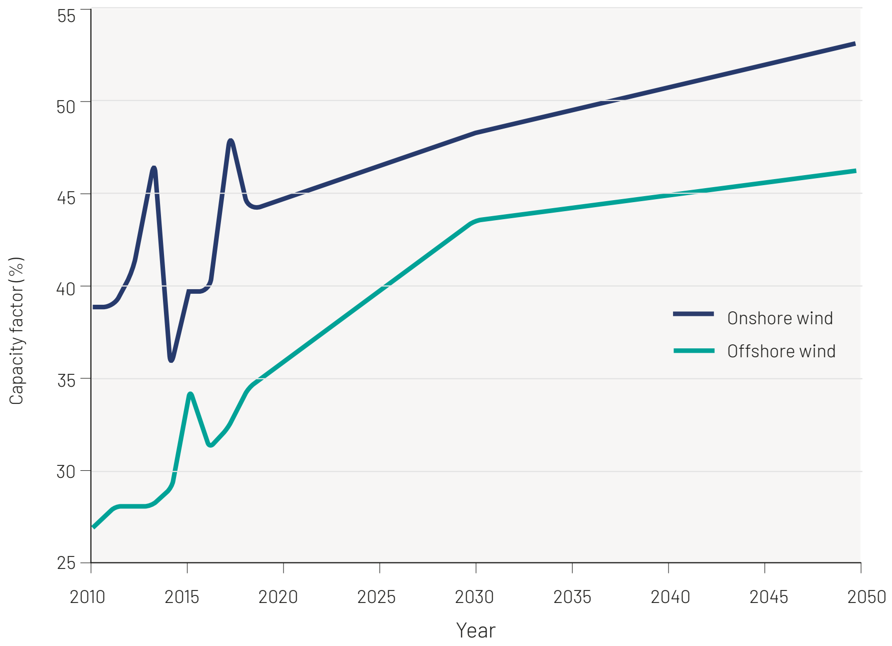
[93] Floating Offshore Wind Outlook, International Renewable Energy Agency (IRENA), 2024, https://www.irena.org/Publications/2024/Jul/Floating-offshore-wind-outlook.

FIG. 16 **INCREASE IN CAPACITY FACTOR AS TECHNOLOGY ADVANCES FOR ONSHORE AND OFFSHORE WIND FARMS**[94]



SOURCE: Cleaner Engineering and Technology 2023, vol. 17

This specific aspect (improving capacity factor) has limited applicability to nuclear power, as nuclear reactors inherently operate at the highest capacity factors among all major energy sources (typically around or above 90%).

Application to nuclear technologies. Focusing on iterative design improvements, achieving economies of scale in manufacturing, and fostering 'learning-by-doing' during construction can undoubtedly help lower costs for subsequent nuclear investments. Early investment in R&D and developing a robust domestic supply chain in Poland will be crucial. Pursuing multiple, distinct technologies from different vendors simultaneously could be counterproductive, as it would dilute the benefits gained from the learning curve as subsequent plants and units are built. (Further discussion on SMR project scalability can be found in the previous Sobieski Institute report, SMR for Poland). Therefore, encouraging potential investors pursuing the Coal-to-Nuclear pathway to cooperate on procurement for Generation III/III+ reactor technologies is important. These efforts should be supported by the Polish government, potentially by promoting nuclear technology transfer from suppliers located in countries considered high-priority political and economic partners. Furthermore, for Generation IV reactors, Poland, in collaboration with institutions like the National Centre for Nuclear Research (Narodowe Centrum Badań Jądrowych, NCBJ), should actively seek opportunities to host demonstration reactors. Such a step would not only potentially establish technological leadership but also allow Poland to identify and address organizational challenges associated with constructing novel nuclear facilities domestically. Preferred incentives in this area should include enhanced tax relief for R&D activities and their commercialization, relaxed requirements for applying the IP BOX tax relief, adjustments to regulations within Special Economic Zones (SEZs), and stronger support for collaboration between scientific institutions and businesses in securing public funding for implementation projects.

