Modern Systems Engineering Principles and Tools to Support Decision Making for Novel Energy Systems

With a Case Study of Investments into Nuclear-based Hydrogen Generation

WALTER SCOTT, JR.
COLLEGE OF ENGINEERING
COLORADO STATE UNIVERSITY

Svetlana (Lana) Lawrence
Preliminary Examination
December 12, 2023

Presentation Outline

- Introduction
- Background and reasoning for the research
- Research proposition
- Research questions and tasks
- Research plan
- Thoughts on future research and applications

Introduction and Background

The WHY

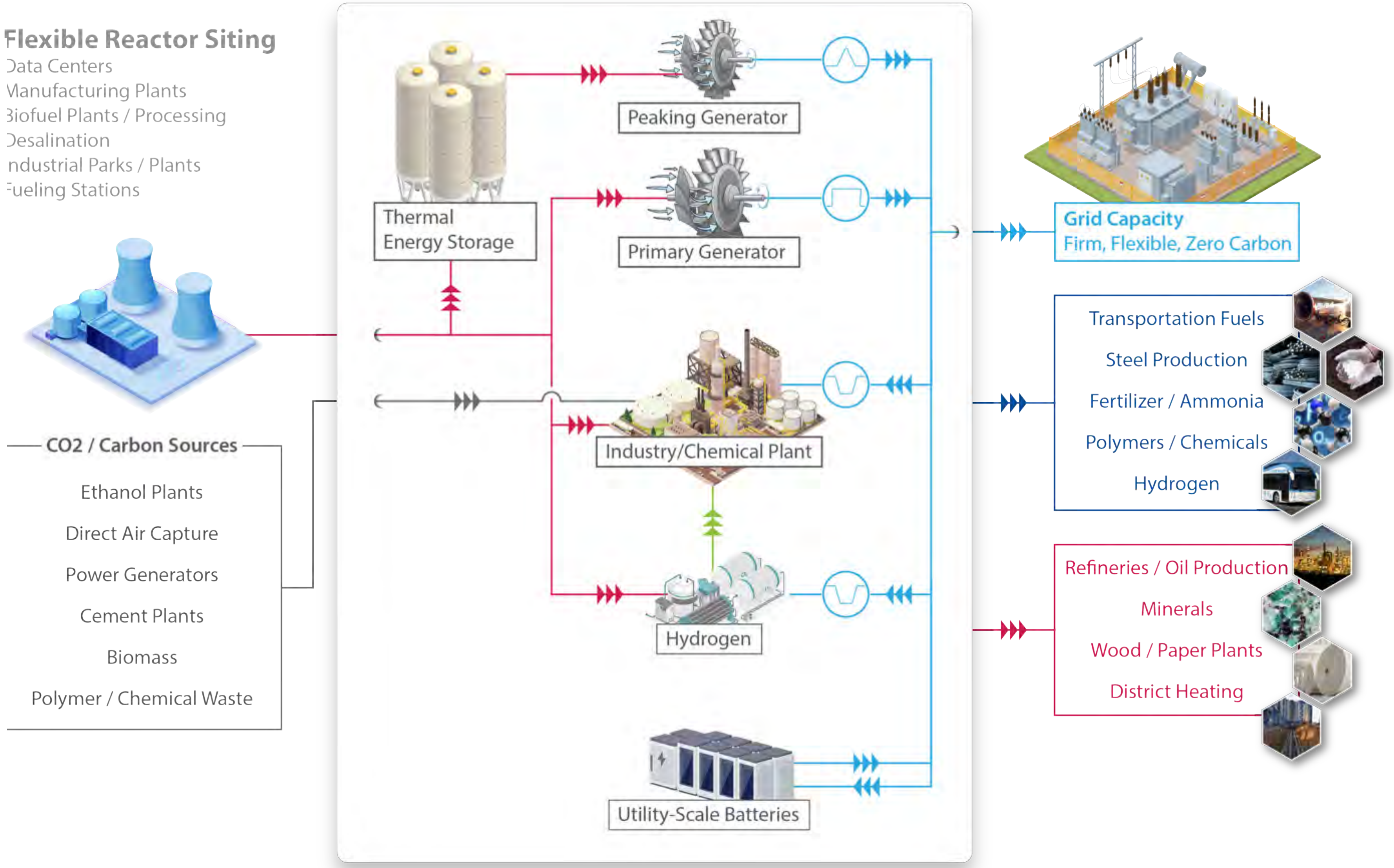
Novel Solutions for Energy System

Challenging yet exiting times

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



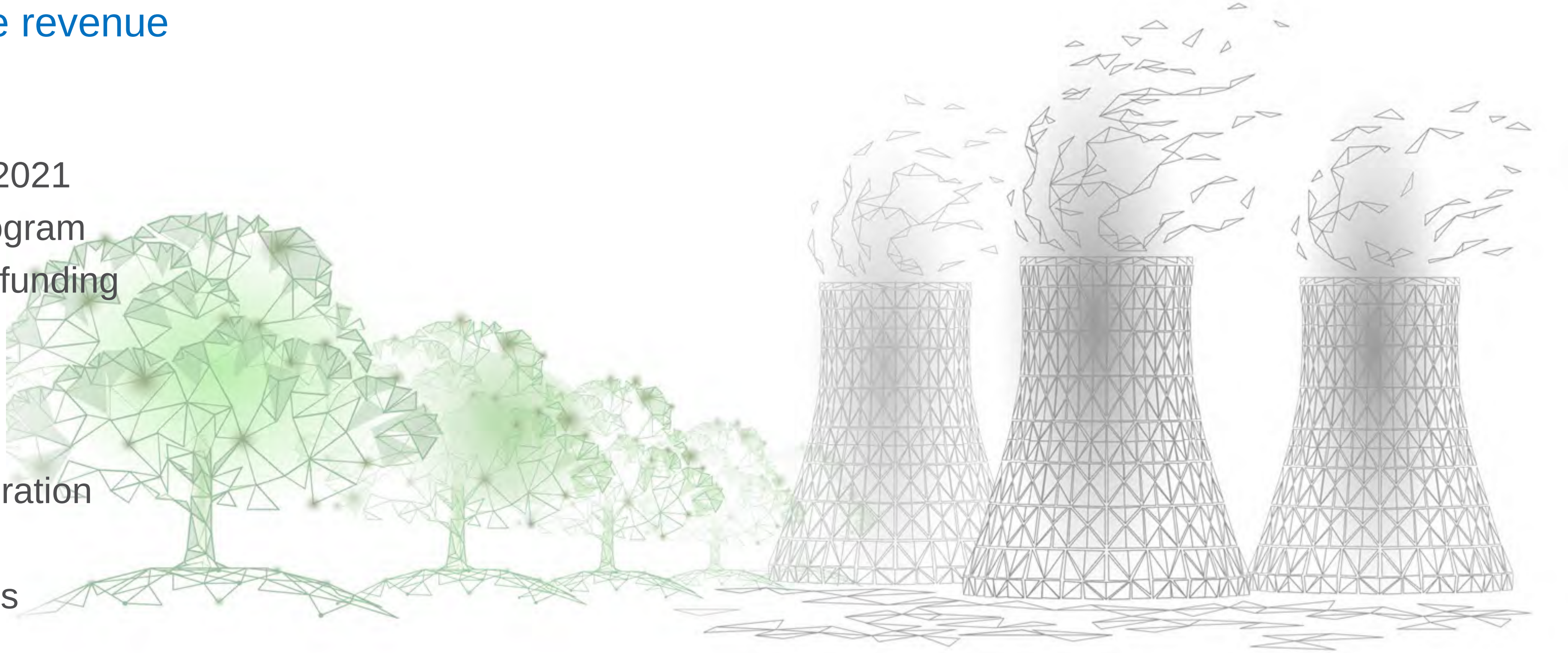
Integration of Nuclear and Hydrogen into Energy System (Graphic credit: Idaho National Laboratory)

Unprecedented Opportunity for Existing NPPs

Support by U.S. Federal Government

- DOE-NE Goal [1] – Enable continued operation of existing U.S. nuclear reactors
  - Develop technologies that reduce operating costs
  - Expand to markets beyond electricity
  - Provide scientific basis for continued operation of existing plants
  - ➢ Objective could be added: Increase revenue

- **Historical Federal Legislation**
  - Infrastructure Investment & Jobs Act of 2021
    - Operating nuclear plant credit program
    - Advanced reactor demonstration funding
    - Large-scale H2 demos
  - Inflation Reduction Act (IRA) of 2022
    - Tax credits for existing reactors
    - Tax credits for all new clean generation
    - Tax credits for H2 generation
    - Expanded federal loan guarantees



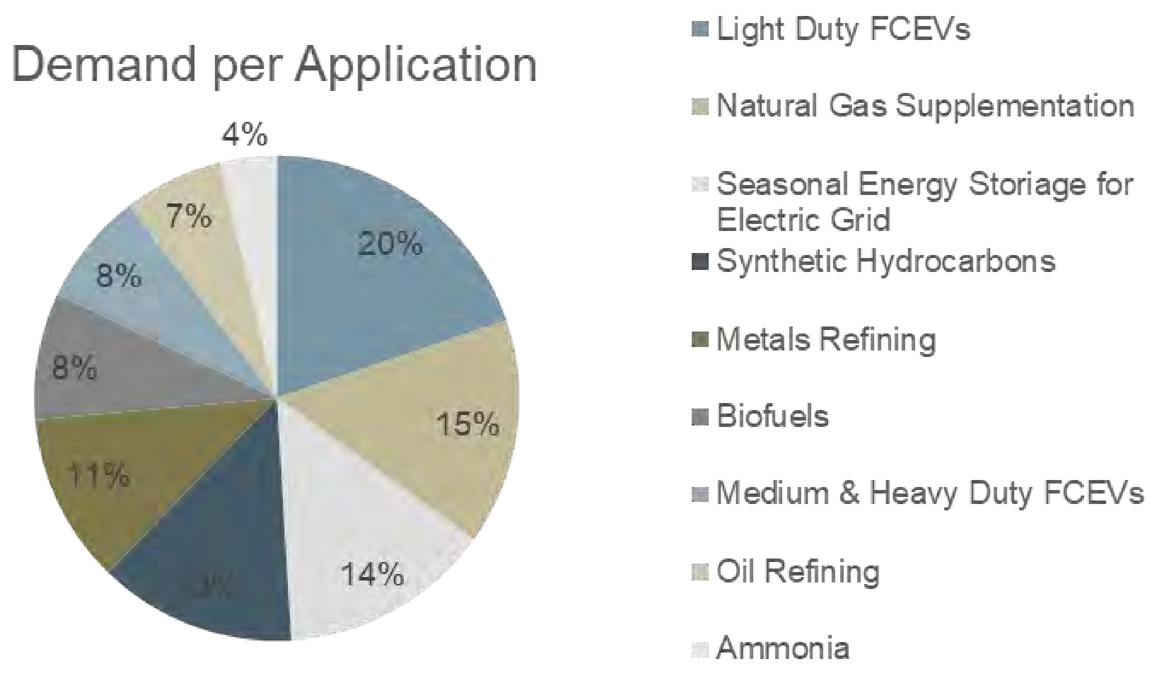
Inflation Reduction Act (IRA) - Incentives for Nuclear

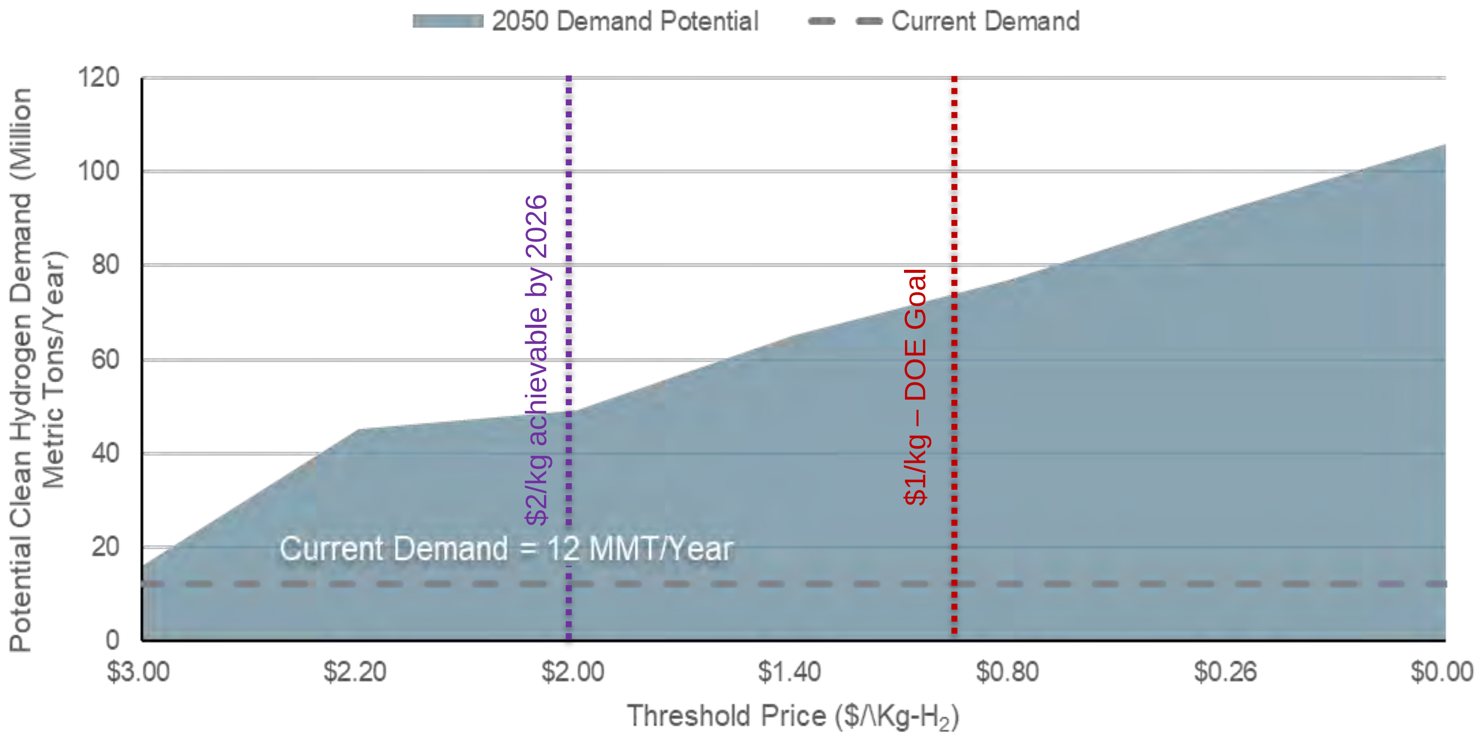
- PTC[1] for Operating Nuclear Plants (§45U)
  - Up to $15/MWh
- PTC (§45Y) or ITC[2] (§48E) for Carbon-Free Generation (§45Y)
  - **PTC:** At least $30/MWh for the first 10 years of operation; indexed to inflation
  - **ITC:** Credit for 30% of construction expenses when plant enters service
  - Applies to all carbon-free generators
  - Plants entering service in 2025 or later
  - Select the PTC (§45Y) or the ITC (§48E), not both
  - Lasts until CO2 emissions from electricity are 75% below 2022 levels
  - Increases by 10% for energy /coal communities; increases by 10% for domestic content
- PTC for Carbon-Free Hydrogen (§45V)
  - $3/kg of H2 for the first 10 years of operation; indexed to inflation
  - Applies to all low-carbon generators (with lifecycle emissions below 0.45 kg of CO2 / kg of H2)
  - Size of the credit based upon emission intensity
  - Plants beginning construction in 2033 or sooner
  - **Credit significant enough to consider moving away from electricity production**
    - $3/kg of H2 is equivalent to ~$60/MWh
    - Nuclear generating cost is ~ $30.2/MWh (Data from Nuclear Energy Institute)

