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Data-Informed Evaluation Framework for Integrated Energy Systems: Insights from Power, Process Heat, and Hydrogen Production Applications

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Data-Informed Evaluation Framework for Integrated Energy Systems: Insights from Power, Process Heat, and Hydrogen Production Applications

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Selecting suitable technologies for integrated energy systems (IES) can be likened to an "apples-to-oranges" comparison, given the heterogeneous factors at stake. Consequently, past research has often employed the multi-criteria decision analysis (MCDA) methods with a mixture of qualitative and quantitative criteria. The MCDA provides a systematic evaluation of the diverse preferences and performance metrics associated with alternative solutions. While the method proves effective in handling the intricate interplay of criteria, the resulting rankings and scores can vary from study to study. As a result, decision-makers frequently find it challenging to establish clear connections between specific criteria and the resulting scores, as the transformation of criteria into ordinal scores results in a substantial loss of information. To address this challenge, we introduce a data-informed IES evaluation framework that offers comprehensive, interpretable, and traceable evaluations backed by quantifiable rationale. First, we identified key IES evaluation criteria from a decade of literature, focusing on relevant IES applications in power, process heat, and hydrogen production. Next, we established thresholds by applying change-point analysis, categorizing the preferences of decision-makers into distinct utility functions. To demonstrate the impact of our framework, we conducted case studies on six reactor designs (AP1000, NuScale, BWRX-300, Xe-100, eVinci, iMSR) for the three applications. Our approach yielded two main outcomes: (i) it provided consistent assessments across different stakeholder groups and (ii) it visualized uncertainties in the decision-making context via comprehensive sensitivity analysis.

Keywords: integrated energy systems; multi-criteria decision analysis; evaluation framework; advanced reactors

I. INTRODUCTIONS

The multi-criteria decision analysis (MCDA) evaluates the preferences and performance of different alternatives in a way that is transparent to decision makers [1]. The MCDA framework includes (1) criteria identification, (2) alternatives formulation, (3) threshold values and descriptive standards establishment (with each accompanied by a well-reasoned justification), and (4) weights determination to the criteria, as illustrated in Figure 1. The difference between a threshold value and a descriptive standard is that the former allows the range of values which is associated to a specific unit, while the latter has unitless qualitative attributes. Despite being qualitative, descriptive standards are systematically organized using a specific taxonomy or discrete ordering to effectively cover various attributes. For example, classifications can be 'significant,' 'moderately significant,' and 'insignificant' can be used, often based on published papers or expert surveys [2]. Table 1 provides definitions for the MCDA elements, namely: requirements, criteria, indicators. In addition, we also establish the notions of assessment and scoring, along with the concept of thresholds.

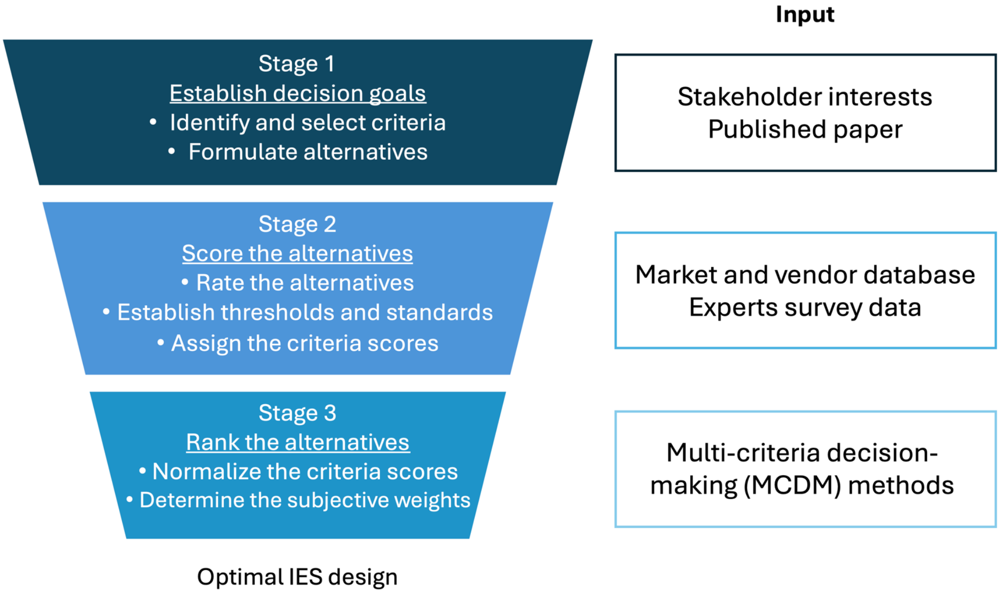

Figure 1. Overview of the MCDA process for selecting the optimal IES design.

Table 1. Key definitions for MCDA elements and concepts.

Term	Definition
Requirement	a fundamental goal that serves as the foundation for the execution of the IES project or system.
Criterion	a criterion is a standard or principle used to evaluate an attribute of the system. It can function independently or be aggregated with other criteria to assess a specific requirement.
Indicator	an indicator is a measurable or qualifiable variable that reflects the status of a specific criterion. It is expressed in a unit (or index) that conveys a 'single meaningful piece of information' pertinent to the particular metric.
Assessment	a process involves estimating or gathering the value or level of an attribute based on a specific indicator.
Threshold	a scoring rule is expressed as 'if-then' conditions that reflect the decision-makers' levels of indifference and preference when comparing alternatives [3]. Thresholds are determined on an indicator-by-indicator basis, tailored to the specific needs and values of the decision-makers [4]. An effectively determined threshold should discriminate the relative importance of the alternatives for each criterion
Scoring	a technique where decision-makers are prompted to assign a score to each criterion based on a relative numerical scale, which, in this study, ranges from 1 to 5. Assessment data and determined thresholds and facilitate this process.

Compared to single criterion approach, the selection of suitable nuclear technologies and their subcomponents, as well as their configuration into an integrated energy system (IES) is influenced by many factors ranging from economics and performance parameters to geological compatibility and environmental impacts. As a result, previous studies employed the MCDA methods with a mixture of qualitative and quantitative criteria to navigate complex IES design problems characterized by different interests among stakeholders and high uncertainty in market and technology domains [2, 5-7]. Some of these studies focused on the subcomponents of IES, specifically, storage technologies [2, 6] and heat exchangers [7], driven by their specific business motivations, such as power, process heat, and hydrogen production.

