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A novel system of provision-based model for nuclear large technical systems readiness and resilience: Insights from ECOSENS's WP3

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1 Abstract

This white paper presents a novel model for the holistic assessment of nuclear large technical systems (LTSs), grounded in the System of Provision (SoP) approach. Moving beyond traditional techno-economic assessments, the SoP approach reconceptualises nuclear energy as a socio-technical and historically situated system, embedded in wider structures of production, distribution and consumption. The paper advances a multidimensional model structured around five analytical dimensions (socio-economic, political, technological, socio-cultural, environmental), and systematically maps the preconditions, enablers, and barriers that shape nuclear development across diverse national settings.

A central contribution lies in rethinking value in nuclear infrastructure programs. Indeed, moving beyond outputs such as delivery timelines or cost efficiency, the paper distinguishes between first-order outputs, intermediate outcomes, and long-term systemic impacts. It introduces the notion of second-level value, i.e., the indirect, often transformative effects of nuclear programs on adjacent systems such as education, industrial policy, health and research. This layered understanding foregrounds how nuclear infrastructure generates value over time and across provisioning domains. The integration of the Social Discount Rate (SDR) into this framework further anchors long-term value assessment in intergenerational equity and societal preferences.

Empirical application to eight European countries, including in-depth assessments of Italy, Romania, Belgium and Spain, shows the model's utility and comparative robustness. In fact, by capturing the complexity, historicity and political contingency of nuclear pathways, the SoP-based model offers both a theoretical advance and a practical tool for policy evaluation and strategic planning in the governance of energy transitions.

2 The System of Provision approach

The provision of nuclear energy is a complex socio-technical process, shaped not only by technological and economic factors but also by political, cultural, institutional and historical dynamics. Evaluations based on traditional approaches such as cost-benefit analysis or purely techno-economic assessments have long dominated the discourse on nuclear energy infrastructure. While useful, these approaches tend to obscure the broader systems within which nuclear energy is embedded and fail to capture the multiplicity of actors, values and social processes that shape its provisioning.

This white paper presents a novel model based on the System of Provision (SoP) approach, which aims to address the aforementioned limitations of other evaluation methods. The SoP approach is a socio-economic framework originally developed to study consumption and provisioning chains (Bayliss and Fine, 2020; Fine and Leopold, 1993). It enables a richer, more holistic analysis by situating nuclear energy within the broader societal structures that produce, distribute, consume, and regulate it. This section introduces the conceptual foundations of the SoP approach, its origins in critical political economy, and its relevance and applicability to the nuclear domain.

2.1 Origins and foundations of the SoP approach

The SoP approach emerged in the early 1990s as a response to the inadequacies of mainstream economic and sociological theories in explaining patterns of consumption. Initially applied to commodities such as food, housing and clothing (Chappells and Shove, 2000; Fine, 2002), the SoP approach emphasizes that consumption cannot be understood without reference to the systems through which goods and services are produced, circulated and rendered meaningful. Rather than treating consumption as an individual act driven by preferences or utility functions, the SoP perspective highlights the institutional, political and cultural factors that shape provisioning systems across time and space.

The systematisation of the SoP approach into a framework includes five main themes, identified by (Bayliss and Fine, 2020) as the main drivers of consumption: Agents, individuals or groups (structured or unstructured) of individuals that participate in the system; Structures, forms of provisioning of goods or services (e.g., institutional, social, organisational); Processes, the sequences of activities that take place at a systemic level within the SoP or around the SoP; Relations, connections between agents and distribution of power (e.g., social classes, ages, income levels); Material culture, the meaning that the agents attribute to a product or a service. Crucially, the SoP approach considers that each system of provision is commodity-specific and historically situated. There is no universal template for analysing provisioning systems; rather, each

SoP approach must be empirically delineated based on the nature of the good and the context of its production and use. This flexibility renders the approach particularly suitable for studying complex infrastructure and technology systems, such as those underpinning civil nuclear energy.

