

Nuclear energy: modeling dimensions from an “adequacy for purpose” view¹

Abstract

In emergencies, political decisions often require rapid scientific input, highlighting the critical role of expertise—especially in complex fields like nuclear energy, where safety, regulation, public trust, and political pressures intersect. This paper adopts the “adequacy-for-purpose” approach, which evaluates scientific models based on their fitness for specific goals, to assess modeling dimensions in the nuclear case. We focus on four key areas: reactor design, environmental impact, economic sustainability, and risk mitigation. Through this lens, we examine how models can be developed, adapted, and evaluated to support decision-making. Using adequacy-for-purpose as a guiding principle, we explore the intertwinement of the various modeling dimensions in the nuclear energy case. Our goal is to offer an adaptive framework that bridges theoretical rigor with real-world applicability, providing policymakers with clear, evidence-based guidance.

1. Introduction

In times of emergency, the acceleration of political decision-making processes typically demands expedited scientific analyses. This raises crucial questions about the proper role of scientific expertise in informing policy, particularly in complex sectors such as energy and climate. A paradigmatic case is that of nuclear energy, where decisions must balance rigorous safety and environmental standards, strict regulatory requirements, public skepticism, and political pressure. Navigating this terrain requires robust scientific models that are both precise and adaptable.

From the perspective of contemporary philosophical reflections on scientific modeling,² a convenient framework for analyzing such cases, especially those involving the modeling of complex phenomena and future scenarios, is to conceive models as *tools*. These tools are constructed and selected for specific epistemic goals (e.g., theoretical consistency, predictive accuracy, representational fidelity) and/or non-epistemic goals (e.g., environmental protection, social justice, and economic viability). In this view, instead of evaluating models mainly in terms of how well they represent specific targets, emphasis is placed on how suitably they fulfill particular purposes. Accordingly, model assessment shifts from representational accuracy to *fitness for purpose*.

From this perspective, a natural approach to model evaluation is the “adequacy-for-purpose” (AFP) view, first developed in the context of climate modeling by Wendy S. Parker (2009)³ and successively refined and expanded for broader applications.⁴ The AFP perspective highlights the

¹ This work was supported by the Italian Ministry of University within the scope of the project “Science in times of emergency: the role of scientific knowledge in policy-making during crises” (CUP Master: B53D23032600001; CUP: B53D23032600001; Codice Progetto: P2022ACHYA) – Piano Nazionale di Ripresa e Resilienza Missione 4 Componente 2 Investimento 1.1 – Fondo per il Programma Nazionale Ricerca (PNR) e Progetti di Ricerca di Significativo Interesse Nazionale (PRIN).

² For an updated discussion on scientific modeling, see R. Frigg, J. Nguyen, *Modeling Nature: An Opinionated Introduction to Scientific Representation*, Springer Nature Switzerland, 2022.

³ W. S. Parker, *Confirmation and Adequacy-for-Purpose in Climate Modelling*, “Aristotelian Society Supplementary Volumes”, LXXXIII, 2009, pp. 233–49.

⁴ See, in particular, W. S. Parker, *Model Evaluation: An Adequacy-for-Purpose View*, “Philosophy of Science”, LXXXVII (3), 2020, pp. 457–77; W. S. Parker, G. Lusk, *Incorporating user values into climate services*, 2019, “Bulletin of the American Meteorological Society”, C (9), 2019, pp. 1643–50; G. Lusk, K. C. Elliott, *Non-epistemic values and scientific assessment: an adequacy-for-purpose view*, “European Journal for Philosophy of Science”, XII, 2022, pp. 1–22.

contextual character of modeling practices and argues for a “constrained framework” defined by a combination of target systems, user needs, methodology, and background conditions.⁵ Since models are constructed with a range of epistemic and non-epistemic aims, their appraisal should follow *context-sensitive* standards of appropriateness.⁶ For example, one might assess whether Newtonian mechanics is an adequate modeling framework for designing an aerodynamic structure—not in absolute terms, but relative to additional constraints such as the required passenger capacity, material properties, atmospheric turbulence conditions, and budgetary limitations.

In this contribution, we examine how the adequacy-for-purpose framework can be effectively applied to the nuclear energy sector. A pragmatic approach of this kind seems particularly well-suited for evaluating models in such a complex and multifaceted domain. Nuclear models involve simplifications and assumptions that prevent from offering fully accurate representations. However, this does not exempt from a rigorous and accountable evaluation of such models. In this respect, the AFP framework might provide a powerful way to capture the full range of scientific, technological, socioeconomic, and political dimensions involved.

Indeed, contemporary research on the civil use of nuclear energy must address how modeling practices account for complex interactions among physical processes, technological developments, and societal factors. This is especially important since this form of energy continues to be met with public apprehension, despite notable advancements in research, including new-generation reactors, strict protocols for radioactive waste, and internationally standardized risk management guidelines. In fact, much of this hesitation stems from non-epistemic concerns, such as a general preference for alternative low-carbon sources or fears surrounding potential accidents.

In short, nuclear energy modeling serves a plurality of aims, which can be classified across four major dimensions:

- a) **Reactor design**
- b) **Environmental impact**
- c) **Economic viability**
- d) **Safety and risk management**

Each of these dimensions requires a perspective that integrates epistemic and non-epistemic factors. In Sections 2-4, we examine how the adequacy-for-purpose framework can guide the development and evaluation of models in each of these dimensions. More precisely, Section 2 surveys the landscape of nuclear energy models, emphasizing the interplay between the various modeling dimensions; Section 3 explores the application of the AFP perspective in this context, considering its conceptual and practical implications with some reflections on the specificity of modeling activities in the nuclear energy case; Section 4 briefly concludes.

