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PSI

Evaluating Nuclear Reactor Designs for Deployment in Europe

A Multi-Criteria Decision Support Framework with Uncertainty Propagation

Tesi di Laurea Magistrale in Nuclear Engineering - Ingegneria Nucleare

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Alla mia famiglia.

Abstract

European policymakers face pressing imperatives: decarbonizing electricity generation, ensuring system reliability, and safeguarding energy sovereignty. These challenges have renewed interest in nuclear deployments. This study supports reactor design decision-making in Europe by applying a Multi-Criteria Decision Analysis (MCDA) framework to evaluate mature and near-commercial technologies.

Decision-support problems are inherently uncertain, stemming not only from uncertainties in input data but also from the subjectivity of preferences. To address these uncertainties, this thesis develops the Uncertainty Propagated MAVT (UP-MAVT) method, which systematically propagates all uncertain variables within a Multi Attribute Value Theory (MAVT) framework. This framework serves as a building block due to its mathematical simplicity and explicit structure, facilitating the integration of uncertainty across all components. The objective of UP-MAVT is to propagate uncertainties in input data, subjective information, and preferences to the final results, yielding more transparent decision support.

The elicitation process combined well-established and state-of-the-art methods, with improvements introduced for uncertainty characterization in the former. To streamline the process, which was based on expert interviews, digital tools were developed to support elicitation through interactive graphical interfaces.

The analysis adopts the perspective of governmental energy policy and planning agencies tasked with selecting a reactor design for mid-2030s deployment. It compares three traditional large reactors and three Small Modular Reactors (SMRs), repeating the assessment for four European countries with distinct energy requirements. Results reveal a consistent preference for traditional large reactors over emerging SMRs, regardless of national context. These findings underscore the challenges facing SMR adoption, primarily due to scepticism over their unproven operational track record.

Keywords: Nuclear Power, MCDA, Uncertainty Propagation, Energy Policy, Decision-making

Abstract in lingua italiana

I responsabili delle politiche energetiche europee devono affrontare sfide urgenti: ridurre le emissioni nella produzione di energia elettrica, garantire la stabilità della rete e assicurare l'indipendenza energetica. Queste esigenze hanno riacceso l'interesse verso l'energia nucleare. Questo studio offre un supporto alle decisioni sulla scelta dei reattori in Europa, applicando un metodo MCDA per valutare tecnologie già consolidate o in fase di commercializzazione.

I processi decisionali sono per loro natura incerti, sia a causa dell'incertezza dei dati iniziali sia della soggettività delle preferenze. Per gestire queste incertezze, la tesi propone il metodo UP-MAVT, che analizza sistematicamente tutte le variabili incerte all'interno di un modello MAVT. Tale modello, grazie alla sua struttura chiara e matematicamente semplice, permette di integrare l'incertezza in ogni suo componente. L'obiettivo è propagarele incertezze fino ai risultati finali, rendendo il supporto decisionale più trasparente.

Per raccogliere le preferenze degli esperti, sono stati combinati metodi tradizionali e innovativi, migliorando in particolare la valutazione dell'incertezza. Per semplificare il processo, basato su interviste a specialisti del settore, sono stati sviluppati strumenti digitali con interfacce interattive.

Lo studio si pone dal punto di vista delle istituzioni pubbliche incaricate di pianificare le politiche energetiche e di selezionare un progetto di reattore da avviare a metà degli anni Trenta. L'analisi confronta tre reattori tradizionali di grande potenza e tre SMRs, ripetendo la valutazione in quattro paesi europei con fabbisogni energetici diversi. I risultati mostrano una netta preferenza per i reattori tradizionali rispetto ai SMRs, indipendentemente dal contesto nazionale. Questo orientamento riflette le difficoltà che i piccoli reattori modulari incontrano nel guadagnare fiducia, soprattutto per la mancanza di una comprovata esperienza operativa.

Parole chiave: Energia nucleare, Analisi multicriterio Propagazione delle Incertezze, Politiche energetiche, Supporto decisionale

Contents

Introduction

The global energy landscape is undergoing a significant transformation, driven by the imperative to decarbonize electricity generation while ensuring energy security and system reliability. Within this context, the European energy transition is accelerating, and nuclear power can play a critical role in both providing low-carbon electricity and stabilizing the grid amid the increasing use of renewable power sources.

National energy requirements vary significantly. Some countries prioritize baseload capacity to reduce import dependence, while others require flexible solutions to complement existing and future renewables. The emergence of small modular reactors alongside established Generation III+ designs expands the range of options but also introduces complexities into the decision-making process. Selecting a specific nuclear reactor design involves navigating complex trade-offs across technical, economic, regulatory, social, environmental, and geopolitical dimensions, with consequences that will endure for decades. This thesis studies a novel case-study to compare specific reactor models within a clearly defined context, moving beyond the technology assessments or site-selection studies prevalent in existing literature.

However, such decision problems are inherently uncertain. Data limitations, reliance on estimates and projections, and evolving scenarios create ambiguity in the analysis inputs. The complexity of the problem also makes it difficult to quantify all aspects, necessitating the incorporation of qualitative judgments. This introduces additional layers of uncertainty, which, if not systematically addressed, can undermine the robustness of the decision-making process. Uncertainty arises at multiple stages, from the elicitation of expert judgments to the aggregation of criteria, and must be rigorously propagated to ensure the reliability of the final results. To tackle these challenges, this thesis introduces UP-MAVT, a method built upon Multi Attribute Value Theory (MAVT). As a decision-support methodology, MAVT provides a structured, transparent framework for modelling preferences [1]. UP-MAVT extends this framework by systematically propagating uncertainty through the analysis, ensuring final rankings reflect the full range of potential outcomes.

This thesis addresses two critical research gaps, case-study limitations and methodological challenges in MCDA under uncertainty, by answering the following key questions:

- How to systematically address, evaluate and present all uncertainties arising from quantitative and qualitative information intrinsic to the MCDA process in a MAVT framework?
- Which reactor designs are viable for European deployment in the mid-2030s based on geopolitical issues, technology maturity, market availability, energy requirements, and sociopolitical contexts?
- What are the key technical, economic and social attributes that differentiate the viable reactor designs?
- How does the application of a MAVT framework reveal differences in reactor design rankings across countries?

Chapter 1 presents the literature review, beginning with an overview of nuclear power's historical challenges before focusing on MCDA applications in the nuclear sector. This review identifies the research gaps addressed in this thesis. The uncertainty propagation framework, named UP-MAVT, is detailed in Chapter 2, alongside other methodological components. To support expert elicitation during the case study, complementary digital tools and procedures for quantifying uncertainty in subjective inputs are also developed. Chapter 3 applies this framework to evaluate and rank nuclear reactor designs for deployment in selected European countries. The results, their interpretation, and broader implications are examined in Chapter 4, while proposed future directions and conclusions are summarized in Chapter 5.

1 | Literature Review

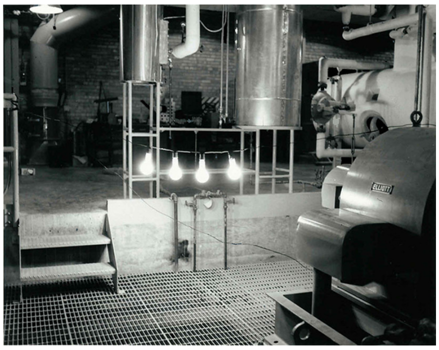
In this chapter, a historical overview of nuclear power development is presented, followed by a review of decision-support methodologies relevant to nuclear energy deployment decisions. The literature review identifies gaps in existing research, establishing the foundation for the current study.

1.1. A brief History of Nuclear Power

The 1930s and 1940s witnessed rapid advancement in nuclear science. In 1932, James Chadwick discovered the neutron [2] and a year later Leó Szilárd hypothesized fission chain reactions. In 1938, Otto Hahn and Fritz Strassmann produced barium by neutron bombardment of uranium, demonstrating nuclear fission was possible [3]. Further advancements like the first controlled nuclear chain reaction in the Chicago Pile-1 achieved by Enrico Fermi's team in 1942, were speed up by World War II efforts as part of the Manhattan Project which ultimately resulted in the atomic bombings of Hiroshima (6 August 1945) and Nagasaki (9 August 1945). The recognition among the scientific community of the peaceful potential of nuclear technology lead to the famous speech "Atoms for Peace" by USA President Eisenhower in 1953 to the United Nations [4] which established the foundation for international nuclear cooperation. The International Atomic Energy Agency (IAEA) and the EURopean ATOMic energy community (EURATOM) were established 4 years after, in 1957. The two agencies are tasked with promoting peaceful nuclear applications while serving as independent authorities for safety regulation and non-proliferation oversight.

1.1.1. Generation I Reactors

In the 1950s early reactor models were deployed, now classified as Generation I reactors, they represented the first prototypes of nuclear power at utility scale. The Experimental Breeder Reactor 1 (EBR-I) in Idaho (USA), was the first to generate electricity in 1951, powering four light bulbs. The Obninsk Nuclear Power Plant (USSR) became the first to feed a local power grid (5 MWe) in 1954. Calder Hall-1 (UK), the world's first commercial-scale nuclear power station (50 MWe), was the first to be connected to a national grid in 1956.

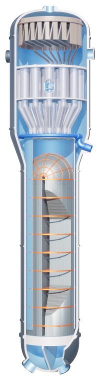


(a) EBR-I, 1951

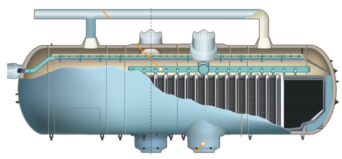
(b) Calder Hall-1, 1956

Figure 1.1: (a) The four light bulbs powered by the EBR-I in Idaho, USA. [5]. (b) Calder Hall-1 Nuclear Power Station in the UK. [6]

The United States pioneered Light Water Reactor (LWR) technology through two distinct designs: the Boiling Water Reactor (BWR), developed at the Argonne National Laboratory, and the Pressurized Water Reactor (PWR) originally developed for naval propulsion. The first commercial implementation of the BWR was the Dresden-I (1960) while for the PWR it was the Shippingport Atomic Power Station (1957) [7]. Not long after, the USSR developed its own pressurized water technology, the "Water-Water Energetic Reactor" (VVER). Design differences between US-PWRs and VVERs still persist to this day, such as the orientation of the steam generators as depicted in Figure 1.2.



(a) PWR steam generator



(b) VVER steam generator

Figure 1.2: Comparison of steam generator orientations in PWR (vertical) and VVER (horizontal) designs. Credit: energyencyclopedia.com [8]

Technological diversification occurred also on other fronts as each nation developed its own reactor designs. The United Kingdom advanced gas-cooled magnox reactors, the

Soviet Union initiated development of the graphite-moderated, water-cooled "high-power channel-type reactor" (RBMK) design, while Canada's nuclear program focused on Pressurized Heavy Water Reactor (PHWR) technology, culminating in the first commercial CANDU reactor at Douglas Point in 1968 [7].

1.1.2. Generation II

Between the 60s and 70s Generation II reactors were deployed, taking advantage of previous experience, reactors are now developed as commercial products rather than experiments or prototypes. In these decades numerous countries commissioned their first nuclear reactors: Belgium (1962), Italy (1963), Japan (1963), Sweden (1964), Switzerland (1969), Slovakia (1972), Argentina (1974), Bulgaria (1974) and Armenia (1976) [7]. Following the 1973 oil crisis, the deployment of nuclear power plants was accelerated in some countries as an energy security strategy. Most notably France implemented the Messmer Plan, named after the Prime Minister at the time, to greatly expand the nuclear plant fleet [9].

Nuclear expansion continued through the 1980s until 1986. As news from the Chernobyl disaster came to western countries, fear of the potential risks of nuclear power intensified. The public opposition grew significantly so that, even if safety and regulatory updates were implemented, several countries decided to slow down, reduce, or halt their nuclear programs altogether, such was the case of Italy after the results of the 1987 referendum, which resulted in a complete phase-out of nuclear power [10, 7].

By the 1990s, multiple western countries had suspended nuclear deployment entirely, including Germany and Switzerland. France, previously the most active builder, connected 10 reactors between 1990 and 1999, while the United States and the United Kingdom only deployed 4 and 1 reactors respectively during the same period. Italy completed its nuclear phase-out by 1990 with the permanent shutdown of all operating reactors [7].

Contrastingly, Russia and China pursued an opposite trajectory. Following the post-Soviet economic transition, Russia resumed its nuclear program and has since continued expansion of its reactor fleet [7]. China initiated its nuclear program in the 1990s with Qinshan-1 (connected in 1991) and has since maintained aggressive expansion. Over the past three decades, China has brought 56 additional reactors online and currently has 29 under construction, closing the gap with the United States, as illustrated in figure 1.3 [7]. According to recent projections China is expected to greatly surpass the US within the coming decade [11].

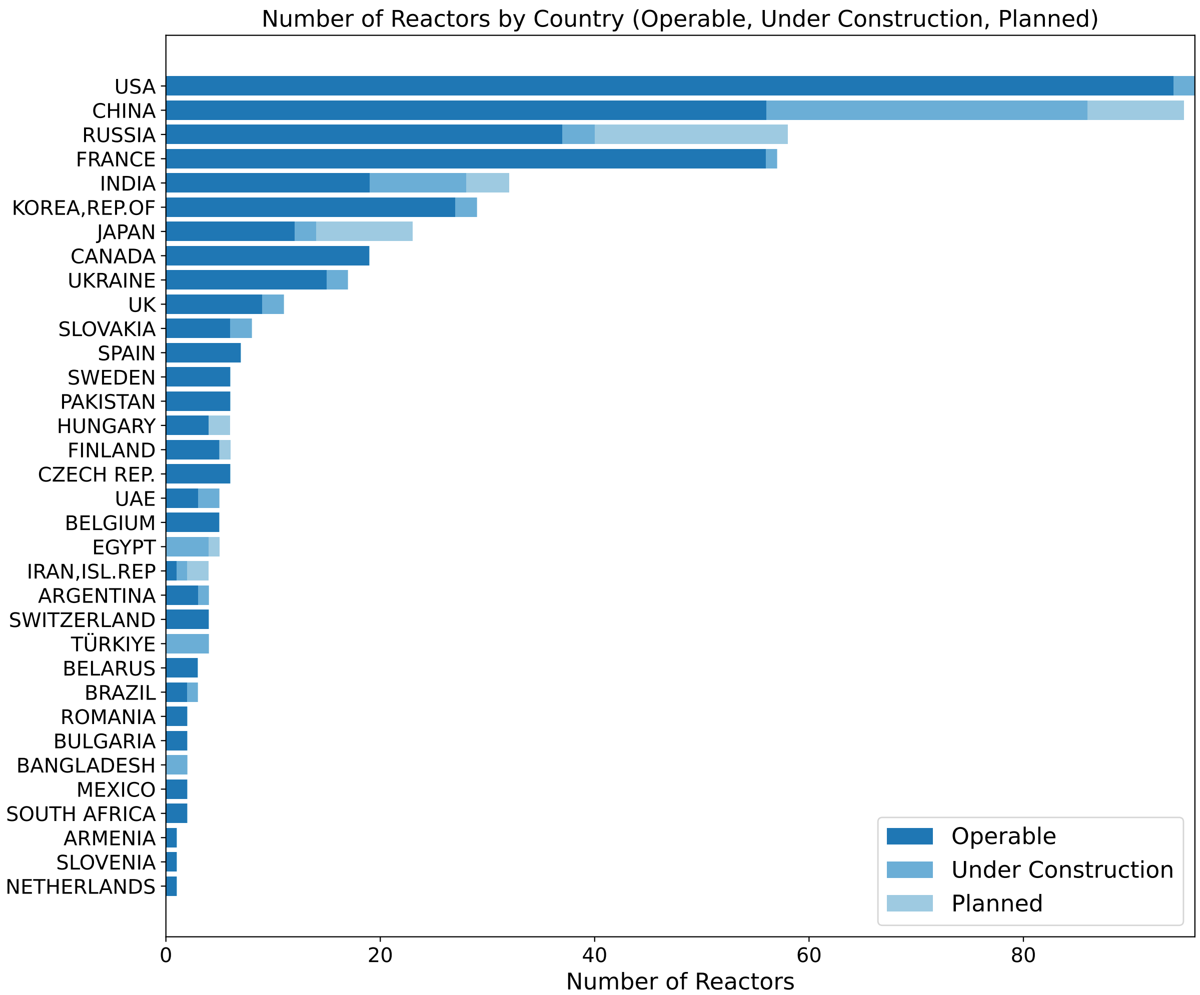


Figure 1.3: Nuclear reactors deployed and in deployment, per country. Representation obtained with data from [7]

1.1.3. Generation III

As a result of the regulatory safety improvements, a stabilized choice of technology with LWRs settling as the go-to choice all over the world and even larger capacities, Generation III reactors started to be deployed by the end of the 90s. The new generation introduced several improvements, comprehensively documented by the World Nuclear Association [12]. Notable advancements include:

- Higher availability factors and extended 60-year operating lifetimes
- Substantially reduced core melt accident probabilities
- More effective fuel utilization
- Strengthened protection against external events

With the new millennium, incremental improvements to these designs resulted in Generation III+ reactors, including the European Pressurized Reactor (EPR) and the American Advanced Passive (AP-1000). This designation represents an evolutionary step rather than a significant generational jump, serving primarily to distinguish between contemporary reactors that incorporate the most recent safety standards and earlier, but similar, designs.

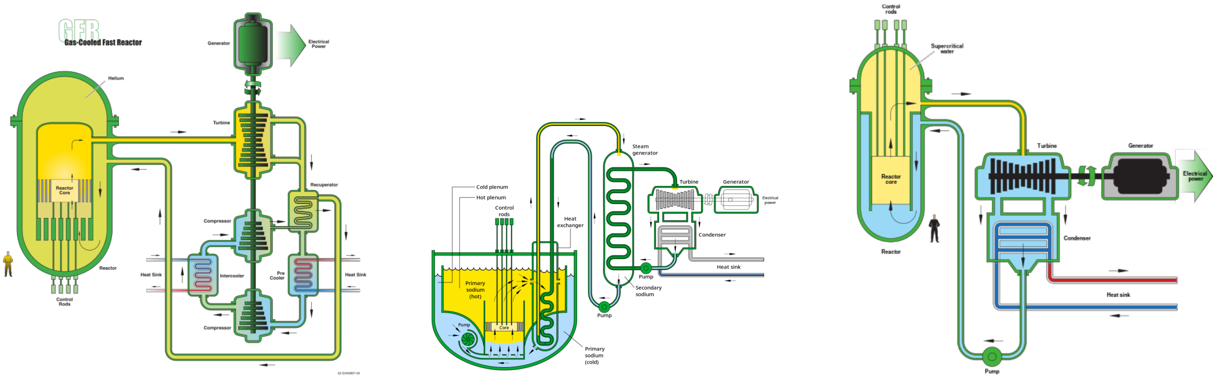
However, after the 2011 Fukushima Daiichi accident, Western nations experienced a second setback: Germany accelerated its nuclear phase-out policy, while Italy reaffirmed its anti-nuclear position through another popular referendum [13]. In the following years, projects faced substantial delays, cost overruns, and public opposition, with France's Flamanville-3 EPR serving as a particularly illustrative case, experiencing budget increases of more than four times the original estimates and construction timelines tripled from initial projections [14].

1.1.4. Generation IV

From the late 2000s to nowadays, new nuclear commissioning projects such as the EPR at Flamanville-3 can be classified as "Mega Projects", such term is used to refer to very large commitments where economies of scale tend to fail due to the complexity of the task at hand, resulting in massive delays and cost overruns, well known examples of Mega Projects are Suez and Panama Canals, the Sydney Opera House or the development of the Concorde Supersonic Aeroplane [15, 16].

To counter this phenomenon, the nuclear industry is developing SMRs, which are part of Generation IV reactors. SMRs are smaller, standardized reactors that can be built mostly off-site to take advantage of economies of multiples. Some SMR designs are based on novel technologies, such as those presented in figure 1.4, while others take advantage of well-known water-based designs.

Other generation IV reactors are being designed to address other aspects of nuclear power, such as waste minimization and higher efficiency. Mainly by employing different means of cooling to exploit neutrons at higher energies (fast neutrons), or by using thorium instead of uranium as fuel, or even using direct gas-based cycles to increase thermal efficiency.



(a) Gas cooled Fast Reactor (GFR)

(b) Sodium cooled Fast Reactor (SFR)

(c) SuperCritical Water Reactor (SCWR)

Figure 1.4: Schematic representations of advanced Generation IV designs [17]

1.1.5. Current European Landscape

In recent years, three critical developments have reshaped Europe's energy strategy. First, the COVID-19 pandemic in 2020 revealed structural vulnerabilities in the continent's economic systems. Second, the Russian invasion of Ukraine in 2022 exposed Europe's dependence on external energy suppliers and the associated geopolitical risks [18, 19, 20]. Third, the accelerating imperatives of decarbonization have intensified the need for a rapid transition toward low-carbon energy systems.

Collectively, these developments have compelled European policymakers to reassess the role of nuclear energy, increasingly viewing it as a dual-response option: on one hand, contributing to climate-mitigation goals through the provision of low-carbon electricity, and on the other hand, enhancing energy security and grid resilience [21].

This strategic reassessment of nuclear is evident in recent policy initiatives. The European Union's classification of nuclear power as a sustainable investment under its taxonomy for climate mitigation [22], alongside programs like the European Industrial Alliance on SMRs, are clear indicators of the renewed interest in nuclear technologies [23].

However, nuclear-related commitments present challenges that cannot be addressed by intuitive judgment. The Decision Makers (DMs), in this context government agencies, energy policymakers and utility executives, face high-stakes choices, as Nuclear Power Plant (NPP) commissioning involves decades long commitments and billions in public and private investment. Moreover, the far-reaching economic, social and political consequences of nuclear infrastructure decisions necessitate systematic approaches to ensure responsible outcomes.

1.2. Nuclear power decision support

The decision-making process begins by identifying the decision problem and the possible solutions to such a problem. From this point, there are several ways to make a decision. The most common approach to decision-making, which is encountered by anyone in our day-to-day life, is to look at the possible solutions or "alternatives", intuitively compare positive and negative outcomes based on own preferences and find the best, or "less worst", between them. However, when decisions carry significant responsibility, justification based solely on intuition is not sufficient. For this reason, analytical frameworks have been developed to assist DMs. One of the most employed approaches is Cost-Benefit Analysis (CBA), which systematically evaluates the advantages and disadvantages of a project or decision by converting all aspects into monetary terms to determine the net cost or revenue of a decision [24].

The present study is focused on nuclear energy related decisions, which, as the previous historical overview demonstrated, extend far beyond technical and economic considerations, inevitably encompassing social and political dimensions which cannot be readily reduced to monetary terms alone. The literature review reveals that, to address such complexity, MCDA methods predominate in energy decision-support research. This observation aligns with findings from Seran et al. (2025), whose comprehensive analysis of renewable energy studies demonstrated that the vast majority employed MCDA methodologies [25].

MCDA systematically evaluates alternative solutions by decomposing decision problems into distinct criteria representing either the consequences of each alternative or their distinguishing characteristics [26]. This criterion-based approach offers two primary advantages: first, it enables the structured analysis of complex problems involving many criteria; second, it reveals preference patterns from different perspectives, which becomes particularly valuable when multiple stakeholders are involved. The method's transparency allows decision-makers to identify the most critical aspects of each alternative in relation to specific stakeholder preferences.

While there exist many MCDA methodologies (see Greco et al. 2016 [27] and Cinelli et al. 2020 [28]) their common ground is to model the decision problem considering available information on it, considering trade-offs, and then allowing to choose between alternatives [29]. MCDA can be used for solving different decision problems or *problematics* as they are presented in the book "Multiple Criteria Decision Analysis" by Greco et al. (2016) [30]:

- Choice: Selecting the most preferred alternative(s) from a large pool of options.
- Sorting: Classifying alternatives into predefined categories.
- Ranking: Ordering all alternatives from most to least preferred.
- Scoring: Ranking alternatives while also quantifying the differences between them.

A fundamental distinction exists between American and European MCDA methodologies. American-developed approaches, including the Analytic Hierarchy Process (AHP) [31] and MAVT [32, 33], were born on the basis of the compensatory principle, emphasizing trade-off dynamics where a loss in one criterion can be offset by a gain in another. Value functions are usually used to model importance structures across performance ranges, considering the whole dataset (e.g., the value of criterion C1 increases linearly from 0 to 1 between its minimum and maximum data points).

In contrast, European researchers developed non-compensatory methods based on the outranking principle, such as ELECTRE [34] and PROMETHEE [35]. These methods, normally, establish preferences through pairwise comparisons of differences between alternatives (e.g., if alternative A1 exceeds A2 by 5% on criterion C1, then A1 is preferred to A2) and may incorporate veto conditions between criteria [30, 36, 27].

1.2.1. Relevant Studies

A literature review, targeted at studies applying MCDA to nuclear power decision-making, reveals several methodological approaches.

Site selection studies represent the most common application, typically employing Geographic Information System (GIS)-based software, to evaluate potential locations for new nuclear installations within limited geographical regions. These analyses frequently incorporate quantitative non-technical factors such as population proximity [37, 38]. Abdullah et al. (2025) extend this approach by including social dimensions such as public acceptance and tourism impacts, which pose challenges for quantification [39]. Notably, Devanand et al. (2019) develop an algebraic optimization model to identify optimal SMR locations in Singapore, though like most site-focused studies, they favour a design without systematic comparison [40].

Study	MCDA Methods	Objectives
Damoom et al. (2019) [37]	MCDA method not mentioned	GIS-based analysis, Evaluate potential locations for new nuclear installations, focusing on geographical criteria.
Basegmez et al. (2025) [38]	AHP	Another GIS-based analysis, assess site suitability for nuclear installations, mostly focused on geographical features. More comprehensive than the previous one
Abdullah et al. (2025) [39]	AHP, ELECTRE	Extend site selection by including public acceptance and tourism impacts.

Table 1.1: Site selection studies for nuclear installations.

A second category compares different nuclear technologies. Kiser and Otero (2023) evaluates PWRs, SMRs, and Molten Salt Reactor (MSR) [41], while Locatelli and Mancini (2011) compares large and small reactor designs [42]. Birikorang's study stands out for its regional focus on South Africa and comparison of three specific reactor models (Nuscale Power Module (NPM), EM2-HTGR, FTR-MSR), though its technological comparisons mix designs at different maturity levels [43]. Notably, all three studies utilize the AHP or its Fuzzy variant. The last one (Birikorang) draws on the IAEA's INPRO methodology for advanced nuclear technology comparison [44].

Broader energy comparison studies by Hernández-Torres (2025), Pasaoglu (2018), and Atilgan (2016) evaluate multiple generation options (typically eight alternatives) employing hybrid AHP-Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), AHP, and MAVT methodologies respectively. These studies use generic, averaged parameters for each technology class [45, 46, 47]. In contrast, Castelazo (2014) adopts a more precise approach using MAVT to compare thirteen energy technologies, employing specific reference plants (e.g. EPR reactor for nuclear power) rather than generalized technology averages [48].

Study (Authors, Date)	MCDA Methods	Objectives
Kiser and Otero (2023) [41]	AHP	Compare PWRs, SMRs, and MSRs, includes a rough, qualitative evaluation of public opinion as a risk factor.
Locatelli and Mancini (2011) [42]	AHP	Compare large and small reactor designs.
Birikorang (2026) [43]	Fuzzy AHP	Application of IAEA INPRO method to compare SMR, HTGR and MSR technologies in South Africa.

Table 1.2: Studies comparing different nuclear technologies.

Three studies are particularly relevant to the current research, as summarized in Table 1.4. Zolkaffly et al. (2014) evaluate nuclear plant models for Malaysian deployment, focusing on a governmental perspective by using national requirements as indicators. However, the study's age renders most reactor data outdated. Moreover, they employ a strictly technical assessment, excluding economic, social and environmental [49].

Topaloğlu (2025) applies the Analytic Network Process (ANP) to compare the deployment of four reactor types (PWR, BWR, PHWR, Gas Cooled Reactor (GCR)) across four Turkish regions. The analysis employs 20 criteria, including technical factors (cooling water availability, electrical system compatibility), environmental considerations, and site-specific social criteria (proximity to forests/historical sites, transportation access, vicinity to population centres) [50].

Goushis (2025) employs TOPSIS to assess SMR deployment in the EU to replace 193 coal-fired power plants. Though focused on a single reactor model rather than comparative technology evaluation, the premise of their study aligns with the current research in recognizing the current European energy landscape and nuclear crucial role and finally, by employing MCDA to address these challenges [51].

The literature review reveals four gaps in nuclear energy decision-making research:

- Most studies focus solely on site selection rather than comparing different nuclear technologies
- Comparisons of nuclear designs lack consideration of specific decision-making con-

Study (Authors, Date)	MCDA Methods	Objectives
Hernández-Torres (2025) [45]	Hybrid AHP-TOPSIS	Evaluate multiple energy generation options (8 alternatives) using generic technology parameters.
Pasaoglu (2018) [46]	AHP	Compare multiple energy generation options (8 alternatives) using generic technology parameters for Turkish deployment. Considers numerous indicators (22) mostly on economics and political related factors
Atilgan (2016) [47]	MAVT	Compare multiple energy generation options (8 alternatives) using generic technology parameters for Turkish deployment. Smaller set of indicators, considers more social indicators.
Castelazo (2014) [48]	MAVT	Compare the LCA of thirteen energy technologies, using specific reference plants (e.g., EPR reactor).