Nevertheless, several limitations have emerged: (1) Not every criterion is not linked with quantitative indicator(s); (2) the criteria set sometimes is incomplete or exhibits redundancies; (3) the use of stakeholders judgmental values in weighting can influence rankings, leading to information distortion; (4) the justification for determining thresholds is often unclear, resulting in information loss; and (5) there is a dependency among alternatives—where the addition or removal of an alternative may affect the rankings of other alternatives. While employing quality function deployment (QFD) and/or MCDA methods, such as analytic hierarchy process (AHP), has addressed many of the issues [7], the third concern regarding the determination of thresholds remains unresolved. This is attributed to the fact that thresholds have to be established individually for each indicator, based on the needs and values of the stakeholders (or decision-makers) [4]. In other words, rigorously justifying and classifying their preferences by each criterion can be a time-consuming and prohibitive task.

To address this challenge, we introduce a data-informed IES evaluation framework that offers comprehensive, interpretable, and traceable evaluations backed by quantifiable rationale. We begin by collecting all relevant criteria and their respective indicators for evaluating IES configurations across power, process heat, and hydrogen applications. We then construct a database to match criteria-indicator matrices. In this pursuit, state-of-the-art cost estimates [8] and technical data from 78 reactor designs [9-11] are utilized as case studies to evaluate the competitiveness of the reactors in three applications. Lastly, we statistically determine thresholds by using change-point analysis. This method effectively estimates thresholds based on the distributions of indicator values related to a specific criterion [12].

The next section outlines the methods and scope for developing the framework. Subsequently, we examine the refined criteria-indicator matrix and the derived thresholds, which provide guidelines for consistent assessments. Finally, we conclude with a discussion of our findings and offer recommendations for expanding the potential of the proposed framework.

II. METHODS

We aim to offer a guide to assist decision-makers in the identification and selection of quantitative indicators that are tailored to their unique IES subsystem requirements. To demonstrate the impact of our framework, we conduct case studies on five advanced reactor (AR) reactor designs nearing deployment: VOYGR[1], NuScale; BWRX-300, BWRX; Xe-100, X-energy; eVinci, Westinghouse; iMSR, Terrestrial Energy; and one commercially operating design: AP1000, Westinghouse for the three applications. As detailed in Table S 2, these reactors show a variety of operating temperatures and thermal outputs; the most current cost estimates for these reactors (adjusted to 2019 values), are utilized; all design parameters are collected from an extensive review of vendor data, as well as information from the International Atomic Energy Agency (IAEA) and the OECD-Nuclear Energy Agency (OECD-NEA), to provide desired granularity for our framework.

II.A. Criteria and Indicator Mapping

To this end, we present the comprehensive set of key criteria and their corresponding indicators for IES, by reviewing papers published from 2012 to 2023. The eight studies [2, 5-7, 13-16] are selected based on the following standards—explicit focus on nuclear-coupled systems, consideration of IES subcomponent technology, inclusion of defined criteria and indicators for evaluation, and the examination of multiple design options for comparative analysis (Table S 1). The criteria from the eight studies are refined by eliminating redundancies among their corresponding indicators. These refined criteria are then organized into four core

[1] While we introduce its newly-branded name, VOYGER, in the remaining chapters we will refer to it as NuScale, following the convention used in the cost and technical sources [8-10, 29].

domains: (1) economic, (2) performance, (3) reliability and safety, and (4) environmental. The objective of this task is to identify decision-makers' diverse preferences for each specific application of ARs.

II.B. Database Construction

Based on data availability we construct database utilizing state-of-the-art cost estimates [8] and technical data from 78 reactor designs [9-11]. The objective of constructing this database is to serve as a reference system that not only evaluates the relative competitiveness among alternatives (such as the six reactor designs) but also reveals the magnitude of their impacts in a broader context of reactor designs. This approach, external normalization, allows each reactor to establish its own relative standing based on the evaluation criteria within the reference database [17]. In other words, adding or removing one alternative does not change the relative positions of the remaining alternatives, which enables consistent threshold establishments and resulting scores in evaluation frameworks.

II.C Thresholds Determination for Scoring

The traditional approach (internal normalization) for determining thresholds involves normalizing values of alternatives by the largest or smallest observed values within the group and then assigning ordinal scores based on the normalized values. However, this method leads to a permanent loss of information regarding the magnitudes of differences in the criteria, potentially penalizing high-performing alternatives disproportionately. For instance, a ramp rate score of 5 for Reactor A and 1 for Reactor B only indicates relative competitiveness without providing insight into the magnitude of the difference [18]. To address this issue, we apply change-point analysis to the externally normalized dataset (derived in section **II.B**) to bring consistency to establishing thresholds for IES evaluation. Change-point analysis is an iterative procedure used to identify points (thresholds) where a statistical property of a dataset changes abruptly. Either mean, variance, root mean square (RMS), or slope statistics can be selected in this procedure. A detailed mathematical formulation of the change-point analysis is available in [12, 19].

To account for threshold variations in the selection of the statistics, we derive thresholds using the four statistics for the selected criteria from section **II.A**. Variations from the choice of statistics can be considered uncertainties that decision-makers encounter, specifically the uncertainty associated with the valuation of each criterion based on decision-makers' preferences.

II.D Reactor Design Evaluation

The framework developed in sections **II.A-C** is tested for the evaluation of six reactor designs in power, process heat, and hydrogen applications. The objective of this task is not to rank IES design options. Rather, we focus on (1) the range of scores for each criterion that arise from uncertainties in decision-makers’ preferences (i.e., thresholds), as well as from input cost and technical data, and (2) how those uncertainties propagate through the core criteria domains of economic viability, performance, reliability and safety standards, and environmental impact, which ultimately shape the final evaluation. Thus, no weights are considered in this evaluation.

III. RESULTS

The findings are organized to correspond with each subsection in Section **II**.

III.A. Criteria and Indicator Mapping

Effective criteria and indicators for IES must balance a broad range of project requirements, including economic viability, performance, reliability, and safety, as well as considerations related to environmental and policy impacts. Figure 2 summarizes the percentage breakdown of IES criteria by application from the selected literature. A notable difference in criteria selection is observed across the applications. For instance, more performance criteria are included in evaluations for power and hydrogen applications, whereas economic and environmental and policy factors are more prominent in process heat applications. Note that Figure 2 only counts the occurrence of criteria that fall into the four categories; weights are not represented. However, the stakeholders' preference can still be inferred from the more frequent selection of criteria within specific domains. Thus, when aggregating criteria across all applications and adjusting for duplications by indicators[2], the preference for any specific domain becomes less pronounced (see Application Total, Total Adjusted for Overlaps in Figure 2).

In developing the criteria-indicator mapping, we focus on indicators or units rather than criteria, as criteria tend to be based on system-oriented attributes and may be overrepresented. For example, studies [6-7] individually evaluated discharge time and response time required for power maneuvering. Both metrics are counted towards the ramp time criteria in this study.

[2] if two criteria use the same units, such as roundtrip efficiency for storage technologies and thermal-to-electricity conversion ratio for reactors, they are counted as one.

