INL/MIS-23-72614-Revision-0

Thermal and Experimental Systems Overview IES Program 2023

May 2023

Changing the World's Energy Future

Daniel Mark Mikkelson, Amey Shigrekar, Rami M Saeed, Ramon Ken Yoshiura, Abdalla Abou Jaoude, Jun Soo Yoo, Elizabeth Kirkpatrick Worsham, Daniel S Wendt, Terry James Morton, Shannon M Bragg-Sitton

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/MIS-23-72614-Revision-0

Thermal and Experimental Systems Overview IES Program 2023

Daniel Mark Mikkelson, Amey Shigrekar, Rami M Saeed, Ramon Ken Yoshiura, Abdalla Abou Jaoude, Jun Soo Yoo, Elizabeth Kirkpatrick Worsham, Daniel S Wendt, Terry James Morton, Shannon M Bragg-Sitton

May 2023

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

IES

Integrated Energy Systems

IES Program Review Thermal and Experimental Systems

Overview of Capabilities & Projects

May 10, 2023

Presented by:
Dr. Daniel Mikkelson

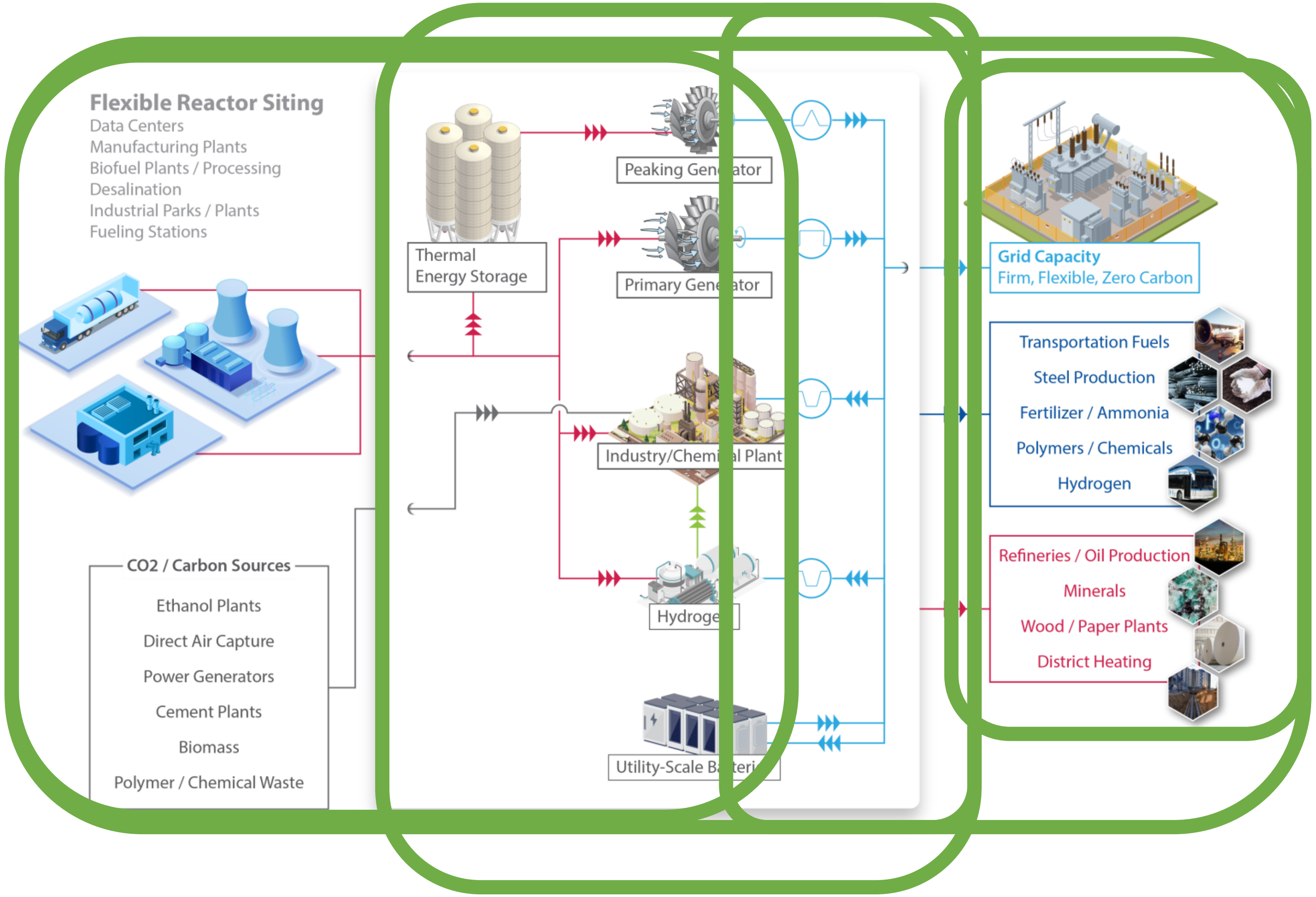
Material developed by: Daniel Mikkelson, Amey Shigrekar, Jun Soo Yoo, Abdalla Abou Jaoude, Shannon Bragg-Sitton, T.J. Morton, Ramon Yoshiura, Rami Saeed, Vineet Kumar, Elizabeth Worsham, Dan Wendt

