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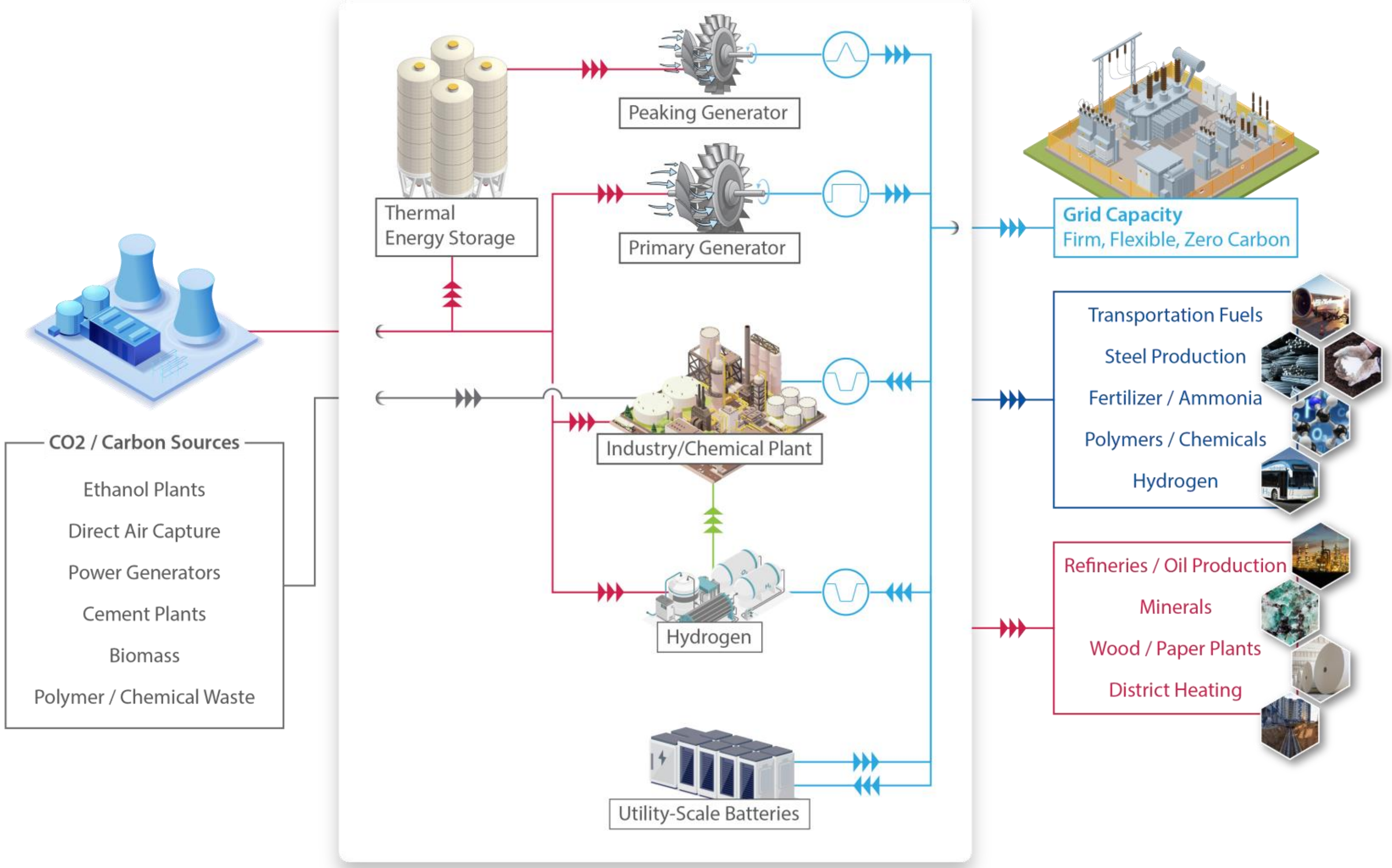
MBSE to Support Decisions for Energy Systems

2024 DICE Conference

Introduction and Background

- National Needs:
  - Energy security and resiliency enabled by diversification
  - Decarbonization of energy sector:
    - renewables (inconsistent, small-scale)
    - nuclear (expensive to add capacity)
- Alternative Solution:
  - Hydrogen generated using nuclear power
    - Clean, reliable, 24/7 energy source
    - Potential for large scale
    - Industrial uses other than energy



Introduction and Background (cont’d)

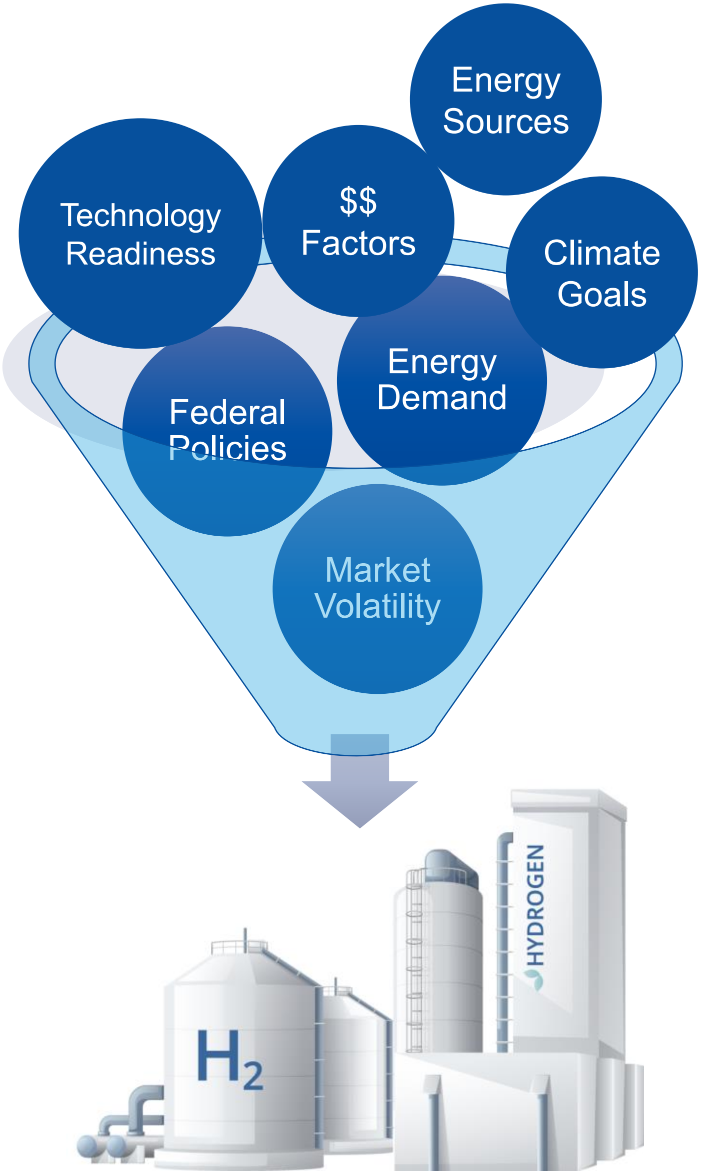
- Feasibility:
  - Hydrogen demand is expected to double by 2030
  - Inflation Reduction Act offers substantial benefits for clean hydrogen production
  - Possible to achieve DOE 2026 Goal of $2 per kilogram
- The obvious business case then? Not quite this simple…
  - Complexity of energy system
  - Intricate interrelationships between elements
  - Multiple stakeholders with competing objectives

→ Investment Uncertainties

- Let’s Invest! Hmmm… in which solution???
  - Technology
    - High-Temperature / Low-Temperature Electrolysis
  - Scale
    - Small (e.g., 1MW), Medium, Large (e.g., 500-1,000 MW)
  - Technical objectives and constraints
    - Storage, transportation, integration with existing plant and grid, regional demands, etc.

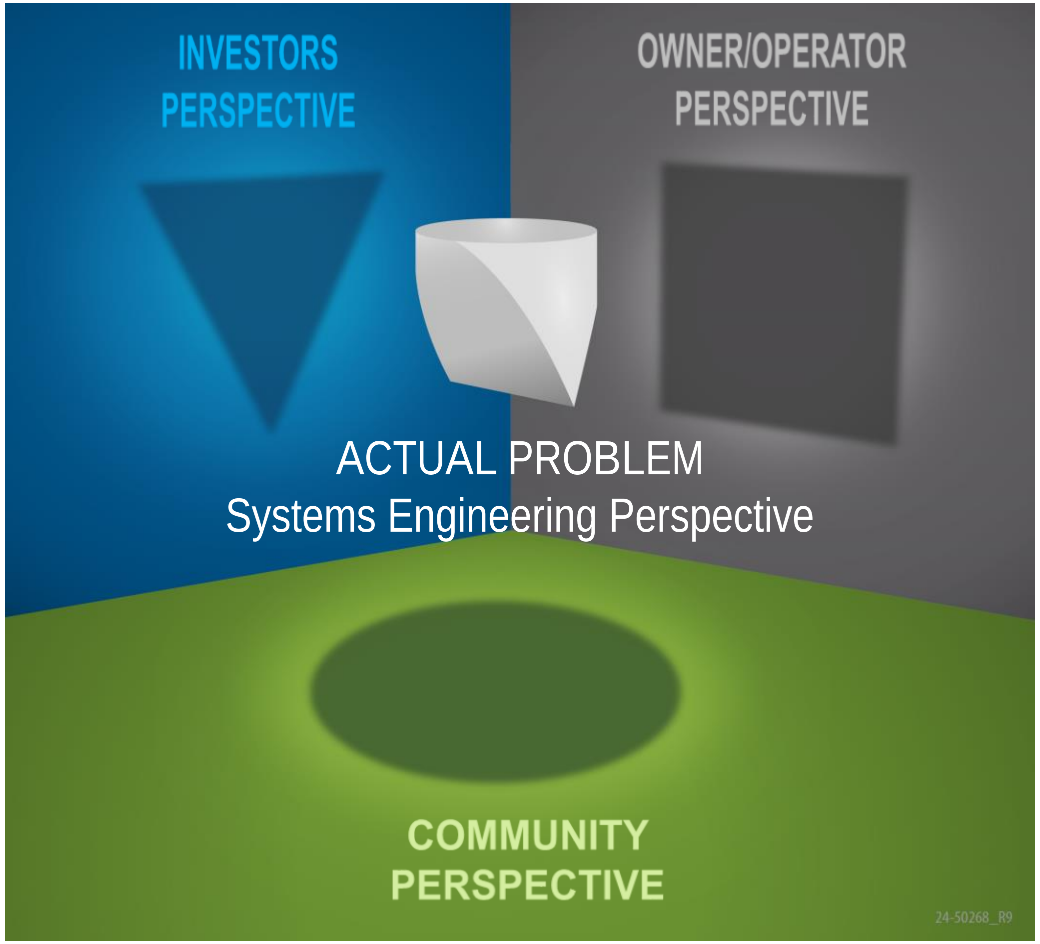
Complex Problem

- Many influencing factors
  - Federal and state policies
  - Electricity market fluctuations
  - Availability of other energy sources
  - Predictions of regional and national demands in electricity and H2
  - Microeconomic and macroeconomic considerations
- Strategies must be carefully investigated:
  - Hydrogen generation technology selection
  - Energy sources
  - Support of climate goals
  - Supply chain
  - Long-term economical success
- Need to consider multiple “potential futures”
- Need to weigh associated uncertainties and risks