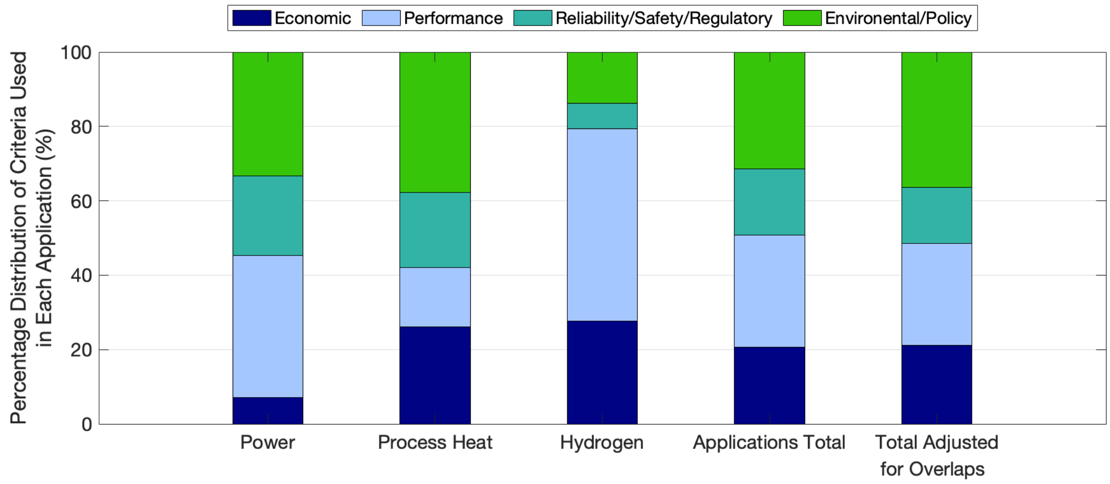

Figure 2. Percent breakdown of IES criteria by applications.

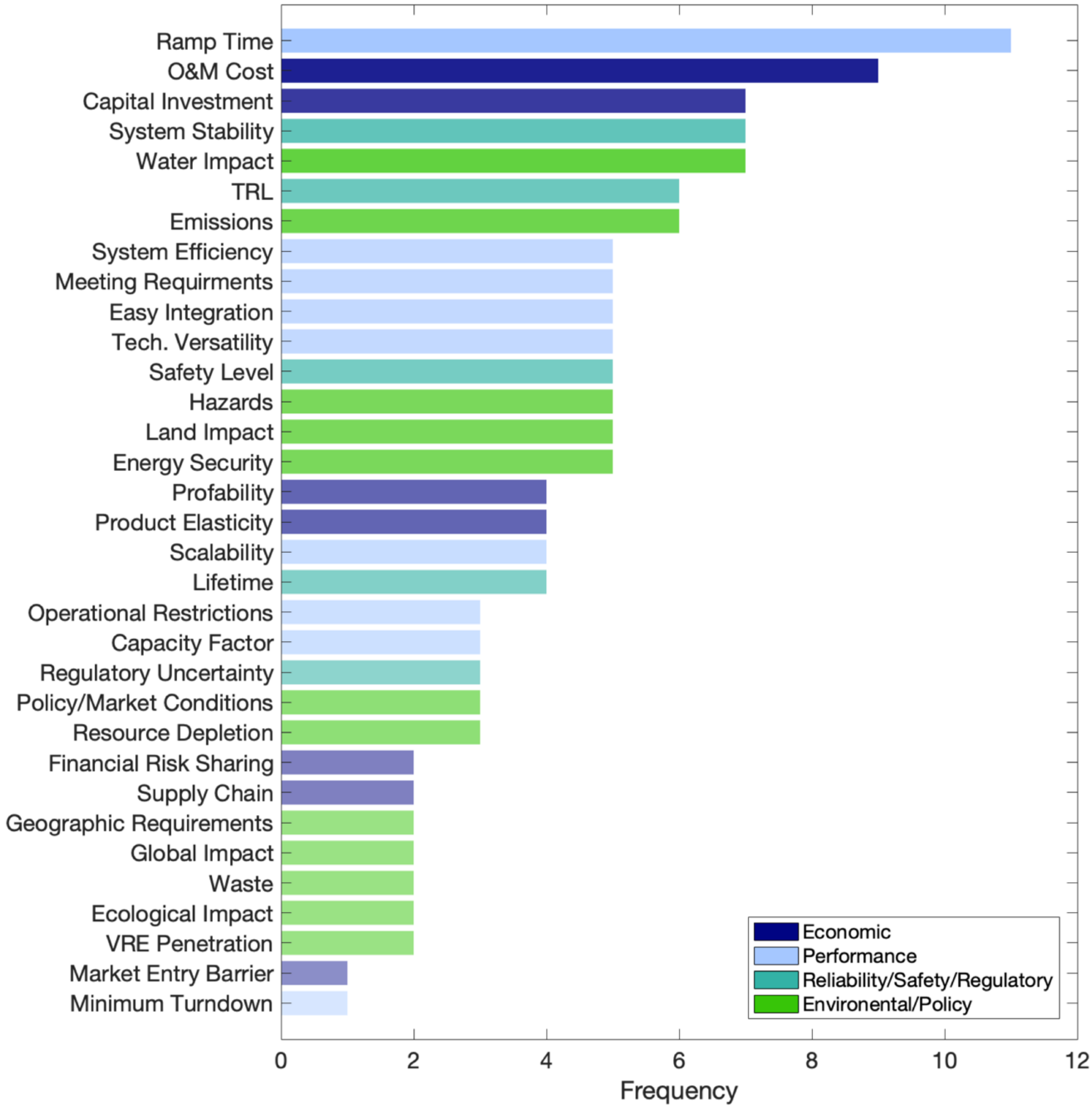

Figure 3. Counts distribution of criteria based on indicator/unit usage

Figure 3 shows the count distribution of criteria from the literature reviewed in this study. Their domains are represented by different colors. Detailed definitions of each criterion are available in Table S 3-Table S 6. From a total of 33 criteria, we further refined the list to 12 (Table 2), considering their importance (the number of times they are used in the literature) and data availability (having more than 15 samples to apply the change point analysis using a 5-point numerical scale, 1-5). Table 2 also indicates which criteria are uniquely preferred or universally considered important across applications (see Application column).

Table 2. Selected criteria and indicators for case study evaluation.