[1] PTC – Production Tax Credit
[2] ITC – Investment Tax Credit

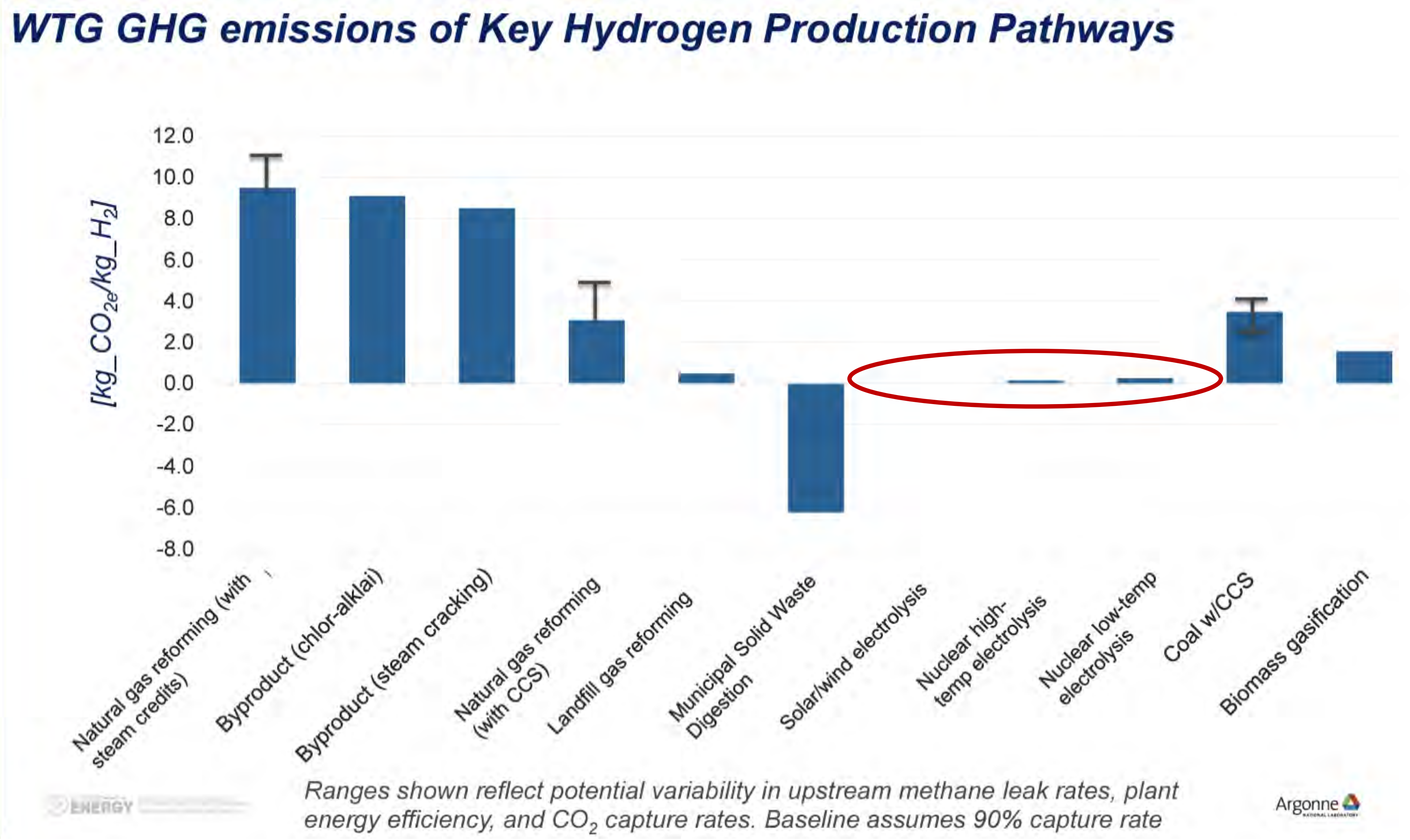
Market for Hydrogen

- Hydrogen demand is projected to increase [2]
  - from ~ 12 MMt/yr to 106 MMt/yr by 2050 for 11 industrial applications
  - Demand in clean hydrogen is dependent on hydrogen cost





CO2 Emissions from Hydrogen Production



Nuclear and renewable H2 production exceeds the "Clean H2" standard (0.45 kg of CO2/kg of H2) of Inflation Reduction Act

Nuclear-based energy source has the distinct advantage of **24/7 production rain or shine**.

A highly important attribute for large industrial applications (e.g., refineries, chemical production, steel manufacturing).

WTG: well-to-gate (lifecycle)
CCS: Carbon Capture and Sequestration
GHG: Green House Gas
GREET: Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model

Source: GREET Model for Emissions Lifecycle Analysis

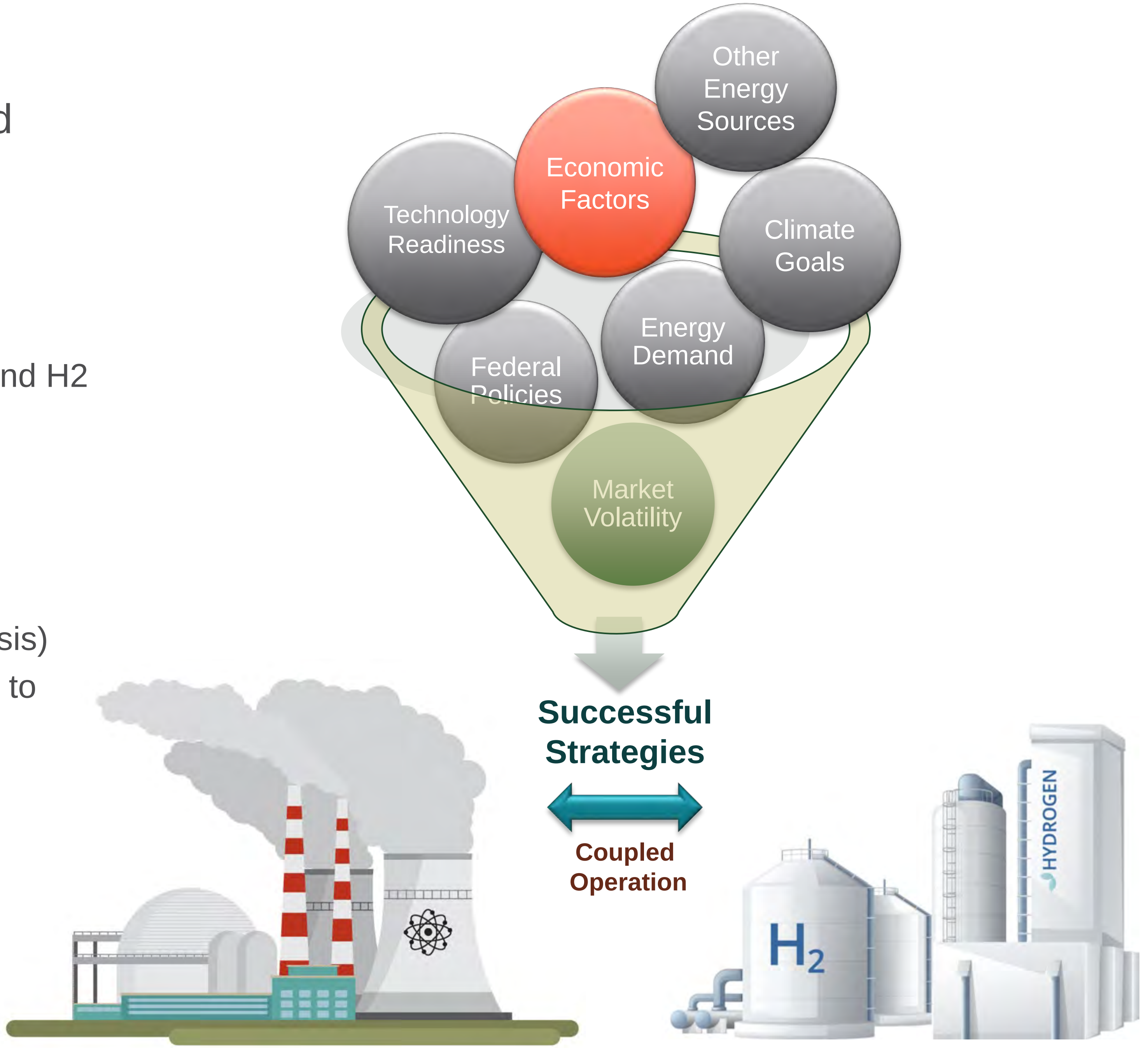
Invest or Not???

- 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.

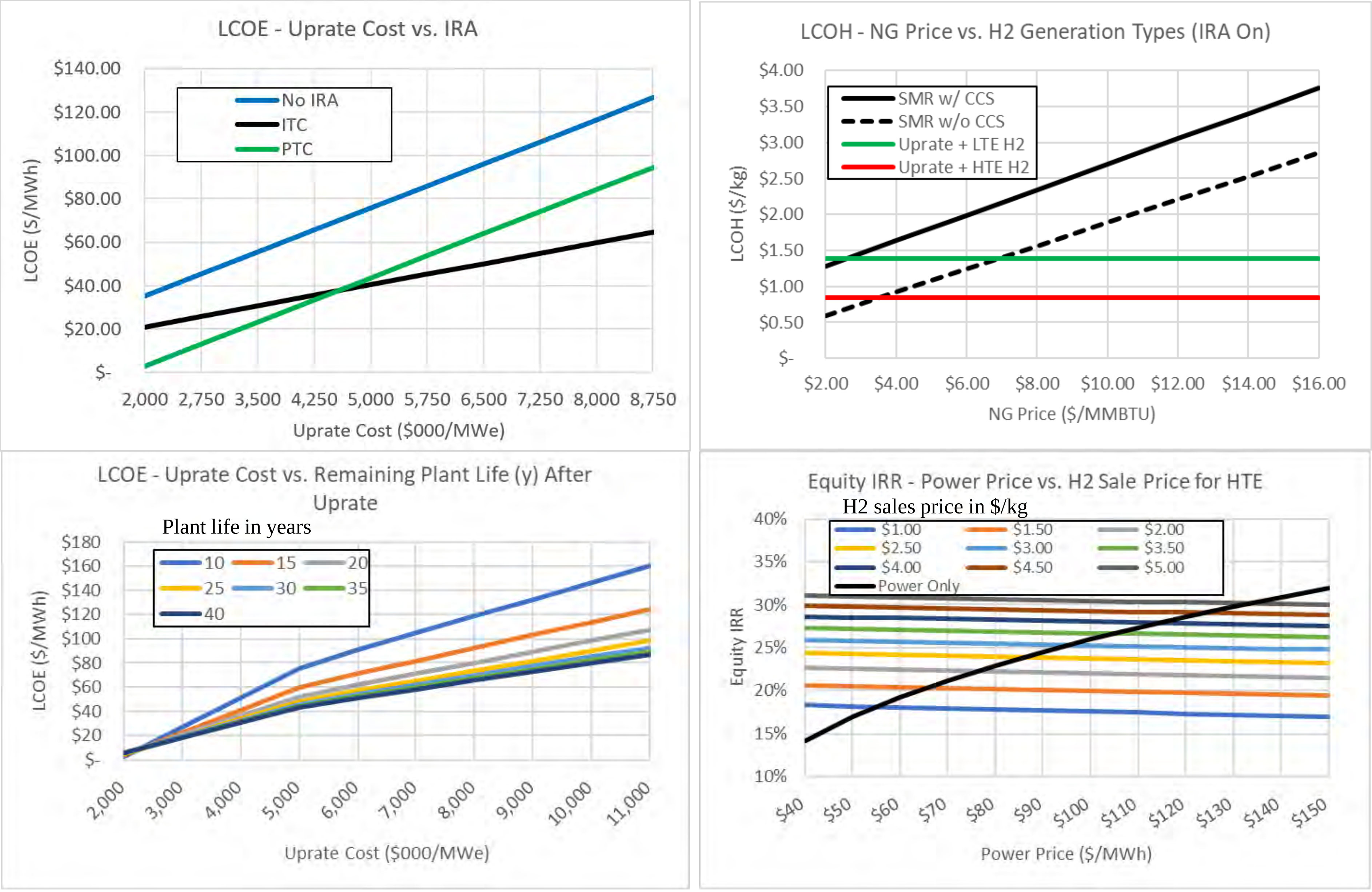
Complex Problem

- 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
- Current assessment are focused on **economics**
  - Understandable, yet other factors do matter



Traditional Business Assessments

- Discounted cash flow
  - Net present Value (NPV)
  - Internal Rate of Return (IRR)
  - Levelized Cost of Electricity (LCOE)
  - Levelized Cost of Hydrogen (LCOH)

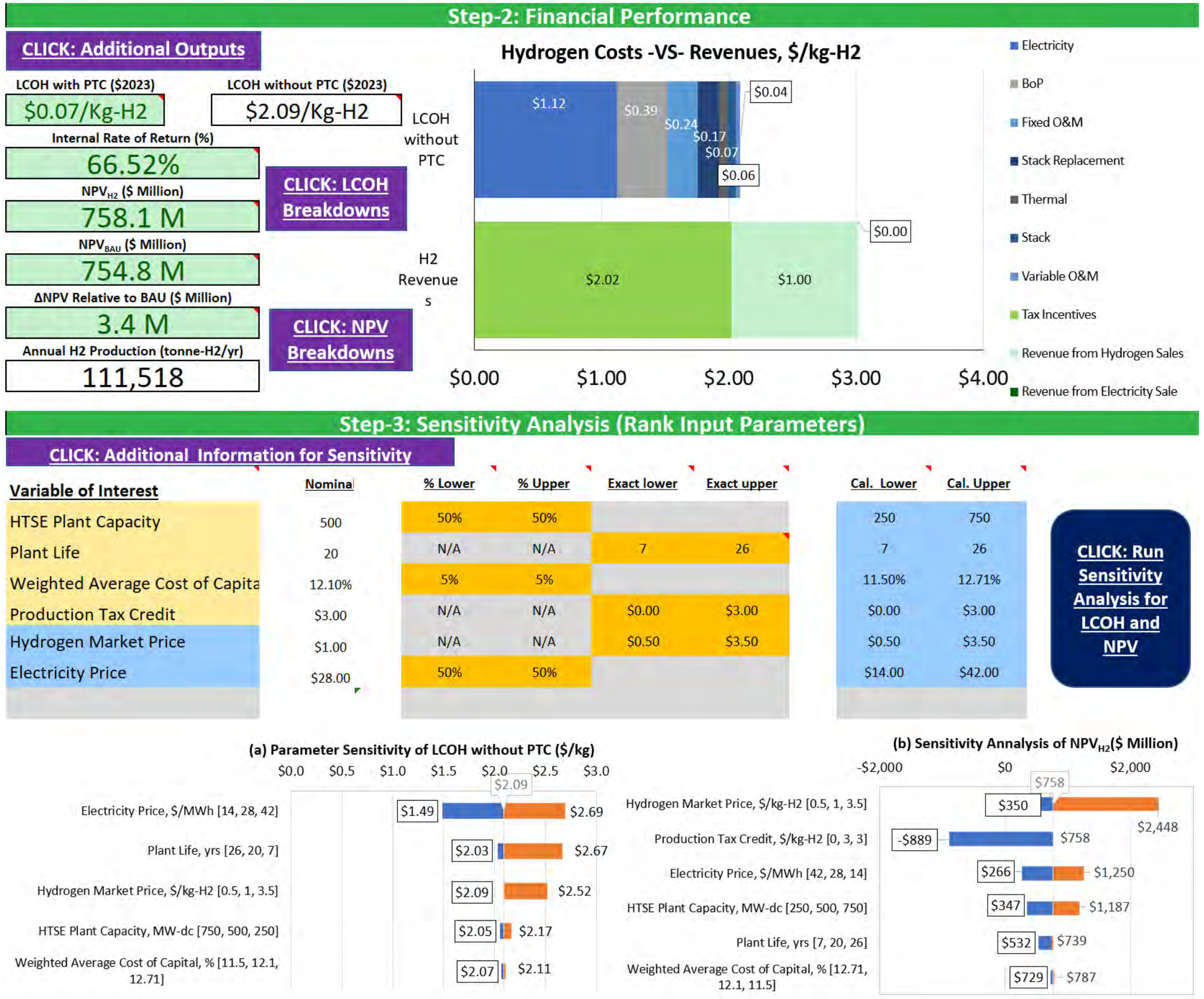


Example of Business Assessment [3]

LCOE – Levelized Cost of Electricity
LCOH – Levelized Cost of Hydrogen

Traditional Business Assessments (cont'd)

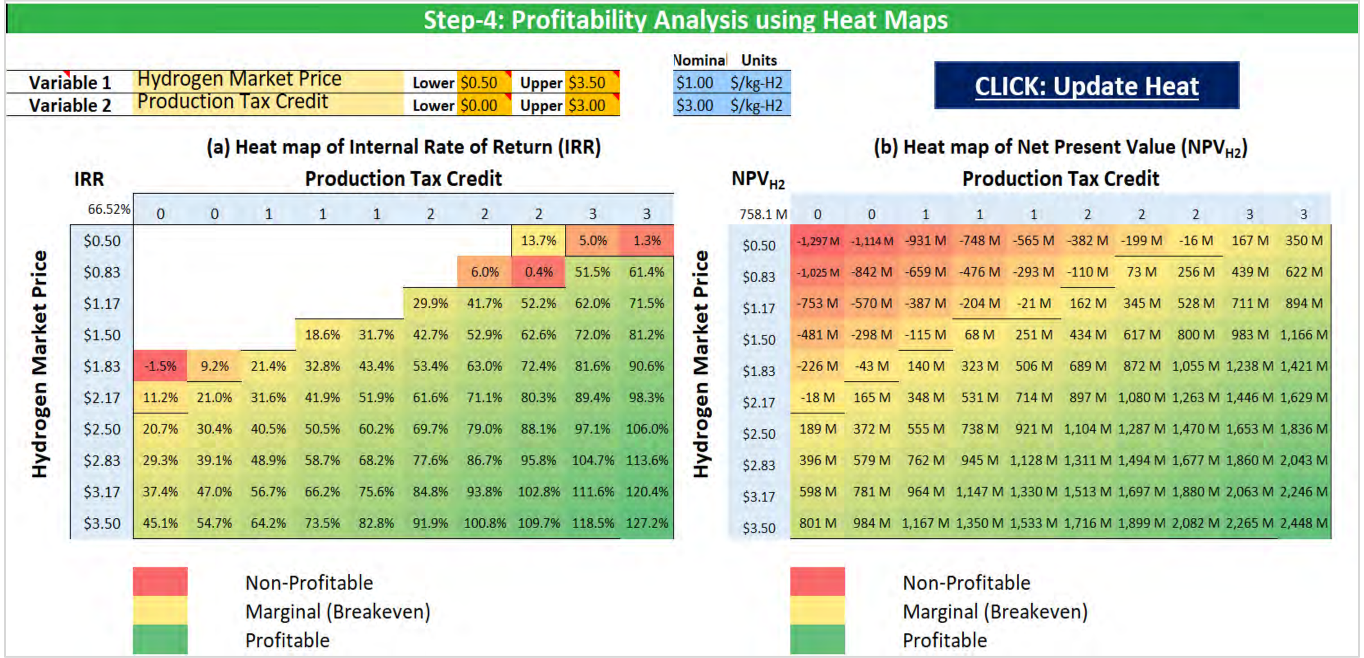
- Sensitivity analyses
  - Variation of NPV, IRR, LCOE, LCOH to changes in process, inflation, production capacity, etc.



