Towards the Integration of Hydrogen Production with Nuclear with Model-Based Systems Engineering

2023 ANS Winter Conference

Svetlana Lawrence

Svetlana.Lawrence@inl.gov

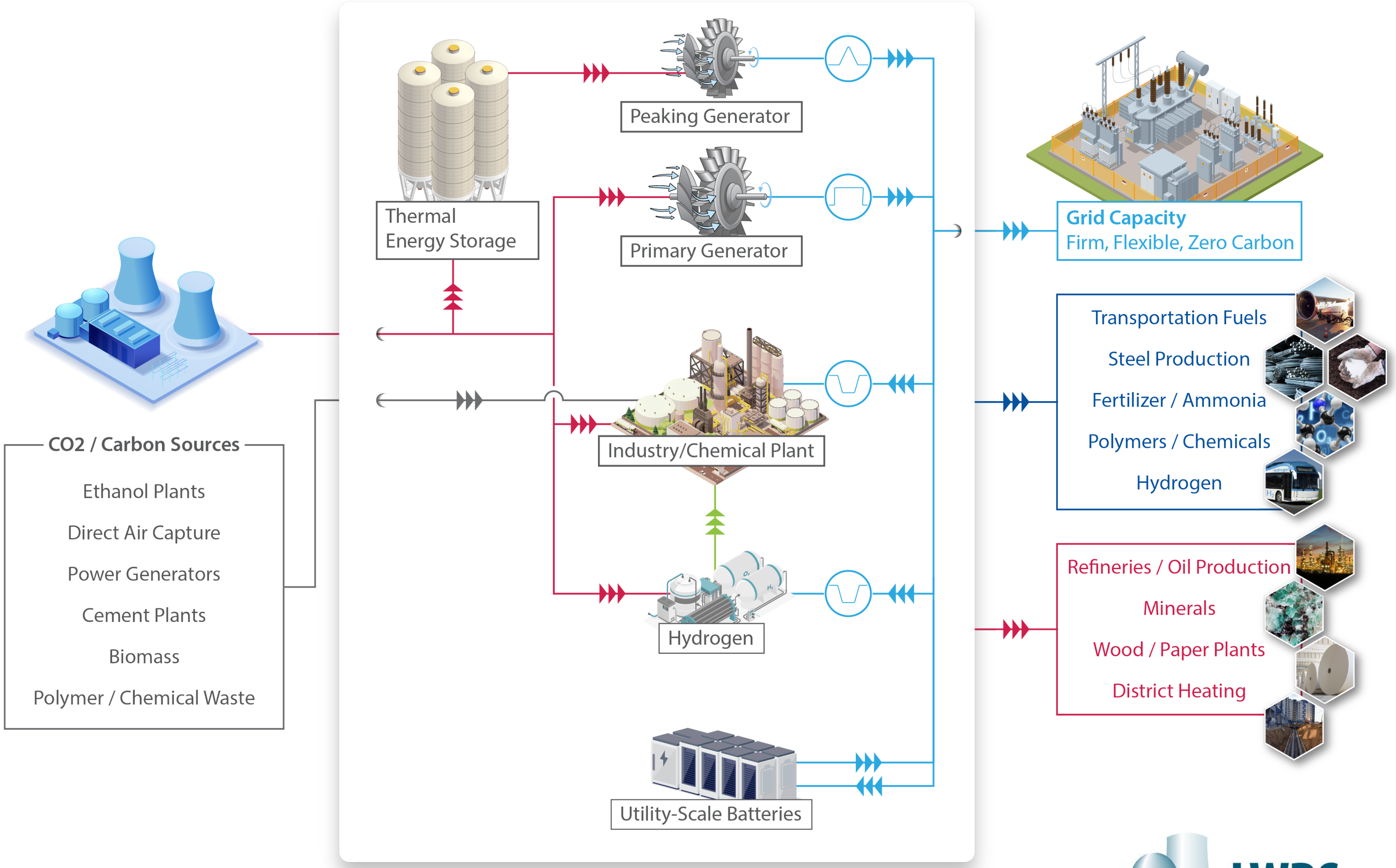
Dr. Daniel Herber

Daniel.Herber@colostate.edu

November 14, 2023

Introduction and Background

- National Needs:
  - Energy security and resiliency → 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



LWRS LIGHT WATER REACTOR SUSTAINABILITY

Introduction and Background (cont'd)