Criteria domain	Criterion	Criterion description/ Quantitative measure	Indicator(s)/ Assessment	Application P	Application PH	Application H2	Justification
Economic	O&M cost	Variable O&M cost	[$/kWh] Direction: ↓		✓	✓	Industrial users may be more sensitive to O&M costs than to natural gas expenses.
	Capital investment	Overnight capital cost (OCC)	[$/kW] or [$/kWh] Direction: ↓	✓	✓	✓	OCC primarily accounts for the LCOE and LCOH.
	Supply chain	Public announcements by suppliers and partners	NEA Index Direction: ↑	✓	✓	✓	The NEA estimated the supply chain readiness levels for 42 AR designs [9].
Performance	System efficiency	Thermal-to-electric conversion efficiency	[%] Direction: ↑	✓			Industrial users may prioritize heat-delivery efficiency over thermal-to-electric conversion efficiency.
	Meeting requirements	Steam temperature	[°C]* Direction: ↑			✓	Industrial user needs are not covered in this study; Temperature specifications are expected to be established during the early phases of the hydrogen facility's planning.
	Ramp time	Ramp rate	[%/min]* Direction: ↑	✓			IES may need increased flexibility, even when coupled to storage systems.
	Scalability	Electrical output Thermal output	[MWe]* [MWt]* Direction: ↑	✓	 ✓	 ✓	Industrial users may be more concerned with thermal output than electrical output.
Reliability/ Safety	Lifetime	Technology lifetime	[yr] Direction: ↑	✓	✓	✓	
	System stability	Minimum generation level	[%] Direction: ↓	✓			IES may need to reduce its power output in response to negative pricing signals.
	Regulatory uncertainty	Licensing interactions with regulators	NEA Index Direction: ↑	✓	✓	✓	The NEA estimated the licensing readiness levels for 42 AR designs [9].
Environmental	Land impact	Plant footprint	[$10^3 \times m^2$] Direction: ↓		✓	✓	The spatial footprint of the plant could be a critical factor in the transition from traditional fossil fuel boilers to IES.

AR: advanced reactor; H2, hydrogen application; LCOE: levelized cost of electricity; LCOH: levelized cost of heat; NEA: Organisation for Economic Co-operation and Development-Nuclear Energy Agency; O&M cost: operational and maintenance cost; P, power application; PH, process heat application; SMR: small modular reactor; ↓ : smaller-the-better; ↑ : larger-the-better

III.B. Database Construction

During the scoring process (assigning a score of 1-5 based on thresholds), a common inferential challenge is determining thresholds within datasets that exhibit heterogeneous distributions of criteria. Figure 4 illustrates this decision-making challenge in the evaluation of IES. The design parameters from 78 reactors [10, 11], 67 cost estimates across 51 reactors [8], and estimates for supply chain and licensing criteria for 48 reactor designs [9] are incorporated to construct the distributions. As discussed in Section **II. B**, an extensive dataset for a particular criterion minimizes the role of decision-makers' subjective judgments, as the accumulation of data justifies the application of standard statistical methods [20]. The next section discusses how to effectively synthesize the relative standing of each criterion in determining individual thresholds for this database.

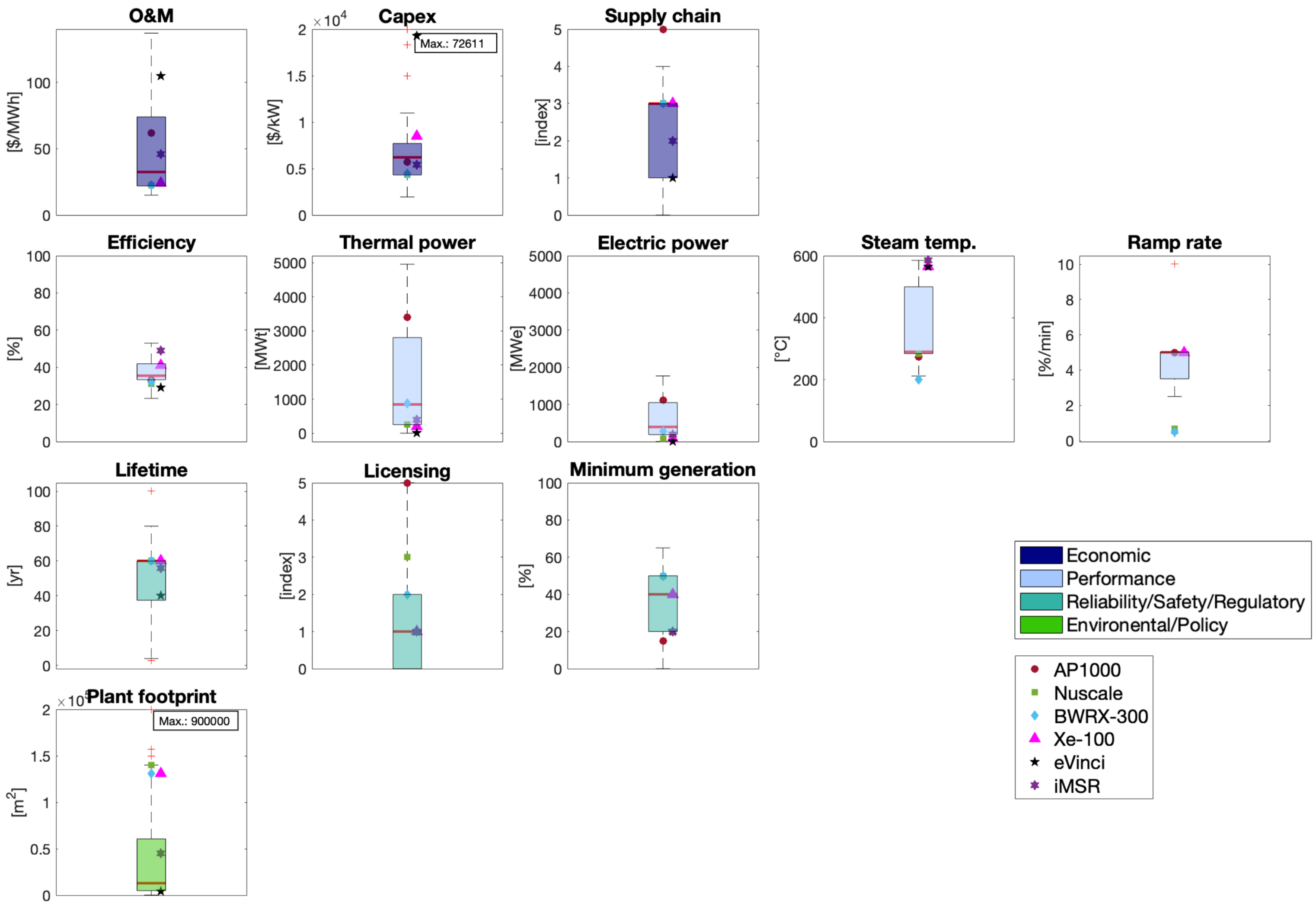

Figure 4. Boxplots showing the distribution of values for each criterion across reactors, with the data for six individual reactors highlighted.