Complex Problem (cont'd)

- Multiple stakeholders – many perspectives
  - Investors
  - Hydrogen plant owner / operator
  - Hydrogen consumers (industrial consumers)
  - Electricity consumers
  - Local community
  - Regulatory agencies
- Often competing objectives
  - Hydrogen producers → high price
  - Hydrogen consumers → low price
- Non-technical, qualitative objectives
  - Public perspectives and acceptance
  - Climate goals
  - Preservation of natural resources
- Listen to your stakeholders
  - The dialog with stakeholders is extremely important to ensure that a right system is being developed

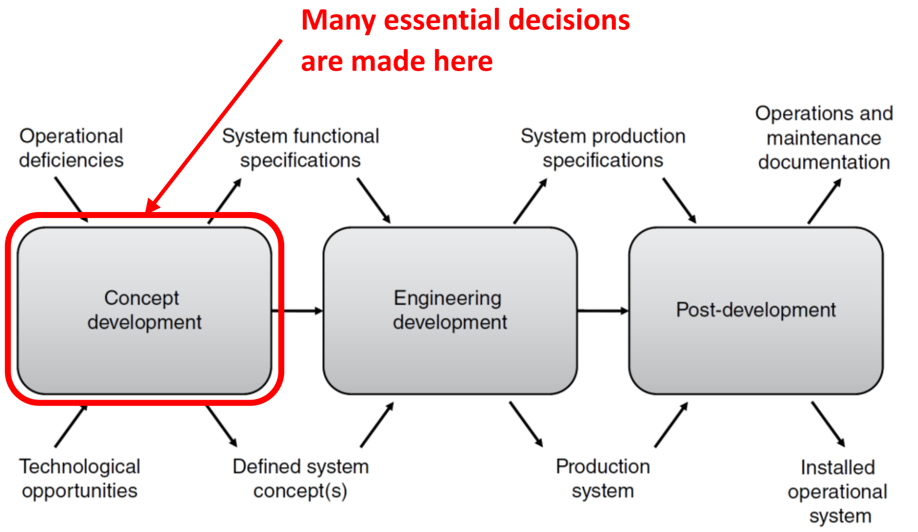


Actual problem vs multiple perspectives

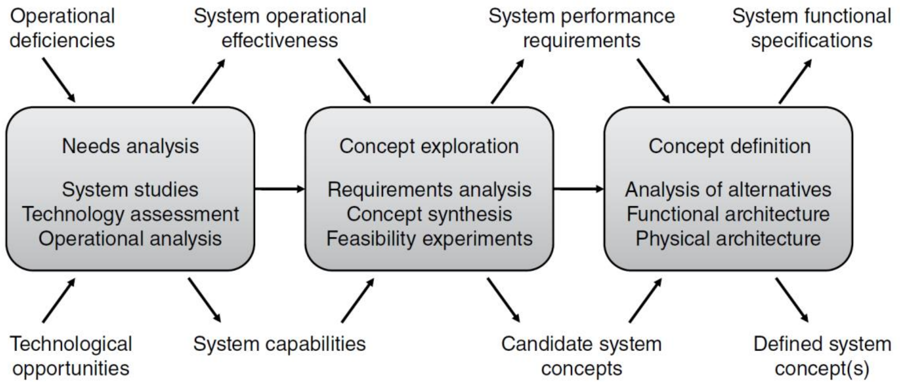
Systems Engineering Approach

A Potential Solution to Management of Complex Problems

- What is Systems Engineering (SE)?
  - The function of SE is to **guide** the **engineering and development** of **complex systems** [1]
- SE Focuses on [2]
  - Establishing, balancing, and integrating stakeholders' goals, purpose, and success criteria
  - Generating and evaluation alternative concept solutions
  - Considering necessary enabling systems and services
- Selection of energy solutions
  - Would benefit significantly from the approach and phases in Concept Development stage



Principal stages in system life cycle [1]



Concept development phases [1]

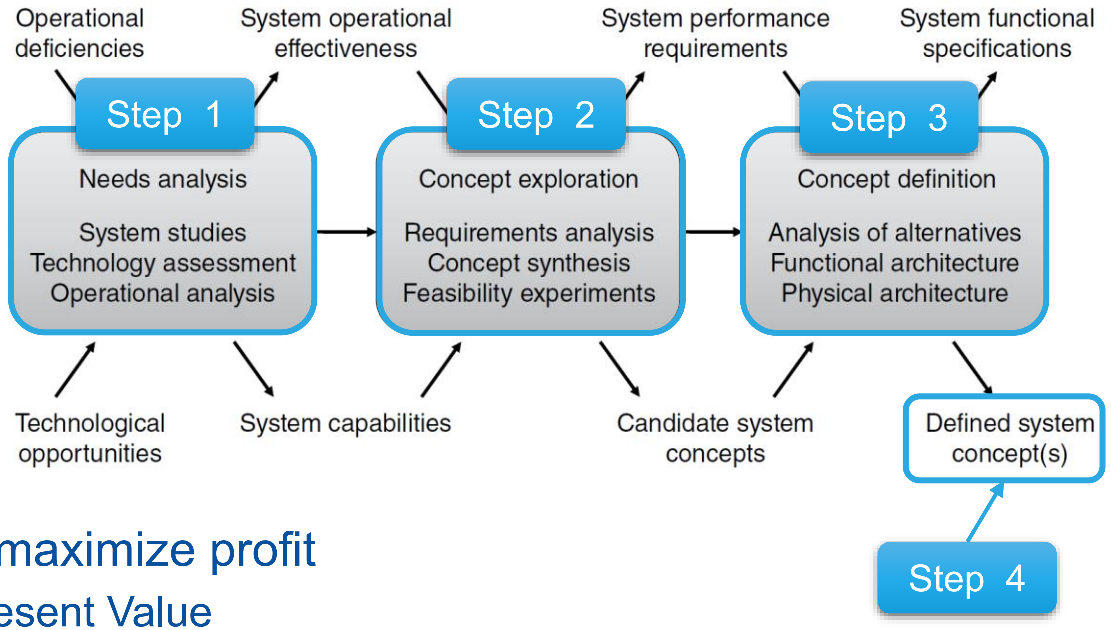
Proposition:

Use SE principles and tools to support decision making for complex energy systems

Decision-Making Process for Energy Systems

- General decision-making (DM) process
  1. Identify the problem
  2. Generate solution alternatives
  3. Evaluate alternatives
  4. Select the best alternative

Note the resemblance



- Traditional DM process for energy systems
  - Reliance on a single-criteria approach with an objective to maximize profit
    - General capital investment techniques are used, e.g., Net Present Value (NPV), Internal Rate of Return (IRR)
    - In some cases, uncertainties in the metrics are included and considered
  - Extension to energy systems
    - Reliance on cost-benefits, multicriteria DM, lifecycle analysis
    - A Levelized Cost of Energy (LCOE) is a widely-adopted metric to compare various options for a new energy system
    - The combination of economic metrics, e.g., NPV and IRR with LCOE is a more inclusive, better-informed approach to DM
  - Not much attention on the formulation of the problem (Steps 1 and 2)

The formulation of the problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill.

~ Albert Einstein

Decision-Making Process for Energy Systems (cont'd)

- General decision-making (DM) process
    1. Identify the problem
    2. Generate solution alternatives
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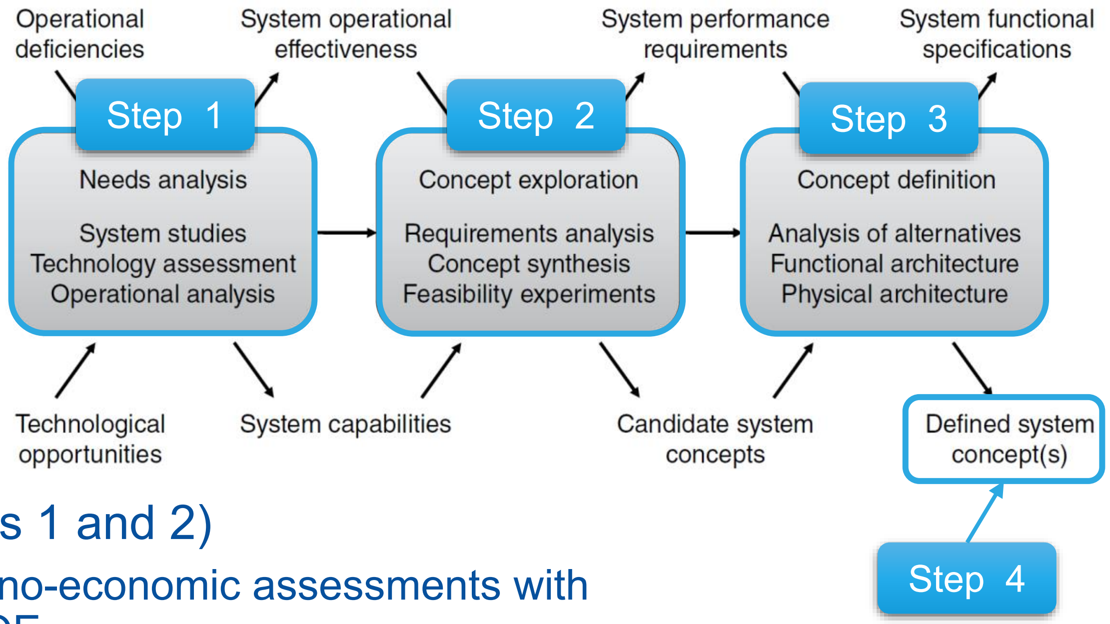
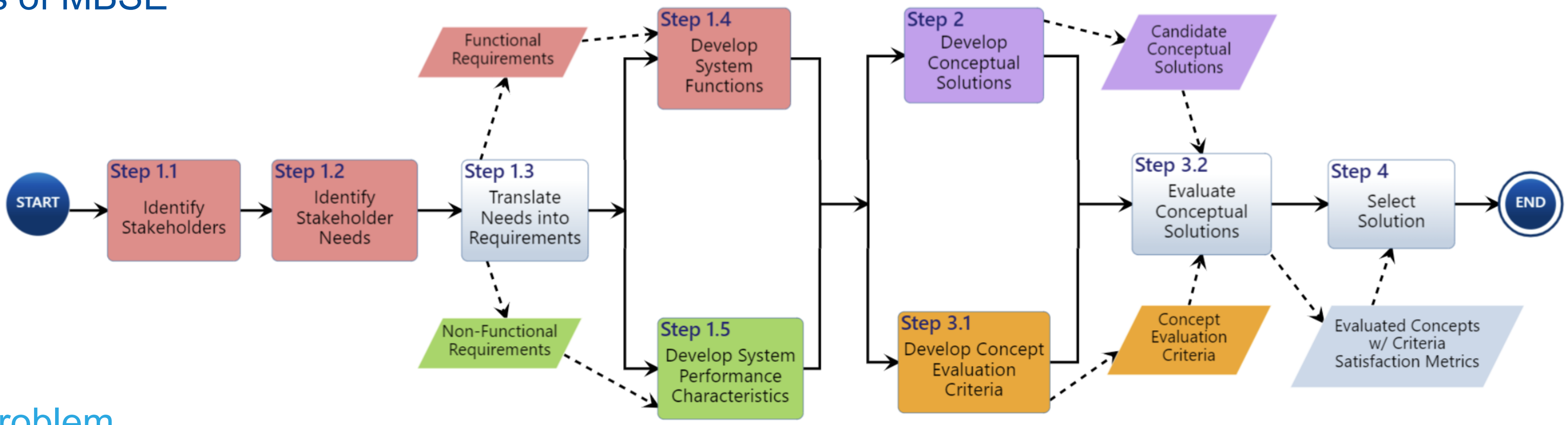
Note the resemblance