2.2 From commodities to civil nuclear systems

Applying the SoP approach to nuclear systems requires rethinking the boundaries of analysis. Nuclear energy is not simply a technological solution or a commodity traded in energy markets; it is a large technological system (LTS) embedded within multiple overlapping provisioning systems such as electricity, defense, research, health, and increasingly, hydrogen production and decarbonization strategies (Hughes, 1983). Each of these systems entails specific agents, rules, material configurations, and symbolic narratives, which vary significantly across countries and over time.

The application of SoP to nuclear energy thus entails two complementary moves. First, it involves identifying and mapping the nuclear system of provision in a given context (e.g., France, Germany, Italy), examining how nuclear infrastructure is shaped by socio-political support, industrial capabilities, labor markets, public attitudes and institutional frameworks. Second, it means recognizing that the meaning and function of nuclear energy are contingent on how it is positioned within broader socio-technical systems (ST-systems) (Geels, 2004) and provisioning systems. In this way, the SoP approach allows for a multi-level and multidimensional analysis of nuclear provisioning, linking micro-level decisions with macro-level institutional dynamics.

There are at least four main reasons why the SoP approach is a uniquely valuable lens for analysing nuclear systems.

First, it foregrounds the non-technological dimensions of nuclear energy. Traditional assessments often focus on techno-economic criteria, yet empirical evidence shows that the success or failure of nuclear programs often hinges on political leadership, public perception, regulatory coherence and historical legacies. For instance, France's successful deployment of a standardized nuclear fleet under the Messmer Plan can be traced not only to technical efficiency but also to centralized governance, political continuity and institutional lock-in.

Second, the SoP approach is inherently comparative and contextual, allowing scholars and policymakers to explore why nuclear programs evolve differently across nations, despite similar technological capabilities. As shown in the ECOSENS project's cross-country comparisons (Italy, Spain, Belgium and Romania), divergent nuclear trajectories result from varied alignments (or misalignments) between several determinants, such as public trust, media narratives, and energy security discourses.

Third, the SoP perspective accommodates dynamic and systemic thinking. Unlike static models, the SoP approach recognizes that provisioning systems are historically contingent and evolve over time. For instance, decisions made during the initial phase of a nuclear program (e.g., reactor design or workforce training) can produce long-term path dependencies, lock-ins, or institutional inertia. This insight is particularly relevant for today's nuclear policy debates, where countries consider extending lifetimes of existing reactors, re-entering the nuclear field, or transitioning to small modular reactors (SMRs) and advanced nuclear technologies.

Fourth, the SoP approach integrates qualitative and quantitative insights. While it does not replace techno-economic modelling, it complements it by revealing hidden assumptions, distributional effects, and institutional prerequisites. For instance, combining the SoP approach with social discount rate models enables a richer cost-benefit assessment that includes societal preferences, long-term equity considerations, and political acceptability.

3 Rethinking Nuclear Program Value through Provisioning Systems

Nuclear infrastructure programs are among the most capital-intensive and politically sensitive undertakings in modern economies. Yet, conventional frameworks for assessing their value often remain narrow, focusing on technical outputs, construction timelines, and cost efficiency. This reductionist approach is particularly ill-suited to nuclear programs, which operate over multi-decadal timescales and interact with a wide array of socio-technical and institutional systems. To advance a more comprehensive evaluation, this chapter draws on recent scholarship that integrates program management theories with the SoP approach to conceptualize value as a dynamic, relational and multi-scalar process. In doing so, we shift attention from project-centric metrics to a broader lens that considers how nuclear programs shape and are shaped by the provisioning systems they inhabit and transform.

3.1 Beyond outputs: A multi-layered view of program value

Traditional evaluation frameworks tend to conflate value with delivery performance, i.e., whether nuclear plants are delivered on time, on budget, and according to specifications. While these dimensions are undoubtedly relevant, they only capture the first-order value of infrastructure programs, i.e., their outputs. A more meaningful assessment must also incorporate outcomes (the immediate benefits derived from those outputs) and impacts (long-term, often indirect systemic transformations) (Martinsuo and Hoverfält, 2018). For example, France's civil nuclear program, launched in the 1970s under the Messmer Plan, delivered not just a fleet of standardized PWRs, but also created a techno-institutional regime that realigned national

industrial strategy, reinforced geopolitical autonomy, and fostered public acceptance rooted in a technocratic ethos (Hecht, 1998). These layers of value - technical, institutional, and cultural - are inseparable from the physical infrastructure and persist long after the original program has concluded.