Example of Business Assessment [4]

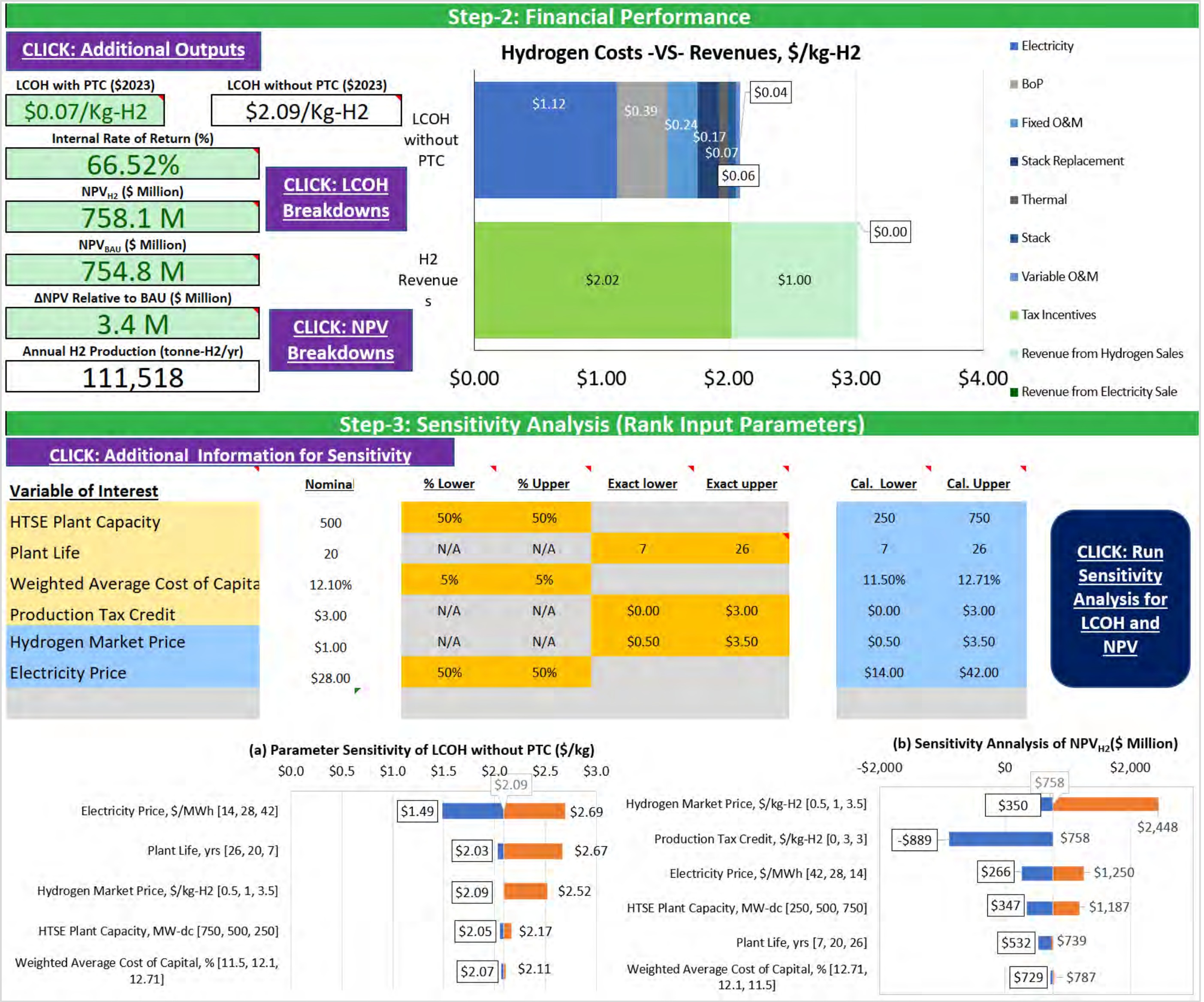
Traditional Business Assessments (cont'd)

- Sensitivity analyses
  - Variation of NPV, IRR, LCOE, LCOH to changes in process, inflation, production capacity, etc.



IRR 66.52%	0	0	1	1	1	2	2	2	3	3
$0.50								13.7%	5.0%	1.3%
$0.83							6.0%	0.4%	51.5%	61.4%
$1.17						29.9%	41.7%	52.2%	62.0%	71.5%
$1.50				18.6%	31.7%	42.7%	52.9%	62.6%	72.0%	81.2%
$1.83	-1.5%	9.2%	21.4%	32.8%	43.4%	53.4%	63.0%	72.4%	81.6%	90.6%
$2.17	11.2%	21.0%	31.6%	41.9%	51.9%	61.6%	71.1%	80.3%	89.4%	98.3%
$2.50	20.7%	30.4%	40.5%	50.5%	60.2%	69.7%	79.0%	88.1%	97.1%	106.0%
$2.83	29.3%	39.1%	48.9%	58.7%	68.2%	77.6%	86.7%	95.8%	104.7%	113.6%
$3.17	37.4%	47.0%	56.7%	66.2%	75.6%	84.8%	93.8%	102.8%	111.6%	120.4%
$3.50	45.1%	54.7%	64.2%	73.5%	82.8%	91.9%	100.8%	109.7%	118.5%	127.2%

NPV_{H2} 758.1 M	0	0	1	1	1	2	2	2	3	3
$0.50	-1,297 M	-1,114 M	-931 M	-748 M	-565 M	-382 M	-199 M	-16 M	167 M	350 M
$0.83	-1,025 M	-842 M	-659 M	-476 M	-293 M	-110 M	73 M	256 M	439 M	622 M
$1.17	-753 M	-570 M	-387 M	-204 M	-21 M	162 M	345 M	528 M	711 M	894 M
$1.50	-481 M	-298 M	-115 M	68 M	251 M	434 M	617 M	800 M	983 M	1,166 M
$1.83	-226 M	-43 M	140 M	323 M	506 M	689 M	872 M	1,055 M	1,238 M	1,421 M
$2.17	-18 M	165 M	348 M	531 M	714 M	897 M	1,080 M	1,263 M	1,446 M	1,629 M
$2.50	189 M	372 M	555 M	738 M	921 M	1,104 M	1,287 M	1,470 M	1,653 M	1,836 M
$2.83	396 M	579 M	762 M	945 M	1,128 M	1,311 M	1,494 M	1,677 M	1,860 M	2,043 M
$3.17	598 M	781 M	964 M	1,147 M	1,330 M	1,513 M	1,697 M	1,880 M	2,063 M	2,246 M
$3.50	801 M	984 M	1,167 M	1,350 M	1,533 M	1,716 M	1,899 M	2,082 M	2,265 M	2,448 M



Examples of Business Assessment [4]

Traditional Business Assessments (cont'd)

Parameters	Units	Simluation Values	User-defined Inputs	Descriptions	Assumptions	Data sources
HTSE Plant Capacity	MW-dc	500		The target plant capacity calculated by the multiplication of number of modules and plant capacity per module	It is assumed that the H2 is produced based on the modular design of High-Temperature Steam Electrolysis (HTSE) system, where 25 MW-dc is used for each module and 0.731 ton of hydrogen can be produced per hour.	1000 is used as a baseline case in INL/PRT-22-66117; 100 is used as a baseline case for APS cases.
Hydrogen Market Price	$/kg-H2	$1.00		The average price that the hydrogen sold in the market		The nominal value of 1.8656 is used to have the NPV equivalent to 0 based on the analysis from INL/PRT-22-66117
Plant Life	yrs	20		The amount to the time that NPP-HTSE designed to be operated		20 is a defaut value in H2A model by NREL(v3.2018)
Electricity Price	$/MWh	$28.00		The market price per MWh for producing the electricity	All the costs assoicated with nuclear power plants are assumed to be represneted by the electricity price. The site-specific electricity market price is not incorporated into the tool	$30.00 is a defaut value in INL/PRT-22-6617
Weighted Average Cost of Capital	%	12.10%		Weighted Average Cost of Capital (WACC) as a function of % debt costs and % equity costs		https://www.investopedia.com/terms/w/wacc.asp#citation-1
Production Tax Credit	$/kg-H2	$3.00		The tax credit for producing H2 with consideration of inflation		$0 is a defaut value (no consideration of PTC). A maximum $3 is adopted from Inflation Reduction Act (IRA): https://theicct.org/ira-unlock-green-hydrogen-jan23/#:~:text=On%20average%2C%20the%20IRA%20tax,until%20they%20expir
Natural Gas Price	$/MMBtu	$4.22		The NG price is correlated with electricity price and H2 market price		EIA AEO database: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2021&region=1-0&cases=highmacro~lowmacro~highprice~lowprice~highogs~lowogs~hirencst~lorencst&start=2019&end=2050&f=A&linechart=highmacro-d113020a.118-3-

Additional Inputs given the default values (not on Dashboard)

Parameters	Units	Simluation Values		Descriptions	Assumptions/notes	Data sources
Stack Service Lifetime	yrs	4		The average stack service lifetime.	The current data range is only applicable from 2 years to 7 years. 4 is selected as a default for both GW and APS case study	4.0 is a defaut value in INL/PRT-22-6617
Depreciation Period	yrs	20		The amount of time to consider depreciation.		The depreciation period is set to be 20 years for NPP-HTSE plant.
Tax Status	-	Profit		For "Non-Profit" orgnaization, no tax payment is required. For "Profit" organization, tax payment is required when the taxable income is positive.		
Plant Type	-	NOAK	NOAK	First-of-a-kind (FOAK) or Nth-of-a-kind (NOAK)	The FOAK considers the entire capital costs at the first year while the NOAK design consider the learning rate effect (set as 95%) for N=100 that may reduce the total amount of capital costs	NOAK is used for the baseline case in INL/PRT-22-66117; FOAK is used as a baseline case for APS cases.
Depreciation Type	-	MACRS		The method to consider depreciation for the NPP-HTSE	The MACRS depreciation allows a larger deduction in the early years of operation while straight-line depreication use the same tax deduction each year	MACRS is a defaut value in H2A model by NREL(v3.2018)
Length of Construction	yrs	1		The amount of the time to construct the HTSE systems that can be integrated with NPP	It is assumed that the maximum of the length cannot be more than 4 years.	1 is a defaut value in INL/PRT-22-66117
% of Capital Spent in 1st Year of Construction	%	100.00%		The percentage of the capital spent during the first year of constructing HTSE system		100.0% is a defaut value in H2A model by NREL(v3.2018)
% of Capital Spent in 2nd Year of Construction	%	0.00%		The percentage of the capital spent during the second year of constructing HTSE system		0.0% is a defaut value in H2A model by NREL(v3.2018)
% of Capital Spent in 3rd Year of Construction	%	0.00%		The percentage of the capital spent during the third year of constructing HTSE system		0.0% is a defaut value in H2A model by NREL(v3.2018)
% of Capital Spent in 4th Year of Construction	%	0.00%		The percentage of the capital spent during the fourth year of constructing HTSE system		0.0% is a defaut value in H2A model by NREL(v3.2018)
Reference Year	-	2020		The year when all cost and revenue are assigned. This value should be between 2020 to 2022.	All the $ value in this sheet is based on the $ value in this reference year if not specified. The default value is 2020.	2020 is a defaut value in INL/PRT-22-66117

Year of Interests	-	2023		This is the year the user would like to see the dollar value.		
Start-up Year	-	2025		The year when the NPP-HTSE starts operation and produce hydrogen		2025 is a defaut value in INL/PRT-22-66117. Note that this is the year that the tax creidt can be applicable based on IRA in 2022
Plant Operating Capacity Factor	%	90.00%		The capacity factor before considering the adjustments		90.00% is a defaut value in INL/PRT-22-6617
NPP Capacity Factor	%	0.00%		The NPP plant capacity factor between 0 and 1	Assume zero if there is no electricy to be sold to the grid.	92.4% at Year 2020 can be used from EIA data. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b
HTSE modular block capacity	MW-dc	25		The modular capacity for HTSE	The user would need to run a HTSE process model if a new HTSE system is specified.	25 MW-dc is a default value from INL/PRT-22-66117
Hydrogen Production Rate per Module	tonne-H2/hr	0.731		hydrogen production rate (per hour) simulated for one 25 MW-dc module in the HTSE system.	The user would need to run a HTSE process model f a new HTSE system is specified.	0.731 tonne-H2/hr is a default value from INL/PRT-22-66117
Additional Stack Cost: Contingency	%	0.00%		An additional stack costs associated with the contingency		0% is a default value from INL/RPT-22-66117; 10% is used for APS cases
Additional Stack Cost: Markup	%	0.00%		An additional stack costs associated with the Markup		0% is a default value from INL/RPT-22-66117; 30% is used for APS cases
NPP Thermal Efficiency	%	34.00%		The percentage of the thermal energy that can be used from NPP heat generation.	The value of 34% is suitable only for light water reactor. The efficiency is used for calculating the thermal energy price	34% is a deafult value from INL/PRT-22-66117
Density of Process Water	kg/m^3	998		water density at room temperature (20 °C)		https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html
Density of Cooling Water	kg/m^3	998		water density at room temperature (20 °C)		https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html
Start-up Period	yrs	1		The period when the plant is not operated with 100% power		1 is a defaut value in INL/PRT-22-66117
% of Fixed Operating Cost During Start-up	%	100.00%		The percentage of the fixed operating cost at the start-up year		100.0% is a defaut value in INL/PRT-22-66117
% of Variable Operating Costs During Start-up	%	75.00%		The percentage of the operating costs during the start-up period		75.0% is a defaut value in INL/PRT-22-66117
% of Revenue During Start-up	%	50.00%		The percentage of revenue in terms of the hydrogen production (kg) for the NPP-HTSE at the start-up year		50.0% is a defaut value in H2A model by NREL(v3.2018)
State Tax	%	6.00%		This is state-dependent variable		6% is used as the default value in H2A model by NREL(v3.2018)