Session Agenda

1. HYBRID Modeling Activities
   a) New HYBRID structure: integrating static & dynamic modeling
   b) Validation & verification
2. Thermal Systems Research Projects
   a) Thermodynamic system characterization
   b) Costing information: components and systems
3. Experimental Systems
   a) Current: DETAIL
   b) Future: DOME, CFA
   c) DSS and V&V connects experiments to modeling, full reactors
4. Thermal Systems Capabilities
   a) HYBRID + Experiments + Cost Information
   b) Enabling Use Cases

IES
Integrated Energy Systems

Thermal Systems Modeling in IES

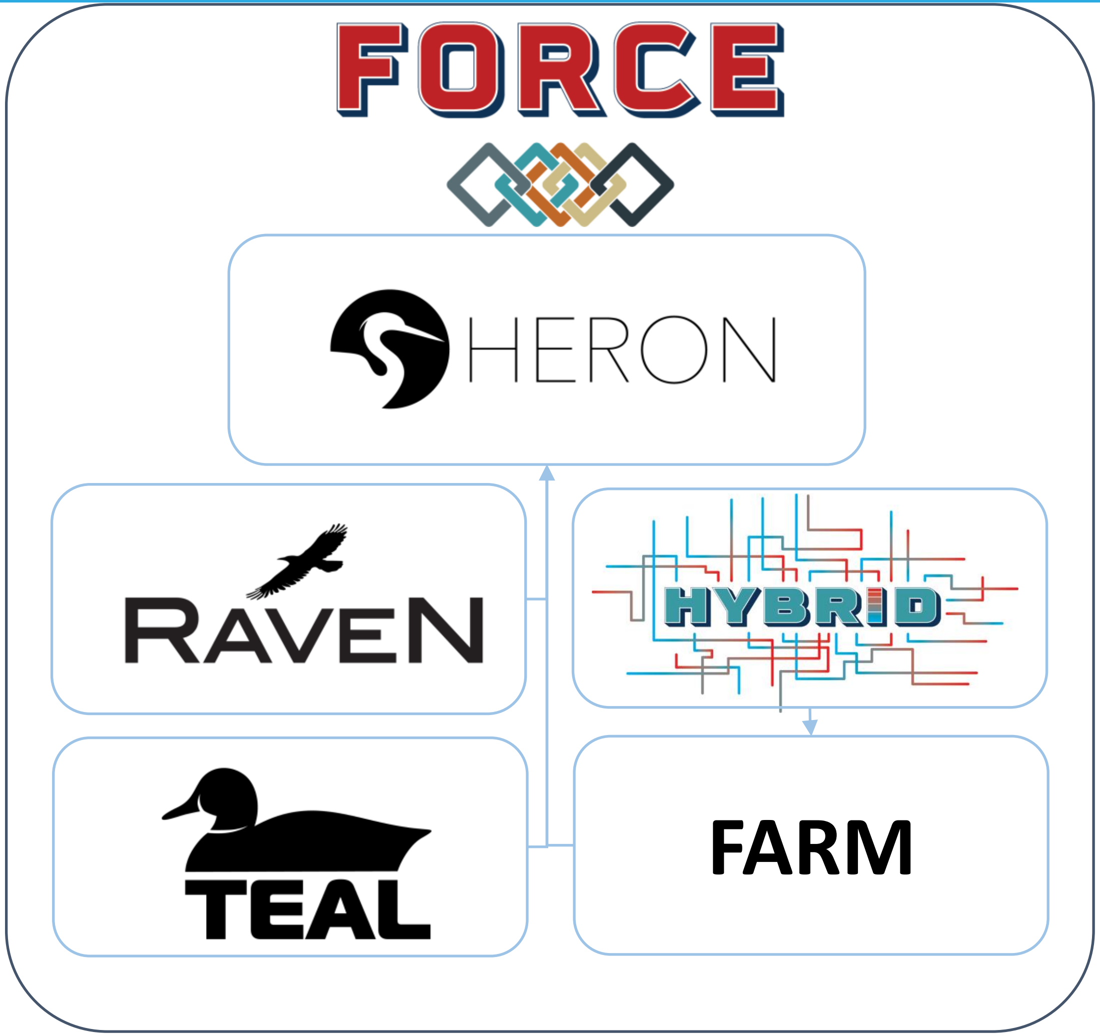


- How do subsystems operate?
  - Ramp rates
  - Internal energy flows
  - Control response
- How do systems respond to dispatch?
  - What is governing system control?
- What are external energy requirements?
  - Thermal and electrical energy use
- What are heat and chemical balances for IES?
  - How should energy interfaces operate in IES?