- Shortcomings of the traditional DM process
    - Not much attention on the formulation of the problem (Steps 1 and 2)
        - A pre-determined solution is picked and evaluated using techno-economic assessments with results presented in economic terms, i.e., NPV, IRR, and LCOE
        - Other general solutions are not considered as the focus is already on the single picked solution
    - Focus on a single perspective – economics
        - While technical aspects of a system are considered, they are included only to support economic analyses, not for a purpose to select the best technology that would satisfy the needs and goals
        - Social aspects, e.g., policies, GHG emissions, are not considered at all or included implicitly (e.g., technology generally passes GHG emission expectations)
    - Static assessments of highly-dynamic problems
        - Energy systems are highly dynamic, e.g., market process of energy change daily, policies affect energy sector in the long-run, yet potential changes in energy system are not considered

Model-Based Systems Engineering (MBSE) as a Decision Support System

- Align the traditional decision-making process with a systematic approach offered by SE
- Leverage capabilities of MBSE



Step 1 – Identify the problem

- The **What**: what is the problem, who are stakeholders, what are stakeholder needs?

Step 2 – Generate alternatives

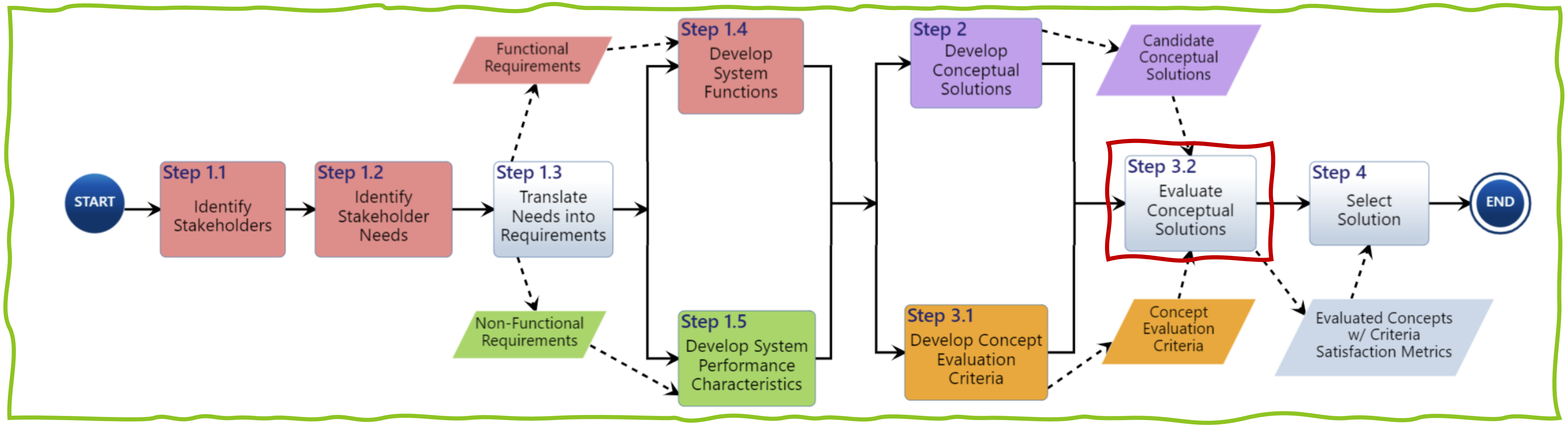
- The **How**: what solutions could potentially solve the problem?

Step 3 – Evaluate alternatives

- Which solution addressing problem's objective the best? Use The **How Well** performance characteristics and **multiple criteria** important to system success for comprehensive and objective analyses.

Step 4 – Select the alternative

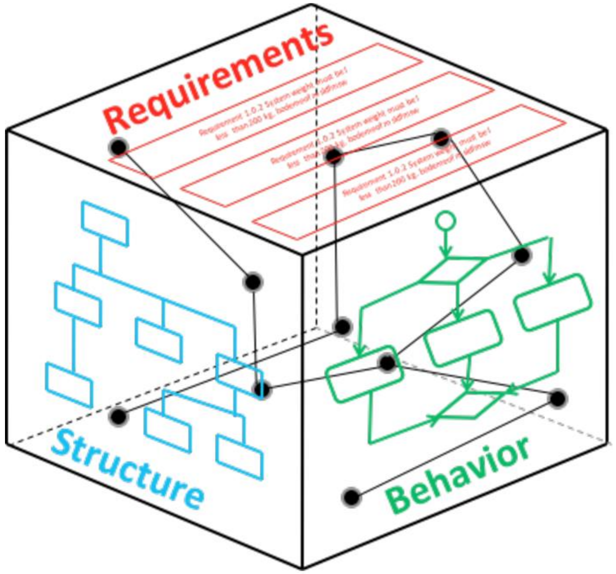
Modeling Tools – Fitting within Framework



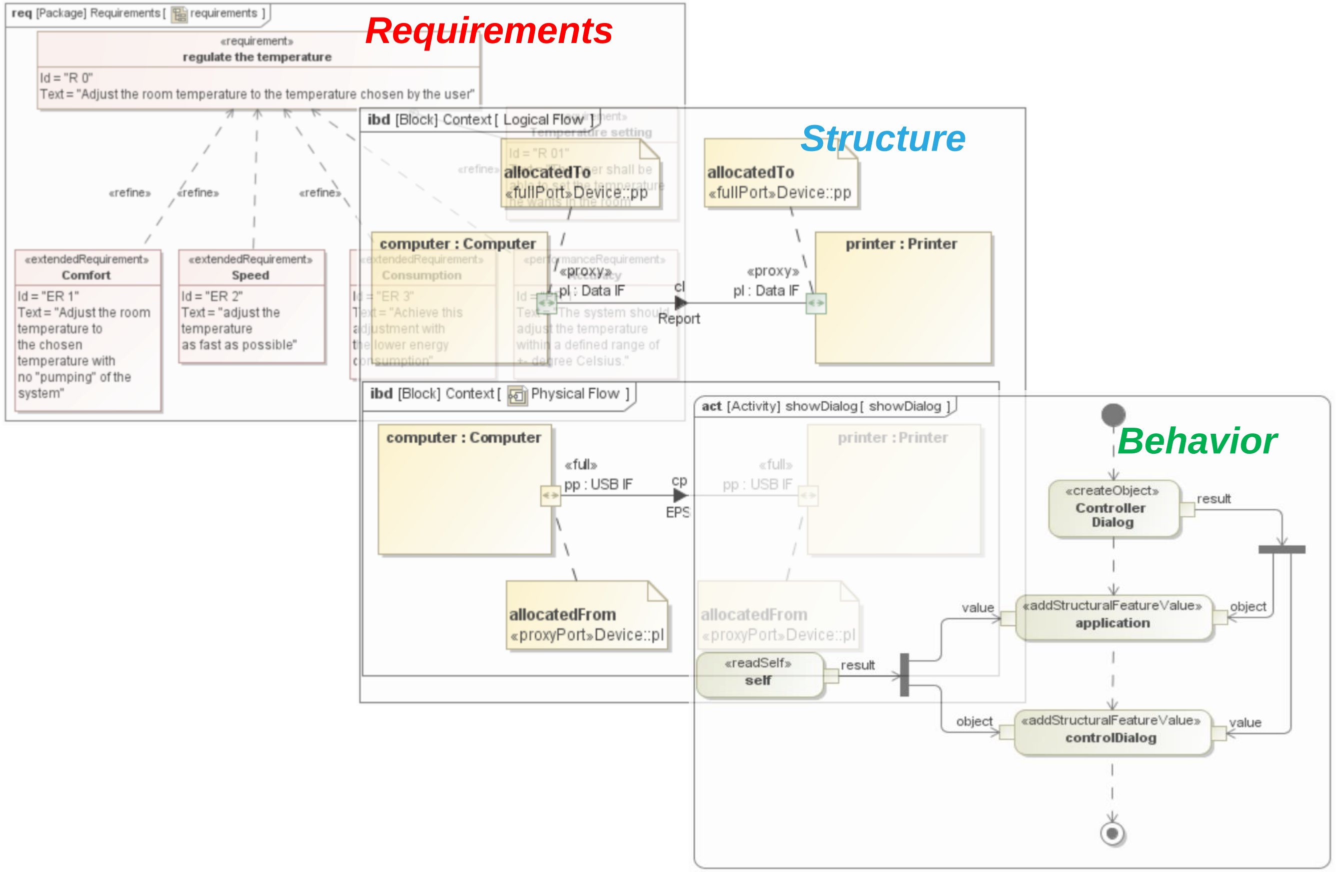
- MBSE
  - **The foundation** of the decision support system, guides the overall framework
  - **Integration** of multiple steps / processes / variables
  - **Collaboration:** serves as a single source of truth, enables access for multiple people, version control
  - **Repository:** data collection, record keeping & version control, knowledge collection & transfer
- Discipline-specific / Focused Assessments
  - **Technical perspective:** sub-system and component options, technology maturity, performance parameters
  - **Economics perspective:** capital investment metrics (NPV, IRR), energy-specific metrics (LCOE, LCOH)
  - **Social perspective:** climate-related metrics, policies, regulatory requirements, community needs
  - **Dynamics:** system behavior in changing context, success scenarios, prognostics
  - **Risks:** consideration of risks from technical, economic, and social perspectives