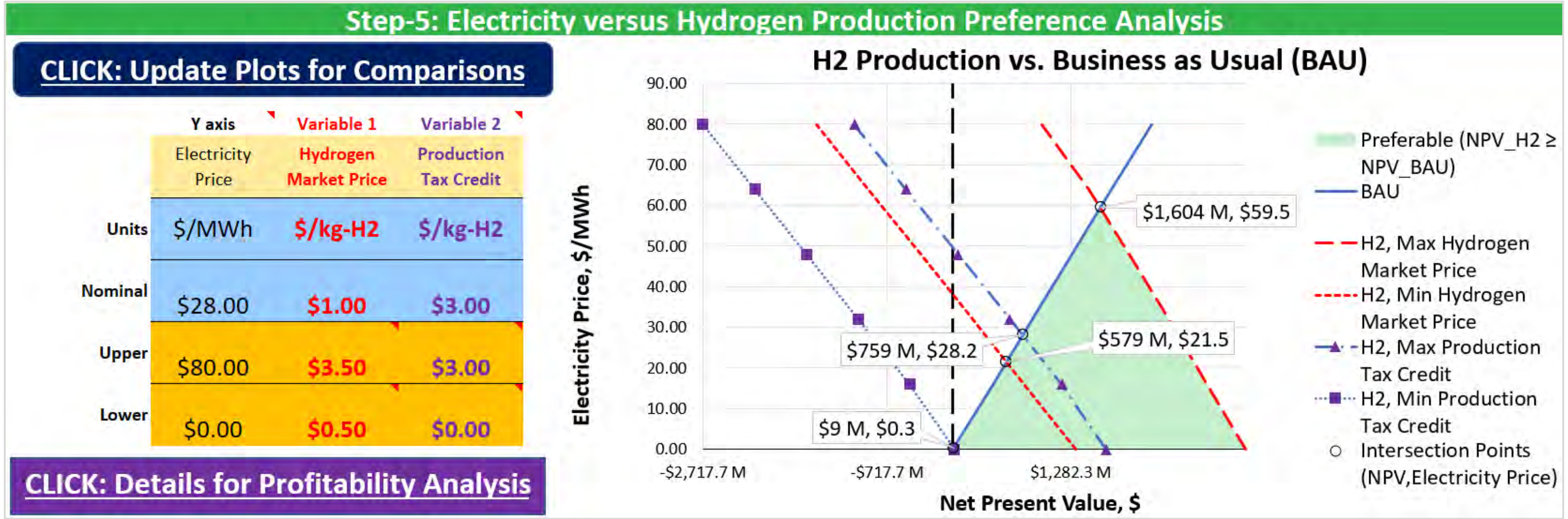
Federal Tax	%	21.00%			This value is only applicable for united states.	21.0% is a defaut value in H2A model by NREL(v3.2018)
Inflation Rate	%	1.90%		This is a default value in the original H2A model from NREL		Original H2A model: https://www.nrel.gov/hydrogen/h2a-production-models.html
Working Capital	%	15.00%		The percentage of the yearly change in operating costs		15.0% is a defaut value in H2A model by NREL(v3.2018)
Clean tax reduction percentage	%	10.00%		The user can specify this value to account for the tax reduction due to the monetization cost.		10% is obtained from NREL's study: https://www.nrel.gov/docs/fy23osti/85242.pdf
H2 transportation piping diameter	inch	0		The averaged diameter of the pipe for transoprting the produced hydrogen. Enter 0 if no H2 transportation cost is considered.	Note that this is a new variable	
% of Site Preparation	%	2.00%		The percentage of the total DCC associated with the site preparation.		2.0% is a defaut value in INL/PRT-22-6617
% of Project Contingency	%	7.17%		The percentage of the total DCC associated with the project contingency.		7.2% is a defaut value in INL/PRT-22-6617
% of One-time Licensing Fee	%	0.00%		The percentage of the total DCC associated with the one-time Licensing Fee.		0.0% is a defaut value in INL/PRT-22-6617
% of Up-Front Permitting Costs	%	15.00%		The percentage of the total DCC associated with the legal and contractors fees		15.0% is a defaut value in INL/PRT-22-6617
% of Additional Indirect Depreciable Costs	%	0.00%		The percentage of the total DCC associated with the addiioinal indirect DCC that is depreicable.		0.0% is a defaut value in INL/PRT-22-6617
% of Land costs	%	1.00%		The percentage of the land cost of Total Depreciable Capital Costs		1.0% is a defaut value in INL/PRT-22-6617
Total Unplanned Replacement Capital Cost Factor (% of total depreciable capital costs/year)	%	0.50%		Enter a fixed percentage. This input is meant to include, in the Cash Flow Analysis, a factor for unplanned capital expenditures.		0.5% is a defaut value in INL/PRT-22-6617
Total Plant Staff	-	8		The number of Full-time equivalents (FTEs) employed by plant per 50000 kg-H2/day production.	Assume that staffs working for H2 production are different than NPP operation.	8 is a defaut value in INL/PRT-22-6617
Burdened labor cost	$/man-hr	50		The hourly labor cost per person		$50/man-hr came from NREL centralized SOEC case study
G&A rate (% of labor cost)	%	20.00%		General and administrative (G&A) expenses rate		20.0% is a defaut value in INL/PRT-22-6617
% of Licensing, Permits and Fees	%	0.00%		The percentage of TCI associated with the licensing, permits, and fees		0.0% is a defaut value in H2A model by NREL (v3.2018)
Property tax and insurance rate	%	2.00%		The percentage of TCI associated with property tax and insurance		2.0% is a defaut value in H2A model by NREL (v3.2018)
% of Rent	%	0.00%		The percentage of DCC associated with rent		0.0% is a defaut value in INL/PRT-22-6617

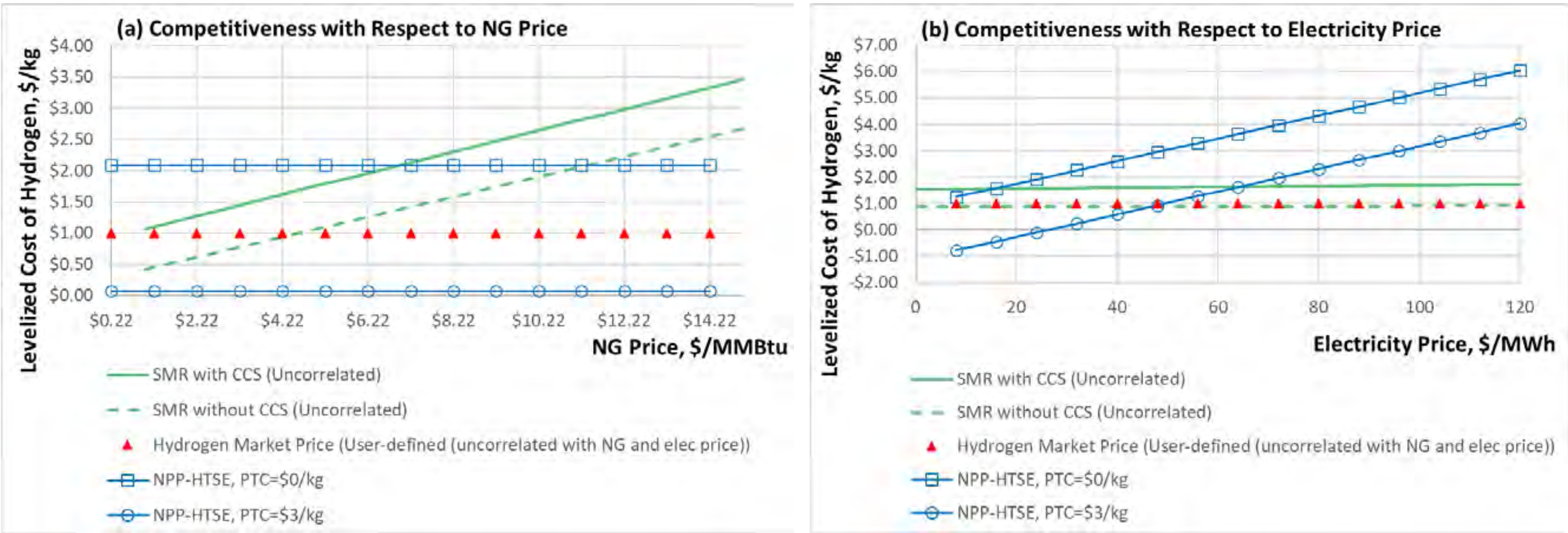
Inputs in a Business Assessment [4]

Traditional Business Assessments (cont'd)

Difficulties / shortfalls

- Difficult to visualize for non-economists
- Fairly complicated to be used for understanding dependencies
- Option comparison based on "single-point" representative values (e.g., NPV, IRR, LCOH)
- Larger context is often not included to manage complexity
- Analyses are static
  - E.g., a single-value electricity price is assumed for the entire duration of the investment, fluctuation of market prices are addressed as sensitivities

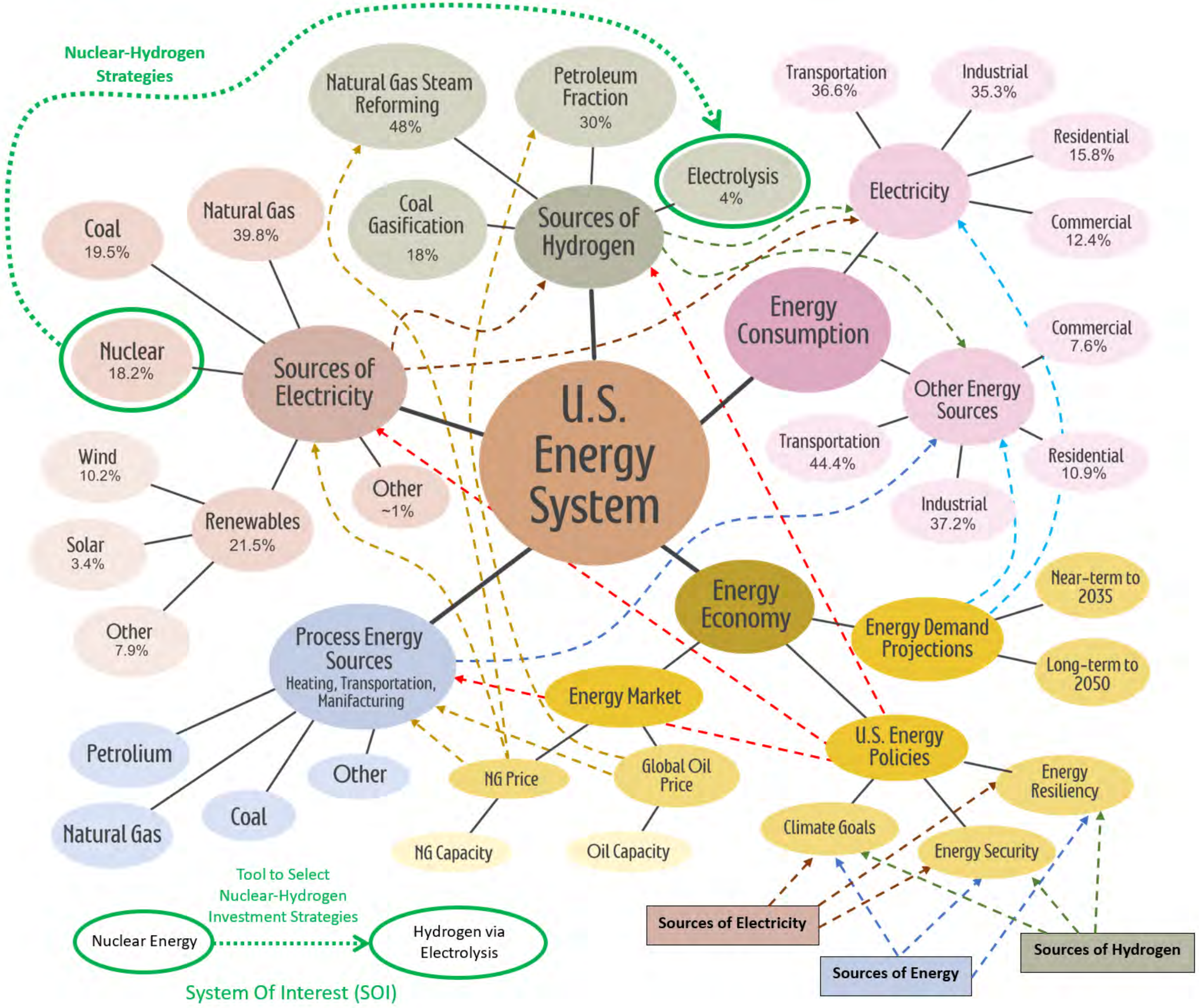




Examples of Business Assessment [4]

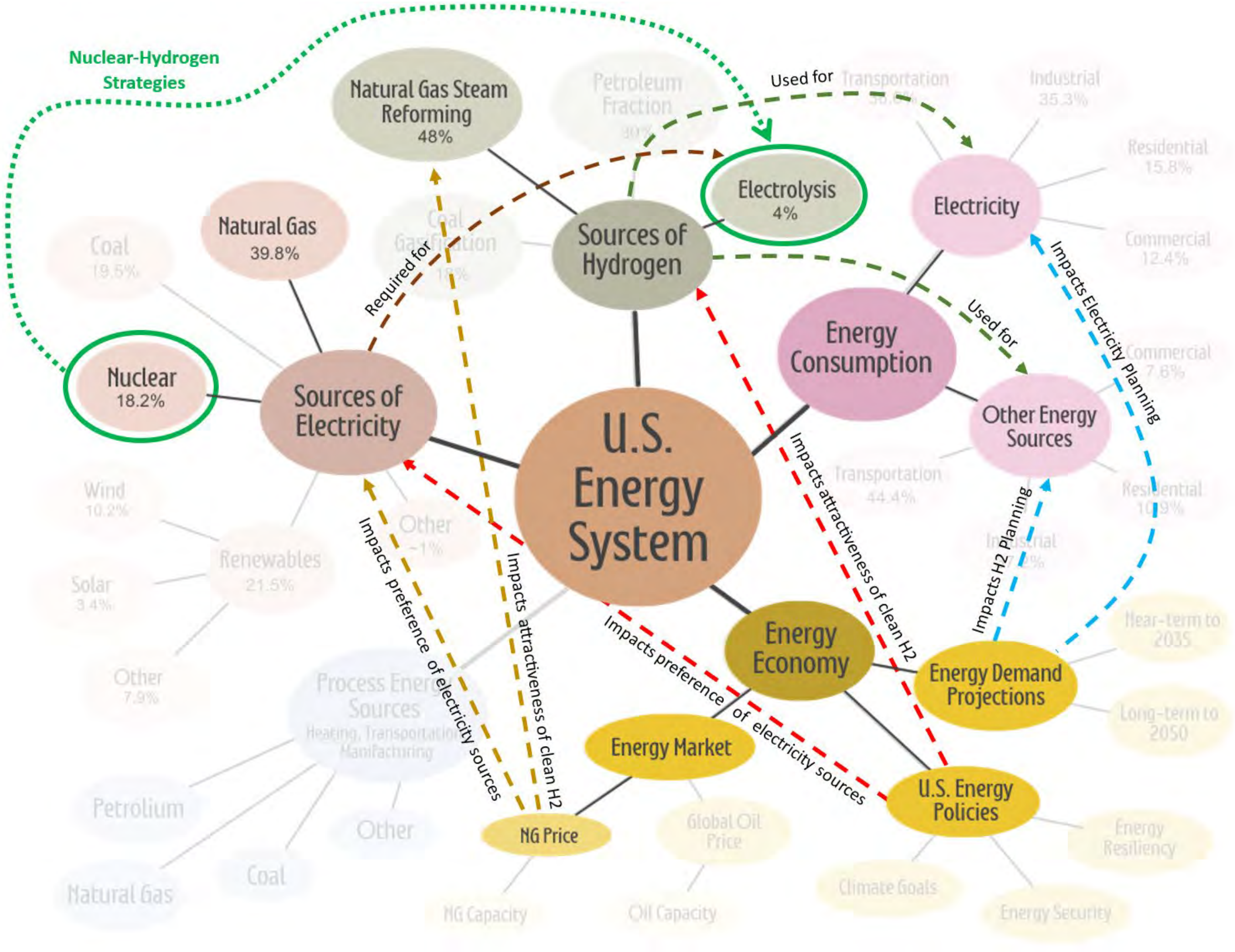
Energy Systems are Complex

- **A need for improved decision-making**



Energy Systems are Complex

- **Other industries offer approaches for evaluation of complex system problems**
  - Systems-based thinking
    - Considers benefits from the perspective of a system overall, not to individual parts
    - Include context – no system operates in isolation, they are affected by other systems
    - Allows to explicitly incorporate risk and uncertainty considerations (e.g., trade-off analyses)
  - Modern systems engineering principles and tools support systematic consistent application of systems thinking → **Research Topic!**

