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Article

A Model-Based Systems Engineering Approach for Effective Decision Support of Modern Energy Systems Depicted with Clean Hydrogen Production

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Abstract: A holistic approach to decision-making in modern energy systems is vital due to their increase in complexity and interconnectedness. However, decision makers often rely on narrowly-focused strategies, such as economic assessments, for energy system strategy selection. The approach in this paper helps considers various factors such as economic viability, technological feasibility, environmental impact, and social acceptance. By integrating these diverse elements, decision makers can identify more economically feasible, sustainable, and resilient energy strategies. While existing focused approaches are valuable since they provide clear metrics of a potential solution (e.g., an economic measure of profitability), they do not offer the much needed system-as-a-whole understanding. This lack of understanding often leads to selecting suboptimal or unfeasible solutions, which is often discovered much later in the process when a change may not be possible. This paper presents a novel evaluation framework to support holistic decision-making in energy systems. The framework is based on a systems thinking approach, applied through systems engineering principles and model-based systems engineering tools, coupled with a multicriteria decision analysis approach. The systems engineering approach guides the development of feasible solutions for novel energy systems, and the multicriteria decision analysis is used for a systematic evaluation of available strategies and objective selection of the best solution. The proposed framework enables holistic, multidisciplinary, and objective evaluations of solutions and strategies for energy systems, clearly demonstrates the pros and cons of available options, and supports knowledge collection and retention to be used for a different scenario or context. The framework is demonstrated in case study evaluation solutions for a novel energy system of clean hydrogen generation.

Keywords: energy systems; decision support; systems engineering; model-based systems engineering; systems thinking; multicriteria decision analysis; hydrogen production

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1. Background

The national energy system is constantly evolving, especially given the urgent national goals for energy independence, resiliency, and ambitious goals for decarbonizing the energy sector. These national goals are mirrored by many commercial companies that have their own decarbonization goals. Large companies, including utilities (e.g., Duke Energy, Southern, Vistra, NextEra Energy, Ameren, American Electric Power, Exelon, First Energy, Dominion Energy, WEC Energy Group, Xcel Energy), industrial companies (e.g., Ford Motor, General Motors, American Airlines, Dow, United Airlines, Lockheed Martin, Boeing), IT and communication technology companies (e.g., Apple, Oracle, Microsoft, AT&T, T-Mobile, Verison, Meta), and even oil and gas companies (e.g., Conoco Phillips, Devon Energy, Chevron, Exxon Mobil), announced their goals to achieve net-zero by 2050 [1]. These ambitious targets create a large demand to be met by alternative clean energy solutions. One such solution is clean hydrogen, a unique energy source that enables the deep, large-scale decarbonization of energy sectors that are hard or even impossible to electrify. These sectors include large industrial processes like steel manufacturing, petrochemical processing, pulp and paper production, refining, and medium- and heavy-duty transportation, where electrification is not achievable due to large power demands [2]. Recognizing the high potential of clean hydrogen to make a measurable impact on decarbonization and energy independence goals, the U.S. government has launched several large-scale initiatives focused on enabling an energy system transition to a cleaner, more independent and resilient system. Two large legislative actions, the Infrastructure Bill [3] and Inflation Reduction Act [4], directly support clean energy sources. Industry is actively searching for opportunities to capitalize on the federal incentives to support their financial and decarbonization aspirations. However, given multiple choices and various potential outcomes, selecting a strategy is very complex and multidimensional.

The decision-making around enterprise strategies and portfolio selection has long relied on the traditional well-accepted methodologies like cost depreciation presented via net present value and internal rate of return and cost–benefit analyses [5,6]. In the energy sector, other representative metrics to select a given technology versus others are the levelized cost of energy (LCOE) and avoided cost of carbon. However, the decision makers are faced with multidimensional problems that go well beyond the traditional economic analyses. For example, the net present value (NPV) or internal rate of return (IRR) metrics do not explicitly account for the company goal to achieve net-zero by 2050 or other social factors, such as customers specifically requiring low-carbon sources of electricity, which may shift the dynamics of the company strategy. Therefore, a novel approach is needed for decision makers that integrates multiple interdisciplinary aspects, such as technical, economical, and social.

Therefore, this article describes a novel methodological framework to address the gaps identified in the currently used decision-making approaches for energy systems and explains the concepts, underlying methodologies, and processes of the proposed framework. The remainder of the article is as follows: Section 2 describes the general decision-making process and explains why humans struggle with decisions for complex systems. It also explains the decision-making specifically for energy systems along with supporting methodologies and tools typically used. Lastly, the shortcomings in existing decision-making approaches for energy systems are outlined, suggesting the need for a new approach. Section 3 describes the proposed framework. Section 4 presents a case study demonstrating the framework application for selecting the conceptual solution for a novel energy system tasked with clean hydrogen production.

2. Decision-Making for Complex Systems

This section provides an overview of the decision-making process in general and, more specifically, the methods and tools used for decisions in energy systems. Section 2.1 describes how we, as humans, make decisions and explains why humans struggle with decisions for complex systems. To assist with decision-making, especially for complex problems, a systematic approach and enabling tools are needed. Section 2.2 describes decision-making approaches specifically for energy systems along with supporting methodologies and tools typically used. Lastly, Section 2.3 outlines the shortcomings of existing decision-making approaches for energy systems, and Section 2.4 presents the need for a new type of approach.

2.1. Humans and Decision-Making

We make decisions, small or large, important or not, using four simple steps: (1) understand the problem or need, (2) gather information and identify alternatives, (3) evaluate alternatives, and (4) select the best solution within our understanding. Most contemporary decision-making theories operate on the premise of rationality, assuming that decision makers consistently select the optimal course of action available to them, ending with the best possible solution [7]. However, these theories often overlook the challenge of determining what exactly constitutes the best action. They fail to differentiate between decision scenarios involving just two options and those involving ten, twenty, or even thousands of choices. Numerous studies have suggested that, when confronted with complex decisions, humans rely on heuristics—solutions derived through trial and error or loosely defined guidelines—to guide their choices [8–10].

A considerable body of research indicates that individuals struggle to make rational decisions when faced with an abundance of options, a phenomenon commonly referred to as information overload. Information overload refers to the discrepancy between the sheer volume of information available and humans' capacity to process it effectively. This surplus of information can impede problem-solving abilities and task execution, consequently influencing decision-making. Human brains have finite capacities for information retention, and excessive data can hinder their ability to arrive at rational decisions [11–13]. In fact, ref. [12] suggests that the span of human memory is about seven pieces of information with some small variation.

This natural limitation of the human brain to process information necessitates measures to assist with decision-making, a *decision support system*, especially for decisions for complex problems like the ones in energy systems.

2.2. Decision-Making for Energy Systems

Energy systems are difficult to analyze due to their complexity, which stems from the heterogeneity of and dynamic interdependence between subsystem components and the complexity of the networks that connect them, as well as the uncertainty related to their future state [14]. The complexity of evaluating energy and environmental issues is pointed out by many research studies [15–20] that point to the many sources of uncertainty, long time frames, heavy capital investments, multidisciplinary affecting factors, and a large number of stakeholders with often competing objectives. As such, an application of formal decision analysis methods is warranted and highly encouraged.

The general techniques for capital investments are discussed in [21]. The majority of the methods are economic measures (e.g., IRR and NPV), with only a few capable of integrating uncertainties and non-economic measures, such as real options and sensitivity analyses. IRR and NPV are financial metrics used to assess the profitability and viability of investments. The NPV of an investment represents the present value of its associated cash inflows and outflows, discounted at the market's required rate of return. An investment is financially beneficial and adds value if it has a positive NPV, while it is considered value-diminishing and should be rejected if its NPV is negative [22]. The IRR is the break-even rate of return for an investment. If an investment's IRR exceeds the market's required return, then the investment is financially sound. In contrast, an investment is not financially viable if its IRR falls below the required rate of return that compensates for its risk [22].

Decision-making processes in the energy sector have advanced, drawing from broader investment strategies but tailoring techniques to suit the unique needs of energy systems. A study by Strantzali [16] identifies life cycle assessment, cost–benefit analysis, and multi-criteria decision-making as the top modeling methods for renewable energy investments. Liu's 2021 review [20] adds that, within offshore wind power investment, levelized cost of energy (LCOE), Modern Portfolio Theory, and Real Option Theory are also prevalent. Reference [20] categorizes decision-making techniques into four main groups: basic, advanced, those accommodating uncertainties, and multicriteria methods. Basic methods encompass life cycle assessment and life cycle cost — which assess environmental impacts and economic performance across a system's life span, respectively — as well as discounted cash flow, a conventional tool for early-stage investment evaluation that employs NPV and IRR metrics. A few of the most common methods for multicriteria decision-making are outlined here.

- Pugh concept selection method: Uses a matrix for comparing alternatives as worse, same, or better but does not consider the varying importance of different attributes to the decision-makers [23].

- The multi-attribute utility theory (MAUT): Involves creating a utility function based on the decision-maker's preferences to rank options, typically using a weighted additive function for different attributes, though more complex functions like multiplicative can be used if attributes are interdependent [23,24].
- The analytic hierarchy process (AHP): Relies on pairwise comparisons by experts to measure intangible criteria and establish a hierarchy of priorities. The outranking methods also use pairwise comparisons but allow for the possibility that alternatives may be incompatible [16].
- Agent-based simulation models: These are increasingly popular for energy applications, modeling complex systems with diverse agents and rules, capable of capturing nonlinearity, emergence, heterogeneity, and coevolution, making them effective for evaluating policy impacts on investment decisions and energy markets [19].

A few other methods for strategic capital investment decision-making exist, including the balanced scorecard, value chain analysis, and logical decision trees. However, these methods are less common.

References [25,26] include an in-depth literature review of existing approaches for the evaluation of energy systems. Although these approaches were not specifically designed to aid in decision making, they do offer a comprehensive understanding of current methods for assessing energy systems. The authors incorporated insights from many of these frameworks into their review.

Regarding the use of MBSE to assist in the strategic decision making for new systems, an extensive literature search revealed only a few targeted studies [27–29]. These investigations have provided insightful information, supporting the hypothesis of this paper that MBSE is valuable in the conceptual design stages. However, these studies fall short of combining system concepts with strategic decision making, which is the innovative aspect of the methodology and framework presented in this paper.

2.3. Shortcomings of Currently Used Decision-Making Methods

Each method previously described in this section has strengths and weaknesses when considering its application for the energy systems domain and are discussed below.

The discounted cash flow method has been successfully used for decades to evaluate investment alternatives for various domains, including energy systems. However, the finance-focused assessments tend to be biased towards short-term, less strategic investments whose benefits are easy to quantify [30]. The economics-based investment appraisal methods are also considered inadequate and incomplete to support evaluations of strategic investments because they do not address intangible attributes (e.g., goals for reducing greenhouse gas emissions or social acceptance). As a result, the discounted cash flow method is only considered suitable for short-term investment projects where market uncertainties are small. As noted in [20], due to limited flexibility, the discounted cash flow method is not appropriate for evaluating energy-related projects due to a volatile investment environment, and it should be used in combination with other methods rather than alone.

LCOE is the economics-based methodology commonly used for evaluating strategies and investments for energy systems. It is appropriate and applicable for a wide range of scenarios with different system strategies, investment amounts, regions, and power generation technologies [20]. However, as with the discounted cash flow method, it is not suitable to comprehensively evaluate energy-related projects because of its inability to incorporate multidisciplinary insights. Furthermore, the economics-centered approach and tools may bias decision makers against long-term strategic investment projects, which would impede business innovations [30].

The multicriteria decision-making methods and tools are generally applicable for evaluating energy systems due to their capability to include multiple variables and assess strategies even when competing objectives exist. One should be careful with applying a multicriteria decision analysis when inputs are based on incomplete or vague data since this method may produce unrealistic and misleading results [20]. A significant concern for evaluating strategies in the energy domain is attributed to the fact that many inputs are indeed based on imprecise data, especially when novel energy systems are evaluated.

Another concern is making decision analyses too complex for evaluating conceptual strategies relying on advanced modeling and simulation tools or complex formulas. For the initial selection of potential strategies, decision makers prefer simple-to-understand approaches and would reject complex methods and tools even if they are valid and beneficial for identifying the optimal solution. For example, Idaho National Laboratory has developed a comprehensive and extremely capable Framework for Optimization of Resources and Economics tool suite to analyze the economic potential of various integrated energy systems to identify the optimal operational strategies of such systems [31]. However, the tool can be too complex for decision makers selecting which concept of a new energy system is a better option for their organization.

Other tools available for evaluating energy systems are focused on a specific aspect, usually a single criteria, supporting an in-depth analyses of that given aspect. For example, the Nuclear–Renewable Hybrid Energy Systems framework described in [32] is focused on optimizing the operational strategies of an integrated energy system where nuclear power plants (NPPs) are coupled with renewable energy generators like solar and wind. The framework is flexible and capable of handling many different approaches and analysis needs to evaluate optimal operational strategies between the demand, supply, and dispatching energy to either the electrical grid or industrial process like hydrogen generation. However, this framework is focused on the specific application (i.e., the operational strategy), which precludes its use for an initial evaluation of conceptual energy systems.

Some other examples of tools focused on a single aspect are the FECM/NETL Hydrogen Pipeline Cost Model, which estimates costs for transporting gaseous hydrogen in a pipeline from a source such as a hydrogen production facility to a final destination [33]; the Hydrogen Financial Analysis Scenario Tool, which provides a quick and convenient in-depth financial analysis for new energy systems [34]; and the Hydrogen Demand and Resource Analysis tool, which allows users to view, download, and analyze hydrogen demand, resource, and infrastructure data spatially and dynamically [35].

These tools are incredibly valuable for conducting detailed analyses of specific aspects of an energy system, such as storage or market demands. However, they do not facilitate the initial high-level decision-making process that considers all feasible options for a new energy system. Decision makers often choose concepts that are familiar or widely advertised as the “best solution”. This quick selection is followed by numerous in-depth analyses and evaluations to assess the feasibility of the chosen system configuration. These detailed evaluations often uncover conditions that render the concept unfeasible or challenging to implement, leading decision makers back to the drawing board with wasted efforts and time spent on detailed analyses.

Instead of diving deep into the analysis of a single concept, systems engineering principles in conceptual design strongly advocate for initially exploring as many concepts as possible to ensure the potentially best solution is not overlooked. Ensuring that selected options are highly likely to be feasible is crucial in the design of complex systems and systems of systems before advancing to the detailed analysis phase. This broad, unrestricted exploration, not limited to predetermined solutions, often reveals possibilities that were not originally envisioned. Using systems-thinking practices compels analysts and decision makers to adhere to the “system-as-a-whole” principle. In summary, the traditional economics-focused approach to evaluating energy systems is no longer sufficient, as it is too narrow and too complex to support the informed strategy selection and investment decision-making for novel energy systems.