Tools:
Model-Based Systems Engineering (MBSE)

- A single model, multiple perspectives
  - A much more efficient way to exercise SE methodology
  - Creates and manages a single model of the system, a single source of truth
  - Enables multiple perspectives
  - All elements are connected and a change in one perspective updates the entire model



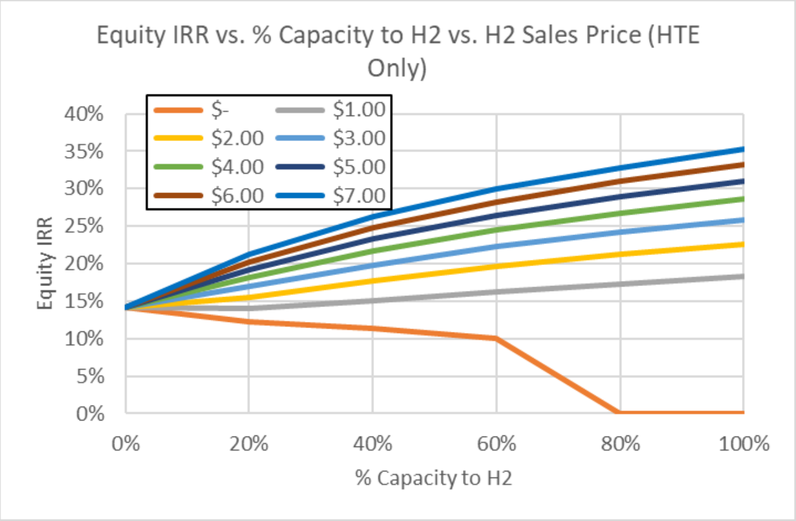
Dimensions of MBSE models [3]

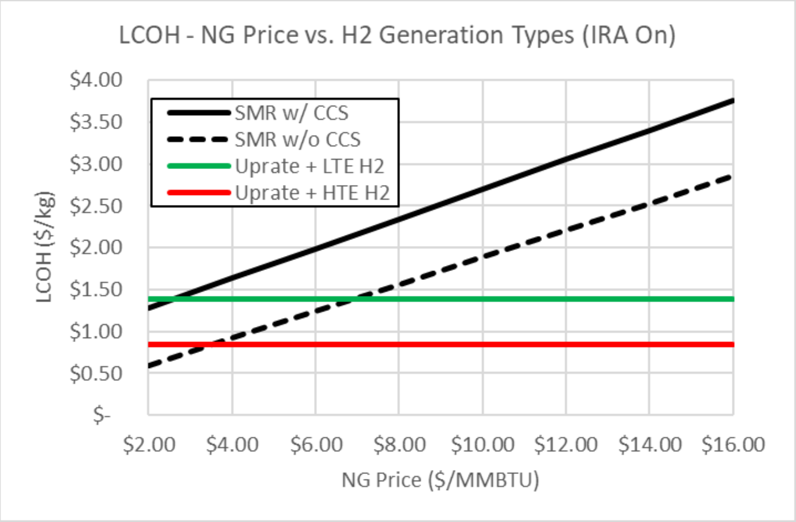


MBSE diagrams representing various perspectives [4]

Tools (cont'd):
Economic Assessments

- The preferred DM approach for energy systems
  - Cash Flow Analysis
    - Net Present Value (NPV), Internal Rate of Return (IRR)
  - Levelized Cost of Energy Product
    - Levelized cost of electricity (LCOE), levelized cost of hydrogen (LCOH)
- Strengths and Weaknesses
  - Strengths:
    - Easy to understand, direct correlation between various energy system solutions
  - Limitations:
    - Missed social perspectives
    - Difficult to add qualitative metrics (e.g., social acceptance, energy equity, climate impacts, resource dependence)
    - Based on the current state of the energy system(s) with static inputs and assumptions (system dynamics are not considered)
    - Risks are considered only partially via a sensitivity assessments

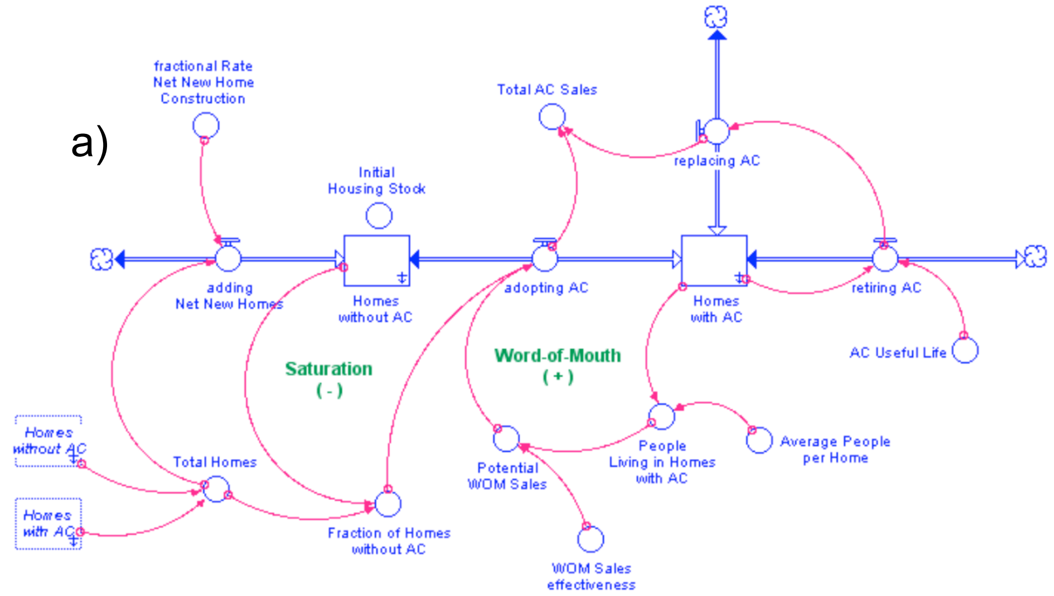


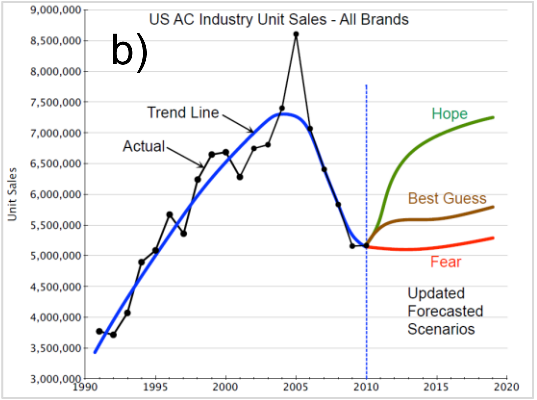


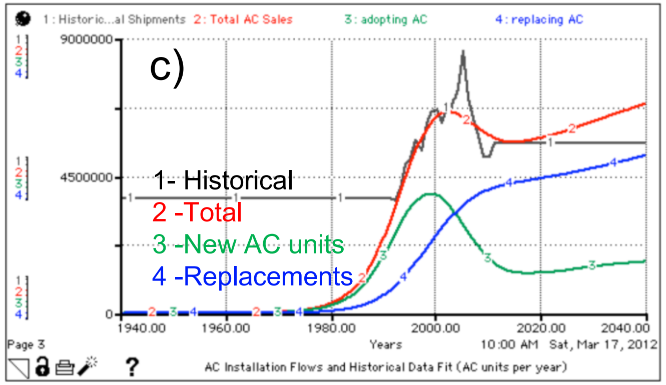
Examples of Economic Assessment Outcomes [5]

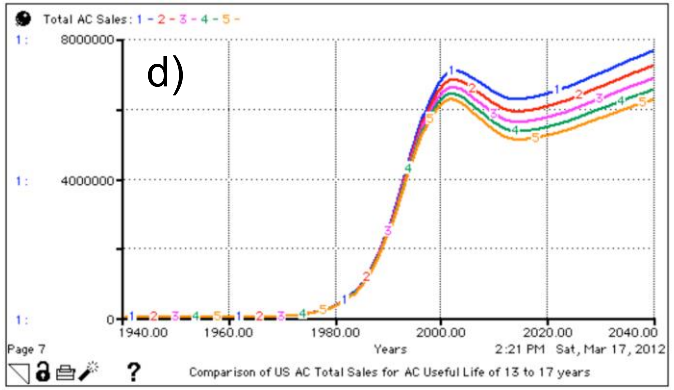
Tools (cont'd):
System Dynamics Models

- How successful the energy system / strategy will be long-term?
  - Anticipated, better-, and worth-than-anticipated scenarios
  - Which factors are most influential?
- How multiple factors will affect the system behavior in years to come?
  - Technology maturity promises significant cost reduction
    - What is the trajectory of the costs given anticipated technological advances?
    - Will costs change given anticipated adoption scale?
  - Social factors are expected to affect energy sector, what are the potential impacts?
    - Increased focus on reduction of GHG emissions
    - Expected federal policies to support green energy / penalize CO2 emissions







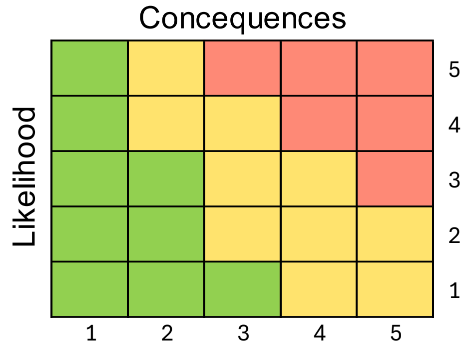


Example of a System Dynamics (SD) Model – Evaluation of Air Conditioning Market in the U.S. [6]