III.C Thresholds Determination for Scoring

Thresholds for the 12 criteria are calculated by identifying four change points that create five ranges for 1-5 scale scoring. Table *3* shows the thresholds calculated based on the mean values of each dataset respective to its criteria. The results for variance, RMS, and slope are provided in Table S 7-Table S 9. As noted in Figure *5*, the identified change-points vary depending on the statistical measures applied. While mean RMS, and slope (denoted as linear) tend to produce similar thresholds, variance (denoted as standard deviation) shows a drastic change at certain levels. This indicates that the results from the mean-based statistics highlight a central tendency within a similar set of balance-of-plant technologies (e.g., Rankine supercritical CO_2 cycle) or reactor technologies (light-water reactor, LWR or high-temperature gas reactor, HTGR). In contrast, the closely clustered change points from the variance suggest that many reactor designs are predominantly developed based on the LWR-Rankine cycle, characterized by around 33% efficiency and 300ºC outlet temperature.

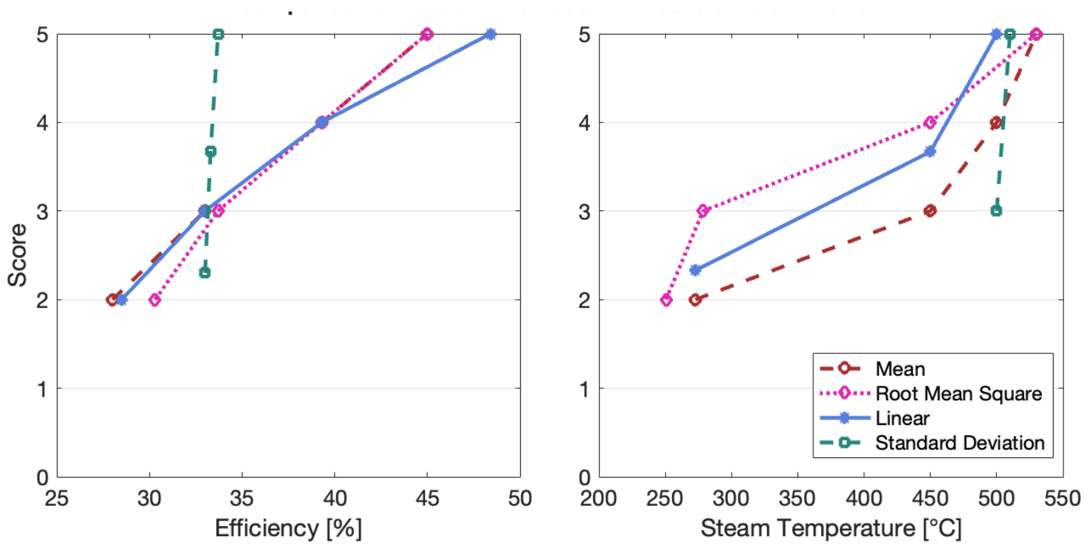

Figure 5. Comparison of different methods for determining thresholds: thermal-to-electric conversion efficiency (left) and steam temperature (right)

Table 3. Calculated thresholds based on mean values.

Criteria domain	Criterion	Criterion description/ Quantitative measure	Indicator(s)/Assessment	Thresholds 5	4	3	2	1
Economic	O&M cost	Variable O&M cost	[$/kWh] Direction: smaller-the-better	< 22	22	42	74	103 ≤
	Capital investment	Overnight capital cost (OCC)	[$/kW] or [$/kWh] Direction: smaller-the-better	< 4820	4820	8340	15000	26554 ≤
	Supply chain	Public announcements by suppliers and partners	OECD-NEA Small Modular Reactor Index Direction: larger-the-better	≥ 4	3	2	1	1 >
Performance	System efficiency	Thermal-to-electric conversion ratio	[%] Direction: larger-the-better	≥ 45	39.3	33	28	28 >
	Meeting requirements	Steam temperature	[°C]* Direction: larger-the-better	≥ 530	500	450	272.7	272.7 >
	Ramp time	Ramp rate	[%/min]* Direction: larger-the-better	≥ 10	5	3	2.5	2.5 >
	Scalability	Power capacity	[MWe]* [MWt]* Direction: larger-the-better	≥ 3926 ≥ 1356	2800 1000	1250 468	480 185	480 > 185 >
Reliability/Safety	Lifetime	Technology lifetime	[yr] Direction: larger-the-better	≥ 70	50	30	10	10 >
	System stability	Minimum generation level	[%] Direction: smaller-the-better	< 15	15	40	50	60 ≤
	Regulatory uncertainty	Licensing interactions with regulators	OECD-NEA Small Modular Reactor Index Direction: larger-the-better	≥ 5	3	2	1	1 >
Environmental	Land impact	Plant footprint	[$10^3 \times m^2$] Direction: smaller-the-better	< 24	24	65	100	200 ≤

III.D Reactor Design Evaluation

The total scores of each reactor are evaluated based on the four thresholds, each derived from different statistical measures: mean, variance, RMS, and slope. When aggregating the scores for each criterion, no weights are assigned. Consequently, each reactor design has a distribution of total scores established from the four thresholds (y-axis: frequency, x-axis: total score). This distribution is then smoothed using a kernel density estimator. Additionally, each total score across the applications is normalized (x-axis) to its respective full points[3]. For example, in power applications, AP1000 consistently scores 30-31 regardless of thresholds, leading to a bell-shaped distribution centered around 0.77 (normalized to its full points of 40). In hydrogen applications, due to its diverse total scores (28-29 from mean, RMS, and linear thresholds; 26 from variance threshold), a bimodal distribution is observed. The results are presented in Figure 6.

As selectively chosen based on the application, the degree of overlap among the reactors varies. Excluding eVinci, there are substantial overlaps observed among SMRs; specifically, NuScale, BWRX-300, Xe-100, and iMSR. This suggests a high level of uncertainty in potential ranking reversals, based upon the decision maker's preferences or project requirements in determining thresholds. AP1000 design consistently shows the lowest uncertainty with low variance or a narrow distribution, regardless of application. This is largely owing to its established technology readiness level (TRL), supported by high scores in minimum generation level, supply chain, licensing criteria, low overnight capital costs, and substantial thermal or electrical output. This suggests

[3] Since the criteria used for the applications vary (see Table 2), total scores differ accordingly. For instance, the criteria for power, process heat, and hydrogen applications include 8, 6, and 7 items, respectively, so the total scores are normalized to their respective full scores of 40, 30, and 35.

that the AP1000 has reduced sensitivity to statistical measures (e.g., mean, variance, root mean square (RMS), and slope) used in change-point analysis.