2.4. The Need for a New Approach

Assessing energy systems requires a multidisciplinary approach that considers various disciplines representing the objectives and perspectives of different stakeholders. This approach allows us to evaluate whether the energy system is achieving its diverse objectives and whether these objectives are achieved in a mutually beneficial way that satisfies all the stakeholders with some interest or connection to the system. Evaluations of energy systems in the literature vary from simplistic, one-dimensional assessments focusing solely on aspects like the environmental and social sustainability of energy technologies [36,37] to more comprehensive, multidimensional studies that incorporate multiple perspectives on energy systems [38,39]. The reference [25] suggests that using just one metric to evaluate results can be incomplete and potentially misleading. This could result in poor decision-making and the choice of less effective solutions.

The multiperspective studies and approaches allow users to gain a better understanding of system scenarios and aid in strategy formulation. Many of these multidimensional analyses aim to compare energy generation technologies, including renewable energy sources [40,41].

In supporting decision-making processes, it is crucial not just to consider multiple dimensions for evaluation but also to be able to recognize and assess trade-offs between them [38,42,43]. This enables designing alternative strategies that can improve all objectives, rather than only prioritizing a single obvious aspect like economics.

3. Proposed Evaluation Framework to Support Decision-Making in Energy Systems

A novel methodological framework is proposed to address identified gaps in the approaches currently used to assess strategies for novel energy systems. The proposed framework also addresses the difficulties associated with a typical decision-making process for any complex system. Section 3.1 describes the concept, methods, and tools used within the framework. Section 3.2 explains the process steps within the framework.

3.1. Framework Concept

Decision makers tend to rely on their experiences and preferences rather than conducting objective evaluations among alternative solutions. Energy systems involve multiple interconnected elements, making it challenging for the human mind to manage the complexity. Without a proper methodology, concept selections carry a high risk of inconsistency and personal biases. This issue increases the risk of choosing a concept that might not be the best fit, potentially rendering the system unfeasible or unsuitable for its intended objectives. The informal evaluation of system concepts typically lacks documentation, which makes it difficult to understand the rationale behind design decisions when they are revisited (e.g., in subsequent project phases or when selecting a solution for a different region). The proposed framework addresses these challenges by facilitating comprehensive early-stage decision-making in energy systems. It offers a conceptual approach, underlying methodologies, and tools to support objective, comprehensive, systematic, and innovation-promoting evaluations of energy system solutions.

The proposed framework uses two conceptual approaches: systems thinking using systems engineering principles and tools and formal decision-making using a multicriteria decision analysis. The application of systems thinking concepts is supported by systems engineering formal approaches and the model-based systems engineering (MBSE) method. The concept of formal decision-making is supported by a combination of Pugh matrix and MAUT methods. The MBSE approach within the system thinking concept is used for guiding the steps within the framework, organizing the problem, and describing the systems in sufficient detail. The multicriteria decision analysis supports the need for an objective, comprehensive, and systematic approach to decision-making.

3.1.1. Systems Thinking

Systems thinking focuses on the interactions of internal system elements and the external interaction of the system with the elements of the larger system that the original system is a part of. Peter Senge called systems thinking the fifth discipline, defining systems thinking as "a way of thinking about, and a language for describing and understanding, the forces and interrelationships that shape the behavior of systems. This discipline helps us to see how to change systems more effectively, and to act more in tune with the natural processes of the natural and economic world" [44]. Systems thinking is one of the core competencies defined in the INCOSE Systems Engineering Competency Framework [45], and it is based on *systems science*, which INCOSE defines as a "transdisciplinary approach interested in understanding all aspects of systems" [46].

It is important to define a *system* to understand better the concept of systems thinking. Donella Meadows defined a system as "an interconnected set of elements that is coherently organized in a way that achieves something" [47]. This simple definition reveals three major elements that must be present in each system: elements, interconnections, and purpose. This definition leads to the key principle of systems thinking: a system is more than the sum of its parts.

Systems thinking relies on a holistic approach that is capable of connecting and contextualizing systems, system elements, and their environment to understand difficult-to-explain patterns of organized complexity [46]. This capability to understand and represent complex interactions is imperative for decision-making for complex systems, which is why systems thinking is seen as the foundational methodology to build the decision support framework in this paper.

Throughout each phase of system development, systems engineers should employ systems thinking. This task involves considering the system holistically, taking into account the entire life cycle, including stakeholders' expectations, user needs, technological advancements, and environmental, social, and policy influences. Systems thinking is a mindset that views the parts of a system in relation to each other and to other systems, rather than in isolation. The systems engineer embodies this approach, ensuring that from design to production, the system meets customer requirements, satisfies user needs, interacts smoothly with other systems, and is economically viable [48].

A systems thinker can see the big picture, recognize interconnections, consider multiple perspectives, and maintain creativity without getting bogged down in details, effectively anticipating future outcomes. This mindset is a must when considering a novel energy system that will be integrated into the large complete energy system involving many elements and stakeholders.

When envisioning a novel energy system, one must also anticipate unexpected behaviors, given the extreme complexity of the energy sector and the integration of a new player into a well-established environment. These unintended consequences can be mitigated by proactively considering how the system will perform and making necessary adjustments from the early stages, starting from system conceptualization. It is essential to adopt a long-term perspective when addressing the need and proposing solutions, as requirements and worldviews can and will change. Technical and societal advancements present new challenges and opportunities that must be integrated into the system design. While revolutionary energy concepts are beneficial, single-purpose designs may not align with future trends. Effective leaders design robust, resilient systems and communicate clearly with stakeholders.

Common methods and tools in systems thinking include systems dynamics and causal loop diagrams, which illustrate relationships between contributors and the system, showing the effects of changing relationships and system behavior over time. Agent-based modeling is another valuable tool, defining the attributes and behaviors of contributors based on changes in the external environment. These approaches help predict system operation, determine necessary relationships, and define required behaviors within the system's context [48].

3.1.2. Systems Engineering

Systems engineering is "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods [46]". The objective of systems engineering is to direct and support the development of complex systems. The discipline of systems engineering is different from traditional engineering disciplines (e.g., electrical, mechanical, structural), as it focuses on a system as a whole instead of a specific part or function of a system. A systems engineer connects multiple disciplines and evaluates system context and stakeholder needs to achieve the optimal system solution.

The goal of systems engineering is to support the delivery of the right product (or right service) on time and within budget. This goal is supported by the objective to provide a common understanding of the system current state and a common vision of the desired future state shared by system customers and suppliers achieved by the application of standardized methods and tools throughout the system life cycle. Systems engineering is particularly important for complex systems where traditional engineering and project management practices are no longer sufficient to manage complexity effectively.

Each system experiences stages in its life cycle as depicted in Figure 1 with systems engineering being able to support each stage. This research is focused on the decision-making at the first stage, the concept development. The phases of the concept development guided by systems engineering methods are presented in Figure 2.

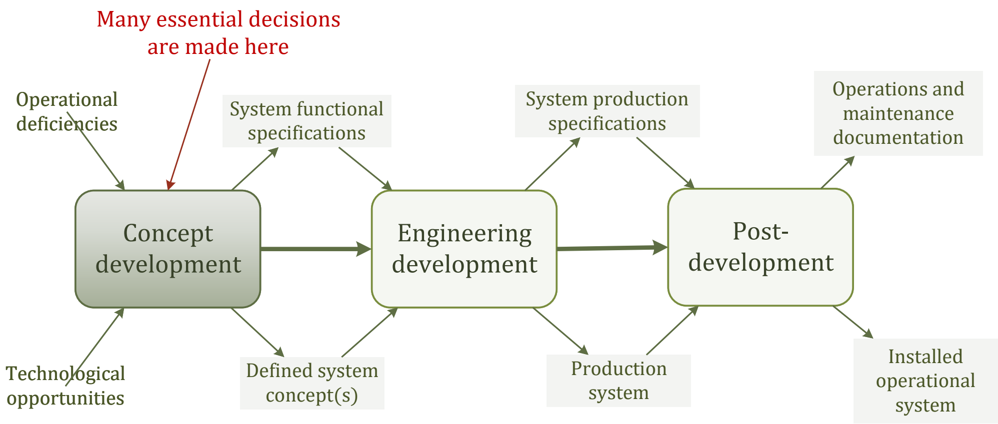

Figure 1. Stages in system life cycle (adopted from [48]).

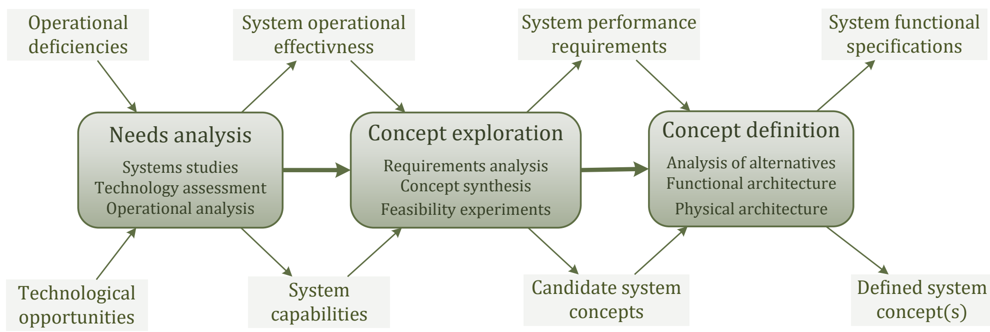

Figure 2. Concept development phases (adopted from [48]).

3.1.3. Model-Based Systems Engineering

The systems engineering processes can be further improved by implementing an MBSE approach. Noguchi describes MBSE as "an emerging paradigm for improving the efficiency and effectiveness of systems engineering through the pervasive use of integrated descriptive representations of the system to capture knowledge about the system for the benefit of all stakeholders" [49]. The system representation artifact (i.e., the *model*) is created in a consistent way by using MBSE modeling languages (e.g., Systems Modeling Language

(SysML) or Lifecycle Modeling Language (LML)). The modeling language allows the system to be holistically described with interactions between its elements, system behaviors, and more via MBSE tools like Cameo Systems Modeler [50] and Innoslate [51].

The INCOSE handbook [46] discusses the benefits of MBSE compared to the traditional, document-based practice, which are improved communications between stakeholders, better capability to manage system complexity, improved product quality, and enhanced knowledge capture and transfer. The primary benefit of MBSE is attributed to the integrated, holistic, single source of truth way to represent the system as depicted in Figure 3.

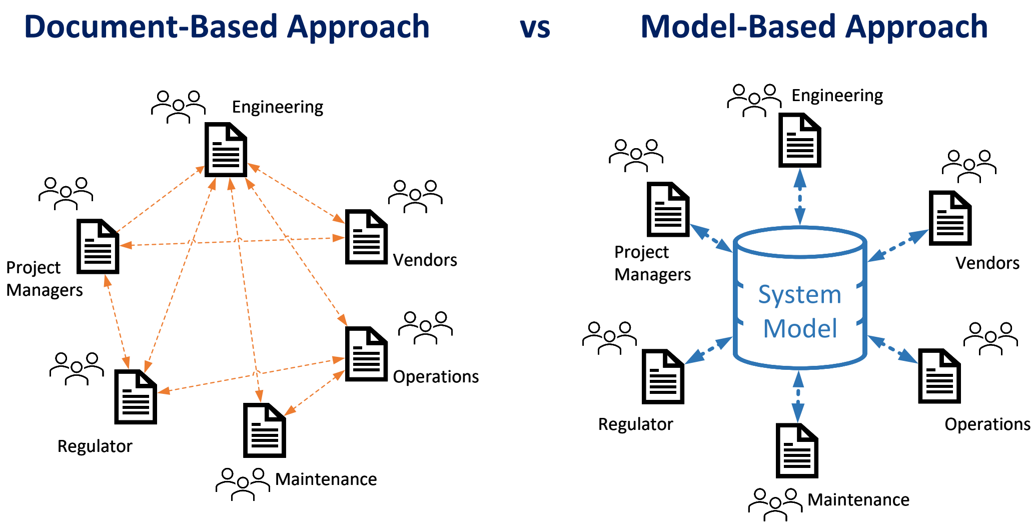

Figure 3. Document-based (**left**) versus model-based systems engineering (**right**).

There is a pressing need for advanced information handling with the large volume of data that must be collected and analyzed to support truly informed decisions. The supporting information and data are multidisciplinary, including technical engineering disciplines (e.g., mechanical, electrical, computer science), economics, and social aspects. Data collection, repository, and analysis is a large task requiring significant time investment. MBSE greatly simplifies the task of information collection and processing and, more importantly, allows added traceability between system elements and associated documents. For example, energy systems are associated with a set of specific regulations from multiple federal and state-level governing organizations. Due to the large amount of information, it is a very complex task to develop a comprehensive set of requirements for a given system. After the set of regulatory requirements has been developed, it is an even more complicated task to identify later on which regulatory document was the basis for the requirement assigned to a component. MBSE enables traceability between system artifacts, such that a given requirement can be assigned a relationship like "sourced from" to a document where the document is also stored as a model artifact. Such a comprehensive data repository is not possible without MBSE.

With all the information captured in a model, the system can be viewed from multiple perspectives (e.g., disciplines, tasks, stakeholders, levels of details) to address specific interests and needs. A change in a system element is reflected in each perspective, which ensures consistency and accuracy of information, version control, and clear communication. These capabilities enable enhanced yet simple visualization of information. At the initial stage of a concept evaluation for a system solution, there is a significant amount of information being collected. This information is to be presented to various stakeholders and decision makers who have different levels of technical background and various interests, thus requiring a specific set of information and level of detail to be presented to provide a clear and concise representation of the proposed system. MBSE provides an ability to create various viewpoints of the same system, each tailored to a specific need or specific audience. MBSE dramatically simplifies change management compared to the document-based approach since a change in one place is reflected throughout the model, ensuring consistency and accuracy of information, version control, and clear communication.

Furthermore, an MBSE approach aids significantly with evaluating trade-offs guiding design decisions. MBSE also permits the examination of "what-if" scenarios, which helps decision makers to try and assess different design options way before finalizing any decisions, which dramatically reduces risk and uncertainties, especially when developing complex novel energy systems.

Moreover, MBSE also enables the reuse of the first-of-a-kind model for an N-of-a-kind application. The idea is to retain the system architecture represented by the model and only modify elements that must be changed to address different conditions (e.g., a site location may necessitate changes in the system design). An MBSE model retains all the information that was used to select the optimal solution for an energy system given specific objectives, context, and constraints. When the context changes, e.g., due to different resources available in a different region, the optimal solution may be different. The evaluation of system conceptual solutions in a changed context would be significantly faster given the first-of-a-kind solution was developed using MBSE compared to a large set of disparate documents that would have to be analyzed to see if a changed context affects any of the requirements and ultimate system conceptual solution.