3.2 Programs, large technical systems and second-level value

Infrastructure programs rarely operate in isolation. They often form the backbone of LTSs, which integrate technology, institutions, and user practices over long timeframes (Bijker et al., 1989; Hughes, 1983). Nuclear programs are archetypal LTS-enablers: they coordinate upstream activities like uranium processing, engineering R&D, and reactor construction with downstream systems such as electricity distribution, regulatory oversight, and waste management.

This vertical integration creates what we refer to as first-level value relationships: value generated within the program-LTS domain. These include efficiencies from standardization, economies of scale, knowledge spillovers, and reliability improvements in base-load power generation (Locatelli et al., 2014). However, the LTS lens, while useful, overlooks how these vertically integrated systems affect other provisioning domains such as education, medicine, water, housing and defence.

To fully grasp the value of nuclear programs, we must consider their second-level value relationships, those between the enhanced LTS and other provisioning systems. This is where the SoP approach proves valuable. Indeed, the SoP approach supports us to trace how value propagates across systems via institutional change, knowledge transfer, or technological diffusion (Bayliss and Fine, 2020; Fine and Leopold, 1993). Examples of provisioning systems impacted by the nuclear LTS could be (drawing on the French case):

- *Education*: Institutionalized nuclear engineering programs created a durable pipeline of elite technocrats that now influence not just energy, but finance, transport and industrial policy (CEA, 2025; Sovacool, 2012).
- *Industry*: The coordination of nuclear supply chains stimulated technological upgrading in sectors like aerospace, robotics and precision manufacturing (Cohen, 1992; Thomas, 1989).
- *Health*: Nuclear R&D enabled the development of radiotherapy and diagnostic techniques now widely embedded in the medical system (Miller et al., 2013).
- *Food*: Nuclear by-products and technologies were adapted for food sterilization and isotope tracing in agriculture (IAEA, 2023).
- *Defense*: Civil nuclear capabilities enhanced France's strategic autonomy and export power, shaping diplomatic relations and geopolitical influence (Finon and Staropoli, 2001).

These examples illustrate how nuclear programs act as structuring agents across multiple systems of provision. Value thus cannot be assessed solely within the electricity sector but must encompass these broader systemic interdependencies.

3.3 Value creation as temporal and path-dependent

Nuclear infrastructure programs also illustrate how value unfolds over time and is deeply path-dependent. Early decisions, such as reactor technology choices or governance structures, generate lock-ins that shape the trajectory of entire systems (Lehtonen, 2021; Maréchal, 2009). The French case is emblematic: the PWR standardization, centralized grid design, and elite technocratic governance model enabled large-scale deployment but also hindered the country's transition to distributed renewables decades later (Raineau, 2022).

This temporal layering of value means that programs must be evaluated not only at delivery, but decades after, as outcomes mature and systemic impacts become visible. Some impacts may even emerge as negative externalities (e.g., waste management costs), while others may yield unexpected synergies (e.g., radiological innovation in healthcare) (Abadie, 2020; Barthe and Mays, 2001).

3.4 Toward a new framework for program value assessment

Based on these insights, a revised framework for nuclear program evaluation must:

- Distinguish between outputs, outcomes and impacts, acknowledging that the most significant value often lies in the last category (Martinsuo and Hoverfält, 2018).
- Identify both first- and second-level relationships: value generated within the program-LTS and across adjacent provisioning systems (Normann, 2001).
- Account for historical path dependencies, recognizing how earlier programs shape the scope of current and future initiatives (Pellegrinelli, 1997; Pellegrinelli et al., 2007; Thiry, 2004).
- Incorporate institutional and cultural factors, such as public acceptance, technocratic legitimacy, and governance routines, as core dimensions of value (Hecht, 1998; Sovacool and Valentine, 2012).
- Adopt a lifecycle-based perspective, allowing for dynamic reassessment as systems evolve, externalities emerge, or societal goals shift (Liu et al., 2019; Martinsuo, 2020).