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[94] B. Desalegn, D. Gebeyehu, B. Tamrat, T. Tadiwose, A. Lata, Onshore versus offshore wind power trends and recent study practices in modeling of wind turbines' life-cycle impact assessments, „Cleaner Engineering and Technology" 2023, Vol. 17, https://doi.org/10.1016/j.clet.2023.100691.

6.5 PUBLIC PERCEPTION AND STAKEHOLDER ENGAGEMENT

Lesson learned. Wind farm projects sometimes faced public resistance due to visual impact and environmental concerns. Transparent communication and demonstrating clear community benefits (e.g., local job creation, potential for lower energy costs for direct local offtakers) help gain public acceptance.

Application to nuclear technologies. A proactive approach is needed to address public concerns regarding nuclear safety, waste management, and environmental impact. Highlighting the benefits of modern nuclear projects – such as zero CO_2 emissions during operation, the potential for district heating electrification or nuclear cogeneration to combat 'low-stack' air pollution, reliability, and energy security – while actively involving the local community in the decision-making process is advisable. This long-term engagement can build trust and acceptance for hosting a nuclear facility. (Further details are available in the report Coal-to-Nuclear for Poland: Social Diagnosis). However, while the Coal-to-Nuclear pathway might seem inherently "easier" for gaining public acceptance at former coal sites, the specific characteristics of each location must not be underestimated. Analysis of the local community should encompass demographic, economic, infrastructural (social and technical), cultural, and historical aspects, including past experiences with resident involvement in other large investment projects. Local community expectations regarding a nuclear power plant project can vary dramatically, not just between counties (powiats) but even between municipalities (gminas) within the same 'region'. Therefore, promoting the Coal-to-Nuclear decarbonization concept requires not only national-level communication but also tailored local information campaigns addressing specific community concerns. Such activities should be initiated early in the investment process, similar to standard practice for nuclear projects.

6.6 FINANCIAL MODELS AND RISK MINIMIZATION

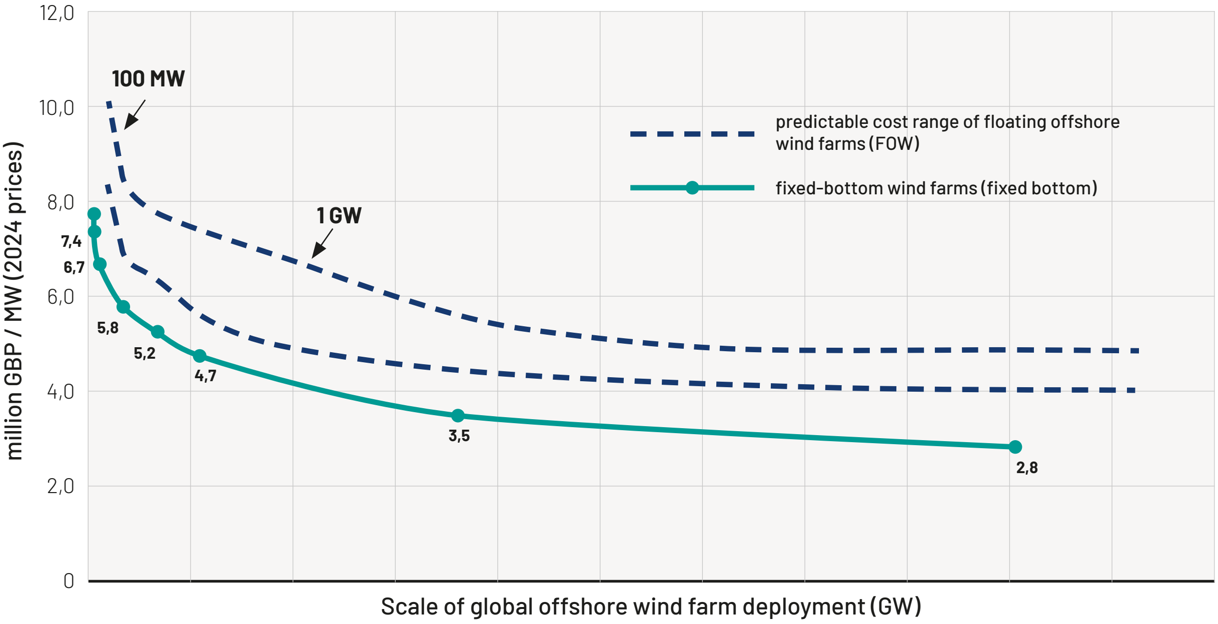
Lesson learned. Floating offshore wind projects (still largely pre-commercial) have utilized public-private partnerships, government grants, and innovative financial models to attract investment during the high-risk development and demonstration phase.