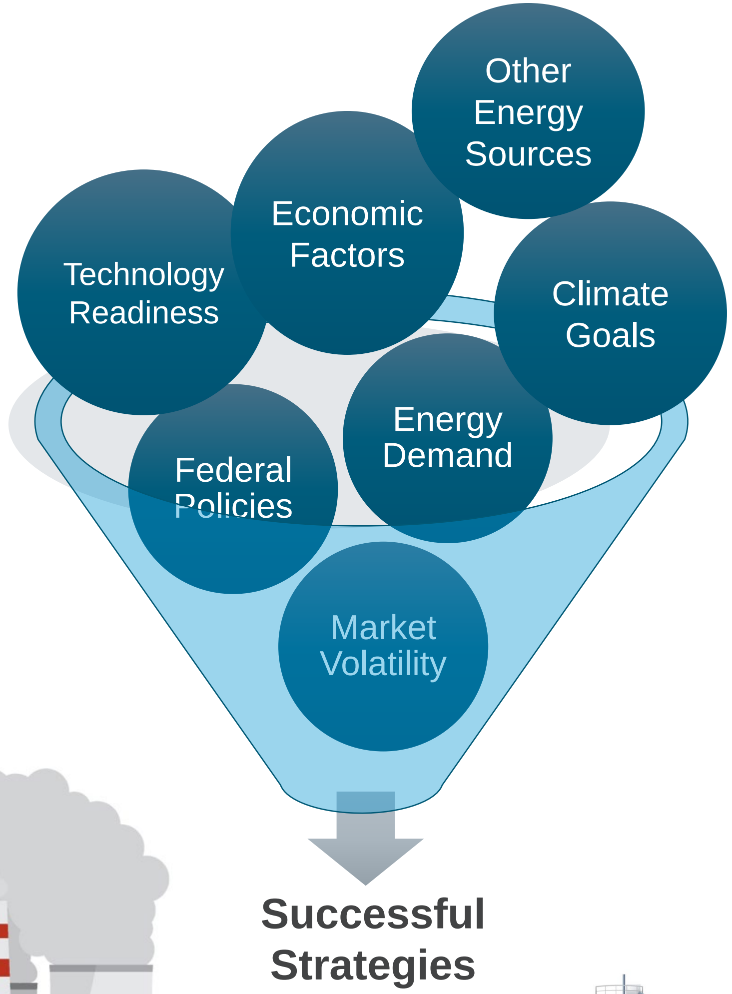
- Feasibility:
  - Hydrogen demand is expected to double by 2030
  - Inflation Reduction Act offers substantial benefits for clean hydrogen production
  - Possible to achieve DOE 2026 Goal of $2 per kilogram with Nuclear Power Plants
- The obvious business case then? Not quite this simple…
  - Complexity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

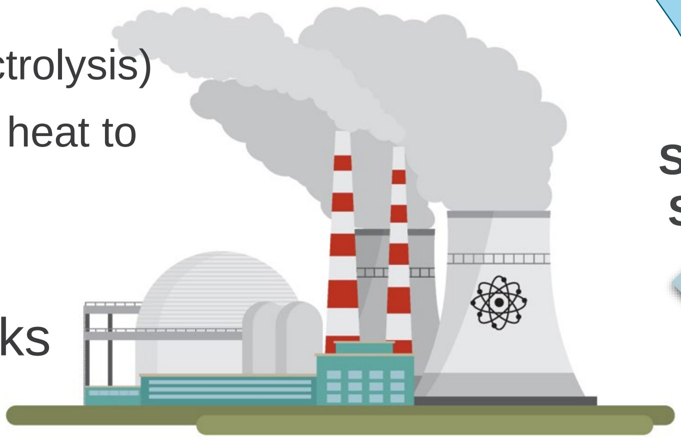
→ Investment Uncertainties

- 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 for Nuclear-Hydrogen Hybrid operation
  - 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:
  - Increased NPP power output (power uprates)
  - How much electricity to allocate to H2
  - H2 technology selection (low- vs high-temperature electrolysis)
  - Potential to support other non-electrical products (e.g., heat to industrial or chemical facilities)
- Need to consider multiple “potential futures”
- Need to weigh associated uncertainties and risks





Complex Problem (cont'd)

- Stakeholder Needs
  - By itself, it is already a complex task to analyze
- System solution options
  - The configuration of the system is affected by dozens of factors → extremely complex to analyze and select the best alternative

System general configuration options

Category	Options	Constrains
Steam intake location for HTE	Main steam Feedwater system Others	Thermal efficiencies Added risks Complexity of plant modifications ($$)
Electricity intake location	Behind the meter Off the grid	IRS regulations on production credits Agreements with power authorities
Distance of H2 facility from nuclear plant	1,000 m 500 m 250m	Risks due to hydrogen hazards (explosion) Thermal efficiencies Plant site configuration
Hydrogen storage	Large volume (> 1000 tones) Medium volume (100 – 1000 tones) Small volume (< 100 tones)	Hydrogen demand Hydrogen user requirements
Distribution	Existing H2-specific pipelines New H2-specific pipelines Existing natural gas pipelines Auto transport Railroad transport Other	Hydrogen users Demand Costs
Use of hydrogen as energy storage	Yes / No % of produced H2 to be used as energy storage	Business case Regional electricity prices Fluctuation of electricity prices Renewable energy sources in the region
Additional profit from oxygen (by-product of electrolysis)	Yes / No If YES: Storage capacity Distribution options	Demand Costs