IES Integrated Energy Systems

How HYBRID Fits Within FORCE

- INL tools enable IES modeling analysis
  - *Physical process, integration modeling*
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - *Stochastic analysis, multiple commodities*
  - *Energy storage, varied markets*
  - *Real-time optimization*



IES
Integrated Energy Systems

HYBRID Structure

Modelica Dynamic Models
Primary Heat Systems
Energy Manifold
Balance of Plant
Industrial Process
Energy Storage
Secondary Energy Source
Primary Heat Switch Yard
Electrical Grid
Control System Center
Experimental Systems

Steady-State	**Transient**	**ROMs**	**Cost Information**
Tech 1	Tech 1	Tech 1	Tech 1
Tech 2	Tech 2	Tech 2	Tech 2
Tech 3	Tech 3	Tech 3	Tech 3
Tech 4	Tech 4	Tech 4	Tech 4
…	…	…	…
Aspen, Mathcad, Excel, etc.	*non-Modelica or "Save-total" Modelica*	*Trained on other models*	*HERON-readable format*

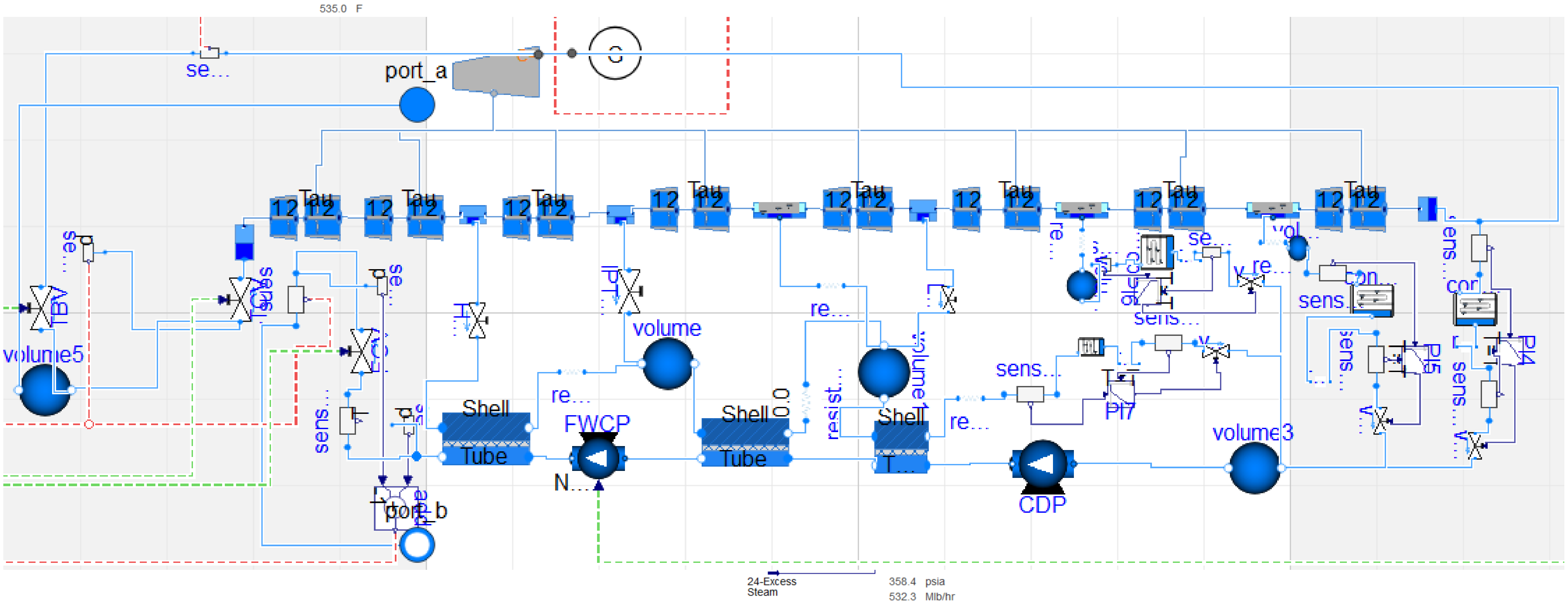
Aspen: Primary Steady-State Modeling Tool

- Aspen HYSYS
- Aspen Exchanger Design and Rating (EDR)
- Aspen Process Economic Analyzer (APEA)

- Process engineering simulation software
  - Design and optimization of several systems
  - Steady-state as well as dynamic modeling
  - User-friendly interface