2. Intertwined dimensions in nuclear energy modeling

In nuclear energy modeling, multiple, often competing objectives shape every stage of scientific inquiry. Models in this case must concurrently be aligned with the Basic Principles and the Nuclear General Objectives,⁷ ensuring that they serve specific, policy-relevant goals, rather than solely striving for representational accuracy. These models are aimed at demonstrating that nuclear energy

⁵ Cfr. W.S. Parker, *Model Evaluation: An Adequacy-for-Purpose View*, cit., p. 460.

⁶ This perspective has flourished in a number of interesting research directions, such as an analysis of how epistemic and non-epistemic features can be integrated based on contextual considerations (cfr. G. Lusk, K. C. Elliott, *Non-epistemic values and scientific assessment: an adequacy-for-purpose view*, cit.), the promotion of customized services incorporating user values (see W. S. Parker, G. Lusk, *Incorporating user values into climate services*, cit.), or the role of representational decisions in science, namely the definition of what, and how, to represent specific phenomena and mechanisms of interest (e.g., E. Winsberg, S. Harvard, *Scientific Models and Decision-Making*, Cambridge, Cambridge University Press, 2022).

⁷ Details about these objectives can be found in International Atomic Energy Agency, *Nuclear Energy General Objectives*, Vienna, IAEA 2011.

produces net benefits and operates transparently while ensuring the protection of people and the environment, maintaining security, upholding non-proliferation, and honoring long-term commitments in minimizing risk.⁸

Guided by these criteria, modeling nuclear energy inherently addresses the interdependent and dynamic nature of nuclear systems, incorporating complex feedback loops between its various dimensions, especially in view of evolving policies and long-term uncertainties (see Figure 1). Effective modeling in this situation requires continuously integrating insights across these interconnected dimensions, ensuring that the underlying models remain adaptive, robust, and consistently aligned with overarching nuclear energy objectives throughout the full facility lifecycle. It is this variety of entangled dimensions that causes interference among scientific activities, whereby one modeling dimension both contributes to shaping, and is shaped by, the scientific agenda of the other ones.

In the following, we explore the previously identified dimensions involved in nuclear energy modeling and focus on a few examples to outline how respective objectives interact with each other. Throughout, we underline that modeling risk is embedded in every dimension, and it is this pervasive integration of safety that renders nuclear modeling philosophically distinctive and in some sense unique. This is why more emphasis is devoted to the safety-and-risk-management dimension (d).

a) Reactor design and fuel management. Among the four modeling dimensions, reactor design and fuel management are the most physics-saturated: their models rest on rigorous, quantitative accounts of core neutronics, thermal-hydraulic flows, and fuel-cycle optimization. Yet, however varied the reactor types, configurations, materials, and operating regimes may be, they all converge on a single aspiration—sustained performance and efficiency under stringent regulatory oversight.⁹ In particular, the nuclear fuel itself is the facility’s driving agent, its full life cycle—from (i) ore extraction, (ii) ore enrichment, (iii) in-core burn-up to (iv) disposal or reprocessing—must be woven into the same modeling fabric.¹⁰ In this respect, on the side of the scientific activities one pursues safety, efficiency, and sustainability in tandem, while on the side of the normative commitments a reactor model counts as genuinely successful only when its seemingly objective predictions remain answerable to three arenas that, in turn, reshape the model’s own architecture: environmental impact (can the predicted source terms be absorbed without unacceptable ecological cost?), economic viability (do life-cycle costs justify continued operation or design changes?), and risk ethics (how do probabilistic safety margins translate into public acceptability?).¹¹ In this interplay, the physics does not stand apart from value-laden considerations; rather, the two continuously co-constitute one another, making reactor modeling a paradigmatic case of how scientific rigour and normative commitments become mutually interconnected.

b) Environmental Impact. Modeling in these dimensions undertakes two main goals. First, the models are built to run local dispersion studies, showing where radioactive material would go in both normal operation and accident scenarios. Second, the models are set to compile full lifecycle

⁸See, in particular, Nuclear Energy Agency/Organisation for Economic Co-Operation and Development (NEA/OECD), *Nuclear Energy Today*, Paris, OECD, 2013.

⁹ See, for instance, International Atomic Energy Agency, *Core Management and Fuel Handling for Nuclear Power Plants*, Vienna, IAEA, 2022. Another relevant reference is S. M. Weston, *Nuclear Reactor Physics*, Hoboken, Wiley-VCH, 2018.

¹⁰ See, for example, International Atomic Energy Agency, *Handbook on the Design of Physical Protection Systems for Nuclear Material and Nuclear Facilities*, Vienna, IAEA, 2021.

¹¹ A useful reference is International Energy Agency, *The Path to a New Era for Nuclear Energy*, Paris, IEA, 2025.

records, counting the land disturbed by uranium mining, the greenhouse gases avoided or emitted, the area the plant occupies, and the effort needed to finally dismantle it.¹²

Moreover, their task is not merely descriptive: each model interrogates whether nuclear power can meet energy demands while preserving ecosystem integrity and inter-generational equity. For instance, performance assessment models of geological repositories attempt to predict the behavior of a repository for thousands to even a million years ahead. Obviously, no model is expected to be “true” over such timescales, but models are still indispensable for policy-makers since governments must make decisions on repository sites and designs. In this regard, models are built and evaluated on the following aspect: *will this repository contain the waste safely within regulatory limits over time?* For example, in a site like Yucca Mountain (USA) or Onkalo (Finland), modelers must consider groundwater flow, volcanic activity, container corrosion, radionuclide decay and transport, and even future human intrusion scenarios. Taking each of these factors into account requires input from different fields – geology, hydrology, materials science, etc. – and each activity carries with it a variable amount of uncertainty. By integrating these disciplines, model building implies systemic risk management. For example, the modeler might calculate the probability distribution of radiation dose a person may experience in the year 12,000 AD under various assumptions. In this case, if all plausible realizations of the model show the existence of doses below the legal threshold, the repository design at hand is regarded as acceptable.¹³