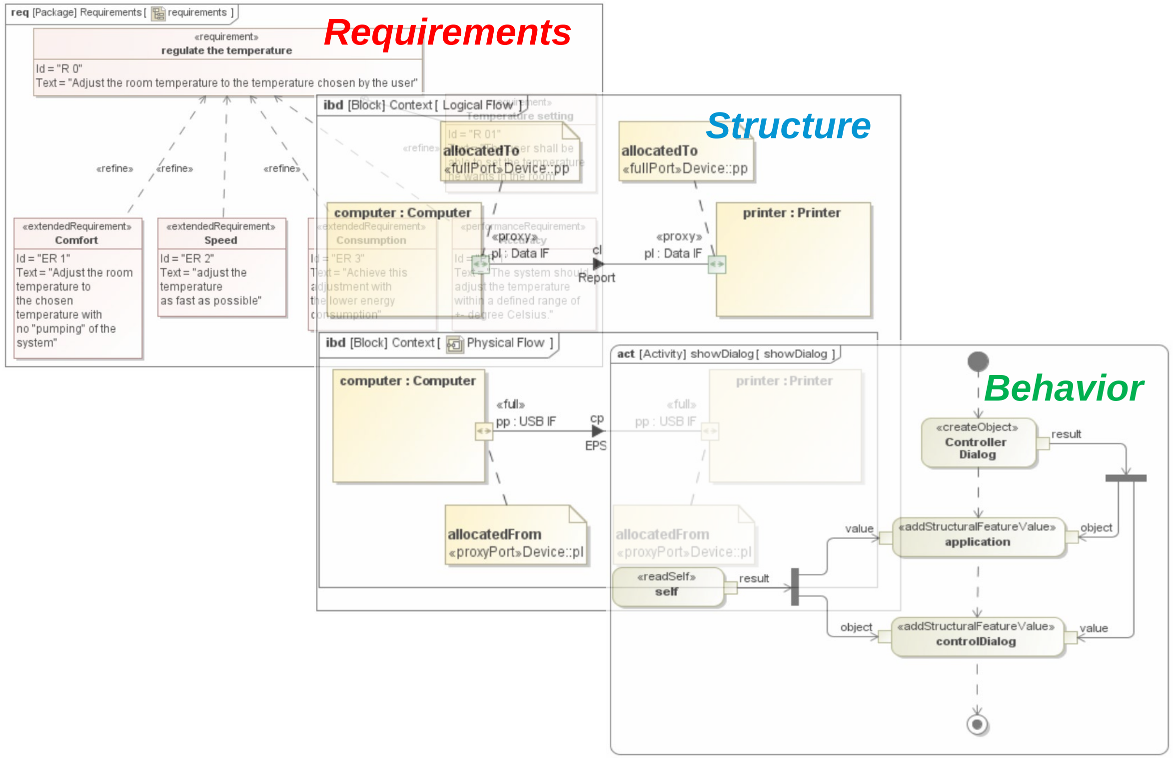
?

System stakeholders and their concerns

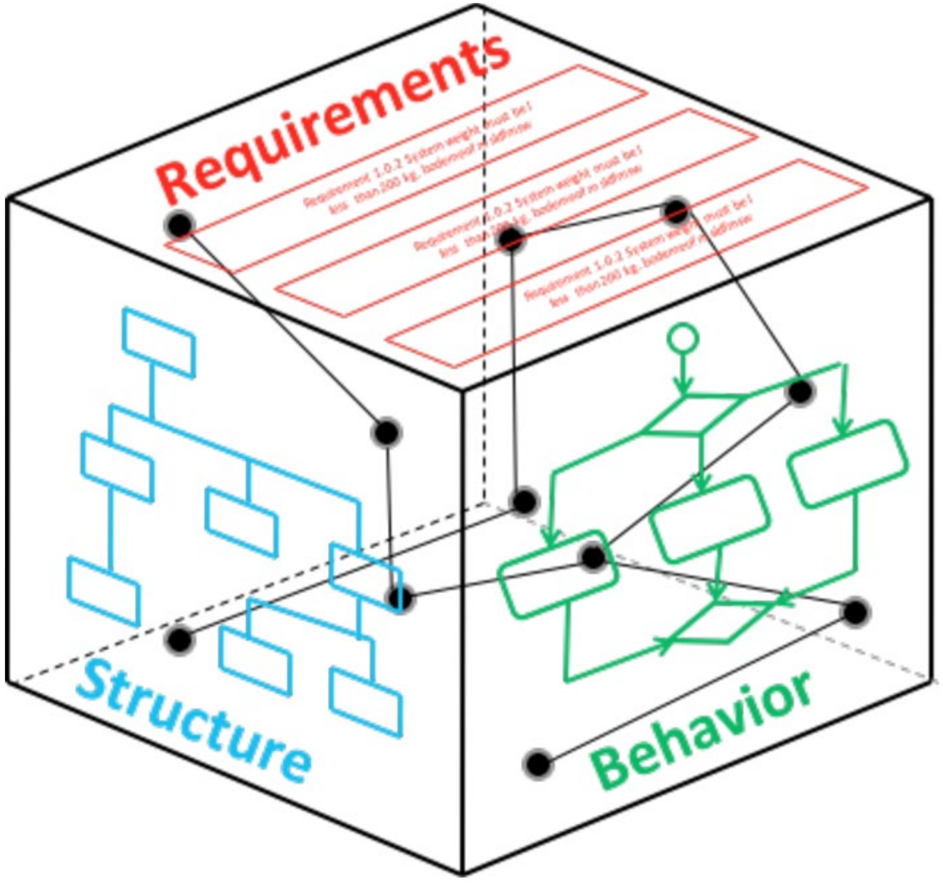
Stakeholders	Concerns
Electricity Consumers	Affordable electricity Consistent availability (24/7/365) Climate goals
Hydrogen Consumers	Affordable hydrogen Consistent availability (24/7/365) Hydrogen quality Climate goals
Owner(s) Investor(s)	Return on Investment Costs Revenue Funding sources Regulatory approvals and compliance Federal energy policies Technology maturity Reliability and availability Climate goals
Facility Operations and Maintenance	Safe and easy operation of the integrated system(s) Technology maturity Reliability and availability Regulatory compliance Spare parts
Hydrogen technology vendors	Technology maturity Reliability and availability Affordable hydrogen Consistent availability (24/7/365) Hydrogen quality Climate goals
Federal government	Federal energy policies Climate goals Energy resiliency Energy independence Affordable energy sources Technology maturity
Regulators	Regulatory approvals and compliance Reliability and availability Technology maturity Climate goals