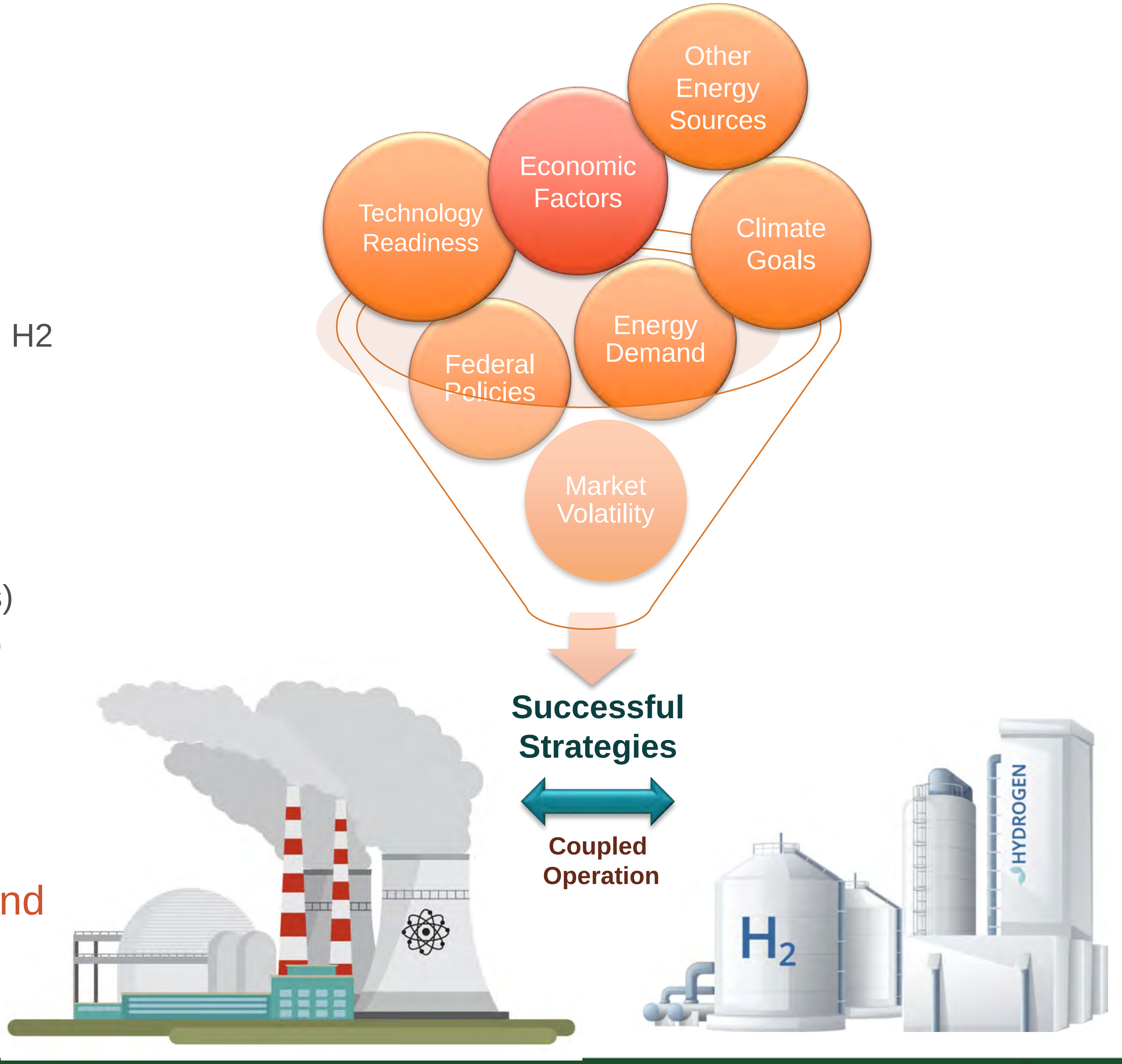


Research Proposition

The WHAT**:** Application of Modern Systems Engineering Principles and Tools to Support Decision Making for Novel Energy Systems

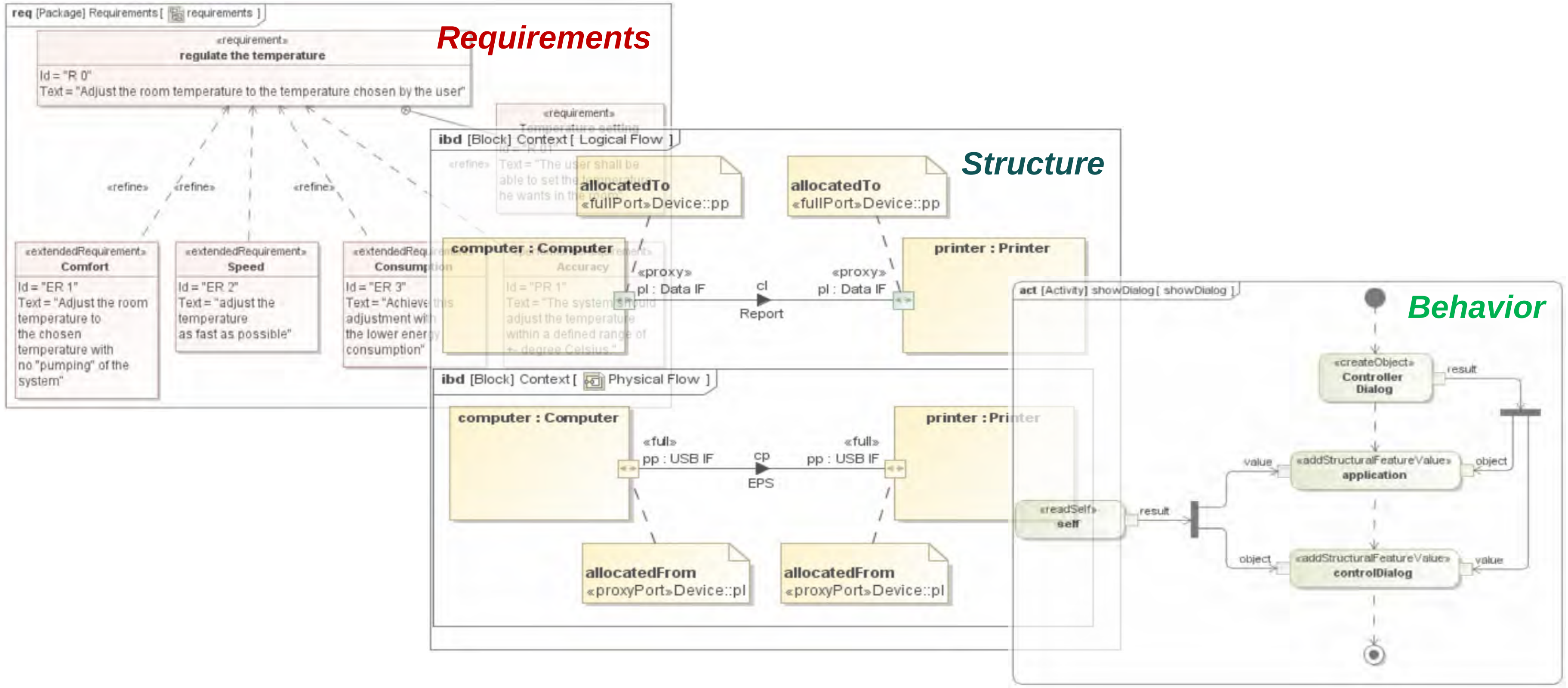
Complex Problem

- **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:
  - 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
- Systems thinking and systems engineering principles and tools are well-positioned to help with the complexity!

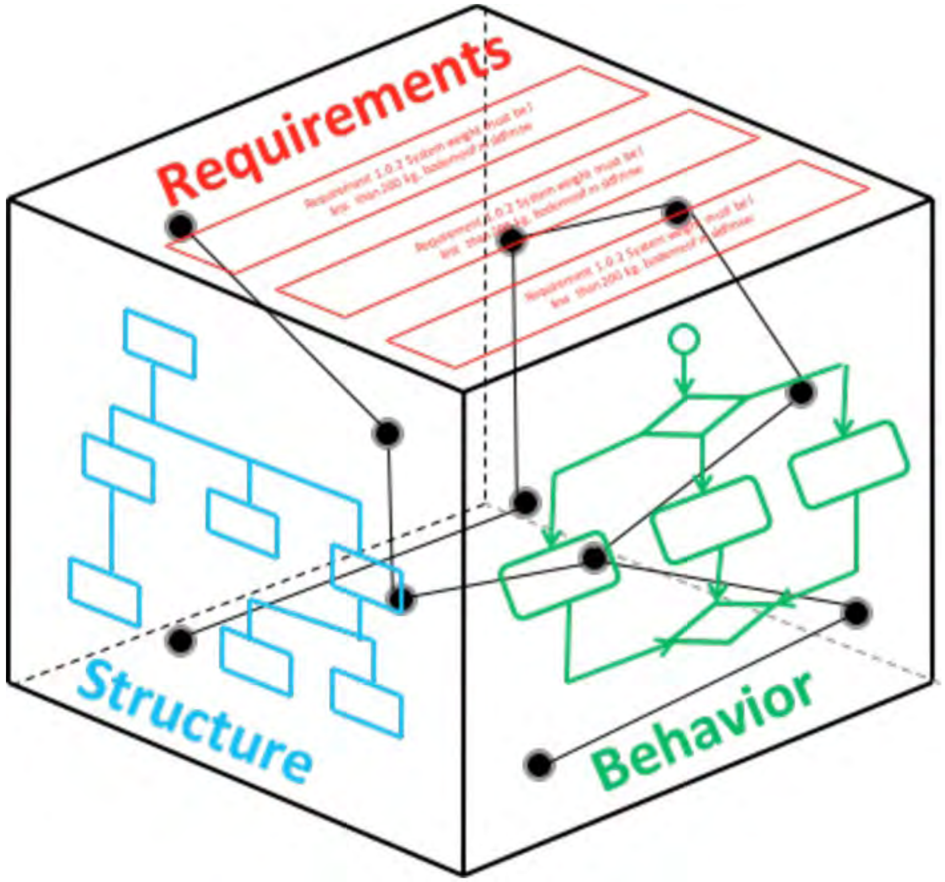


Model-Based Systems Engineering (MBSE)

- 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 [6]



Dimensions of MBSE models [5]

MBSE(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

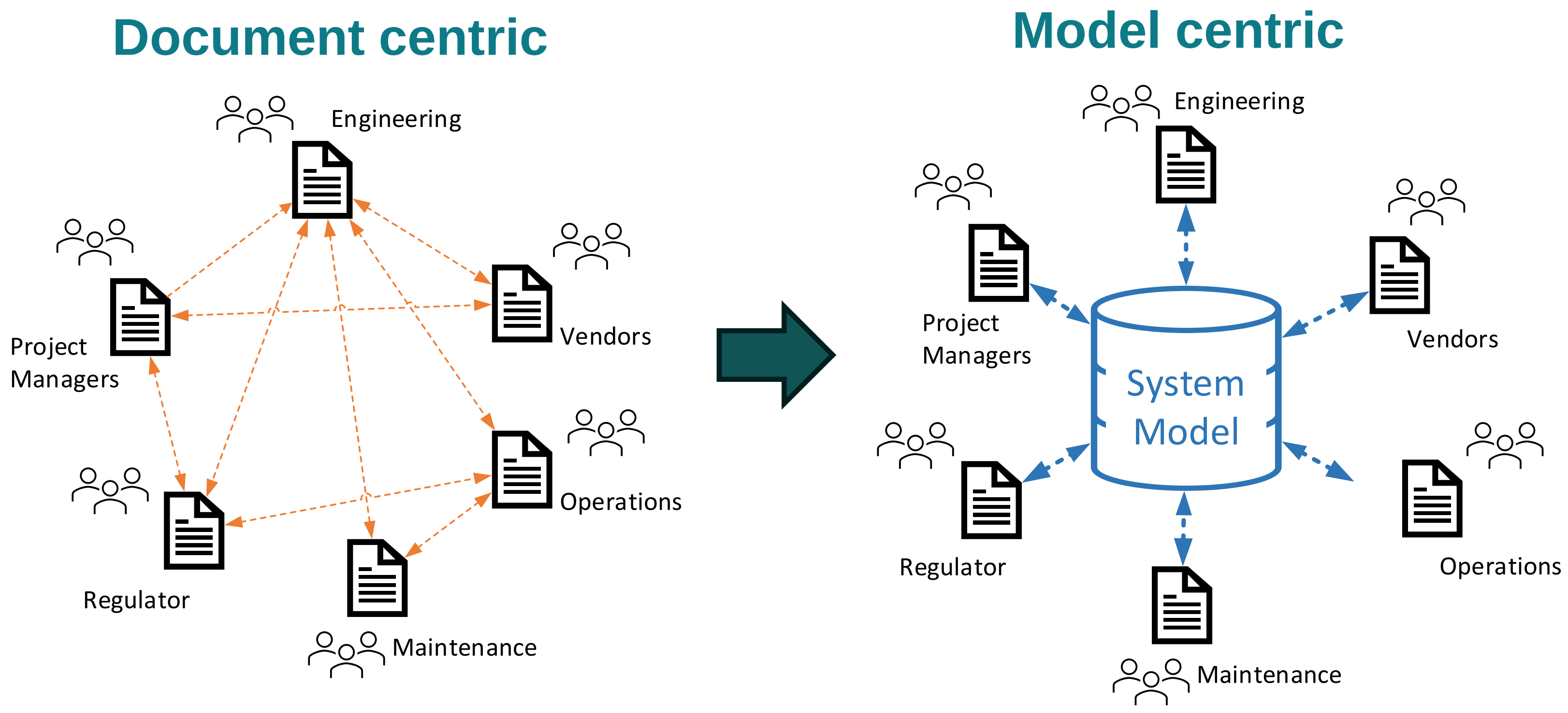
System stakeholders and their concerns

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

Why Model-Based?

- 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
  - A change in one part of the model is reflected everywhere else automatically
  - All team members access the current, most recent version of the system being developed

- Benefits
  - Superior knowledge capture and transfer
  - Effective complexity management
  - Improved communications
  - Improved product quality
  - Dramatic reduction of cost and schedule overruns



Document-Based Systems Engineering vs Model-Based

Example MBSE Artifacts

- Simple representation, clear transitions

0 Stakeholder Concerns [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

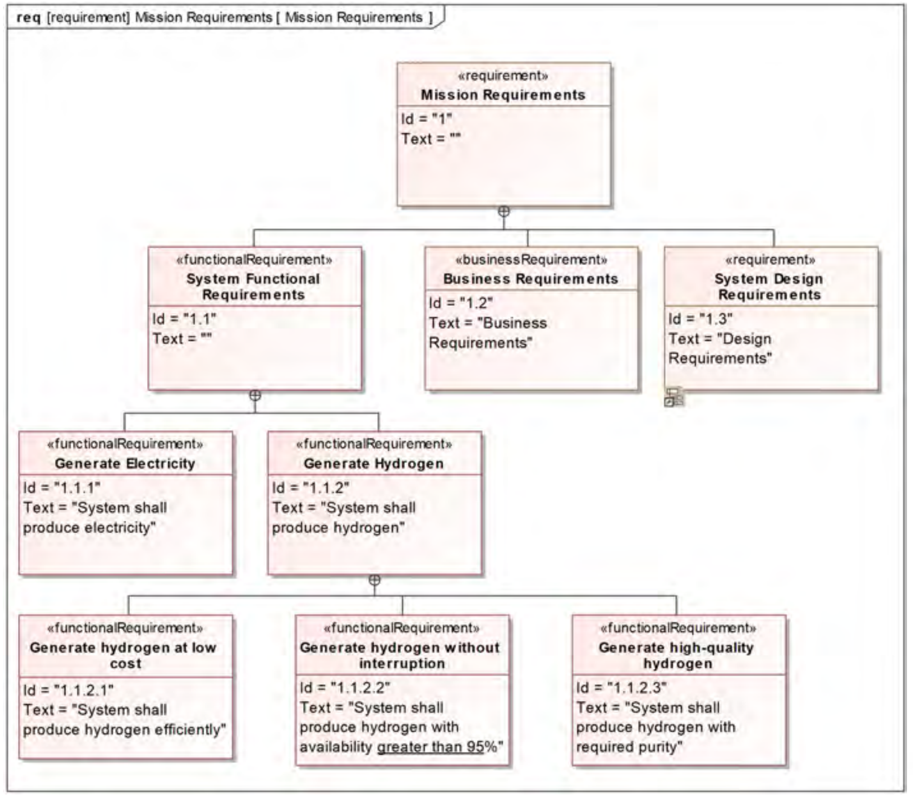
System requirements

Example MBSE Artifacts (cont’d)

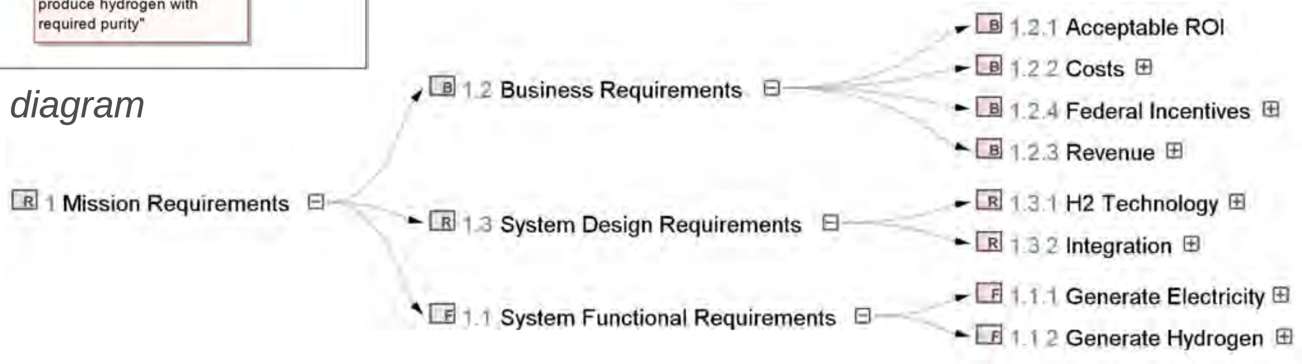
- Multiple options for presenting system elements and views