Importantly, modelers use multiple lines of evidence and scenario analyses, meaning that since we are incapable of empirically verifying the model over 10,000 years, a possible way to build confidence is through peer review, keeping in mind the social issues involved,¹⁴ and by showing that the model behaves reasonably against shorter-term observations¹⁵ (like current groundwater measurements). Therefore, the modelers must reassure society that the repository will not harm future generations (an ethical commitment), and it must satisfy the regulators who are tasked with upholding stringent environmental standards. This leads to practices like “pragmatic validation”,¹⁶ where the model is stress-tested for usefulness, that is, modelers are faced with questions such as: *does it handle the critical scenarios? Are its uncertainty bounds communicated clearly?* The decision to license and open a repository relies on demonstrating an adequate safety case via these models.

c) Economic dimension: Sustainability and energy production. Modeling the economic aspects of nuclear energy production plays a crucial role in evaluating the financial characteristics and related risk factors of projects encompassing nuclear energy. This includes assessing these projects according to their costs, returns on investment, and market competitiveness with the main goal of defining adequate financing plans for such projects.¹⁷

The associated models analyze capital and operational expenses, the current trends of energy markets, and the impact of government policies and regulations on economic viability. This, in turn,

¹² For more information see, International Atomic Energy Agency, *Regulatory Control of Radioactive Discharges to the Environment*, Vienna, IAEA, 2000.

¹³ See, for example, Nuclear Energy Agency OECD (Organisation for Economic Co-Operation and Development), *Geologic Disposal of Radioactive Waste in Perspective*, Paris, OECD, 2024.

¹⁴ See the recent guidelines for peer review on safety in International Atomic Energy Agency, *Guidelines for the Peer Review of Operational Safety of Nuclear Fuel Cycle Facilities*, Vienna, IAEA, 2024.

¹⁵ This works in the case of nuclear modeling, but shorter-term observations are not always representative, as exemplified by the case of climate modeling. For a philosophical discussion on the topic see, e.g., R. Frigg, R., J. Reiss, *The Philosophy of Simulation: Hot New Issues or Same Old Stew?*, “Synthese”, CLXIX(3), pp. 593–613.

¹⁶ Cfr. S. Finsterle, B. Lanyon, *Pragmatic Validation of Numerical Models Used for the Assessment of Radioactive Waste Repositories: A Perspective*, “Energies”, XV, 2022, pp. 3585–600.

¹⁷ A reference on this matter is, J. Lovering, A. Yip, T. Nordhaus, *Historical construction costs of global nuclear power reactors*, “Energy Policy”, XCI, 2016, pp. 371–82.

provides insights that inform stakeholders, such as investors and policy-makers, to ensure the establishment of strategic planning for the nuclear facility.

In the broader context of economic sustainability, the assessment of nuclear energy production relies on comprehensive models that integrate technological, economic, and environmental factors. Examples thereof are the Energy System Models (ESM)¹⁸ and the Integrated Assessment Models (IAMs).¹⁹ These models, once applied to the nuclear case, position it as one option among many in achieving climate targets (e.g., the green energy transition plan),²⁰ combining plant operating costs—such as cost structures, build-times, reactor lifetimes, and fuel availability—with economic variables like carbon-emission pricing, electricity demand growth, and grid stability requirements.²¹

In particular, the economic sustainability of nuclear projects depends on key factors such as: 1) the ability to provide dependable and continuous power supply over prolonged periods of time;²² 2) a certain operational flexibility, which allows reactors to adjust power output dynamically to accommodate fluctuations in electricity demand and integrate variable renewable sources; 3) and product flexibility, which enables participation in multiple energy markets through ancillary services like frequency regulation and voltage support.²³ For instance, a government model charting an energy roadmap to 2050 locates nuclear energy among several other energy resources (renewables, coal, oil, hydraulic etc) and considers all of these parameters to simulate different economic scenarios—one with high nuclear deployment, another phasing nuclear out—comparing their sustainability and revenue metrics while ensuring compliance with dictated safety guidelines (cfr. the report *World Energy Issues Monitor*, cit.).

A very concrete example to consider when addressing this dimension in nuclear modeling is that of advanced reactor systems (i.e., reactors of generation IV). The latter aim to be more sustainable by using closed fuel cycles to minimize radioactive waste and better fuel utilization.²⁴ When evaluating whether these designs are fit for their intended purposes, one must consider not just the reactor physics, as described above in (a) but also how much waste is generated and how dangerous it remains over time, as described above in (b). A design that produces significantly less long-lived waste might score better in a multi-criteria decision analysis for sustainability, even if it is more expensive or technically complex. Thus, policy-makers might support that design.

This stands as a clear example of how intertwined the different nuclear modeling dimensions are (waste reduction vs. cost vs. proliferation risk), and how models help clarify them quantitatively. If an IAM, including nuclear energy, helps a government confidently chart a path to net-zero carbon (by comparing scenarios and showing trade-offs), it is considered successful. If it omitted key issues (say, the intermittency of renewables or the baseload contribution of nuclear), it would be considered inadequate for that purpose.

¹⁸ Details on these models can be found in International Atomic Energy Agency, *Modelling Nuclear Energy Systems with MESSAGE: A User's Guide*, Vienna, IAEA, 2016.

¹⁹ Consider, for example, International Atomic Energy Agency, *Integrated Safety Assessment of Nuclear Installations by the Regulatory Body*, Vienna, IAEA, 2021. An up-to-date discussion of Integrated Assessment Models in relation to policy making in the energy context is provided in F. Palazzi, *Democracy, Expertise, and Energy. The Case of Climate and Energy Modelling*, “Politica e Società” II, 2025, pp. 233-62.