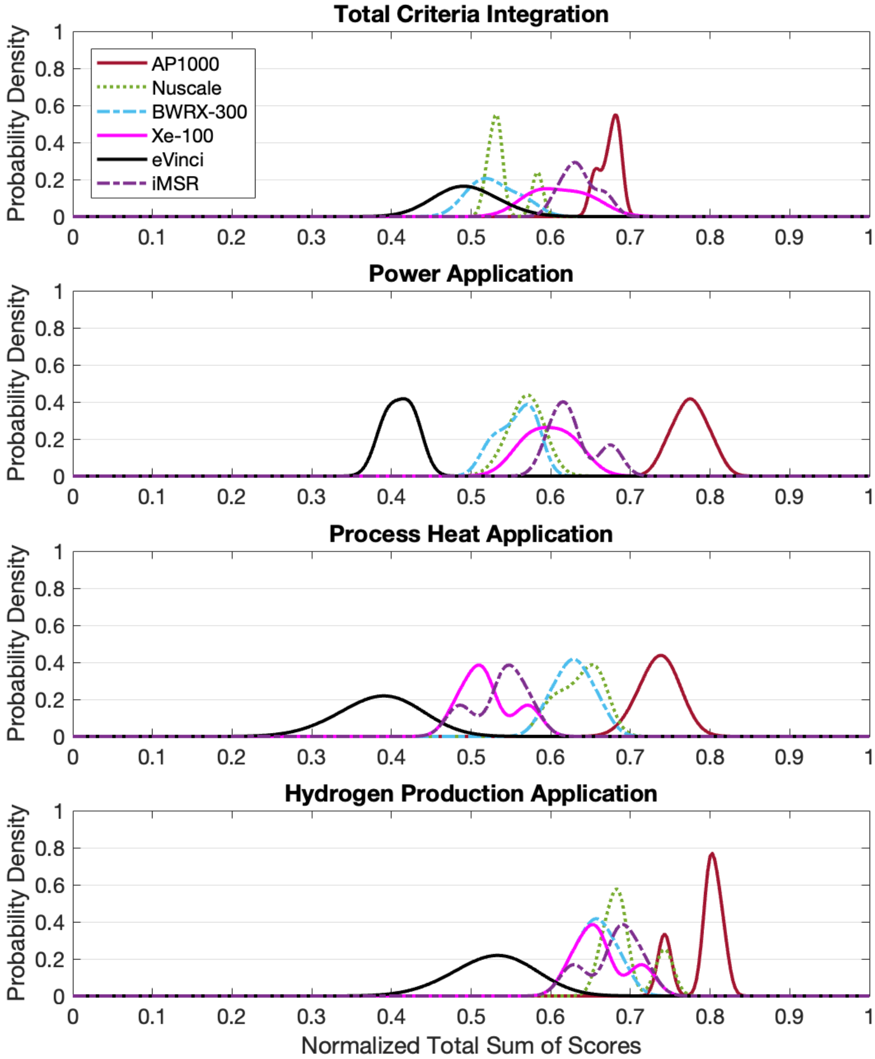

Figure 6. The distributions of total scores for six reactor alternatives across various applications, with equal weight assigned to each criterion: the x-axis represents the total score normalized to its respective full points (see footnote on page 17) , while the y-axis indicates the probability of those levels being observed.

In contrast, due to the distinctive characteristics of eVinci, often being the most expensive, smallest, or having the highest input parameters across each criterion distribution, threshold determination is highly sensitive to the statistics applied, yielding a greater variance when compared to other reactor designs. This implies that its competitiveness will greatly depend on the application (power vs. process heat), and on plant specifications, (general process heat vs. hydrogen applications), which will be reflected in the thresholds.

IV. CONCLUSION

This study presents an evaluation framework designed to guide the selection of optimal IES designs while mitigating bias stemming from decision-makers' subjective preferences. The framework is built upon key IES evaluation criteria derived from a decade of literature, with a particular focus on applications in power generation, process heat production, and hydrogen production. By leveraging state-of-the-art cost estimates and technical data from 78 reactor designs, our approach (1) achieves consistent assessments across diverse stakeholder groups and (2) visualizes uncertainties within the decision-making context. To illustrate the effectiveness of our framework, we conducted case studies on six reactor designs (AP1000, NuScale, BWRX-300, Xe-100, eVinci, iMSR) across the three applications. Our data-driven framework proves highly effective in addressing the heterogeneous uncertainties faced by varied decision-makers' preferences and IES applications, as well as the cost and technical estimates of advanced reactors.

The criteria and indicators introduced in this study are intended to be universally applicable across IES applications. However, assigning weights to rank alternatives will depend on the specific context faced by decision-makers, which is beyond the scope of this study. Hence future work may include the incorporation of weights that account for plant-specific technical specifications, such as market size, target industry, or required process heat temperature, to enable more tailored evaluations.

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SUPPLEMENTARY INFORMATION

Data-Informed Evaluation Framework for Integrated Energy Systems: Insights from Power, Process Heat, and Hydrogen Production Applications

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Table S 1. Review of IES studies across applications.

Application	Criteria	Scope	Literature
Power	TES	Comparative evaluation of TES technologies integrated with LWRs for grid services	[2, 13]
	TES	Comparison of TES integrated with AR based on operating temperature and thermal output	[6]
	PWR- TES coupling	Comparative evaluation of PWR-TES coupling designs for power generation	[14]
Process heat	IES subsystem	Regional IES subsystem design options for industrial processes	[5]
	Heat exchanger	Comparative evaluation of heat exchangers for high-temperature applications	[7]
Hydrogen	Hydrogen production	Comparative evaluations of Nuclear-Hydrogen hybrid systems	[15]
	PWR-HTEF coupling	Assessment of PWR-HTEF facilities	[16]

AR: advanced reactor; HTEF: high temperature electrolysis facility; IES: Intergard Energy Systems; LWR: light water reactor; PWR: pressurized water reactor; TES: thermal energy storage.

Table S 2. Design and performance parameters of six reactors.