IES Integrated Energy Systems

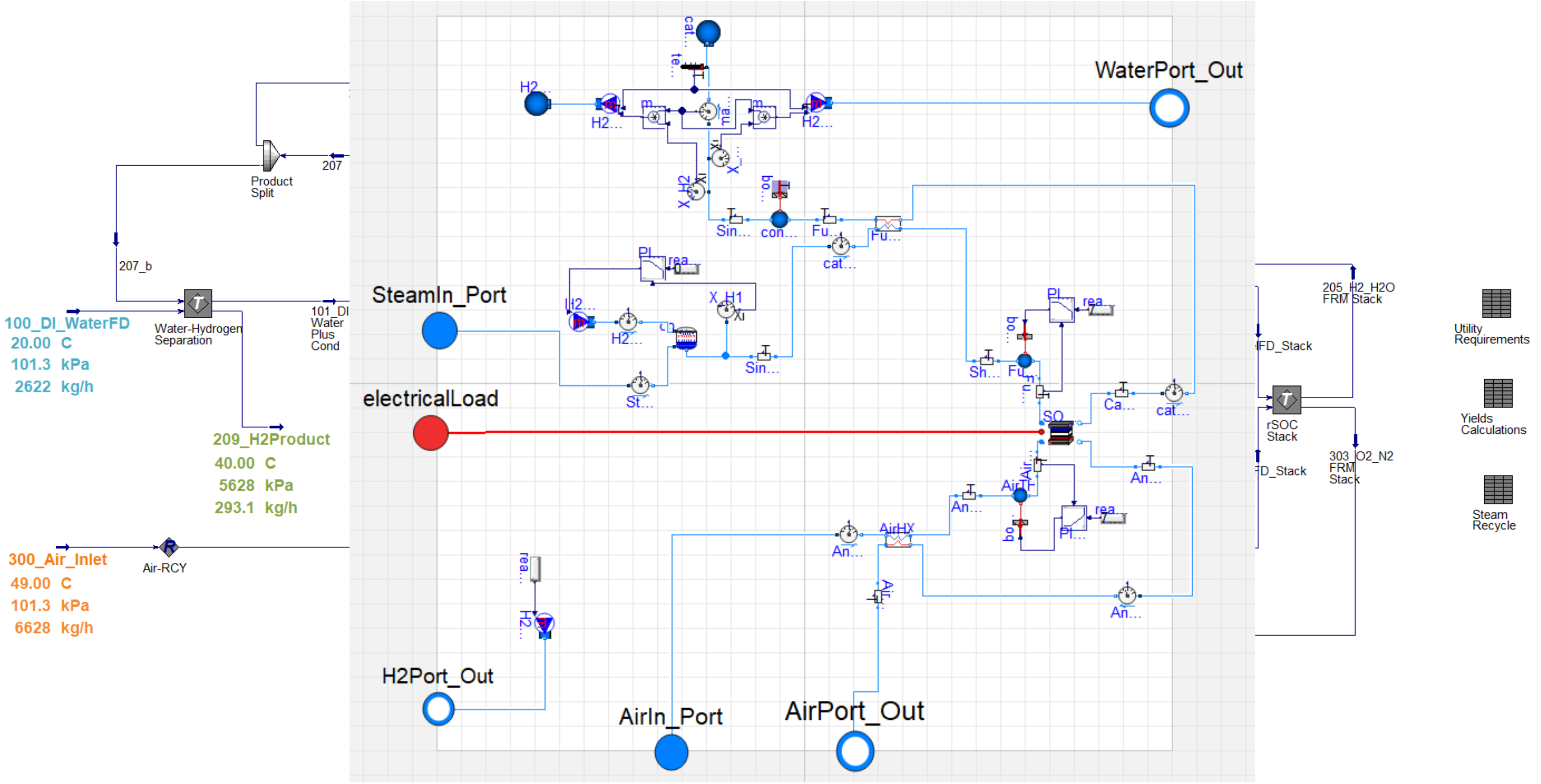
Balance of Plant



Detailed Rankine Cycle

IES Integrated Energy Systems

High Temperature Steam Electrolysis

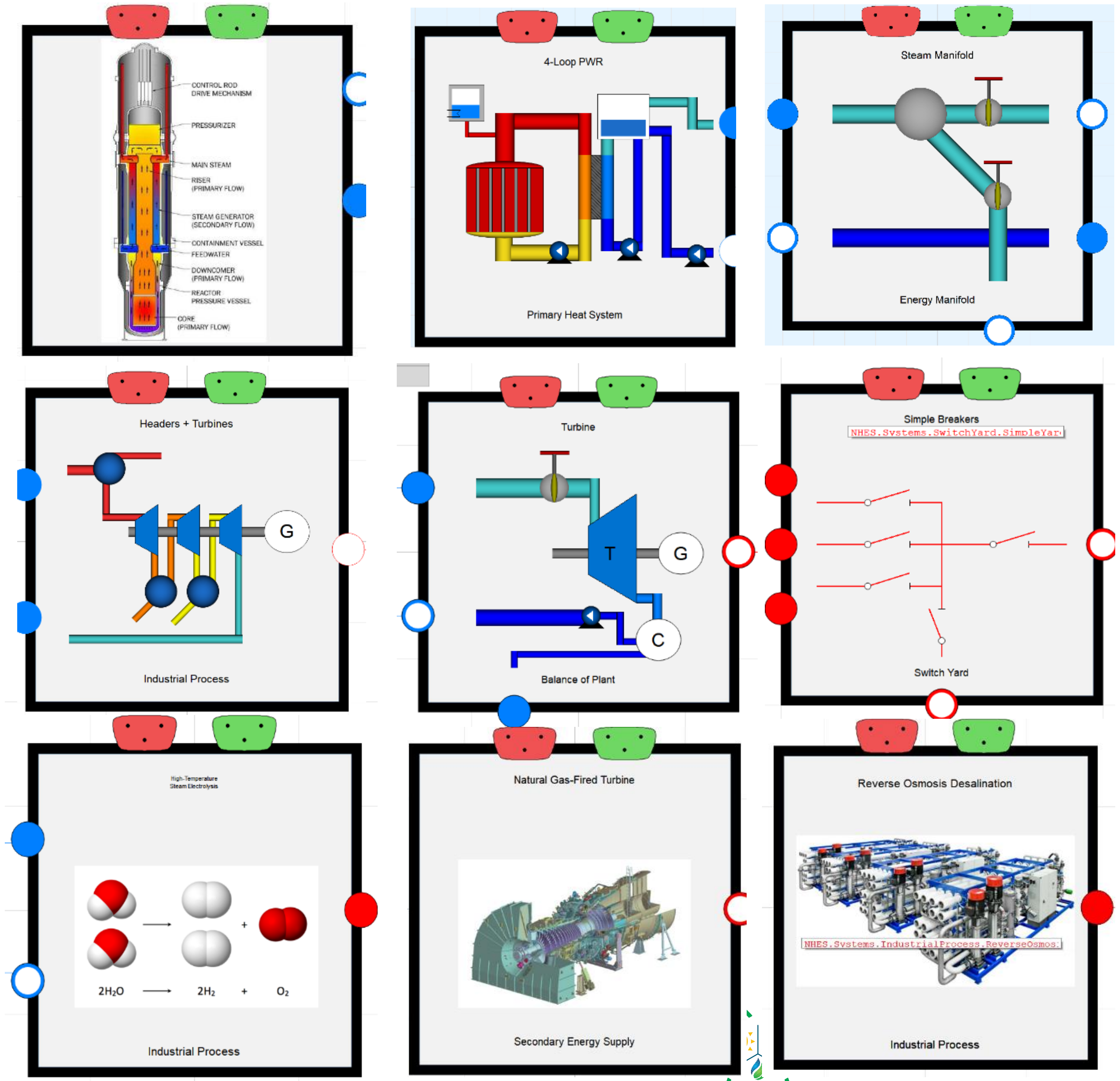


Balance of Plant for HTSE

IES Integrated Energy Systems

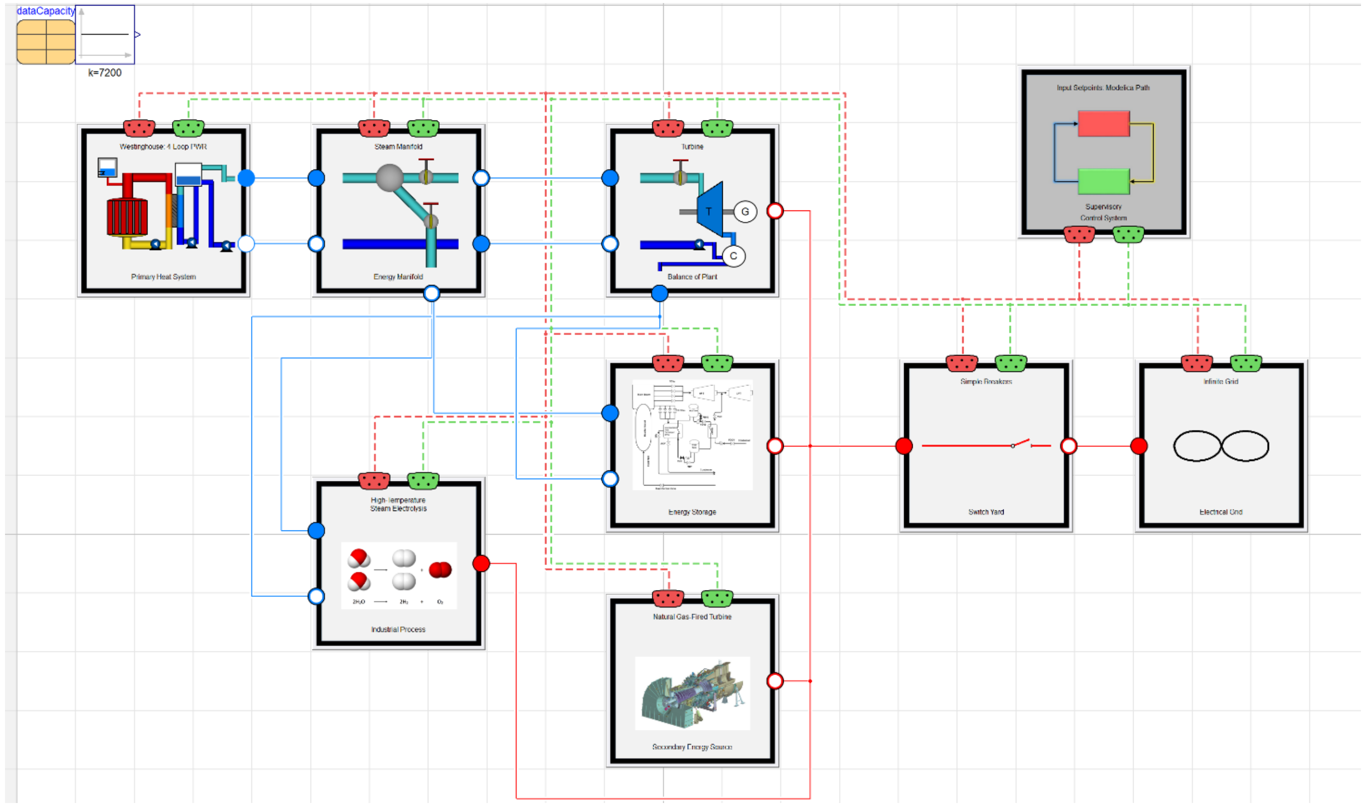
HYBRID Dynamic Modeling

- HYBRID dynamic modeling evaluates the feasibility of systems developed within FORCE and provides constraint data necessary for broader system evaluations
  - An ideal intermediary for determining:
    - Integration design
    - Control methods
    - Ramp rate feasibility
    - Determination of off-design behaviors