Solution for Complexity Management:
Model-Based Systems Engineering (MBSE)

- A single model, multiple perspectives
  - MBSE creates and manages a single model of the system and can show multiple perspectives, e.g., requirements, structure, and behavior
  - All elements in the model are connected and a change in one perspective updates the entire model



MBSE diagrams representing various perspectives [2]



Dimensions of MBSE models [1]

[1] Bajaj et al, "Architecture to Geometry – Integrating System Models with Mechanical Design"
https://www.omgsysml.org/Arch-to-Geom_Bajaj-Cole-Zwemer_Space-2016.pdf

[2] CATIA | NoMagic, MagicGrid User Guide
https://docs.nomagic.com/display/SYSMLP190/User+Guide

Example MBSE Artifacts

- Simple representation, clear transitions

0 Stakeholder Conserns [Model::0 Prelimina	1 Stakeholder Needs [Moc	Electricity Customers	Hydrogen Customers	Plant Owner	Investors	Engineering	Technology Vendors	Manufacturing	Plant Operators	Maintenance	Regulators	Government
		2	3	16	7	8	8	3	3	3	3	10
SC-1 Affordable Electricity	3	↙		↙								↙
SC-2 Electricity Availability (24/7/365)	4	↙		↙		↙						↙
SC-3 Affordable Hydrogen	4		↙	↙			↙					↙
SC-4 Hydrogen Availability (24/7/365)	5		↙	↙		↙	↙					↙
SC-5 Hydrogen Quality	4		↙	↙		↙	↙					
SC-6 Return on Investment	2			↙	↙							
SC-7 Revenue	2			↙	↙							
SC-8 Costs	3			↙	↙		↙					
SC-9 Funding Sources	5			↙	↙		↙	↙				↙
SC-10 Technology Maturity	5			↙	↙	↙	↙					↙
SC-11 Reliability and Availability	7			↙	↙	↙	↙	↙	↙	↙		
SC-12 Safe and Easy Operation	3			↙		↙			↙			
SC-13 Spare Parts	5			↙		↙	↙	↙		↙		
SC-14 Regulatory Approvals	4			↙	↙	↙					↙	
SC-15 Regulatory Compliance	4			↙					↙	↙	↙	
SC-16 Climate Goals	3			↙							↙	↙
SC-17 Energy Independence	1											↙
SC-18 Energy Resiliency	1											↙
SC-19 Federal Energy Policies	1											↙

Stakeholder needs and concerns

Translated into

Name
1 Mission Requirements
1.1 System Functional Requirements
1.1.1 Generate Electricity
1.1.1.1 Generate electricity at low cost
1.1.1.2 Generate electricity without interruption
1.1.2 Generate Hydrogen
1.1.2.1 Generate hydrogen at low cost
1.1.2.2 Generate hydrogen without interruption
1.1.2.3 Generate high-quality hydrogen
1.2 Business Requirements
1.3 System Design Requirements
1.3.1 H2 Technology
1.3.1.1 H2 Production Capacity
1.3.1.2 Reliability
1.3.1.3 Efficiency
1.3.2 Integration
1.3.2.1 H2 Plant Electric Load
1.3.2.2 H2 Plant Aux Load
1.3.2.3 H2 Plant Thermal Load
1.3.2.4 Steam Temperature
1.3.2.5 Steam Pressure
1.3.2.6 Separation Distance from Nuclear Plant