This integrative approach, combining program management theory with the SoP lens, expands the evaluative focus from delivery success to systemic transformation, enabling policymakers to better align infrastructure investments with long-term societal goals.

3.5 Integrating the social discount rate into programmatic value assessment

To capture the long-term, systemic nature of nuclear program value, it is essential to incorporate temporal instruments that reflect intergenerational trade-offs, risk perceptions, and societal preferences. The Social Discount Rate (SDR), widely used in public policy to evaluate the present value of future costs and benefits, offers a critical yet often underexplored alignment with the SoP perspective (Boardman et al., 2018; Weitzman, 2001). While traditional SDR frameworks are typically rooted in welfare economics and cost-benefit analysis (Arrow et al., 2014), their application can be enriched by embedding them in provisioning systems that reflect real-world institutional, political, and cultural dynamics. In this view, the SDR is not a neutral numerical input but a socially and politically mediated parameter, an expression of how societies value future impacts, distribute risk, and weigh long-term sustainability against short-term performance.

Nuclear programs are particularly sensitive to the choice of SDR due to their unique temporal profile: high upfront capital costs, extremely long asset lifespans, delayed benefits, and enduring responsibilities such as waste management and decommissioning. A lower SDR increases the present value of long-term positive impacts, such as climate mitigation, energy sovereignty, and industrial capacity-building, thereby legitimizing investments that deliver value primarily over extended horizons. This directly resonates with the SoP-informed framework introduced earlier, which distinguishes between first-order outputs, mid-term outcomes, and long-term systemic impacts. Just as the SoP lens encourages a relational, temporally embedded analysis of value, the SDR functions as a scalar that adjusts how future outcomes are considered in present-day decisions. Integrating SDR into program evaluation thus supports a value logic that is aligned with provisioning system dynamics, intergenerational equity, and strategic foresight.

4 Developing a System of Provision-Based Model of Nuclear LTSs

Building on the theoretical foundations of the SoP approach (Fine and Leopold, 1993), this section introduces the novel analytical model conceived to respond to a central question in the governance of energy transitions: under what circumstances can nuclear technologies emerge, stabilize, or be dismantled within specific national contexts?

Rather than adopting a universalist or techno-economic perspective, the model is grounded in a political economy view of energy systems, emphasizing the socio-institutional configurations and historical trajectories that shape national energy choices. By adopting the SoP approach to develop an operational tool, we aim to provide policymakers, researchers and stakeholders with a robust structure for assessing nuclear energy strategies across diverse contexts.

The core ambition of this work is to move from conceptual understanding to a structured model that can be used to evaluate the feasibility, resilience and sustainability of nuclear LTSs. In doing so, we seek to capture the complexity of nuclear provisioning, not only in terms of infrastructure or finance, but also in relation to institutions, culture and public perception.

In particular, the development of this model is motivated by two main goals: 1) to build a tool capable of mapping the systemic interactions that affect nuclear energy adoption, taking into account multiple dimensions such as political will, industrial capacity, public acceptance, and environmental considerations; and 2) to facilitate a comprehensive and comparative analysis between countries, shedding light on why some states pursue nuclear strategies while others abandon or resist them, despite facing similar technological and economic conditions.

To achieve these objectives, we designed a SoP-based model that integrates the determinants, preconditions, enablers and barriers affecting nuclear energy pathways. The model does not assume that nuclear deployment is universally desirable or feasible but rather provides a structured diagnostic lens to assess context-specific trajectories and decision-making environments.

4.1 Methodological approach

The model was constructed through an iterative process combining empirical investigation and theoretical abstraction. Methodologically, we employed a multiple-case study approach, focusing on four European countries (i.e., France, United Kingdom, Germany, Italy), each representing a distinct trajectory in nuclear energy policy. This choice allowed us to compare divergent paths (expansion, stagnation, phase-out), while ensuring that all cases shared a baseline of industrial and political development. Each case was analysed using the five core analytical categories of the SoP approach: agents, structures, relations, processes and material culture (Dei et al., 2025). Data were gathered from over 260 sources, including scientific publications, government documents, industry reports, and media content, allowing for a comprehensive understanding of national nuclear systems. The model emerged inductively from this empirical material, through a process of thematic coding and cross-case comparison. Theoretical concepts were used to interpret data, but the structure of the model itself was shaped by empirical regularities and contrasts.