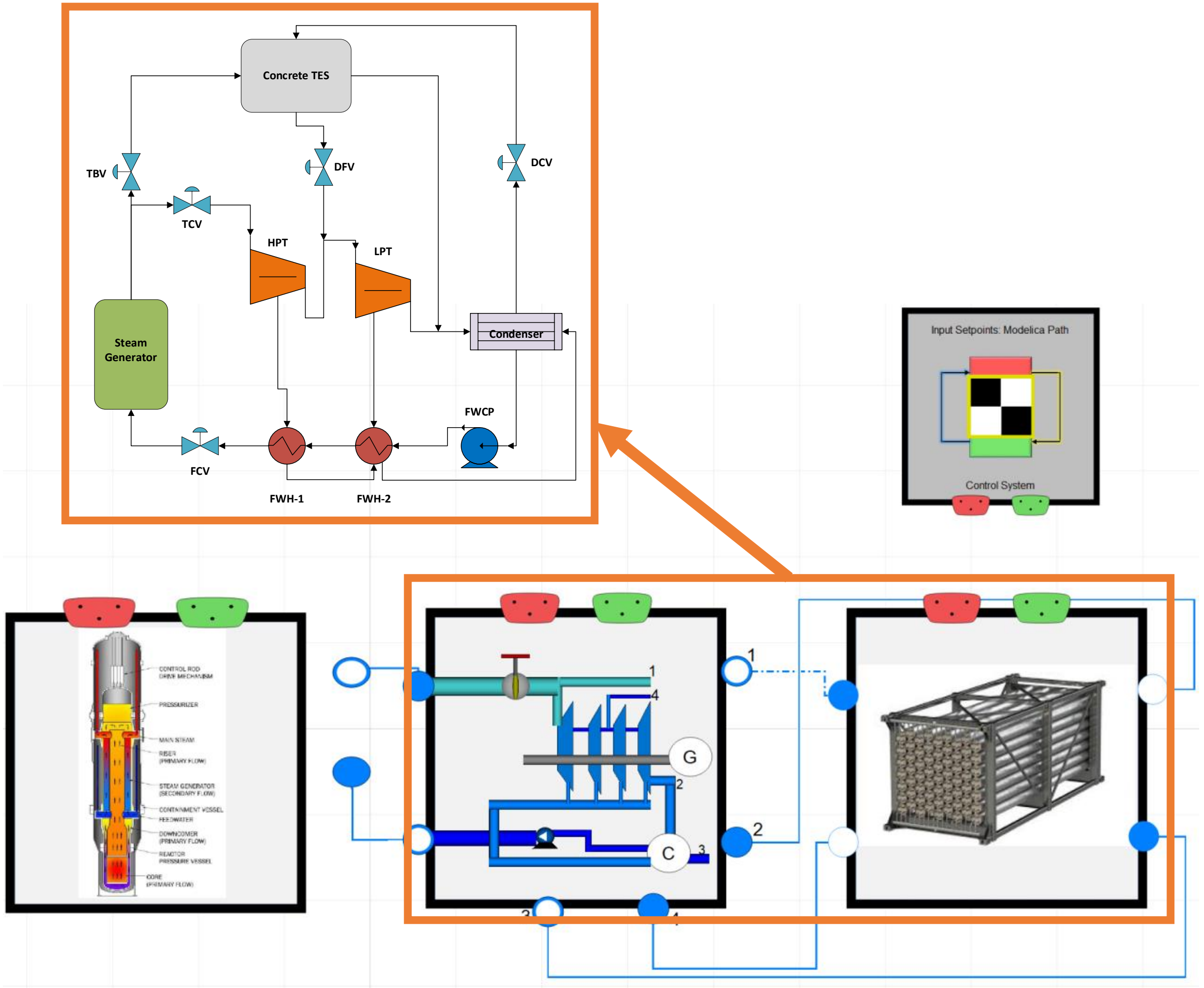
Design Capability

- Physical models are focused on process system bases
- Subsystem models are fully defined based on interconnects
- Dynamic balance across full system is calculated