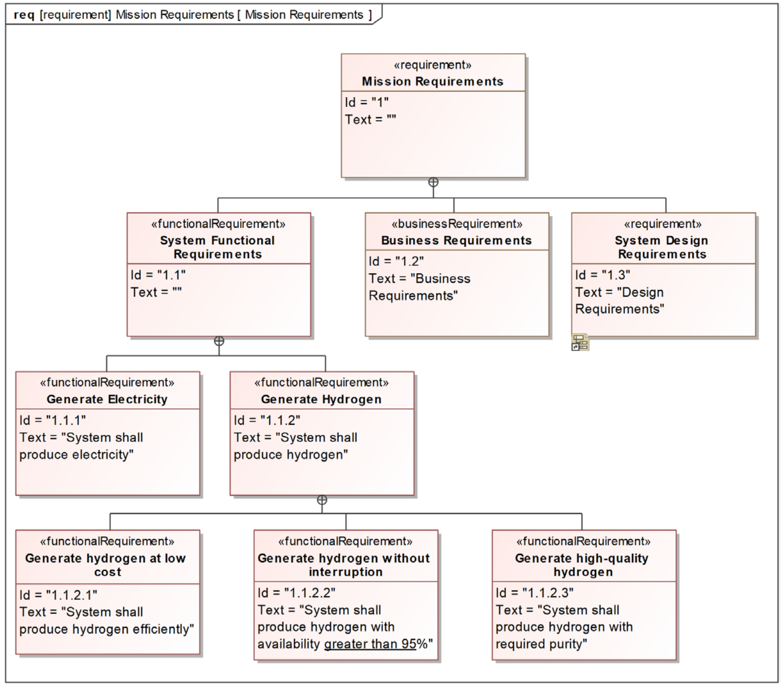
System requirements

Example MBSE Artifacts (cont'd)

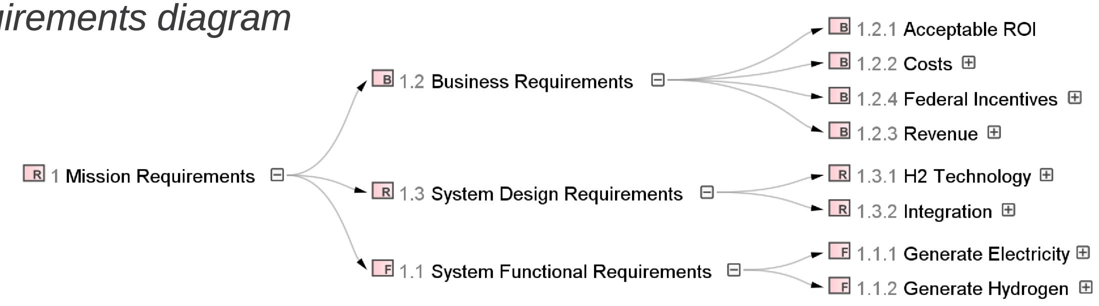
- Multiple options for presenting system elements and views

Name
1 Mission Requirements
1.1 System Functional Requirements
1.1.1 Generate Electricity
1.1.1.1 Generate electricity at low cost
1.1.1.2 Generate electricity without interruption
1.1.2 Generate Hydrogen
1.1.2.1 Generate hydrogen at low cost
1.1.2.2 Generate hydrogen without interruption
1.1.2.3 Generate high-quality hydrogen
1.2 Business Requirements
1.3 System Design Requirements
1.3.1 H2 Technology
1.3.1.1 H2 Production Capacity
1.3.1.2 Reliability
1.3.1.3 Efficiency
1.3.2 Integration
1.3.2.1 H2 Plant Electric Load
1.3.2.2 H2 Plant Aux Load
1.3.2.3 H2 Plant Thermal Load
1.3.2.4 Steam Temperature
1.3.2.5 Steam Pressure
1.3.2.6 Separation Distance from Nuclear Plant