Yet, some disadvantages and limitations exist. One disadvantage of using MBSE for decision support is the need for initial investment in the software tool(s) and training, where some tools can be complex and are associated with a steep learning curve. To address complexity, it is crucial to develop simple, comprehensive models using tools and languages specifically designed to handle complex systems [52]. The use of MBSE for decision support also has limitations, mainly when dealing with less complex systems where MBSE might be unnecessarily complicated and costly. Furthermore, integrating specialized evaluations into MBSE can be difficult, and using a dedicated external tool for specific analyses may be more effective. For instance, economic assessments involving NPV and IRR are typically conducted in tools like Excel. In such scenarios, carrying out the evaluations using the appropriate external tool may be preferable. Then, if an MBSE approach is utilized, one can import the results into the MBSE model to ensure a complete capture and preserve knowledge.

3.1.4. Lifecycle Modeling Language with Innoslate

As mentioned in the previous section, there are many tool and language alternatives for MBSE. Here, we use Innoslate as the MBSE tool, which is designed to support the entire system lifecycle. It offers a wide array of features, including project management, requirements definition, system modeling and simulation, and verification and validation. Innoslate users can use either the Lifecycle Modeling Language (LML) or Systems Modeling Language (SysML) to develop a system model and present it via diagrams. LML was developed to simplify the elements, relationships, attributes, and diagrams used in systems engineering and project management. In this project, LML language is used.

The LML utilizes a streamlined framework consisting of 12 primary classes and eight subclasses where the subclasses inherit attributes from their parent classes. This structure is designed to capture critical information elements effectively. Attributes of these classes include a "type" attribute, enhancing the definition of each class. LML also encompasses an extensive array of relationships between classes, with the capability for almost every class to relate to itself and to other classes. These relationships also have attributes. The meta-meta model of LML mirrors components of natural language, corresponding to nouns, verbs, adjectives, and adverbs, facilitating a comprehensive language-like structure for practitioners [53].

Several types of LML diagrams are presented later in the case study. Spider diagrams are charts showing hierarchical organization with improved visualization of traceability. A spider diagram can present up to nine levels of decomposition of entities. This diagram conforms to the LML Specification 1.4 [54] definition of a 'spider diagram', which requires visualization for traceability beyond what a typical hierarchy-type diagram can offer [52]. A spider diagram can represent a hierarchical organizational chart for many classes, such as actors, actions, artifacts, requirements, resources, tasks, etc. Asset diagrams are used to show use cases or system concepts. The asset diagram is traditionally known as a block diagram or a physical block diagram. This diagram conforms to the LML Specification 1.4 [54] definition of an 'asset diagram', which requires a diagram representation of the physical components of a system model [52]. The high-level concept of operations is presented as LML action diagrams. The action diagram, traditionally known as a functional flow diagram, is a method of displaying action entities, their interactions via input/output and resource entities, and logical flow. The action diagram conforms to the LML Specification 1.4 [54] definition of an 'action diagram', which requires a diagram representation of the functional components of a system model [52].

Innoslate offers both LML diagrams (e.g., action diagram, asset diagram) and SysML diagrams (e.g., activity diagram, block definition diagram, internal block diagram). There are also several general diagrams (e.g., diagram, N-squared diagram, tree diagram) that users can employ to improve visualization of the system being modeled and the audience the system being presented to. The LML specification [54] provides a correlation between SysML diagrams, LML diagrams, and LML entities, as presented in Table 1.

Table 1. SysML diagram mapping to LML diagrams and ontology [54].

SysML Diagram	LML Diagram	LML Entities (Ontology)
Activity	Action Diagram	Action, Input/Output
Sequence	Sequence	Action, Asset
State Machine	State Machine	Characteristic (State), Action (Event)
Use Case	Asset Diagram	Asset, Connection
Block Definition	Class Diagram, Hierarchy Chart	Input/Output (Data Class), Action (Method), Characteristic (Property)
Internal Block	Asset Diagram	Asset, Connection
Package	Asset Diagram	Asset, Connection
Parametric	Hierarchy, Spider, Radar	Characteristic
Requirement	Hierarchy, Spider	Requirement and Related Entities

3.1.5. Multicriteria Decision Analysis

A Pugh concept selection method, also known as a Pugh matrix, was introduced in 1991 by Stuart Pugh [55]. It was a groundbreaking work at the time, presenting a simple yet powerful and well-structured method for the concept evaluation and selection process. This approach aids in the evaluation of alternative solutions against essential criteria to determine the concept that best fulfills these criteria.

The Pugh matrix is formatted for user-friendliness, prioritizing the clear expression of ideas and evaluation criteria instead of using strict mathematical representations. It organizes criteria vertically and alternatives horizontally, using symbols + (plus), − (minus), and S to indicate better than, worse than, and the same compared to the reference alternative, respectively. Each criterion is assessed simultaneously across all cases. Once completed, the matrix presents a summary at the bottom, highlighting how each alternative aligns with requirements and its strengths and weaknesses. This approach involves iterative reviews of the matrix until the team confirms and approves a preferred concept.

Pugh emphasized the importance of thoroughly evaluating all potential solutions, underscoring the need for a disciplined approach to concept formulation and evaluation to minimize the risk of selecting the wrong concept. The Pugh concept selection approach offers numerous benefits, such as gaining deeper insights into requirements, improving understanding of design problems and potential solutions, visualizing the interactions between proposed solutions, and fostering creativity to generate new ideas. The matrix representation is also very useful because of its simplicity and clear visualization of alternatives' performance against each other. An example of a Pugh matrix is presented in Table 2. Based on the presented criteria scores, Alternative 3 is the best option.

Table 2. Pugh matrix.

Criteria	Alternative 1	Alternative 2	Alternative 3
Criterion A	+	S	+
Criterion B	-	+	S
Criterion C	-	-	+
Total (+)	1	1	2
Total (-)	2	1	0
Total (S)	0	1	1

However, the Pugh matrix approach has limitations. Most notably, it ignores the importance of the decision maker's criteria, meaning all the criteria are equally important. This assumption is typically not the case in reality—decision makers usually prioritize evaluation criteria where, for example, cost could be much more important than the incremental gain in efficiency. As such, the Pugh matrix approach is supplemented in this research by the MAUT method. MAUT uses a utility function developed based on criteria scores where decision makers specify their importance of each criteria compared to others.

This hybrid approach was explored for the concept selection in a subsea processing domain [56]. The concept selection was conducted with team engineers and subject matter experts, and the Pugh matrix approach was used to guide the process and document the results. After completion, the study teams filled out a questionnaire to evaluate the application of the Pugh matrix. The feedback was positive and indicated that a matrix approach to concept evaluation is a good visual communication tool, facilitates an objective dialogue, and helps to improve the overall process and quality of the concept selection.

The study concluded that the suggested layout of the matrix and screening process could be implemented as a decision-making tool for the subsea processing department to enable quality assurance during concept selections [56]. A similar approach is employed in this research—an evaluation matrix is used as a tool to assist with decision-making for energy systems.

The limitations of the Pugh concept evaluation approach are overcome by adding weights based on decision maker preferences and using quantitative scores instead of symbols. A traditional MAUT methodology is adjusted by grouping evaluation criteria into categories. This change allows the prioritization of categories in addition to weighting criteria within each category as compared to a traditional MAUT approach where all evaluation criteria are weighted at the same time. Another small tweak in the methodology is the use of percentages as weights and priorities measures instead of scores, a preference from the participants in [56].

A modified evaluation matrix is presented in Figure 4. Equations used in the matrix are:

$$\text{Weighted Criterion} = \frac{\text{Score}}{\text{Maximum Score}} * \text{Weight} \quad (1)$$

$$\text{Sub-category Weighted Score} = \sum(\text{Weighted Criterion}) \quad (2)$$

$$\text{Category Sum} = \text{Sub-category Weighted Score} * \text{Priority} \tag{3}$$

The meaning of scores and their values should be established via discussion with the decision makers based on their preferences and project specifics. The score ranges could be 1–3, 1–10, or 1–100, where the lower score represents "the worst" and the highest score represents "the best". The meaning of the scores can vary greatly between the projects and even teams performing the assessment.

		Priority	Evaluation criteria	Weight	Alternative 1		Alternative 2		Alternative 3	
		%		%	Score	Weighted	Score	Weighted	Score	Weighted
CATEGORIES	Category A		Criterion A.1							
			Criterion A.2							
			Criterion A.3							
			Sub-category weighted score							
			Category Sum							
	Category B		Criterion B.1							
			Criterion B.2							
			Criterion B.3							
			Criterion B.4							
			Sub-category weighted score							
			Category Sum							
	Category C		Criterion C.1							
			Criterion C.2							
			Sub-category weighted score							
			Category Sum							
Σ%			Overall weighted score							

Figure 4. Modified evaluation matrix.

For example, an evaluation of system performance could use the following scoring scheme:

1. Much worse than required;
2. Somewhat worse than required;
3. As required;
4. Somewhat better than required;
5. Much better than required.

An evaluation of compliance with the requirements could use a different scoring scheme [56]:

1. Not compliant;
2. Major compliance gap;
3. Compliance gap;
4. Minor compliance gap;
5. Insignificant compliance gap;
6. Fully compliant.

The weight and priority scores should add up to 100% in the approach presented here.

An example of a completed modified matrix is presented in Figure 5 with the score scheme of 1–5, with 1 being the worst and 5 being the best.

		Priority %	Evaluation criteria	Weight %	Alternative 1 Score	Alternative 1 Weighted	Alternative 2 Score	Alternative 2 Weighted	Alternative 3 Score	Alternative 3 Weighted
CATEGORIES	Category A	50%	Criterion A.1	50%	3	30%	2	20%	3	30%
			Criterion A.2	30%	4	24%	2	12%	3	18%
			Criterion A.3	20%	3	12%	3	12%	5	20%
			Sub-category weighted score	100%		66%		44%		68%
			Category Sum		**33%**		**22%**		**34%**	
	Category B	40%	Criterion B.1	40%	5	40%	5	40%	5	40%
			Criterion B.2	30%	4	24%	2	12%	4	24%
			Criterion B.3	10%	4	8%	2	4%	3	6%
			Criterion B.4	10%	3	6%	3	6%	4	8%
			Sub-category weighted score	90%		78%		62%		78%
			Category Sum		**31%**		**25%**		**31%**	
	Category C	10%	Criterion C.1	60%	5	60%	4	48%	3	36%
			Criterion C.2	40%	4	32%	3	24%	2	16%
			Sub-category weighted score	100%		92%		72%		52%
			Category Sum		**9%**		**7%**		**5%**	
	Σ%	100%	Overall weighted score		73%		54%		70%	

Maximum score: 5

Figure 5. Example of a completed matrix.

3.2. Framework Processes

The proposition of this research is the new decision support system, a framework that uses systems engineering principles and tools to support decision-making in energy systems. This section outlines the processes within the proposed framework, as well as the tools and methods used to support them.

As discussed in Section 2.1, the typical decision-making process has four steps:

1. Identify the problem;
2. Generate solution alternatives;
3. Evaluate alternatives;
4. Select the best alternative.

The steps in the decision-making process are well aligned with the phases in the concept development, as shown in Figure 6. This alignment is the basis of the proposed decision support system—instead of relying on heuristic approaches to make decisions, why not employ a structured, systematic, well-established approach offered by systems engineering? The decision support system workflow is presented in Figure 7. The framework workflow is subdivided into three phases, which are discussed here.

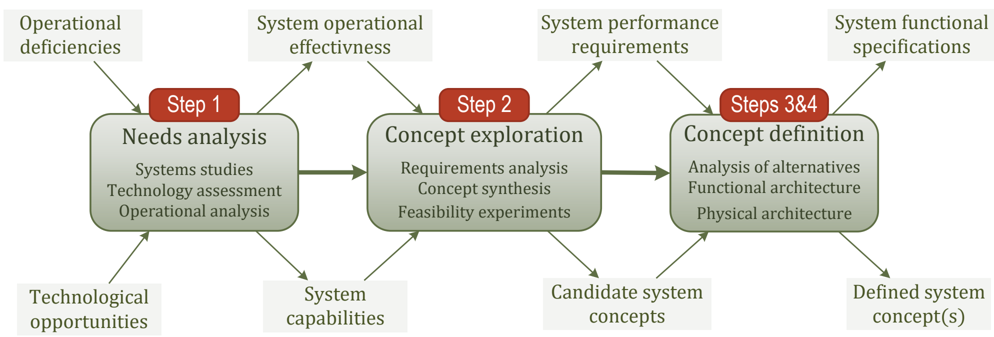

Figure 6. Decision-making step alignment with the concept development process (adopted from [48]).

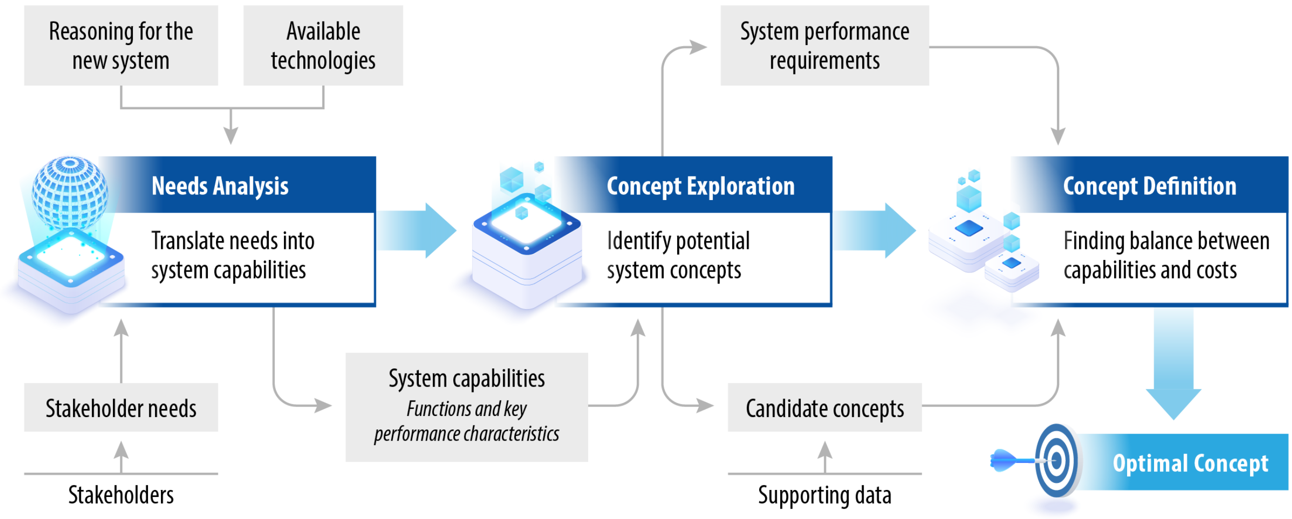

Figure 7. Proposed framework phases for a decision support system for energy systems.