4.2 Toward a comprehensive tool

The resulting model provides a structured representation of the various determinants (e.g., human resources, public financial resources) that influence nuclear energy policy, organized across five key dimensions: socio-economic, political, technological, socio-cultural and environmental. For each determinant, we identified the preconditions that must be fulfilled, the enablers that facilitate progress, and the barriers that may impede or reverse adoption. This section introduces the rationale and development process of the model.

The following sections detail the architecture and components of the model, along with its empirical grounding and operationalization through a dedicated evaluation tool. The SoP-based model thus represents a significant step forward in applying a political economy perspective to the study of nuclear energy transitions. By offering both a theoretical and practical lens, it contributes to current debates on sustainable energy futures and the role of nuclear technologies therein.

4.3 Preconditions, enablers, and barriers

For each determinant within the model, the framework distinguishes between three evaluative categories: preconditions, which refer to essential requirements that must be in place before a country can realistically pursue nuclear development; enablers, which are contextual features or interventions that facilitate the satisfaction of those preconditions; and barriers, which represent factors that directly or indirectly hinder them. This tripartite logic is central to the model's analytical utility, as it allows for a granular evaluation of national readiness, while also identifying leverage points for policy intervention. The strength of the model lies in its capacity to move beyond binary judgments about whether nuclear energy is feasible or not. Instead, it provides a continuum of analysis that recognizes varying degrees of readiness and opportunity. The model has been operationalized through a scoring system that can be used by policymakers, analysts and researchers to assess national contexts in a systematic way. While primarily developed through empirical analysis of European cases, the model is adaptable to other geopolitical settings, offering a flexible yet robust tool for the assessment of nuclear transitions under complex socio-technical conditions.

4.4 Analytical dimensions of the SoP-based model

As aforementioned, the SoP-based model is articulated around five interrelated analytical dimensions: socio-economic, political, technological, socio-cultural and environmental. These dimensions derive conceptually from the SoP approach (Bayliss and Fine, 2020; Dei et al., 2025), and they allow for a systemic understanding of how nuclear technologies are embedded within national contexts.

The socio-economic dimension captures the economic and labor-related foundations necessary for the development of nuclear energy. This includes the availability of qualified human capital, the presence of an industrial base capable of supporting a nuclear supply chain, and the availability of public and private financial resources to sustain long-term capital-intensive investments. This dimension also considers the ability of a national system to manage and deliver large infrastructure projects, which is crucial for nuclear energy deployment.

The political dimension refers to the formal and informal institutions, governance arrangements, and power configurations that influence nuclear policymaking. It includes indicators such as political stability, government leadership, strategic vision, commitment to energy independence, and the nature of energy market governance (e.g., centralized vs. liberalized). This dimension is relevant for understanding how state structures either enable or constrain the continuity and credibility of long-term nuclear strategies.

The technological dimension focuses on the material infrastructure and innovation systems that underpin the feasibility and scalability of nuclear energy. It considers elements such as reactor standardization, national R&D capacity, radioactive waste management, electricity grid integration, and siting logistics. This dimension also addresses the role of past technological trajectories and path dependencies, which often shape current options for nuclear adoption or phase-out.

The socio-cultural dimension captures the role of public opinion, cultural values, media discourse, and societal narratives in shaping the acceptability and legitimacy of nuclear energy. It includes citizens' support for nuclear projects, local community attitudes toward siting, and the role of framing in shaping risk perception and technological desirability.

The environmental dimension reflects both objective and perceived environmental considerations, including national ecological priorities such as the transition to a circular economy, anti-nuclear environmental movements, and the role of nuclear energy within broader climate mitigation strategies. This dimension assesses whether nuclear is framed as an environmental liability or as a low-carbon solution aligned with decarbonization goals. It also includes physical factors such as access to water, seismic stability, and the ecological implications of siting decisions.

4.5 The SoP-based Model

The following Table 1 presents the determinants, preconditions, enablers and barriers included in the SoP-based model.