Criteria domain	Criterion	Indicator/ Assessment	Criterion Ratings						
			Reactor	AP1000	Nuscale	BWRX-300	Xe-100	eVinci	iMSR
			Tech.	PWR	iPWR	iPWR	HTGR	Microreactor	MSR
Economic	O&M cost (variable)	[$/MWh]		62 [8]	22 [a][8]	22 [a][8]	24 [a][8]	105 [a][8]	46 [a][8]
	Capital investment (OCC)	[$/kW]		5736 [b][8]	4348 [b][8]	4467 [a][8]	8497 [a][8]	19278 [a][8]	5450 [a][8]
	Supply chain	OECD-NEA SMR Dashboard Index		5 [9]	3 [9]	3 [9]	3 [9]	1[9]	2[9]
Performance	System efficiency	[%]		0.33 [c]	0.31-33 [c]	0.32[c]	0.41[c]	0.29 [c]	0.49 [c]
	Meeting requirements	[°C] Outlet temp.		324.7 [11]	321 [10]	287 [10]	750 [10]	750 [10]	700 [10]
		Steam temp.		272.8 [11]	283 [21]	100-200 [10]	565 [22]	565 [23]	585 [24]
	Ramp time	[%/min]		5 [11]	0.67 [25]	0.5 [11]	5 [26]	20 [27]	1 [d][28]
	Scalability	[MWt]		3400 [23]	250 [21]	870 [10]	200 [10]	7-12 [10]	400 [10]
		[MWe]		1117 [23]	77 [21]	270-290 [10]	82.5 [10]	2-3.5 [10]	195 [10]
Reliability/ Safety	Lifetime	[yr]		60 [11]	60 [21]	60 [11]	60 [10]	40 [10]	56 [10]
	System stability (minimum generation level)	[%]		15 [11]	50 [e]	50 [11]	40 [26]	20 [27]	20 [29]
	Regulatory uncertainty	OECD-NEA SMR Dashboard Index		5 [9]	3 [9]	2 [9]	1 [9]	1 [9]	1 [9]
Environment	Land impact (plant footprint)	$[10^3 \times m^2]$		2590-3367 [30]	140 [10]	130.9 [10]	130.9 [10]	< 4 [10]	45 [10]

[a] Average from respective reactor technology; [b] Averaged different estimates for identical reactors; [c] Derived from power-to-thermal efficiency; [d] 60 %/hr converted into minute-by-minute change assuming a linear rate of change during the hour; [e] Estimated based on BWRX-300 data.

Table S 3. Categorized economic criteria for IES from the literature.

Criteria domain	Criterion	Criterion description/Quantitative measure	Indicator(s)/Assessment
Economic	O&M cost	Fixed O&M cost Variable O&M cost	[$/kW-yr] [$/kWh] Direction: smaller-the-better
	Capital investment	Total capital investment including the cost of plant modification and the associated equipment and labor Overnight capital cost (OCC)	[$] [$/kW] or [$/kWh] Direction: smaller-the-better
	Profitability	IRR, NPV, and ROI	[%], [$], and [%], respectively Direction: larger-the-better
	Supply chain	Purchase delivery time Domestic or import of metals or martials Public announcements by suppliers and partners	[weeks] Direction: smaller-the-better Resource security index OECD-NEA Small Modular Reactor Index Direction: larger-the-better
	Product elasticity	Adaptability to market changes Existence of partnership (bilateral contract)	[% change in quantity demanded]/[% change in price] Number of similar product & service strategy Direction: smaller-the-better Yes or no

IRR: internal rate of return on equity; NPV: net present value; O&M cost: operational and maintenance cost; ROI: return on investment

Table S 4. Categorized performance criteria for IES from the literature.

Criteria domain	Criterion	Criterion description/Quantitative measure	Indicator(s)/Assessment
Performance	System efficiency	Thermal-to-electric efficiency Round-trip efficiency (RTE) Heat delivery efficiency Conversion of energy to by-products	[%] [%] [%] [kg/kWh] Direction: larger-the-better
	Meeting requirements	Capability to discharge/supply high quality heat Storage output temperature Desired grid/process heat service applications Hydrogen purity	[°C]* [$]* Number of compatible applications* [mol.%]* Direction: larger-the-better
	Capacity factor	Performance at name-plate capacity (system integrity)	[%] Direction: larger-the-better
	Ramp time	Ramp rate Storage discharge time System response time (controllability)	[%/min]* Direction: larger-the-better [s],[min], [hr]* [s],[min], [hr]* Direction: smaller-the-better
	Scalability	Power capacity Energy capacity	[MW]* [MWh]* Direction: larger-the-better
	Technology versatility	Reactor compatibility Operating temperature and pressure ranges Apportionment of heat and electricity in application	Number of compatible reactor designs* [°C] and [MPa], respectively Direction: larger-the-better [%] and [%], respectively
	Easy integration	Available space: energy and power density Available weight: specific energy power On-site versus field construction/assembly	[kWh/m^3] and [kW/m^3], respectively* [kWh/kg] and [kW/kg], respectively* Direction: larger-the-better Yes or no

	Operational restrictions	Planned maintenance	Number of service downtime days per year Direction: smaller-the-better
		Transition rate from one phase to another (e.g., charging to discharging)	On-demand or [number of cycles/day] Direction: smaller-the-better
		Nuclear heat diversion (extraction) ratio (HDR)	[%] Direction: larger-the-better
		System realignment for engineered performance	Yes or no

* For illustration purposes, we consider only those indicators that fall into two categories: 'larger-the-better,' and 'smaller-the-better,' which are to be maximized and minimized, respectively. Nevertheless, certain indicators may be more closely aligned with the 'distance-to-ideal,' which is highly dependent on the specific requirements of a plant. For instance, with a technology that can be scaled up to meet a project's predefined size, decision-makers might not value scalability beyond this size. Similarly, a ramp time shorter than the system's characteristic response time (electric: ~milliseconds, thermal: seconds to minutes) may not yield any perceived advantage to decision-makers.

Table S 5. Categorized reliability and safety criteria for IES from the literature.

Criteria domain	Criterion	Criterion description/Quantitative measure	Indicator(s)/Assessment
Reliability/Safety	Lifetime	Technology lifetime	[yr]
		Storage degradation rate	[%/day], [%/cycle]
		Operation beyond design life or capital payback	[yr] Direction: larger-the-better
		Thermal stress/corrosion mitigation strategy	Yes or no
	System stability	Upset incident recovery	[min]
		Startup and shutdown time (black-start capability)	[hr] Direction: smaller-the-better
		Minimum turndown or thermal support needs	Yes or no
		Operation control autonomy	Yes or no
		Thermal resilience (the ability to recover from and adapt to disruptions): SAD, Heat transfer area (A_s) per duty (Q), HTF volume	[m^2/m^3], [A_s/Q], and [m^3], respectively
	TRL	Technology maturity and readiness level	TRL index Direction: larger-the-better
		Years to commercial operations	[yr]
	Safety level	Robust pressure boundary: SAD, hydraulic diameter (D_h), channel wall thickness (t)	[m^2/m^3], D_h/t Direction: smaller-the-better
		Cross-contamination prevention: heat transfer area per heat duty, channel wall thickness	[A_s/Q] and [cm], respectively Direction: smaller-the-better
		Probabilistic risk assessment (PRA)	PRA of LOCA, LOFA, and LOOP Direction: smaller-the-better
		Safety assurance for operators and the public	Risk assessment matrix
		Minimum clearance from the reactor (e.g., hydrogen plant or storage)	Direction: smaller-the-better
	Regulatory uncertainty	Years to license, construction, and startup	[yr] Direction: smaller-the-better
		Material and fabrication readiness	ASME BPVC

	Licensing interactions with regulators: pre-licensing, license under review, construction, and operation license	OECD-NEA Small Modular Reactor Index Direction: larger-the-better

SAD: Surface area density; HTF: heat transfer fluid; LOCA: loss of coolant accident; LOFA: loss of flow accident in the secondary loop; LOOP: loss of offsite power; ASME: American Society of Mechanical Engineers; BPVC: Boiler Pressure Vessel Code

Table S 6. Categorized environmental criteria for IES from the literature.