Table 1.3: Broader energy comparison studies including nuclear technologies.

Study (Authors, Year)	Key Contributions to Current Research
Zolkaffly et al. (2014) [49]	Governmental perspective analysis; reactor model comparison framework
Topaloğlu (2025) [50]	Comprehensive multi-criteria evaluation considering social aspects
Goushis (2025) [51]	European context analysis; premise regarding nuclear role in the European energy transition

Table 1.4: Selected studies informing the methodological approach for nuclear technology evaluation

texts

- Studies that do consider specific decision-making context, examine various energy generation options as broad technology categories (e.g., nuclear, solar, wind) rather than conducting detailed analyses of specific power plant designs
- Social dimensions are frequently overlooked or applied only to site selection criteria

The case study in Chapter 3 addresses these gaps by analysing specific reactor designs within a clearly defined context, while integrating sociopolitical dimensions, without requiring site-selection constraints.

1.3. Uncertainties in MCDA

Decision-making processes inherently involve uncertainty, stemming from input data, multi-actor dynamics, and subjective elements. While the literature recognizes the need to address uncertainty, few studies do so comprehensively. Monte Carlo methods, as noted by Ezbakhe and Pérez-Foguet (2018), are particularly effective for propagating uncertainties in MCDA. They generate full probability distributions at the cost of a higher computational effort [52]. While several studies take advantage of this technique, they all focus on aggregated metrics rather than distributional insights.

Feizizadeh et al. (2015) apply Monte Carlo techniques to parameter and spatial uncertainty in GIS-MCDA, visualizing results through rank statistics and sensitivity maps. While effective for spatial variability, their method emphasizes rank-based summaries rather than full distributions [53]. Zheng et al. (2016) integrate socio-economic, predictive, and preference uncertainties in wastewater planning, combining Stochastic multiobjective acceptability analysis (SMAA) (Section 2.4.1) with Monte Carlo simulation. Their rank acceptability indices and holistic rankings provide robust scenario analysis, but still rely on summarized outputs [54]. Geldermann et al. (2006) use Monte Carlo simulation to address data and parameter uncertainties. Their stacked-bar charts for worst-case, best-case, and most probable scenarios illustrate practical applications but again simplify uncertainty into aggregated forms [55].

From this review, two key limitations arise from the present literature:

- Distributional uncertainty remains underexplored: most studies reduce it to ranges or confidence intervals, neglecting the depth of full probability distributions.
- Open-source tools are lacking: no publicly available frameworks exist, limiting reproducibility and innovation.

This gap highlights the need for a transparent, adaptable framework that propagates uncertainty in MCDA while ensuring accessibility across decision contexts.

2 | Methodology

As presented in the Section 1.2, several MCDA methodologies exist, requiring, firstly, a choice between outranking and value-based approaches. Outranking methods were discarded for this analysis on the basis that no clear non-compensatory dynamics were evident in the decision context.

Among American-school methods, MAVT stands out as particularly suitable for this study. Its transparency, a key strength as highlighted by Schuwirth et al. (2012) [1], stems from its value functions, which effectively capture non-linear relationships in indicator values across their ranges. This feature is especially relevant for economic and social criteria and aligns well with the methodological extension proposed in Section 2.4. While this method was previously introduced in Section 1.2, the following paragraphs provide a detailed explanation.

Variable	Description
A_i	Alternative
C_j	Criteria
x	Elicited Criterion Performance
$v_j(x)$	Value Function
w_j	Weight
$\vec{h}$	Vector of Hypothetical Result
z	Auxiliary variable for minimization
G_j	High-level group of criteria
Subscripts	
b	Best Criterion
w	Worst Criterion
(j, w)	Comparison of Criterion j to Worst Criterion
(b, j)	Comparison of Best Criterion to Criterion j

Table 2.1: Description of Variables and Subscripts

2.1. Applying MAVT to choose a Reactor

Multi Attribute Value Theory, first presented by Keeney in 1996, is a value-focused approach to decision-making that centres its analytical process on the core values and objectives of the DM rather than on the available alternatives A_i. This allows DMs to explicitly define their *fundamental objectives* (what they seek to achieve) rather than *means objectives* (how those objectives will be achieved) [32]. Preferences are modelled across performance ranges by means of value functions, $v_j(x)$ which are able to capture both linear and non-linear importance relationships between criterion values. Once the values of each criterion C_j are established, the criteria are aggregated based on weights w_j that convey the relative importance among them. The explicit nature of both value functions and weights make MAVT a particularly transparent decision analysis method, which is especially valuable for research applications.

The first methodological step requires **establishing indicators and their hierarchical structure**. Morton and Fasolo (2009) identify two traditional approaches: top-down and bottom-up [56]. The top-down approach begins with macro-level objectives that are subsequently decomposed into lower-level objectives through the guiding question "How can we achieve this?". On the other hand, the bottom-up approach, which is employed in the present study, starts with low-level objectives derived by comparing alternatives A_i, asking: "What differentiates these alternatives?". Higher-level objectives are then constructed by aggregating similar indicators.

Morton and Fasolo also note that top-down structuring tends to produce general value trees, difficult to apply to a specific study. Bottom-up approaches, instead, create context-specific trees that are difficult to generalize. Additionally, this study found the bottom-up approach particularly useful in ensuring even indicator distribution across high-level objectives. This practice mitigates splitting bias, in which an objective divided into multiple sub-objectives will typically receive a higher cumulative weight than the equivalent single objective [57], accordingly, even distribution should prevent artificial favouring of objectives with greater indicator counts.

Value Functions are the defining feature of MAVT that allow to, first, reduce any metric, based on qualitative or quantitative data, to a scalar comparable with other different metrics. And second, it conveys more implicit information than a single metric might be able to carry. Consider the evaluation of a job offer, where salary appears as an obvious quantitative metric. The perceived value, that is how the personal judgment of the salary, rarely scales linearly with the compensation. Any offer below a subsistence threshold dictated by essential monthly expenses (rent, food, transportation) have a significantly lower value than those offer exceeding it. Similarly, a €100 difference between two low salary offers typically carries greater weight than the same difference between two high salary proposals. These non-linear relationships in the perceived value can be represented through a carefully tailored value function like the one shown in figure 2.1.

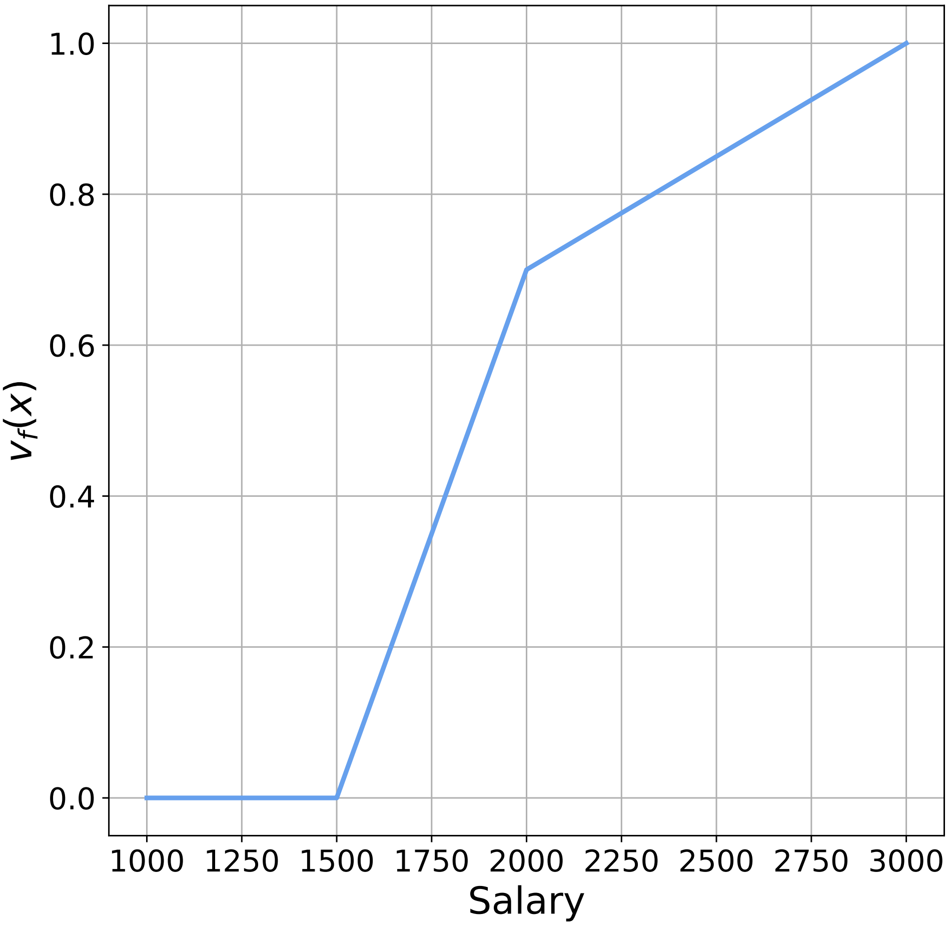


Figure 2.1: Example of a Value Function

This study employs the mid-value splitting technique for value function elicitation, originally developed by Keeney and Raiffa [58]. While the original study provides the fundamentals of the method, it offers limited guidance on elicitation of value function shapes. The technique is focused on identifying **indifference points** which, in general terms, are a point P in the data range of the criterion C such that the improvement from a lower bound A to point P is indifferent to the improvement from P to an upper bound B.

The elicitation process begins by determining the 0.5 indifference point between the criterion's minimum and maximum values, effectively dividing the range into two segments of equivalent perceived value. This procedure is then applied to each resulting segment to establish the 0.25 and 0.75 indifference points. To ensure systematic application, this thesis developed a flowchart to guide the elicitation process (Figure 2.2). In principle, the methodology could allow experienced DMs familiar with value function concepts to bypass indifference point elicitation when linearity can be confidently established. Moreover, to ease the work of DMs, it is recommended to begin with a straightforward example criterion to familiarize participants with the both the method and any aid that might be employed in the elicitation process.

The primary limitation of mid-value splitting lies in its time-intensive nature. To mitigate this, the current study implemented a staged approach: the initial expert (whose results will be referred to as "first elicitation") performed complete value function elicitation, while subsequent specialists reviewed and modified this baseline. This methodology rests on the reasonable assumption that the fundamental shape of a value function remains stable across experts, necessitating only minor adjustments to the established curve.

Aggregation within a fully compensatory framework, is typically performed using weighted summation (Equation 2.1). The need to explore non-fully compensatory scenarios led to the development of alternative approaches employing non-linear aggregation techniques (for a comprehensive description of aggregation methods, see [59]). For the MCDA application of the present study, the work by Langhans et al. (2014) [60] and its implementation in the MCDA calculator tool [61] will be used as a reference, which includes the following aggregation methods:

- Fully compensatory: weighted sum (sum) (equation 2.1)
- Partially compensatory: geometric mean (geo) (equation 2.2) and harmonic mean (har) (equation 2.3)
- Non-compensatory: minimum aggregation (min) (equation 2.4) and maximum aggregation (max) (equation 2.5)

$$V_{sum} = \sum_{j=1}^{n} w_j \cdot v_j \tag{2.1}$$

$$V_{geo} = \prod_{j=1}^{n} v_j^{w_j} \tag{2.2}$$

$$V_{har} = \begin{cases} \frac{1}{\sum_{j=1}^{n} \frac{w_j}{v_j}} & \text{if } v_j > 0 \text{ for all } j, \\ 0 & \text{otherwise} \end{cases} \tag{2.3}$$

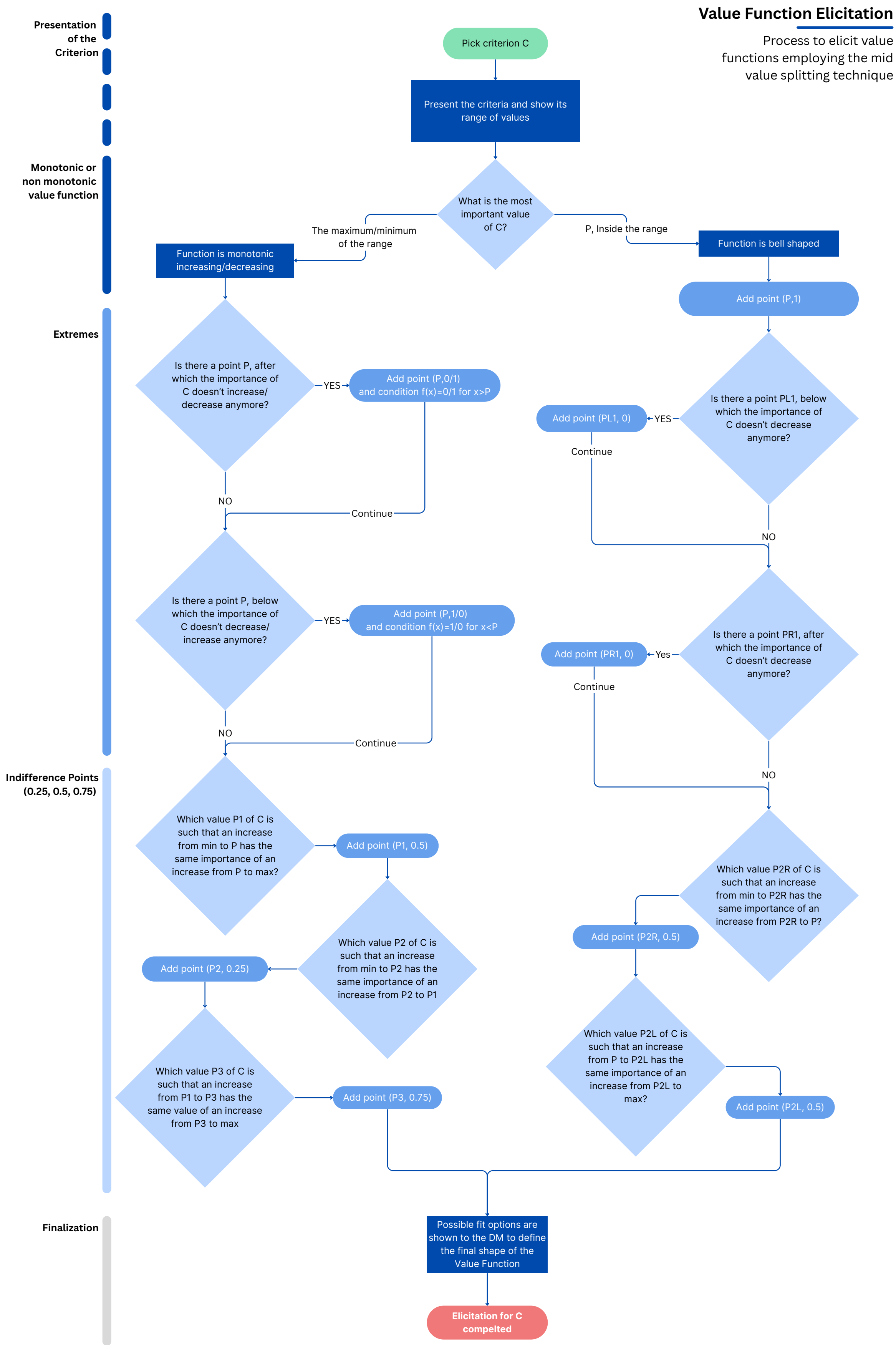


Figure 2.2: Value Function Elicitation Flowchart

$$V_{min} = \min_{j=1,\ldots,n} v_j \quad (2.4)$$

$$V_{max} = \max_{j=1,\ldots,n} v_j \quad (2.5)$$

Equations 2.1, 2.2 and 2.3 are subject to the normalization condition $\sum_{j=1}^{n} w_j = 1$

Elicitation of weights in MCDA varies according to methodological choices. While survey-based approaches using direct elicitation methods (e.g., ranking criteria or expressing judgments) offer simplicity and intuitiveness for public participation, they face significant criticism from experts. Morton and Fasolo (2009) [56] highlight fundamental concerns: *"People's ability to understand and respond to direct importance questions baffles us. Both of us regard such questions as meaningless and refuse to answer them. It could be that our intuitions have been destroyed by our atypically extensive exposure to DA"*. Reichert et al. (2015) [62] recommend a differentiated approach: technical criteria should be weighted through expert elicitation, while higher-level objectives reflecting major societal trade-offs may incorporate population or stakeholder opinions.

Sophisticated methods like swing elicitation [63], present challenges for public comprehension. Aubert et al. (2020) [64] demonstrated this limitation when approximately 73% of general public respondents failed to correctly understand the swing elicitation method in their study (later utilized by Haag et al., 2022 [29]). This indirect weighting technique evaluates the relative importance of improvements between worst and best-case scenarios for different criteria. For example: *"On a scale from 1 to 10, how much more important is increasing your salary from €1,200 (minimum wage) to €1,800 (market maximum) compared to increasing annual paid leave from 4 weeks (legal minimum) to 12 weeks (market maximum)?"*.

Rezaei (2015) proposed the Best-Worst Method (BWM) which first identifies the most and the least important criteria to then perform pairwise comparisons between these two reference criteria against all others [65]. This method reduces the number of evaluations required: given n criteria to evaluate, only $2n-3$ pairwise comparisons are needed, against the $\frac{n(n-1)}{2}$ available unique pairs. Another significant advantage is that by employing two reference criteria rather than one, the method mitigates anchoring bias, which is the tendency for importance judgments to be influenced by the chosen reference point. Moreover, BWM allows for consistency checks to verify the results of the elicitation process. However, unlike swing elicitation, BWM does not provide trade-off elicitation between criteria, focusing instead on relative importance assessment which lacks explicit compensatory comparisons.

2.2. Best Worst Tradeoff Method

Liang et al. (2022) proposed the Best-Worst Tradeoff (BWT) which combines the range sensitivity of swing elicitation with the consistency verification offered by the BWM [66]. Huang et al. (2026) extended this methodology to hierarchical structures. It is important to note that to implement this methodology, the knowledge of value functions for each criterion is required beforehand [67].

The weighting process begins by identifying the most and least important criteria through comparative evaluation of hypothetical consequence vectors $\vec{h}$. Each vector component represents a criterion's value in a hypothetical scenario. For an illustrative case with four criteria (C_1, C_2, C_3, and C_4), the vector $(1,0,0,0)$ indicates that C_1 achieves its maximum value while all other criteria remain at their minimum. DMs are asked to rank four $\vec{h}$ vectors: $(1,0,0,0)$, $(0,1,0,0)$, $(0,0,1,0)$, and $(0,0,0,1)$. This ranking identifies the best (C_b) and worst (C_w) performing criteria, which then serve as dual reference points throughout the weighting process.

The best criteria comparison employs the best criterion C_b as the reference standard. For the four-criterion example, let's assume C_1 represents C_b. Experts are requested to determine the value x that makes each pair of $\vec{h}$ indifferent:

- $(0,1,0,0)$ vs $(x,0,0,0)$ will determine $x_{(b,2)}$
- $(0,0,1,0)$ vs $(x,0,0,0)$ will determine $x_{(b,3)}$
- $(0,0,0,1)$ vs $(x,0,0,0)$ will determine $x_{(b,4)}$

Given these points, it is possible to establish the following proportional relationships between value functions:

$$w_1 = \frac{w_2}{v_b(x_{(b,2)})} = \frac{w_3}{v_b(x_{(b,3)})} = \frac{w_4}{v_b(x_{(b,4)})} \tag{2.6}$$

For comparisons against the worst-performing criterion C_w (assumed to be C_4 in this example), experts determine what value x of each remaining criterion would be equivalent to $(0,0,0,1)$. Unlike the previous comparisons, this process yields values for the non-worst criteria rather than the worst criterion itself, this distinction is reflected in the notation as $x_{(j,w)}$ rather than $x_{(w,j)}$.

- $(0, 0, 0, 1)$ vs $(0, x, 0, 0)$ will determine $x_{(2,w)}$
- $(0, 0, 0, 1)$ vs $(0, 0, x, 0)$ will determine $x_{(3,w)}$

Similarly to the best comparison, it is possible to establish the following relationships between value functions:

$$w_1 \cdot v_1(x_{(w,1)}) = w_2 \cdot v_2(x_{(w,2)}) = w_3 \cdot v_3(x_{(w,3)}) = w_4 \cdot 1 = w_w \tag{2.7}$$

Abstract

Combining the relationships from equations 2.7 and 2.6 with the normalization condition $\sum_{i=1}^{n} w_i = 1$ produces a linear system of equations:

$$\begin{cases} w_j \cdot v_j(x_{(j,w)}) = w_w \quad \forall j \in \{1, 2, 3\} \\ w_b = \frac{w_j}{v_b(x_{(b,j)})} \quad \forall j \in \{2, 3, 4\} \\ \sum_{j=1}^{4} w_j = 1 \end{cases} \tag{2.8}$$

Given the inherent subjectivity in expert judgments, this system typically lacks an exact solution. The optimal weight vector is therefore determined by minimizing the greatest absolute violation of these equations:

$$\begin{aligned} &\text{minimize:} \quad \mathbf{MAX} \begin{cases} |w_j \cdot v_j(x_{(j,w)}) - w_w| & \forall j \in \{1, 2, 3\} \\ |w_b - \frac{w_j}{v_b(x_{(b,j)})}| & \forall j \in \{2, 3, 4\} \end{cases} \\ &\text{subject to:} \quad \begin{cases} \sum_{j=1}^{4} w_j = 1 \quad \forall j \\ w_j \geq 0 \quad \forall j. \end{cases} \end{aligned} \tag{2.9}$$

For computational implementation, a single objective variable is preferred, therefore the problem is reformulated as:

$$\begin{aligned} &\text{minimize:} \quad \mathbf{MAX}(z) \\ &\text{subject to:} \begin{cases} z \geq |w_j \cdot v_j(x_{(w,j)}) - w_w| \quad \forall j \in \{1, 2, 3\}, \\ z \geq \left| w_b - \frac{w_j}{v_b(x_{(b,j)})} \right| \quad \forall j \in \{2, 3, 4\}, \\ \sum_{j=1}^{4} w_j = 1 \quad \forall j, \\ w_j \geq 0 \quad \forall j. \end{cases} \end{aligned} \tag{2.10}$$

The linear formulation 2.10 was developed to guarantee unique solutions while preserving

BWM's core principles [68]. In contrast, the original nonlinear version (Equation 2.11) [65] may yield multiple optimal solutions when expert comparisons are inconsistent. Far from being problematic, solution multiplicity proves valuable in group decision contexts where different viewpoints require explicit representation. This characteristic aligns particularly well with the focus of the current study on uncertainty, as multiple valid solutions directly reflect the natural variability in expert judgments.

$$\begin{aligned} \text{minimize:} \quad & \mathbf{MAX}(z) \\ \text{subject to:} \quad & \begin{cases} z \geq |v_j(x_{(w,j)}) - \frac{w_j}{w_w}| \quad \forall j \in \{1,2,3\}, \\ z \geq \left| \frac{1}{v_b(x_{(b,j)})} - \frac{w_b}{w_j} \right| \quad \forall j \in \{2,3,4\}, \\ \sum_{j=1}^{4} w_j = 1 \quad \forall j, \\ w_j \geq 0 \quad \forall j. \end{cases} \end{aligned} \tag{2.11}$$

On this regard, [67] developed the PILE-BWT, which starts by applying the BWT pairwise comparison elicitation to each group to obtain **intergroup** results. Then it identifies the highest-ranked criterion among all groups and applies the same elicitation logic to this "best-of-all" subset, named **intra-group-B**. The same process can also be applied to the "worst-of-all" set (**intra-group-W**) to improve robustness. All of this information is then used in a nonlinear optimization problem, based on that of the "traditional" BWT (Equation 2.11).

Since the problem is non-linear, the solution will be a set of viable weights rather than a single weight vector. The optimization problem will only find one from an $n_{criteria}$-dimensional space of valid weights, and its error (maximum absolute violation of the constraints, here z). Once this information is obtained, it is possible to further explore the solution space to obtain more valid weight sets. River et al. (2026) note that any weight inside the set is equally valid, which is an important property to consider when exploring the weight space [67]. The hierarchical BWT elicitation procedure follows this structured sequence:

1. **Intra-Group Elicitation**
   - For each criterion group G_j:
     (a) Identify best (B_j) and worst (W_j) criteria:

       "If all criteria were at their minimum value, which one would you increase to its maximum first (B_j) / last (W_j) ?"

(b) Compare each remaining criterion C_{other} against B_j:

> *"How much must B_j increase to compensate for reducing C_{other} from maximum to minimum?"*

(c) Compare each remaining criterion C_{other} against W_j:

> *"How much must C_{other} increase to compensate for reducing W_j from maximum to minimum?"*

2. **Inter-Group Elicitation**

- Among all group-best criteria $(B_1, B_2, \dots)$:

  (a) Select overall best criterion (BB).

  (b) Select overall worst criterion (WB).

- Compare each non-best group criterion against BB and WB using equivalent compensatory questions.

- Repeat for all group-worst criteria $(W_1, W_2, \dots)$

2.3. Uncertainty Characterization

One of the main research objectives of this thesis regards the handling of uncertainties within a MCDA framework. The investigation begins by identifying primary uncertainty sources.

The first source of uncertainty is the input data, arising from measurement errors, estimation procedures, Monte Carlo simulations, or probabilistic models. In the early stages of a MCDA, the practitioner must research and gather the data needed to characterize the indicators. Where quantifiable, these uncertainties can be systematically propagated through all subsequent calculations in the MCDA process. In other cases, indicators may be composite, requiring assumptions that introduce their own uncertainties. Again, it is the analyst's responsibility to reasonably quantify the associated uncertainty. For instance, when assuming capacity factor (CF) values, the author examined European operational reactor data from the IAEA Power Reactor Information System (PRIS) database [7]. After filtering relevant cases and removing outliers, the data yields a mean CF value of 81.64% with a standard deviation of 5.52%, therefore by considering a 68% confidence (assuming normal distribution) the CF can be assumed to be as $81.6\% \pm 5.5\%$, see Figure 2.3 where the distribution of CF data for European reactors, sourced from [7], is reported as well as the fit Gaussian distribution and the confidence interval [1].

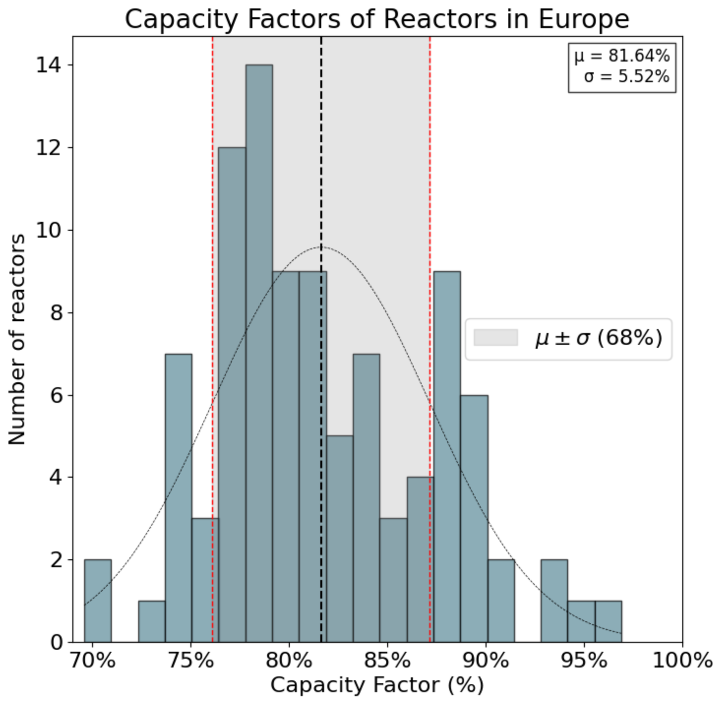


Figure 2.3: Distribution of the CF for European Operational Reactors, possible Gaussian fit and 68% confidence interval

Another important aspect regarding data uncertainty is to properly consider the origin of the uncertainty and the relevance to the study in order to avoid propagation of misleading errors.

For instance, to quantify the indicator about Green House Gas (GHG) emission reduction, annual hourly data for each country was obtained. If the average values were to be considered, assuming a normal-like distribution of the GHG emission intensities throughout the year, a reasonable way to represent the data would be, for instance, 238.5 ± 64.7 gCO_2-eq/kWh (Data for Italy [69]). However, propagating the standard deviation of this data as uncertainty within the present framework would be incorrect. The data variation here reflects hourly fluctuations in GHG emission intensity rather than data uncertainty. To circumvent the use of average values altogether in the definition of the GHG emission reduction indicator, this study uses the data from an entire year to compute the total amount of emissions and the potential yearly reduction following deployment of one NPP

[1]Computational details available in Reactor Analysis.ipynb; see Appendix A

(See Section 3.3.4). To do so, the data was taken from the year 2024, which obviously cannot be considered as fully representative of the reality of the considered scenario (which is based a decade in the future). However, this approach highlights reactor-specific uncertainties, preserves relative differences between models, and uses a metric that DMs can easily understand.

On a different note, several challenges emerge as soon as qualitative elements come into play, which in the case of this study are qualitative indicators, weights, and value functions. These inherently contain subjective components likely to vary among DMs. While statistical approaches using multiple experts can quantify uncertainty, the substantial time requirements and difficulties in maintaining consistency across elicitation sessions can make the approach impractical. Some MCDA practitioners recommend workshop formats where multiple experts work simultaneously, though these present significant organizational challenges.