3.2.1. Needs Analysis

This phase looks into the **"Why"**, that is, why the new system is needed and if there are technologies that can address the need. The main goal of the needs analysis phase is to prove that there is a real need and market for a new system. It must show that this need can be met cost-effectively and with acceptable risk by available technologies or technologies to be developed as part of the project.

When determining the need for a new energy system, engineers and decision makers must employ systems thinking; i.e., the system is evaluated holistically taking into account the entire life cycle, including user needs, technological advancements, and environmental, social, and political aspects [48]. This mindset is a must when considering a novel energy system being integrated into a large, whole energy system involving many elements and stakeholders. Systems thinking is especially important at the very early stage when strategies for new systems are being developed and explored. The assessment of potential strategies should be wide, considering as many solutions as possible, instead of going deep into analyses of a single concept. Focusing on the details of a single solution inevitably restricts the consideration of other solutions, which often results in a suboptimal strategy selection. The importance of being able to see the big picture, recognize interconnections, consider multiple perspectives, and maintain creativity without getting hampered by details cannot be overstated when deciding strategies for novel energy systems.

The needs analysis phase has three inputs—the initial reasoning for the new system, available applicable technologies, and stakeholder needs for the new energy system. The stakeholder needs must be comprehensive such that, ideally, the needs of all potential stakeholders are collected and analyzed. To have a comprehensive picture of all the needs for the new system, one must first have a clear understanding of all the stakeholders. Therefore, the phase includes identifying all the entities, including organizations and individuals, who may have an interest or involvement with the new energy system throughout its life cycle.

After all the stakeholders are identified and their respective needs and preferences for the system are collected, the next step is to translate the needs and desires into a clearly defined set of system capabilities. The system capabilities, which are the outcome of this phase, must include high-level system functions and key performance characteristics. The high-level functions describe what the system must do to satisfy the needs of the system. The key performance characteristics should describe, at a high level, how well the system should perform to satisfy the need. For example, the main functions for an energy system could be as simple as generate energy, convert energy to electricity, and deliver electricity to the grid. The key performance characteristics will specify, for example, required capacity, availability, and costs.

The activities in this phase are conducted using MBSE modeling tools. Stakeholders are identified, their needs are collected and analyzed, and initial requirements are developed using MBSE language artifacts like requirements, blocks, and relationships. While the systems engineering principles could be invoked using a document-based approach, an MBSE approach offers significant improvements. Section 3.1.3 offers additional details about the benefits of using MBSE versus a document-based approach.

3.2.2. Concept Exploration

In this phase, potential system concepts are identified and examined to address two key questions: "What performance is required of the new system to meet the perceived need?" and "Is there at least one feasible approach to achieving such performance at an affordable cost?" [48]. The goal of this phase is to establish a feasible goal for a new energy system before committing significant resources to its detailed exploration and development. The outputs of this phase are high-level performance requirements and a set of candidate system concepts.

It is critical to have more than one alternative to explore and understand the range of possibilities for satisfying the need. Having multiple alternatives allows decision makers to realize the possible solutions and understand the pros and cons of each. Such an exploration-driven attitude allows and promotes the possibility of finding the optimal solution given the unique set of circumstances driven by stakeholder needs (e.g., reliable and cost-efficient green energy), regional context (e.g., favorable meteorological environment for wind power), market demands (e.g., projected energy demands given regional economics), social preferences (e.g., local community acceptance of a certain energy solution), etc.

To enable the identification of an optimal solution, various concepts of a new energy system must be considered and later evaluated given multiple technical and economical considerations (e.g., capital costs, operations and maintenance costs, technology maturity, reliability, and operability). As discussed in Section 2.4, it is important to include a third dimension in the decision-making: social considerations. These include aspects ranging from federal policies affecting the future of the energy sector to local community preferences toward a certain energy technology. All three dimensions are important to the overall system success, and thus they must be included in the concept development stage to make a truly informed solution selection.

This phase includes evaluations needed to develop supporting data to evaluate and compare identified candidate concepts. The evaluations, as mentioned earlier, fall under three large areas: technical, economical, and social. Technical analyses include aspects like required capacity, reliability, availability, maintenance, technology readiness, necessary workforce, and supply chain. The technical characteristics are mostly quantitative (e.g., capacity, efficiency, reliability), but some can be qualitative (e.g., technology maturity).

Economical analyses are mostly traditional financial assessments of investments and profits with metrics like NPV and IRR with metrics like LCOE included for energy systems. The economic assessments are largely quantitative, but some evaluations (e.g., investment risks) could be qualitative.

Assessments of social perspectives are generally less definitive and, therefore, could be more challenging, since they are mostly qualitative. The social considerations for an energy system involve things like climate goals, energy justice, and local community preferences. Stakeholder needs identification and evaluation becomes very important to support an evaluation of the social dimension of a proposed energy system.

It is worthwhile to mention that some considerations are cross-disciplinary. Federal policies, as an example, affect each dimension. The technology development and maturity are affected by federal funds allocated to research and development, while the commercial sector's willingness to further invest into a given technology is affected by the general energy policies of the federal government. The technology maturation promotes technology adoptions and deployment, which in turn significantly affects economics where larger-scale deployments reduce the costs, phenomena known as economies at scale and the technology learning curve.

The economics of a given energy technology may be dramatically affected by federal policies like investment or production tax credits and special financing schemes. There can be a reinforcing behavior where favorable economic conditions incentivize more deployments and larger-scale deployments drive the cost down. The social perspectives affect the federal policies, which affect both the technical and economic perspectives, as discussed above. On the other hand, federal policies also influence social perspectives. This impact can happen by providing information to the public about the pros and cons of various energy technologies or by incentivizing private investments and engagement in the novel energy solutions (e.g., household solar panels).

This phase is supported by MBSE, as well as multiple discipline- and application-specific tools and methods. Technical, physics-based models are available to develop insights into system performance, while numerous economic models and tools are available to evaluate financial performance. Some social aspects could be evaluated quantitatively using appropriate models and tools (e.g., GHG emissions for various technologies could be assessed using the GREET model [57]). Other social parameters (e.g., local community acceptance) will remain qualitative and could be documented using the requirements in MBSE and then evaluating how well each concept satisfies the requirement.

To summarize, it is important for the concept exploration phase to consider as many alternatives as possible and gather as much information as practical to derive technical, economical, and social metrics for each alternative. It is important to keep the evaluation at a high level to keep the efforts manageable and proportional to the level of detail needed to enable an informed decision about the optimal solution.

3.2.3. Concept Definition

This phase selects the preferred system concept. It answers the question "What are the key characteristics of a system concept that would achieve the most beneficial balance between capability, operational life, and cost?" [48].

This is the phase where the identified candidate concepts are evaluated based on the collected and developed supporting data. A trade-off analysis is conducted using the multicriteria decision analysis approach described in Section 3.1.5. The evaluation criteria are also developed in this phase to support the decision analysis. It is critically important that the decision makers participate in developing evaluation criteria so that resulting trade-off analyses are realistic and truly supportive of decision-making process.

The activities in this phase are guided by MBSE. The trade-off studies could be conducted using dedicated tools (e.g., Excel spreadsheet or Matlab) or MBSE-specialized tools if they are available within the chosen MBSE modeling software.

4. Case Study on Clean Hydrogen Production

This section presents a case study demonstrating an application of the proposed framework for selecting the conceptual solution for a novel energy system tasked with clean hydrogen production with the focus on supporting investors and utility executives with their strategic decision making. As mentioned in Section 3.1.4, the MBSE approach is accomplished with Innoslate using LML. The models and other files for this case study are available in https://github.com/lawrencesv/MBSE-for-decision-support, accessed on 26 July 2024.

4.1. Phase 1: Needs Analysis

Here, we define the reasoning for the system development, identify available technologies, and identify stakeholders and their needs.

4.1.1. Problem Definition

System objective: generate clean hydrogen. The motivation for the new system is attributed to the incentives for clean hydrogen generation offered by the Inflation Reduction Act (IRA) [4] signed into the law in 2022. IRA offers production tax credits for clean hydrogen generation up to USD 3 per kg of hydrogen given the lifetime emissions are less than 0.45 kg of CO_2 per kg of hydrogen. Therefore, the must-have requirement for the new system is to generate hydrogen with a system where the GHG lifetime emissions are at or below 0.45 kg CO_2 / 1 kg H_2.

4.1.2. Available Technologies

Given the main prerequisite of low GHG emissions, a few technical solutions are possible.

A. Steam methane reforming with carbon capture and sequestration. In a steam methane reforming (SMR) method, hydrogen is produced by reforming methane gas using steam. Natural gas is the feedstock and primary energy source for the system. Nearly all hydrogen in the United States is produced using this method. The method is well known and relatively inexpensive, using mature technologies. The main concern is the high level of GHG emissions—about 9 kg of CO_2 is released per 1 kg of generated hydrogen.

To overcome the challenge of high GHG emissions to satisfy the primary requirement for the new system, a carbon capture and sequestration (CCS) system must be included. Several CCS methodologies exist and are mature and available for large commercial applications [58].

B. Water electrolysis. In this process, water is split into hydrogen and oxygen using electrochemical processes. Electrolysis is a zero-carbon process, and lifetime carbon emissions are only attributed to supporting processes in the life cycle, such as electricity sources. Currently, the electrical grid in the United States is not qualified as low carbon since the majority of its electricity is generated using fossil-based energy sources [59]. Therefore, to satisfy the prerequisite for the system, a low-carbon or carbon-free energy source must be used for hydrogen generation via electrolysis, which includes renewable and nuclear energy sources. The two main electrolysis types are low-temperature electrolysis (LTE) with operating temperatures slightly below 100°C and high-temperature steam electrolysis (HTSE) with operating temperatures of 700–850°C [60]. The available LTE technologies are alkaline water electrolysis, anion exchange membrane water electrolysis, and polymer electrolyte membrane (PEM) water electrolysis. HTSE uses solid oxide water electrolysis cell (SOEC) technology.

Alkaline water electrolysis is a well-established mature technology for industrial hydrogen production up to the multimegawatt range in commercial applications across the globe [60]. The benefits are a well-established technology commercialized for industrial applications, relatively low cost, stability in the long term, and non-reliance on noble metals.

Anion exchange membrane water electrolysis is a developing technology, seen to be more beneficial compared to alkaline technology due to its low cost and high performance. Despite the significant advantages, it requires further research and development (R&D) toward the stability and cell efficiency essential for large-scale or commercial applications [60].

PEM electrolysis is another mature technology applicable to large-scale commercial applications. It is faster and safer than alkaline water electrolysis. The major challenge associated with PEM electrolysis is the high cost of the components [60].

SOEC is an electrochemical conversion cell converting electrical energy into chemical energy. Typically, an SOEC operates with steam at high temperatures (500–850 °C), which significantly reduces the power consumption and increases the energy efficiency, leading to a strong reduction in hydrogen cost due to power consumption being the main contributor to the hydrogen production cost in electrolysis [60]. The disadvantage of SOEC technology is that it has a lower technical maturity. However, the recent technological advancement demonstrates a dramatic increase in efficiency, stability, and durability [61]. These developments have the potential to outperform conventional water electrolysis systems, paving the way for highly efficient and cost-effective hydrogen production.

C. Microbial biomass conversion. This method takes advantage of the ability of microorganisms to consume biomass and release hydrogen. Microbial electrolysis cells harness the energy and protons produced by microbes, with an added small electric current to produce hydrogen. This technology allows us to produce hydrogen from resources that otherwise cannot be used for fuel production while significantly reducing the amount of energy normally needed for wastewater treatment. While this technology is valuable and promising, it is still at the initial stages of R&D, and it will take several years before it can be commercialized and scaled for large-scale hydrogen production.

This brief overview of available technologies leads to the conclusion that, to meet the essential requirement of low GHG emissions, appropriate technologies are either an SMR with a CCS system or electrolysis with a clean energy source like renewable or nuclear energy. From this comparison of the advantages and disadvantages of electrolysis technologies [60], alkaline and PEM LTE technologies are ready for large-scale commercial deployment. The two technologies compare fairly similarly to each other [62] in terms of performance, cost, lifetime, and safety. Given the similarity between the two, the choice can be made at a later stage of the system design when the physical architecture is developed.

For the case study of a high-level concept selection, the general technology of LTE is detailed enough without specifying PEM or LTE. On the HTSE side, SOEC is rapidly maturing in terms of commercialization and large-scale deployment [61]. Therefore, three technologies are considered in the case study:

1. An SMR with a CCS system, often referred to as blue hydrogen;
2. Electrolysis using LTE technology;
3. Electrolysis using HTSE technology.

The preference for a technology depends on the client's need and regional conditions (for example, the availability of natural gas for the SMR method or access to nuclear energy). For this case study, all three technologies are assumed feasible, there is access to the natural gas supply, and there is an NPP in close proximity to the envisioned site for the new hydrogen production plant.

Other large parts of the conceptual hydrogen generation system are:

- **Hydrogen production capacity**: the main input to the system initial design. The system capacity depends on specific customer needs as well as current and projected market demands. Capacity dramatically affects the unit cost of hydrogen due to the economies-at-scale factor; that is, a larger capacity results in a lower unit price. The capacity is also the main factor affecting capital costs and, therefore, the economics of the system.
- **Hydrogen storage capacity**: determined based on how much hydrogen should be stored before it is transported to the customer. The availability of hydrogen, that is, the consistent delivery of hydrogen, is important to industrial hydrogen consumers, and storage capacity could serve as the means to ensure hydrogen availability even if the facility is down for a short period of time (e.g., for maintenance).
- **Transportation of hydrogen**: options are determined based on the location of the hydrogen generation facility compared to the points of use. Possible solutions are high-pressure hydrogen tube trailers, liquefied hydrogen tankers, or pipelines. Other transportation solutions are currently being developed, but they are not ready for commercial deployment and are not considered for this case study.