²⁰ A relevant reference on this plan is represented by International Atomic Energy Agency, *Climate Change and Nuclear Power 2020*, Vienna, IAEA, 2020.

²¹ One can find more details in this regard in the report *World Energy Issues Monitor* by the World Energy Council, 2019.

²² For more details, see for example J. Bistline, S. Bragg-Sitton, W. Cole, B. Dixon, E. Eschmann, J. Ho, A. Kwo, L. Martin, C. Murphy, C. Namovicz, A. Sowder, *Modeling nuclear energy's future role in decarbonized energy systems*, “Science”, XXVI (2), 2023, pp. J. Bistline, S. Bragg-Sitton, W. Cole, B. Dixon, E. Eschmann, J. Ho, A. Kwo, L. Martin, C. Murphy, C. Namovicz, and A. Sowder, *Modeling nuclear energy's future role in decarbonized energy systems*, “iScience”, XXVI., 2023., art. 105952.

²³ Cfr. World Nuclear Association. *The New Economics of Nuclear Power*, London, 2004.

²⁴ See, in particular International Atomic Energy Agency, *Fast reactors and related fuel cycles: Sustainable clean energy for the future*, Vienna, IAEA, 2025.

d) Safety assessments and modeling risk. The safety of a nuclear installation is defined by its ability, through both technical systems and trained personnel, to achieve two fundamental objectives: first, to prevent accidents from occurring, and second, to minimize the consequences in the event of an accident.²⁵ The International Atomic Energy Agency (IAEA) plays a crucial role in this process by enforcing Safety Standards designed to protect human health and minimize risks to life and property.²⁶ These standards are developed through an open and transparent process that integrates scientific research, technological advancements, and operational experience and defines a certain *safety culture to be respected*.

In more detail, to address the *first safety objective* stated by the IAEA, an evaluation of both normal operational scenarios and potential accident conditions is in order, and this can be done through the employment of techniques such as the methods of Probabilistic Risk Assessment (PRA), failure modes, and effects analysis. Specifically, the safety design encompasses the implant's integrated protection systems, along with the organization's framework, operator training, procedural protocols, and operator attitudes. These aspects are usually managed internally, but with the mandatory external evaluation, which is conducted through the verification and inspection activities carried out by an independent regulatory body.²⁷

Risk quantification uses the risk triple as a set of three questions that can be used to define *risk*, namely: i) what can go wrong?; ii) how likely is it?; iii) what are the consequences?²⁸ PRA models address these primary questions in the following steps: a) identify initiating faults and event sequences that could cause core damage, b) understand the consequences of such damage and potential radioactive releases, and c) determine the probability of these events occurring. Thus, by quantitatively evaluating both the probability²⁹ and impact of foreseeable faults, this method is able to assess risks for each scenario.

In this way, the PRA method encompasses both internal events, like component failures and human errors, and external events, such as natural disasters and man-made incidents like aircraft crashes.³⁰ Once the setting and modeling parameters are identified for each risk scenario, the outcome of a given PRA analysis is typically expressed through metrics like Core Damage Frequency (CDF) and Large Release Frequency (LRF).³¹ CDF measures the likelihood of events that could damage the reactor core based on the plant's design and operation, while LRF estimates the frequency of accidents that could lead to significant, unmitigated radioactive releases into the environment, thereby illustrating the potential risk to both the public and the ecosystem.³² Additionally, Frequency-Consequence (F-N) plots are typically utilized in these cases to quantitatively represent collective or societal risks, where their plotted curves represent the probability of accidents against their potential consequences, such as fatalities, by displaying the

²⁵ A concrete example in this regard is discussed in P. L. Aksenov, I. A. Komolov, and P. A. Molodov, *Development of a Risk Monitoring Model for NPPs with a VVER-440 Reactor*, "Atomic Energy", CXXXIII, 2023, pp. 1063-4258.

²⁶ The Safety Standards consist of three sets of publications: the Safety Fundamentals, the Safety Requirements, and the Safety Guides. While the first type establishes the fundamental safety objective and the principles of protection and safety, the second sets out the requirements that must be met to ensure the protection of people and the environment, both now and in the future. The Safety Guides provide recommendations and guidance on how to comply with the requirements.

²⁷ See, for more details, International Atomic Energy Agency, *Regulatory Authorization and Related Inspections for Nuclear Security During the Lifetime of a Nuclear Facility*, Vienna, IAEA, 2024.

²⁸ Cfr. International Atomic Energy Agency, *Probabilistic Safety Assessment*, Vienna, IAEA, 1992.

²⁹ In the context of nuclear modeling, PRA methods employ a pragmatic mix of frequentist, Bayesian, expert-elicited, and Monte Carlo methods to quantify risks and uncertainties in complex, safety-critical systems.

³⁰ In this regard, a useful discussion is provided in the report *The Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants*, by the U.S. Nuclear Regulatory Commission, 2016.

³¹ Cfr. International Atomic Energy Agency, *Governmental, Legal and Regulatory Framework for Safety*, Vienna, IAEA, 2016; International Atomic Energy Agency, *Safety Assessment for Facilities and Activities*, Vienna, IAEA, 2016.

³² See, for instance, Nuclear Energy Agency/Organisation for Economic Co-Operation and Development (NEA/OECD), *Comparing nuclear accident risks with those from other energy sources*, Paris, OECD, 2010.

cumulative frequency of events resulting in a specified number of fatalities. F-N curves offer a visual estimate of the risk associated with accidents affecting large populations, aiding in comprehensive risk assessment and decision-making processes.³³

As powerful and useful as PRA analyses can be, the static character they are endowed with makes them only *partially* adequate to fulfill the safety objectives and risk mitigation plans. As a result, the traditional PRA approach is becoming less and less popular in nuclear modeling and is slowly being replaced or compensated by the so-called dynamic PRA method that simulates how an accident might unfold over time, including complex interactions and feedback.³⁴ These models are capable of capturing the timing of operator actions, evolving plant conditions, and real-time system behavior. They treat the plant as *an integrated network* of systems, combining hardware, software, and human operators into one single interactive analysis.