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



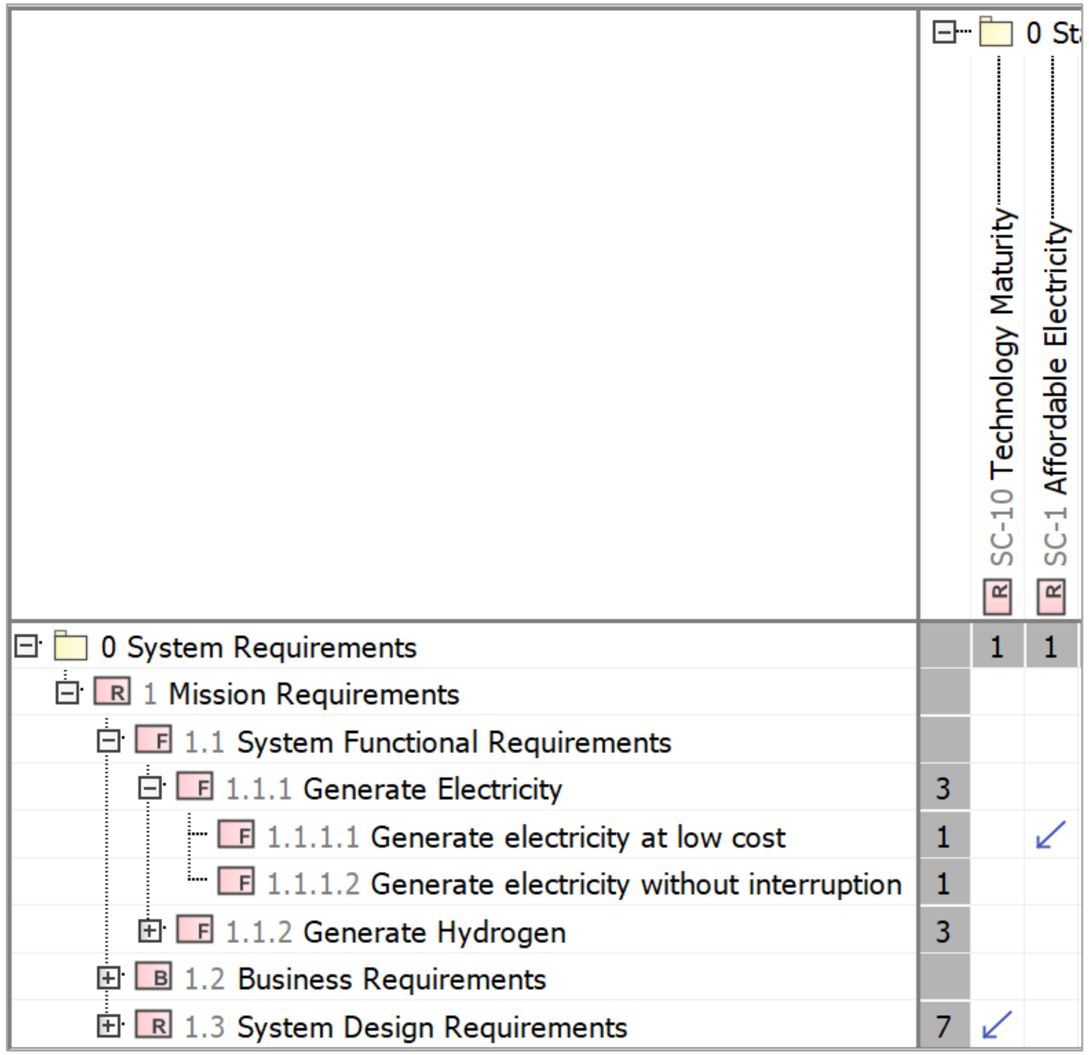
System requirements diagram



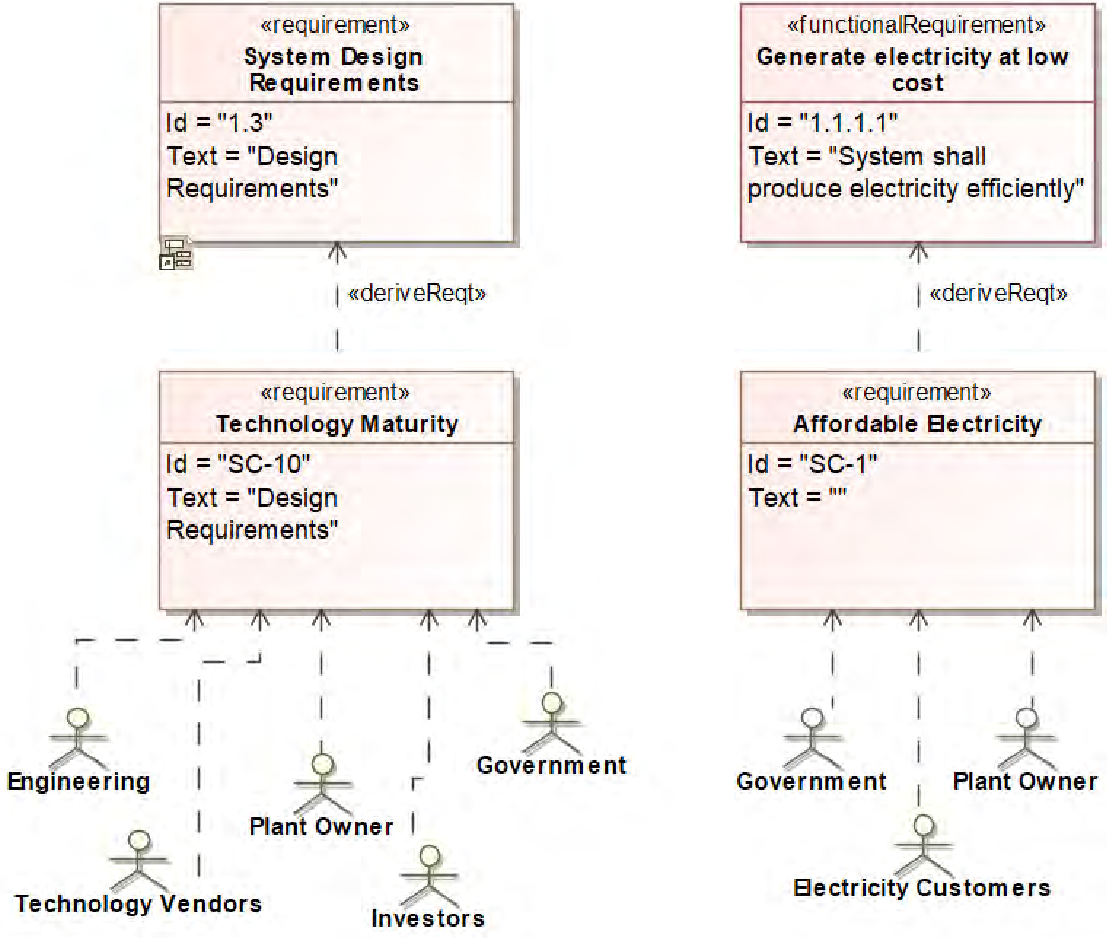
System requirements map

Example MBSE Artifacts (cont'd)

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



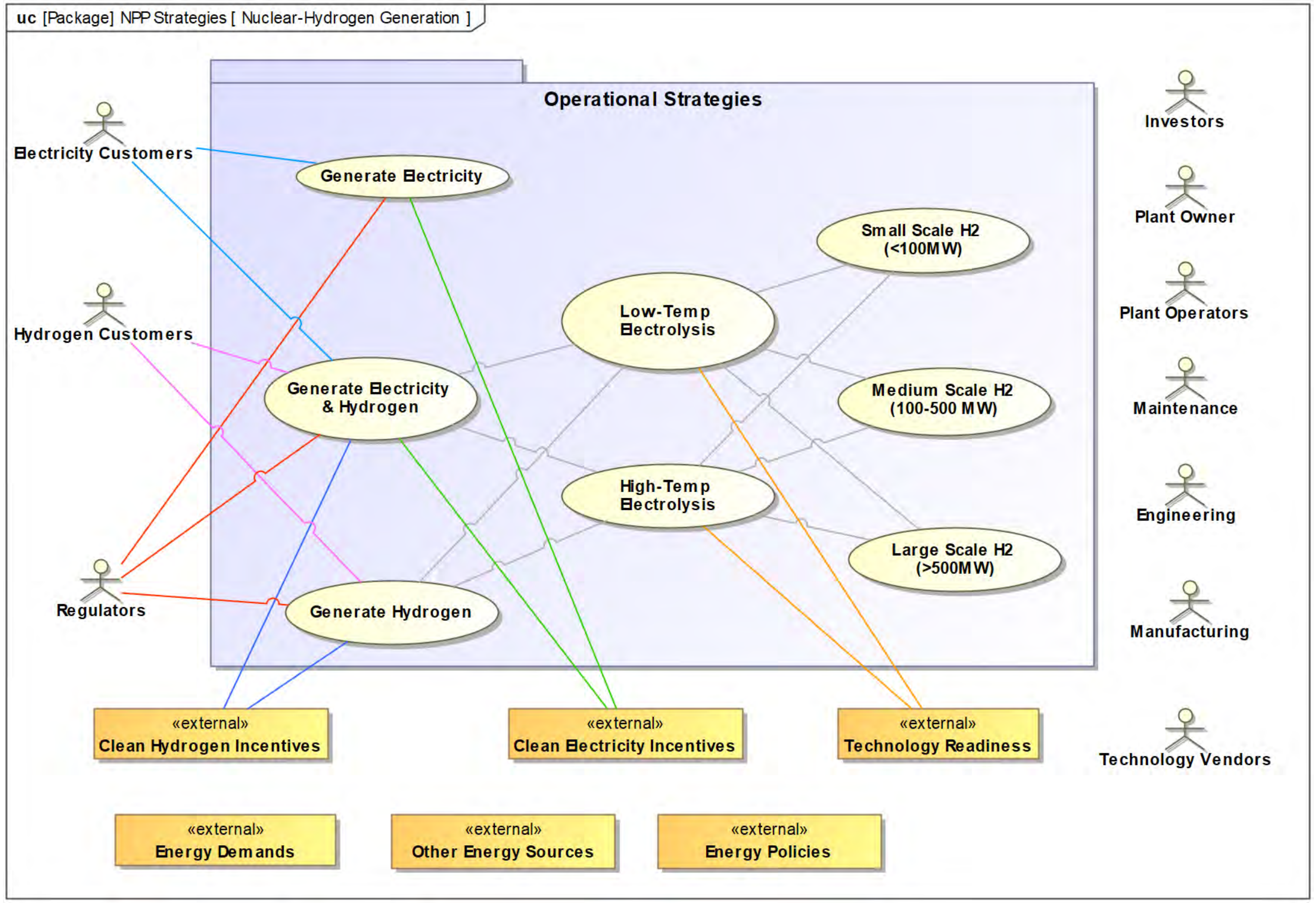
Requirements traced to stakeholder concerns



Stakeholders → Stakeholder Concerns → Requirements

Example MBSE Artifacts (cont'd)

- Graph-based representation of elements and relationships



Operational strategies shown via a context diagram

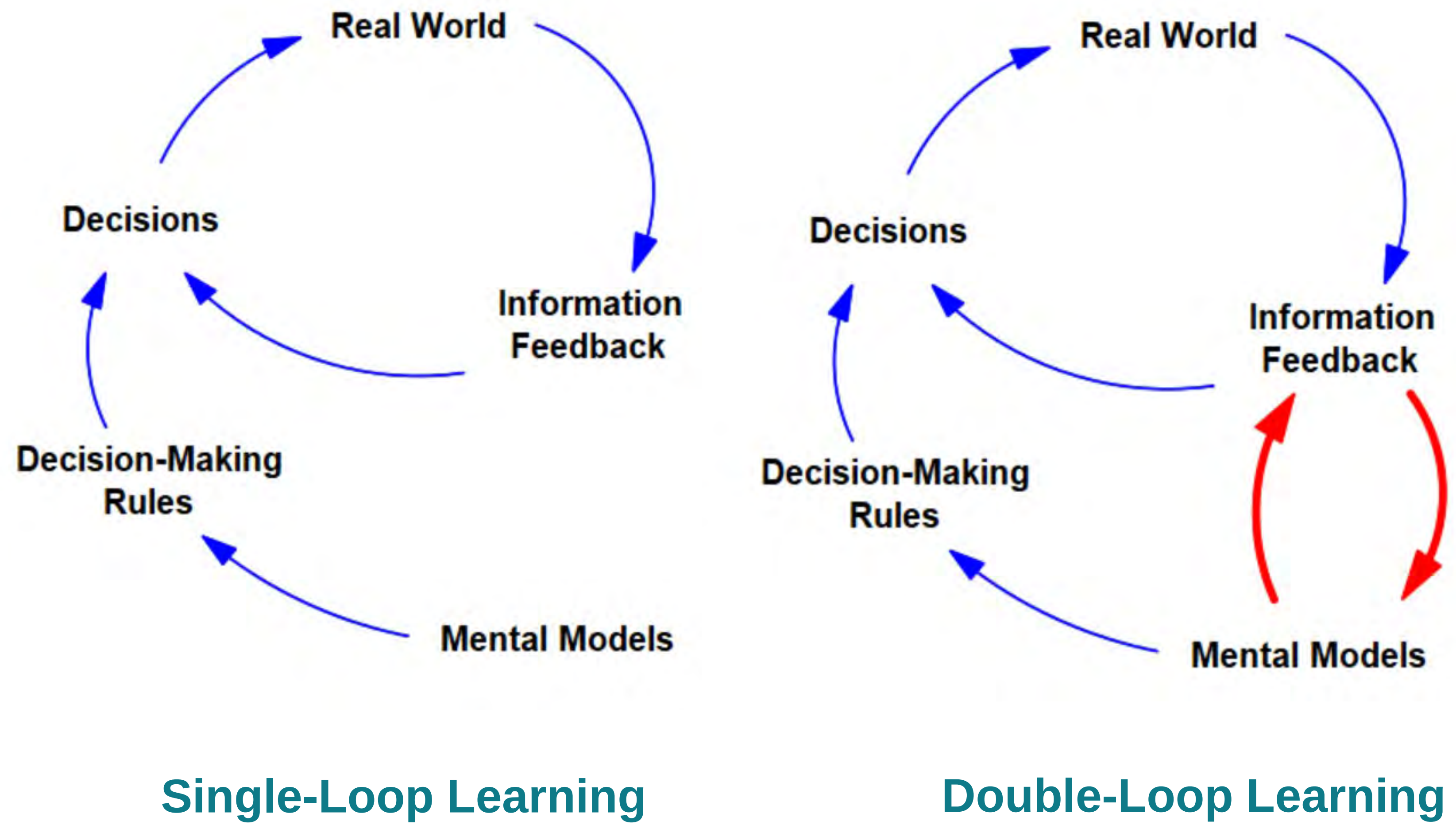
“*The [Systems Engineering] perspective is based on systems thinking – a perspective that sharpens our awareness of wholes and how the parts within those wholes interrelate*”

~ INCOSE, Systems Engineering Handbook, 5th ed. [7]