2.3.1. Efficient Expert Elicitation for Qualitative Information

For qualitative indicators and value functions, this study, instead of relaying on multiple opinions from the start, employs a single expert to carry the "first elicitation" of all qualitative information. Subsequent experts then review the results rather than replicate the complete elicitation process. These reviewers indicate their agreement or disagreement with the initial results and provide alternative perspectives when discrepancies exist. The resulting diversity of opinions forms the basis for quantifying uncertainty around the first elicitation. This approach may introduce some anchoring bias in expert opinions, nonetheless this was considered acceptable, as the primary focus of this work is methodological development rather than achieving perfect results.

Consider a simplified example where the main expert provides a qualitative judgment on a 1-to-5 scale, selecting a value of 4. Five additional experts then review this initial assessment, either confirming the original evaluation or proposing alternatives (Table 2.2 provides an example). In this hypothetical scenario, two experts agree with the initial judgment while three suggest different values. From this information, it is possible to construct a distribution (Table 2.3) that can be propagated through the rest of the analysis.

While this elementary case demonstrates the method's conceptual simplicity, its efficiency advantages become particularly evident in long and complex elicitation tasks such as value function development, where it significantly reduces the overall time requirements. Unfortunately, it is not possible to employ this approach in the PIvot Linked Elicitation

BWT (PILE-BWT) since the fundamentals of the model itself are based on tradeoff between pairs, and we cannot mix a tradeoff based elicitation with a direct review of the results. The same constraint applies to BWM, BWT and swing elicitation processes.

Table 2.2: Example of Expert Elicitation Results for Qualitative Judgment (Scale: 1–5)

Expert	**Score**
Main Expert	4
Expert 1	✓
Expert 2	5
Expert 3	3
Expert 4	✓
Expert 5	3

Table 2.3: Example of Probability Function of the Qualitative Criterion

Score	$\mathbb{P}$
5	$1/6 = 0.17$
4	$3/6 = 0.50$
3	$2/6 = 0.33$
2	$0/6 = 0.00$
1	$0/6 = 0.00$

The characterization of qualitative indicators is defined as a two-step process. First, the ranking of all alternatives is defined, then the value function shape is elicited to convey the relative differences between alternatives. To speed up the process and to align, as much as possible, all experts on the same interpretation, the author created a **starting point** for the evaluation: based on available information the analyst creates a ranking of the alternatives and assumes a linear value function. The reasoning behind the starting point is then presented to each expert, whom are then asked to adjust the ranking if they disagree. The value functions make use of *hypothetical best* and *hypothetical worst* values to anchor the function to its extremes, which is particularly useful whenever the experts deem that none of the available alternatives is worth the maximum or minimum value of the criterion.

As an additional tool to evaluate uncertainty in qualitative information, for every elicited information the expert can adjust its own **confidence level**, defined on a point scale from 0 (not confident at all, pure guess) to 5 (completely confident, no doubt). For value functions this can be used to add a deviation from the elicited points, while for qualitative indicator it is used to assign sampling probability to each judgment.

2.4. Uncertainty Propagated MCDA

This study develops a novel framework, Uncertainty Propagated MCDA (UP-MCDA). The core concept underlying this approach is to discard single-point estimates altogether and instead to provide DMs with a complete overview of all the possible solutions to the decision problem, in other words, it provides a distribution of potential values that each alternative might assume. This distribution-based perspective enables quantitative assessment of differences between options that may fall within uncertainty bounds, and enhances the transparency of the MCDA process by explicitly representing uncertainty.

The proposed UP-MAVT methodology operates on probabilistic representations of all components. Building upon the stochastic approach pioneered in SMAA [70], UP-MAVT considers each input (criterion weights, value functions, or data) as a Probability Density Function (PDF) that describes the complete distribution of possible values rather than a single point estimate. This transformation yields the generalized formulation shown in Equation 2.13, where the notation $\mathrm{PDF}_\Theta(\theta)$ is used to represents the continuous probability distribution of a random variable Θ, capturing the full spectrum of potential values and their associated likelihoods.

$$A_i = \sum_{j=1}^{N} w_j \cdot v_j(x_{ij}) \tag{2.12}$$

$$\mathrm{PDF}_{A_i}(a) = \sum_{j=1}^{N} \iiint \delta\left(a - v_j(x_{ij})w_j\right) \cdot \mathrm{PDF}_X(x_{ij}) \cdot \mathrm{PDF}_V(v_j) \cdot \mathrm{PDF}_W(w_j)\, dx\, dv\, dw \tag{2.13}$$

In practice, the most convenient way to properly propagate diverse distributions in UP-MAVT is by means of Monte Carlo (MC) simulations. MC codes rely on repeated random sampling, making them particularly valuable for complex systems where capturing the full range of possible outcomes is essential. In this context, rather than relying on fixed or deterministic values, a MC code enables sampling from the actual distributions of weights, value functions, and input data, ensuring a robust representation of their variability. To this end, two approaches have been identified:

- Strict Montecarlo (S-MC): Each "opinion" from the elicitation process is preserved as independent. Results are presented per expert or, more generally, per stakeholder.
- Non-strict Montecarlo (NS-MC): Introduces variability by sampling uncertain information from any possible opinion, therefore presenting a single value distribution per each alternative that aggregates all points of view.

Related approaches exist in the literature, each with distinct focuses and limitations. Lahdelma and Salminen's (1998) SMAA [70] employs stochastic methods primarily for decision-making under uncertain preferences, particularly addressing unknown or partially known weights. Baudry et al.'s (2017) work [71] similarly adopts stochastic techniques but targets group decision support contexts. Goers and Horton's (2023) Combinatorial multi-criteria acceptability analysis (CMAA) [72] preserves individual judgments in the first part of the analysis to then aggregate results through combinatorial aggregation.

These methods present several constraints for the current application. SMAA fundamentally addresses an inverse problem centred on weight uncertainty, representing solutions to different core questions. CMAA systematically explores all possible expert opinion combinations and, like SMAA, presents the results by means of acceptability indices but doesn't provide any tool to evaluate their consensus. The Range-based Multi-Actor Multi-Criteria Analysis approach [71] produces outputs incompatible with weight space representations, as comparing alternative value distributions creates potential misinterpretation, as overlapping distributions may result from calculations using entirely different weight sets rather than representing comparable evaluations. Most notably, all of these methods consider uncertainty only in a subset of the decision components, typically either weights or input data.

The UP-MAVT methodology addresses these limitations by (i) systematically handling uncertainties across all decision components, (ii) providing DMs with complete control over uncertainty characterization and (iii) delivering transparent results that fully preserve propagated uncertainties.

Within this framework, the S-MC approach serves as a consensus diagnostic tool, visually representing expert or stakeholder agreement. This allows DMs to identify areas requiring further research, elicitation, or discussion. When consensus is satisfactory, the NS-MC method generates conservative aggregate results, delivering final evaluations while retaining uncertainty bounds. The NS-MC results are presented as a heatmap, showing the probability of each alternative achieving a specific rank.

The UP-MAVT framework is illustrated in Figure 2.4, which details the sources of uncertainty in both criterion data and elicitation results, as well as their propagation through the MC code. Pseudocode for the two methods (S-MC and NS-MC) is also included to illustrate how the uncertainties are propagated.

The general procedure applied to the case study (Section 3) is summarized in Figure 2.5. This figure outlines the MCDA process, from alternative selection and criterion definition to data collection, uncertainty characterization, qualitative elicitation, and the final application of the UP-MAVT framework to obtain results.

Figure 2.4: Uncertainty Propagation Workflow in UP-MAVT

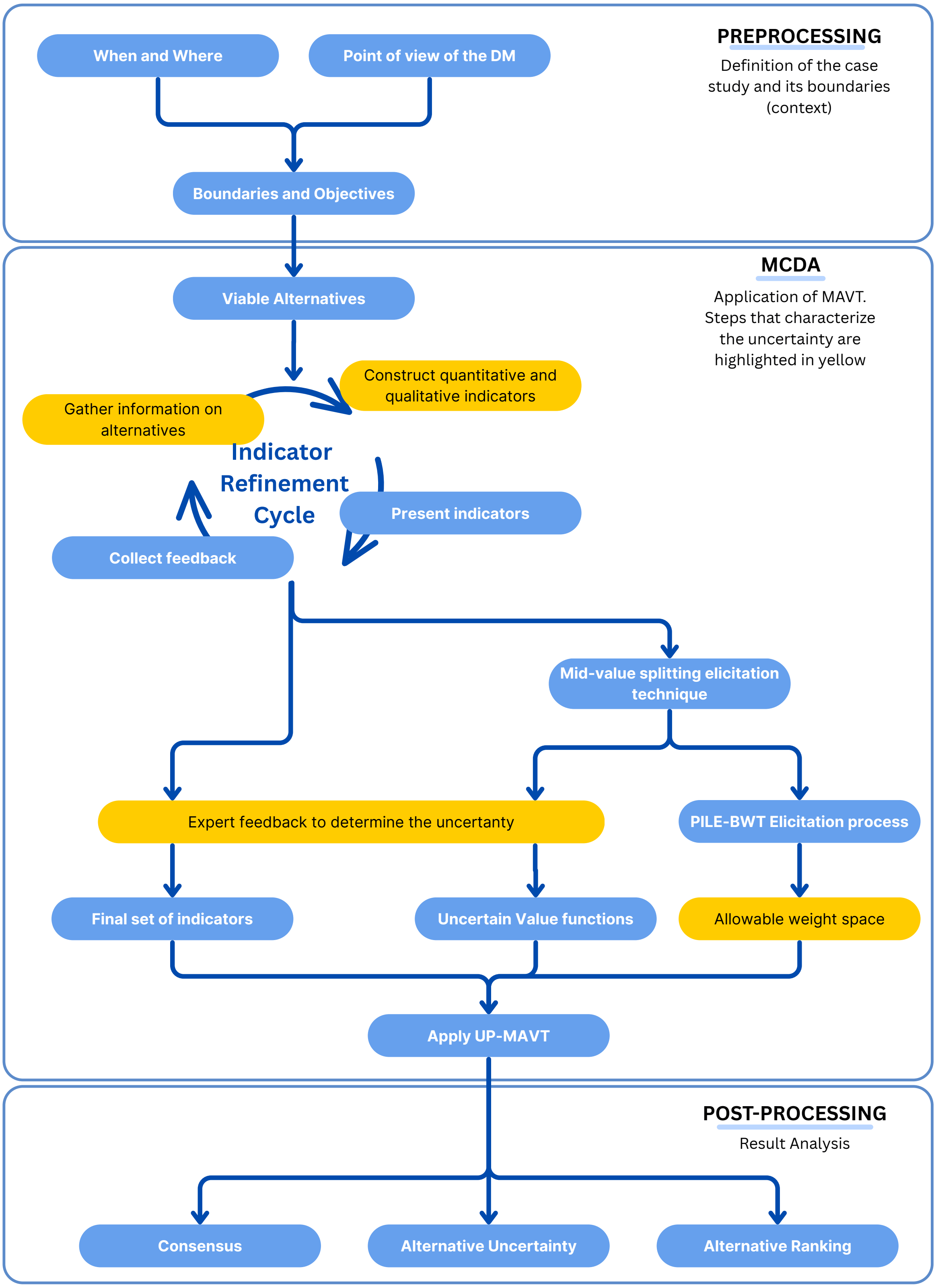


Figure 2.5: Case Study Workflow

2.4.1. Consensus in Group Decision-Making

Real-world applications of MCDA often involve decision-making processes among diverse stakeholders, which could include individuals, organizations, or even more broader groups (e.g., local communities or industrial workers). In such participatory contexts, Multi-Actor Multi-Crieria Analysis (MAMCA) is frequently used to account for varying perspective from distinct actors [73].

In participatory context, the goal often centres on achieving consensus through iterative discussions and revisions of elicited preferences. This approach, called consensus-reaching process, is particularly relevant to public participation, where transparency and collective agreement are essential. Proposed methods for facilitating consensus vary: some focused on minimization of one of the components of the analysis [74], while others solve inverse optimization problems [75, 76].

However, when the decision problem is not participatory, structured methods such as CMAA or SMAA (discussed in Section 2.4) are used to aggregate and analyse opinions systematically.

This study aligns with the latter approach, focusing on expert opinions to determine the optimal reactor model for deployment. The broader policy question of whether to deploy a reactor in the first place is assumed to have been resolved beforehand. While unanimity among experts strengthens the validity of the results, stakeholder negotiation is not required for the scope of this analysis.

3 | Case Study

This study conducts a comparative analysis of six nuclear reactor designs: three Generation III+ reactors: Advanced Power Reactor (APR-1400), EPR-1750, and AP-1000 and three SMRs: Boiling Water Reactor X-300 (BWRX-300), Rolls-Royce SMR, and Nuscale. Four European countries are taken into consideration (Italy, France, Poland, and Switzerland). The analysis adopts the point of view of governmental energy policy and planning agencies. The primary objective is to evaluate which reactor design is most suitable for deployment by the mid-2030s within each national context. This study does not consider siting as MCDA analysis of this type are plentiful in the literature as presented in Section 1.2.1 [37, 38, 39]

3.1. Step 0: Definition of the Study Context

As previously discussed in Section 1.1.5, several European nations are actively re-evaluating the role of nuclear power in their energy mixes, making the continent an ideal case study to examine how different environments can influence technology selection. A selection of four, among all European countries that are reconsidering nuclear (see Figure 3.1), has been made to balance research interest with practical constraints. The chosen nations: France, Italy, Poland, and Switzerland were deliberately selected to capture a wide range of possible scenarios as detailed in the following analysis.[1]

Italy's nuclear landscape is constrained by the 1987 post-Chernobyl referendum which mandated complete phase-out of nuclear power and its 2011 reaffirmation following Fukushima. However, since Italian referendums are abrogative rather than prescriptive, government decrees are enough to reverse these policies [78]. The current administration seems willing to reintroduce nuclear power [79], however, Italy's history of political volatility and the long-term nature of nuclear projects create significant implementation challenges regardless of public opinion trends.

[1]Data regarding electricity loads and cross border flows presented in the following paragraphs is sourced from the European Network of Transmission System Operators for Electricity (ENTSO-E) Transparency Platform and refers to the year 2024 [77]. The complete data analysis can be found in the repository, see Appendix A.

Figure 3.1: Map of European countries considering nuclear energy.

For this study, only the northern part of Italy was taken into consideration due to the country's fragmented electricity market structure [2]. The north bidding zone is the most energy-intensive with an average load of 17.66 ± 4.35 GW ($\pm\sigma$), for reference, by analysing data from the Italian Transmission System Operator (TSO) [80] and the Italian institute for statistics [81], it is possible to conclude that the North bidding zone, despite only hosting 35% of the Italian population, represents 56% of the total electric demand. In addition to the significant load, the bidding zone has a substantial dependence on imports, which averaged 5.23 ± 1.67 GW in 2024, accounting for almost 30% of its electric demand. Analysis of cross-border flow data shows that imports are active 99% hours of the year.

[2]The fragmentation into seven bidding zones is mostly a consequence of infrastructure and geographical constraints that prevent efficient transmission across the country. As a result, power generated in a bidding zone will first serve the zone where it was generated and only then, as long as its bidding price is below the national marginal price, can be sold to neighbouring bidding zones. Since this study will consider characteristics of the electric grid, it was deemed appropriate to take into consideration the boundaries of the grid rather than the political ones. All the other countries under study only have one bidding zone for their whole territory.

Poland shows strong public backing for nuclear energy development, with surveys reporting up to 92% support [82]. Public sentiment aligns with tangible progress in the country's nuclear program, including preliminary site work and vendor agreements [83, 84], suggesting a robust governmental commitment to nuclear deployment. The Polish grid produced 55% of its electricity with coal [85], making it the country with the highest green house gas emission intensity in Europe [69].

Switzerland presents a more complex picture. Following the 2011 Fukushima accident, the government adopted a phase-out policy later confirmed by a referendum in 2017 [86]. However, recent surveys indicate shifting public opinion, with 53% now supporting nuclear power [87, 88, 89]. The federal government has subsequently signalled potential reconsideration of nuclear role in meeting climate targets [90], though the narrow margin of support and Switzerland's direct democracy system create policy uncertainty.

The Swiss grid is characterized by a low demand, averaging 6.79 ± 1.12 GW, and generation dominated by renewables (65% average share) particularly hydroelectric which provided 59% of the electricity in 2024 [85]. This high dependence on renewables is reflected in substantial cross border flow variability which average 2.71 ± 3.14 GW. The large standard deviation reflects the oscillating nature of the Swiss cross-border flows, a consequence of periodic exports due to overproduction, alternating with imports when renewable output is low.

France demonstrates consistent public support for nuclear energy, with 75% favouring continued operation of existing plants and 65% supporting new construction according to a 2022 survey [91]. Given the long-standing consensus on nuclear power as a strategic energy pillar and the country's established industrial base, significant policy reversals appear unlikely. The country electric grid relies heavily on nuclear power, which accounted for 67% of its electricity generation, [85]. Despite the substantial demand, which averaged 49.05 ± 9.83 GW, France is a net electricity exporter, with 21% of total domestic production crossing the border to neighbouring countries.

3.2. Step 1: Definition of the alternatives - Reactor Selection

This study focuses on a curated set of reactor designs at an advanced stage of development. The selection process begins with the analysis of the IAEA PRIS database data, collected in their "Nuclear Reactors in the World" annual publication [7, 92], which catalogues operational, under-construction, and decommissioned reactors globally.

The initial selection process applied two primary exclusion criteria. First, designs were eliminated based on supplier origin, removing all reactors associated with countries unlikely to engage in nuclear technology transfer with European countries, namely, Russia, China and India. Second, reactors commissioned before 2000 were excluded from consideration, as their designs represent outdated technological standards [3].

From this pre-selected group, three designs were prioritized for comprehensive analysis: the EPR-1750, APR-1400, and AP-1000. It should be noted that while the EPR (1650 MWe) and EPR-1750 share significant design similarities, they are treated as separate models in this study. Additionally, the Advanced Boiling Water Reactor (ABWR), though listed as operational in the IAEA Advanced Reactor Information System (ARIS) database, was excluded following verification through the PRIS database, which indicates that all ABWR units have suspended operation since 2011 [7]. The selection process and its outcomes are summarized in Table 3.1.

The author acknowledges the controversy between Westinghouse and KEPCO regarding the APR design derivation from the System 80 design. However, as no official documentation prohibits its commercialization in Europe, and considering recent evaluations of the Korean design (including the 2023 Czech tender, though later contested by Électricité de France (EDF) and Westinghouse [93]), the APR-1400 has been included in this analysis. Most importantly, it offers a valid alternative to the US and French designs, serving as a middle ground between the two in terms of nameplate capacity, thereby enhancing the comparative analysis.

The EPR2 and EPR1200 designs, while reviewed positively by the French nuclear safety authority [94], lack commercial commitments (the EPR1200 was proposed for the Czech tender but ultimately unsuccessful [93]). Moreover, considering their absence from the ARIS database and overall limited available technical documentation, these EDF designs have been excluded from the current study.

Subsequently, the IAEA ARIS database [95], was consulted to identify advanced reactor models classified as under design, under regulatory review, under construction, or operational. To avoid redundancy, Generation III+ designs captured in both ARIS and PRIS datasets were removed. Demonstration units and prototypes were also excluded from this set, yielding 10 candidate designs. Each of them was then assessed for development status, technological readiness, and applicability to European deployment as summarized

[3] The complete filtering is documented in the repository, see Appendix A

Reactor Name	Country	F1	F2	F3	Decision
APR-1400	S.Korea	✓	✓	✓	**Selected**
CAREM Prototyp	Argentina	✓	✗	✓	Rejected
PRE KONVOI	Germany	✓	✓	✗	Rejected
EPR 1750	France	✓	✓	✓	**Selected**
CAP1000	China	✗	✓	✓	Rejected
AP-1000	USA	✓	✓	✓	**Selected**
ABWR	Japan	✓	✗	✓	Rejected
VVER-1200	Russia	✗	✓	✓	Rejected
APWR	Japan	✓	✗	✓	Rejected
EPR	France	✓	✓	✗	Rejected
OPR-1000	S.Korea	✓	✓	✗	Rejected

Table 3.1: Selection of reactor models for analysis. F1: Supplier country compatible with European deployment, F2: Currently under commercial operation, F3: Design is up-to-date and still available for commissioning.

in Table 3.2.

The overall selection produced a set of six reactors, three Generation III+ and three SMRs. Their main characteristics are summarized in Table 3.3. The most notable differences are the integrated designs of the BWRX-300 and Nuscale SMR which eliminate external primary loops in favour of steam generators positioned inside the reactor pressure vessel. This allows to reduce the overall size and to exploit natural circulation for cooling. The Nuscale SMR, referred to as US460 in technical documentation, is the only model designed to be deployed in a multi unit configuration, with up to 12 modules in the same containment building, for this study the 6 module plant (VOYGR-6) has been selected as it recently obtained the Standard Design Approval (SDA) by the US Nuclear Regulatory Commission (NRC) in May 2025 [5].

[5] *"A standard design approval indicates that a proposed reactor design meets applicable agency safety requirements. Companies that seek to use the US460 design would have to file applications seeking permission to build and operate a nuclear reactor using the approved design"* [104]

Reactor	Country	Used	Reasoning
APR+	S.Korea	✗	Manufacturer reports the design is an *"indigenous reactor cleared of obstacles to export"* [96]
ATMEA	Japan, France	✗	Joint venture between Mitsubishi and EDF/Framatome was abandoned [4]
BWRX300	USA, Canada	✓	A design from GEV-H, shows support from US and Canada as well as interest in the European countries [97, 98].
i-SMR	S.Korea	✗	No interest for European deployment has been shown.
iMSR400	US	✗	The design appears to be at an early developmental stage, as indicated by its current regulatory status. [99]
Natrium	US	✗	Demo plant [100].
Nuward	France	✗	Lack of detailed information, most likely consequence of the significant strategic shift in 2024 [101].
Nuscale	US	✓	Most progressed in the regulatory process [102, 103, 104].
PRISM	US	✗	GEV-H states it is a *"concept ... currently being put into practice in two reactors: Natrium and ARC-100"* [105].
Rolls-Royce SMR	UK	✓	Ongoing regulatory activity and interest for deployment [106, 107].
SMART	S.Korea, Saudi Arabia	✗	Plan to export only to South-East Asia and Middle East [108].

Table 3.2: Step 1: Selection of advanced reactor models for analysis

Reactor Name	Type	Construction	P_e (MWe)	Supplier
APR-1400	PWR	1 Unit	1340	KEPCO (S.Korea)
EPR 1750	PWR	1 Unit	1630	Framatome (France)
AP-1000	PWR	1 Unit	1120	Westinghouse (USA)
BWRX-300	i-BWR	1 Unit	300	GEV-H (USA)
Rolls-Royce SMR	PWR	1 Unit	470	Rolls-Royce (UK)
Nuscale	i-PWR	4 to 12 Units	77	Nuscale Power (USA)

Table 3.3: Final selection of reactor models for analysis

3.3. Step 2: Definition of the indicators

The initial phase of this MCDA study focuses on indicator selection and hierarchical structuring. The following sections outline the methodological process employed to develop the final indicator set. It should be noted that this study primarily evaluates the feasibility of the proposed approach rather than generating definitive results. Accordingly, this study serves to identify which indicators or areas may require further detailed development in future iterations, as the weighting process will naturally reveal priority areas. Indicators receiving minimal weights may not justify further refinement, while those with substantial weights could benefit from more granular analysis. With this context established, the subsequent sections present the process that resulted in the final indicator set used in this study.

Following the bottom-up approach outlined in Section 2.1, the initial analytical step involved identifying all potential differentiating factors among the six reactor alternatives. The process began with a series of personal brainstorming sessions by the author, followed by a preliminary selection phase. The resulting comprehensive list of 35 potential indicators[6] was then extensively reviewed with the support of three domain experts to evaluate:

- Completeness (identifying missing aspects)
- Redundancy (eliminating repetitive measures)
- Relevance (removing irrelevant indicators)
- Granularity (balancing overly specific or aggregate measures)

Further discussion with several experts from different backgrounds was helpful to identify other possible aspects, as well as to collect feedback that helped improve the justifications.

[6]The complete list is available as a CSV file in the repository, with an example Python script provided for navigation (see Section A for details)

On this regard it is really important that the analyst takes into serious consideration every suggestion provided by others, and, whenever these have to be discarded, it is important to report it and properly justify the omission to ensure full transparency.

As anticipated, the extensive indicator list required systematic screening for several reasons:

- Double counting: The same aspects might be represented by multiple indicators, leading to biased weights
- Scope: Some aspects might be valid but not relevant for the point of view of the study, in this case, European governmental agencies
- Data availability: This wouldn't be the case for a field application but for the purpose of this thesis obtaining data outside the public domain was deemed unfeasible.

Table 3.4 provides examples of excluded indicators. The most significant exclusions are justified in Section 3.3.6 while possible improvements for future studies are documented in Section 4.1.

Indicator	**F1**	**F2**	**F3**	**Decision**
Load Following Capabilities	✓	✓	✓	**Selected**
Mining waste	✓	✓	✗	Rejected
Land Usage	✗	✗	✓	Rejected
Core Damage Frequency	✗	✓	✓	Rejected
Spent Nuclear Fuel	✓	✓	✓	**Selected**
Local Economy Turnaround	✗	✗	✓	Rejected
Capital Investment Budgeted	✓	✓	✓	**Selected**
Supplier Availability	✓	✓	✓	**Selected**

Table 3.4: Example of the selection process of indicators. F1: High relevance to the case study, F2: Data is available, F3: Not redundant nor highly correlated with other indicators

Following this systematic screening process, twelve indicators remained and were subsequently aggregated into higher-level objectives, presented in Table 3.5. In this bottom-up approach, each group collects indicators that share a common high-level point of view. The subsequent sections describe each retained indicator, covering its data sources, conceptual explanations, and the methodological rationale for its inclusion.

3.3.1. Technical parameters

The first category of indicators comprises technical parameters that characterize each reactor designs from an engineering standpoint. This technical perspective is included to reflect the expertise likely present within governmental decision-making bodies, where technically trained members may prioritize these engineering metrics. Table 3.6 presents an overview of the selected technical parameters.

Thermal Efficiency Thermal efficiency represents the proportion of fission-generated thermal power converted to net electrical power, accounting for in-plant consumption. It provides insight into the reactor's thermal-hydraulic design quality and overall energy conversion in the Balance Of Plant (BOP). It is calculated using net electrical power output ($P_{el,net}$) and thermal power (P_{th}) data from the IAEA ARIS database [95], this indicator is expressed as:

$$\eta = \frac{P_{el,net}}{P_{th}}$$

Discharge Burnup Discharge burnup quantifies the energy extracted per unit of heavy metal from nuclear fuel, measured in $MWd/tonHM$. The analysis utilizes APR-1400 and AP-1000 data from the IAEA ARIS database [95], while EPR values were obtained from NRC documentation [109]. For SMR designs, burnup ranges are reported to account for design variability across different configurations. This parameter serves as a key indicator of the core design and neutron economy of the reactor.

Net Power Output Net power output represents a critical selection criterion that cannot be judged in absolute terms but rather in relation to each country's energy needs. For instance, countries facing persistent energy import dependencies may favour large-capacity reactors, while nations with renewable-dominated energy mixes might prioritize smaller, more flexible power sources. The difference between countries will be considered during value function elicitation. Technical specifications for the three large reactors were sourced from the IAEA PRIS database [7], whereas SMR performance data was obtained from the ARIS database [95].

Load-Following Capabilities Load Following Capabilities (LFC) are quantitatively evaluated using characteristic curves that illustrate ramp-up and ramp-down rates, expressed as a percentage of nominal power ($\%P_{nom}$), as functions of load $x \in [0, 1]$ as shown in Figure 3.2. To enable direct comparison between designs, these performance curves are synthesized into scalar values by calculating the area under each curve. Thanks to this reduction, the LFC indicator considers both the ramp rates and the minimum allowable power, which is another significant aspect to judge the flexibility of operation of a nuclear power plant. For the same reason as the previous indicator, LFC will be evaluated differently depending on the country electric demand by means of value functions. The indicator LFC considers both the rates and the minimum power level achievable by each design.

LFC are quantitatively assessed through characteristic curves that plot ramp-up and ramp-down rates (expressed as percentage of nominal power, $\%P_{nom}$) against load fraction $x \in [0,1]$, as illustrated in Figure 3.2. To facilitate cross-design comparisons, these performance profiles are reduced to scalar metrics by integrating the area under each curve. This aggregation method captures both the ramp rates and the minimum operational power thresholds, two critical flexibility parameters for nuclear power plants. As with the previous technical indicators, the evaluation of the LFC metric will consider country-specific demand profiles through tailored value functions, reflecting how different grid requirements may influence the relative importance of load-following capabilities.