To provide an example, a socio-technical risk model might include how operator decisions or organizational factors influence the progression of an incident, where accounting for human reliability and organizational processes is equivalent to acknowledging that safety is not just a matter of equipment but a holistic property of the entire system (people included). This systemic approach is increasingly relevant for long-term and emerging risks as well. Dynamic safety assessments likewise inform emergency planning – e.g., simulation of a severe accident and radioactive plume dispersion guides how large an evacuation zone should be and what interventions are most effective. These examples show modeling not as a one-off calculation but as a continuous risk management practice, updating as new data come in and as systems evolve over time.³⁵

For instance, the primary purpose in the case of an emergency event within a nuclear facility is for the PRA model to prove that the reactor can either safely shut down or maintain the containment of radiation. In practice, this means that if the safety regulations impose, in any credible accident, that the public radiation needs to remain below a certain value X , the model must show this condition is met, often by intentionally exaggerating the scenario to maximize protection. This was experienced in the adoption of conservative bounding analyses for licensing: if the model, using worst-case assumptions, still meets safety limits, regulators consider it a *sufficient* demonstration of safety. It is precisely in this sense that safety models directly inform decision-making: a reactor design might be modified (adding, e.g., an extra cooling tank) if the model indicates a too minimal safety margin. After real incidents, safety assessment models were updated. To provide two examples, after the 1979 Three Mile Island accident – one of the most serious in US, classified as a level 5 accident according to the *International Nuclear and Radiological Event Scale* (INES) – PRAs were expanded to include small sequence precursors; after Fukushima, models started incorporating multi-unit failures and long-term station.³⁶

To achieve the ***second safety objective***, namely to minimize the consequences in the event of an accident, technical and organizational measures such as the *defense in depth principle* are in order.³⁷ In particular, this principle applies across several levels, namely: i) the prevention of failures, ii) the detection and control of failures, iii) the control of design-based and severe

³³ On this we refer the reader to V. de Vasconcelos, W.A. Soares, A. C. L. da Costa, *FN-Curves: Preliminary Estimation of Severe Accident Risks after Fukushima*, Sao Paulo (Brazil), INAC, 2015.

³⁴ A reference on this subject is N.E. Wiltbank, C.J. Palmer, *Dynamic PRA prospects for the nuclear industry*, 2021, “Frontiers in Energy Research”, IX, 2021, art. 750453.

³⁵ Cfr. International Atomic Energy Agency, *Human Reliability Analysis in Probabilistic Safety Assessment for Nuclear Power Plants: A Safety Practice*, Vienna, IAEA, 1996.

³⁶ See, for example, Organisation for Economic Co-Operation and Development, *Status of Site-Level (Including Multi-Unit) Probabilistic Safety Assessment Developments*, Paris, OECD, 2021.

³⁷ The basic principle underlying nuclear facilities is the defense-in-depth, which provides multiple independent levels of protection against the release of radioactive substances (see NEA/OECD, *Nuclear energy today*, cit.).

accidents, and the mitigation of the radiological consequences in the case of a serious release during an off-site emergency plan. These levels are integrated in place at all stages of a nuclear facility's lifetime, starting with its siting and design, through manufacturing, construction, and commissioning, during operation, and finally, during its decommissioning.

Along with the predictions of the dynamic PRA method, a tangible exercise to evaluate the reliability of the obtained theoretical results is the actual simulation of nuclear emergencies with the primary goal of checking the efficiency of the Emergency Preparedness and Response (EPR) of the State Members. As discussed in the 16th Meeting of the EPR Standards Committee (EPReSC, June 2023) by the Emergency Response Officer, Stacey Horvitz, these simulations address “(i) widespread radioactive release; ii) serious transnational and/or transboundary impact; iii) medical and public health; iv) import/export of goods and products; v) foreign nationals and tourism; vi) international assistance”. In 2024, several exercises were conducted among the member states. Particularly interesting is the one organized on the 10th of October. The objective was to simulate a transnational nuclear emergency in Pakistan, designing a plausible scenario to test the members' capability to respond and deal with such a scenario. The emergency simulation ran for 48 hours and was designed to involve the state members in international cooperation and real-time decision-making.³⁸

As noted earlier, the peculiarity of nuclear-energy modeling is the tight interweaving of its multiple dimensions, an interconnection that actively shapes the scientific practices and modeling tools employed in each. To emphasize this aspect more explicitly, we illustrate a couple of examples.

At its core, nuclear modeling builds on physics. For example, a reactor core model couples nuclear physics with heat transfer and structural mechanics to predict temperatures and stresses. These are physical elements ensuring that the model accurately represents the reactor's behavior. However, as we discussed above, nuclear systems are so complex that even within the sole engineering dimension, multiple sub-disciplines intersect, in this way opening the space for various criteria of appropriateness to play a role. A reactor safety model must incorporate reactor physics, mechanical engineering, and electrical engineering. All these pieces come together to simulate a transient or accident scenario. An inadequate model might omit one of these interactions; an adequate model includes enough of them to capture the system's behavior under the conditions of interest. When evaluating such multifaceted models, a key criterion is their ability to offer a continuous, dynamic representation of data across all disciplines, thereby enabling robust construction and analysis of diverse scenarios.