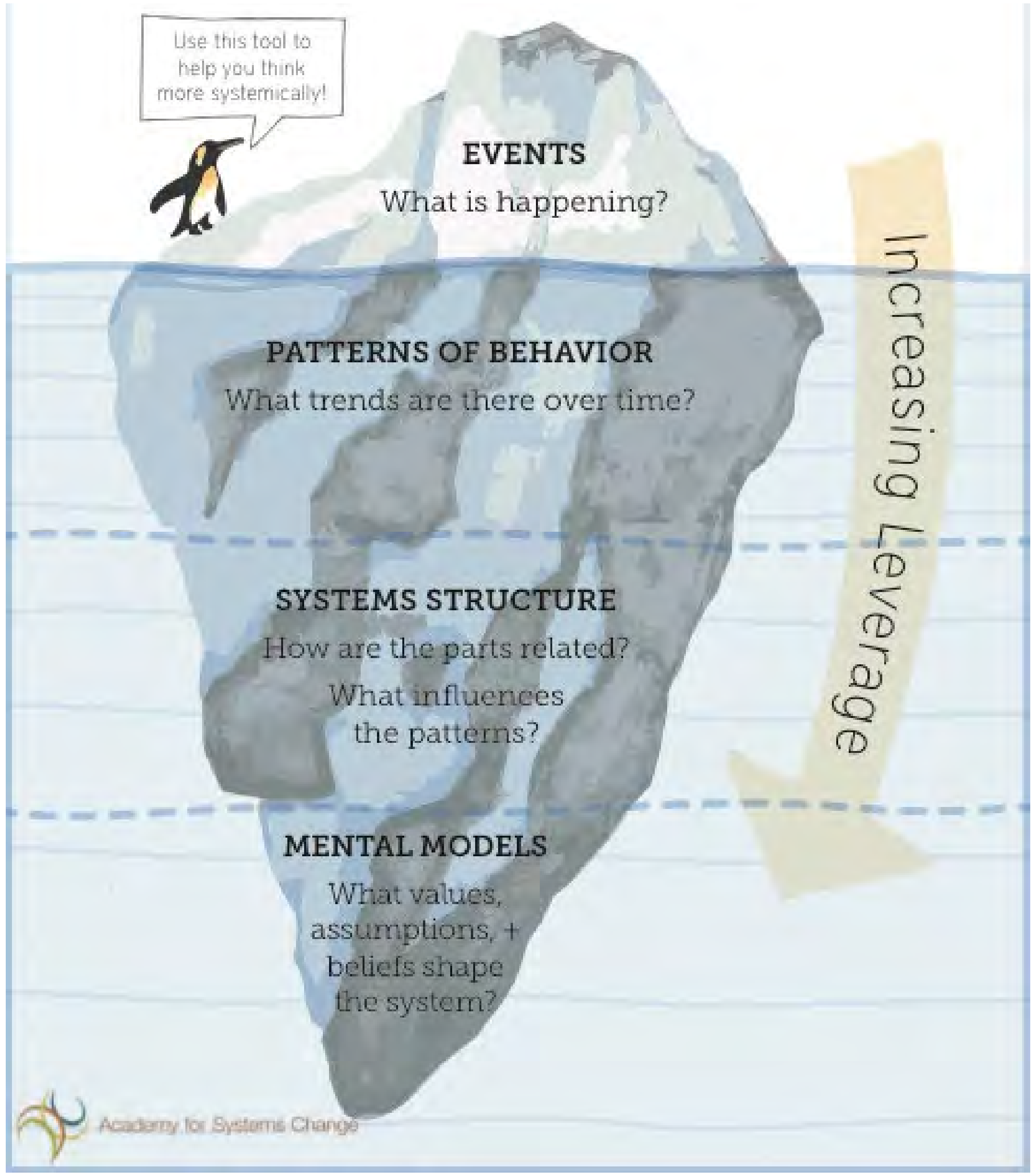
“*Systems thinking [is] a way of thinking about, and a language for describing and understanding, the forces and interrelationships that shape the behavior of systems. This discipline helps us to see how to change systems more effectively, and to act more in tune with the natural processes of the natural and economic world.*”

~ Peter Senge, The Fifth Discipline, The Art and Practice of The Learning Organization [8]

Systems Thinking



Single and Double-Loop Learning [10]



Iceberg Model [9]

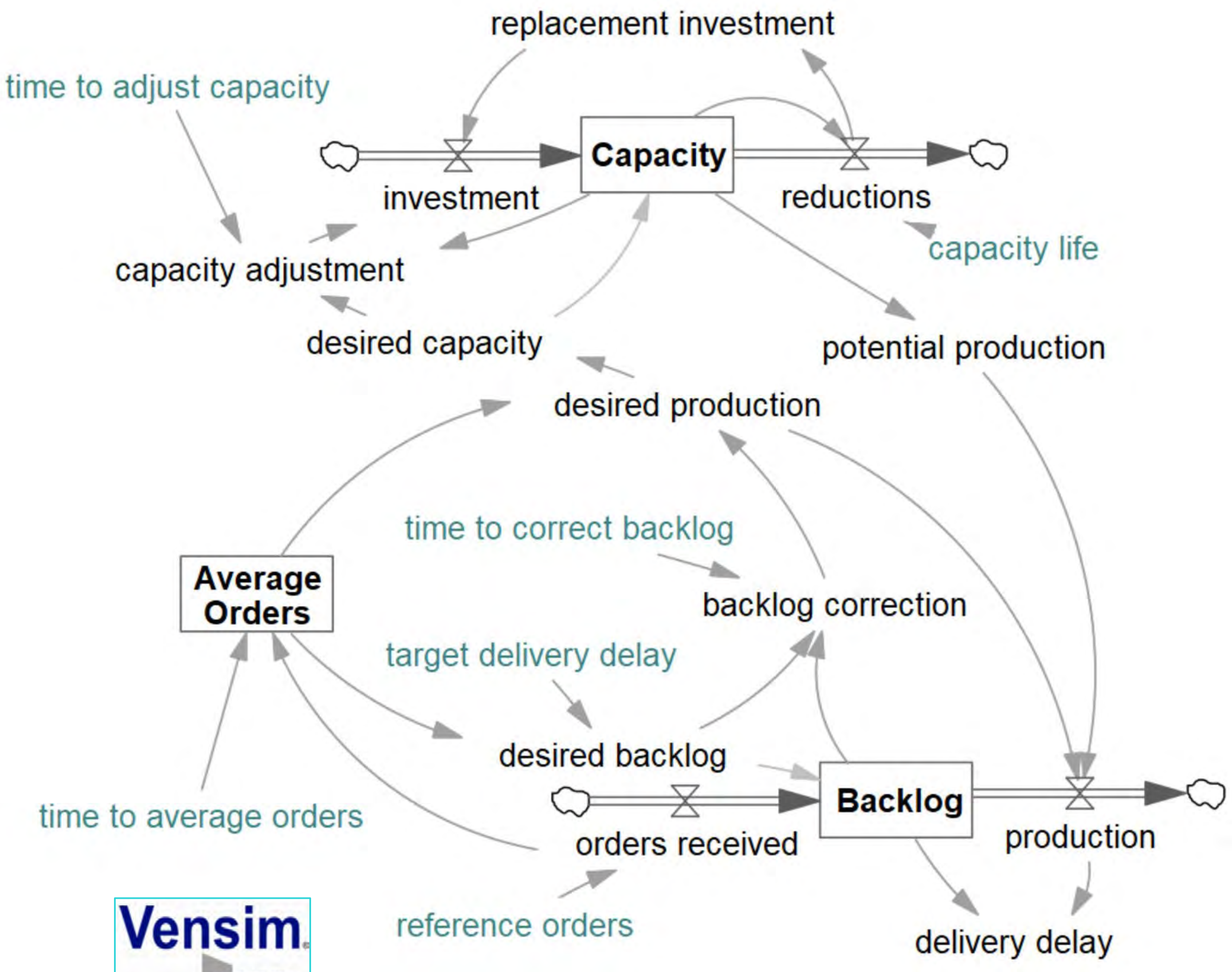
Systems Thinking (cont'd)

Seven Key System Principles [10]:

1. **Holism:** A system is more than the sum of its parts: Elements, Interconnects(interdependence) and Purpose.
2. **Purpose:** The (true) purpose of a system is the biggest determinant of its Structure.
3. **Systems:** Systems come in (at least) 3's: System Context, System of Interest (SOI), Enabling System.
4. **Boundaries:** Systems boundaries depend on the Perspective, Purpose, and area of Responsibility.
5. **Evolution:** Systems have a life cycle, and they evolve.
6. **Emergence:** The complexity of systems is often due to emergent (nonlinear) behavior
7. **Feedback:** Wanted or unwanted emergent (nonlinear) behavior is often determined by feed-back loops (with delays) or interactions within and between the 3 systems

MBSE Tool – System Dynamics

- Modeling language and mathematical solution
- System Dynamics Elements:
  - Causal relationships
    - Variable A depends on Variable B
  - Loops
    - Closed chain of causal relationships
  - Stocks
    - Represent the state of the system changing in time, integration of the difference between inflows and outflows
  - Flows
    - Inputs and outputs from stocks, a rate of change



Vensim

Vensim Help, Production Model [11]

Research Questions and Tasks

The HOW

Research Questions and Tasks

- **Primary Research Question:** How can modern systems engineering principles and tools be used to develop a framework supporting decision-making for novel energy systems?
- **Research Question 1:** What are the shortcomings in the state-of-the art methods and tools for decision making for energy systems?
  - To answer this research question, a literature review is performed to identify methods and tools currently being used to support decision making for energy systems.
- **Research Question 2:** What are the required characteristics of a decision support framework for investment strategies in energy systems with MBSE supporting the understanding of the characteristics?
  - As part of this research question, an MBSE SysML model will be developed to capture the System of Interest (SOI), which is the decision support framework, SOI context, supporting systems, and interrelationships between them.

Research Questions and Tasks (cont'd)

- **Research Question 3:** How can system dynamics methodology be used to create decision making tool for energy systems given the requirements identified for an advanced state-of-the-art decision support system?
  - This question seeks to understand how economical, technical, and social aspects can be integrated into decision making with the goal to inform selection of operational and investment strategies for novel energy systems. The research under this question also explores how system dynamics modeling and its module, management flight simulator, can improve energy systems decision making.
- **Research Question 4:** How can MBSE support the conceptual design of a novel energy system?
  - This question expands the decision-making framework to include systematic evaluation of conceptual system design options with the goal of selecting the one that is best-aligned with stakeholder needs.

Progress

Work up-to-date

Progress – SysML

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

Translated into ←

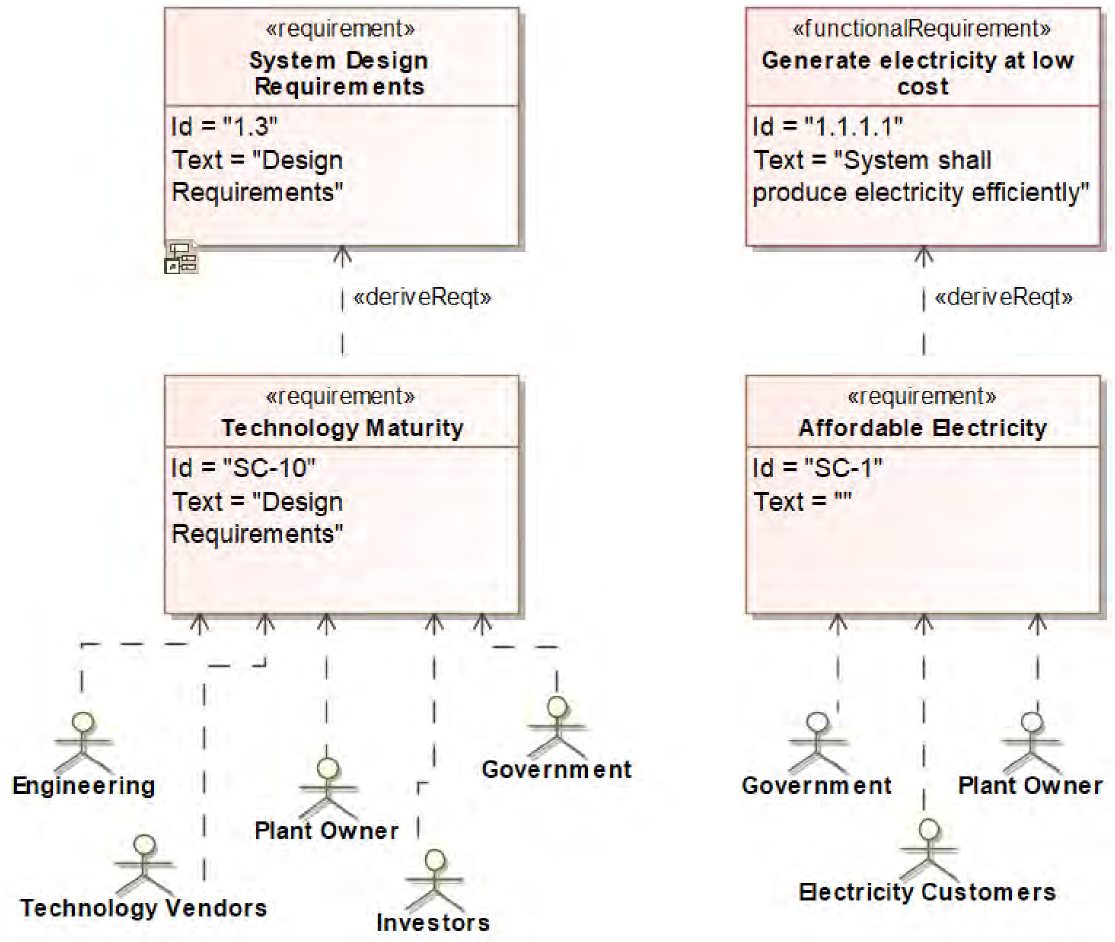
Stakeholder needs and concerns

Stakeholder(s)	Needs / Concerns / Interests
Electricity Consumers	Affordable electricity Consistent availability (24/7/365) Climate goals
Hydrogen Consumers	Affordable hydrogen Consistent availability (24/7/365) Hydrogen quality Climate goals
Coupled Facility 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
Electrolysis 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 Reliability and availability Technology maturity Funding sources
Regulators	Regulatory approvals and compliance Reliability and availability Technology maturity Climate goals

Progress – SysML Model (cont'd)

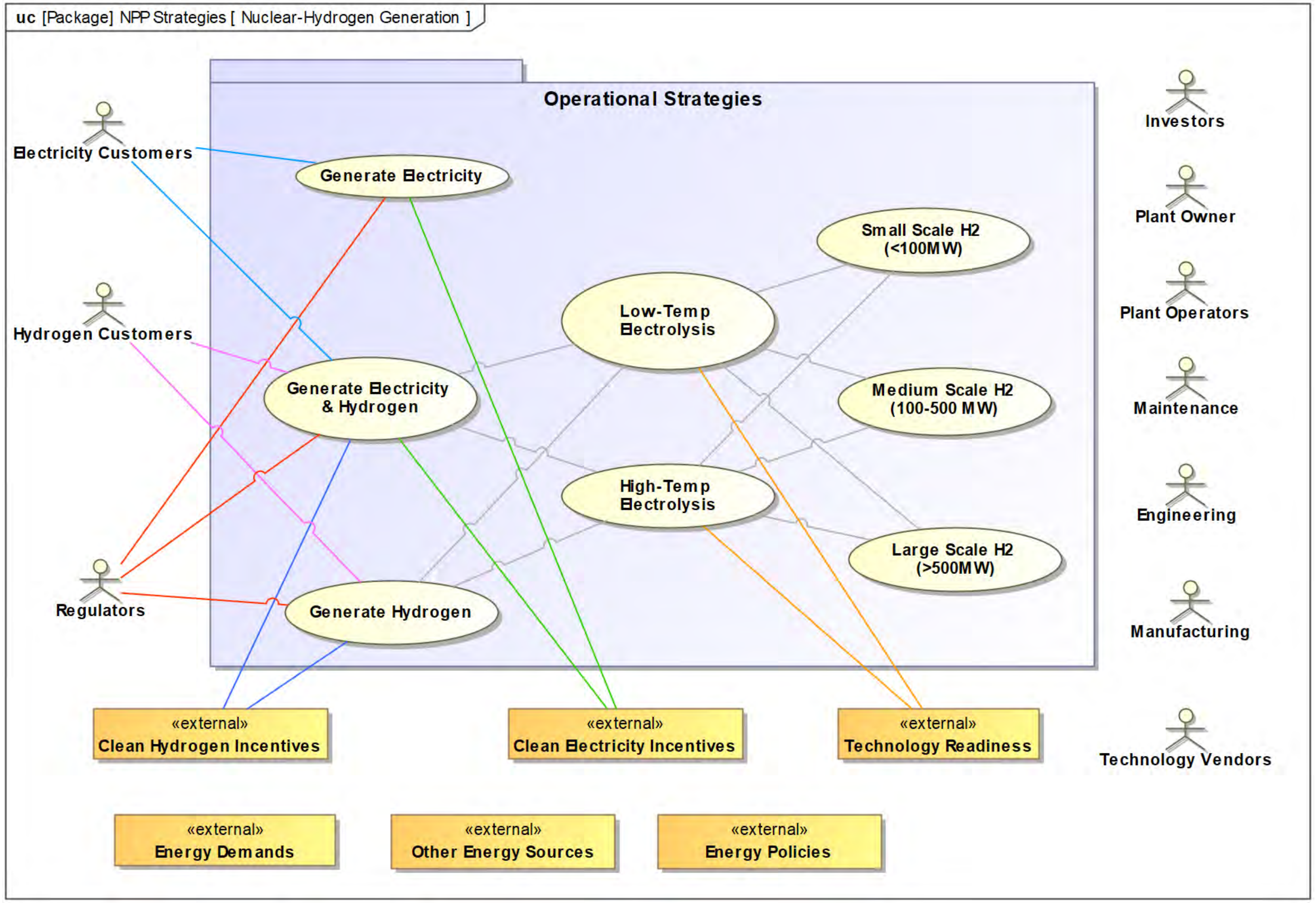
0 Stakeholder…		R SC-10 Technology Maturity	R SC-1 Affordable Electricity
0 System Requirements		1	1
R 1 Mission Requirements			
F 1.1 System Functional Requirements			
F 1.1.1 Generate Electricity	3		
F 1.1.1.1 Generate electricity at low cost	1		↙
F 1.1.1.2 Generate electricity without interruption	1		
F 1.1.2 Generate Hydrogen	3		
B 1.2 Business Requirements			
R 1.3 System Design Requirements	7	↙	