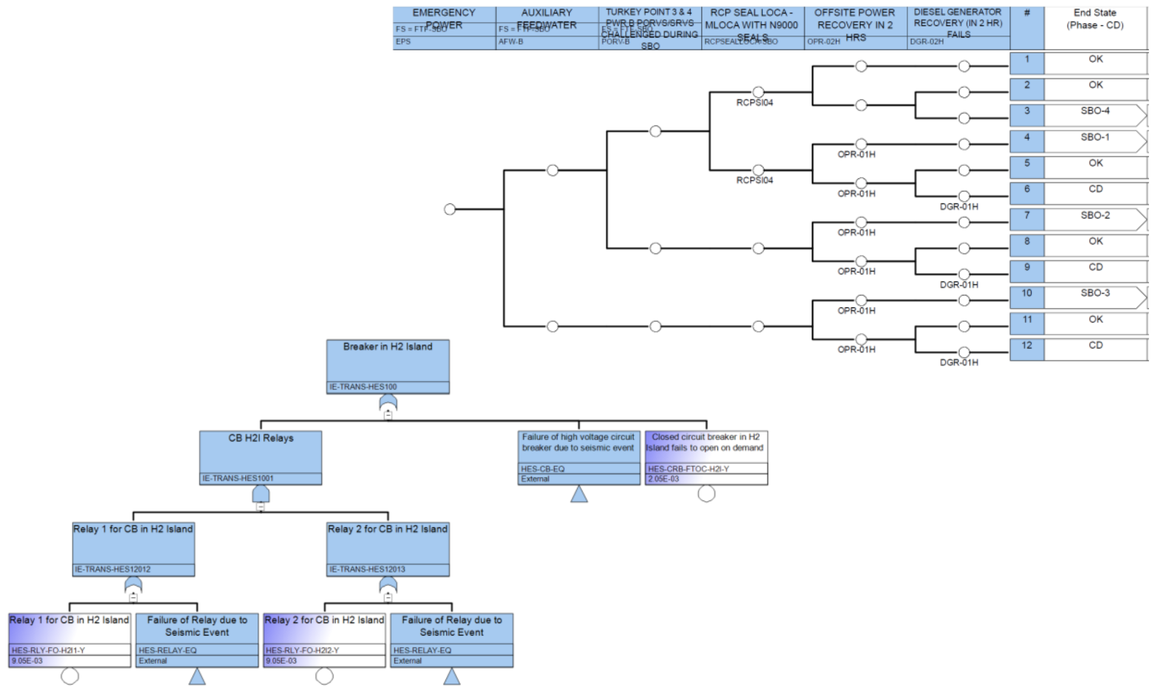
a) SD model for new and replaced AC units
b) Modeled dynamics of - AC sales, historical & projected
c) Modeled projected AC sales
d) Sensitivity to AC useful life

Tools (cont'd):
Risk Assessment Methods and models

- Risk assessment is critical for informed DM
  - Risks must be understood for each evaluated concept
  - The final concept is informed by identified risks and the ability to mitigate them
- Multiple risk assessment methods and tools
  - Failure Modes and Effect Analysis (FMEA)
    - Well-known and widely used
    - Qualitative
    - Does not capture details of system architecture and behaviors
  - Probabilistic Risk Assessment (PRA)
    - Used mostly in nuclear and space industry.
    - A quantitative rigorous approach that provides a comprehensive evaluation of system risks
    - Captured dependencies and expected system performance (behavior) under normal and accident conditions
- Can be adopted for evaluation of success of proposed energy solutions



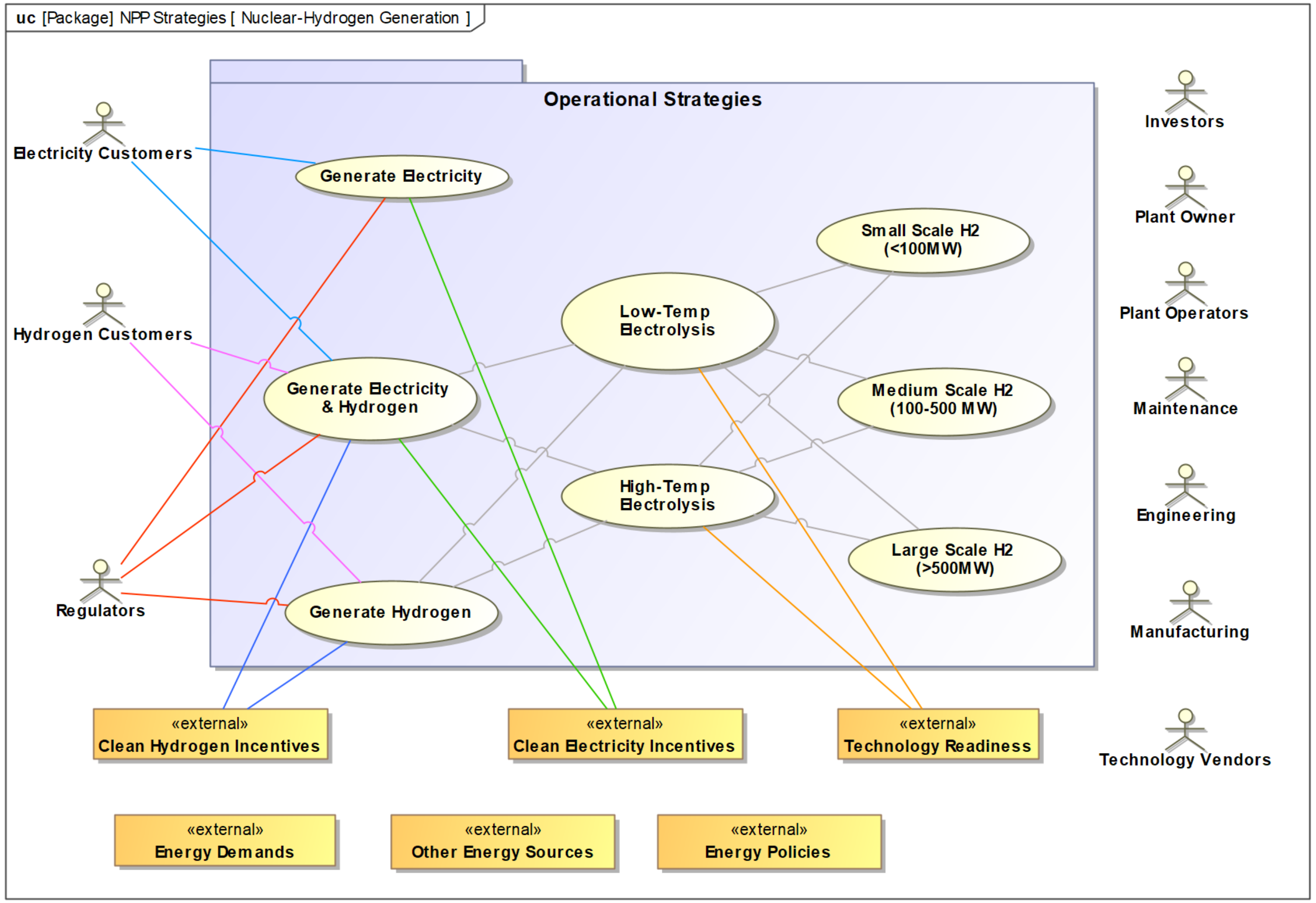
Example of FMEA Matrix



Examples of PRA Model Artifacts – Event and Fault Trees [7]

Step 1: Identify the Problem

- Problem: Generate clean hydrogen
  - Clean: use technologies supporting low green-house gas emissions
- Identify conceptual solutions that:
  - Best fit the identified needs and expectations
  - Have the highest probability of success
  - Have lowest risks
- Specify pros and cons for each solution to support decision-making



Problem defined as a context diagram

Steps 1: Identify Stakeholders and Stakeholder Needs

- Stakeholders, their needs and concerns

Stakeholders	Needs and Concerns
Investors	**Needs:** - Generate profit from hydrogen generation **Relevant concerns:** - Return on Investment, costs, revenue - Federal policies, regulatory approvals
Hydrogen plant owner / operator	**Needs:** - Generate profit from hydrogen generation - Safely operate hydrogen generating facility **Relevant concerns:** - Costs, revenue - Regulatory compliance - Technical performance
	Needs: - Generate profit from selling hydrogen-generating equipment **Relevant concerns:** - Costs - Technical performance
Hydrogen Consumers	**Needs:** - Have consistent source of hydrogen **Relevant concerns:** - Technical characteristics: availability, volume, quality, price - Reduction of GHG emissions
Electrical gride operators	**Needs:** - Reliable and resilient grid operations **Relevant concerns:** - Reliability and availability of generation - Flexibility of operations
Community	**Needs:** - Reliable electricity - Reduction of GHG emissions - Preserve natural resources **Relevant concerns:** - Safety
Regulators	**Needs:** - Ensure safe operations of hydrogen facilities - Preserve and protect natural resources

- The same information in the model

Stakeholders

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

Consolidated concise list of stakeholder needs

	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		X							X		X
2 Hydrogen plant owner/operator		X	X						X		X
3 Hydrogen equipment manufactur...	X	X	X	X	X				X		X
4 Hydrogen consumers	X		X	X	X		X		X		
5 Electrical grid operators								X			
6 Community						X	X	X			X
7 Government						X	X	X		X	
8 Regulators						X					X

Traceability between stakeholders and needs

Step 1: Translated System Requirements

- Functional Requirements

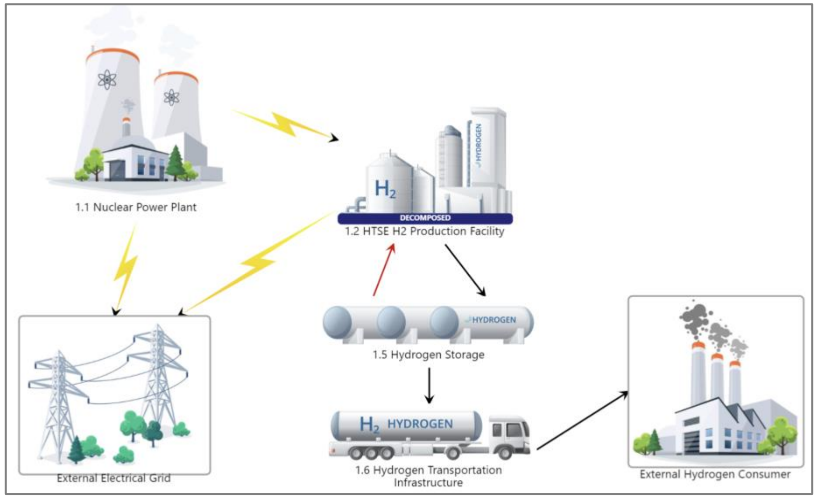
Entity	Rationale	Labels
FR-1 Generate Hydrogen The system shall generate hydrogen at required production rate	The system production rate and availability of hydrogen supply is specified by the hydrogen customer(s)	Functional Requirement
FR-1.1 Provide infrastructure for … The system shall provide infrastructure 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