Options for a hydrogen generation system are depicted in Figure 8. There are five major choices for the system: production capacity, technology, energy source, storage capacity, and transportation option. One feasible solution is highlighted in Figure 8, i.e., a capacity of 100 tons of hydrogen per day, HTSE technology, nuclear energy source, small capacity for hydrogen storage system, and transportation of high-pressure hydrogen via tube trailers. However, many other solutions are feasible. With only three alternatives considered for each main choice, there are $3^5 = 243$ possible options for a system configuration or system architecture patterns [27]. Understandably, making an informed decision between these many options using heuristics is not a reasonable approach, which only strengthens the argument of a need for a better decision support system.

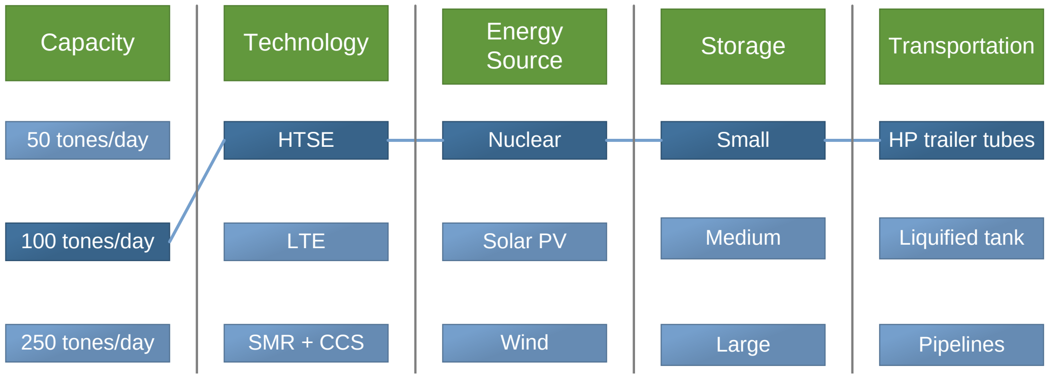

Figure 8. Possible solutions for a hydrogen production system (one feasible solution is highlighted).

4.1.3. Stakeholders

The system's success is improved dramatically when all stakeholders are identified and their needs are carefully examined. In many cases, stakeholders are overlooked at the initial system development stage, which results in large modifications to the initially envisioned approach when stakeholders and their needs are discovered later. For example, the local community is usually affected by a new energy system, yet community needs and preferences traditionally have not been considered in the process for the initial system design decisions. Consider a scenario where a hydrogen production system is envisioned with solar power as an energy source. With all the economic and technical analyses in place, developers move with a site selection only to discover that the local community opposes the installation of solar farms to preserve the aesthetics of the natural surroundings. This important information needs to be considered at the beginning of the project to either select another energy source or a different location for the hydrogen facility.

MBSE provides the opportunity to integrate different views of multiple disciplines at a very early stage of system development. Stakeholders of a hydrogen generation system are shown in Figure 9, where system stakeholders are represented via a spider diagram in Innoslate [51]. In this case, spider diagram elements representing stakeholder types, e.g., Investors are "statements" class artifacts sourced from an external "Stakeholders" Word document that was used to collect information about the system stakeholders. The arrows in the spider diagram are the "source of" type of LML relationships, showing the traceability between the artifact in the model and the source of information. Alternatively, stakeholder types could be represented as the Artifact class with parent–child relationships between "Stakeholders" and stakeholder groups, e.g., "Investors" represented as the "decomposed by" type of LML relationship.

This case study considers the following stakeholders:

- **Investors:** a single investment company or a set of investors.
- **Hydrogen plant owner or operator:** a company that owns a single facility or a utility owns and operates multiple energy systems, potentially including generation, transmission, and in some cases, distribution energy systems in their portfolio.
- **Hydrogen equipment manufacturers:** companies manufacturing main hydrogen production systems and components (e.g., electrolyzers) and supporting systems (e.g., hydrogen storage systems and components).
- **Hydrogen customers:** existing and potential large-scale commercial hydrogen users. A hydrogen consumer could be a large industrial facility that already uses hydrogen as the feedstock for their processes (e.g., ammonia production), industrial enterprises with an interest in novel hydrogen applications (e.g., synthetic fuel producers), or large-scale hydrogen suppliers, like hydrogen hubs supporting smaller hydrogen consumers.

- **Electrical grid operators:** companies that operate regional and national electrical grids. The relevance of the electrical grid is twofold. First, the concern about electricity otherwise available to the grid being diverted to generate hydrogen, which is the case with existing NPPs. Secondly, the benefit of using hydrogen as an energy storage to supplement grid demands during emergent electricity shortages (e.g., weather-related unavailability of renewable electricity generators).
- **Local community:** cities, towns, indigenous tribes, etc.
- **Government:** federal, state, and local governments.
- **Regulators:** federal, state, and local entities whose objectives and obligations are to ensure public and environmental safety of the new energy system throughout its entire life cycle.

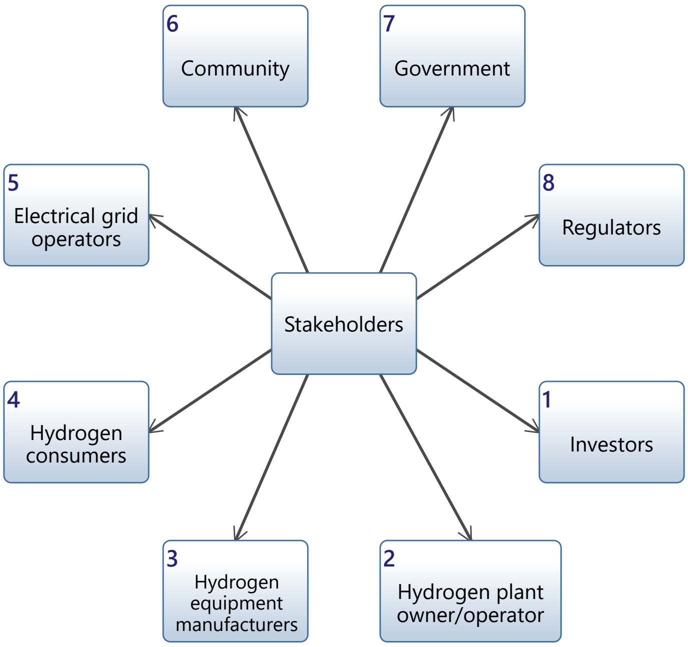

Figure 9. Stakeholders of a hydrogen generation system.

Additional stakeholders may include legal entities, certification organizations, workforce development organizations, etc. However, these secondary stakeholders become important during the later stages of system development and do not need to be considered at the conceptual system selection stage.

4.1.4. Stakeholder Needs

Either one or multiple stakeholders have a need for the new system, which is the reason for the system design and construction. Other stakeholders may not have a need for the system itself, but they have requirements for the system performance. The stakeholder needs and concerns for a hydrogen generation system are discussed below. MBSE assists greatly with the needs analysis, where it serves as a data collection and analysis tool. MBSE enables traceability between stakeholders and their needs and model artifacts provide a clear representation of the information; see Figure 10 for MBSE examples.

- **Investors:** The need for the new energy system is to generate profit.
- **Hydrogen plant owner or operator:** The main objective is the safe and profitable operation of the facility. An objective that recently became the top priority for many utilities is reducing GHG emissions. Driven by the net-zero goals set at the enterprise level, many electrical utilities are developing long-term strategies for an integrated energy system where preferences are being shifted from fossil-based to clean energy sources. The decarbonization goals become even more important given the plans

of shutting down coal-driven power plants, where the lost energy sources must be efficiently and urgently replaced with clean energy sources.

- **Hydrogen equipment manufacturers:** The main objective is to generate profit from manufacturing hydrogen-related systems and components with supporting objectives of growing capacity, improving technical characteristics, and ensuring the safe and reliable operation of their equipment. Climate-related goals are also often an important objective.
- **Hydrogen customers:** The main objective is to have consistent access to a large volume of high-quality hydrogen at a reasonable price. The secondary objective that is becoming progressively more important for many enterprises is reducing GHG emissions from their processes.
- **Electrical grid operators:** The objectives of the grid operators are to have reliable grid operations and an adequate system capacity to provide electricity without interruptions to all their customers. This objective is supported by the goal of having a diverse set of generators to ensure grid resiliency in cases of an expected increase in electricity demands (e.g., peak hours) or during emergent conditions when some sources become unavailable.
- **Local community:** The main objectives of a local community are uninterrupted access to electricity and other energy sources, climate-related goals, safe operations of the industrial facilities, and economic goals, such as employment opportunities and tax revenue from the businesses. An equally important objective is the preservation of natural resources—the amount of resources needed to support a new energy system, the environmental quality of natural resources, and the protection of the visual appeal of the local area and its surroundings.
- **Government:** The main objectives of the government for energy systems are to ensure equitable, realizable, and affordable access to energy sources for the people, ensuring environmental quality and the protection and preservation of natural resources, all while supporting the nation's economic goals. Driven by the urgency to combat climate change and the need to enhance energy sector security, resilience, and independence, the government has a large focus on the technological advancement of novel energy solutions and technologies. The government's support of the energy sector is provided through various incentives (e.g., the production and investment tax credits offered in IRA). The incentives are often offered at both federal and state levels, promoting the commercial advancement of certain energy solutions.
- **Regulators:** These agencies include the Nuclear Regulatory Commission, Federal Energy Regulatory Commission, Environmental Protection Agency, Occupational Safety and Health Administration, etc.

	24/7/365 supply of hydrogen	Generate profit	High-quality hydrogen	Large-volume supply of hy…	Low-cost hydrogen	Preserve and protect natura…	Reduce GHG emissions	Reliable and resilient electri…	Reliable operation of hydro…	Resilient energy sector	Safe operation of hydrogen …
1 Investors		×							×		×
2 Hydrogen plant owner/operator		×	×						×		×
3 Hydrogen equipment manufactur…	×	×	×	×	×				×		×
4 Hydrogen consumers	×		×	×	×		×		×		
5 Electrical grid operators								×			
6 Community						×	×	×			×
7 Government						×	×	×		×	
8 Regulators						×					×

Entity	Rationale
Generate profit	Generate profit by producing hydrogen with positive NPV and IRR>5%
Safe operation of hydrogen plant	Hydrogen facility must be safe to operate in compliance with all applicable regulations
24/7/365 supply of hydrogen	Provide uninterrupted supply of hydrogen
Large-volume supply of hydrogen	Provide hydrogen at required large capacity
Low-cost hydrogen	Cost of hydrogen should be comparative to the hydrogen market price in the region
High-quality hydrogen	Hydrogen should be high-purity to support industrial processes
Reduce GHG emissions	Hydrogen generation process should have well-to-gate lifecycle greenhouse gas emissions not more than 4.0 kg of CO2 per kg of hydrogen
Reliable and resilient electrical grid	Electrical grid should provide reliable operations at all times and be resilient against sudden changes in supply and demand
Preserve and protect natural resources	Minimize use of natural resources, such as air, water, land, rare minerals, fossil resources, etc. and ensure the resources are protected from potential harm caused by industrial processes
Resilient energy sector	Energy sector should have adequate capacity to support national needs and be resilient against emergent changes on domestic and international markets

Figure 10. Stakeholder needs analysis in MBSE: (**left**) traceability between stakeholders and needs and (**right**) concise list of stakeholder needs.

4.1.5. System Capabilities

The system capabilities are described as functional and performance characteristics of the system presented as "requirements". Requirements are a sub-class of the "statement" class in LML. Requirements are handled in Innoslate via requirement documents or via SysML requirement diagrams. The requirement document artifact is used for the case study due to its simplicity and intuitive document-like format familiar to the decision makers. Traceability between stakeholders, their needs, and requirements is enabled by MBSE. Another benefit of MBSE is the ability to develop high-quality requirements satisfying established characteristics of well-written requirements: necessary, appropriate, unambiguous, complete, singular, feasible, verifiable, correct, and conforming [46]. The high-quality requirements will not only support the concept development stage as part of the decision support framework, but they will be the foundation of the next phase of the system lifecycle, engineering development.

An example of the relationships between the "safety" performance requirement and associated stakeholder needs and stakeholders is shown in Figure 11 where the "PR-5, Safety" requirement is one of the "performance requirements" which is derived from the stakeholder need "safe operation of hydrogen plant" expressed by five stakeholder groups (i.e., investors, hydrogen plant owner/operator, hydrogen equipment manufacturers, community, and regulators).

The output of this phase, system capabilities, is presented as system functional and performance requirements, shown in Figure 12 and Figure 13, respectively.

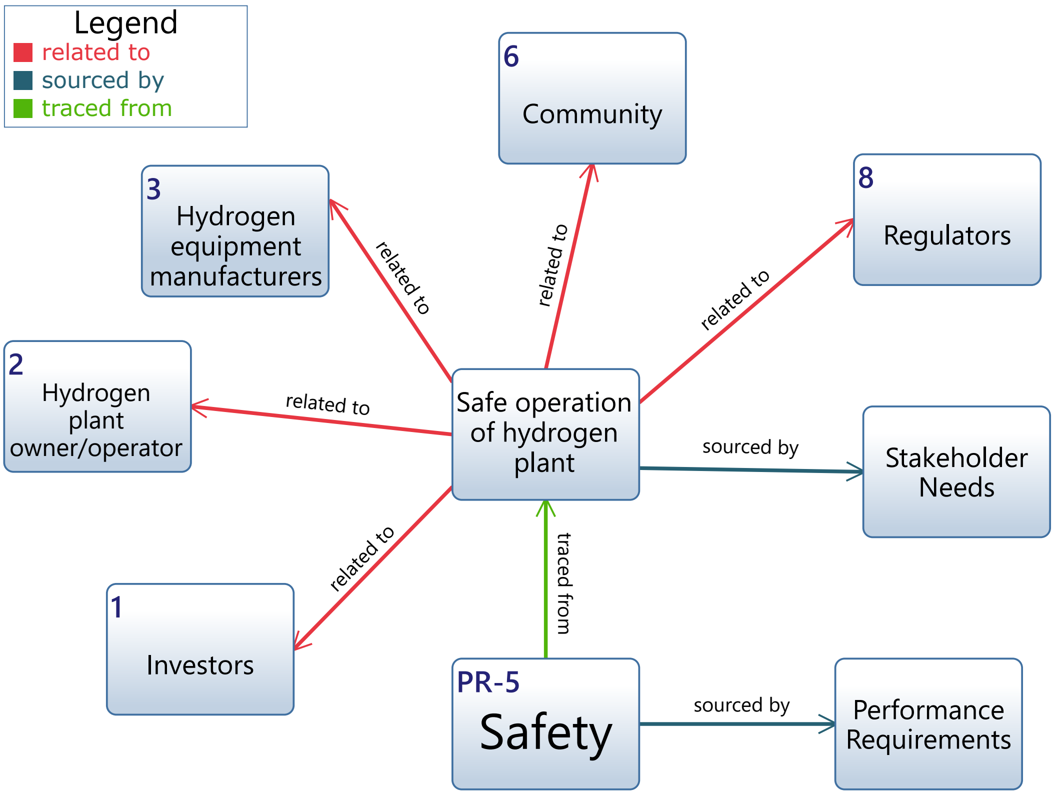

Figure 11. Example of traceability of requirements in Innoslate.