Application to nuclear technologies. Securing government support is often crucial, potentially through grants, loan guarantees, or risk-sharing mechanisms. Promoting public-private partnerships can help reduce investment risk and make Coal-to-Nuclear projects more attractive to private investors. (Further information on financing models for nuclear projects can be found in Chapter 5 of this report).

6.7 SUPPLY CHAIN AND INFRASTRUCTURE DEVELOPMENT

Lesson learned. Floating offshore wind projects have encountered difficulties related to supply chain readiness and infrastructure availability (e.g., ports, specialized vessels), delaying some deployments.

FIG. 17 **PROJECT CAPEX REDUCTION (MILLION GBP/MW) VS. GLOBAL SCALE OF OFFSHORE WIND TECHNOLOGY DEPLOYMENT**[95]



The chart does not include the PRC; the blue lines account for commercial projects up to a maximum scale of 1 GW, while the green line also includes projects exceeding 1 GW.

SOURCE: FOW Cost Reduction Pathways, 2024.

Application to nuclear technologies. Developing a robust supply chain and ensuring the availability of a locally skilled workforce and manufacturing capabilities are essential. The government should prepare and implement an infrastructure investment strategy, encompassing areas like transportation, manufacturing facilities, and grid development, to support the deployment of nuclear technology. Furthermore, Polish authorities should strive for technology 'localization' or 'naturalization', aiming for technology transfer to domestic companies. An example, albeit under different circumstances, is China, where the Westinghouse AP1000 reactor design eventually formed the basis for the domestic CAP1000 version, involving intellectual property transfer[96]. While the primary goal of the Polish nuclear program may not be developing indigenous reactor technology, securing the interests of Polish industry through contractual requirements within agreements involving the state (or state-controlled entities leading the projects) is crucial for maximizing domestic content and benefits ('Polonization').

6.8 COOPERATION IN INNOVATION ECOSYSTEMS

Lesson learned. Floating offshore wind has benefited from collaboration among developers, academia, and governments, fostering innovation and knowledge sharing. An example is the UK's Offshore Renewable Energy (ORE) Catapult[97], a technology innovation and research center for offshore renewables. It col-

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[95] FOW Cost Reduction Pathways, 2024.

[96] Nuclear construction starts 2022: China 4, rest of the world 0, WNISR, 15.07.2022, https://www.worldnuclearreport.org/Nuclear-Construction-Starts-2022-China-4-Rest-of-the-World-0.

[97] ORE Catapult, https://ore.catapult.org.uk/.

laborates with Original Equipment Manufacturers (OEMs), developers, and operators to improve existing technologies and develop next-generation solutions.

Application to nuclear technologies. Poland should promote, including at the EU level, the creation of partnerships among governments, research institutions, and private entities to drive innovation across the entire nuclear value chain, from fuel supply to reactor design and waste management. The previously mentioned European Industrial Alliance on Small Modular Reactors and the European Sustainable Nuclear Industrial Initiative (ESNII) are relevant initiatives in this regard. Domestically, several agreements related to nuclear power development have been signed in Poland over the past two years. In 2023, ORLEN Synthos Green Energy and the Łukasiewicz Research Network launched the European Centre for Nuclear Energy Training[98]. In the same year, a cooperation agreement for establishing a Polish-American Regional Clean Energy Training Center was signed by representatives of the Ministry of Climate and Environment and the U.S. Department of Energy[99]. Furthermore, in 2023 and 2024, Polish Nuclear Power Plants (Polskie Elektrownie Jądrowe, PEJ) signed agreements regarding workforce development for the nuclear industry with the Lodz University of Technology[100], the Fahrenheit Universities in Gdańsk (Medical University of Gdańsk,Gdańsk University of Technology, and University of Gdańsk)[101], the AGH University of Krakow[102], the Warsaw University of Technology[103], and the Maria Curie-Skłodowska University in Lublin[104]. However, it is too early to assess the tangible outcomes of these agreements. Similar collaborative initiatives should be undertaken specifically concerning the Coal-to-Nuclear concept. The DEsire Energy Transformation Platform[105] serves as a precursor for such activities and aims to become a knowledge and networking hub for stakeholders involved in decarbonization projects, including those based on the Coal-to-Nuclear pathway.