System requirements table



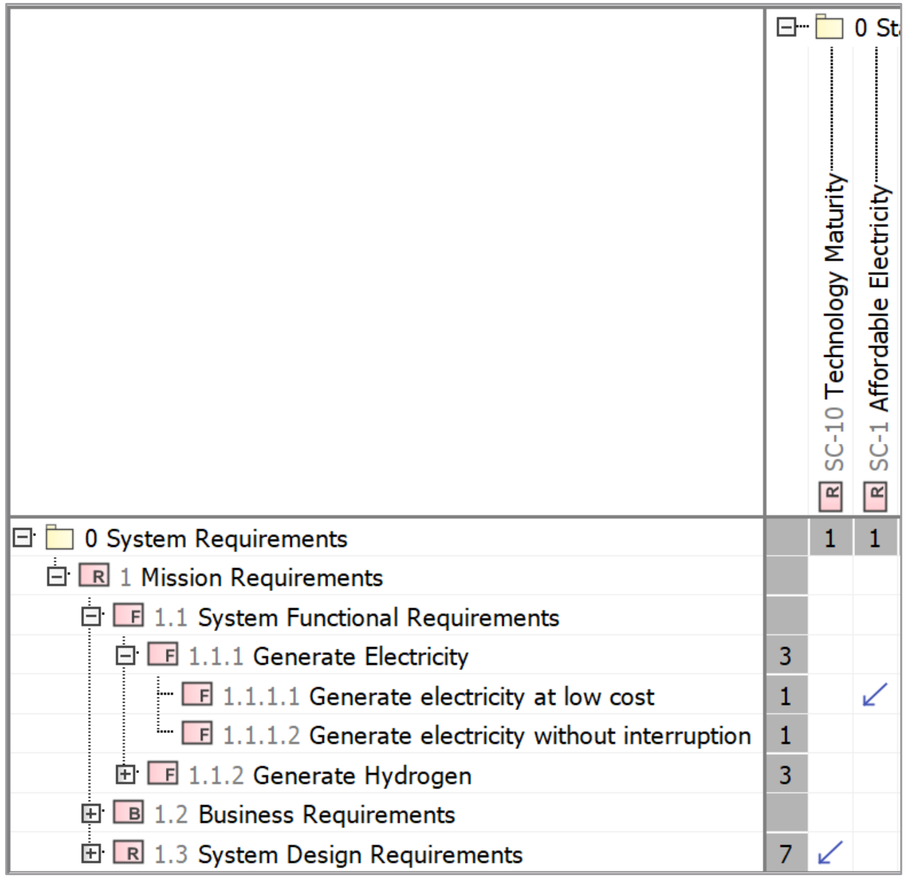
System requirements diagram



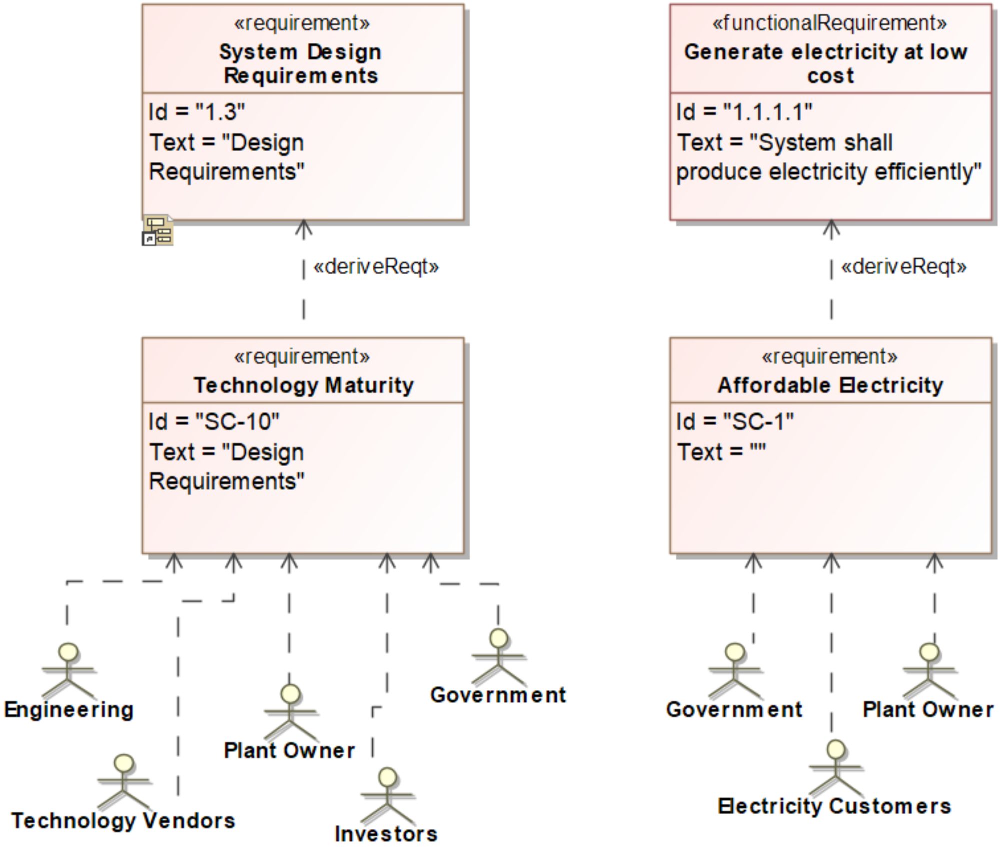
System requirements map

Example MBSE Artifacts (cont'd)