Additionally, as nuclear models must satisfy regulatory standards (such as limits on radiation release and core damage frequency targets), which are often very conservative, the question becomes: *how can one achieve the optimal balance between the interconnected set of purposes defined for each dimension of the problem?* For example, a compliance-oriented model might err heavily on the safety side to leave no doubt, fulfilling the regulatory *purpose* even if it sacrifices operational optimization. On the other hand, for internal optimization or design improvement, engineers may use more realistic models to fine-tune performance. Thus, different modeling approaches are used in parallel and in an intertwined manner, such that one is devoted to ensuring all safety and regulatory constraints are satisfied, while the other aims to maximize performance within the limits set by such bounds.

³⁸ For further details, see the 12 CAM 2024 Meeting Report to EPReSC by C.T. Vidal available on the IAEA website (<https://nucleus.iaea.org/sites/committees/EPReSC%20Documents/E7.2%20CAM%202024.pdf>).

Another noteworthy example is the interplay between economic considerations and safety features. Nuclear projects are capital-intensive, so economic and safety modeling must be reconciled within this character.³⁹ Rigorous safety measures (additional backup systems, thicker containment, etc.) improve risk assessment outcomes but also raise invested costs. In particular, within the modeling process, one ought to find acceptable trade-offs: for instance, the PRA method might identify which safety upgrades yield the biggest risk reduction per Euro, allowing, in turn, a guided investment in cost-effective improvements of the facility's safety. The industry's move toward risk-informed regulation explicitly tries to optimize this balance.⁴⁰ Instead of one-size-fits-all conservative rules, regulators use risk models to focus on the most significant risk, potentially allowing relaxation over (excessively) conservative requirements elsewhere. This risk-informed approach can improve safety while simultaneously minimizing unnecessary costs. Such a procedure is typically realized to identify the most profitable for safety investment, in this way balancing between the protection increase and the maintenance of economic viability.

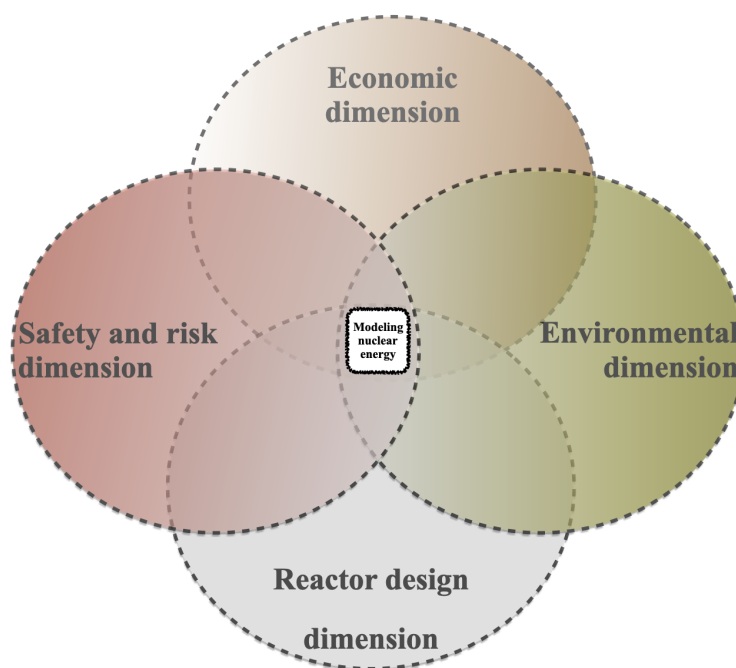


Figure 1: Modeling dimensions for nuclear energy.

3. Nuclear modeling from the adequacy-for-purpose (AFP) perspective

Does the AFP perspective offer useful insights on the relationship between the various modeling dimensions involved in the nuclear energy case? As said, the broad scope of the AFP view is to substantiate the claim that the validity of a model is not to be evaluated primarily in reason of its truth-likeness, rather in terms of its suitability to fulfill a specific intended scope (or, in most cases, a multitude thereof). This is because such a (set of) scope provides indications, during model construction and/or assessment, on which simplifications, idealizations, or other approximations are

³⁹ A relevant reference on this matter is Nuclear Energy Agency (NEA), *Unlocking Reductions in the Construction Costs of Nuclear*, Paris, OECD, 2020.

⁴⁰ This is the approach to regulation taken by the Nuclear Regulatory Commission (NRC: <https://www.nrc.gov/docs/ML1622/ML16225A002.pdf>). This approach incorporates an assessment of safety significance or relative risk, and ensures that the regulatory burden imposed by an individual regulation or process is appropriate to its importance in protecting the health and safety of the public and the environment.

held acceptable within the model in question. Consequently, the chosen purposes and priorities steer the level of detail and accuracy, thereby affecting the overall reliability and applicability of the model. Based on this, the relevance of the AFP view for the nuclear energy case can be ascertained along two main directions, respectively related to the single modeling dimensions and their integrated assessment. The first direction can be straightforwardly implemented by interpreting each modeling dimension from an AFP standpoint:

- a. **Reactor design and fuel management:** To what extent do the models for reactor design and fuel management effectively achieve the intended goals of safety, efficiency, and sustainability while complying with stringent regulatory standards?
- b. **Environmental impact:** How can radioactive waste (and its associated risk) be managed safely within the regulatory limits over time? More specifically, do the models describing a repository comply with the “pragmatic validation”, whereby a model gets stress-tested for usefulness (such as its ability to handle critical scenarios or to clearly account for uncertainty bounds)?
- c. **Economic dimension:** Does the model efficiently capture all of the relevant factors necessary to make an informed policy decision that is economically viable, yet still complies with the safety guidelines and risk management schemes?
- d. **Safety assessment and modeling risk:** How effectively does the model capture the full spectrum of normal and accident scenarios, including rare and complex event sequences? How well do the mitigation measures limit the progression of core damage and the subsequent potential for radioactive release?