Requirements traced to stakeholder concerns



Stakeholders → Stakeholder Concerns → Requirements

Progress – SysML Model (cont'd)



Operational strategies shown via a context diagram

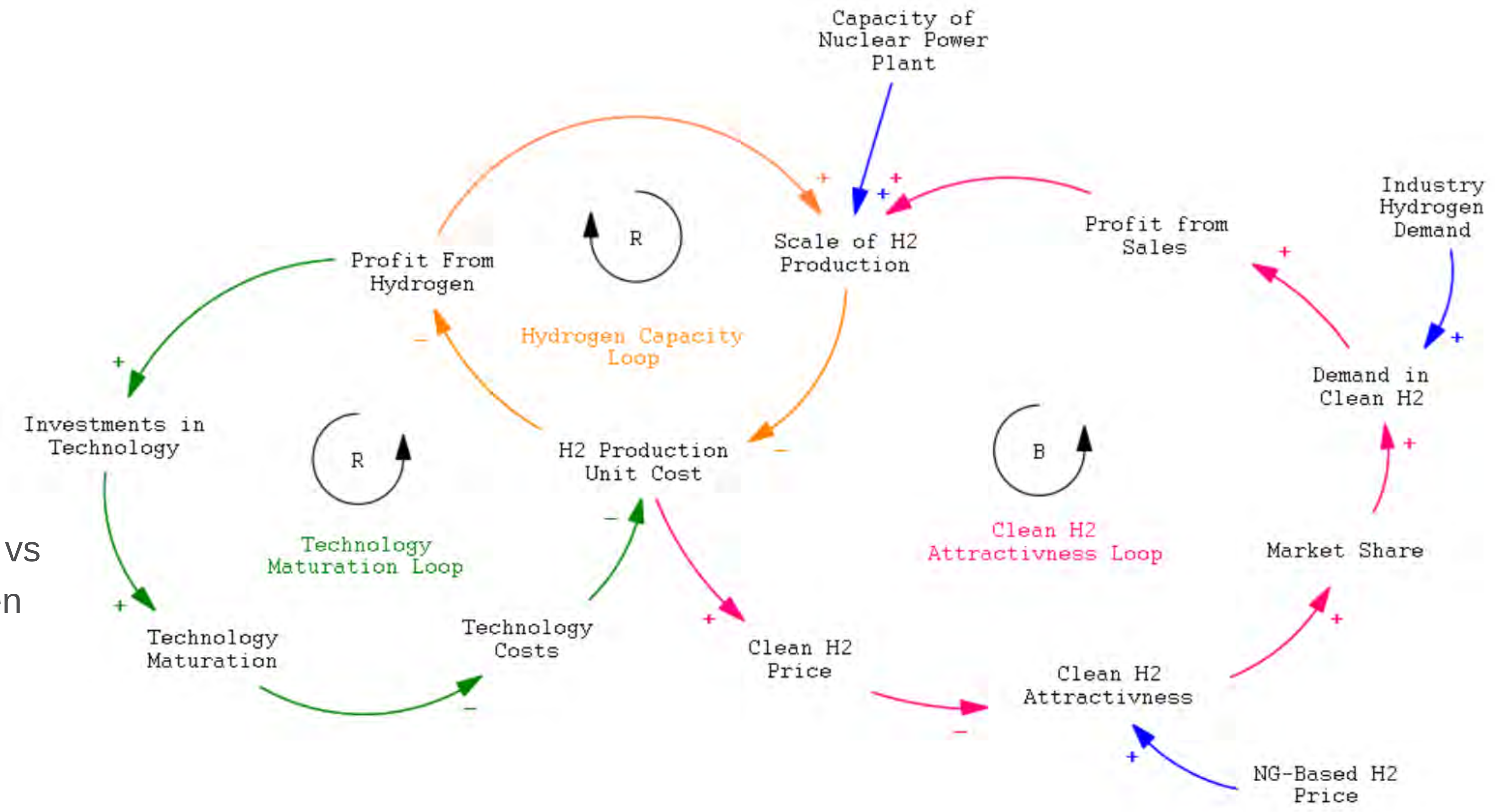
Progress – System Dynamics

Causal Loops in Hydrogen Production

Question:

What affects profits from hydrogen generation?

- Capacity of H2 plant
- Capacity of nuclear plant
- Technology costs
- Price
- Attractiveness of clean hydrogen vs Natural Gas (NG)-based hydrogen
- Price of NG-based hydrogen
- Market share
- Industry demand in hydrogen



Causal Relationships in Clean Hydrogen Production

Progress – System Dynamics

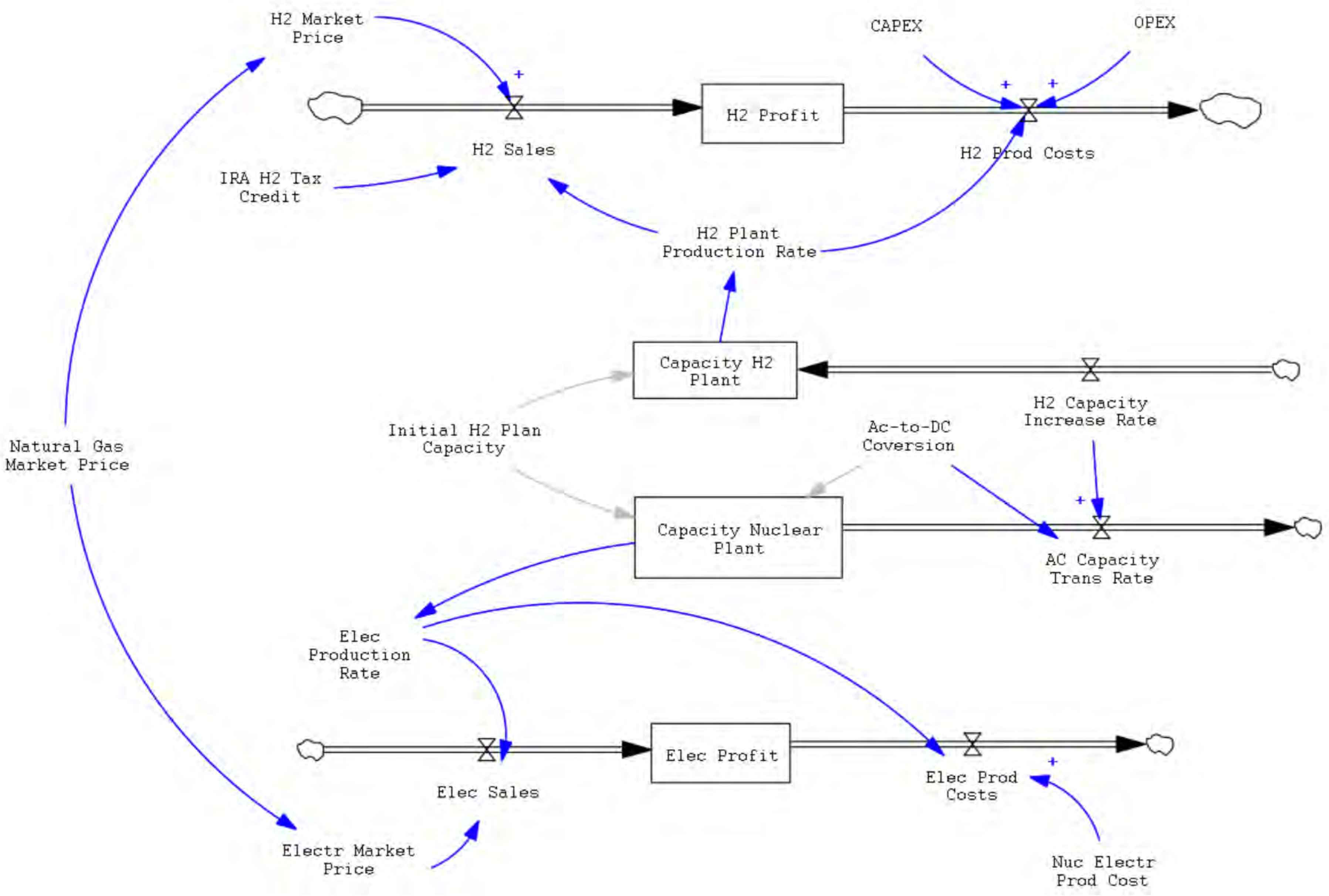
SD Model of Hydrogen Generation Coupled with Nuclear Power Plant

Questions:

1. Should the nuclear plant transition from electricity to hydrogen generation?
2. How much of nuclear plant capacity to use for hydrogen generation?

Parameters affecting the decision:

- Capacity of nuclear plant
- Capacity of H2 plant
- Cost to generate electricity
- Cost to generate hydrogen
- Electricity market price
- Hydrogen market price
- Federal incentives



Research Plan

Roadmap

Publication Plan – Conference Papers

- **Conference Paper 1: completed [12]**
  - Title: Towards the Integration of Hydrogen Production with Nuclear with Model-Based Systems Engineering
  - Conference: ANS Winter Meeting and Technology Expo 2023 | November 12-15 | Washington D.C
  - Submission date: June 26, 2023
  - Presentation: November 14, 2023
- **Conference Paper 2:**
  - Draft Title: A system dynamics approach for investment decision-making into nuclear based hydrogen generation
  - Conference: ANS Pacific Basin Nuclear Conference 2024 (PBNC) | October 7-10, 2024 | Idaho Falls, ID
  - Submission date: February 16, 2024
  - Presentation: October 7-10, 2024

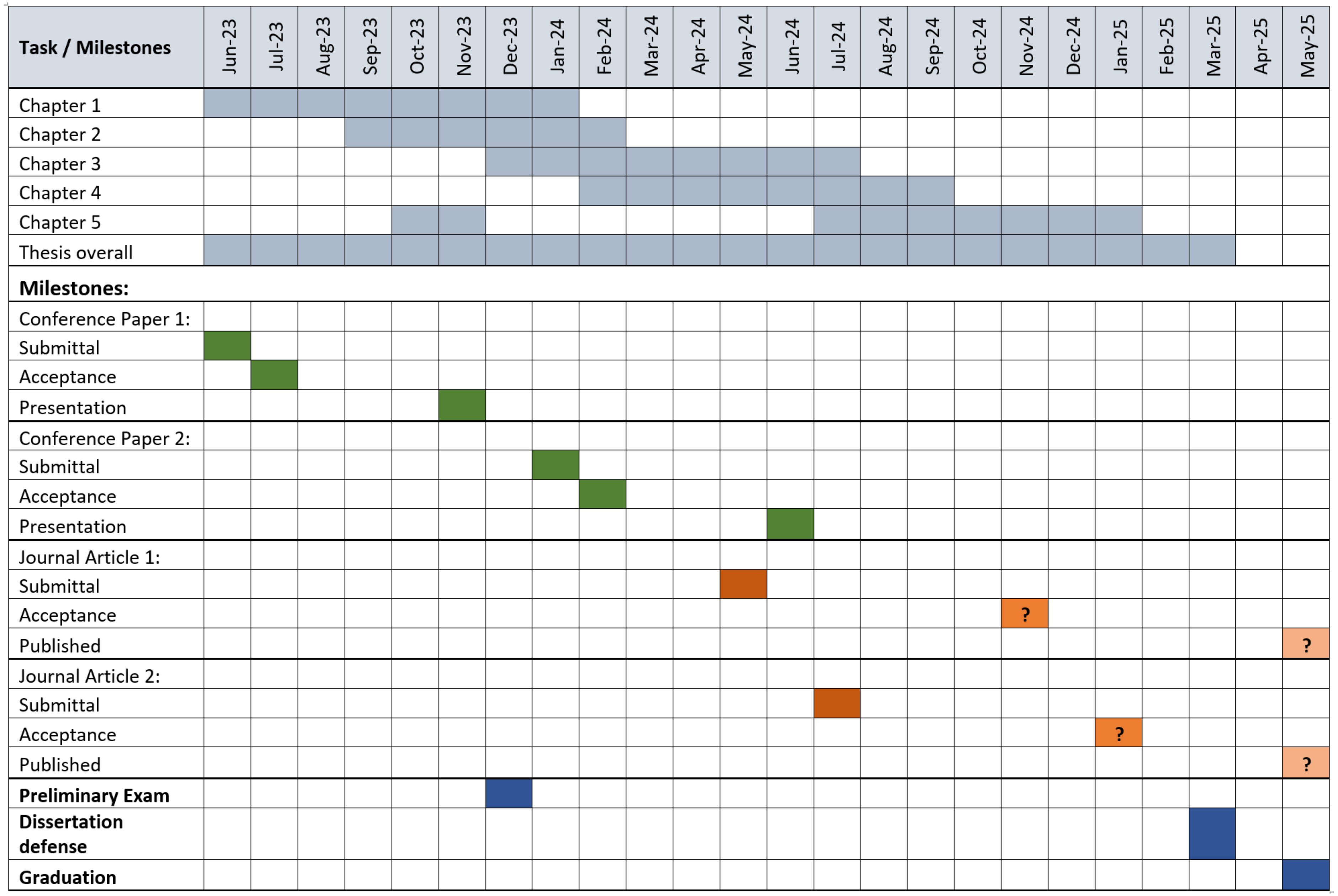
Publication Plan – Journal Articles

- **Journal Article 1:**
  - Draft Title: System dynamics as a decision support tool for investments in novel energy systems, demonstrated via a case study of nuclear-based hydrogen generation.
  - Target submission: May 2024
  - Target acceptance: November 2024
- **Journal Article 2:**
  - Draft Title: Model-Based Systems Engineering for development and evaluation of system concepts for nuclear-based hydrogen production.
  - Target submission: July 2024
  - Target acceptance: January 2025

Candidate Journals	Research Impact Score	Journal Citation Indicator	Impact Factor	H-Index	Submission to Acceptance
Applied Energy	22.3	1.630	11.20	264.0	132 days
International Journal of Energy Research	7.8	1.280	4.60	110.0	63 days
Annals of Nuclear Energy	2.2	0.980	1.90	77.0	140 days
Decision Support Systems	8.69	1.390	7.50	170.0	235 days
System Dynamics Review	4.32	0.810	3.04	63.0	29.2 days
Systems Engineering	1.1	0.390	2.00	55.0	42 - 56 days
Energy Strategy Reviews	2	0.990	8.20	54.0	161 days

Research Schedule

- **Milestones:**
  - Preliminary exam: December 2023
  - Journal article 1: May 2024
  - Journal article 2: June 2024
  - Dissertation defense: March 2025
  - Graduation: May 2025



Future Research

Thoughts on applications

Potential Applications

- Decision support system for evaluation of strategies for novel energy solutions
  - Investments into novel energy systems
  - Nuclear energy to support industrial energy needs (e.g., chemical industry, steel manufacturing)
  - Selection of portfolio of energy sources
    - Renewables
    - New nuclear
    - Natural gas with carbon capture
  - Evaluation of vulnerabilities and uncertainties in novel energy solutions
- Evaluation of policy effects on energy systems
  - Federal policies
  - State and local policies

Questions?

Thank you

Colorado State University

References

1. U.S. Department of Energy, Office of Nuclear Energy: Strategic Vision, https://www.energy.gov/sites/prod/files/2021/01/f82/DOE-NE%20Strategic%20Vision%20-%2001.08.2021.pdf
2. Ruth, M.F., et al. "The Technical and Economic Potential of the H2@Scale Concept within the United States," October 2020. National Renewable Energy Laboratory, NREL/TP-6A20-77610
3. Larsen et al, "Assessing the Impact of the Inflation Reduction Act on Nuclear Plant Power Uprate and Hydrogen Cogeneration," Idaho National Laboratory, INL/RPT-23-74681, September 2023, https://www.osti.gov/biblio/2007297 .
4. Cheng et al, "Estimating the Value of Nuclear Integrated Hydrogen Production and the Dependency of Electricity and Hydrogen Markets on Natural Gas," Idaho National Laboratory, INL/RPT-23-73909, August 2023.
5. 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
6. CATIA | NoMagic, MagicGrid User Guide, https://docs.nomagic.com/display/SYSMLP190/User+Guide
7. INCOSE, Systems Engineering Handbook, 5th ed. John Wiley & Sons, Inc., 2023.
8. P. M. Senge, The Fifth Discipline, The Art and Practice of The Learning Organization. Doubleday, 2004.
9. Academy for Systems Change, https://www.academyforchange.org/2019/12/07/leverage-points-iceberg-model-economic-development/
10. Prof. Kamran Eftekhari-Shahroudi, SYSE 580A2 - Applied Systems Thinking for the Real World, 2023.
11. Vensim Help Website, https://www.vensim.com/documentation/index.html
12. S. Lawrence and D. R. Herber, "Towards the integration of hydrogen production with nuclear with model-based systems engineering." Transactions of the American Nuclear Society, ANS Winter Meeting, vol.129, 2023.