Criteria domain	Criterion	Criterion description/Quantitative measure	Indicator(s)/Assessment
Environmental	Water impact	Impacts on ecosystem and geological disposition Impact of ground water withdrawals Water consumption	Yes or no Yes or no [Gal/yr] Direction: smaller-the-better
	Emissions	Criteria pollutants Particulate matter Climate emission during operation	[Mt/yr] [Mt/yr] [Mt CO_2eq/yr] Direction: smaller-the-better
	Hazards	During operation: hazardous air pollutants and hazardous fumes (particulates or volatiles) During commissioning and decommissioning: hazardous materials Impact on human life	[Mt/yr] and [mg/m^3], respectively Direction: smaller-the-better Yes, no, or recyclable Number of deaths per one million people Cancer risk in one million people Direction: smaller-the-better
	Land impact	Land use requirements: permanently occupied area, temporary disturbed area (e.g., plant construction), capacity density Land use withdrawals or visual aesthetics	[acre]* and [acre]*, respectively Direction: smaller-the-better [MW/km^2] Direction: larger-the-better Yes or no
	Geographic requirements	Locational prerequisites for deployment and construction activities	Yes or no

Table S 7. Calculated thresholds based on variance values.

Criteria domain	Criterion	Criterion description/ Quantitative measure	Indicator(s)/Assessment	Thresholds				
				5	4	3	2	1
Economic	O&M cost	Variable O&M cost	[$/kWh] Direction: smaller-the-better	< 15	15	19	22	42 ≤
	Capital investment	Overnight capital cost (OCC)	[$/kW] or [$/kWh] Direction: smaller-the-better	< 5342	5342	6687	7543	10984 <
	Supply chain	Public announcements by suppliers and partners	NEA Small Modular Reactor Index Direction: larger-the-better	≥ 4	3	2	1	1 >
Performance	System efficiency	Thermal-to-electric conversion ratio	[%] Direction: larger-the-better	≥ 33.7		33.3		33 >
	Meeting requirements	Steam temperature	[°C]* Direction: larger-the-better	≥ 630	600	304	300	300 >
	Ramp time	Ramp rate	[%/min]* Direction: larger-the-better	≥ 10		5		3 >
	Scalability	Power capacity	[MWe]* [MWt]* Direction: larger-the-better	≥ 1800 ≥ 1000	600 443	200 150	30 58	30 > 58 >
Reliability/Safety	Lifetime	Technology lifetime	[yr] Direction: larger-the-better	≥ 70	60	50	40	40 >
	System stability	Minimum generation level	[%] Direction: smaller-the-better	< 15		20		25 ≤
	Regulatory uncertainty	Licensing interactions with regulators	NEA Small Modular Reactor Index Direction: larger-the-better	≥ 2				1 >
Environmental	Land impact	Plant footprint	[$10^3 \times m^2$] Direction: smaller-the-better	< 9.11				10 ≤

Table S 8. Calculated thresholds based on RMS values.

Criteria domain	Criterion	Criterion description/ Quantitative measure	Indicator(s)/Assessment	Thresholds				
				5	4	3	2	1
Economic	O&M cost	Variable O&M cost	[$/kWh] Direction: smaller-the-better	< 16	26	42	74	74 ≤
	Capital investment	Overnight capital cost (OCC)	[$/kW] or [$/kWh] Direction: smaller-the-better	< 4311	6687	10984	21348	21348 ≤
	Supply chain	Public announcements by suppliers and partners	NEA Small Modular Reactor Index Direction: larger-the-better	≥ 4	3	2	1	1 >
Performance	System efficiency	Thermal-to-electric conversion ratio	[%] Direction: larger-the-better	≥ 45	39.3	33.7	30.3	30.3 >
	Meeting requirements	Steam temperature	[°C]* Direction: larger-the-better	≥ 530	450	278.5	250.6	250.6 >
	Ramp time	Ramp rate	[%/min]* Direction: larger-the-better	≥ 10	5	4.5	2.5	2.5 >
	Scalability	Power capacity	[MWt]* [MWe]* Direction: larger-the-better	≥ 1800 ≥ 1000	600 443	200 150	30 58	30 > 58 >
Reliability/Safety	Lifetime	Technology lifetime	[yr] Direction: larger-the-better	≥ 70	50	30	10	10 >
	System stability	Minimum generation level	[%] Direction: smaller-the-better	< 15	15	20	40	60 ≤
	Regulatory uncertainty	Licensing interactions with regulators	NEA Small Modular Reactor Index Direction: larger-the-better	≥ 4	3	2	1	1 >
Environmental	Land impact	Plant footprint	[$10^3 \times m^2$] Direction: smaller-the-better	< 5	14	65	157	157 ≤

Table S 9. Calculated thresholds based on slop values.

Criteria domain	Criterion	Criterion description/ Quantitative measure	Indicator(s)/Assessment	Thresholds				
				5	4	3	2	1
Economic	O&M cost	Variable O&M cost	[$/kWh] Direction: smaller-the-better	< 15	15	30	69	69 ≤
	Capital investment	Overnight capital cost (OCC)	[$/kW] or [$/kWh] Direction: smaller-the-better	< 8340	8340	10984	15000	21348 <
	Supply chain	Public announcements by suppliers and partners	NEA Small Modular Reactor Index Direction: larger-the-better	≥ 4	3	2	1	1 >
Performance	System efficiency	Thermal-to-electric conversion ratio	[%] Direction: larger-the-better	≥ 48.4	39.3	33	28.5	28.5 >
	Meeting requirements	Steam temperature	[°C]* Direction: larger-the-better	≥ 500		450		272.7 >
	Ramp time	Ramp rate	[%/min]* Direction: larger-the-better	≥ 10	5	3	2.5	2.5 >
	Scalability	Power capacity	[MWt]* [MWe]* Direction: larger-the-better	≥ 3530 ≥ 1560	2800 1356	1250 1000	330 443	330 > 443 >
Reliability/Safety	Lifetime	Technology lifetime	[yr] Direction: larger-the-better	≥ 80	70	56	40	40 >
	System stability	Minimum generation level	[%] Direction: smaller-the-better	< 15	40	50	60	60 ≤
	Regulatory uncertainty	Licensing interactions with regulators	NEA Small Modular Reactor Index Direction: larger-the-better	≥ 3		2		1 >
Environmental	Land impact	Plant footprint	[$10^3 \times m^2$] Direction: smaller-the-better	< 20	20	65	100	157 ≤