Entity	Rationale	Labels
FR-1 Generate Hydrogen The system shall generate hydrogen at required production rate	The system production rate and availability of hydrogen supply is specified by the hydrogen customer(s)	Functional Requirement
FR-1.1 Provide infrastructure for … The system shall provide infrastructure to enable and support hydrogen generation	The infrastructure includes production system(s) and supporting system(s) that enable generation of hydrogen and is dependent on selected hydrogen production technology and required technical characteristics (e.g., production rate)	Functional Requirement
FR-1.2 Provide resources for H2 … The system shall supply resources necessary for hydrogen generation	The resources needed for hydrogen generation depend on selected technology and may include: energy, water, land, feedstock, etc.	Functional Requirement
FR-2 Purify Hydrogen The system shall purify hydrogen to meet the required level of hydrogen quality	The required level if hydrogen quality is specified by the hydrogen customer(s)	Functional Requirement
FR-2.1 Provide infrastructure for … The system shall provide infrastructure to enable and support hydrogen purification	The infrastructure for H2 purification is dependent on required quality of hydrogen and selected technology of hydrogen generation; infrastructure includes main and supporting system(s)	Functional Requirement
FR-2.2 Provide resources for H2 … The system shall supply resources necessary for hydrogen purification	The resources for hydrogen purification are dependent on the required quality of hydrogen and technology of hydrogen production	Functional Requirement
FR-3 Store Hydrogen The system shall store generated hydrogen	The hydrogen storage capacity is determined based on the requirement to have uninterrupted supply to the hydrogen customer(s)	Functional Requirement
FR-3.1 Provide infrastructure for … The system shall provide infrastructure to enable and support hydrogen storage	The storage infrastructure is dependent on available hydrogen storage technologies and required characteristics	Functional Requirement
FR-3.2 Provide resources for H2 … The system shall supply resources necessary for hydrogen storage	The resources for hydrogen storage are dependent on hydrogen storage technologies	Functional Requirement
FR-4 Deliver Hydrogen The system shall deliver hydrogen to customer(s)	The hydrogen delivery options are dependent on availability of existing infrastructure and potential of new hydrogen transportation solutions	Functional Requirement
FR-4.1 Provide infrastructure for … The system shall provide infrastructure for hydrogen delivery to the customer(s)	The hydrogen transportation infrastructure depends on available technologies, existing infrastructure, distance to the customer(s), and required technical characteristics (e.g., volume)	Functional Requirement

Figure 12. Hydrogen generation system key functions.

Entity	Rationale	Labels
PR-1 Hydrogen production rate The hydrogen production facility shall supply hydrogen at a minimum rate of 50,000 kg of hydrogen per day	The minimum production rate is specified by the hydrogen customer	Performance Requirement
PR-1.1 Storage capacity The storage system shall provide capacity adequate to support minimum required supply rate from the hydrogen production facility	The capacity of the storage system is determined based on minimum required hydrogen supply rate and availability	Performance Requirement
PR-2 Hydrogen purity The hydrogen generation facility shall supply hydrogen with the purity rate of at least 99.99%	The minimum purity level is specified by the hydrogen customer	Performance Requirement
PR-3 Availability The hydrogen generation facility shall supply hydrogen at least 363 days per year	The maximum unavailability is 2 days per year (minimum availability is 99.5%)	Performance Requirement
PR-4 Reliability Reliability of hydrogen generation facility shall be at least 99.6%	The reliability of hydrogen generation facility is determined based on the required availability of the hydrogen generation facility	Performance Requirement Reliability Requirement
PR-4.1 Reliability of H2 generating system The hydrogen generation system shall have reliability of at least 99.9%	The reliability of hydrogen generation system is determined based on required reliability of the hydrogen generation facility	Performance Requirement Reliability Requirement
PR-4.2 Reliability of H2 storage system The hydrogen storage system shall have reliability of at least 99.9%	The reliability of hydrogen storage system is determined based on required reliability of the hydrogen generation facility	Performance Requirement Reliability Requirement
PR-4.3 Reliability of H2 purification system The hydrogen purification system shall have reliability of at least 99.9%	The reliability of hydrogen purification system is determined based on required reliability of the hydrogen generation facility	Performance Requirement Reliability Requirement
PR-4.4 Reliability of H2 transportation system The hydrogen transportation system shall have reliability of at least 99.9%	The reliability of hydrogen transportation system is determined based on required reliability of the hydrogen generation facility	Performance Requirement Reliability Requirement
PR-5 Safety The hydrogen production facility shall provide measures for ensuring safe operations	Safety parameters are prescribed in applicable codes and standards and monitored by regulatory agencies	Performance Requirement Safety Requirement

Figure 13. Hydrogen generation system key performance characteristics.

4.2. Phase 2: Concept Exploration

In this phase, we explore system concepts for a hydrogen generation facility to identify feasible solutions for the system with the required capabilities and performance characteristics specified in the needs analysis presented in Section 4.1. Four potential system concepts are identified, with three different hydrogen technologies and two energy sources, nuclear and solar.

4.2.1. Solution 1—HTSE and Nuclear Energy Source

The main system characteristics are:

- An NPP provides thermal energy and electricity to the hydrogen generation facility
- The hydrogen generation facility is located next to the NPP.
- Modifications for the NPP are needed to support thermal energy (i.e., steam) extraction to support HTSE.
- The NPP continues to supply the remaining electricity to the grid.
- Produced hydrogen is already high purity, but remaining moisture and oxygen must be removed to meet the required ultra-high purity level.
- The storage capacity is driven by the requirement of an uninterrupted supply of hydrogen to the customer. Given the constant hydrogen production, storage must be sized for the unavailability of hydrogen generation caused by either planned or unplanned downtime of the hydrogen facility. Maintenance of the hydrogen facility is planned to be performed online supported by the built-in redundancies in the configuration of the hydrogen generation system. However, the energy supply by the NPP is interrupted when the plant is offline for refueling outages, which typically last 15–40 days

every 2 years. During the planned NPP outages, the hydrogen generation facility will be powered by the electrical grid, which will cause reduced profitability due to the inability to claim clean hydrogen production tax credits because grid electricity does not satisfy the low GHG emissions requirement. This period also causes stresses for grid operation since the normal electricity supply from the NPP is unavailable, and additional electricity from the grid is being used to produce hydrogen.

- Transportation infrastructure is required since the hydrogen customer is located approximately 20 miles from the hydrogen generation facility adjacent to the NPP (an assumed condition). The regional circumstances pose significant constraints on building a dedicated pipeline; therefore, a traditional mode of transporting hydrogen in high-pressure tube trailers is the selected transportation solution after a quick comparison of costs with the hydrogen transportation approach.
- Stored hydrogen could be used to produce electricity if needed to support emergent grid operations by reversing SOECs to act as solid oxide fuel cells to generate electricity instead of hydrogen.

The system concept is presented in Figure 14 as an LML asset diagram. The high-level concept of operation is presented in Figure 15 as an LML action diagram. As discussed previously, MBSE supports system development by providing a clear understanding of the relationships between system elements, which is enabled by the traceability between modeled elements. The relationships between actions and assets are explicitly included as modeled artifacts, a specific benefit of MBSE compared to a document-based approach to system development. An example of traceability between *asset, action, input/output, and resources* system artifacts is presented in Figure 16. In this case, *HTSE.3 Generate hydrogen via HTSE* action *generates* output *Hydrogen*; it is *performed by* asset *1.2.1 Solid Oxide Electrolizers*, and it *consumes* resources *DC Power* and *High-Temp Steam*, provided by actions *HTSE 1, 1.2, 2, 2.4*.

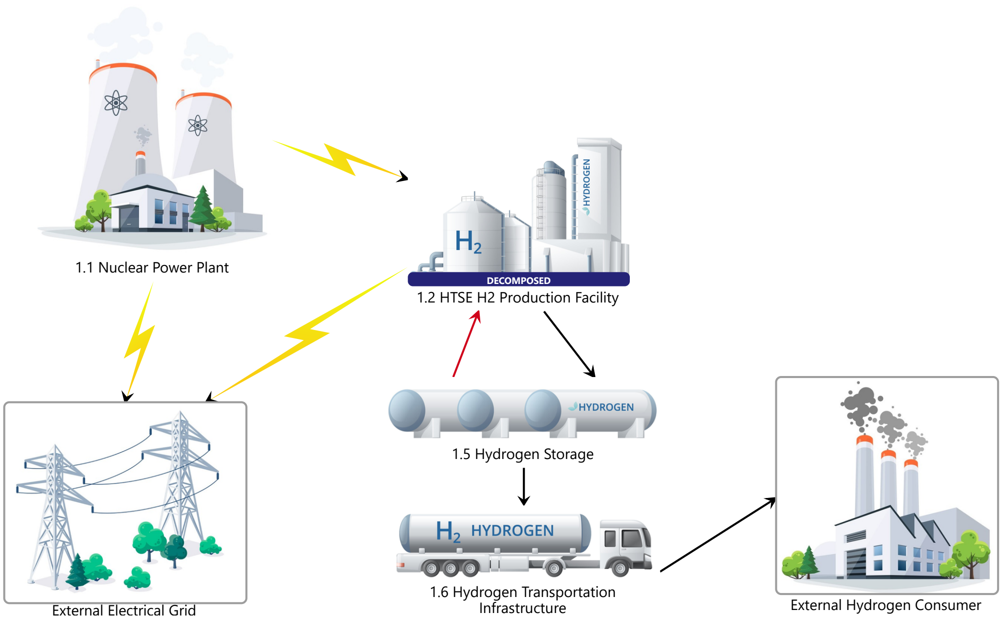

Figure 14. Solution 1: hydrogen generation via HTSE with a nuclear energy source.

While not shown here for brevity, traceability to system functional and performance requirements and inherently to stakeholders and their needs is also maintained for asset and action artifacts. Such detailed yet simple integration of all system elements, top to bottom, enables quick and intuitive system exploration by users such as system designers and engineers, project managers, decision makers, and other stakeholders. The all-inclusive system representation also supports enhanced knowledge collection, retention, and transfer. Lastly, the model being the single source of truth enables quick changes of a conceptual solution or the development of additional conceptual solutions as required, given the system context, stakeholder-specific objectives, or site-specific constraints.

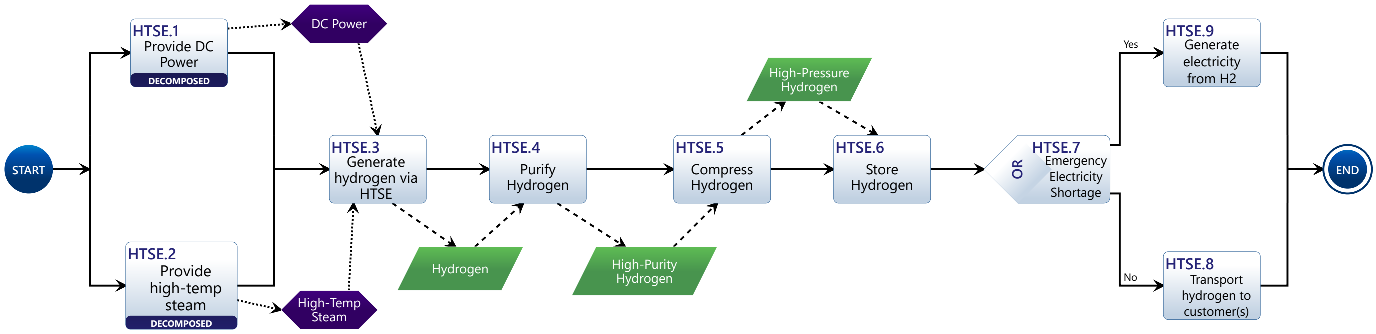

Figure 15. Solution 1: concept of operations.

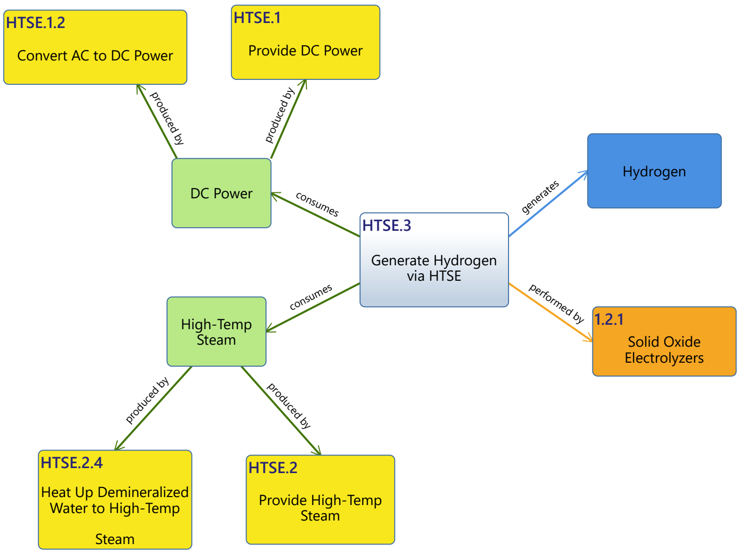

Figure 16. Traceability of asset and action model artifacts.

4.2.2. Solution 2—LTE and Nuclear Energy Source

The main system characteristics are:

- An NPP provides electricity as the only energy source to the hydrogen generation facility.
- The hydrogen generation facility is located next to the NPP.
- The NPP continues to supply the remaining electricity to the grid.
- Storage and transportation aspects are the same as in Solution 1.

Key differences from Solution 1:

- Instead of HTSE, LTE PEM is the electrolysis technology.
- No modifications are required for the NPP since thermal energy is not extracted.
- A purification system is not required as the hydrogen generated from PEM electrolysis is already at the required level of purity.
- There is no reverse operation option of electricity generation from stored hydrogen, but there is still an option to curtail hydrogen production to supply electricity generated by the NPP to the grid instead of producing hydrogen.

The system concept is presented in Figure 17 as an asset diagram. The high-level concept of operation is presented in Figure 18 as an action diagram.