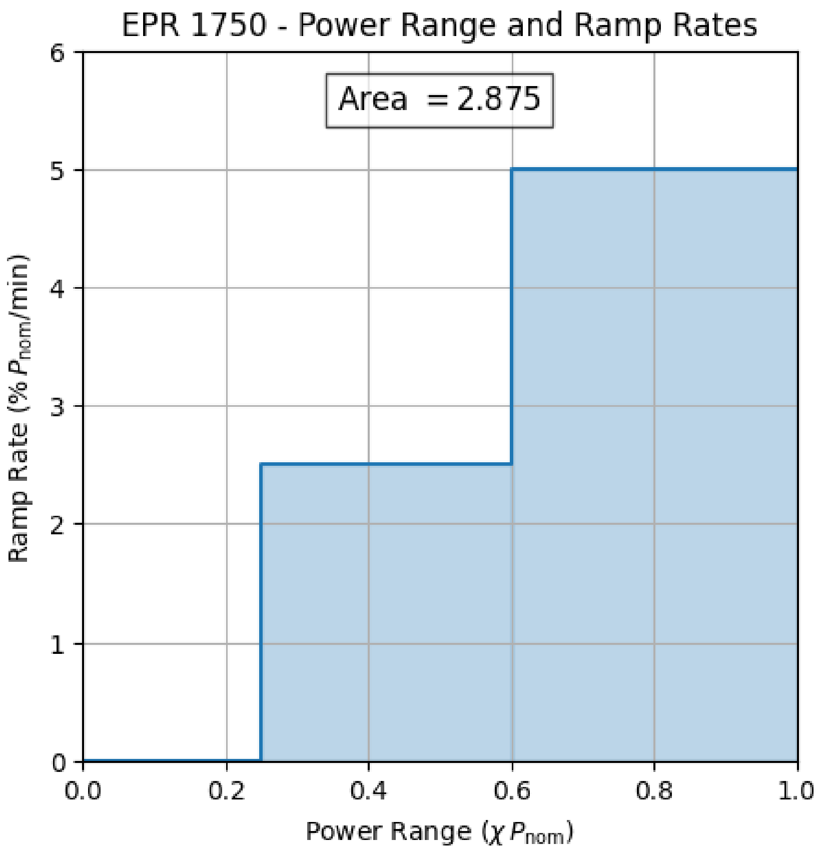


Figure 3.2: Example load-following characteristic curve for EPR-1750

To provide the reader with more insight, the load-following performance of a reference gas-powered plant was calculated using data from a combined-cycle configuration featuring two GEV-H 9HA.02 heavy-duty gas turbines (2015 specifications) [110]. Load-following data for the APR-1400, AP-1000, BWRX-300, and Rolls-Royce SMR were obtained from the IAEA ARIS database [95], while EPR data was sourced from Nuclear Energy Agency (NEA) [111] and NuScale data from a report on SMRs prepared for the Austrian government [112].

3.3.2. Feasibility Indicators

This group reflects the concerns of stakeholders who question the feasibility of the entire deployment process, from licensing to construction. These indicators capture all practical factors that may influence ease of implementation, with evaluations conducted using qualitative scales based on current conditions (status quo) as detailed in the following analysis. All the indicators in this group are qualitative in nature. Each is described hereafter, alongside with the author's evaluation, which will serve as starting point during expert consultations, as presented in section 2.3.1.

Design Maturity Design maturity was evaluated on an ordinal scale reflecting current deployment status. Among large reactors, the EPR received a 4/5 score due to its limited construction experience, while both APR-1400 and AP-1000 achieved 5/5 ratings. For SMR designs, only the Rolls-Royce reactor scored 2/5 rather than 1/5, as its design closely resembles existing PWRs featuring forced circulation and external steam generators. Table 3.7 presents the supporting data for this preliminary maturity assessment.

Licensing Status Licensing progress was evaluated based on each reactor current regulatory status within the European context. The three conventional reactors received baseline scores of 4/5 due to their established international licensing history, with the EPR achieving 5/5 given its existing European deployments, with the previous iteration, in France and Finland [7].

For SMRs designs, NuScale and Rolls-Royce received 1/5 scores, as their licensing processes remain confined to overseas markets (United States for NuScale; United States and United Kingdom for Rolls-Royce). The BWRX-300 was assigned 2/5 despite similar

[7]For clarity regarding nuclear reactor nomenclature: Internet searches for "EPR" will present results for Flamanville and Olkiluoto plants as well as UK units (Hinkley Point and Sizewell) and China's Taishan plant. This is actually an aggregation of two distinct designs: the original 1600 MWe "European Pressurized Reactor" (Flamanville/Olkiluoto) and the evolved 1750 MWe "Evolutionary Pressurized Reactor" (Hinkley Point/Sizewell/Taishan) analysed in this study.

overseas licensing status (United States, United Kingdom, and Canada) to acknowledge three distinguishing factors: exceptional financing support (scoring 6/6 in the NEA SMR Dashboard [113]), the issue of a Canadian building permit, and utilization of existing fuel designs that eliminate requirements for new fuel licensing procedures. The 3/5 score was intentionally omitted to clearly differentiate between established and emerging reactor designs. Table 3.8 summarizes the licensing status evaluation.

Supplier Availability Market entry ease and local industry involvement significantly affect commissioning timelines and national economic benefits, both of which are key considerations for governmental agencies. While a comprehensive evaluation would require detailed analysis of each country's nuclear industry status and expansion potential, this preliminary study implements a simplified assessment approach.

The methodology employs a country-reactor matrix (with each reactor representing a different vendor) to evaluate two primary factors: supplier presence and potential industry capacity. The initial scoring assigns +0.25 points for supplier legal presence through registered offices and an additional +0.25 points for existing fabrication capabilities. These allocations produce the baseline scores presented in Table 3.9.

The broader nuclear industry is also evaluated to consider domestic firms qualified to manufacture nuclear-certified materials and components, essential for the "nuclear island". Nuclear certification requirements extend beyond basic materials to include specialized components: structural steel for pressure vessels must conform to stringent nuclear standards, primary coolant pumps require dedicated certification, and certain elements demand highly specialized fabrication techniques[8]. If the country presents any level of industry to support nuclear activities gets a +0.25, if it also has capability of manufacturing large Nuclear Steam Supply System (NSSS) components it gets an additional +0.25. For this reason, Switzerland get a +0.25 while both France and Italy a +0.5. The combined scores from both evaluation phases are presented in Table 3.10.

Two significant considerations emerge from this analysis. First, while Poland is currently experiencing a period of strong economic growth, the potential acceleration of its nuclear sector remains uncertain and challenging to quantify. Second, established supply chains were excluded from France's evaluation due to the country having completed only one nuclear power plant (Flamanville-3) in the past 25 years, likely indicating supply chain degradation despite its historical capabilities in this sector.

[8]For instance, EPR reactor pressure vessels require precision manufacturing of a 4.8 m diameter, 13 m height steel cylinder with walls 25 cm thick, which can currently be produced only in Japan.

3.3.3. Economic Indicators

The economic consequences are always part of MCDA studies, common metrics provide essential insights into the financial implications associated with technology deployment and long-term operation. Table 3.12 summarizes the selected economic indicators for nuclear technologies, with corresponding values included for three renewable energy benchmarks: onshore wind, solar photovoltaic with battery storage, and hydroelectric power [114].

For solar and wind technologies, commissioning time estimates were sourced from Gumber et al. (2024) [115], which notes that reported average values significantly exceed median values. This analysis utilizes average figures, as they more accurately represent the time requirements for large-scale installations.

Capital Costs Capital costs represent the initial investment required for nuclear power plant construction. As Rothwell (2022) demonstrates [116], recent European and U.S. nuclear installations have consistently exceeded initial cost projections. Given the broad range of possible costs and the intrinsic uncertainty of cost estimates, this analysis employs a trapezoidal distribution to model all the possible costs outcomes. The chosen distribution is shaped as a trapezoid, therefore needing four points: minimum, low most likely, high most likely and maximum. The PDF is set to 0 at the extremes, and is constant between the two "most likely" points, the value of the plateau is determined by the normalization condition. Unfortunately data in this regard is scarce, but by collecting the available information, most importantly that from AP-1000 and EPR, it is possible to determine ratios between points in the curve (See figure 3.3). The ratios between the low most likely and minimum and that between the high most likely and maximum are both close to 22%, the low most likely point is also 22% of the value of the high most likely point. Based on this information, it is possible to reconstruct the curve for any other reactor even when only one estimate point is available. (All data is reported in 2024 EUR/kWe). The AP-1000 cost distribution incorporates U.S. construction experience (Vogtle units 3 and 4) for the "high most likely" point, Polish deployment estimates for the "low most likely", and recent U.S. projections [117], judged as "the best out there, yet still a bit optimistic" by domain experts, for the minimum point. For the EPR, ongoing UK projects provide the two reference points: estimated completion cost for Sizewell unit C (14,154 EUR2024/kWe) establishes the "high most likely" value, while Hinkley Point C represents an unfavorable outlier (17,300 EUR2024/kWe) defining the maximum bound. The APR-1400 minimum reflects current estimates for Czech deployment [118].

Consultations with nuclear economics experts provided critical perspective on cost as-

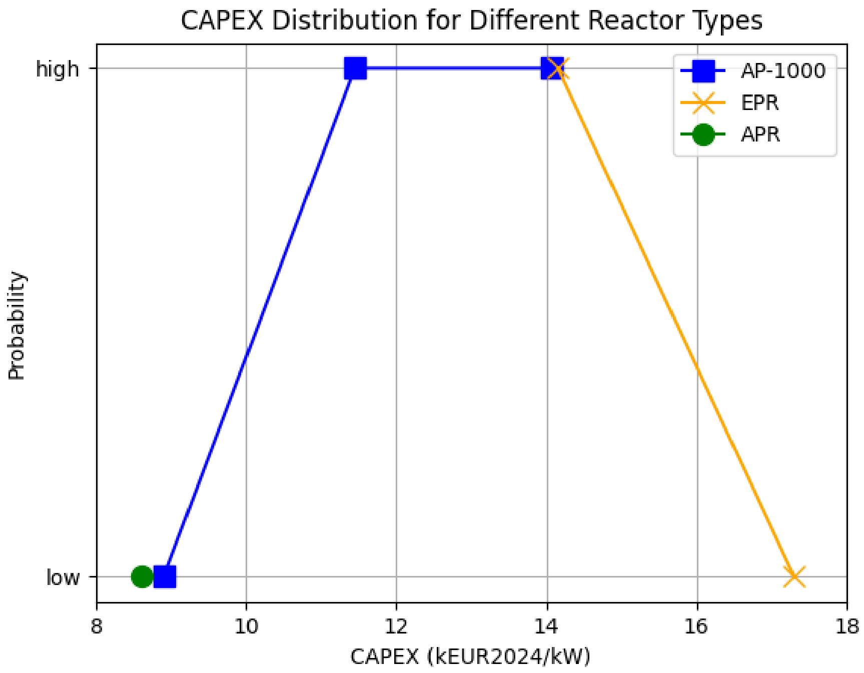


Figure 3.3: Available data on capital costs from existing NPPs

sumptions. Manufacturer estimates were regarded as overly optimistic. The discussion also challenged learning curve assumptions, noting the absence of recent cost reduction evidence in nuclear construction. Conservative deployment cost estimates converged near 9000 USD2022/kWe, significantly exceeding all vendor claims. The U.S. Energy Information Administration's 2024 report [114] offers relevant benchmarks, documenting SMR costs at 8936 USD2023/kWe and large reactor costs at 7861 USD2023/kWe.

The capital cost distributions (Table 3.11) were constructed using the previously established cost ratios and expert-sourced reference points (shown in bold). While some of these specialist inputs remain unpublished or unverified for the time being, their preliminary nature aligns with the study's focus on uncertainty quantification, providing an opportunity to incorporate a highly uncertain indicator into the analysis framework.

Design complexity serves as a proxy for manufacturing and procurement risks, where greater component counts increase management burden and error potential. Cooling loop quantity was considered a simple and practical complexity metric, with the EPR (4 loops) representing the most complex design, followed by APR-1400, AP-1000 and Rolls-Royce SMR (3 loops each). The integrated designs of NuScale and BWRX-300 demonstrate the simplest configurations. Being a qualitative indicator, this starting point evaluation will be refined through expert judgment.

Construction complexity evaluates the preferred strategy for the construction process. Traditional reactors rely primarily on on-site construction, Rolls-Royce employs extensive off-site fabrication but still maintains significant on-site assembly requirements due to the large capacity and the multi-loop configuration. The BWRX-300 reduces on-site work through its integrated design, and NuScale represents the most modular approach with sequential deployment of, smaller, fully manufactured units. The author recognized that neither construction paradigm demonstrates clear superiority: even if on-site methods face well-documented challenges [14], modular approaches introduce supply chain coordination complexities. The evaluation of this qualitative indicator presents construction approaches as a spectrum (Figure 3.4) rather than imposing an initial ranking to avoid implying that one approach is better than the other.

After the expert judged the spectrum, they are asked to determine the value function for this criterion, starting from a neutral linear baseline. In this second step, they will be able to express and quantify the preference towards one of the two approaches.

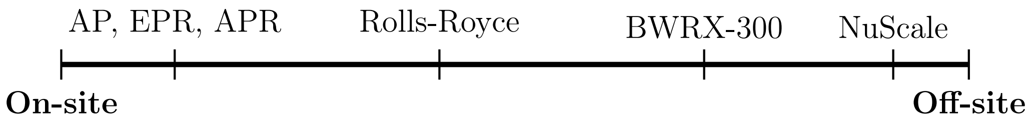


Figure 3.4: Construction complexity spectrum: reactor models from on-site to off-site manufacturing approaches.

Operational Costs represent the recurring expenditures associated with nuclear power plant operation and maintenance, including fuel expenses and routine maintenance activities. Steigerwald et al. (2023) [119] provides detailed cost projections for future nuclear installations, reporting both capital and operational expenditures for SMRs and large reactors. The study presents operational costs for EPR and APR-1400 designs, while the "Long-Term US" category was utilized as a proxy for AP-1000 operational costs. All opex data has been standardized to 2020 USD to ensure consistency with the primary reference source [119].

For SMR designs where operational costs were originally reported in power-based units (USD_{2020}/MW_e), conversion to energy-based measurements (USD_{2020}/MWh_e) was performed, applying the CF distribution presented in Section 2.3 to the following relationship:

$$\frac{USD_{2020}}{MWh_e} = \frac{USD_{2020}}{MW_e} \cdot \frac{1}{CF \cdot 8760 \frac{h}{year}}$$

The analysis from [119] incorporates fuel cost estimates of $6.23 USD_{2020}/MWh_e$ for PWR-based technologies, with two exceptions: NuScale at $7.15 USD_{2020}/MWh_e$ and the BWRX-300 at $29.55 USD_{2020}/MWh_e$. The latter appeared inconsistent given the order of magnitude difference from other LWR designs, a discrepancy also noted by Hjelmeland (2024) [120]. Consequently, an alternative estimate of $7.19 USD_{2020}/MWh_e$ was selected, aligning more closely with both Hjelmeland's critique and Zubair et al. (2026) [121]. The estimates for Rolls-Royce was originally sourced from [107], but the figure of 68 USD_{2022}/MWh_e was deemed unrealistic and undocumented by domain experts. For this reason a conservative 25 ± 5 USD_{2020}/MWh_e was adopted in this study. Moreover, operational cost data for utility-scale onshore wind, hydroelectric, and solar photovoltaic (PV) (with single-axis tracking and DC battery storage) were sourced from the US Energy Information Administration [114] to provide a comparison benchmark to the reader.

3.3.4. Sociopolitical Indicators

The last category of indicators regards all aspects that are considered to be of most importance to the general public. The main rationale behind the choice of these indicators is to capture aspect that can most likely end up in public debates and therefore influence the public opinion.

Potential electricity market benefit To assess the potential consumer impact of nuclear reactor deployment, this analysis evaluates its effect on electricity pricing. The study assumes that NPPs will generate only electricity, excluding cogeneration, given the relatively short-term time horizon of the analysis and the likelihood that such integrations will emerge later. The investigation proceeds from the assumption that all examined markets operate under marginal pricing mechanisms, which accurately describes France, Poland, and Italy, and largely applies to Switzerland as well, despite some additional price adjustment measures. In marginal pricing markets, the wholesale price of electricity is determined through a bidding process, where the final price equals the cost of the last generating source required to meet demand. For instance, if a bidding zone requires 100 MW of capacity with renewables only able to supplying 80 MW and gas generation covering the remaining 20 MW, the electricity price of the zone will reflect the cost of gas-powered generation.

The first step involves identifying the marginal generating source and quantifying its contribution to total electricity production. This assessment utilized country-specific data from the International Energy Agency (IEA) Electricity Overview [85] and the ENTSO-E Transparency Platform [77], which also provided annual electricity cost data. All referenced data pertain to 2024, and the complete analytical methodology is available in the accompanying repository (see Appendix A).

Annual energy production for each reactor was then calculated by applying a capacity factor distribution to the nameplate capacity. The analysis employs Equation 3.1 with capacity factors assumed with a distribution representative of the average performance of existing nuclear reactors in Europe (see Section 2.3).

$$E_{reactor,yr}[GWh] = P_e[MW_e] \cdot 8760[h] \cdot CF[-] \cdot \frac{1}{1000} \tag{3.1}$$

The price impact evaluation uses France as the reference case, representing Europe's only nuclear-saturated electricity market. Consequently, all reactor designs yield a zero price reduction for France, as expected in a market where nuclear already dominates the generation mix.

For other countries, the analysis calculates potential price reductions by comparing each nation's 2024 average electricity cost against France's lower nuclear-based pricing. The projected benefit is then adjusted by the number of reactor units required to fully displace the current marginal generating source. The final results express the potential annual reduction in average electricity prices in EUR/MWh.

Potential Reduction of Greenhouse Gas Emissions Potential greenhouse gas emission reductions were quantified by comparing the average emissions from each country in 2024 with projected reductions following deployment of one reactor unit. Country-specific emission intensities were derived from Electricity Maps aggregated data [69], while total load figures were obtained from the ENTSO-E Transparency Platform [77].

For nuclear generation's lifecycle emissions, the analysis adopts Liu et al.'s (2023) global meta-analysis of 42 studies [122], which reports a worldwide average of 15.815 ± 3.59 gCO_2-eq/kWh for light water reactors. This conservative estimate was selected despite context-specific variations: French nuclear operations typically demonstrate lower intensities ($2 \sim 6$ gCO_2-eq/kWh) according to both operational data [123] and IAEA assessments [124], with some French reactor studies reporting values up to 12 gCO_2-eq/kWh [123]. The global average was preferred as a conservative estimate.

SMRs were assigned a slightly higher emission intensity of 17.24 ± 3.91 gCO_2-eq/kWh, reflecting Carless et al.'s (2016) finding that SMRs demonstrate approximately 9% higher lifecycle emissions than conventional large LWRs [125].

Spent Nuclear Fuel Production Given public sensitivity regarding nuclear waste, this analysis includes Spent Nuclear Fuel (SNF) production as a key indicator, quantified in tons and normalized per 1 GW-annum to facilitate comparison of waste generation efficiency across reactor designs. Spent fuel estimates were calculated through material balance as outlined in equations 3.2 through 3.5, deriving the values from each reactor's thermal efficiency and discharge burnup parameters. The variables employed are presented in Table 3.13.

Variable	Description	Unit
Bu_d	Discharge burnup	$\left[\frac{GWd}{tonHM}\right]$
η	Thermal efficiency	[%]
$Bu_{d,e}$	Discharge burnup in electrical terms	$\left[\frac{GWd_e}{tonHM}\right]$
$Bu^*_{d,e}$	Annual discharge burnup	$\left[\frac{GWa_e}{tonHM}\right]$
SNF^*_{prod}	Mass of metal in spent nuclear fuel discharged per GWa produced	$\left[\frac{tonHM}{GWa_e}\right]$
SNF_{prod}	Mass of spent nuclear fuel (oxide) produced per GWa produced	$\left[\frac{tonUO_2}{GWa_e}\right]$
MM_{UO_2}	Molar mass of uranium dioxide	$\left[\frac{g}{mol}\right]$
MM_U	Molar mass of uranium	$\left[\frac{g}{mol}\right]$

Table 3.13: Variables used in the computation of Spent Nuclear Fuel production

Step 1: Convert discharge burnup to electrical terms

$$Bu_{d,e} = Bu_d \cdot \eta \tag{3.2}$$

Step 2: Convert from daily to annual units

$$Bu^*_{d,e} = \frac{Bu_{d,e}}{365} \tag{3.3}$$

Step 3: Calculate the mass of heavy metal discharged per GWa produced

$$SNF^*_{prod} = \frac{1}{Bu^*_{d,e}} \tag{3.4}$$

Step 4: Convert from heavy metal mass to oxide mass

$$SNF_{prod} = SNF^*_{prod} \cdot \frac{MM_{UO_2}}{MM_U} \tag{3.5}$$

Perceived Safety To account for public acceptance, a critical yet subjective factor in nuclear deployment, this analysis incorporates "perceived safety", defined as the general public's trust in a reactor design based on media portrayal and supplier messaging rather than technical risk metrics. The reason behind the exclusion of engineering safety parameters, such as the core damage frequency, is detailed in section 3.3.6. In short, for this analysis we recognize that, from an engineering standpoint, all reactors can be considered safe. Nonetheless, from the history of nuclear power it is evident that the opinion of the public is much more important than the one of probabilistic risk assessments (see Section 1.1 and 3.1). This study therefore tries to quantify the opinion of the public on different reactor designs, mostly based on their potential appearance in the media. The first assumption that the author was confident to make is that any large "traditional" reactor will be judged the same way, so the difference might lie between the broad category of "large" reactors and SMRs models. To have a baseline understanding, a small survey was conducted presenting the three SMRs models by the key points that their own suppliers use, Rolls-Royce is mostly focused on the modularity, size, and flexibility while Nuscale and GEV-H emphasize, in slightly different ways, the safety advantages of their integrated design, mostly the ability to shut down safely without human intervention (which is something that all commercial reactors do anyway) and the ability to cool down without external power. For each design, the participants were asked to say if they believed the reactor was safer, as safe as, or less safe than traditional large reactors. The survey also provided images of the reactor to better represent the way they might appear in the media. The results of this small survey (n=50) show that both Nuscale and the BWRX-300 were perceived as safer than traditional large reactors by a majority while Rolls-Royce SMR was perceived as safer by a minority of participants (only one respondent thought it was less safe, for this analysis this response was grouped with the "as safe as" category). A detailed presentation of the survey can be found in appendix B, the results are summarized as follows:

- Nuscale: 62% safer, 38% as safe as
- BWRX-300: 62% safer, 38% as safe as
- Rolls-Royce SMR: 30% safer, 70% as safe as

If we state that the amount of people that think that nuclear reactors are safe is x we can create the distribution presented in Table 3.14 for each reactor type. While it is obvious that the lowest score ("unsafe") will correspond to a value of 0 and to the highest ("safer") the value function shall return 1, we cannot assume linearity for the middle ground, this information will be elicited from experts through value functions elicitation (see Section

3.4).

The value of x is unknown, and will be treated as an uncertain parameter sampled from a uniform distribution between 0.3 and 0.7 to capture both a generally pro-nuclear and a generally anti-nuclear public opinion. Public surveys were not employed in this regard for reasons disclosed in section 3.3.6.

3.3.5. Conflicts and Interactions between Indicators

Methodological transparency requires explicit examination of indicator interdependencies and potential conflicts identified during expert elicitation, where most consideration concerned perspective differences. For instance, while electricity market costs inevitably depend on capital and operating costs, these indicators serve distinct analytical purposes. Market cost impacts fall under sociopolitical evaluation (reflecting public concerns), whereas capital/operating costs represent economic indicators (addressing budgetary perspectives).

Some interrelationships are inherent to complex systems. For instance, thermal efficiency affects both operating costs and waste generation, which, in turn, influences lifecycle GHG emissions. Such "weak dependencies" are expected and acceptable in system-level analysis. However, the methodology explicitly avoids "strong dependencies" that would create redundant evaluation. For example, in this analysis consideration of both capital costs and Levelized Cost Of Electricity (LCOE) was avoided given the capital-intensive nature of nuclear energy.

3.3.6. Notable examples of Discarded Indicators

In this section we reason about some discarded indicators that, among all, require further explanation. Any other that is not present in this section was discarded for trivial reasons.

Data-based safety indicators The observant reader may have noted the omission of explicit safety indicators among technical parameters in our analysis. Table 3.15 presents the Core Damage Frequency (CDF), a critical regulatory metric representing the likelihood of severe accidents, expressed as events leading to core damage per reactor-year, computed by probabilistic risk assessment.

While CDF values demonstrate marginal differences between designs, all modern reactors exhibit exceptionally high safety performance in absolute terms. Comparative energy safety data underscores this point: nuclear energy's fatality rate of 0.03 deaths per TWh places it among the safest energy sources, comparable to wind (0.04) and solar (0.02), and 2-3 orders of magnitude safer than fossil fuels (2.82 for gas, 32.72 for brown coal) [128, 129, 130]. Radiation exposure data from the US EPA [131], based on NCRP measurements [132], reveals that 48% of average annual radiation dose comes from medical procedures, 37% originates from natural background radiation and less than 0.2% is attributable to occupational/industrial sources, including nuclear power plants. Moreover, technical safety metrics are considered to have limited influence on public opinion when risk perception prevails over risk assessment.

Public surveys

During this study's execution, multiple public surveys were reviewed, based on the initial assumption that such instruments could provide quantitative measures of qualitative factors, such as public support for nuclear installations. However, the analysis exposed frequent methodological limitations, introducing bias into the results. In Italy, a 2024 survey reported 81% opposition to nuclear power [133]. However, analysis of the survey report reveals problematic question design. The primary question was phrased as: *"The debate on nuclear energy has returned to the forefront. What is your opinion on the matter?"* with response options structured as:

- A1: "The current situation is complex; a return to nuclear should be evaluated"
- A2: "Nuclear has more risks than benefits and is not the right path"
- A3: "Nuclear energy entails excessive hidden costs and is not advantageous"
- A4: "Only safer technologies than current ones should be considered"

This framing demonstrates clear bias: two options (A2 and A3) explicitly oppose nuclear, A1 offers only conditional support, and A4 introduces safety concerns before suggesting potential support. Notably, the 81% opposition figure includes A4 responses, which represent conditional rather than absolute opposition. When considering only explicit opposition (A2+A3), the figure decreases to 43%.

Another study from 2024 presents a more methodologically sound approach, though its presentation emphasized positive findings. The actual data reveals a more nuanced picture: over 80% of respondents consider themselves insufficiently informed about nuclear topics, and further investigation found that approximately 90% were unaware of SMRs or Generation IV reactors [134]. These findings suggest that public opinion on nuclear energy may be more influenced by lack of information than by firmly held positions.

Water usage indicators Use of water is certainly a critical aspect to be considered when deploying a NPP, as noted multiple times by several experts when asked about feedback on the indicator list presented in this work. However, multiple reasons determined their exclusion. The main one is that the parameters would be intrinsically site dependent, since the overall water usage will be determined by the cooling solution implemented and its boundary conditions. NPPs require cooling for the condensation part of the Rankine cycle, for this, some plants use cooling towers, others rely on rivers to dissipate the heat or the sea, and sometimes these solutions are combined. Water related indicators are therefore out of scope for this study, but they are accounted for future implementations that might want to consider site specific conditions.

Land usage indicators Similar to water usage, land usage is a parameter that is highly site-specific. While NPPs generally have a small land footprint compared to renewable energy sources, the actual land usage can vary significantly based on site conditions, safety buffer zones, and associated infrastructure. Therefore, land usage indicators were excluded from this analysis but are recommended for future studies that incorporate site-specific evaluations.

Indicators related to construction time Estimated construction time was collected for all reactors, and found to be all between 3 and 5 years (GEV-H reports a construction time between 2 and 3 years for the BWRX-300 [135]), but from analysis of previous projects is it clear that assuming these construction times would not be realistic [14]. As a better approach, the use of a "risk of delays" indicators was suggested by an expert in the field of risk assessment. To do so, in this study, a significantly simplified and qualitative approach was used to determine the complexity of manufacturing and construction (Section 3.3.3).

More social aspects While some researchers have proposed incorporating additional social dimensions such as landscape impact or job creation potential, these, and similar factors, were again excluded since they are mostly site-dependent and cannot be generalized. The potential influence of NSSS suppliers on social acceptance was acknowledged as a valid concern. For this study, the exclusion of Russian and Chinese suppliers was considered an essential requirement for the final selection rather than a possible point of discussion. For this reason, it was implemented *a priori* during the alternative selection process (Section 3.2). Additionally, recent developments (2025-2026) were deliberately omitted, as may not reliably represent long-term trends. Incorporating such factors would require in-depth analysis and geopolitical expertise beyond the scope of this study.

System management Another interesting argument suggested by several researchers is the consideration of wider system response to the deployment of nuclear reactors, such as the grid capabilities; these were excluded because, once again, they are mostly dependent on site-specific conditions. Other aspects like supply chain and waste management problems scale up with the number of reactors deployed rather than the specific technology chosen.

Proliferation Concerns Proliferation risk is a reasonable concern when dealing with new nuclear installations. For this thesis, the setting in European countries makes the risk of proliferation less relevant than it could have been in other geopolitical contexts. Moreover, the technologies considered in this study all LWRs using low enriched uranium (LEU) fuel, therefore even if the deployment of several small NPPs could in principle increase the risk of proliferation, the settings and selections for the present case study make such a concern irrelevant.