- Interconnections are traced throughout the model from one view to another



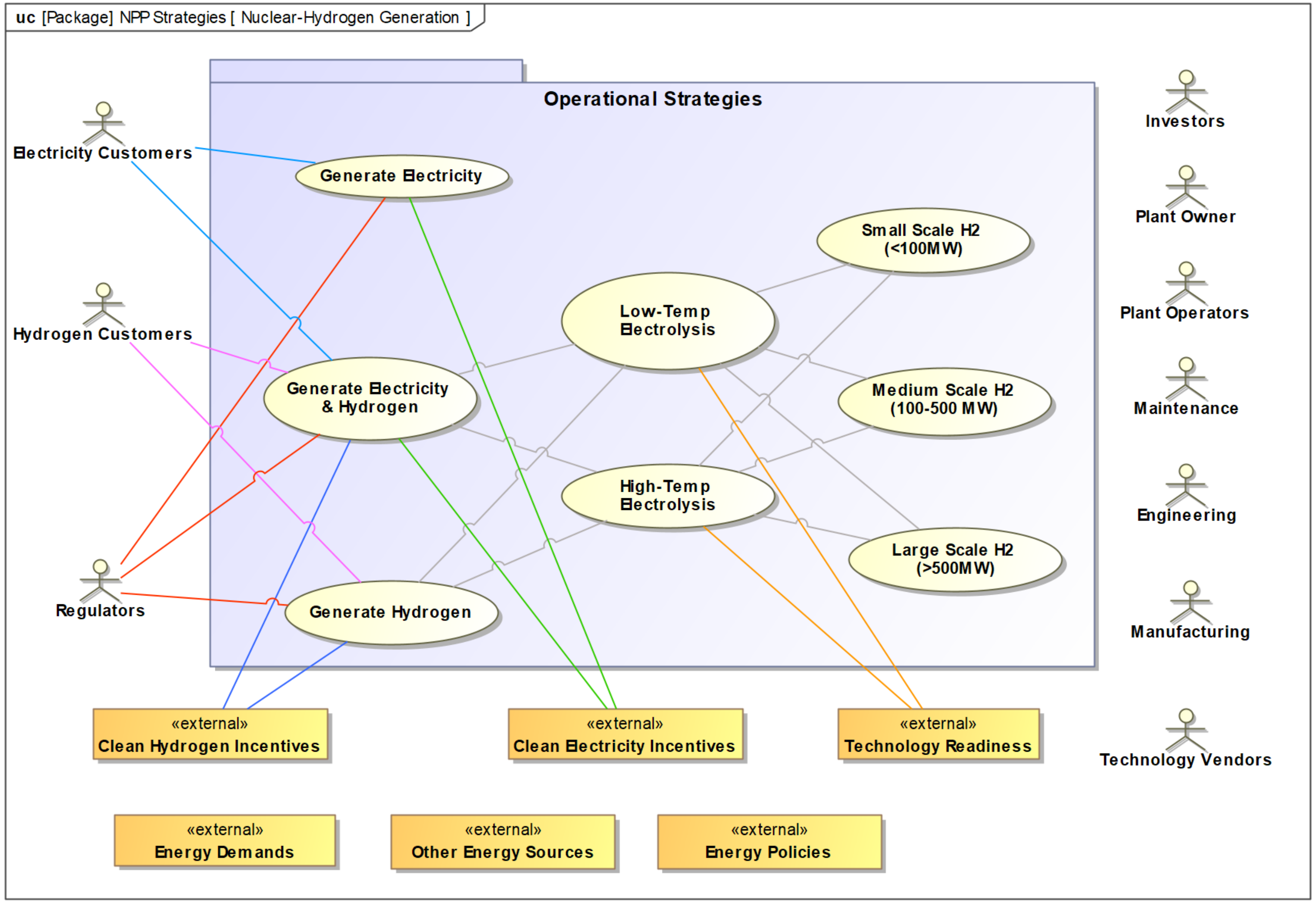
Requirements traced to stakeholder concerns



Stakeholders → Stakeholder Concerns → Requirements

Example MBSE Artifacts (cont'd)

- Graph-based representation of elements and relationships



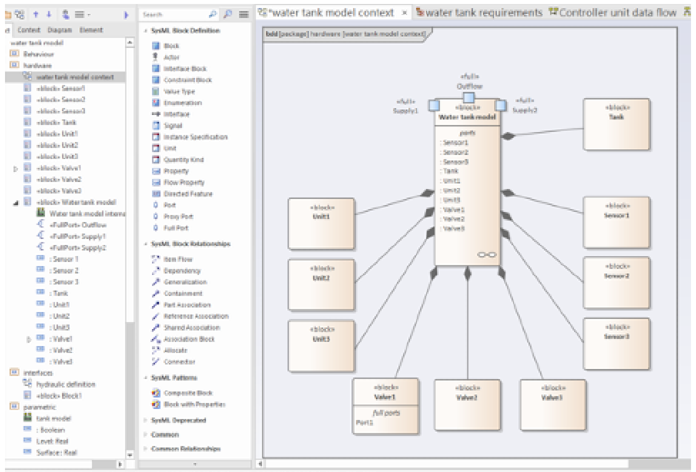
Operational strategies shown via a context diagram

Why MBSE?