6.9 UTILIZATION OF POLICIES AND INCENTIVES

Lesson Learned: Energy policies such as feed-in tariffs and Renewable Portfolio Standards (RPS) were instrumental in driving the development and deployment of wind and solar technologies.

Application to Nuclear Technologies: The Polish government should seek partners at the EU level and actively lobby to change the European Commission's often perceived skeptical stance towards nuclear projects (evident, for example, in the limited eligibility of nuclear projects for major EU funds – see Table 4). Promoting policies supportive of nuclear energy, such as including it robustly in clean energy regulations or providing targeted tax incentives, is necessary to create a favorable market environment for deploying Generation IV reactors and SMRs.

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[98] Biznes i nauka łączą siły przy budowie małego atomu, 31.05.2023, https://www.gov.pl/web/edukacja/biznes-i-nauka-lacza-sily-przy-budowie-malego-atomu.

[99] Powstanie polsko-amerykańskie centrum szkoleniowe czystych technologii. Minister Moskwa: to przedsięwzięcie na lata, 21.09.2023, https://www.pap.pl/aktualnosci/powstanie-polsko-amerykanskie-centrum-szkoleniowe-czystych-technologii-minister-moskwa.

[100] Politechnika Łódzka wykształci specjalistów we współpracy ze spółką Polskie Elektrownie Jądrowe, 7.10.2022, https://p.lodz.pl/uczelnia/informacje-dla-mediow/politechnika-lodzka-wyksztalci-specjalistow-we-wspolpracy-ze-spolka-polskie-elektrownie-jadrowe.

[101] W kierunku energetyki jądrowej – porozumienie Uczelni Fahrenheita i Polskich Elektrowni Jądrowych, 2.02.2023, https://ug.edu.pl/news/pl/4736/w-kierunku-energetyki-jadrowej-porozumienie-uczelni-fahrenheita-i-polskich-elektrowni-jadrowych.

[102] AGH rozpoczyna współpracę ze spółką Polskie Elektrownie Jądrowe, 27.02.2023, https://www.krakow.pl/aktualnosci/268555,34,komunikat,agh_rozpoczyna_wspolprace_ze_spolka_polskie_elektrownie_jadrowe.html.

[103] Polskie Elektrownie Jądrowe i Politechnika Warszawska podpisały umowę o współpracy przy kształceniu kadr dla sektora jądrowego, 7.08.2023, https://www.gov.pl/web/klimat/polskie-elektrownie-jadrowe-i-politechnika-warszawska-podpisaly-umowe-o-wspolpracy-przy-ksztalceniu-kadrdla-sektora-jadrowego.

[104] K. Skałecka, UMCS i PEJ na rzecz kształcenia kadr dla polskiego sektora jądrowego, 26.11.2024, https://www.umcs.pl/pl/aktualnosci,4622,umcs-i-pej-na-rzecz-ksztalcenia-kadr-dla-polskiego-sektora-jadrowego,157710.chtm.

[105] DEsire, Platforma Transformacji Energetyki, https://projektdesire.pl/klaster-projekt-desire/.

TAB.4 **ACCESS TO EUROPEAN FUNDS FOR NUCLEAR ENERGY PROJECTS**[106]

EU FUNDING	ACCESSIBILITY FOR NUCLEAR POWER PROJECTS
Innovation Fund – EUR 38 billion (2020-2030)	Nuclear power is not included
Modernisation Fund – EUR 57 billion (2021-2030)	Nuclear power is not included, could potentially access up to 20% of funds as a low priority investment
Horizon Europe – EUR 95,5 mld (2021-2027)	Nuclear power is not openly excluded, but the sector is not included in the calls for funds
Cohesion Fund – EUR 36,6 billion (2021-2027)	Construction and decommissioning of nuclear infrastructure excluded
European Regional Development Fund – EUR 313 billion (2021-2027)	Construction and decommissioning of nuclear infrastructure excluded
The Just Transition Fund – EUR 19 billion (2021-2027)	Construction and decommissioning of nuclear infrastructure excluded - as in the case of InvestEU
Instrument for Reconstruction and Resilience – EUR 338 billion (2021-2027)	Nuclear power is not explicitly ruled out, but is not promoted as a renewable energy source
Connecting Europe - Energy – EUR 5,8 billion (2021-2027)	Nuclear power is not included
LIFE – EUR 5,4 billion (2021-2027)	Nuclear power is not included among the target sectors.