Technical Indicators		
T1	Thermal Efficiency [%]	Indicator of the thermal hydraulics efficiency
T2	Discharge Burnup [GWd/tonHM]	Indicator of the fuel utilization efficiency and neutron economy
T3	Net Power Output [MWe]	How much does the output of one unit fit the grid demand
T4	Load Following Capabilities [-]	How much do the load following capabilities satisfy the grid demand
Feasibility Indicators		
F1	Design Maturity [Score]	Technological readiness of the design
F2	Licensing Status [Score]	How close to having a licence is the reactor?
F3	Supplier Availability [Score]	Is the supplier established in the country? Even partially, for instance has offices
Economic Indicators		
E1	Capital Investment Budgeted [2024EUR/kWe]	Overnight, budgeted construction costs (estimates include decommissioning etc.)
E2	Design Complexity [Score]	From which delays in the manufacturing processes might arise
E3	Construction Complexity [Score]	From which delays in the building processes might arise
E4	Operative and Fuel Costs [USD2020/MWh]	Ongoing costs
Social Indicators		
P1	Electricity Market Benefit [2024EUR/MWh]	Potential reduction of cost in the Electricity Market by marginal price logic, by constructing one unit
P2	GHGe Benefit [tonCO2eq]	Potential Yearly Reduction on GHG Emissions by installing one unit
P3	Perceived Safety [Score]	Based on public opinion, how much each reactor sounds safe?
P4	Nuclear Waste [tonSNF]	Estimation of amount of spent fuel produced

Table 3.5: Final selection of indicators, categorized and coded for evaluation.

Reactor Model	T1	T2	T3	T4
APR1400	35.2	46.5	1340	0.21
EPR 1750	36.2	55	1630	2.88
AP1000	32.4	50	1120	4.25
BWRX-300	34.5	50 ± 5	300	0.25
Rolls-Royce SMR	34.6	55 ± 5	470	2.00
NuScale	30.8	52.5 ± 2.5	462	2.00
GEV-H 9HA.02 2xCC	–	–	1515	7.02

Table 3.6: Technical Indicators: T1: Thermal Efficiency [%], T2: Discharge Burnup $[MWd/tonHM]$, T3: Net Power Output $[MW_{e,net}]$, T4: LFC $[\%P_{nom}/min]$.

Parameter	APR	EPR	AP	BWRX	Rolls-Royce	NuScale
Operational units	9	2 (+2)	7	0	0	0
Under construction	3	2	2	0	0	0
Technology	PWR	PWR	PWR	i-BWR	PWR	i-PWR
Construction strategy (Units)	1	1	1	1	1	4–12
Fuel	Existing	Existing	Existing	Existing	Variation	Variation
Design Maturity Score	5/5	4/5	5/5	1/5	2/5	1/5

Table 3.7: Data to support design maturity.

Reactor Model	Information
APR-1400	• Built in Korea, UAE • Licensed in US • Approved by EUR
EPR-1750	• Built in UK, China (+ FR, FIN) • Approved by EUR
AP-1000	• Built in China, US • Approved by EUR
BWRX-300	• Build licence in CAN 2025 (subject to VDR 2023) • Pre-application in US in 2019 • UK GDA started 2024
Rolls-Royce SMR	• Pre-application in US in 2025 • UK GDA started in 2022
NuScale	• SDA in US (2025)

Table 3.8: Licensing and construction information for selected reactor models.

Country	APR	EPR	AP	BWRX	RR SMR	NuScale
France (FR)	0.00	0.50	0.50	0.25	0.25	0.00
Italy (IT)	0.00	0.25	0.25	0.25	0.00	0.00
Switzerland (CH)	0.00	0.25	0.25	0.25	0.00	0.00
Poland (PL)	0.00	0.00	0.25	0.25	0.00	0.00

Table 3.9: First step of supplier availability scores for each reactor model in the selected countries.

Country	APR	EPR	AP	BWRX	RR SMR	NuScale
France (FR)	0.50	1.00	1.00	0.75	0.75	0.50
Italy (IT)	0.50	0.75	0.75	0.75	0.50	0.50
Switzerland (CH)	0.25	0.50	0.50	0.50	0.25	0.25
Poland (PL)	0.00	0.00	0.25	0.25	0.00	0.00

Table 3.10: Final supplier availability scores for each reactor model in the selected countries.

Reactor Model	**Minimum**	**Low Likely**	**High Likely**	**Maximum**
AP-1000	**8900**	**11500**	**14100**	17000
EPR-1750	9000	11600	**14200**	**17300**
APR-1400	**8600**	11000	13600	16300
BWRX-300	8600	**11100**	13600	16300
Rolls-Royce SMR	**8000**	10300	12600	15100
NuScale	**4100**	5300	16500	**19800**

Table 3.11: Trapezoidal capital cost distributions [2024EUR/kWe] for each reactor model, rounded up to the nearest hundred. Known points in bold.

Reactor Model	**OPEX (includes fuel costs) [USD2020/MWh]**
APR-1400	24.67 ± 1.65
EPR-1750	20.49 ± 1.37
AP-1000	24.92 ± 1.67
BWRX-300	25.49 ± 1.71
Rolls-Royce SMR	25.00 ± 5.00
NuScale	29.91 ± 2.00
Other Power Plants	
Onshore Wind	28.08
Solar PV + Battery	33.33
Hydroelectric	28.49

Table 3.12: Operative and fuel costs [USD2020/MWh] for each reactor model and renewable benchmarks.

Table 3.14: Summary of Public Perception of Reactor Safety

	Traditional	NuScale	BWRX-300	Rolls-Royce
Unsafe	$1 - x$	$0.38 \cdot (1 - x)$	$0.38 \cdot (1 - x)$	$0.70 \cdot (1 - x)$
Safe	x	$0.62 \cdot (1 - x) + 0.38 \cdot x$	$0.62 \cdot (1 - x) + 0.38 \cdot x$	$0.30 \cdot (1 - x) + 0.70 \cdot x$
Safer	0	$0.62 \cdot x$	$0.62 \cdot x$	$0.30 \cdot x$

Reactor Model	**CDF [1/reactor-year]**	Source
APR-1400	2.25×10^{-6}	[126]
EPR-1750	1.18×10^{-7}	[127]
AP1000	2.41×10^{-7}	[103]
BWRX-300	$< 1.0 \times 10^{-8}$	[112]
Rolls-Royce SMR	$< 1.0 \times 10^{-7}$	[112]
NuScale	$< 2.0 \times 10^{-7}$	[112]

Table 3.15: Core Damage Frequency (CDF) for Selected Reactor Models

3.4. Elicitation process

The elicitation process consisted in three steps: (1) qualitative indicators, (2) value functions for quantitative indicators, and (3) PILE-BWT.

Qualitative Indicators As presented in section 2.3.1, the author prepared an informed starting point for all qualitative indicators included in the analysis. The starting point determines the order of the alternatives and a linear value function, either increasing or decreasing, assuming all points are equally spaced. Hypothetical worst and hypothetical best points are included to give more flexibility during value function design. Experts are first requested to review the ranking and correct it if necessary. Then the linear value function can be adjusted to increase or decrease the difference between alternatives.

The indicators subject to this procedure are presented in table 3.16 along with their descriptions. To improve the statistical robustness and given that this process is straightforward and not time-consuming, a total of nine experts were consulted (See Section 4.1 for details about the consulted experts).

Table 3.16: Qualitative indicators elicited through ordering and value function adjustment.

Qualitative indicator	Description
Design maturity	How close to NOAK installation
Licensing status	How close / Ease of obtaining building licence (Country-dependant).
Supplier availability	Ease of building up a supply chain within the country (Country-dependant).
Design complexity	Proxy to determine likelihood of delays in the manufacturing and procurement of components.
Construction complexity	Proxy to determine likelihood of delays in the construction and installation phases. (Country-dependant)

Value Functions The mid-value splitting technique, described in section 2.1, is a well-established elicitation method for constructing value functions. However, its application is extremely time-consuming and cognitively demanding for experts. To address these challenges, this study carried out a *first elicitation* adhering to the mid-value splitting technique to establish an initial set of value functions.

Subsequent elicitations employed a similar approach to that used for qualitative indicators (section 3.4), where the expert is first presented with an initial value function (the result of the *first elicitation*) and is then asked to provide feedback and modify it as they see fit. This approach noticeably sped up the process, but is also likely to have introduced some anchoring bias. In regard of this study it is deemed not to be a major issue since the main goal is to evaluate the proposed methodology rather than obtaining definitive results.

Weights The last part of the elicitation is the definition of the weights applying the PILE-BWT methodology presented in section 2.2. This session was deemed intensive by the experts due to the intrinsic difficulty of the questions at hand. An observation that must not be interpreted as negative, since it properly reflects the difficulty of a trade-off problem. Nonetheless, this has to be considered by the analyst when planning elicitation sessions, by properly allocating time and breaks, to avoid tiredness and loss of focus that could compromise the quality of the answers.

Unfortunately, in this case, it is not possible to circumvent the time-consuming nature of this task due to the method itself requiring the expert to reason about all trade-offs. To ensure consistency, since the BWT method requires the knowledge of value functions, only experts who already participated in the value function elicitation sessions were involved in this step.

3.5. Digital Tools to aid the Elicitation Process

A suite of Python-based tools (using Qt5) was developed to support the elicitation process across three key stages. These interactive prototypes were deemed essential by all experts for visualizing and refining inputs. Future iterations will be released as open-source software to assist similar processes.

The first graphical tool was used to support the qualitative indicator elicitation. Following the logic detailed in 3.4, experts were first presented with the possibility of modifing the author's ranking (Figure 3.5). Then, a linear value function can be adjusted to increase or decrease the difference between alternatives (Figure 3.6).

The second tools was used for the value function elicitation of quantiative indicators (igure 3.8). This tool was developed to assist the mid-value splitting technique. This proved to be useful in the "first elicitation" but presented limitations in the subsequent elicitations where experts were asked to refine existing value functions. In this case, the experts felt that being tied to alter the 0.25, 0.5 and 0.75 indifference points was too restrictive. Future versions of the software might evaluate to allow more flexibility in this regard.

The final tool, developed for weight elicitation (Figure 3.9), significantly simplified this inherently complex task by providing graphical for both the expert and the analyist. It also incorporated an "on-the-fly" consistency check that monitored ordinal consistency within each group. The interface highlighted compliant and non-compliant regions through slider coloring and boundary arrows, allowing analysts to immediately spot inconsistencies. This design offers flexibility: minor inconsistencies can be corrected in real time, while substantial discrepancies prompt the analyst to rephrase questions and request expert revisions without interrupting the elicitation workflow.

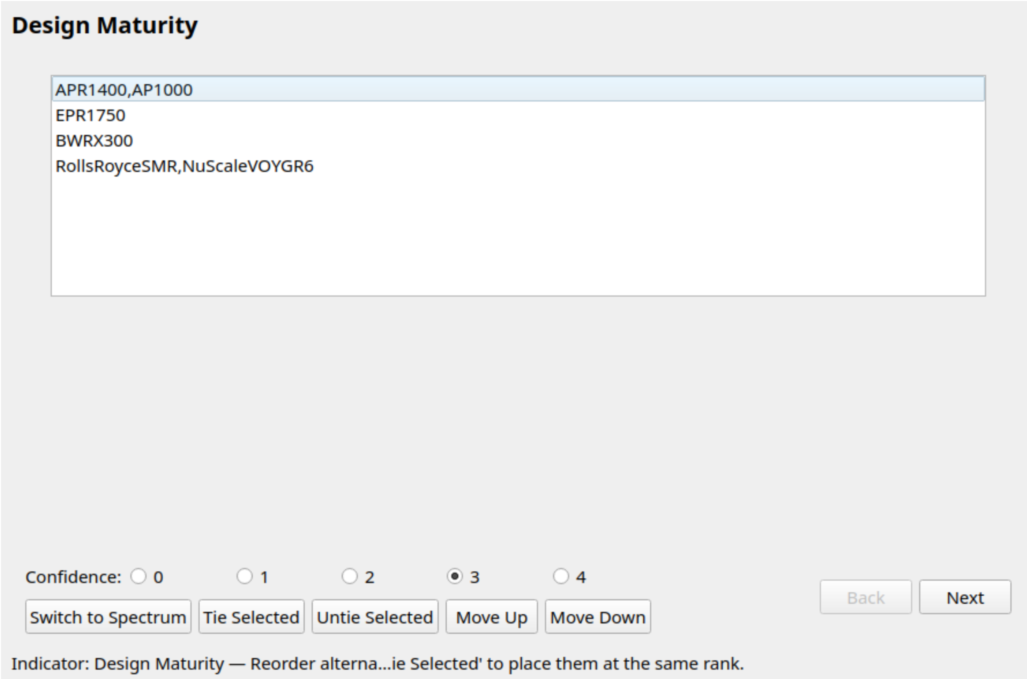


Figure 3.5: Ranking screen.

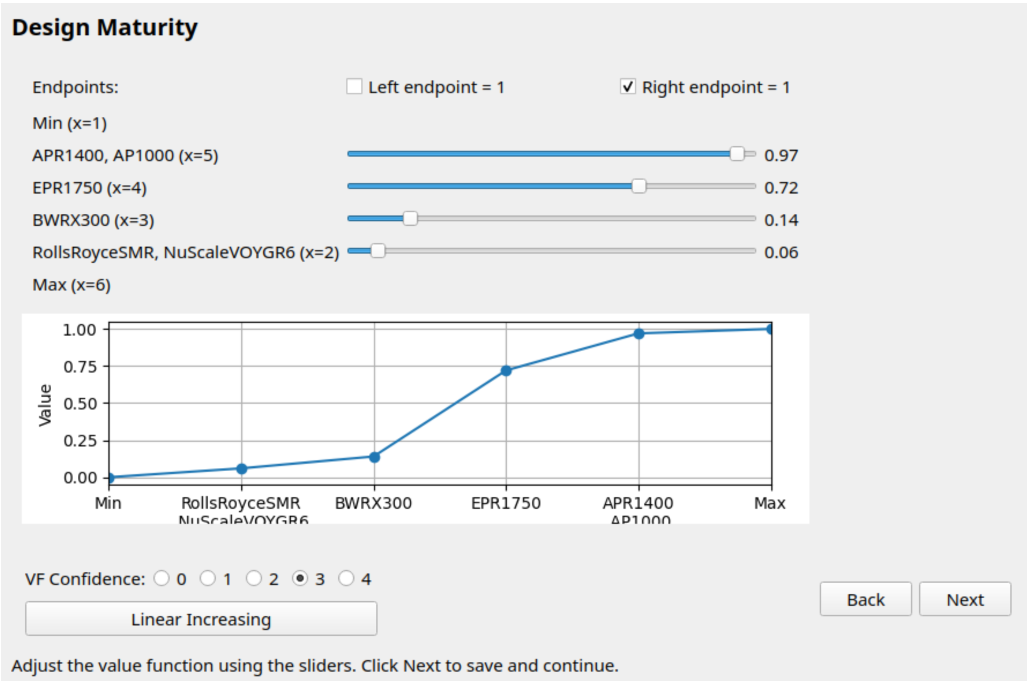


Figure 3.6: Value function screen.

Figure 3.7: Graphical interface for the elicitation of qualitative indicators.

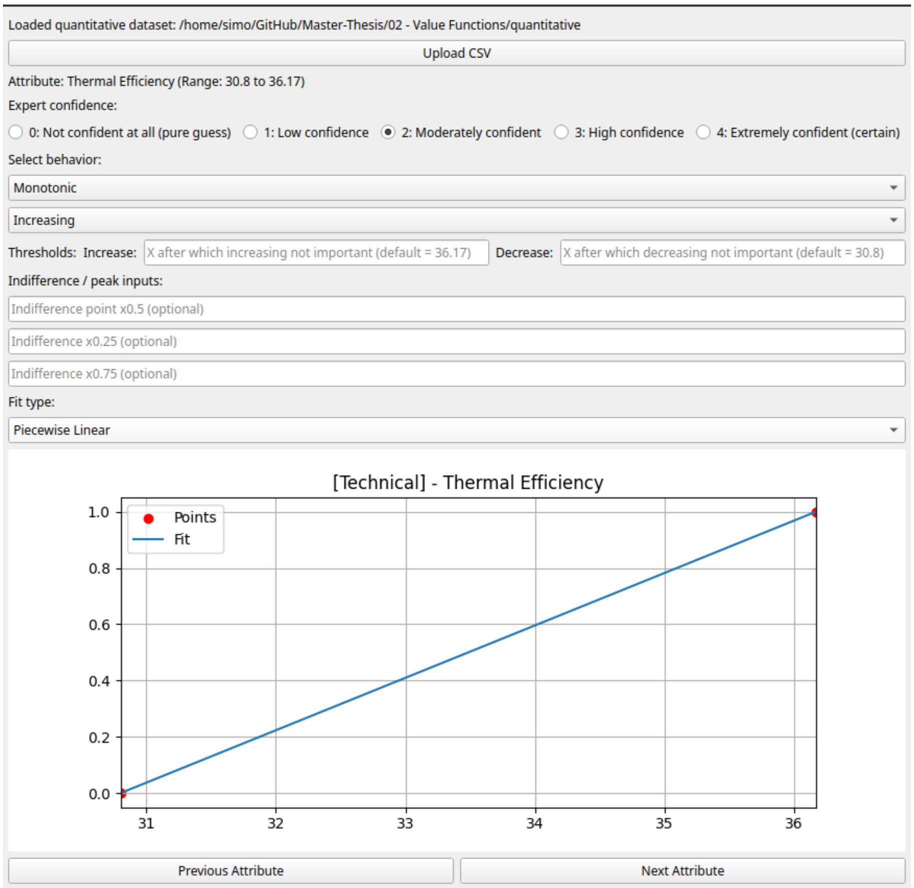


Figure 3.8: Value function elicitation interface showing mid-value splitting technique implementation.

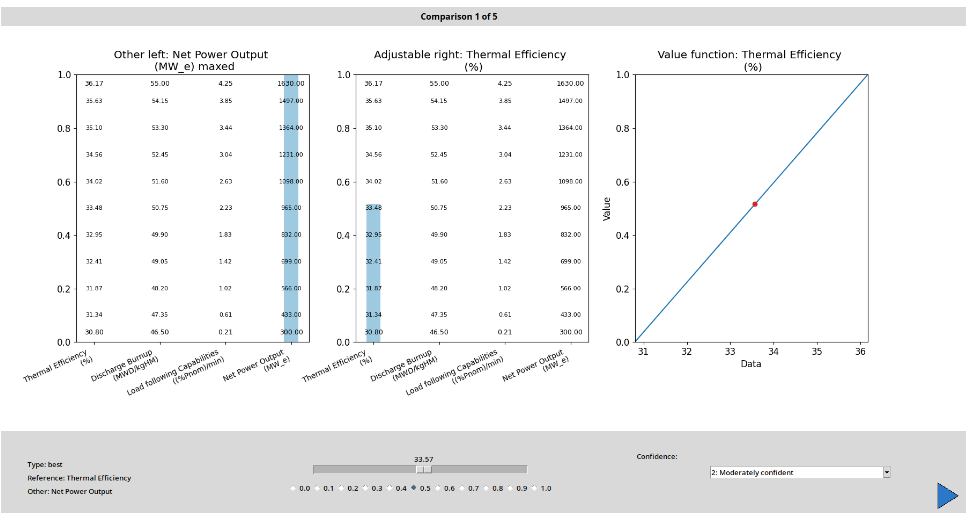


Figure 3.9: Weights elicitation interface showing BWT implementation.

4 | Discussion and Results

This chapter reports the results of this thesis analysis, the first section presents the results. Interpretation and methodological implications are discussed in Section 4.2. And finally, conclusions and suggestions for future work are provided in Section 5.

4.1. Results of the analysis

Results are presented starting from the data obtained from the elicitation process, followed by the UP-MAVT outcomes. Only rapresentative results are shown, the complete set of reuslts is available in the online repository (See Section A).

4.1.1. Elicitation outputs

The "full elicitation" process involved four experts who performed all analytical steps: (1) quantitative indicator value function development, (2) qualitative indicator assessment and value function construction, and (3) weight determination using the PILE-BWT methodology. Table 4.1 summarizes the expert panel composition, listing each expert's area of expertise and experience level, identities are maintained confidential. The first of these sessions ("first elicitation") took 3.5 hours, with subsequent sessions demonstrating progressive efficiency gains, culminating in a final session duration of just over one hour. This reduction in time primarily reflects the author's learning process and increasing familiarity with the procedure.

Expert	Area of Expertise	Experience
E1	Risk Assessment (Academia)	Senior Scientist
E2	Nuclear Safety (Academia)	Senior Scientist
E4	Nuclear Safety (Industry)	Junior Engineer
E8	Energy System Modelling (Academia)	PhD Student

Table 4.1: Experts involved in the elicitation process.

To enhance the characterization of qualitative indicators, five additional experts participated in an abbreviated "quick elicitation" process focused exclusively on the assessment of qualitative indicators (step 2). Table 4.2 presents these additional expert panel, detailing the area of expertise (spanning nuclear plant operations, construction, safety assessment, and project management) and years of experience for each participant. These sessions were significantly shorter, lasting no more than 30 minutes each.

Expert	Area of Expertise	Experience
E3	Nuclear Plants (Academia)	Academic Professor
E5	Project Controlling for Nuclear (Industry)	20 years in Project Management positions
E6	Nuclear new Construction (Industry)	17 years in Nuclear Construction
E7	Nuclear Plant Management (Industry / EU)	17 years in Nuclear Operations, currently working for EU JRC
E9	Probability Safety Assessment (Industry / UN)	15 years in PSA for Nuclear related projects, currently working at IAEA

Table 4.2: Experts involved in the quick elicitation process.

Figure 4.1 illustrates the qualitative assessment results for "Design Complexity" indicator across all nine experts. The heatmap displays alternatives on the horizontal axis and experts on the vertical axis, with cell colours representing the elicited value (colour scale from low to high values). This visualization reveals the degree of consensus or divergence among experts for this particular qualitative indicator, for instance it in this case the EPR is consistently rated as having the highest design complexity.

Representative elicitation outputs

Figure 4.2 presents the value functions elicited from the four experts for the "Net Power Output" indicator. The horizontal axis shows the indicator's raw values (net power output in MWe), while the vertical axis displays the normalized value function output (0 to 1 scale). Each coloured curve represents an expert's preference structure, illustrating divergent valuations of power output levels. While most experts favour higher nameplate capacities, Expert E9 assigns equal value to all capacities, indicating no preference. Among the remaining three experts, opinions split: two advocate a linear relationship (i.e., "the larger, the better"), whereas the last one (E4) consider capacities above 1000 MWe equally valuable. Figure 4.3 shows weight elicitation outcomes presenting the feasible weight space, explored via differential evolution (SciPy implementation [136, 137]). The horizontal axis represents the allowable weight range (0 to 1), and the vertical axis

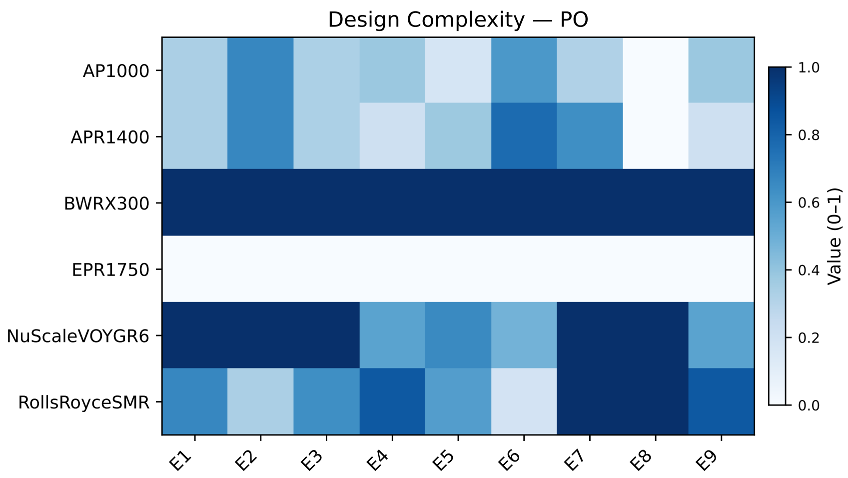


Figure 4.1: Values for the qualitative indicator Design Complexity, which are **inversely scaled**: higher scores indicate lower complexity and thus more desirable alternatives.

lists all criteria; each horizontal bar shows the feasible weight interval for that criterion. Figure 4.4 presents the consistency plots, which compare the declared pairwise comparison ratios (obtained from elicited data) with the ratios between the optimized weights (results of the optimization model). For each pairwise comparison, the plot shows two bars: the first (green) represents the declared ratio from the expert, while the second (orange) shows the computed ratio from optimized weights with error bars indicating $\pm\sigma$ to quantify solution variability. Good consistency is demonstrated when the declared value falls within the error bars of the computed ratio. This representation allows for visual assessment of consistency while also taking into account the inherent uncertainty of the PILE-BWT results.

4.1.2. UP-MAVT Results

As established in Section 2.4, the S-MC and NS-MC approaches serve complementary purposes. S-MC results can be used to judge pre-aggregation uncertainty and expert consensus levels, while NS-MC generates final rankings. Representative outputs for France are presented in Figures 4.5 and 4.6. These probability histograms display the aggregated value (horizontal axis, ranging 0-1) against probability density (vertical axis) for each reactor alternative (shown as separate subplots). Each coloured distribution represents one expert's assessment distribution, with overlapping curves indicating consensus and separated peaks revealing divergent expert opinions.

Ranking heatmaps are reported for each country across the three aggregation methods. These heatmaps display ranking position on the horizontal axis and reactor alternatives

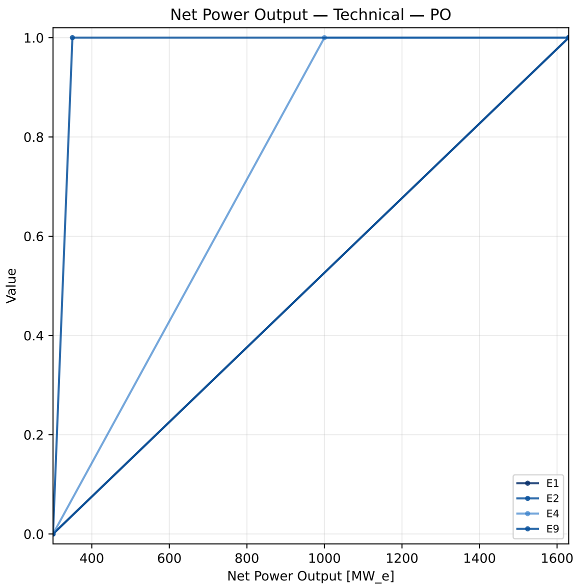


Figure 4.2: Value function elicited by experts for "Net Power Output - IT".

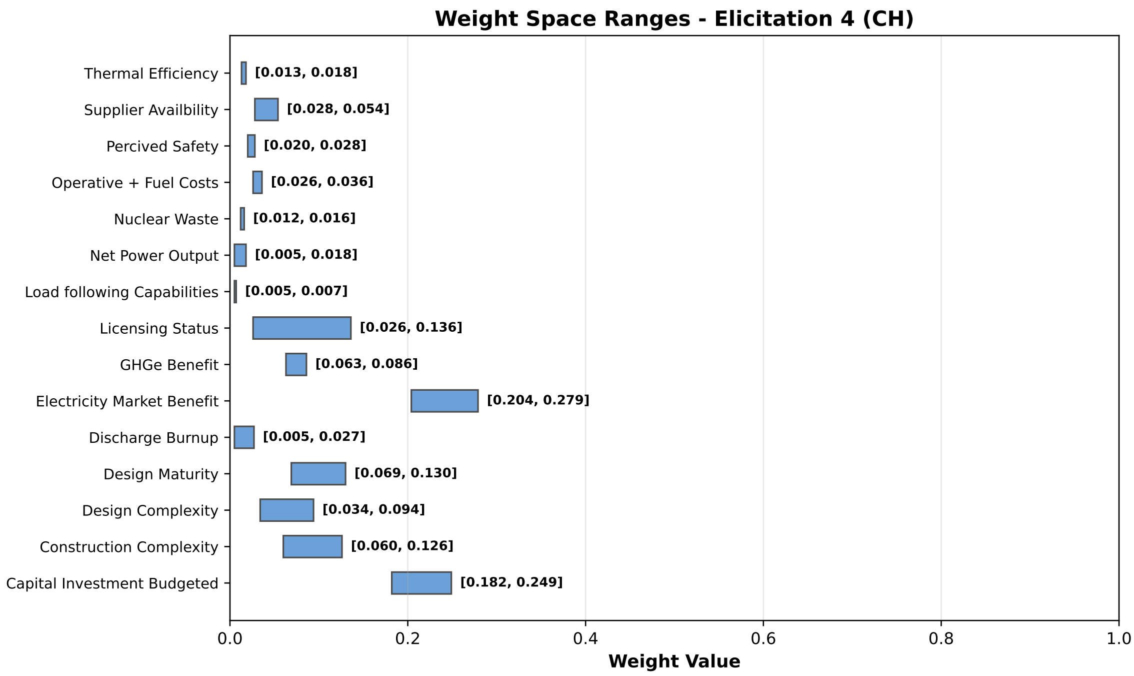


Figure 4.3: Weight space ranges for CH, from expert E4.