Determinants	Preconditions	Enablers	Barriers
SOCIO-ECONOMIC			
Human Resources	Availability of human capital (technical expertise)	High-Quality Technical Universities (FR) / Public and Private investments in Education (DE, FR) / Creation of Employment Opportunities (UK)	Shortage of skilled professionals (UK)

Public Financial Resources	Long-term availability of high capital from public finances	Country GDP sufficient to generate (DE, UK, IT, FR) / Tax Revenue for public financing (DE, UK, IT, FR) / Government willing to support nuclear technologies through subsidies (DE, UK, FR)	Low electricity price (DE) / High cost of capital (UK)
Lenders and Private Investors support	Ensure bankability and willingness to invest	Public-private partnerships (DE) / Consortium (FR) / Energy-intensive industry willing to co-finance nuclear technologies (FR).	Liberalisation of the electricity market increasing investors risk-averse attitude (DE, UK)
Nuclear supply chain	Existing capabilities on nuclear technologies within the country / Existence of nuclear military industry	Willingness of the domestic industry to develop capabilities and invest on nuclear technologies / Access to industrial capabilities outside the country (UK, IT) / Connection with other countries that have a robust nuclear supply chain (UK, IT)	Major actors in nuclear energy sector withdrawing from the nuclear market (DE)
Ability to undertake major projects	Strong project management infrastructure and expertise	Positive track record in large-scale infrastructure projects (DE, FR) / Effective government intervention (FR)	Negative track record in large-scale infrastructure projects (Cost overruns / Public opposition / Delays) (UK, IT)
POLITICAL			
Political Support	Guarantee of long-term political support on nuclear investment decisions	Political consensus on the role of nuclear technologies (UK, FR) / Political structure that minimizes parliamentary interference in energy decisions (UK, FR)	Parties' coalitions opposing nuclear (DE) / Influence of political interests on energy policy (Politicization) (DE, IT)
Political stability	Stable political environment (general, not directly related to nuclear)	Powerful and effective governmental institutions (UK, FR)	Frequent changes in leadership and government (DE)
Governmental leadership	Active and centralized involvement of the government over energy decisions	Direct control of the key actors (FR)/ Unified decision-making body (UK, FR)	Weak government control (DE, IT)/ Decision-making process inefficiencies (IT)
Commitment to energy independence and security	Existence of a strategic energy plan	Long-term energy self-sufficiency planning (DE, UK, FR) / High imports dependence (DE, UK, IT, FR	
Long-term planning	Long term commitment to nuclear technologies (e.g., do not plan for a single reactor, but for a program of power plants)	Centralised decision-making (FR)	Privatization (DE, UK)

Liberalized market	Well-functioning market mechanisms and regulatory frameworks that ensure fair competition among energy providers	Corporate investment and innovation drive, allowing for competitive pricing and technology advancement	Market volatility and corporate interests prioritize short-term profits over long-term national energy security or safety, (DE, UK)
Centralised Governance	Strong state institutions capable of long-term planning and effective coordination	Centralised capabilities under a single entity (FR)	
TECHNOLOGICAL			
Radioactive Waste	Existence of a national waste repository in the country/ Long-term agreements on waste management with other countries/ Existence ofa radioactive waste management program and of a national radioactive waste organization	To have a nuclear industry with competencies in managing radioactive waste (FR)	Social opposition to the waste repository (IT) / Poor waste management (IT)
Electricity Demand	High electricity demand. Scale is not adequate: should have a neutral connotation	Electricity demand growth (DE, UK, IT, FR)/ Electricity export market available (FR)	Demand for energy coming from renewables (DE)
Standardisation of design	Commitment to a single nuclear technology/design	Centralised decision-making (i.e., single utility) (FR)	Diversification (IT, UK)
Siting	Localised consumption centres	Efficient construction methods and regulatory framework well-established (FR)	
R&D on nuclear technologies	High investment on R&D project on low TRL	Excellent technical universities (FR)/ Research centres (DE)	
Grid capacity	To have a reliable electricity grid	Grid centralised under the same utility (DE, FR)	Aging infrastructure (UK)
Primary energy sources	Scarcity of primary energy sources (e.g., coal, oil, methane, Hydro, wind)	Volatility price and uncertainty of alternatives (DE, UK, IT, FR)	Sunk costs and pathway dependency on long-term assets and investments for supply of other energy sources (e.g., pipelines) (DE)
SOCIO-CULTURAL			
Media Support	Dominant narrative favourable to nuclear technologies.	Transparent government communication (UK, FR)	Misinformation (IT)
Siting	Communities willing to host nuclear infrastructure	Job Opportunities in depressed areas (FR)	Local community opposition (UK, IT)
Citizens Support	High public acceptance of nuclear power (on average, considering different types of infrastructure)	Public trust in government actions (FR)/ Reframing of the technology (UK FR)	Anti-nuclear movements (DE)