ŹRÓDŁO: Departament energii jądrowej, Ministerstwo Przemysłu, 2024.

6.10 RESILIENCE TO SETBACKS

Lesson learned. First-of-a-kind (FOAK) technologies, such as floating offshore wind, initially faced significant challenges, including delays and cost overruns, but projects progressed through perseverance and incorporating lessons learned from early setbacks.

Application to nuclear technologies. It is prudent to anticipate potential challenges now, such as cost overruns or public resistance, and develop corresponding mitigation strategies and contingency plans. Continuous adaptation based on accumulating experience is essential to refine the commercialization pathway for new nuclear technologies.

Adopting these strategies learned from RES deployment and tailoring them to the specific needs and challenges of advanced nuclear technologies increases the likelihood of achieving successful commercialization and scaled deployment, enabling nuclear power to contribute significantly to Poland's energy transition.

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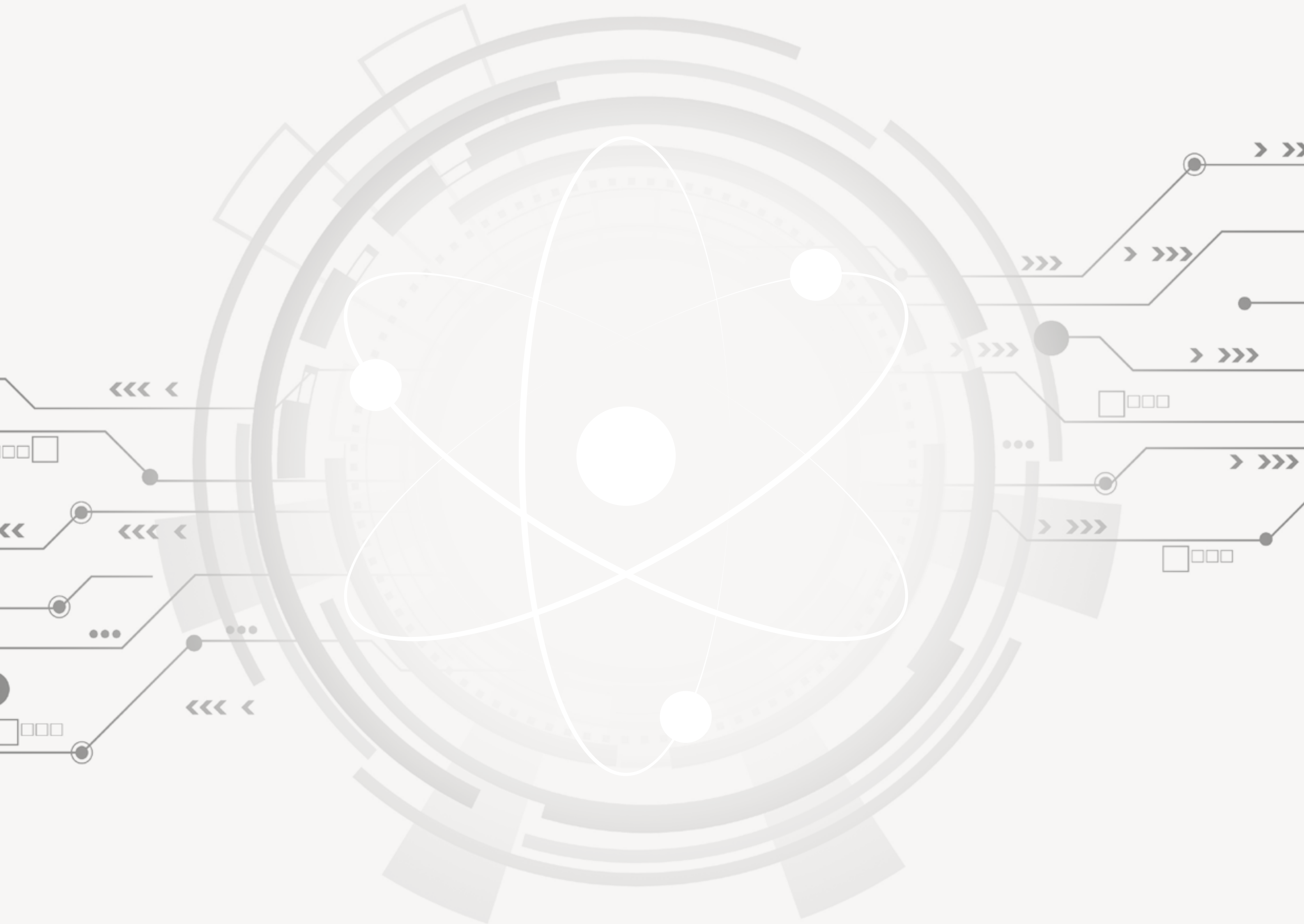
[106] A. Juszczak i in., What policies for a secure and competitive Europe? 10 ideas for the European Commission, Polish Economic Institute, Warsaw 2024,.https://pie.net.pl/wp-content/uploads/2024/12/PIE_Policy-Paper_10-ideas-for-the-European-Commission.pdf.