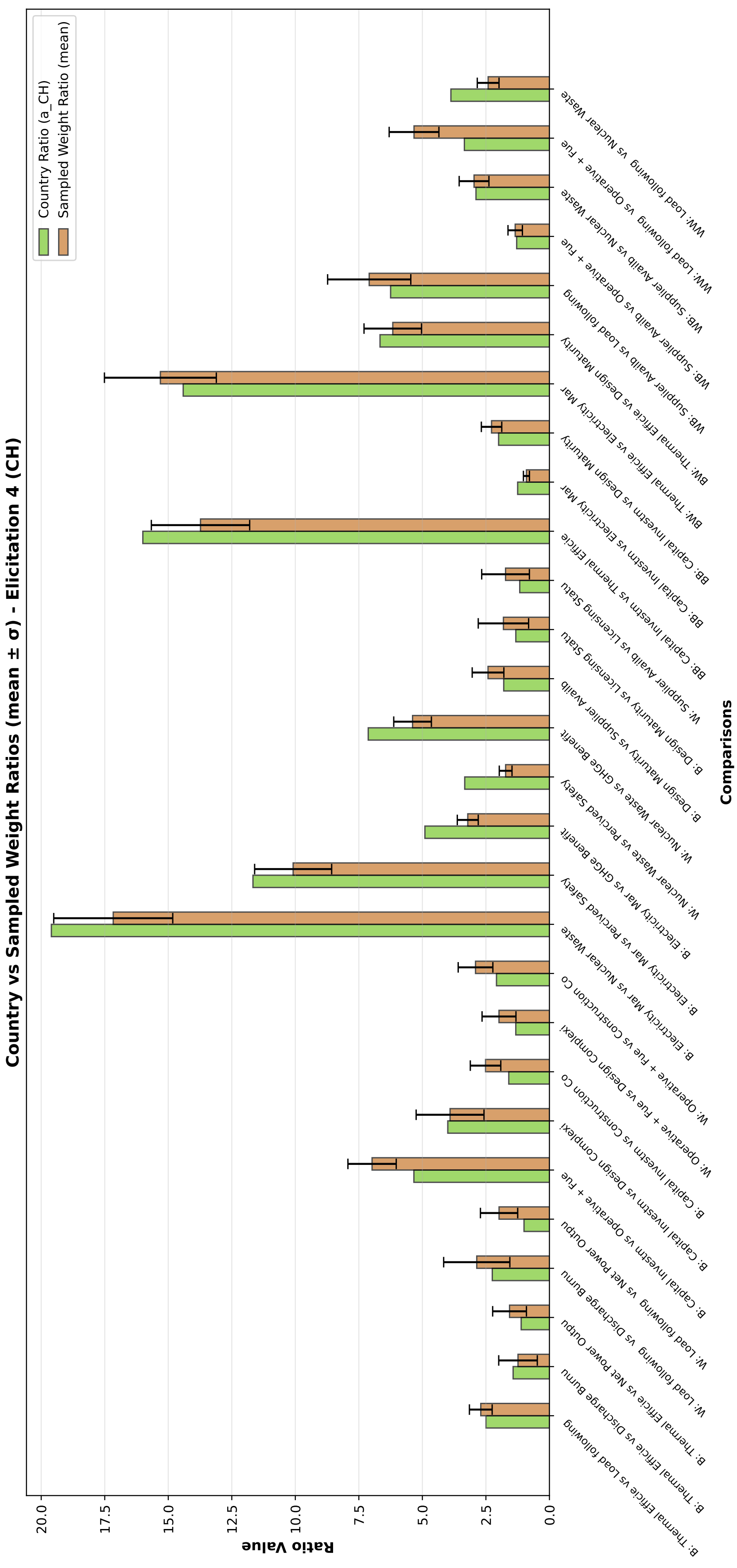


Figure 4.4: Consistency plot for CH, from expert E4.

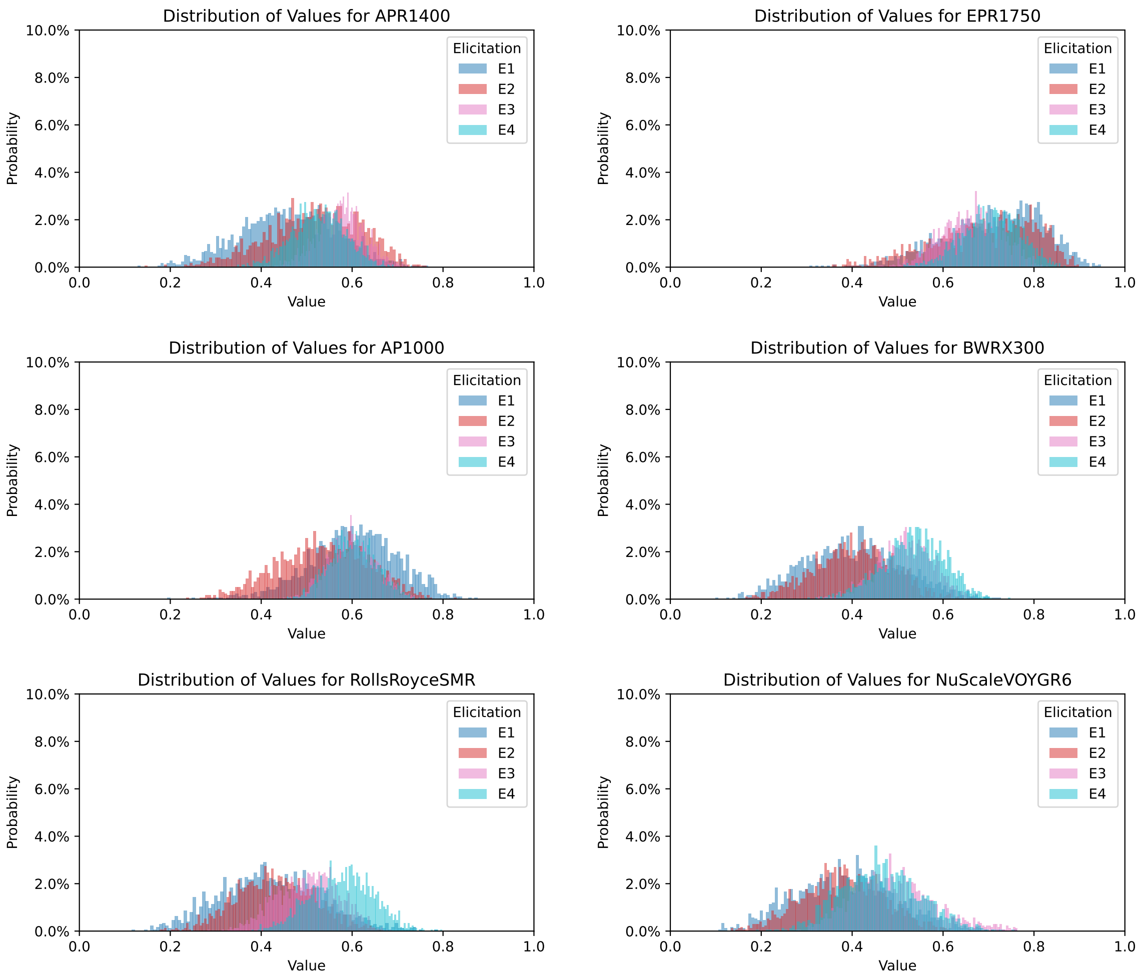


Figure 4.5: S-MC results for France using weighted sum aggregation.

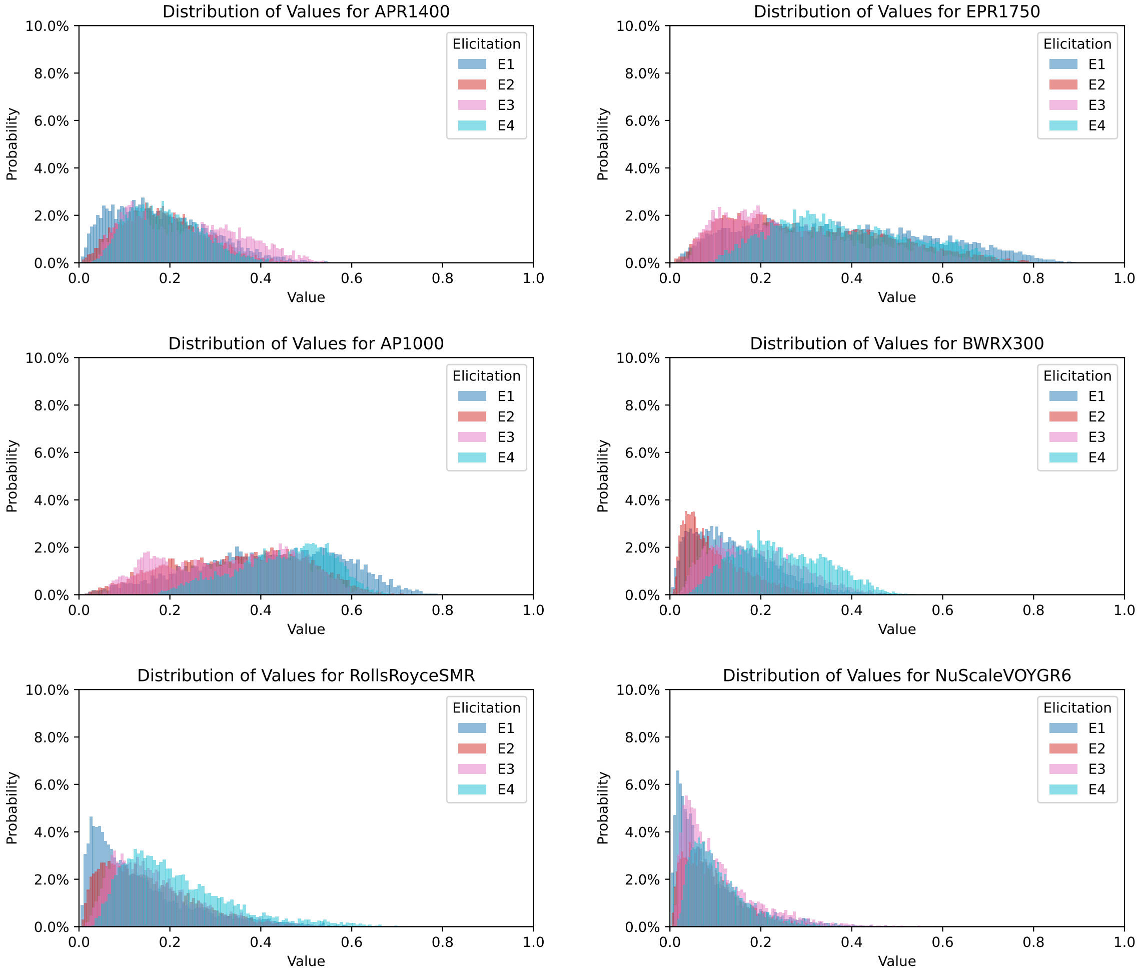
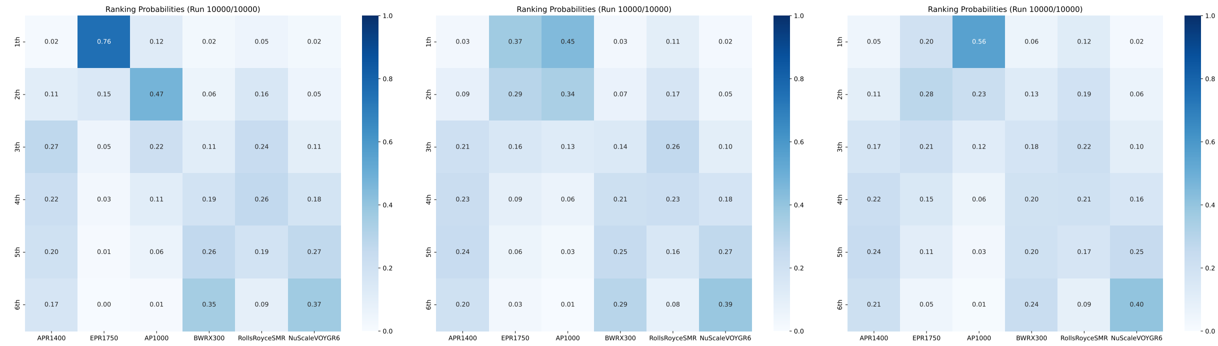


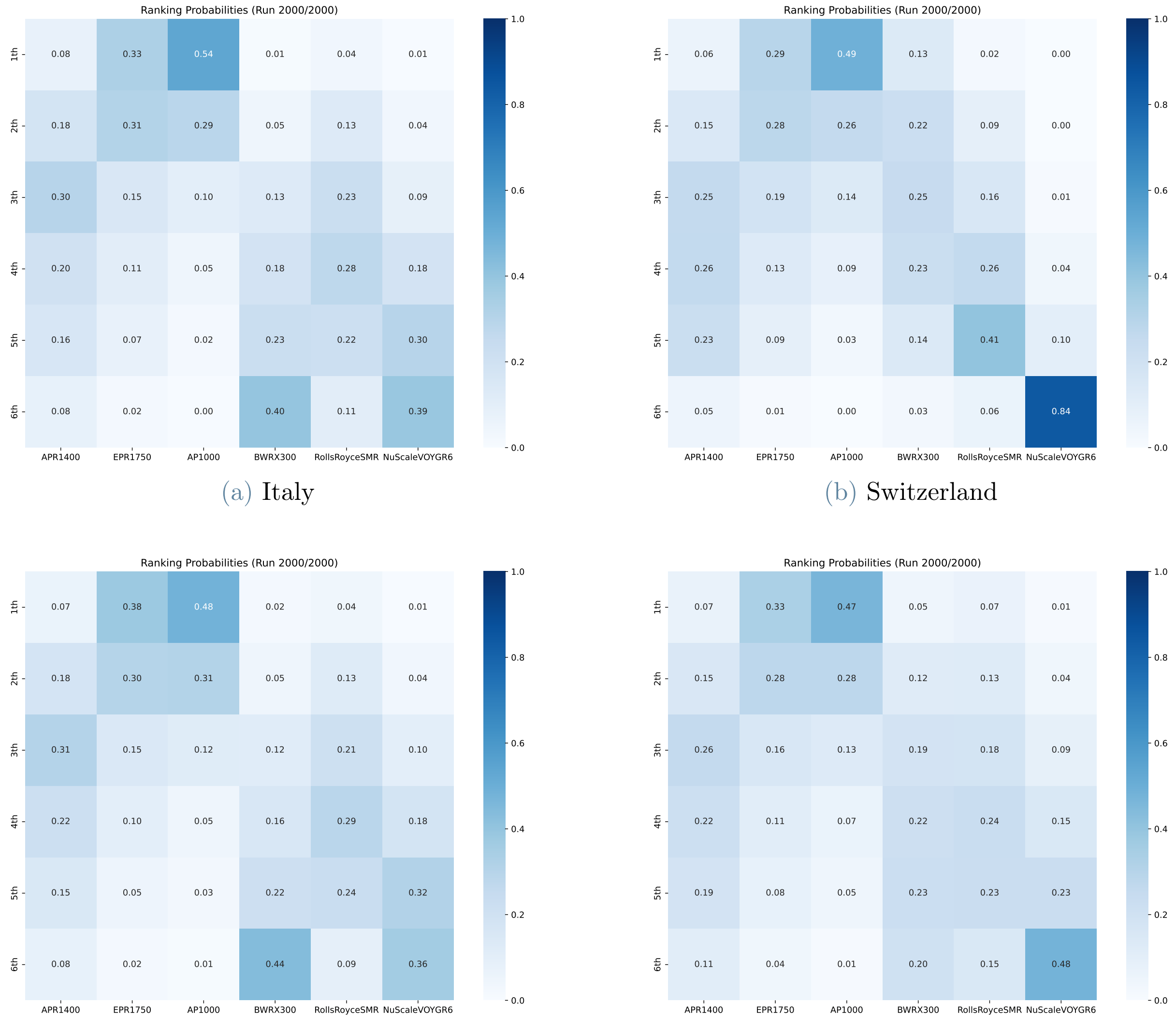
Figure 4.6: S-MC results for France using geometric mean aggregation, showing broader distributions.

on the vertical axis, with cell colours representing the probability of achieving that rank (darker colours indicate higher probability). Figures 4.7 present the results for Italy applying the three aggregation methods (weighted sum, geometric mean, and harmonic mean shown in panels a, b, and c respectively) to random weight simulations, which highlights the differences arising from aggregation methods. Figures 4.8 present the NS-MC results using geometric mean aggregation for Italy, Switzerland, Poland, and France.



(a) sum (b) geo (c) har

Figure 4.7: NSMC ranking heatmaps for Italy under random weight sampling across aggregation methods, demonstrating persistent large reactor dominance. Columns represent alternatives, rows denote ranking tiers, and cells coloured in darker shades indicate higher probabilities of an alternative achieving a given rank.



(a) Italy

(b) Switzerland

(c) Poland

(d) France

Figure 4.8: NS-MC ranking heatmaps with geometric mean aggregation for Italy, Switzerland, Poland, and France.

4.2. Discussion

In this section the results presented in Section 4.1 are discussed and interpreted. Methodological implications are also examined, highlighting strengths and limitations of the applied UP-MAVT framework in this context.

4.2.1. Dominance Patterns and Compensatory Analysis

This analysis employs NS-MC with random weight sampled from a Dirichlet distribution to achieve two complementary objectives: identifying persistent dominance patterns across weight spaces and evaluating how different aggregation methodologies affect ranking outcomes.

Dominance Patterns

A dominance pattern is observed when alternatives maintain consistent rankings across varying weight assignments. Such behaviour requires the analyst to conduct a careful analysis. While such patterns may genuinely reflect superior performance of some alternatives over the others, they can also reveal latent indicator biases. For example, in this study, there is a clear preference towards large reactors as seen from Figures 4.7–4.8.

This is partially a consequence of the criterion "Net Power Output" criterion, which was expected to favour SMRs in context like Switzerland, but instead consistently advantaged large reactors. Contrary to initial assumptions, all experts preferred large-scale solutions, arguing that nuclear power's primary value lies in its role as a stable, large-scale baseload source for national energy strategies, even at the expense of flexibility or grid adequacy.

Critically, the value function elicitation for this indicator explicitly directed experts to evaluate performance in the context of the country's 2024 grid adequacy and flexibility needs, rather than absolute terms. To ground their judgments in real-world constraints, they were provided with detailed data on national electricity demand (average, distribution, and variation) cross-border exchange dynamics, and share of renewable generation.

Multiple experts suggested that SMRs will be successful in future applications within the private sector (industrial process heat or remote energy systems) rather than central grid integration. It is therefore safe to conclude that the observed dominance of large reactors is a genuine reflection of expert judgments and not an artefact of indicator bias.

Aggregation Methods

Table 4.3 presents the modal rankings for each reactor alternative across the three aggregation approaches in the case of Italy. The EPR and AP-1000 exhibit sensitive ranking to the aggregation method: the EPR secures first position under fully compensatory sum aggregation but drops to second under both partially compensatory methods, in favour of the AP-1000. The APR-1400 maintains remarkable stability at third position regardless of aggregation method, while the Rolls-Royce SMR fluctuates between third and fourth places. Both smaller SMRs (BWR and NuScale) consistently occupy the lowest ranks (5th–6th), with minor positional exchange between methods.

Table 4.3: Modal rankings for reactor alternatives under different aggregation methods (Italy, random weight sampling, 10000 iterations).

Alternative	Weighted Sum	Geometric Mean	Harmonic Mean
EPR	1	2	2
AP-1000	2	1	1
APR-1400	3	3	3
Rolls-Royce SMR	4	3	4
BWRX-300	6	5	6
NuScale	5	6	5

Under fully compensatory aggregation, the EPR's strong technical performance (e.g., efficiency, discharge burnup) offsets its poor scores in critical, heavily weighted criteria such as capital cost and construction complexity. However, this approach risks overestimating the EPR's overall advantage by allowing multiple lower-priority attributes to compensate for failures in high-priority ones. Partially compensatory methods, namely geo and har, address this by prioritizing highly valued indicators, aligning more closely with expert opinions from interviews. Because geo also minimizes dominance effects in the rankings, the final discussion centres on its results.

4.2.2. Weight Elicitation and Consistency Analysis

The elicitation process revealed significant variability in the quality of expert weight assessments. While ordinal consistency was ensured within each comparison group, the overall results exhibited intra-group inconsistencies that resulted in unsatisfactory weight spaces for some experts. Of the four experts who performed the complete elicitation, only one (E4, already familiar with MCDA) produced satisfactory and internally consistent weight spaces. Regardless, the author notes that potential weaknesses in the mathematical formulation of the problem may have contributed to these issues, and acknowledges that for the scope of this thesis, all weight elicitation results are worth using.

Expert E1 participated in the "first elicitation" that established baseline value functions for subsequent evaluations (steps 1 and 2), but demonstrated the lowest consistency in weight elicitation (step 3).

Weight space representations use horizontal bar plots, displaying allowable weight values on the x-axis and criteria on the y-axis. Expert E4's results (Figure 4.3) exemplify acceptable consistency: clear weight ranges with evident criteria importance ordering and limited span. In contrast, other experts produced substantially wider ranges, with highly uncertain criterion ordering that does not reflect expected human preference patterns.

Consistency plots (Figure 4.4) compare declared pairwise comparison ratios (the a value, computed as $1/vf(x)$) with ratios derived from optimized weights. The optimized weight ratios are presented as mean values sampled from the feasible solution space, with error bars ($\pm\sigma$) quantifying solution variability. Consistency is demonstrated when the declared value falls within the computed weight ratio range. Expert E4 shows generally good consistency across criteria. Other experts exhibit larger discrepancies, with wider error bars indicating larger weight solution spaces and poor alignment between preferences declared during elicitation and the computed optimal weights.

4.2.3. Consensus and Uncertainty Analysis via SMC

The S-MC procedure examines expert consensus on alternative values before aggregation, revealing both consensus levels and individual expert variation. Figure 4.5 presents probability histograms for each alternative under weighted sum aggregation for France (based on 10000 iterations per expert).

Clear expert agreement is evident: all distributions occupy similar value ranges with comparable shapes. Notable individual variations exist, as expected: Expert E4 values the Rolls-Royce design higher than other experts; Experts E4 and E3 assign higher values to the BWRX-300. Expert E1 slightly favours the AP-1000 while undervaluing the APR-1400 relative to other experts. Overall consensus on alternative values remains very high, with maximum diversity appearing for the BWRX-300 design (exhibiting two distinct probability peaks) and the Rolls-Royce design (where one expert clearly favours it).

Under geometric mean aggregation (Figure 4.6), distributions appear substantially more spread, explaining reduced dominance patterns in this method. The NuScale design exhibits a well-defined low-value peak with a long tail toward higher values; similar (though less pronounced) distributions appear for Rolls-Royce, BWRX-300, and APR-1400 alternatives. Conversely, AP-1000 and EPR designs show wider, flatter distributions.

This pattern suggests a practical interpretation: non-top alternatives exhibit well-defined (unfavourable) values that can be confidently discarded from consideration, whereas top alternatives present riskier profiles in which the decision-maker must accept greater uncertainty. The AP-1000 emerges as the lowest-risk choice, being the only top alternative without increasing probability toward lower values, though its potential best-case value (~ 0.75) remains below the EPR's possibilities (~ 0.85).

4.2.4. Policy Implications

In the following paragraphs, we present broader considerations derived from the analysis of the NS-MC results using geometric mean aggregation (Figures 4.8), which are considered most representative of expert judgments. These insights aim to inform policymakers on strategic directions for nuclear energy deployment in Western Europe.

Most Important Criteria

“Capital investment costs”, “supplier availability” and complexity indicators emerged as universally critical criteria among all but one expert, while “load-following capabilities” was mostly dismissed as irrelevant for nuclear applications. Social acceptance factors revealed significant polarization: some experts considered "GHG reduction" and "nuclear waste produced" to be insufficient to sway public opinion, while others viewed these as fundamental to gaining societal approval. "Economic benefits to electricity markets" represented the sole universally acknowledged public concern.

Technical parameters, particularly thermal efficiency and discharge burnup, were consistently deemed irrelevant from a policy perspective. On the other hand, construction complexity and design complexity received high weights in the analysis. For this reason, it is suggested that future studies explore possible ways to quantify their assessments instead of relying on qualitative expert judgment.

Technology Preferences and Regional Patterns

Contrary to initial hypotheses, experts across all countries demonstrated strong, uniform preference for established large reactor designs. This consensus extends even to Switzerland, where smaller designs were expected to gain traction. SMRs consistently ranked lowest, with experts citing lack of demonstration as the primary limitation for current deployment considerations.

Among large reactor options, the APR-1400 design received the least favour due to perceived deployment challenges in European contexts. Expert interviews revealed multifaceted concerns including:

- Political barriers to Korean-designed reactors
- Licensing difficulties arising from divergent safety standards
- Supply chain integration challenges

This pattern underscores how real-world feasibility considerations fundamentally shape technical preferences in expert judgments.

Subtle national variations emerge in the lower rankings: Italy and Poland both favour the Rolls-Royce SMR, while France and Switzerland demonstrate a preference for the BWRX-300 design. Particularly notable is the case of Switzerland, where the BWRX-300 shares third position with the APR-1400 design. These country-specific differences remain confined to secondary alternatives and exhibit limited magnitude, suggesting consistent preferences across Western European contexts.

System-Level Considerations and Strategic Recommendations

While it is clear that large reactors dominate national energy strategies across Western Europe, their dominance introduces long-term grid stability risks. The 2025 Spanish blackout, caused by insufficient flexible capacity in a system with increasing renewable penetration, highlights this vulnerability [138]. Yet NPPs struggle with load-following, and even when feasible, reducing capacity factors incurs economic penalties. To prevent exaggeration of these risks, policymakers should adopt a pan-European perspective when planning nuclear capacity expansions, prioritizing:

- Grid flexibility and resilience metrics that take into account cross-border interdependencies
- Balanced deployment strategies that account for interconnection capabilities
- Stability assessments that transcend national boundaries

The current trajectory toward large-reactor fleets may undermine continental energy security if flexibility requirements are overlooked in the transition to high-renewable systems.

5 | Conclusions

This thesis developed and applied the UP-MAVT framework to evaluate nuclear reactor deployment strategies in France, Italy, Poland, and Switzerland. The work addresses the challenge of strategic energy decision-making under deep uncertainty by explicitly accounting for both preference subjectivity and data uncertainty.

5.1. Methodological Contribution

The primary contribution is the UP-MAVT framework, which systematically propagates uncertainty through the entire decision analysis pipeline. It combines uncertain input data, qualitative indicators derived from expert judgment, uncertain weights elicited via the PILE-BWT method, and uncertain value functions, all processed through stochastic Monte Carlo procedures to propagate uncertainty and extract probabilistic rankings. The thesis also introduces a robustness analysis procedure to examine the influence of aggregation methods, the presence of dominant alternatives, and the degree of consensus among experts.

5.2. Case Study Findings

The analysis yielded a robust yet counterintuitive finding: large reactor designs consistently outperformed SMRs in all four countries and across expert assessments. Their dominance is consequence of advantages in licensing, supplier availability, and an overall preference towards proven designs over emerging alternatives. Expert interviews revealed that SMRs face deployment challenges not due to technical limitations but primarily because of their lack of operational demonstration. For this case study, experts unanimously agreed that large-capacity reactors were better suited to the context of national deployment plans in the near future. On the other hand, some also suggested that in the future, SMRs might find more appropriate applications in private-sector niches, such as industrial process heat or remote energy systems, rather than central grid integration.

Among large reactor options, Western designs like the EPR and AP-1000 were consistently preferred, while the APR-1400 encountered perceived deployment challenges in European markets despite its strong technical performance. The study also found that partially compensatory aggregation methods, such as the geometric and harmonic mean, aligned more closely with expert preferences than fully compensatory approaches like the weighted sum.

5.3. Software Tools

A significant practical outcome of this thesis is the development of open-source tools to support the UP-MAVT framework. The elicitation interfaces for value functions, qualitative indicators and weights, provide intuitive graphical support that reduce elicitation time and improve data quality. These, alongside the complete UP-MAVT analysis codebase, are being prepared for public release to facilitate wider adoption of the uncertainty propagation method.

5.4. Limitations and Future Research

Case Study Limitations The analysis employed a simplified approach by relying on current data to quantify some indicators. Future work could enhance its scope by incorporating forecasted trajectories for emissions, costs, electricity prices, and demand, better capturing the dynamic nature of energy systems. Additionally, site-specific analyses would benefit from expanded indicators, including landscape impact, grid integration requirements, demand proximity, local employment potential, and water system impacts. At the national level, introducing import-reduction objectives would allow direct comparisons of deployment configurations, such as evaluating a single large reactor against multiple SMRs providing equivalent capacity.

Elicitation Process Refinements The most impactful improvement to the elicitation process would be the development of interactive software to enable remote, self-paced expert participation. This would reduce the need for analyst supervision while expanding the expert panel capacity, ultimately strengthening result robustness through broader specialist engagement.

A key challenge observed was the sensitivity of the PILE-BWT method to expert judgment inconsistencies. Despite efforts, even minor inconsistencies led to unreasonably wide weight spaces, requiring manual adjustments in some instances. Future work should prioritize formal consistency-based weighting mechanisms to weight expert inputs, and enhanced numerical stability in the problem formulation.

UP-MAVT Enhancements The most valuable future enhancement would be the implementation of comprehensive uncertainty tracking, which would document the origins of uncertainty, trace its propagation pathways, and quantify its magnitude. This would enable targeted uncertainty mitigation and improve the transparency of the results. Further research should also explore extending uncertainty propagation techniques to other MCDA frameworks, including outranking methods and fuzzy approaches, to broaden the applicability of the methodology.

Bibliography

[1] N. Schuwirth, P. Reichert, and J. Lienert. “Methodological aspects of multi-criteria decision analysis for policy support: A case study on pharmaceutical removal from hospital wastewater”. In: *European Journal of Operational Research* 220.2 (2012), pp. 472–483. ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2012.01.055. URL: https://www.sciencedirect.com/science/article/pii/S0377221712000938.

[2] James Chadwick. “The Existence of a Neutron”. In: *Proceedings of the Royal Society of London Series A* 136 (1932), pp. 692–708. DOI: 10.1098/rspa.1932.0112. URL: https://doi.org/10.1098/rspa.1932.0112.