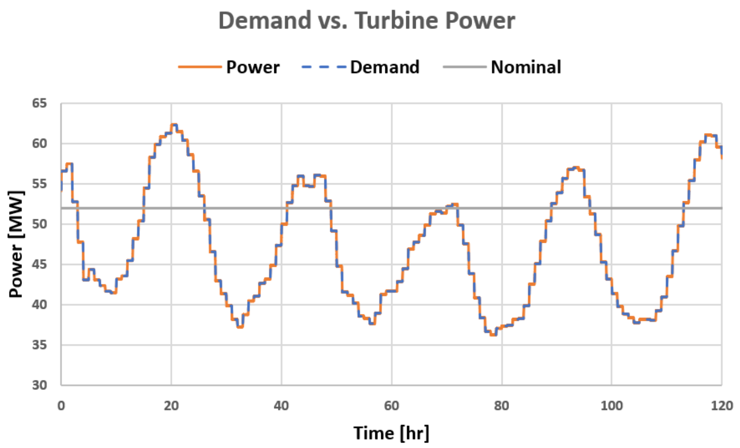


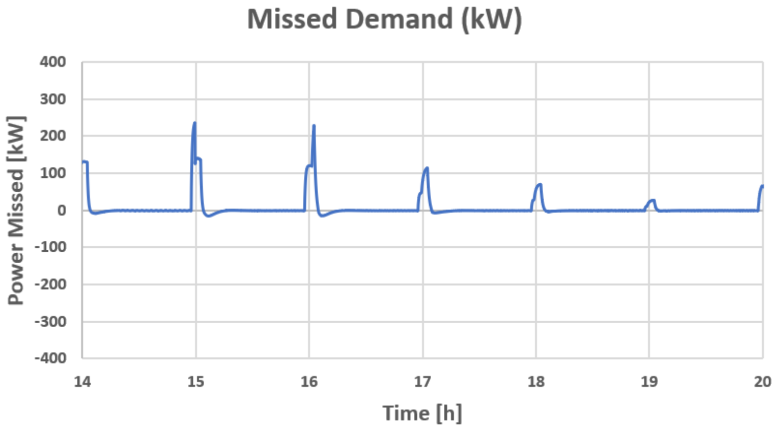
Energy Arbitrage IES

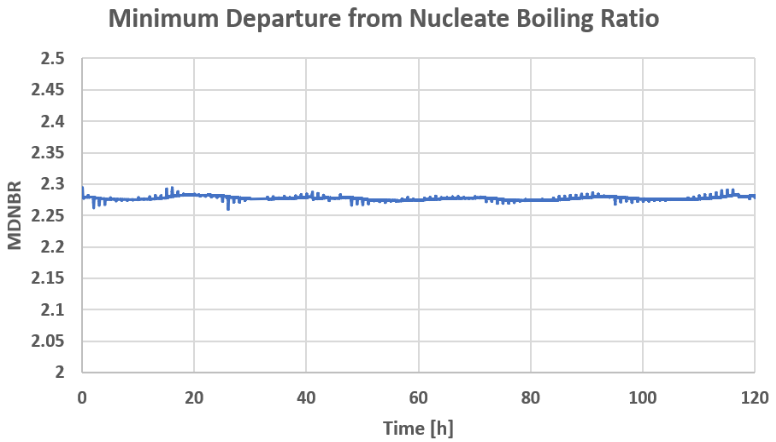
- NuScale-style SMR
- High-fidelity balance of plant
- Integrated-concrete thermal-energy storage system (dual network model)
- Week-long-scaled dispatchable demand profile calculated and input