7. SUMMARY



Nuclear energy constitutes a crucial element of Poland's future energy mix. To effectively execute the energy transition, it is necessary not only to implement modern nuclear technologies but also to establish a coherent state policy ensuring appropriate regulations, investment stability, and public acceptance.

Transparent communication and public education regarding the benefits and safety of nuclear energy are fundamental to its development. Simultaneously, the transition requires innovative financing models adapted to local conditions, such as the Mankala model, SaHo, CfD, or RAB, alongside close integration with European funds and support mechanisms.

Key strategic aspects of an energy transition incorporating nuclear technologies, including the Coal-to-Nuclear pathway, are highlighted below.

PILLARS OF TRANSFORMATION

1. Without an energy transition that includes the implementation of nuclear power, Poland risks high energy prices, blackouts, and supply constraints. Coal-to-Nuclear (CtN) offers an effective transition pathway, potentially allowing the utilization of some existing infrastructure from coal power generation sites.
2. The Coal-to-Nuclear pathway should be promoted as a component of a just transition, helping prevent the marginalization of coal-dependent regions.
3. Implementing pilot installations in communities requiring transformation is necessary to enable gradual scaling of investment and build experience.

FINANCING

1. Securing financing remains a key challenge, as high Capital Expenditures (CAPEX) typically account for a large majority (cited as up to 78%) of total nuclear project lifetime costs.
2. Support mechanisms like CfD, RAB, BOT, and SaHo should be assessed and potentially tailored to the specific characteristics of SMR and Coal-to-Nuclear projects to enhance their investment attractiveness.
3. Poland should advocate for the inclusion of nuclear power in European funding streams, currently earmarked primarily for RES, to help secure long-term investment financing.

EFFECTIVE PROJECT MANAGEMENT AND TECHNOLOGICAL INNOVATION

1. Nuclear projects must be implemented with cross-party political support, independent of electoral cycles, to ensure their stability and long-term viability.
2. Establishing effective Technical Support Organizations (TSOs) and clear institutional structures for oversight (related to unbundling principles) will help build investor and public confidence in new nuclear investments.
3. Polish regulations should align with international standards while seeking flexible solutions that enable pathways like Coal-to-Nuclear.
4. The development and deployment of advanced reactors, such as Generation IV designs, offer potential for improved nuclear fuel utilization and more efficient waste management, aligning with circular economy principles.

KEY RECOMMENDATIONS FOR POLICYMAKERS

1. Integrate nuclear energy, including the Coal-to-Nuclear pathway, into strategic documents like the Energy Policy of Poland and the National Energy and Climate Plan.

2. Promote Coal-to-Nuclear pathway technologies as potentially effective solutions for Poland's industrial regions undergoing transition.