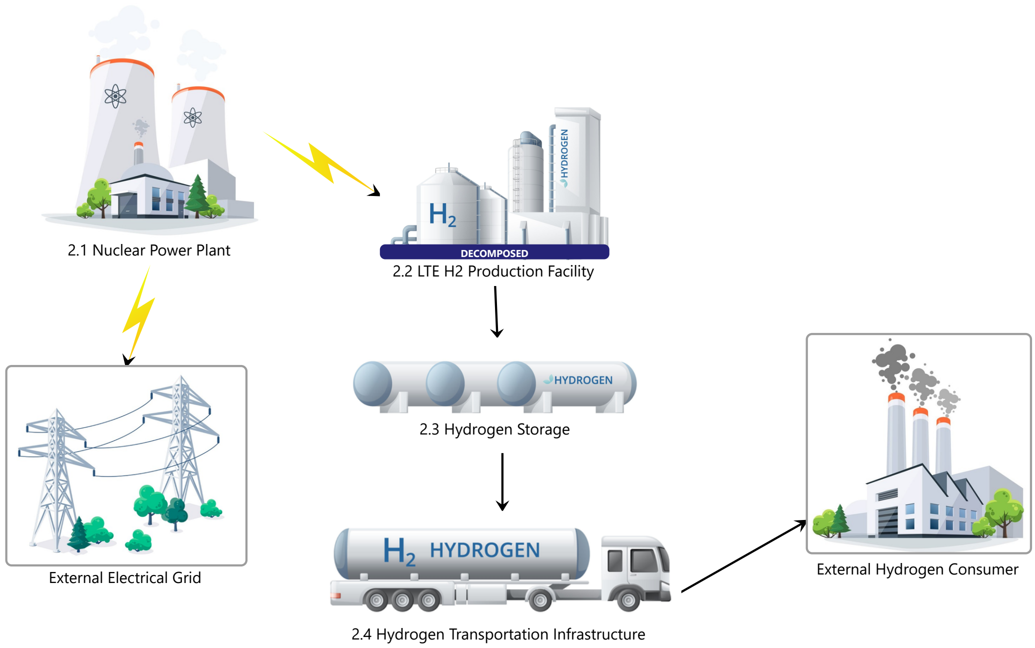

Figure 17. Solution 2: hydrogen generation via LTE with a nuclear energy source.

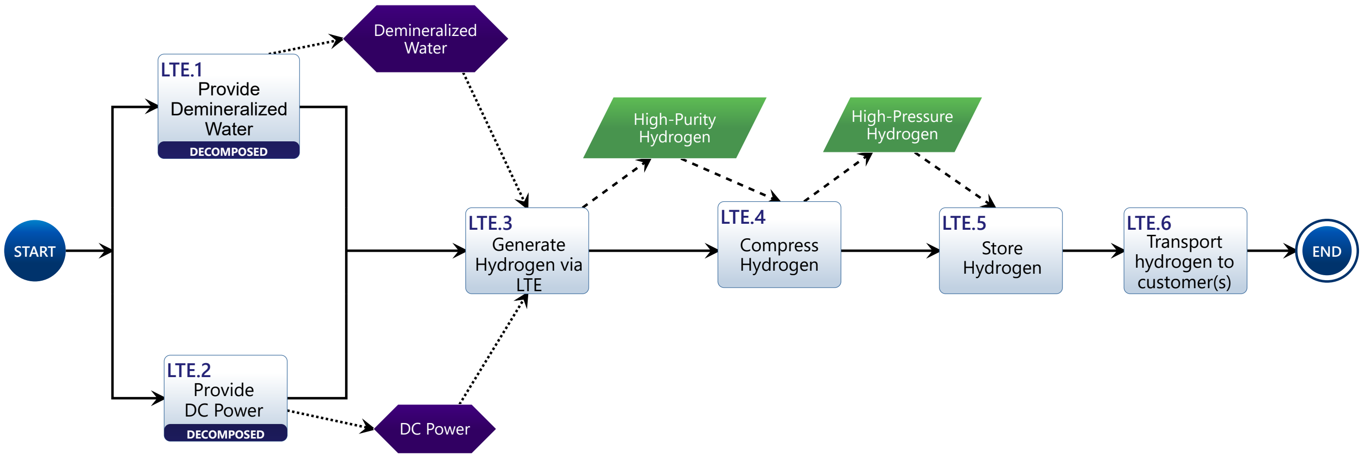

Figure 18. Solution 2: concept of operations.

4.2.3. Solution 3—SMR with a CCS System

The main system characteristics are:

- Currently used technology for hydrogen generation.
- The new hydrogen generation facility will include a CCS system to qualify as a low-carbon hydrogen technology.
- Electrical grid supplies electricity to supporting systems (i.e., hydrogen purification, compression, and storage).
- The hydrogen generation facility, in this case, will be located in close proximity to the industrial consumer, and a dedicated newly built pipeline infrastructure will be used as the transportation system.
- Captured CO_2 is transported via specialized truck trailers and stored offsite in an underground CO_2 sequestration repository.

Key differences from Solutions 1 and 2:

- Feedstock is natural gas instead of water.
- Significant CO_2 emissions necessitate a CCS system, processes, and infrastructure.

- The purification process is much more extensive as produced hydrogen is a low-level purity with many byproducts that must be removed.
- There is no flexible operation option to support the grid other than curtailing hydrogen generation, which only conserves a limited amount of electricity.

The system concept is presented in Figure 19 as an asset diagram. The high-level concept of operation is presented in Figure 20 as an action diagram.

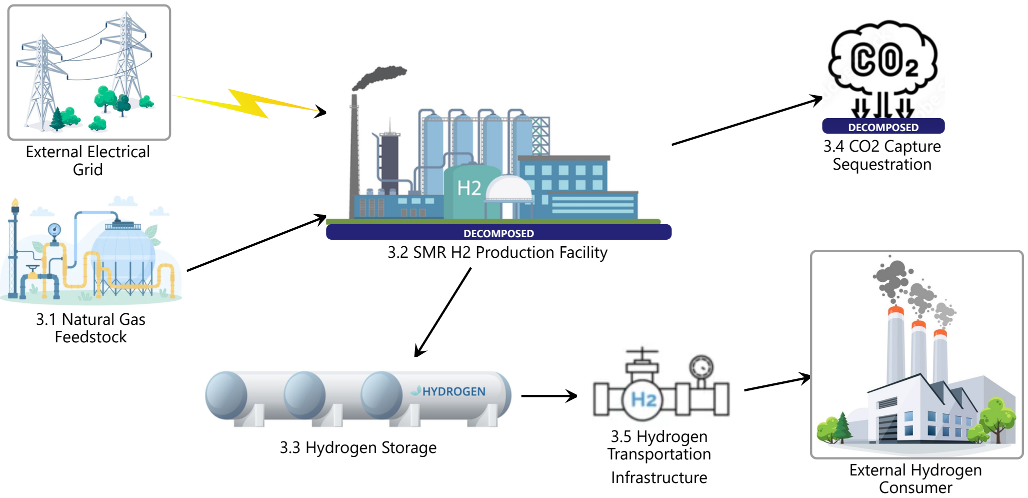

Figure 19. Solution 3: hydrogen generation via an SMR.

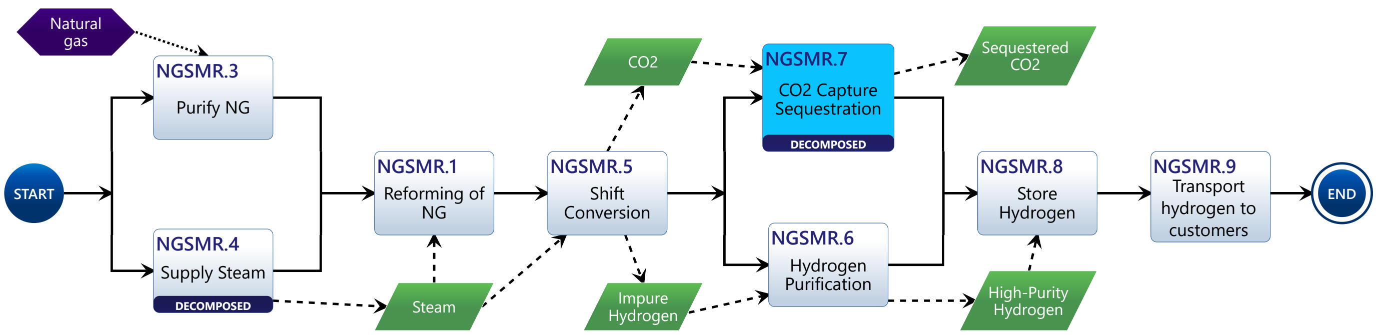

Figure 20. Solution 3: concept of operations.

4.2.4. Solution 4—LTE and Solar Energy Source

The main system characteristics are:

- A solar power plant located next to the hydrogen generation facility provides electricity to the hydrogen generation facility. The hydrogen generation is performed when a solar power plant supplies electricity, where the daylight duration and meteorological conditions affect the availability and efficiency of solar power generation. To ensure the critical requirement of a consistent hydrogen supply to the customer, the solar power plant is sized accordingly to produce a large amount of hydrogen during the day, store generated hydrogen, and not produce hydrogen when solar power is unavailable. Battery energy storage is another possible solution to overcome the challenge of the intermittent availability of solar energy, but this option was less cost-efficient than overproducing and storing hydrogen.
- A purification system is not required as the hydrogen generated from PEM electrolysis is already at the required level of purity.
- Storage capacity is driven by the requirement of an uninterrupted supply of hydrogen to the customer. The hydrogen production rate during the day is much larger than the rate of hydrogen discharge to the customer, requiring a large-capacity storage unit.

- Transportation infrastructure is required since the hydrogen customer is located approximately 10 miles from the hydrogen generation facility (an assumed condition). The shorter distance and regional circumstances allow for the construction of a dedicated pipeline infrastructure, which will be used as the transportation system.

Key differences from Solution 2:

- A new energy source, a solar power plant, needs to be built to support hydrogen generation.
- A much larger storage capacity is needed to account for the consistent hydrogen supply to the customer.
- Hydrogen transportation infrastructure is simpler as the new hydrogen generation facility supported by a solar power plant is located closer to the hydrogen consumer.
- The hydrogen facility combined with a solar power plant requires a large parcel of land to support the large energy demands.

The system concept is presented in Figure 21 as an asset diagram. The high-level concept of operation is presented in Figure 22 as an action diagram.

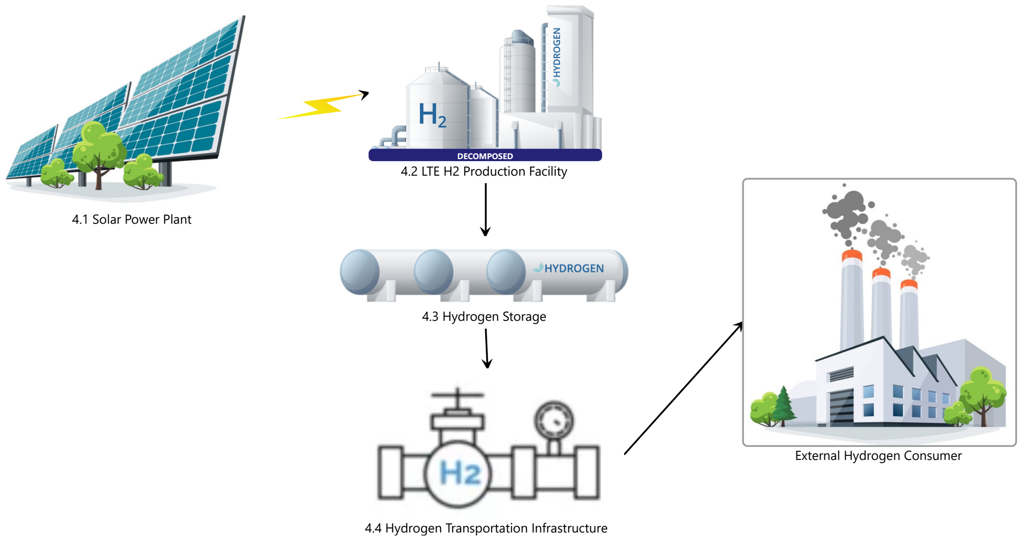

Figure 21. Solution 4: hydrogen generation via LTE with a solar energy source.

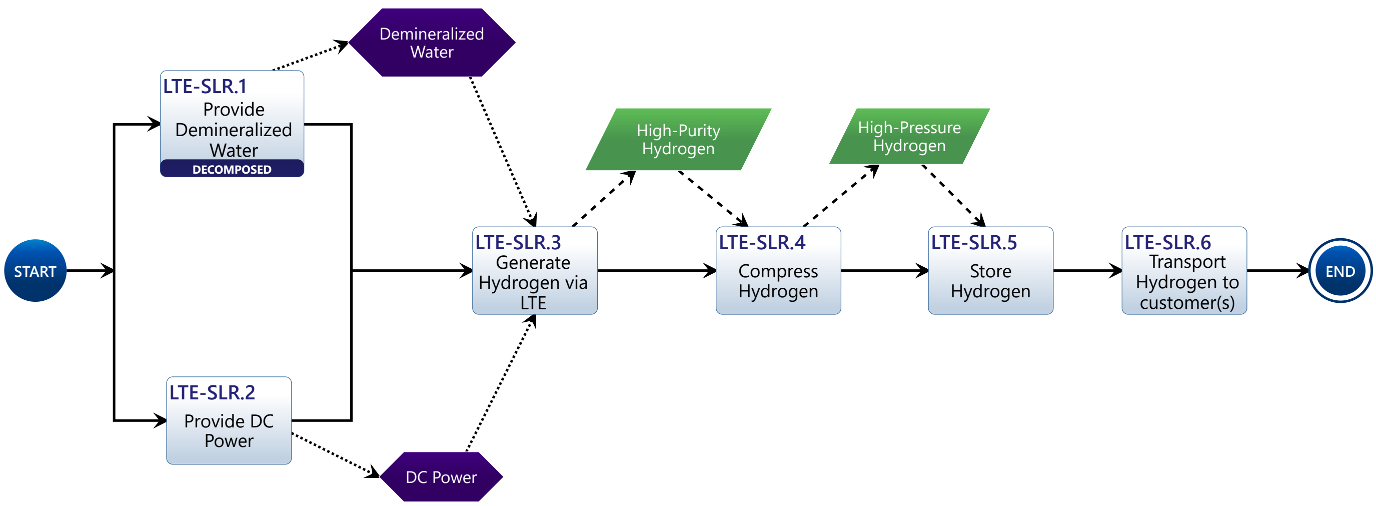

Figure 22. Solution 4: concept of operations.

4.2.5. Supporting Data

Information pertinent to the conceptual system design in all three dimensions (i.e., technical, economical, and social) is developed using discipline-specific tools. Additional

R&D is needed to support integrating external tools with MBSE, which is outside the scope of this research focused on the concept of a new decision support system rather than technical solutions for integrating multiple software tools in MBSE. This paper does not present details of supporting data development, e.g., cost estimates, since they are outside of the main focus (i.e., the decision support framework). Instead, high-level results are used for the trade-off analysis performed in the concept definition phase outlined in Section 4.3. The hydrogen generation cost data were developed using the NREL H2FAST Excel-based tool [34].