[3] Otto Hahn and Fritz Strassmann. “Nachweis der Entstehung aktiver Bariumisotope aus Uran und Thorium durch Neutronenbestrahlung; Nachweis weiterer aktiver Bruchstücke bei der Uranspaltung”. In: *Naturwissenschaften* 27.6 (Feb. 1939), pp. 89–95. ISSN: 1432-1904. DOI: 10.1007/BF01488988. URL: https://doi.org/10.1007/BF01488988.

[4] Dwight D. Eisenhower. *Atoms for Peace: Address to the General Assembly of the United Nations*. Speech. Accessed: 2025-09-30. New York, NY, Dec. 1953. URL: https://www.eisenhowerlibrary.gov/research/online-documents/atoms-peace.

[5] U.S. Department of Energy. *First Four Nuclear-Lit Bulbs*. Photograph. Accessed: 2025-10-16; Public domain. 1951. URL: https://commons.wikimedia.org/wiki/File:First_four_nuclear_lit_bulbs.jpeg.

[6] Nuclear Decommissioning Authority (NDA). *Calder Hall, Sellafield*. Photograph. Accessed: 2025-10-16; Licensed under the Open Government Licence v3.0. 2019. URL: https://nda.blog.gov.uk/wp-content/uploads/sites/165/2019/09/Calder-Request-002.jpg.

[7] International Atomic Energy Agency (IAEA). *Power Reactor Information System (PRIS) Database*. Accessed: 2025-09-30. International Atomic Energy Agency, 2025. URL: https://pris.iaea.org/PRIS/home.aspx.

[8] EnergyEncyclopedia.com. *Images of Steam Generators for PWR and VVER*. Image. Accessed: 2025-10-16; Free Download section; Used under license for non-commercial educational purposes. 2025. URL: https://www.energyencyclopedia.com/en/free-downloads/search?q=steam+generator.

[9] FundingUniverse. *Électricité de France History*. Accessed: 2025-09-30. FundingUniverse, 2025. URL: https://www.fundinguniverse.com/company-histories/electricit%C3%A9-de-france-history/.

[10] Ministero dell'Interno (Italy). *Risultati del Referendum - 8 Novembre 1987*. Election Data. Accessed: 2025-09-30. Ministero dell'Interno, 1987. URL: https://elezionistorico.interno.gov.it/index.php?tpel=F&dtel=08/11/1987&tpa=I&tpe=A&lev0=0&levsut0=0&es0=S&ms=S.

[11] World Nuclear Association. *Nuclear Power in the World Today*. Web Page. Accessed: 2025-10-16; Information used: Number of reactors Planned. 2025. URL: https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.

[12] World Nuclear Association. *Advanced Nuclear Power Reactors*. Web Page. Accessed: 2025-10-16; Last updated: 2021-04-01. 2021. URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/advanced-nuclear-power-reactors.

[13] Ministero dell'Interno (Italy). *Risultati del Referendum - 12 Giugno 2011*. Election Data. Accessed: 2025-09-30. Ministero dell'Interno, 2011. URL: https://elezionistorico.interno.gov.it/index.php?tpel=F&dtel=12/06/2011&es0=S&tpa=Y&lev0=0&levsut0=0&ms=S&tpe=A.

[14] NEA. *Unlocking Reductions in the Construction Costs of Nuclear*. Accessed: 2025-09-10. Paris, 2020. URL: https://www.oecd-nea.org/jcms/pl_30653/unlocking-reductions-in-the-construction-costs-of-nuclear.

[15] Bent Flyvbjerg. "What you Should Know about Megaprojects and Why: An Overview". In: *Project Management Journal* 45.2 (2014), pp. 6–19. DOI: 10.1002/pmj.21409. URL: https://doi.org/10.1002/pmj.21409.

[16] Naomi J. Brookes and Giorgio Locatelli. "Power plants as megaprojects: Using empirics to shape policy, planning, and construction management". In: *Utilities Policy* 36 (2015), pp. 57–66. ISSN: 0957-1787. DOI: https://doi.org/10.1016/j.jup.2015.09.005. URL: https://www.sciencedirect.com/science/article/pii/S0957178715300217.

[17] U.S. Department of Energy, Nuclear Energy Research Advisory Committee. *Diagrams of Generation IV Reactors*. Image. Retrieved from wikimedia commons.

2002. URL: https://web.archive.org/web/20130120130033/http://www.ne.doe.gov/genIV/documents/gen_iv_roadmap.pdf.

[18] Jarosław Brodny and Magdalena Tutak. "Assessing the energy security of European Union countries from two perspectives – A new integrated approach based on MCDM methods". In: *Applied Energy* 347 (2023), p. 121443. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2023.121443. URL: https://www.sciencedirect.com/science/article/pii/S0306261923008073.

[19] Julianna Sterling, Missaka Warusawitharana, and Xiangyu Zhang. "European Energy Import Dependency". In: *FEDS Notes* (Apr. 2025). DOI: 10.17016/2380-7172.3768. URL: https://doi.org/10.17016/2380-7172.3768.

[20] Lasse Boehm and Alex Wilson. *EU energy security and the war in Ukraine: From sprint to marathon*. Briefing. Accessed: 2025-10-15. Feb. 2023. URL: https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/739362/EPRS_BRI(2023)739362_EN.pdf.

[21] European Commission. *2050 long-term strategy*. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en. Accessed: 2025-10-01. 2024. URL: https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

[22] European Commission. *Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives*. Accessed: 2025-10-01. European Union, 2025. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02021R2139-20250108.

[23] European Commission. *Declaration for the European Industrial Alliance on SMRs*. Declaration. Accessed: 2025-10-29. Feb. 2024. URL: https://research-and-innovation.ec.europa.eu/system/files/2023-04/ec_rtd_eu-smr-declaration-2030.pdf.

[24] Anthony E. Boardman et al. *Cost-Benefit Analysis: Concepts and Practice*. 5th ed. Cambridge University Press, 2018.

[25] Karmila Seran, James Rotimi, and An Le. "Decision making support tool for renewable energy prioritization to achieve sustainable development goals (SDGs): Conceptual framework". In: *Energy & Environmental Sustainability* 1.4 (2025), p. 100044. ISSN: 3050-7456. DOI: https://doi.org/10.1016/j.eesus.2025.

100044. URL: https://www.sciencedirect.com/science/article/pii/S3050745625000434.

[26] Bernard Roy. "Decision-aid and decision-making". In: *European Journal of Operational Research* 45.2 (1990). OR for Engineers Expert Systems and Decision-Aid, pp. 324–331. ISSN: 0377-2217. DOI: https://doi.org/10.1016/0377-2217(90)90196-I. URL: https://www.sciencedirect.com/science/article/pii/037722179090196I.

[27] Murat Köksalan, Jyrki Wallenius, and Stanley Zionts. "An Early History of Multiple Criteria Decision Making". In: *Multiple Criteria Decision Analysis: State of the Art Surveys*. Ed. by Salvatore Greco, Matthias Ehrgott, and José Rui Figueira. New York, NY: Springer New York, 2016, pp. 3–17. ISBN: 978-1-4939-3094-4. DOI: 10.1007/978-1-4939-3094-4_1. URL: https://doi.org/10.1007/978-1-4939-3094-4_1.

[28] Marco Cinelli et al. "How to support the application of multiple criteria decision analysis? Let us start with a comprehensive taxonomy". In: *Omega* 96 (2020), p. 102261. ISSN: 0305-0483. DOI: https://doi.org/10.1016/j.omega.2020.102261. URL: https://www.sciencedirect.com/science/article/pii/S0305048319310710.

[29] Fridolin Haag, Alice H. Aubert, and Judit Lienert. "ValueDecisions, a web app to support decisions with conflicting objectives, multiple stakeholders, and uncertainty". In: *Environmental Modelling & Software* 150 (2022), p. 105361. ISSN: 1364-8152. DOI: https://doi.org/10.1016/j.envsoft.2022.105361. URL: https://www.sciencedirect.com/science/article/pii/S1364815222000676.

[30] Salvatore Greco, Matthias Ehrgott, and José Rui Figueira, eds. *Multiple Criteria Decision Analysis: State of the Art Surveys*. 2nd ed. International Series in Operations Research & Management Science. New York, NY: Springer, 2016, pp. XXXIII, 1347. ISBN: 978-1-4939-3093-7. DOI: 10.1007/978-1-4939-3094-4. URL: https://link.springer.com/book/10.1007/978-1-4939-3094-4.

[31] R.W. Saaty. "The analytic hierarchy process—what it is and how it is used". In: *Mathematical Modelling* 9.3 (1987), pp. 161–176. ISSN: 0270-0255. DOI: https://doi.org/10.1016/0270-0255(87)90473-8. URL: https://www.sciencedirect.com/science/article/pii/0270025587904738.

[32] Ralph L. Keeney. "Value-focused thinking: Identifying decision opportunities and creating alternatives". In: *European Journal of Operational Research* 92.3 (1996), pp. 537–549. ISSN: 0377-2217. DOI: https://doi.org/10.1016/0377-2217(96)00004-5. URL: https://www.sciencedirect.com/science/article/pii/0377221796000045.

[33] Ralph L Keeney and Howard Raiffa. *Decisions with multiple objectives: preferences and value trade-offs*. Cambridge university press, 1993.

[34] Bernard Roy. "The outranking approach and the foundations of electre methods". In: *Theory and Decision* 31.1 (1991), pp. 49–73. DOI: 10.1007/BF00134132. URL: https://www.scopus.com/inward/record.uri?eid=2-s2.0-0003099335&doi=10.1007%2fBF00134132&partnerID=40&md5=ff276e0044e6ef27bf975653cbb27046.

[35] Jean-Pierre Brans and Philippe Vincke. "A Preference Ranking Organisation Method". In: *Management Science* 31.6 (1985), pp. 647–656. DOI: 10.1287/mnsc.31.6.647. URL: https://doi.org/10.1287/mnsc.31.6.647.

[36] River Huang et al. "The Multi-Level Cards method: Weights elicitation, consistency checking and restoration for hierarchical criteria". In: *Omega* 138 (2026), p. 103438. ISSN: 0305-0483. DOI: https://doi.org/10.1016/j.omega.2025.103438. URL: https://www.sciencedirect.com/science/article/pii/S0305048325001641.

[37] Mohammed M. Damoom et al. "Potential areas for nuclear power plants siting in Saudi Arabia: GIS-based multi-criteria decision making analysis". In: *Progress in Nuclear Energy* 110 (2019), pp. 110–120. ISSN: 0149-1970. DOI: https://doi.org/10.1016/j.pnucene.2018.09.018. URL: https://www.sciencedirect.com/science/article/pii/S0149197018302464.

[38] Murat Başeğmez. "Strategic multi-criteria framework for nuclear plant siting: Integrating AHP, EWM, and Game Theory with GIS". In: *Progress in Nuclear Energy* 188 (2025), p. 105897. ISSN: 0149-1970. DOI: https://doi.org/10.1016/j.pnucene.2025.105897. URL: https://www.sciencedirect.com/science/article/pii/S0149197025002951.

[39] Ade Gafar Abdullah et al. "The social factors considered in site selection for nuclear power plants: A case study of Borneo Island, Indonesia". In: *Progress in Nuclear Energy* 180 (2025), p. 105626. ISSN: 0149-1970. DOI: https://doi.org/10.1016/j.pnucene.2025.105626. URL: https://www.sciencedirect.com/science/article/pii/S0149197025000241.

[40] Aravind Devanand, Markus Kraft, and Iftekhar A Karimi. "Optimal site selection for modular nuclear power plants". In: *Computers and Chemical Engineering* 125 (2019), pp. 339–350. ISSN: 0098-1354. DOI: https://doi.org/10.1016/j.compchemeng.2019.03.024. URL: https://www.sciencedirect.com/science/article/pii/S0098135419300997.

[41] Lauren Kiser and Luis Daniel Otero. "Multi-criteria decision model for selection of nuclear power plant type". In: *Progress in Nuclear Energy* 159 (2023), p. 104647. ISSN: 0149-1970. DOI: https://doi.org/10.1016/j.pnucene.2023.104647. URL: https://www.sciencedirect.com/science/article/pii/S0149197023000823.

[42] Giorgio Locatelli and Mauro Mancini. “A framework for the selection of the right nuclear power plant”. In: *International Journal of Production Research* 50.17 (2012), pp. 4753–4766. DOI: 10.1080/00207543.2012.657965. URL: https://international.anl.gov/training/materials/BL/Literature/Giorgio%20Locatelli%20Papers/A%20framework%20for%20the%20selection%20of%20the%20right%20nuclear%20power%20plant.pdf.

[43] S.A. Birikorang et al. “Choosing the right reactor technology: A key step to strengthen nuclear security in West Africa’s nuclear energy plans”. In: *Annals of Nuclear Energy* 226 (2026), p. 111837. ISSN: 0306-4549. DOI: https://doi.org/10.1016/j.anucene.2025.111837. URL: https://www.sciencedirect.com/science/article/pii/S0306454925006541.

[44] International Atomic Energy Agency (IAEA). *Application of Multi-criteria Decision Analysis Methods to Comparative Evaluation of Nuclear Energy System Options: Final Report of the INPRO Collaborative Project KIND*. Technical Report. Accessed: 2025-09-30. International Atomic Energy Agency, 2019. URL: https://www-pub.iaea.org/MTCD/Publications/PDF/P1853_web.pdf.

[45] José Antonio Hernández-Torres et al. “Integrated multi-criteria decision-making approach for power generation technology selection in sustainable energy systems”. In: *Renewable Energy* 243 (2025), p. 122481. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2025.122481. URL: https://www.sciencedirect.com/science/article/pii/S0960148125001430.

[46] Guzay Pasaoglu, Nicolas Pardo Garcia, and Ghassan Zubi. “A multi-criteria and multi-expert decision aid approach to evaluate the future Turkish power plant portfolio”. In: *Energy Policy* 119 (2018), pp. 654–665. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2018.04.044. URL: https://www.sciencedirect.com/science/article/pii/S030142151830260X.

[47] Burcin Atilgan and Adisa Azapagic. “An integrated life cycle sustainability assessment of electricity generation in Turkey”. In: *Energy Policy* 93 (2016), pp. 168–186. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2016.02.055. URL: https://www.sciencedirect.com/science/article/pii/S030142151630091X.

[48] Edgar Santoyo-Castelazo and Adisa Azapagic. “Sustainability assessment of energy systems: integrating environmental, economic and social aspects”. In: *Journal of Cleaner Production* 80 (2014), pp. 119–138. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2014.05.061. URL: https://www.sciencedirect.com/science/article/pii/S0959652614005381.

[49] Muhammed Zulfakar Zolkaffly and Ki-In Han. “Reactor technology assessment and selection utilizing systems engineering approach”. In: *AIP Conference Proceedings*

1584.1 (Feb. 2014), pp. 22–31. ISSN: 0094-243X. DOI: 10.1063/1.4866099. eprint: https://pubs.aip.org/aip/acp/article-pdf/1584/1/22/11739325/22_1_online.pdf. URL: https://doi.org/10.1063/1.4866099.

[50] Fatih Topaloğlu. "Analytic network process (ANP) based decision support tool for nuclear power plant location and reactor type selection". In: *Nuclear Engineering and Technology* 57.3 (2025), p. 103228. ISSN: 1738-5733. DOI: https://doi.org/10.1016/j.net.2024.09.031. URL: https://www.sciencedirect.com/science/article/pii/S1738573324004777.

[51] Rahul Goushis. "Evaluating the feasibility of modular nuclear reactors in the European Union: A GIS-based multicriteria decision analysis approach to meet Paris Agreement". In: *Applied Energy* 400 (2025), p. 126565. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2025.126565. URL: https://www.sciencedirect.com/science/article/pii/S0306261925012954.

[52] Fatine Ezbakhe and Agusti Perez-Foguet. "Multi-Criteria Decision Analysis Under Uncertainty: Two Approaches to Incorporating Data Uncertainty into Water, Sanitation and Hygiene Planning". In: *Water Resources Management* 32.15 (Dec. 2018), pp. 5169–5182. DOI: 10.1007/s11269-018-2152-9. URL: https://doi.org/10.1007/s11269-018-2152-9.

[53] Bakhtiar Feizizadeh, Stefan Kienberger, and Khalil Valizadeh Kamran. "Sensitivity and uncertainty analysis approach for GIS-MCDA based economic vulnerability assessment". In: *J. Geogr. Inf. Sci* 1 (2015), pp. 81–89.

[54] Jun Zheng, Christoph Egger, and Judit Lienert. "A scenario-based MCDA framework for wastewater infrastructure planning under uncertainty". In: *Journal of environmental management* 183 (2016), pp. 895–908.

[55] Jutta Geldermann, Valentin Bertsch, and Otto Rentz. "Multi-criteria decision support and uncertainty handling, propagation and visualisation for emergency and remediation management". In: *Operations Research Proceedings 2005: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR), Bremen, September 7–9, 2005*. Springer. 2006, pp. 755–760.

[56] A Morton and B Fasolo. "Behavioural decision theory for multi-criteria decision analysis: a guided tour". In: *Journal of the Operational Research Society* 60.2 (2009), pp. 268–275. DOI: 10.1057/palgrave.jors.2602550. URL: https://doi.org/10.1057/palgrave.jors.2602550.

[57] Mika Marttunen, Valerie Belton, and Judit Lienert. "Are objectives hierarchy related biases observed in practice? A meta-analysis of environmental and energy applications of Multi-Criteria Decision Analysis". In: *European Journal of Operational Research* 265.1 (2018), pp. 178–194. ISSN: 0377-2217. DOI: https://doi.

org/10.1016/j.ejor.2017.02.038. URL: https://www.sciencedirect.com/science/article/pii/S0377221717301777.

[58] Ralph L. Keeney and Howard Raiffa. *DECISION ANALYSIS WITH MULTIPLE CONFLICTING OBJECTIVES PREFERENCES AND VALUE TRADEOFFS*. WP-75-053. Accessed: 2025-10-16. 1975, pp. 152–158. URL: https://pure.iiasa.ac.at/id/eprint/375/1/WP-75-053.pdf.

[59] Gleb Beliakov, Ana Pradera, Tomasa Calvo, et al. *Aggregation functions: A guide for practitioners*. Vol. 221. Springer, 2007.

[60] Simone D. Langhans, Peter Reichert, and Nele Schuwirth. "The method matters: A guide for indicator aggregation in ecological assessments". In: *Ecological Indicators* 45 (2014), pp. 494–507. ISSN: 1470-160X. DOI: https://doi.org/10.1016/j.ecolind.2014.05.014. URL: https://www.sciencedirect.com/science/article/pii/S1470160X14002167.

[61] He Huang and Peter Burgherr. "MCDA Calculator: A Streamlined Decision Support System for Multi-criteria Decision Analysis". In: *Decision Support Systems XIV. Human-Centric Group Decision, Negotiation and Decision Support Systems for Societal Transitions*. Vol. 506. Lecture Notes in Business Information Processing. Cham: Springer, 2024, pp. 28–42. DOI: 10.1007/978-3-031-59376-5_3.

[62] Peter Reichert et al. "The conceptual foundation of environmental decision support". In: *Journal of Environmental Management* 154 (2015), pp. 316–332. ISSN: 0301-4797. DOI: https://doi.org/10.1016/j.jenvman.2015.01.053. URL: https://www.sciencedirect.com/science/article/pii/S0301479715001140.

[63] Paul Goodwin and George Wright. *Decision Analysis for Management Judgment*. Wiley, 2004. ISBN: 978-0-470-86108-0. URL: https://books.google.ch/books?id=yxPgmAEACAAJ.

[64] Alice H. Aubert, Fabien Esculier, and Judit Lienert. "Recommendations for online elicitation of swing weights from citizens in environmental decision-making". In: *Operations Research Perspectives* 7 (2020), p. 100156. ISSN: 2214-7160. DOI: https://doi.org/10.1016/j.orp.2020.100156. URL: https://www.sciencedirect.com/science/article/pii/S2214716020300464.

[65] Jafar Rezaei. "Best-worst multi-criteria decision-making method". In: *Omega* 53 (2015), pp. 49–57. ISSN: 0305-0483. DOI: https://doi.org/10.1016/j.omega.2014.11.009. URL: https://www.sciencedirect.com/science/article/pii/S0305048314001480.

[66] Fuqi Liang, Matteo Brunelli, and Jafar Rezaei. "Best-worst Tradeoff method". In: *Information Sciences* 610 (2022), pp. 957–976. ISSN: 0020-0255. DOI: https://

doi.org/10.1016/j.ins.2022.07.097. URL: https://www.sciencedirect.com/science/article/pii/S0020025522007861.

[67] River Huang and Matteo Brunelli. *PIvot-Linked Elicitation (PILE): A Unified Approach to Hierarchical Weight Elicitation and Its Application to Best Worst Methods*. Under Review. 2026.

[68] Jafar Rezaei. "Best-worst multi-criteria decision-making method: Some properties and a linear model". In: *Omega* 64 (2016), pp. 126–130. ISSN: 0305-0483. DOI: https://doi.org/10.1016/j.omega.2015.12.001. URL: https://www.sciencedirect.com/science/article/pii/S0305048315002479.

[69] Electricity Maps. *2024 Carbon Intensity Data for Poland, Switzerland, France, and Northern Italy*. Accessed: 2025-09-30; Data version: January 27, 2025. Electricity Maps, Jan. 2025. URL: https://www.electricitymaps.com.

[70] Risto Lahdelma, Joonas Hokkanen, and Pekka Salminen. "SMAA - Stochastic multiobjective acceptability analysis". In: *European Journal of Operational Research* 106.1 (1998), pp. 137–143. ISSN: 0377-2217. DOI: https://doi.org/10.1016/S0377-2217(97)00163-X. URL: https://www.sciencedirect.com/science/article/pii/S037722179700163X.

[71] Gino Baudry, Cathy Macharis, and Thomas Vallée. "Range-based Multi-Actor Multi-Criteria Analysis: A combined method of Multi-Actor Multi-Criteria Analysis and Monte Carlo simulation to support participatory decision making under uncertainty". In: *European Journal of Operational Research* 264.1 (2018), pp. 257–269. ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2017.06.036. URL: https://www.sciencedirect.com/science/article/pii/S0377221717305775.

[72] Jana Goers and Graham Horton. "Combinatorial multi-criteria acceptability analysis: A decision analysis and consensus-building approach for cooperative groups". In: *European Journal of Operational Research* 308.1 (2023), pp. 243–254. ISSN: 0377-2217. DOI: https://doi.org/10.1016/j.ejor.2022.12.002. URL: https://www.sciencedirect.com/science/article/pii/S0377221722009316.

[73] He Huang, Shary Heuninckx, and Cathy Macharis. "20 years review of the multi actor multi criteria analysis (MAMCA) framework: a proposition of a systematic guideline". In: *Annals of Operations Research* 343.1 (Dec. 2024), pp. 313–348. ISSN: 1572-9338. DOI: 10.1007/s10479-024-06357-y. URL: https://doi.org/10.1007/s10479-024-06357-y.

[74] David Ben-Arieh, Todd Easton, and Brandon Evans. "Minimum Cost Consensus With Quadratic Cost Functions". In: *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 39.1 (2009), pp. 210–217. DOI: 10.1109/TSMCA.2008.2006373.

[75] Julien Roland, Yves De Smet, and José Rui Figueira. "Inverse multi-objective combinatorial optimization". In: *Discrete Applied Mathematics* 161.16 (2013), pp. 2764–2771. ISSN: 0166-218X. DOI: https://doi.org/10.1016/j.dam.2013.04.024. URL: https://www.sciencedirect.com/science/article/pii/S0166218X13002266.

[76] He Huang et al. "Collaborative decision-making in sustainable mobility: identifying possible consensuses in the multi-actor multi-criteria analysis based on inverse mixed-integer linear optimization". In: *International Journal of Sustainable Development & World Ecology* 28.1 (2021), pp. 64–74. DOI: 10.1080/13504509.2020.1795005. URL: https://doi.org/10.1080/13504509.2020.1795005.

[77] European Network of Transmission System Operators for Electricity (ENTSO-E). *Transparency Platform.* Accessed: 2025-09-30. ENTSO-E, 2025. URL: https://transparency.entsoe.eu/.

[78] *Costituzione della Repubblica Italiana.* Constitutional Article. Art. 75. Dec. 27, 1947.

[79] Il Sole 24 Ore. "Sustainable Nuclear Comes into Law: Here Is the Government Strategy in Ten Questions and Answers". In: (2024). Accessed: 2025-09-30. URL: https://en.ilsole24ore.com/art/sustainable-nuclear-comes-law-here-is-government-strategy-ten-questions-and-answers-AGvZZsDD.

[80] Terna S.p.A. *Fabbisogno di Energia Elettrica in Italia.* Data. Accessed: 2025-10-16, Aggregate Energy Requirment by Bidding Zone. 2024. URL: https://dati.terna.it/fabbisogno#fabbisogno-italia.

[81] ISTAT (Istituto Nazionale di Statistica). *Popolazione Residente per Età, Sesso e Stato Civile al 1° Gennaio 2024.* Data Set. Accessed: 2025-10-16, Total Population by Region. 2024. URL: https://demo.istat.it/app/?l=it&a=2024&i=POS.

[82] NucNet. "Poland Survey". In: (Dec. 2024). Accessed: 2025-09-30. URL: https://www.nucnet.org/news/more-than-92-support-plans-for-first-nuclear-power-plant-12-5-2024.

[83] Westinghouse Electric Company. "Poland's First Nuclear Plant Moves Forward with Westinghouse-Bechtel-PEJ Agreement". In: (2025). Accessed: 2025-09-30. URL: https://info.westinghousenuclear.com/news/polands-first-nuclear-plant-moves-forward-with-westinghouse-bechtel-pej-agreement.

[84] World Nuclear News. "Go-Ahead for Preliminary Works at Polish Plant Site". In: (Sept. 2025). Accessed: 2025-09-30. URL: https://www.world-nuclear-news.org/articles/go-ahead-for-preliminary-works-at-polish-plant-site.

[85] International Energy Agency (IEA). *Switzerland, France, Poland and Italy: Electricity Profile.* Web Page. Accessed: 2025-10-16. International Energy Agency, 2024. URL: https://www.iea.org/countries/.

[86] World Nuclear Association. *Switzerland's Nuclear Industry Profile.* Accessed: 2025-09-30. World Nuclear Association, 2025. URL: https://world-nuclear.org/information-library/country-profiles/countries-o-s/switzerland.

[87] European Nuclear Society (Euronuclear). *Opinion Poll: The Majority of the Swiss Support Nuclear Energy.* Accessed: 2025-09-30. European Nuclear Society, 2023. URL: https://www.euronuclear.org/news/opinion-poll-the-majority-of-the-swiss-support-nuclear-energy/.

[88] NucNet. "Majority Continues to Support Nuclear Energy, Says Survey". In: (Mar. 2023). Accessed: 2025-09-30. URL: https://www.nucnet.org/news/majority-continues-to-support-nuclear-energy-says-survey-3-1-2023.

[89] World Nuclear News. "Poll Finds Majority of Swiss Support Nuclear New Build". In: (2023). Accessed: 2025-09-30. URL: https://www.world-nuclear-news.org/articles/poll-finds-majority-of-swiss-support-nuclear-new-build.

[90] SWI swissinfo.ch. "Risks Remain as Switzerland Weighs a Return to Nuclear Power". In: (2025). Accessed: 2025-09-30. URL: https://www.swissinfo.ch/eng/emissions-reduction/risks-remain-as-swiss-weigh-a-return-to-nuclear-power/89549444.

[91] IFOP. *Les Français et le nucléaire : adhésion et traits d'image.* Accessed: 2025-09-30. IFOP, Sept. 2022. URL: https://www.ifop.com/article/les-francais-et-le-nucleaire-adhesion-et-traits-dimage/.

[92] *Nuclear Power Reactors in the World.* entity 2. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2024. ISBN: 978-92-0-122224-4. URL: /publications/15748/nuclear-power-reactors-in-the-world.

[93] World Nuclear News. *Westinghouse and EDF appeal against Czech nuclear tender process.* News Article. Accessed: 2025-10-16. Aug. 2024. URL: https://www.world-nuclear-news.org/Articles/Westinghouse-and-EDF-appeal-against-Czech-nuclear.

[94] World Nuclear News. *French Regulator Supports Safety Options for EPR 1200.* News Article. Accessed: 2025-10-16. Feb. 2023. URL: https://www.world-nuclear-news.org/Articles/French-regulator-supports-safety-options-for-EPR12.

[95] International Atomic Energy Agency. *Advanced Reactors Information System (ARIS).* Accessed: 2025-06-10. 2025. URL: https://aris.iaea.org/.

[96] KEPCO Engineering and Inc. Construction Company. *Reactor Descriptions.* Accessed: 2025-06-10. 2025. URL: https://www.kepco-enc.com/menu.es?mid=a20202030100.

[97] World Nuclear News. *Early works agreement for BWRX-300 SMRs in Finland and Sweden.* Accessed: 2025-06-10. 2025. URL: https://www.world-nuclear-news.org/articles/early-works-agreement-for-bwrx-300-smrs-in-finland-and-sweden.

[98] World Nuclear News. *Hungary looking at deployment of US small modular reactors.* Accessed: 2025-06-10. 2025. URL: https://www.world-nuclear-news.org/articles/hungary-looking-at-deployment-of-us-small-modular-reactors.