3. Align regulations and licensing processes for Generation III+ and IV reactors (including SMRs) with international requirements, incorporating IAEA safety standards and best practices.

4. Strengthen TSO capabilities and implement clear structures reflecting unbundling principles to increase the transparency and effectiveness of nuclear project oversight.

5. Establish an inter-ministerial team tasked with developing and implementing an optimal support model for nuclear energy, responsible for facilitating the long-term financing of new nuclear projects.

6. Promote synergies between the public and private sectors to facilitate investment and technology transfer.

7. Recognize that EU-level cooperation can be key to developing the necessary capacity for specialized facilities like advanced fuel manufacturing, reprocessing, and waste storage facilities. Support from national governments and European institutions is essential for pilot installations, especially in regions needing transformation or communities transitioning to low-carbon energy.

8. The Polish government should intensify efforts to translate the energy-related theses of the Draghi report into actionable European Commission policy – primarily advocating for the inclusion of nuclear power in EU support funds currently dominated by RES, and shifting the scope of binding energy transition targets from solely RES-focused to encompassing all zero-emission sources.

Through a consistent strategy and cooperation at both national and EU levels, Poland can not only achieve its energy transition goals but also potentially become an exporter of know-how and an expert in implementing nuclear energy internationally.

8. ABOUT THE AUTHORS AND THE PUBLISHER

Rafał Libera
rafal.libera@sobieski.org.pl

He has many years of experience in project finance, gained while working on the structuring and financing of complex projects in Africa, Asia and Europe (including Hinkley Point C). He is currently a manager in a group of companies providing services and technology to corporations in the oil and gas industry and offshore wind farm operators.

Co-founder and chairman of the board of the Transatlantic Forum of Future Leaders, a foundation that works to develop transatlantic relations and runs a unique internship programme in the US Congress and the British House of Commons for Polish students. Chairman of the board of the Polish City Club, an association that brings together and organises regular meetings of Polish professionals and entrepreneurs working in London. He has lived abroad for 19 years (United Kingdom, France, Texas). He graduated from University College London. He is a lawyer by education.

Anna Przybyszewska
anna.przybyszewska@sobieski.org.pl

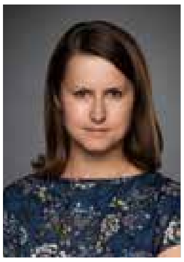
Project manager and specialist experienced in working in the international R&D, nuclear and RES projects. Graduate degree in nuclear power from the Faculty of Energy and Fuels at the AGH University in Krakow.

While working for the National Centre for Nuclear Research, she participated in projects related to nuclear cogeneration and other non-electrical nuclear power applications, Generation IV reactors, and development of requirements for next-generation nuclear reactors. Co-author of reports developed under the ALLEGRO, NC2-IR and HTR-PL reactor initiatives.

Participant of international courses: Training for foreign young researchers and engineers of Orai Resarch and Develop Center (2015) and Intercontinental Nuclear Institute (2016).

Manager in the DEsire project at the Sobieski Institute.

COOPERATION



Hanna Uhl
An expert on energy transition and investment financing, with many years of experience in public administration and the private sector. She specializes in raising funds for energy and R&D projects, as well as in issues related to climate policy, energy efficiency and clean air and sustainable transportation.

The Sobieski Institute is a Polish private think-tank whose mission is to "Create Ideas for Poland."

It was registered in 2005 as a foundation, although it began its activities in 2003. Between 2003 and 2010, the Institute published the quarterly "International Political Review". From 2011 to 2015, it organized the annual congress "Poland - The Great Project." In 2017, it organized the edition of the National League of Innovation.

Since 2017, the Institute has placed great emphasis on publication of studies and recommendations aimed at showing how the Polish economy should explore the opportunities associated with the fourth industrial revolution, innovation and new technologies.

The Sobieski Institute also conducts educational activities through the "Academy of Young Experts" project, which supports young people in developing leadership and soft skills. Each edition of the program focuses on a different key issue, responding to the current needs of the younger generation. Now in its 6th edition, the project focuses on the European Union, imparting knowledge and preparing participants for European Personnel Selection Office (EPSO) recruitment processes. The program opens the door to an international career in EU institutions.