Public awareness	Public knowledge on nuclear energy (awareness of pros and cons).	Educational campaigns (UK, FR)	Low interest on the topic (DE, IT)
ENVIRONMENTAL			
Environmental Sentiment	Positive nuclear environmental sentiment (e.g., no anti-nuclear environmental movements) .	Environmental reframing from the government (UK)	Environmental protest (DE)
Siting	Presence of suitable nuclear sites in the national territory (e.g., water availability, geological conditions).	Availability of water and lowly populated areas (DE, UK, FR)	
Circular Economy planning for reuse	Suitable dimensions of modules and components for transportation and inspection / Monitoring of modules and components' conditions	Early consideration of CE principles / Government support / Design standardization of modules components and interfaces	Modules and components contamination / Political pressure / Inappropriate regulatory framework
Circular Economy planning for life extension	Suitable technology for life extension	Stable electricity market prices / Adequate maintenance during operations / Direct involvement of the State (e.g., subsidies and contractual agreements)	Frequent safety standards changes

Table 1: The SoP-based model

5 Application of the SoP-Based Model to National Contexts

Following the operationalization of the SoP-based model, we applied the model to four additional national contexts: Italy (reassessed), Romania, Belgium, and Spain. The goal of this application is threefold: to test the model's empirical robustness across diverse energy and governance regimes; to explore how national differences shape nuclear readiness and feasibility; and to refine the comparative understanding of nuclear provisioning in Europe by expanding the geographical scope.

This application phase marked a critical step in transitioning from the SoP approach to a diagnostic tool capable of guiding context-specific policy assessments. Indeed, the several applications of the model to the different countries refined the preliminary list of determinants, preconditions, enablers and barriers, ultimately leading to the elements in Table 1.

Furthermore, by examining countries with varying historical legacies, institutional configurations, and energy policy trajectories, this section evaluates the model's transferability and its capacity to generate actionable insights into the conditions underpinning nuclear energy development. Each national case study was developed through a combination of expert interviews, structured workshops, and a standardized scoring framework implemented via an Excel tool. The selection of countries ensures heterogeneity in political

commitment, infrastructural development, and societal attitudes, thus enabling a comprehensive test of the model's explanatory power.

5.1 Overview of national case studies

Italy: A Benchmark for Internal Consistency

Italy was included to verify internal consistency and test the model's reliability across data sources and engagement modes. The reassessment confirms Italy's historically fragmented approach to nuclear energy, shaped by intermittent policy shifts, entrenched public opposition, and infrastructural discontinuities. Despite moderate capabilities in human capital and electricity demand, critical weaknesses persist across the political, socio-cultural, and technological dimensions. Italy thus functions as a comparative anchor, illustrating how institutional and societal inertia can systematically obstruct nuclear redeployment.

Romania: A High-Readiness, Politically-Aligned Context

Romania emerges as the most favorable case among the newly assessed countries. The national nuclear sector benefits from a robust technical legacy, centralized political leadership, and consistent public support. The Cernavodă plant, active engineering faculties, and recent SMR initiatives showcase Romania's strategic commitment to nuclear expansion. Nevertheless, barriers remain in terms of generational workforce renewal and the mobilization of private finance. Overall, Romania exemplifies how post-socialist infrastructure and strong state capacity can be leveraged for contemporary energy transition goals.