[99] U.S. Nuclear Regulatory Commission (NRC). *Integral Molten Salt Reactor (IMSR): Pre-Application Activities.* Web Page. Accessed: 2025-10-16; Last reviewed/updated: 2025-02-11. 2025. URL: https://www.nrc.gov/reactors/new-reactors/advanced/who-were-working-with/pre-application-activities/imsr.

[100] TerraPower. *Natrium Reactor Technology.* Accessed: 2025-06-10. 2025. URL: https://www.terrapower.com/natrium/.

[101] World Nuclear News. *EDF to modify Nuward design to aid commercialisation.* News Article. Accessed: 2025-10-16. July 2024. URL: https://www.world-nuclear-news.org/articles/edf-to-modify-nuward-design-to-aid-commercialisati.

[102] U.S. Nuclear Regulatory Commission. *Standard Review Plan for Environmental Reviews for Nuclear Power Plants.* Technical Report. Accessed: 2025-09-30. U.S. Nuclear Regulatory Commission, 2017. URL: https://www.nrc.gov/docs/ML1700/ML17007A001.pdf.

[103] U.S. Nuclear Regulatory Commission. *Safety Evaluation by the Office of Nuclear Reactor Regulation: NuScale Power Module.* ML23161A411. Accessed: 2025-09-30. U.S. Nuclear Regulatory Commission, June 2011. URL: https://www.nrc.gov/docs/ML1117/ML11171A411.pdf.

[104] U.S. Nuclear Regulatory Commission (NRC). *NRC Approves Standard Design for NuScale US460 Small Modular Reactor.* News Release. Accessed: 2025-10-16. May 2025. URL: https://www.nrc.gov/cdn/doc-collection-news/2025/25-033.pdf.

[105] Gevernova. *Sodium Fast Reactors: A Key Technology for Carbon-Free Power.* Web Page. Accessed: 2025-10-16. 2025. URL: https://www.gevernova.com/nuclear/carbon-free-power/sodium-fast-reactors.

[106] Rolls-Royce SMR. *Generic Design Assessment (GDA) Public Consultation: Have Your Say*. Accessed: 2025-09-30. Rolls-Royce SMR, 2025. URL: https://gda.rolls-royce-smr.com/have-your-say.

[107] Power Technology. "Rolls Royce plans first UK modular nuclear reactor for 2029". In: *Power Technology* (Apr. 2022). Accessed: 2025-10-01. URL: https://www.power-technology.com/news/uk-first-smr-rolls-royce/.

[108] World Nuclear News. *South Korean SMR design approved by regulator*. Accessed: 2025-06-10. Sept. 26, 2024. URL: https://www.world-nuclear-news.org/articles/south-korean-smr-design-approved-by-regulator.

[109] U.S. Nuclear Regulatory Commission. *Design Description*. Technical Report. Accessed: 2025-09-30. U.S. Nuclear Regulatory Commission, 2005. URL: https://www.nrc.gov/docs/ML0522/ML052280170.pdf.

[110] General Electric (GE). *GE 9HA Gas Turbine: Technical Overview and Performance Specifications*. Technical Brochure. Accessed: 2025-10-16. 2015. URL: https://f.machineryhost.com/1c549272d486597e78d102330c36981e/USPE%20GE%209HA%20Gas%20Turbine.pdf.

[111] OECD Nuclear Energy Agency (NEA). *Technical and Economic Aspects of Load Following with Nuclear Power Plants*. Technical Report. Accessed: 2025-09-30. OECD Nuclear Energy Agency, June 2011. URL: https://www.oecd-nea.org/upload/docs/application/pdf/2021-12/technical_and_economic_aspects_of_load_following_with_nuclear_power_plants.pdf.

[112] ENCO. *Analysis of Small Modular Reactor (SMR) Concepts*. Technical Report. Accessed: 2025-09-30. Federal Ministry of Labour and Economy (BMLUK), Austria, 2022. URL: https://www.bmluk.gv.at/dam/jcr:26805e08-47f2-402e-8121-921e1f121144/Analysis_of_SMR_Concepts.pdf.

[113] NEA. *The NEA Small Modular Reactor Dashboard: Third Edition*. Paris: OECD Publishing, 2025.

[114] U.S. Energy Information Administration (EIA). *Capital Cost and Performance Characteristics for Utility Scale Power Generating Technologies*. Technical Report. Accessed: 2025-10-16. U.S. Energy Information Administration, Jan. 2024. URL: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2025.pdf.

[115] Anurag Gumber, Riccardo Zana, and Bjarne Steffen. "A global analysis of renewable energy project commissioning timelines". In: *Applied Energy* 358 (2024), p. 122563. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2023.122563. URL: https://www.sciencedirect.com/science/article/pii/S030626192301927X.

[116] Geoffrey Rothwell. "Projected electricity costs in international nuclear power markets". In: *Energy Policy* 164 (2022), p. 112905. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2022.112905. URL: https://www.sciencedirect.com/science/article/pii/S0301421522001306.

[117] Koroush Shirvan. *2024 Total Cost Projection of Next AP1000*. Technical Report MIT-ANP-TR-201. Massachusetts Institute of Technology, Center for Advanced Nuclear Energy Systems, July 2024. URL: https://web.mit.edu/kshirvan/www/research/ANP201%20TR%20CANES.pdf.

[118] Yonhap News Agency. "(LEAD) S. Korea wins USD18.2 bln deal to build nuclear reactors in Czech power plant". In: *Yonhap News Agency* (Apr. 2025). URL: https://en.yna.co.kr/view/AEN20250430008951320 (visited on 01/14/2026).

[119] Björn Steigerwald et al. "Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors". In: *Energy* 281 (2023), p. 128204. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2023.128204. URL: https://www.sciencedirect.com/science/article/pii/S0360544223015980.

[120] Martin Hjelmeland and Jonas Kristiansen Nøland. "Comments on "Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors" [Energy 281 (2023) 128204]". In: *Energy* 313 (2024), p. 133827. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2024.133827. URL: https://www.sciencedirect.com/science/article/pii/S0360544224036053.

[121] Muhammad Zubair and M.S. Sajna. "Techno-economic analysis of SMR integration into UAE's existing desalination infrastructure". In: *Annals of Nuclear Energy* 227 (2026), p. 111989. ISSN: 0306-4549. DOI: https://doi.org/10.1016/j.anucene.2025.111989. URL: https://www.sciencedirect.com/science/article/pii/S0306454925008060.

[122] Bojie Liu et al. "Critical review of nuclear power plant carbon emissions". In: *Frontiers in Energy Research* Volume 11 - 2023 (2023). ISSN: 2296-598X. DOI: 10.3389/fenrg.2023.1147016. URL: https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2023.1147016.

[123] H. Paillere. "Nuclear energy for a net zero world". In: (2021), [12 p.]

[124] International Atomic Energy Agency (IAEA). *Climate Change and Nuclear Power 2022*. Report. Accessed: 2025-09-30. International Atomic Energy Agency, 2022. URL: https://www.iaea.org/topics/nuclear-power-and-climate-change/climate-change-and-nuclear-power-2022.

[125] Travis S. Carless, W. Michael Griffin, and Paul S. Fischbeck. “The environmental competitiveness of small modular reactors: A life cycle study”. In: *Energy* 114 (2016), pp. 84–99. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2016.07.111. URL: https://www.sciencedirect.com/science/article/pii/S0360544216310350.

[126] Korea Hydro and Nuclear Power Co., Ltd. (KHNP). *Major Characteristics of the EU-APR Reactor*. Presentation. Accessed: 2025-09-30. Apr. 2018. URL: https://sep.com.pl/photo/files/07b%20-%20KHNP%20-%20Major%20Characteristics%20of%20EU-APR%20Reactor.pdf.

[127] AREVA NP, EDF Energy. *Sub-Chapter 15.1: Level 1 Probabilistic Safety Assessment*. Technical Report. Accessed: 2025-09-30. EDF Energy, Nov. 2012. URL: https://www.edfenergy.com/sites/default/files/sub-chapter_15.1_-_level_1_psa.pdf.

[128] Anil Markandya and Paul Wilkinson. “Electricity Generation and Health”. In: *The Lancet* 370.9591 (Sept. 2007), pp. 979–990. ISSN: 0140-6736. DOI: 10.1016/S0140-6736(07)61253-7. URL: https://doi.org/10.1016/S0140-6736(07)61253-7.

[129] Benjamin K. Sovacool et al. “Balancing safety with sustainability: assessing the risk of accidents for modern low-carbon energy systems”. In: *Journal of Cleaner Production* 112 (2016), pp. 3952–3965. ISSN: 0959-6526. DOI: https://doi.org/10.1016/j.jclepro.2015.07.059. URL: https://www.sciencedirect.com/science/article/pii/S0959652615009877.

[130] Our World in Data. *Death Rates from Energy Production per TWh*. Accessed: 2025-09-30; Data sources: Markandya & Wilkinson (2007); Sovacool et al. (2016); UNSCEAR (2008 & 2018). Our World in Data, 2025. URL: https://ourworldindata.org/grapher/death-rates-from-energy-production-per-twh.

[131] U.S. Environmental Protection Agency (EPA). *Radiation Sources and Doses*. Accessed: 2025-10-15; Data sourced from NCRP Report No. 160 (2009). U.S. Environmental Protection Agency, 2025. URL: https://www.epa.gov/radiation/radiation-sources-and-doses.

[132] National Council on Radiation Protection and Measurements (NCRP). *Ionizing Radiation Exposure of the Population of the United States*. Report 160. Paywalled; Data accessed via U.S. EPA summary. National Council on Radiation Protection and Measurements, 2009. URL: https://ncrponline.org/publications/reports/ncrp-report-160-2/.

[133] IPSOS. *Gli italiani e l’energia: Forum QualEnergia 2024*. Survey Report. Accessed: 2025-09-30. Legambiente, 2024. URL: https://www.legambiente.it/wp-content/uploads/2024/11/Forum-QualEnergia-sondaggio-ipsos-2024.pdf.

[134] SWG S.p.A. *Nucleare italiano per i cittadini, le imprese e il territorio*. Survey Report. Accessed: 2025-09-30. iWeek, 2024. URL: https://primapavia.it/media/2024/04/Nucleare-italiano-per-i-cittadini-le-imprese-e-il-territorio-2024-04-15.pdf.

[135] GE Vernova. *Nuclear Energy Solutions*. Accessed: 2025-09-30. GE Vernova, 2025. URL: https://www.gevernova.com/nuclear.

[136] Rainer Storn and Kenneth Price. "Differential Evolution: A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces". In: *Journal of Global Optimization* 11.4 (Dec. 1997), pp. 341–359. ISSN: 1573-2916. DOI: 10.1023/A:1008202821328. URL: https://doi.org/10.1023/A:1008202821328.

[137] SciPy developers. *SciPy Documentation: Optimize Differential Evolution*. Accessed: 2026-02-02. SciPy. 2026. URL: https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.differential_evolution.html.

[138] ENTSO-E ICS Investigation Expert Panel. *Grid Incident in Spain and Portugal on 28 April 2025: Factual Report*. Factual Report. Accessed: February 2, 2026. ENTSO-E, Oct. 2025. URL: https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/.

[139] M. Arslan et al. "MOX recycling in GEN 3 + EPR Reactor homogeneous and stable full MOX core". In: American Nuclear Society, 555 North Kensington Avenue, La Grange Park, IL 60526 (United States). American Nuclear Society - ANS; La Grange Park (United States), July 2013. URL: https://www.osti.gov/biblio/22257897.

[140] Robert J. Fetterman. "AP1000 core design with MOX loading". In: *Annals of Nuclear Energy* 36.3 (2009). PHYSOR 2008, pp. 324–330. ISSN: 0306-4549. DOI: https://doi.org/10.1016/j.anucene.2008.11.022. URL: https://www.sciencedirect.com/science/article/pii/S0306454908002983.

[141] Canadian Nuclear Safety Commission. *BWRX-300 Design: Non-Proprietary Information on Fuel Design Qualification and BWR Fuel Licensing*. Technical Report. Accessed: 2025-09-30. Canadian Nuclear Safety Commission, 2024. URL: https://api.cnsc-ccsn.gc.ca/dms/digital-medias/CMD24-H3-Ref-BWRX-300-DNNP-GNF2-Fuel-Design-Qualification-and-BWR-Fuel-Licensing-Non-Proprietary-Information.PDF.

[142] NuScale Power. *NuScale Announces MOX Capability*. Accessed: 2025-09-30. NuScale Power, Jan. 2016. URL: https://www.nuscalepower.com/press-releases/2016/nuscale-announces-mox-capability.

[143] Rolls-Royce SMR. *Rolls-Royce SMR Select UK-Based Fuel Solution*. Accessed: 2025-09-30. Rolls-Royce SMR, Oct. 2023. URL: https://www.rolls-royce-smr.com/press/rolls-royce-smr-select-uk-based-fuel-solution.

[144] Framatome. *GNF2 Fuel Assembly: Product Sheet*. Accessed: 2025-09-30. Framatome. May 2018. URL: https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a0529-p-us-g-en-328-05-18-htp.pdf?Status=Master&sfvrsn=60b7ce1d_2.

[145] Rolls-Royce SMR. *Our Approach to Small Modular Reactors*. Accessed: 2025-09-30. Rolls-Royce SMR, 2025. URL: https://www.rolls-royce-smr.com/our-approach.

[146] NuScale Power. *NuScale Power Module: Product Overview*. Accessed: 2025-09-30. NuScale Power, 2025. URL: https://www.nuscalepower.com/products/nuscale-power-module.

[147] NEA. *Unlocking Reductions in the Construction Costs of Nuclear*. Paris: OECD Publishing, 2020.

[148] NuScale Power. *NuScale Power Announces an Additional 25 Percent Increase in NuScale Power Module Output*. Accessed: 2025-10-01. Nov. 2020. URL: https://www.nuscalepower.com/press-releases/2020/nuscale-power-announces-an-additional-25-percent-increase-in-nuscale-power-module-output.

[149] Reuters Events. "GE Hitachi chases gas plant displacement with new 300 MW reactor". In: *Reuters Events | Nuclear* (Apr. 2018). Accessed: 2025-10-01. URL: https://www.reutersevents.com/nuclear/ge-hitachi-chases-gas-plant-displacement-new-300-mw-reactor.

[150] U.S. Department of Energy (DOE). *Advanced Reactor Demonstration Program*. Accessed: 2025-10-15. U.S. Department of Energy, Office of Nuclear Energy, 2020. URL: https://www.energy.gov/ne/advanced-reactor-demonstration-program.

[151] J. P. McBride et al. "Radiological Impact of Airborne Effluents of Coal and Nuclear Plants". In: *Science* 202.4372 (Dec. 1978), pp. 1045–1050. ISSN: 0036-8075. DOI: 10.1126/science.202.4372.1045. URL: https://doi.org/10.1126/science.202.4372.1045.

[152] GE Vernova. *LM2500XPRESS Gas Turbine: Product Factsheet*. Product Factsheet. Accessed: 2025-10-16. 2025. URL: https://www.gevernova.com/content/dam/gepower-new/global/en_US/downloads/gas-new-site/products/gas-turbines/gev-aero-fact-sheets/GEA35746-GEV-LM2500XPRESS-Product-Factsheet.pdf.

[153] Congressional Research Service (CRS). *Considerations for Reprocessing of Spent Nuclear Fuel*. Report R48364. Accessed: 2025-10-16. Congressional Research Service, 2025. URL: https://www.congress.gov/crs-product/R48364.

[154] U.S. Congress, Office of Technology Assessment. *Electric Power Wheeling and Dealing: Technological Considerations for Increasing Competition*. Report OTA-E-409. Washington, DC: U.S. Government Printing Office, May 1989. URL: https://ota.fas.org/reports/8913.pdf.

[155] P F Shiers, F S Fisher, and J A Kosberg. "The Mt. Hope Waterpower Project: A pumped storage facility that enhances the environment while supplying on-demand electrical needs". In: American Society of Civil Engineers, New York, NY (United States), Dec. 1995. URL: https://www.osti.gov/biblio/219975.

[156] MWH. *Technical Analysis of Pumped Storage and Integration with Wind Power in the Pacific Northwest*. Technical Report. Accessed: 2025-10-16. U.S. Army Corps of Engineers Northwest Division Hydroelectric Design Center, Aug. 2009. URL: https://www.hydro.org/wp-content/uploads/2017/08/PS-Wind-Integration-Final-Report-without-Exhibits-MWH-3.pdf.

[157] International Energy Agency (IEA). *Energy Statistics Data Browser: Electricity Imports vs. Exports, France, 1990–2024*. Data Set. Accessed: 2025-10-16; Licence: CC BY 4.0. International Energy Agency, 2024. URL: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=FRA&fuel=Imports%2Fexports&indicator=ElecImportsExports.

[158] Daniel J. Power and Ramesh Sharda. "Decision Support and Analytics". In: *Springer Handbook of Automation*. Ed. by Shimon Y. Nof. Cham: Springer International Publishing, 2023, pp. 1401–1410. ISBN: 978-3-030-96729-1. DOI: 10.1007/978-3-030-96729-1_66. URL: https://doi.org/10.1007/978-3-030-96729-1_66.

[159] Institute for Energy Economics and Financial Analysis (IEEFA). *UAMPS Talking Points: Class 3 Project Cost Estimates*. Report. Accessed: 2025-10-16. Institute for Energy Economics and Financial Analysis, Jan. 2023. URL: https://ieefa.org/sites/default/files/2023-01/UAMPS%20Talking%20Points%20_%20Class%203%20_%2020230102%20_%20Final.pdf.

[160] Lucas Sens, Ulf Neuling, and Martin Kaltschmitt. "Capital expenditure and levelized cost of electricity of photovoltaic plants and wind turbines – Development by 2050". In: *Renewable Energy* 185 (2022), pp. 525–537. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2021.12.042. URL: https://www.sciencedirect.com/science/article/pii/S0960148121017626.

[161] Saule Baurzhan, Glenn P. Jenkins, and Godwin O. Olasehinde-Williams. "The Economic Performance of Hydropower Dams Supported by the World Bank Group,

1975–2015". In: *Energies* 14.9 (2021). ISSN: 1996-1073. DOI: 10.3390/en14092673. URL: https://www.mdpi.com/1996-1073/14/9/2673.

A | Code Appendix

All computational materials supporting this research are available in the following GitHub repository: `https://github.com/simo-pagliu/Master-Thesis/`

The repository contains:

- **Reactor Selection and Analysis**: Implementing the methodology described in Section 3.2 (Location: `01-AttributesDefinition/ReactorsData/ReactorAnalysis.ipynb`)
- **Energy Data Analysis**: Supporting the country selection process outlined in Section 3.1 as well as the definition of indicators detailed in Sections 3.3.4 and 3.3.4 (Location: `01 - Attributes Definition/Electricity Data/Electricity Market Analysis.ipynb`)
- **Indicator Database**: List of 35 possible indicators that were considered for the analysis as explained in Section 3.3, a python script to help navigate the csv file is also provided (Location: `01 - Attributes Definition/Attribute_DB.csv`)
- **Indicators**: Spreadsheet containing the final list of indicators, previous revisions and intermediate caluclations referenced in Section 3.3 (Location: `01 - Attributes Definition/Indicators.ods`)
- **Digital Elicitation Tools**: Python scripts are availble at `02-ValueFunctions/main.py` for mid-value splitting and `02-ValueFunctions/qualitative_elicitation.py` for qualitative indicators. Weight elicitation utility is `03-Weighting/main.py`. These scripts are far from being user-friendly and are **provided as proofs of concept only**. More refined tools will be availble in the near future.
- **Complete Results**: All the plots generated are available in the `CompleteResults` folder, including those not reported in the thesis for brevity.

B | Perceived Safety Survey

The survey (Table B.1) illustrates a methodological approach for potential UP-MAVT integration, the limited sample size (N=50) of this study restricts statistical significance. The first question classifies respondents into three tiers (pro-nuclear, anti-nuclear, neutral) that, while necessarily simplistic, better reflects the binary nature of actual referendum decisions (yes or no) rather than very nuanced approach (very, slighlty, not so much . . .). This categorization helps distinguish between respondents with fixed positions and those that are potentially more influenced by campaign messaging.

The second question establishes a baseline nuclear perspective, as the study focuses on relative comparisons rather than absolute judgment. Questions 3-5 present each manufacturer claims about their own SMR designs, emphasizing opinion formation dynamics over searching for an objective truth.

Demographic data collection includes age brackets designed to differentiate between those with firsthand memory of major nuclear accidents (Chernobyl/Fukushima) and those without, considering both voting age (18) and early childhood recollections (down to age 6).

Preliminary findings indicate that both neutral and pro-nuclear respondents slightly favor BWRX-300 and NuScale designs when compared to traditional reactors. The anti-nuclear subgroup (n=4) remains too small for meaningful analysis. A larger sample would enable further analysis of demographic patterns and correlations with initial attitude (Q2)

Table B.1: Public Perception of Nuclear Reactor Safety Survey

Question	**Response options**
What is your overall opinion on using nuclear power?	I strongly disagree I do not hold any strong position I strongly agree
What is your opinion on the safety of traditional nuclear power plants?	Unsafe Neutral Safe
Rolls-Royce SMR: This reactor is a scaled-down version of well-known traditional reactors, with about 1/4th of their power and a smaller footprint. *Do you think the Rolls-Royce SMR is...?*	Safer than traditional reactors Indifferent Less safe than traditional reactors
NuScale Power Plant: This design plans to deploy 6 very small reactors. The design uses natural circulation for cooling (coolant flows without pumps, driven by temperature differences) and can shut down safely and cool down indefinitely with no operator action, no external power and no additional water. *Do you think the NuScale design is...?*	Safer than traditional reactors Indifferent Less safe than traditional reactors
BWRX-300: This design features a single reactor of small dimensions designed to be manufactured off site. It uses natural circulation for cooling (coolant flows without pumps, driven by temperature differences) so it will never need external power to cool down. *Do you think the BWRX-300 is...?*	Safer than traditional reactors Indifferent Less safe than traditional reactors
What is your age group?	Under 20 Between 21 and 44 Over 45
Where are you from?	Italy Switzerland France Poland Other
How much do you know about nuclear power?	0 (I know nothing) to 10 (I'm an expert)
Suggestions or comments?	Open-ended response

C | Suggestions for Practitioners

In this appendix suggestions to practitioners planning to carry similar studies are collected. These suggestions are based on the author's experience during the development of this thesis, shared hoping to facilitate future works in this field.

Knowledge sharing sessions

Elicitation sessions revealed fundamental alignment in expert judgment frameworks, with divergences emerging primarily from differences in thier specialized knowledge. This pattern was particularly pronounced in qualitative indicator assessments, where experts enjoyed greater interpretive freedom. Contextual awareness proved decisive: technological specialists often rated licensing statuses more favorably than colleagues attuned to country-specific political realities.

The SMR evaluations demonstrated how "insider" knowledge significantly influences outcomes. While most experts assigned similar baseline ratings, those with direct technology experience consistently applied more conservative assessments, reflecting awareness of recent, not well known, operational challenges. This underscores the value of multidisciplinary expert panels that incorporate both technical and contextual perspectives.

For these reasons, future studies should consider implementing knowledge-sharing sessions prior to individual elicitations. Such pre-elicitation exchanges would allow experts to present case-specific insights, potentially reducing deviations that stem from information asymmetries rather than genuine differences in professional judgment. This approach maintains individual assessment integrity while ensuring all experts operate from a common factual baseline.

Methodological adherence in PILE-BWT elicitation

During the PILE-BWT elicitation, experts frequently defaulted to intuitive importance comparisons ("How much more important is A than B?") rather than the required compensatory trade-off formulation ("How much must A improvement from its minimum to offset B's decline from minimum to maximum?"). Future applications must emphasize this distinction during expert briefings to maintain methodological rigour.

Flexibility in value function correction

During value function elicitation, when experts were asked to adjust the results of the "first elicitation", the rigid adherence to pre-defined indifference points from initial mid-splitting created unnecessary constraints. Future implementations should permit greater expert flexibility in adjusting these reference points during subsequent sessions.

Possible improvements on QI approaches

Regarding qualitative indicator the use of a standardized reference alternative significantly improved consistency and is recommended for future studies. On the other hand, the "spectrum" approach for the "construction complexity" indicator (Section 3.3.3) caused substantial expert confusion and should be replaced with conventional ranking methods.

Acronyms

ABWR Advanced Boiling Water Reactor. 38, 39

AHP Analytic Hierarchy Process. 10, 11, 12, 13

ANP Analytic Network Process. 12

AP-1000 Advanced Passive. 7, 35, 38, 39, 41, 43, 45, 47, 48, 49, 79, 80, 81, 83

APR-1400 Advanced Power Reactor. 35, 38, 39, 41, 43, 45, 47, 48, 49, 79, 80, 82, 84

APWR Advanced Pressurized Water Reactor. 39

ARIS Advanced Reactor Information System. 38, 43, 45

BOP Balance Of Plant. 43

BWM Best-Worst Method. 22, 23, 25, 29

BWR Boiling Water Reactor. 4, 12, 79

BWRX-300 Boiling Water Reactor X-300. 35, 39, 41, 45, 48, 49, 50, 53, 56, 61, 79, 80, 82

BWT Best-Worst Tradeoff. 23, 25, 29, 64, 67, 117

CANDU CANadian Deuterium Uranium. 5

CBA Cost-Benefit Analysis. 9

CDF Core Damage Frequency. 54

CF capacity factor. 26, 27, 49, 117

CMAA Combinatorial multi-criteria acceptability analysis. 31, 34

DM Decision Maker. 9, 18, 20, 23, 28, 29, 31

EBR-I Experimental Breeder Reactor 1. 3, 4, 117

EDF Électricité de France. 38, 40

ELECTRE "Elimination and Choice Expressing Reality". 10, 11

ENTSO-E European Network of Transmission System Operators for Electricity. 35, 50, 51

EPR European Pressurized Reactor. 7, 11, 13, 35, 38, 39, 41, 43, 45, 46, 47, 48, 49, 70, 79, 81, 83

EURATOM EURopean ATOMic energy community. 3

GCR Gas Cooled Reactor. 12

geo geometric mean. 20, 76, 79

GEV-H General Electric Vernova - Hitachi. 40, 41, 45, 53, 56, 59

GFR Gas cooled Fast Reactor. 8

GHG Green House Gas. 27, 81

GIS Geographic Information System. 10, 11, 14

har harmonic mean. 20, 76, 79

HTGR High Temperature Gas cooled Reactor. 11, 12

i-BWR Integrated Boiling Water Reactor. 41

i-PWR Integrated Pressurized Water Reactor. 41

IAEA International Atomic Energy Agency. 3, 11, 12, 26, 37, 38, 43, 45

IEA International Energy Agency. 50

INPRO International Project on Innovative Nuclear Reactors and Fuel Cycles. 11

LCA Life Cycle Assessment. 13

LCOE Levelized Cost Of Electricity. 54

LEU low enriched uranium. 57

LFC Load Following Capabilities. 43, 44, 59, 119

LWR Light Water Reactor. 4, 7, 50, 51, 57

magnox MAGnesium Non-Oxidising. 4

MAMCA Multi-Actor Multi-Crieria Analysis. 34

MAVT Multi Attribute Value Theory. i, iii, 1, 2, 10, 11, 13, 17, 18

max maximum aggregation. 20

MC Monte Carlo. 30, 31

MCDA Multi-Criteria Decision Analysis. i, iii, 2, 9, 10, 11, 12, 13, 14, 15, 17, 20, 22, 26, 28, 30, 31, 34, 35, 41, 47, 79, 85

min minimum aggregation. 20

MSR Molten Salt Reactor. 11, 12

NEA Nuclear Energy Agency. 45, 46

NOAK N-th of a Kind. 63

NPM Nuscale Power Module. 11

NPP Nuclear Power Plant. 9, 27, 48, 50, 56, 57, 82, 117

NRC US Nuclear Regulatory Commission. 39, 43

NS-MC Non-strict Montecarlo. 30, 31, 71, 76, 77, 78, 81, 118

NSSS Nuclear Steam Supply System. 46, 56

PDF Probability Density Function. 30, 47

PHWR Pressurized Heavy Water Reactor. 5, 12

PILE-BWT PIvot Linked Elicitation BWT. 25, 28, 63, 64, 69, 83, 84, 111

PRIS Power Reactor Information System. 26, 37, 38, 43

PROMETHEE Preference Ranking Organization Method for Enrichment Evaluations. 10

PV photovoltaic. 50

PWR Pressurized Water Reactor. 4, 11, 12, 41, 45, 50, 117

RBMK "high-power channel-type reactor". 5

S-MC Strict Montecarlo. 30, 31, 71, 74, 75, 80, 118

SCWR SuperCritical Water Reactor. 8

SDA Standard Design Approval. 39

SFR Sodium cooled Fast Reactor. 8

SMAA Stochastic multiobjective acceptability analysis. 14, 30, 31, 34

SMR Small Modular Reactor. i, iii, 7, 8, 11, 12, 35, 39, 43, 45, 46, 48, 49, 51, 53, 55, 78, 79, 81, 82, 83, 84, 111

SNF Spent Nuclear Fuel. 52

sum weighted sum. 20, 76, 79

TOPSIS Technique for Order of Preference by Similarity to Ideal Solution. 11, 12, 13

TSO Transmission System Operator. 36

UP-MAVT Uncertainty Propagated MAVT. i, iii, 1, 2, 30, 31, 69, 78, 83, 84

UP-MCDA Uncertainty Propagated MCDA. 29

VVER "Water-Water Energetic Reactor". 4, 39, 117

List of Figures

List of Tables

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