It is a unique opportunity to gain practical skills and for professional development at the highest level.

One of the Sobieski Institute's latest projects is the "Sobieski Channel," which we invite you to subscribe to on YouTube. The channel was created for the purpose of leading inspiring conversations on issues important for Poland. It is where interesting people meet in a space dedicated to a meaningful debate.

In its activities, the Sobieski Institute has cooperated with many entities. To date, these include:

- NGOs: Polish Automation and Robotics Forum, Mutual Insurance Support Foundation, Republican Foundation, Jagiellonian Institute, New Confederation, Ambitna Polska, Youth for Poland, Students for the Republic, Konrad Adenauer Foundation, Central European Energy Partners, Sławomir Skrzypek Foundation, Wacław Felczak Foundation, Institute for Foreign Affairs and Trade (Külügyi és Külgazdasági Intézet), Institute for Politics and Society (Institut pro politiku a společnost), The F. A. Hayek Foundation Bratislava;

- corporations: Aiut, Assay Group, Rohde&Schwarz, WB Electronics, Asseco, Samsung, Lotos, Google, Procter and Gable, PWC, Cisco, EY, Phoenix Systems, Uber, USP Health, Fortum, Orange, Energa, Zysk i Ska, Collegium Wratislaviense, 4CF;

- public/international institutions: the Ministry of Foreign Affairs, the European Commission Representation in Poland, the Ministry of Climate and Environment, the Future Industry Platform Foundation, the Agency for Development and Industry, the Stock Exchange, the Bank of the National Economy, the Chancellery of the Prime Minister, the Ministry of Digitization, the Law and Justice Party, the Hungarian Embassy, the Polish Senate, the European Conservatives and Reformists Party, the European Parliament Office in Poland.

For a full list of reports and publications, as well as information about the Institute's activities, please visit www.sobieski.org.pl.

We also invite you to subscribe to the Sobieski Channel on **youtube.com/kanalSobieski**.

Join us - it's worth it!

Decarbonisation of the energy sector is one of the most important challenges of Poland's energy policy today.

The Sobieski Institute has already analysed this topic in the 2019-2020 publications SMR for Poland and Nuclear Power for Poland. The continuation of these activities is the involvement in the project 'DEsire - Plan for the decarbonisation of the national utility power industry through modernisation with nuclear reactors' and the work on the Coal-to-Nuclear (CtN) concept.

The result is a coherent series of analyses dedicated to the energy transition in Poland using the Coal-to-Nuclear pathway, presenting practical solutions to support this process, the implementation of which would contribute to the achievement of decarbonisation goals and increased energy efficiency and security. This report, entitled Coal-to-Nuclear for Poland. Support Mechanisms, is the second publication in this series.

In the technological context, he points to the need for a comprehensive implementation of nuclear power as a new industry. It is crucial to relax the regulations for the siting of nuclear power plants, e.g. by reducing the protection period for post-mining sites from 60 years to 20 years or by introducing individual ground stability assessments.

The report also analyses the support mechanisms for nuclear power financing in search of an optimal model in Polish conditions, pointing to the need for equal treatment of nuclear and RES in EU funds.

Experience from the implementation of RES, such as offshore wind farms, shows the importance of regulatory support and assistance programmes for the success of large energy projects.

The success of the energy transition therefore requires a synergy of technology, regulation, financing and education. The CtN concept is a real opportunity for an efficient and rapid transition to zero-carbon energy sources, but its successful application depends on stable political support and flexible regulation.

We look forward to reading!

The "Coal-to-Nuclear for Poland" series of reports includes the following publications:

1. National Potential. Coal-to-Nuclear for Poland.

2. Support Mechanisms. Coal-to-Nuclear for Poland.

3. Social Diagnosis. Coal-to-Nuclear for Poland.

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SOBIESKI
INSTITUTE

SOBIESKI INSTITUTE
Lipowa 1a/20
00-316 Warszawa
tel.: 22 826 67 47

sobieski@sobieski.org.pl
www.sobieski.org.pl

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@InstSobieskiego
Instytut Sobieskiego
Instytut Sobieskiego
Kanał Sobieski
Kanał Sobieski

KANAŁ SOBIESKI

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