- Non-Functional Requirements

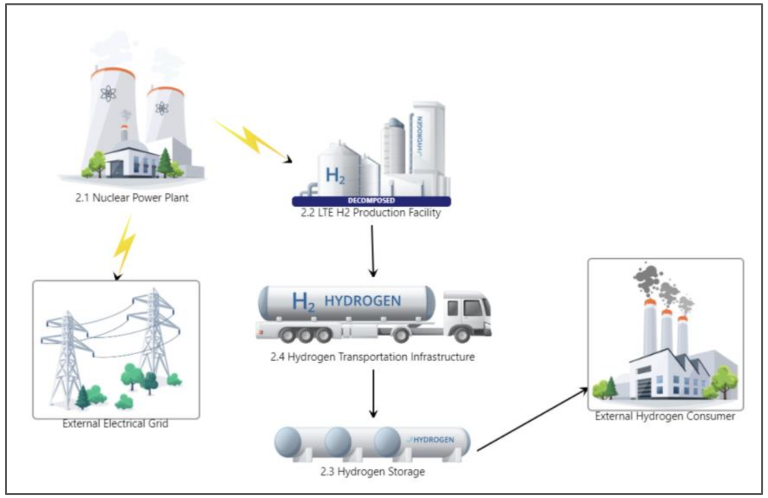
Entity	Rationale	Labels
PR-1 Hydrogen production rate The hydrogen production facility shall supply hydrogen at a minimum rate of 50,000 kg of hydrogen per day	The minimum production rate is specified by the hydrogen customer	Performance Requirement
PR-1.1 Storage capacity The storage system shall provide 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

Step 2: Conceptual Solutions

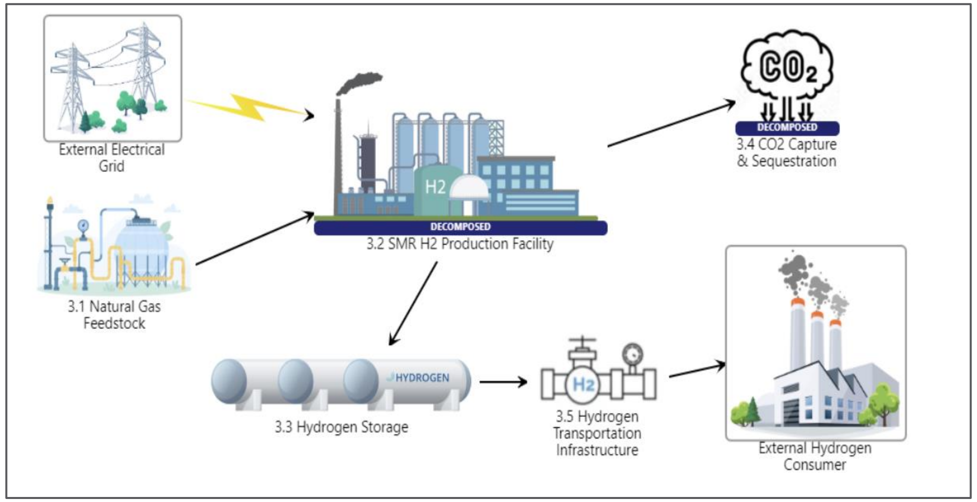
- Potential solutions for clean hydrogen generation:
  1. High-Temperature Steam Electrolysis (HTSE) and energy from a nuclear power plant (NPP)
  2. Low-Temperature Electrolysis (LTE) and energy from a nuclear power plant (NPP)
  3. Steam Methane Reforming (SMR) with carbon capture and sequestration



Solution 1: Hydrogen generation via HTSE using electricity and thermal energy provided by a NPP



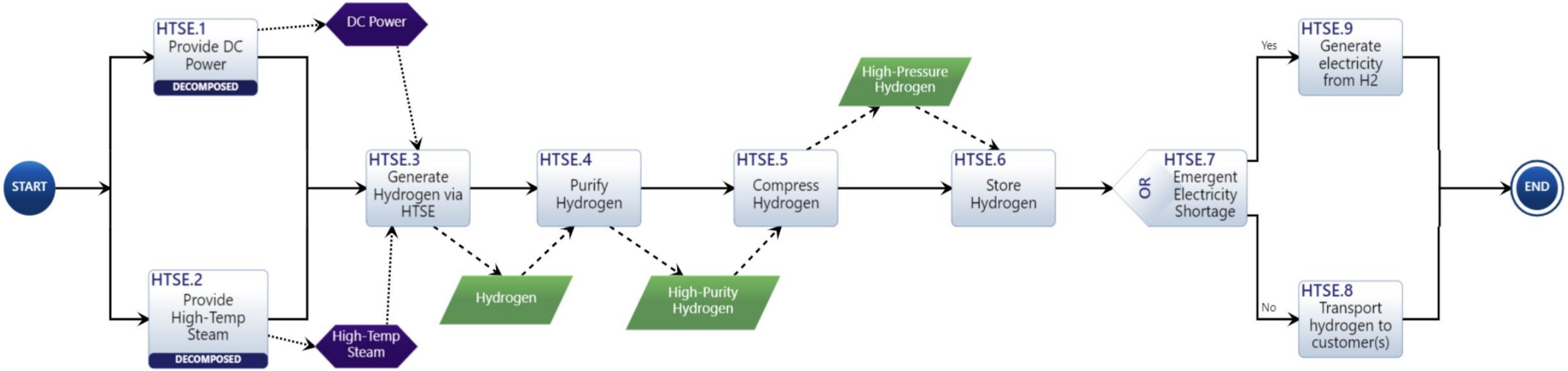
Solution 2: Hydrogen generation via LTE using electricity provided by a NPP



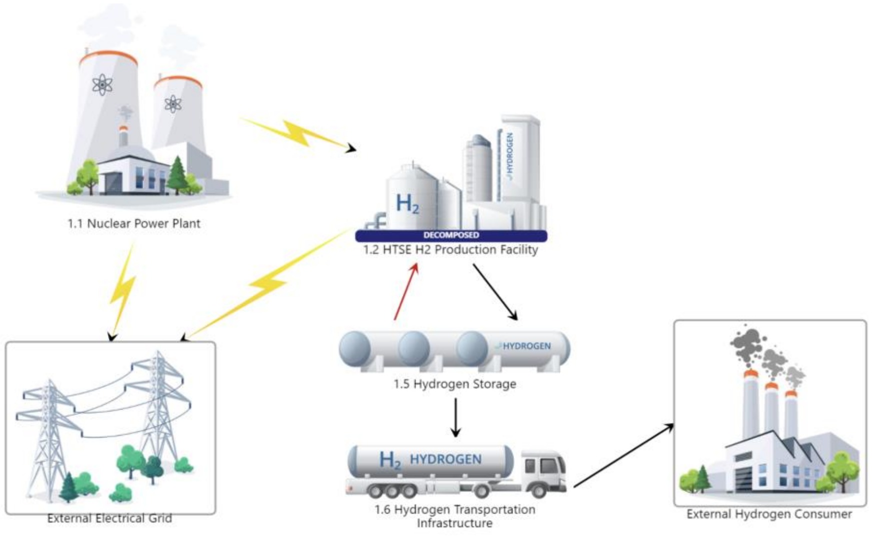
Solution 3: Hydrogen generation via SMR with carbon capture and sequestration supported by electricity supplied by the grid

Step 2 – Conceptual Solutions (cont'd)

Solution 1: Hydrogen generation via HTSE using energy provided by a Nuclear Power Plant (NPP)



Solution 1: Action diagram



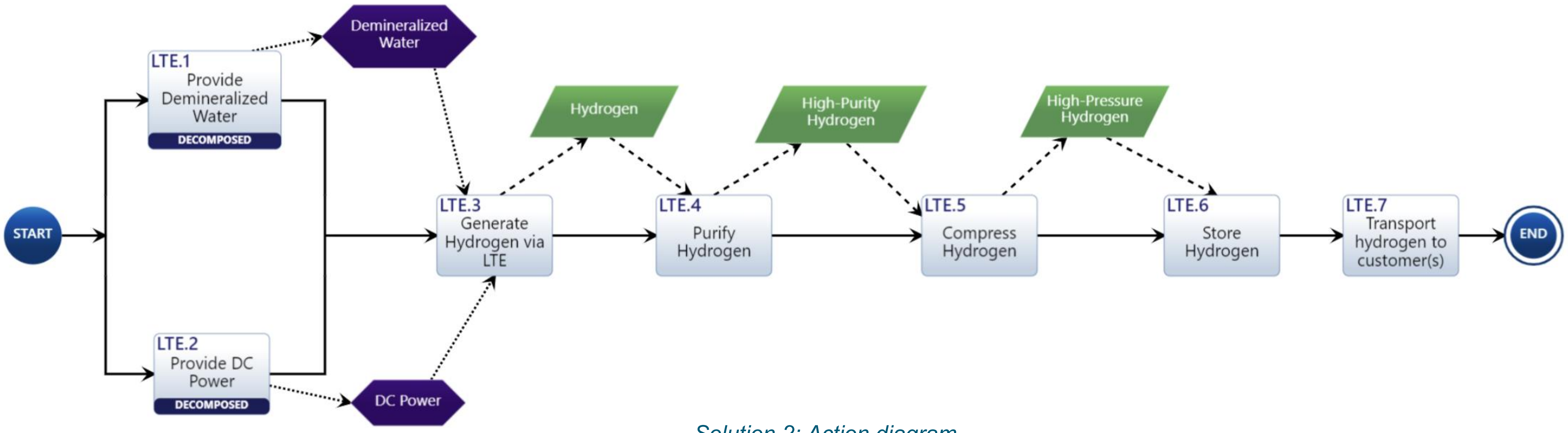
Solution 1: Asset diagram

Main Characteristics:

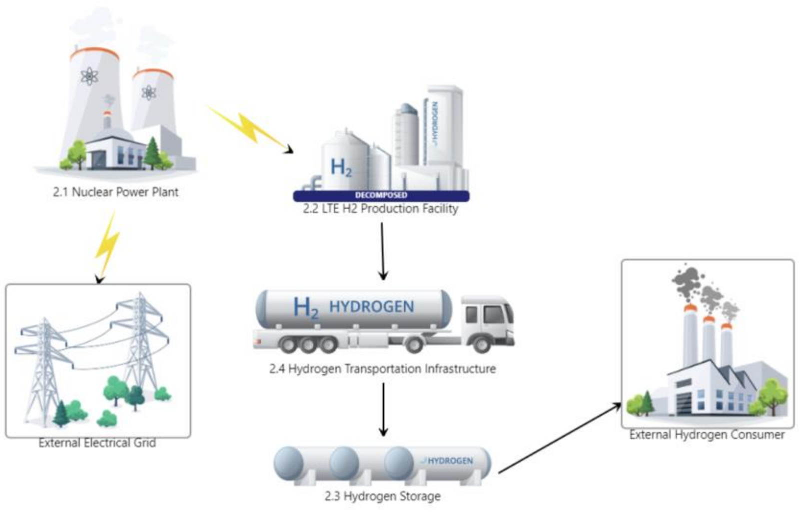
- NPP provides thermal energy and electricity to the hydrogen generation facility
- Modifications for NPP are needed to support thermal energy (i.e., steam) extraction to support HTSE
- NPP continues to supply remaining electricity to the grid
- Produced hydrogen is already high-purity but remaining moisture and oxygen must be removed to meet the required purity level
- Storage capacity is driven by the requirement of uninterrupted supply of hydrogen to the customer
- Transportation infrastructure is required since the hydrogen customer is not immediately next to the NPP
- Stored hydrogen could be used to produce electricity if needed to support emergent grid operations by reversing operations of Solid Oxide Fuel Cells (SOFC) to generate electricity instead of hydrogen

Step 2 – Conceptual Solutions (cont'd)

Solution 2: Hydrogen generation via LTE using electricity provided by a NPP



Solution 2: Action diagram



Solution 2: Asset diagram

Main Characteristics:

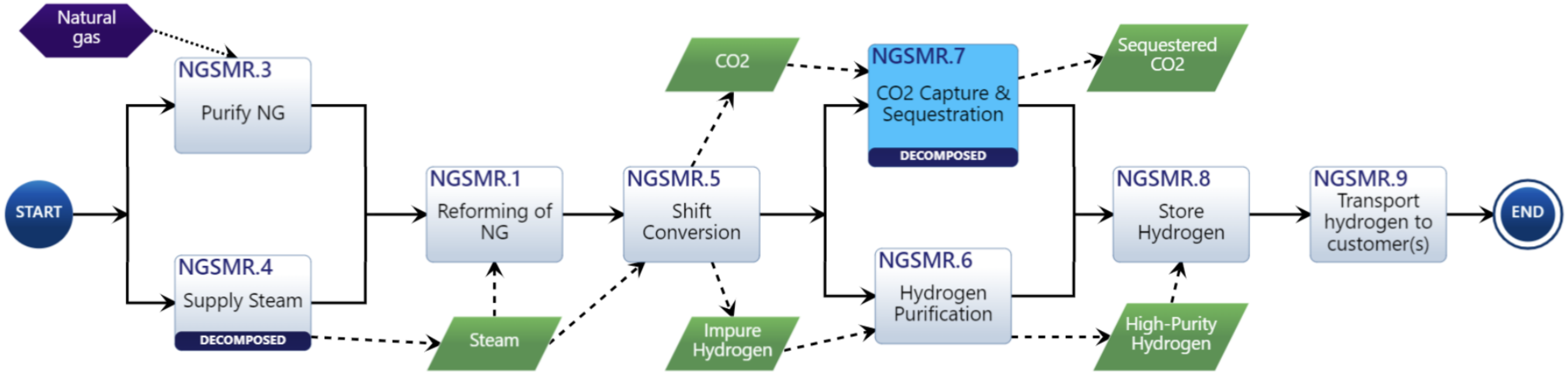
- NPP provides electricity to hydrogen generation facility
- NPP continues to supply remaining electricity to the grid
- Purification, storage and transportation aspects are the same as in Solution 1.

Key differences from Solution 1:

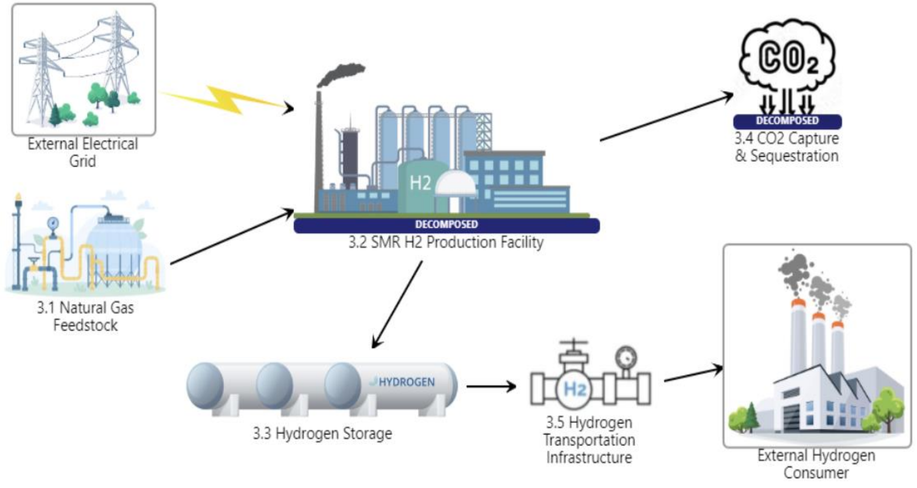
- Instead of HTSE, Low-temperature Electrolysis (LTE) with Proton Membrane Exchange (PEM) is the selected technology for electrolysis; Alkaline Exchange Membrane (AEM) could be another LTE technology choice
- No modifications are required for the NPP since thermal energy is not extracted
- There is no reverse operation option of electricity generation from stored hydrogen, but there is still an option to curtail production of hydrogen to supply electricity to the grid

Step 2 – Conceptual Solutions (cont'd)

Solution 3: Hydrogen generation via Steam Methane Reforming (SMR)



Solution 3: Action diagram



Solution 3: Asset diagram

Main Characteristics:

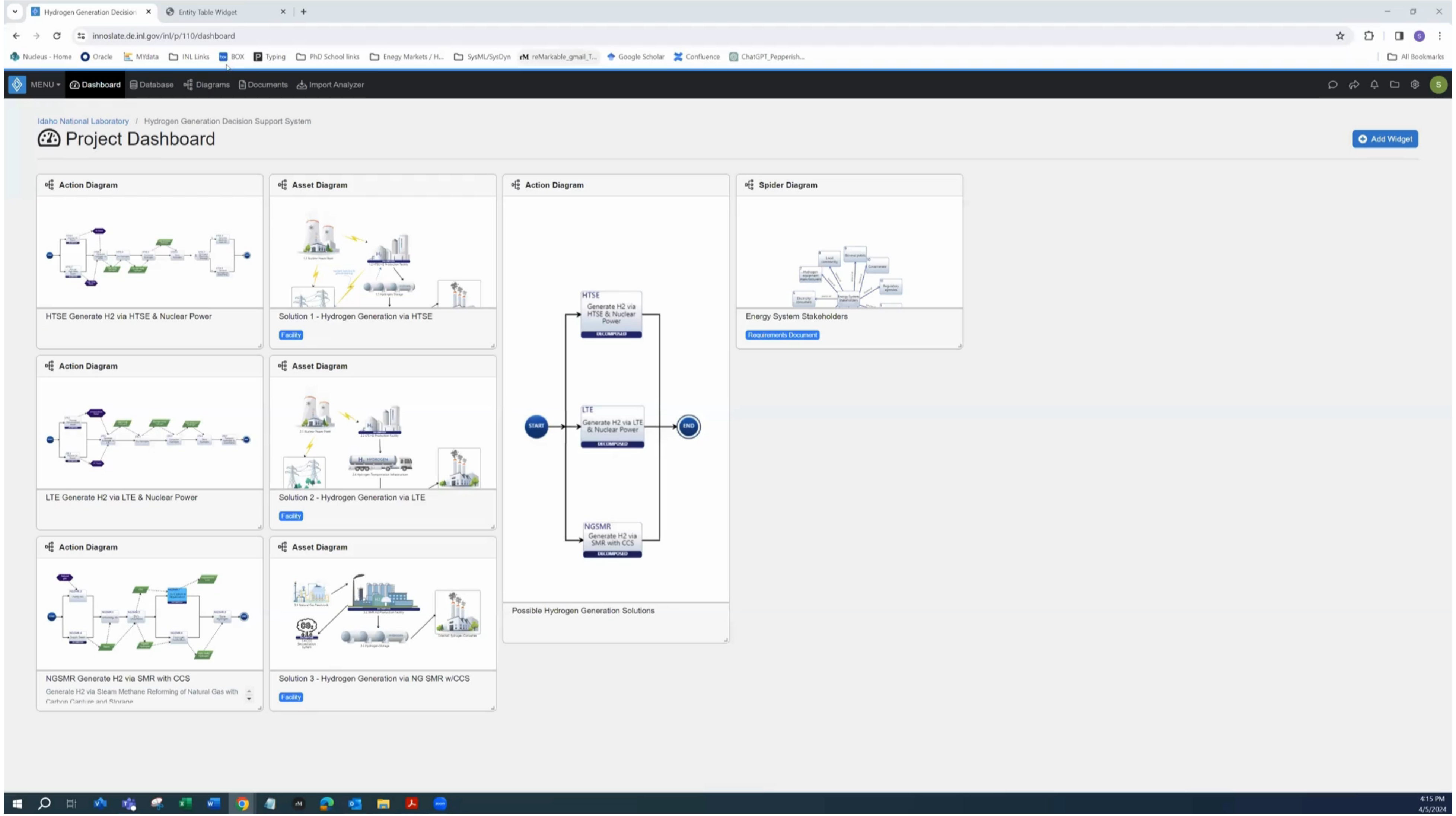
- Currently used technology for hydrogen generation
- The existing hydrogen generation facility is assumed to be used supplemented with carbon capture and sequestration (CCS) to qualify as low-carbon technology
- Electrical grid supplies electricity to the hydrogen generation facility
- Existing storage and transportation infrastructure is used since the existing hydrogen generation facility is located adjacent to the hydrogen consumer
- Captured CO2 is transported and stored offsite

Key differences from Solutions 1 & 2:

- Feedstock – natural gas (NG) instead of water
- Significant CO2 emissions which necessitates CCS system / processes / infrastructure
- Purification process is much more extensive as produced hydrogen is low-level purity with presence of many byproducts that must be removed
- There is no flexible operation option to support grid other than curtailing hydrogen generation which only conserves limited amount of electricity

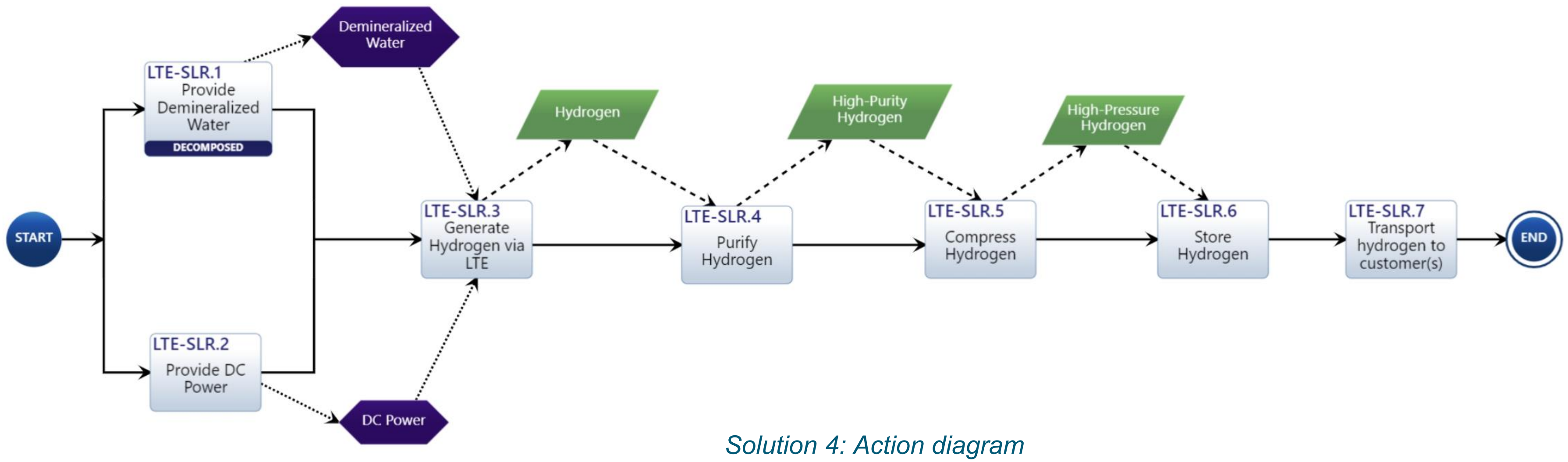
MBSE Capabilities Example

- A quick and easy generation of an additional alternative solution

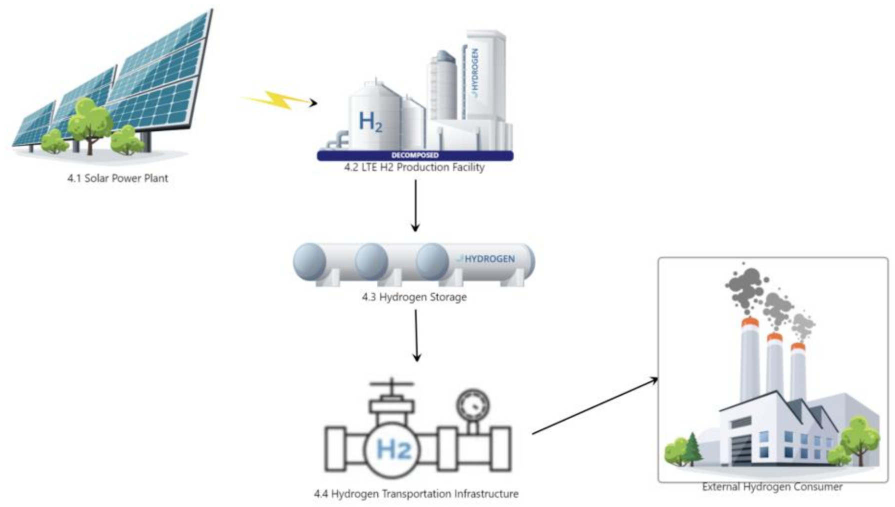


Step 2 – Conceptual Solutions (cont'd)

Solution 4: Hydrogen generation via LTE using renewable electricity



Solution 4: Action diagram



Solution 4: Asset diagram

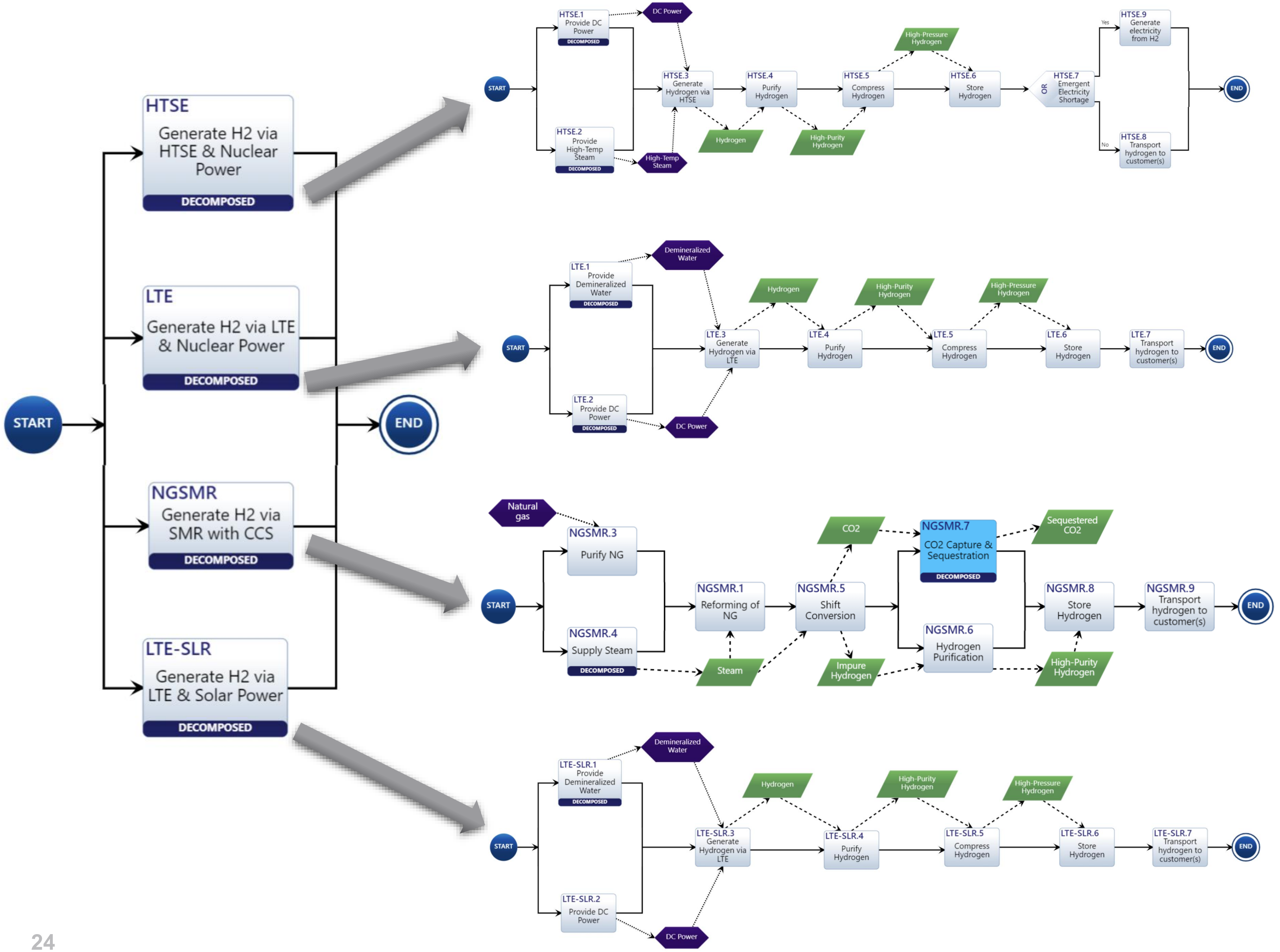
Main Characteristics:

- A solar plant provides electricity to hydrogen generation facility
- A solar plant is next to the hydrogen generation facility
- Purification process is the same as for Solution 1 & 2
- Storage capacity is driven by the requirement of uninterrupted supply of hydrogen to the customer
- Transportation infrastructure is required since the hydrogen customer is not immediately next to the hydrogen generation facility

Key differences from Solution 2:

- A new solar power plant is needed to support hydrogen generation
- A much larger storage capacity is needed to account for interrupted H2 production driven by daylight and weather conditions
- Hydrogen transportation infrastructure could be simpler as solar plant / hydrogen generation facility could be located close to hydrogen customer
- Solar plant requires a large parcel of land to support the energy demands of large-volume hydrogen generation facility

Step 2 Completed



- Summary of Step 2:
  - Identified feasible conceptual solutions
  - Proposed various technology solutions for energy supply and hydrogen generation
  - Outlined key differences that may impact customer preferences
  - All information from Step 1 and Step 2 is stored within a single model
- MBSE support:
  - An objective and systematic process of concept development
  - A simplified, user-friendly visualization solution
  - Documentation and traceability from stakeholder needs to system functions and performance characteristics
  - Knowledge repository and transfer

Next Steps

- Step 3 – Evaluate conceptual solutions
  - Perform assessments needed to generate metrics needed to compare the solutions
    - Economic assessments considering variation in technologies
      - Metrics to develop for each solution: NPV, IRR, LCOH
    - Technical assessments to support selection of physical solutions that would satisfy the concepts
      - Options for electrolysis technology solutions from various manufacturers
      - Technical options for storage and transportation solutions
    - Risk assessments
      - Safety-related risks (e.g., hydrogen safety)
      - Economic risks (e.g., effects of policy changes to future profitability)
    - System behavior assessments
      - Develop a model demonstrating dynamics of energy solutions in the context of the overall energy system with multiple variables influencing system behavior
      - Develop projections for long-term system behavior to support DM
  - Specific assessments could be completed in MBSE framework or using independent tools with results consolidated and documented in MBSE model
- Step 4 – make the decision – select the solution to be implemented
  - Use MBSE to document reasoning for decisions to support other assessments
    - N^{th} hydrogen facility generation
    - Different regional conditions (e.g., higher cost of natural gas)
    - Altered preferences of customers (e.g., larger focus on GHG emissions)

Questions?

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