The second direction requires a more comprehensive analysis, as the process of constructing and evaluating models are deeply intertwined and cannot be clearly separated. Informal assessments frequently occur during the development phase, and insights gained from formal evaluation methods often inform subsequent refinements. These adjustments may involve enhancing the detailed representation of specific processes or incorporating previously omitted elements into the model framework.⁴¹ Through continuous iteration between construction and evaluation, models become more robust and better equipped to appropriately capture the complexities of the systems they aim to simulate.

Note, however, that in the context of nuclear energy modeling, this iterative process faces several significant conceptual issues, since no realistic way to test the accuracy of the model is available. As a result, only partial confidence can be achieved. The reason for this is, obviously, that certain parameters and processes involved in nuclear energy display life-threatening features, making realistic and safe experimentation difficult, if not impracticable. This means, as already discussed, that modeling the various dimensions in this sector to successively define appropriate safety standards heavily relies upon probabilistic assessment methods.⁴² In this respect, it could be interesting to compare the case of nuclear modeling with that of climate modeling. In both cases, evaluating if currently available models perform adequately to predict future behaviour is a challenging goal. And yet, as outlined by Parker, in the case of climate modeling,⁴³ this difficulty

⁴¹ Cfr. W.S. Parker, *Model Evaluation: An Adequacy-for-Purpose View*, cit.; A. Bokulich, W.S. Parker, *Data models, representation and adequacy-for-purpose*, “European Journal for Philosophy of Science”, XI, 2021, pp. 1-26.

⁴² Cfr. International Nuclear Safety Advisory Group, *Probabilistic Safety Assessment*, Vienna, IAEA, 1992.

⁴³ W.S. Parker, *Confirmation and Adequacy-for-Purpose in Climate Modelling*, “Proceedings of the Aristotelian Society, Supplementary Volumes”, vol 83, 2009, pp. 233-249.

does not undermine scientists' trust that such models stand as reliable tools for credible quantitative assessments (p. 247).⁴⁴

It is therefore unsurprising that valuable insights for applying the AFP perspective to nuclear energy modeling can be drawn from philosophical discussions addressing similar modeling challenges in the domain of climate science. This is Kawamleh's argument (2022)⁴⁵, whose main goal is to argue that climate models require the introduction of a dynamic AFP view – where a climate feature is taken as dynamically adequate in case “its spatio-temporal evolution and behavior under intervention on relevant inputs (boundary conditions, parameters, etc.) is consistent with observational data and our background knowledge” (p. 122). The idea is that a dynamic assessment is more apt to capture context variability and to exclude spurious fit with observational data that relate to mechanisms such as model tuning, compensating and/or systematic errors (see, e.g., Katzav et al., 2012),⁴⁶ as well as to deal with the challenge of “confirmational holism”, namely the fact that the level of complexity associated with climate models makes it impossible to evaluate whether a model succeeds or fails for a specific parameter or component. Analogously, modeling the various dimensions in the nuclear sector requires adopting a dynamic standpoint, though the “dynamic” element is not necessarily to be conceived in spatiotemporal terms, but rather in relation to a more abstract feedback mechanism that constantly evolves and updates the space of constraints defining the modeling dimensions at play and required to satisfy a set of (dynamically-varying) purposes.

The general point is that, as for the other case studies (climate science being one of them), the reliability of a given model to fulfill a specific purpose according to a set of constraints is *relative*, rather than absolute. A proper way to frame the nuclear energy sector from the AFP view would be: *how can we strike the proper balance between the modeling dimensions, granted that the evaluation cannot be realized experimentally for obvious safety reasons?* In this regard, the standard AFP and fitness evaluation of the underlying model prove too strict and unidimensional. This implies that the ranking order of purposes according to their weight of importance or priority is limiting in exploring the actual, realistic scenario. In the case of nuclear energy modeling, we see that various dimensions of the model (such as safety and economic efficiency) are deeply interconnected and sometimes in tension with one another. These dimensions reflect competing priorities that are not arranged in a simple hierarchy of importance but must instead be balanced dynamically based on context and purpose, though how to achieve that is a rather complex process, which must be established on a case-by-case basis.

Focusing on the various components of nuclear energy mentioned in Section 2, it becomes apparent that the process of modeling each of these components (with associated targets, parameters, and purpose) calls for an integration that is critical for the *overall* adequacy of nuclear energy modeling. This is what we here identify as the *dynamical-systemic feature of the AFP framework*, which will then require coherence, interdisciplinarity, transparency, adaptability, and accountability, all of which hint at an intertwined analysis of the modeling dimensions. Coherence

⁴⁴ Note that a comparison with climate modelling could indeed be fruitful, especially in the light of possible analogies or disanalogies. In regard to the latter, for example, not all quantitative assessments have the same epistemic status in climate modeling, depending on spatial and temporal scales, on the variables chosen and so on. It would be interesting to establish, when possible, to what extent the case of climate modeling is (dis)similar with respect to the nuclear one.

⁴⁵ Kawamleh, Suzanne, *Confirming (climate) change: a dynamical account of model evaluation*, “Synthese”, vol CC (122), 2022, pp. 1-26.

⁴⁶ A useful reference on this regard is J. Katzav, H. A. Dijkstra, & , H. A. de Laat, *Assessing climate model projections: State of the art and philosophical reflections*, “Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics”, vol XLIII, 2021, pp. 258–76.

ensures that different models are compatible and inform each other, providing a comprehensive understanding of the nuclear energy system (including the reactor design, fuel management, waste management, and safety assessment). The interdisciplinarity element results from the combination of insights from physics, engineering, economics, environmental and social sciences to create holistic models for the production of safe nuclear energy, its maintenance, and sustainability. Transparency relates to the explicit definition of the underlying assumptions, such as the choice of specific approximations to characterize specific parameters of interest. These elements need to be complemented with external, dynamical, criteria, most importantly adaptability, namely the criterion allowing models to evolve with new data, technologies, and societal values, and accountability, that is the traceability, guaranteed by modelers, in model assumptions, methodologies, and limitations – a key component to ensure trust among stakeholders.