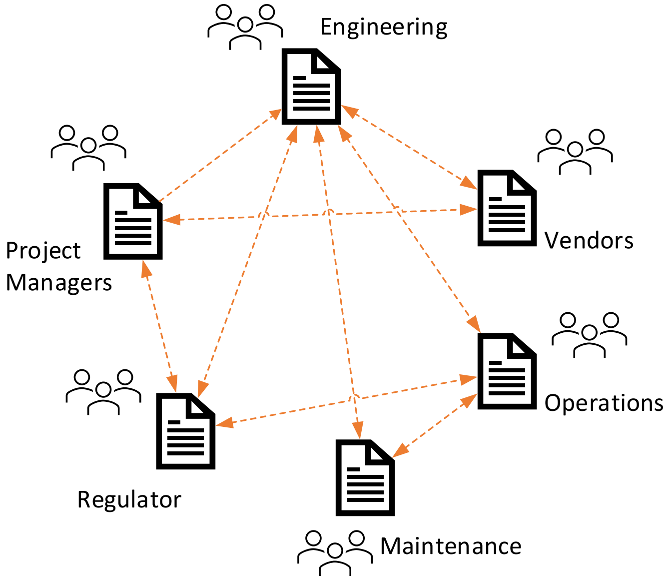
- From multiple documents to a single model
  - Instead of multiple information sources (i.e., hundreds of documents) use digital model as a single source of truth
- Benefits
  - Superior knowledge capture and transfer
  - Effective complexity management
  - Improved communications
  - Improved product quality
  - Dramatic reduction of cost and schedule overruns

Document centric

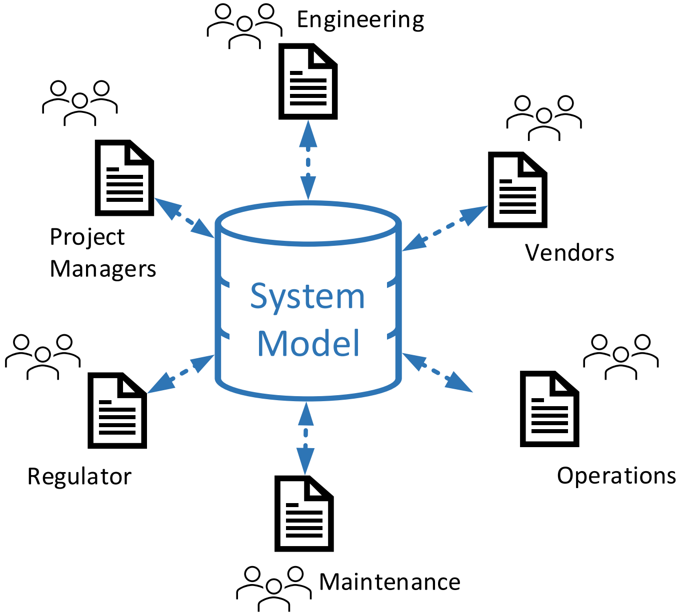
Model centric



Document centric



Model centric



MBSE for Projects in Nuclear Domain

- A simple application – management of regulatory paperwork
  - Nuclear licensing: from GAO-07-1129: "*Design applications may total up to 15,000 pages*"
  - To put in perspective:
    - The 32-Volume set of Encyclopedia Britannica has 1,112 pages, i.e., a design application to license a nuclear power plant could be larger than **13 sets of Encyclopedia Britannica**
  - Non-nuclear regulations and permits for hybrid operations
    - Federal Energy Regulatory Commission (FERC), Environmental Protection Agency (EPA), Occupational Safety and Health Administration (OSHA), National Fire Protection Association (NFPA) codes, Department of Transportation (DOT), Department of Agriculture (USDA), others.
    - Each agency / organization has a set of rules, codes, and standards for large industrial projects

Let's use MBSE to manage regulatory-related information and track regulatory approval processes

MBSE for Projects in Nuclear Domain (cont'd)

- A more complex application – project management
  - Seems simple… People say, e.g., "*we have built large things before*", "*it's not too difficult to track the project progress in a Gantt chart*", "*I have a PMP certification, I certainly know how to manage the budget of a project*", etc.
  - Bent Flyvbjerg and Dan Gardner looked at megaprojects and evaluated "more than 16,000 projects from 20-plus different fields in 136 countries going back to 1910, from Olympic games to nuclear power plants" (Link to the Reference)
  - History-confirmed reality:
    - **91.5%** of projects go over budget, over schedule, or both.
    - **Less than 1%** of projects are completed on time and on schedule, and actually deliver the benefits promised.

Let's give MBSE a chance to help us to manage large projects

MBSE for Projects in Nuclear Domain (cont'd)

- A truly complex application – life cycle development of nuclear systems
  - Think of the amount of research and development resulting in a 15,000-page licensing application…
    - **Engineering disciplines:** nuclear, mechanical, structural, chemical, materials, electrical, instrumentation and control, software, computer, environmental, reliability, industrial, physical security, cybersecurity, etc.
    - **Non-engineering technical disciplines:** human factors, economics, licensing, project management, permitting, emergency preparedness, etc.

  - Must integrate products of all the disciplines above
    - Keep in mind conflicting objectives
  - Problem is much larger than technical - **$$$ is the driving factor!!**
  - Don't forget external factors – social and political concepts are important (e.g., environmental concerns, energy policies, federal and state subsidies, etc.)

Must manage complexity using a systematic, objective, holistic and modern approach → MBSE!

Questions?

LWRS

LIGHT WATER
REACTOR
SUSTAINABILITY

Sustaining National Nuclear Assets

lwrs.inl.gov