Belgium: A Technically Equipped but Politically Divided Case

Belgium occupies an ambiguous position: it retains a mature technical base and environmental motivations for nuclear retention yet suffers from severe political fragmentation. The phase-out policy reversal in 2025 marked a turning point, but institutional inertia and low investor confidence continue to impede decisive action. While the grid infrastructure and R&D institutions remain strong, their future contribution hinges on overcoming coordination issues across federal and regional levels. Belgium's case underscores the role of governance complexity in mediating technological feasibility.

Spain: A Disengaged Context with Latent Capacity

Spain demonstrates a systemic disengagement from nuclear energy, despite possessing substantial technical and institutional assets. Political leadership remains firmly committed to a complete phase-out by 2035, with little room for reconsideration in current strategic frameworks. Public sentiment is predominantly op-

positional, and nuclear is framed as incompatible with national sustainability goals. The lack of CE integration and investment in R&D further signals institutional closure. Spain thus exemplifies a context in which socio-cultural and political barriers outweigh technological potential.

6 Contributions and Implications

The development and application of the SoP-based model for analysing nuclear energy systems represent a significant contribution to the study of energy transitions, infrastructure governance, and policy evaluation. This section synthesizes the core insights emerging from this work and outlines its implications for both academic research and strategic decision-making. By combining theoretical innovation, methodological rigour, and empirical validation across diverse national contexts, the SoP approach advances a new paradigm for understanding nuclear technologies not as isolated technical choices, but as embedded socio-technical systems shaped by historical, institutional, and cultural dynamics.

A central contribution lies in re-conceptualizing nuclear energy not simply as a techno-economic artifact, but as a complex and situated provisioning system. The SoP approach fosters a systemic understanding of how nuclear technologies are embedded in broader structures of production, governance, and meaning-making. Unlike conventional analyses that prioritize cost curves or reactor efficiency, the SoP lens foregrounds political support, social legitimacy, industrial capabilities, and cultural narratives as co-constitutive dimensions of energy systems. Through its five analytical dimensions, socio-economic, political, technological, socio-cultural, and environmental, the model captures the interdependencies and feedback loops that determine the feasibility and desirability of nuclear pathways. These dimensions provide a granular, multi-level understanding of readiness conditions, illuminating why certain contexts facilitate nuclear expansion while others resist it despite having similar technical infrastructure.

Beyond theoretical refinement, the analysis led to a practical diagnostic tool for evaluating national readiness and the feasibility of nuclear development. Through the definition of determinants, preconditions, enablers and barriers, the model allows for a differentiated analysis that moves beyond binary framings of "pro-nuclear" versus "anti-nuclear" countries. It supports a continuum-based assessment that reflects the complexity and contingency of real-world decision-making. The application of the model to Italy, Romania, Belgium, and Spain also shows its comparative utility.

For policymakers, the SoP-based model provides a structured framework to identify intervention points, design targeted strategies, and anticipate challenges. It highlights that successful nuclear programs are not solely the result of technical capacity or financial capital, but depend crucially on institutional coordination, political coherence, and societal engagement. By mapping barriers and enablers, the model can inform priority-setting for investment and reform, whether that means building institutional trust, securing long-

term financing, strengthening regulatory frameworks, or launching educational campaigns to increase public awareness. It also allows for adaptive policymaking: the model can be periodically updated to reflect changes in political leadership, technological innovation, or societal values, making it suitable for dynamic and long-term planning. Moreover, by zooming in on the SDR, this research offers an innovative method to align economic evaluation with intergenerational equity and societal values. It allows for the recalibration of policy timelines and investment rationales in line with the long-term nature of nuclear infrastructure.

For scholars, the SoP-based model opens several avenues for future research. First, it suggests a promising framework for cross-national comparative studies of energy transitions, capable of accommodating both structural regularities and cultural specificities. Second, it invites further integration with adjacent literatures, such as transition studies, large technical systems, and political economy of infrastructure, to deepen our understanding of how provisioning systems evolve and stabilize. Third, it calls for methodological innovation: combining qualitative mapping with structured expert scoring, as done in this project, enhances both the analytical robustness and empirical granularity of transition research. Future work might explore applications of the SoP model beyond nuclear, to other contested or emerging infrastructure such as hydrogen, carbon capture and storage, or geothermal. Additionally, embedding the model within participatory foresight exercises or policy co-design initiatives could further enhance its translational value.

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