Notably, the dynamic aspect of the AFP view is already mentioned by A. Bokulich and W.S. Parker in their *Data models, representation and adequacy-for-purpose* (2021, Sect. 5, cit.) in relation to data re-use and re-purpose, whereby they emphasize that the evaluation of adequacy and the choice of purpose need not be taken as static. However, the dynamical-systemic character feature of the modeling dimensions discussed here is not only concerned with reuse and repurpose mechanisms. The point is that the constrained framework envisaged by advocates of the traditional AFP view needs to be reconceptualized in a dynamical fashion, so as to properly outline the interplay between different and competing factors, most paradigmatically expressed by the need to find the proper balance between energy production and safety standards. This dynamic platform can be regarded as a generalization of the traditional AFP view for contexts in which not only the interplay of various purposes is at stake (being them economic, energetic, political), but where the key scope, namely preventing harm to the environment and the population, can only be evaluated in *probabilistic* terms. This allows singling out the two main insights of an AFP perspective for modeling the nuclear energy sector.

First, this framework helps clarify the interplay and possible tensions between the various modeling dimensions in the case of nuclear energy. This is realized by setting the criteria for a model to effectively fulfill its intended function(s) within each dimension, its reliance, and its capability to properly navigate the multidimensional modeling space. For example, in the safety dimension, models must ensure compliance with stringent regulatory standards while maintaining operational feasibility; in the economic dimension, models must balance cost-effectiveness with long-term sustainability while ensuring an acceptable safety margin. In this case, adequacy typically means comprehensiveness across relevant dimensions and related fields.

Second, the AFP perspective explicitly outlines the pervasive uncertainty involved in both the construction and evaluation of models. A hallmark of nuclear-energy modeling from this perspective is its rigorous treatment of *uncertainty*: probabilistic forecasts are inescapable, and risk analysis stands as a dedicated modeling dimension that intersects with every other domain. The AFP view accepts, in this case, that models will not eliminate uncertainty. The issue becomes whether the uncertainty is *sufficiently constrained and understood to support decisions*. In this regard, the AFP perspective becomes especially relevant when applied to practical cases in nuclear modeling, where managing uncertainty is not just theoretical but central to regulatory and safety decisions.

For example, taking again the geological case of licensing a repository within the safety guidelines (discussed in Section 2) and performing PRA simulations to assess the long-term risks associated with it, model evaluation becomes an exercise in managing uncertainty to acceptable levels, rather than granting whatever sense of certainty. As one waste repository modeling study

conducted by S. Finsterle and B. Lanyon in *Pragmatic Validation of Numerical Models Used for the Assessment of Radioactive Waste Repositories: A Perspective* (cit., p. 10) explains, the process is more like an *audit via critical questions* than a simple yes/no validation – it “redirects attention from a stringent pass-fail comparison with reality to a broader evaluation of the model’s adequacy” heavily relying on expert judgment and uncertainty analysis. This broader view builds confidence that the model is reliable enough for its role. In fact, going through robust validation (or *evaluation*) protocols – testing assumptions, cross-comparing model outputs with evidence, independent peer review “ultimately improve the model and therefore the quality of inferences and decisions made based on the model output”(ibid.).

In sum, by focusing on purpose, nuclear models are tailored and tested to ensure they provide *decision-relevant reliability*, even if they cannot guarantee absolute predictions. All in all, by simulating containment integrity and emergency response effectiveness, modeling risk helps identify vulnerabilities and enhance the overall resilience of nuclear systems.⁴⁷

The more general lesson is that it is not merely the context-dependence of a model that defines its adequacy, a point that is by now widely acknowledged, but rather its capacity to achieve the appropriate balance among competing demands. A nuclear model is adequate not simply because it fits a given context, but because it manages the trade-offs required for the task at hand—whether that involves ensuring safety margins, meeting cost targets, or adhering to regulatory constraints. This flexibility avoids both excessive conservatism that could needlessly hinder operations and excessive optimism that could compromise safety. In both cases, however, conservatism is an unavoidable criterion or, if you like, feature for the specific case of nuclear modeling, and more generally for models that aim to combine both epistemic and non-epistemic values (with a taint of probabilistic nature).

4. Conclusion

This article is aimed to show the relevance of the AFP perspective to model nuclear energy. We started by singling out the major modeling dimensions involved in this case study, which we identified as the reactor design, the environmental impact, the economic dimension, and risk assessment/management. After a general overview of the role and interplay between these various dimensions, we outlined that the import of the AFP perspective is to be evaluated along two directions: the embeddability of each modeling dimension and the combined assessment of their interrelation. We concluded that a dynamical-systemic AFP framework represents a useful entry-point to the case of nuclear energy. More generally, the overarching objective of this work is to reflect on how to establish a comprehensive and adaptive modeling framework capable of meeting specific policy and regulatory needs within nuclear energy while avoiding the compromise of scientific integrity. By adopting the AFP view, the paper outlines a way to bridge theoretical precision with practical applicability, in order to provide policymakers with clear, actionable guidance grounded in robust scientific assessment.

⁴⁷ See, for instance, International Atomic Energy Agency, *Fundamental Safety Principles*, Vienna, IAEA, 2006, as well as, International Atomic Energy Agency, *Methods for Comparative Risk Assessment of Different Energy Sources*, Vienna, IAEA, 1992.