Supporting data for the concepts should be collected in the MBSE model to enable data collection, retention, and sharing. An example of supporting data collection is presented in Figure 23. In this example, cost information for action HTSE.3 Generate hydrogen via HTSE is recorded.

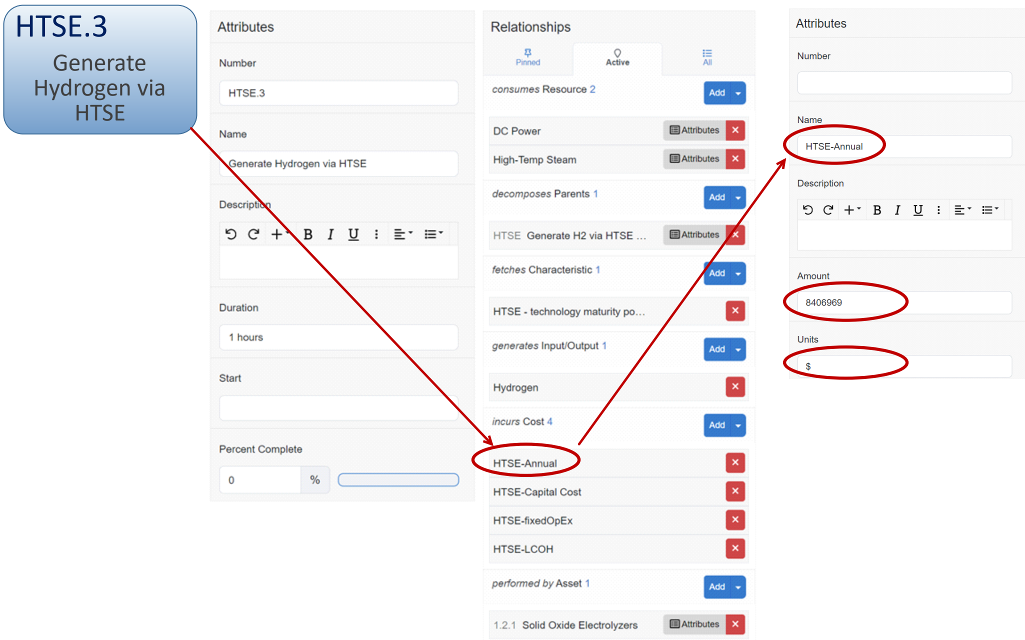

Figure 23. Supporting data in MBSE.

4.3. Phase 3: Concept Definition

This is the phase where the four concepts for the hydrogen generation system are evaluated and compared against the requirements developed from stakeholder needs. A trade-off analysis is conducted using the multicriteria decision analysis approach described in Section 3.1.5.

The evaluation criteria were established across four categories: "Economics of H2 Generation", "Economics of Support Systems", "Other Technical Considerations", and "Social". These categories and evaluation criteria were informed by the stakeholder needs translated into system requirements and performance characteristics as part of the needs analysis phase described in Section 4.1. Industry experts provided their inputs for category priorities and evaluation criteria weights indicating their importance.

The conceptual solutions were identified in the concept exploration phase described in Section 4.2. Supporting information collected and assembled within the MBSE model for each solution was used to evaluate the solutions against each criterion. A scoring system ranging from 1 to 5, where 1 is the lowest and 5 is the highest score, was used to rate the solutions. Finally, the overall weighted score for each solution was determined using the methodology described in Section 3.1.5.

The activities in this phase are supported by MBSE, which enables traceability between the requirements and system elements, which are either system functions shown via action diagrams or system assets performing the functions shown via asset diagrams.

The trade-off studies could be conducted using dedicated external tools (e.g., Excel spreadsheet) or directly in MBSE via specialized integrated solutions. In this case study, an Excel spreadsheet is used to demonstrate the application of a trade-off analysis as part of the decision support system. The decision analysis matrix for the four solutions for hydrogen generation is presented in Figure 24. Supporting data stored in the MBSE model are consolidated in the decision analysis matrix. The weights and priority scores are hypothetically developed based on the authors' experience and familiarity with the stakeholder preferences. In a real system development case, the scores would be developed by the system developers based on the preferences of decision makers.

	Priority	Evaluation criteria	Weight	Solution 1 - HTSE + Nuclear Energy			Solution 2 - LTE + Nuclear Energy			Solution 3 - SMR + CCS			Solution 4 - LTE + Solar		
	%		%	Estimates	Score	Weighted	Estimates	Score	Weighted	Estimates	Score	Weighted	Estimates	Score	Weighted
Economics of H2 Generation	40%	Capital Costs	30%	$108,203,341	4	24%	$76,145,446	5	30%	$302,568,403	2	12%	$279,225,351	3	18%
		Fixed OpEx	10%	$5,032,017	4	8%	$3,700,361	5	10%	$8,680,996	3	6%	$13,569,224	2	4%
		Annualized replacement	30%	$8,406,969	2	12%	$1,281,387	5	30%	$1,503,525	5	30%	$4,698,846	3	18%
		LCOH	30%	$3.46	4	24%	$2.55	5	30%	$5.13	1	6%	$3.96	4	24%
		Sub-category weighted score	100%			68%			100%			54%			64%
		Category Sum			**27%**			**40%**			**22%**			**26%**	
Economics support systems	30%	Purification	30%	simple	3	18%	not needed	5	30%	complex	1	6%	not needed	5	30%
		Storage	30%	small	5	30%	small	5	30%	small	5	30%	very large	1	6%
		Transportation	30%	tube trailers, 20 mi	1	6%	tube trailers, 20 mi	1	6%	pipe, 2 mi	5	30%	pipe, 2 mi	5	30%
		CO2 transport + storage	10%	0	5	10%	0	5	10%	$4,106,250	1	2%	0	5	10%
		Sub-category weighted score	100%			64%			76%			68%			76%
		Category Sum			**19%**			**23%**			**20%**			**23%**	
Other technical considerations	20%	H2 generation techn. maturation	40%	High potential to increase efficiency / decrease costs	5	40%	Medium potential to increase efficiency / decrease costs	4	32%	Mature technology, some potencial for CCS	1	8%	Medium potential to increase efficiency / decrease costs	4	32%
		Support of electrical grid operation	50%	Spinning capacity, flexibility to re-direct production, electricity generation form stored H2	5	50%	Spinning capacity, flexibility to re-direct production	4	40%	None	1	10%	None	1	10%
		Regulatory acceptance / licensing	10%	Modifications to NPP for thermal dispatch and electricity intake, H2 safety risks	2	4%	Modifications to NPP for electricity intake, H2 safety risks	4	8%	H2 safety, EPA rules for NG as feedstock	5	10%	H2 safety, EPA rules for large land use for solar farm	4	8%
		Sub-category weighted score	100%			94%			80%			28%			50%
		Category Sum			**19%**			**16%**			**6%**			**10%**	
Social	10%	Use of resources	60%	water + energy	5	60%	water + energy	5	60%	NG + electr	3	36%	Large land + water	1	12%
		Climate goals contribution	40%	clean / nuclear waste	4	32%	clean / nuclear waste	4	32%	CO2 emmiting + CCS	1	8%	clean / PV recycle	5	40%
		Sub-category weighted score	100%			92%			92%			44%			52%
		Category Sum			**9%**			**9%**			**4%**			**5%**	
Σ%	100%	Overall weighted score		65%			79%			48%			58%		
		Maximum score:	**5**												

Figure 24. Multicriteria decision analysis for hydrogen generation solutions (red-circled cost from the Amount attribute in Figure 23).

The results of the multicriteria decision analysis shown in Figure 24 demonstrate each of the four proposed solutions has pros and cons. **Solution 1—HTSE and Nuclear Energy Source** has low capital and O&M costs, favorable LCOH, and dual-use for grid resilience. It offers a simple purification process and efficient hydrogen storage. However, it faces high replacement costs, inefficient hydrogen transport, and potential regulatory delays. **Solution 2—LTE and Nuclear Energy Source** excels in low costs and simple infrastructure but shares HTSE's transport inefficiencies and lacks the capability to generate electricity from hydrogen. **Solution 3—SMR with a CCS System** offers better transportation options and low O&M costs but has high capital costs and LCOH due to CCS and complex purification and relies on fossil fuels, impacting climate goals negatively. **Solution 4—LTE and Solar Energy Source** has lower LCOH than Solution 3 yet higher capital costs and significant storage demands due to solar intermittency. It benefits from easy transport and climate advantages but requires substantial land for solar infrastructure.

Based on the evaluation results, the best option for a hydrogen generation plant is Solution 2, where LTE technology is used to produce hydrogen supported by nuclear electricity. Solution 1 is the second best option, and it is currently suboptimal compared to Solution 2 due to the higher cost of hydrogen generation. However, HTSE technology has made dramatic improvements in efficiency, reliability, and costs. This indicates that Solution 1 may soon become the best option, surpassing Solution 2.

Additional work is planned to incorporate the trade-off analysis in the MBSE platform, which is expected to further simplify the application of the proposed decision support framework assisting with selecting the optimal energy system solution, in this case a hydrogen generation facility.

5. Conclusions

This paper advocates for a new decision support framework that comprehensively evaluates energy systems based on the key objectives defined by system stakeholders. This framework allows for considering various perspectives, including economic, technical, and social aspects. This paper also reviews existing decision-making approaches in energy systems, highlighting their gaps and shortcomings.

The proposed framework employs systems thinking and systems engineering principles and tools, specifically using a concept exploration approach and MBSE for systems analysis, combined with multicriteria decision analysis. The framework process consists of three phases: needs analysis, concept exploration, and concept definition. The needs analysis phase explores why the new system is needed and if there are technologies that can address the need. The concept exploration phase establishes feasible goals for the new energy system before committing significant resources to its detailed exploration and development. The concept definition phase evaluates identified candidate concepts based on using supporting data, either developed or collected, as part of this phase's work. In this phase, a trade-off analysis is conducted using the multicriteria decision analysis, which allows for an objective, systematic, and transparent comparison of various options and subsequent selection of the solution most suitable to accomplish the key objectives of the new system. The developed framework can support decisions during the planning and design stages of new energy systems and investment strategies in novel energy solutions. The decision support framework presented in this paper is demonstrated in a case study for selecting the conceptual solution for a novel energy system tasked with clean hydrogen production. The case study focused on demonstrating that the proposed framework can aid in making strategic decisions, primarily for investors and utility executives.

Our research contribution is attributed to combining the systems thinking and systems engineering disciplines supported by MBSE methods and tools, with multicriteria decision making methodology in an integrated framework targeting a more comprehensive, multidisciplinary, objective, and systematic approach to strategic decision making for novel energy systems. By adopting systems thinking, the research inherently addresses complex problems in a holistic manner, acknowledging the interdependencies and interactions within the energy systems. Systems engineering provides a disciplined approach to the development and lifecycle management of such systems, ensuring they meet the myriad of requirements and constraints. The utilization of MBSE methods and tools can be a game-changer, as it allows for the creation of a shared, unambiguous model of the system that can be used for the initial strategic decision making and later utilized throughout the entire project lifecycle. This framework enables the incorporation of diverse criteria that reflect economic, environmental, social, and technical perspectives, which are often at odds in the strategic planning of energy systems. The robustness of the decisions can be vastly improved by considering these multiple criteria systematically and objectively.

Unlike previous studies focused on evaluation of energy systems, such as those described in [13,29,36–39,41,42], our research introduces a decision support tool that simplifies the comparison of energy concepts and aids in selecting the best option based on criteria set and ranked by decision makers. Multiple literature sources [25,38–41] point out that understanding energy systems necessitates considering a range of disciplines and dimensions to reflect the diverse goals of energy systems and incorporation of perspectives of different stakeholders. Furthermore, relying on a single metric for evaluation can lead to incomplete and sometimes misleading conclusions [25], potentially resulting in suboptimal decisions and inferior solutions. Therefore, our framework goes beyond the single-discipline evaluations found in works like [31,32,34] by offering a comprehensive approach that evaluates energy solutions from technical, economic, and social perspectives, including stakeholder values regarding climate objectives and conservation of natural resources. Moreover, this framework differs from those centered solely on multicriteria decision-making [40,43,56] by enhancing the multicriteria evaluation matrix with a systematically compiled MBSE model that aggregates detailed information on each energy concept.

There are some challenges that should be considered before immediately utilizing the proposed framework. As discussed in Section 3.1.3, a limitation of the framework can be the extra effort required to gather and organize information within the MBSE model, as well as the potential learning period adopting an MBSE software tool. The framework also includes a multicriteria decision matrix that offers a straightforward comparison of various options but can become cumbersome and information-heavy if too many options are assessed simultaneously.

Future Research

Future research will expand the framework to evaluate system long-term behaviors via the system dynamics approach [63]. This addition will enable a more comprehensive decision-making by improving the understanding of long-term system behaviors and potential futures of the system within the context of the larger energy sector. The integration of discipline-specific evaluations within MBSE may also be beneficial. Additional work fully or partially automating the generation and evaluation of various conceptual designs using identified subsystem options [27] would expand the potential solution set, thereby considering a broader set of possible concepts that may have been overlooked previously. This feature could also help address concerns regarding too many options to evaluate in the multicriteria decision matrix. Direct incorporation of other criteria, such as sustainability, could be explored to address the needs of other interested stakeholders, like policymakers. Overall, the model and results from the case study can be presented to and used by key stakeholders with feedback systematically collected to provide specific evidence of the benefits of this framework and to identify areas for potential improvements. These improvements can make the decision-making framework more automated and interconnected, improving the framework's effectiveness in various systems and contexts.

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Abbreviations

MBSE	model-based systems engineering
SE	systems engineering
DM	decision-making
HTSE	high temperature steam electrolysis
LTE	low temperature electrolysis
FOAK	first-of-a-kind
SSOT	single source of truth
NOAK	N-of-a-kind
SysML	Systems Modeling Language
IRA	Inflation Reduction Act
LCOE	levelized cost of energy
IRR	internal rate of return
NPV	net present value
MAUT	multi-attribute utility theory
GHG	greenhouse gas
AHP	analytic hierarchy process
DSS	decision support systems
LML	Lifecycle Modeling Language
SMR	steam methane reforming
CCS	carbon capture and sequestration
AEM	anion exchange membrane
PEM	polymer electrolyte membrane
SOEC	solid oxide water electrolysis cell
R&D	research and development
NPP	nuclear power plant
O&M	operations and maintenance
LCOH	levelized cost of hydrogen

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