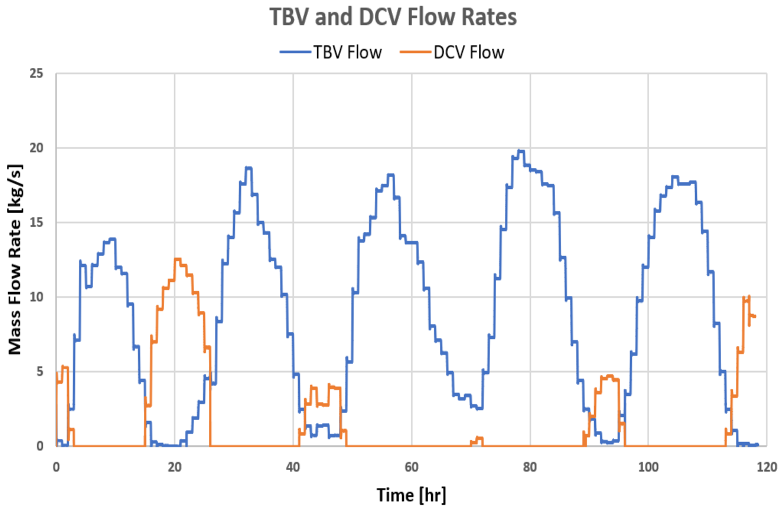


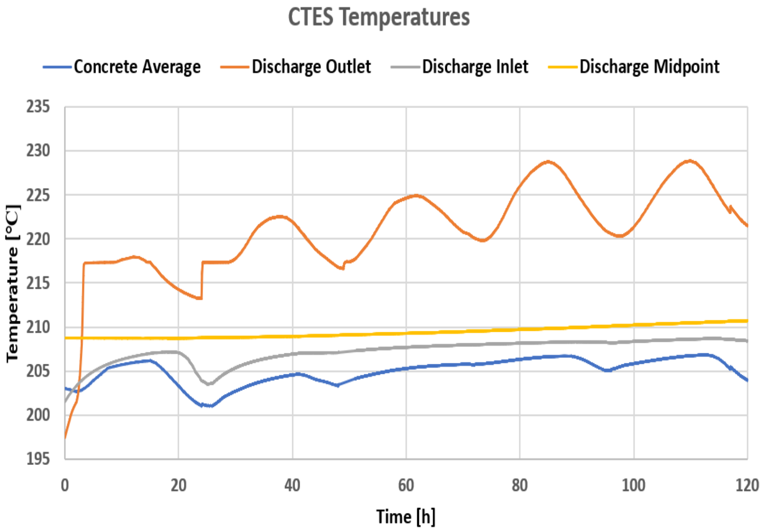
Energy Arbitrage IES

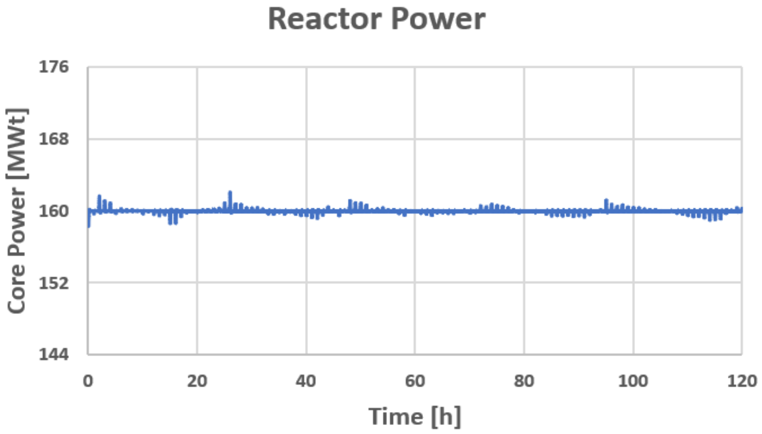












IES Integrated Energy Systems

V&V Matrix

Subsystem Name	V&V	Example Type	ROM generated	Steady-state model	Published documents	Reference documents	Nominal Conditions, Notable Limitations
4-loop PWR	Face	Integrated			INL/EXT-19-55395	Systems Summary of a Westinghouse PWR Nuclear Power Plant 1984 "PWR Description", Jacopo Buongiorno	3400 MWt, Steam: 1750 kg/s, 69 bar, 285°C
Small modular IPWR	Data: steady state	Integrated			INL/CON-16-39032	https://aris.iaea.org/PDF/NuScale.pdf doi: 10.1016/j.desal.2014.02.023	160 MWt, Steam: 35 bar, 300°C, 75 kg/s
Small modular natural circulation IPWR	Data: Steady state	Integrated			INL/EXT-19-55520 doi: 10.1080/00295450.2020.1781497 doi: 10.1016/j.apenergy.2022.118800 INL/RPT-22-69214	NuScale Standard Plant Design Certification Application	200 MWt, Steam: 35 bar, 310°C, 84 kg/s
HTGR	Data: Transient	Integrated			doi: 10.2172/1890160 INL/RPT-22-68222 INL/RPT-22-66941 INL/RPT-22-69214	doi: 10.1016/j.nucengdes.2017.11.041	130 MWt, Steam: 140 bar, 540°C, 50 kg/s
SFR	Physics	Individual			INL/RPT-22-68222		BOP under construction

Integrated Energy Systems

Validation: Code-to-Code or Publications

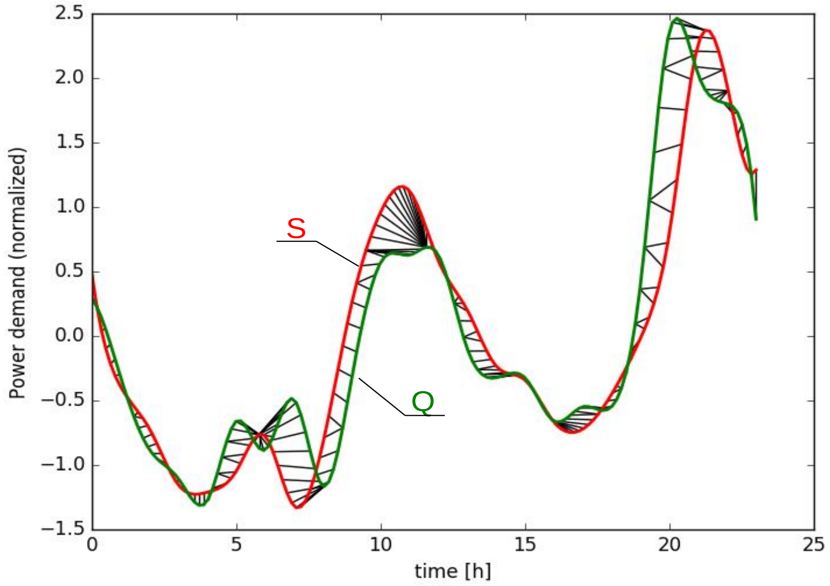
- Code-to-code validation

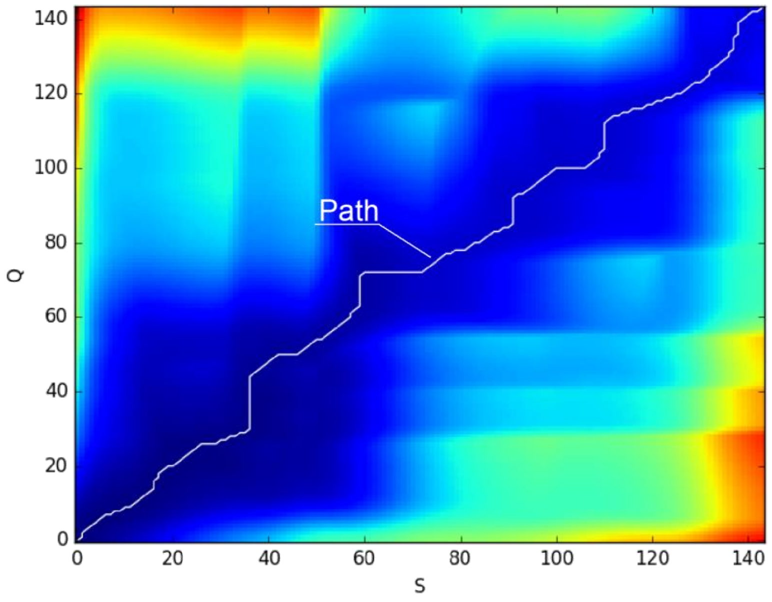
Physical Variable	Reference Value	Simulation Value	Simulation Error Relative to Reference
Electric power (MW)	43.75	43.62	-0.297%
Thermal power (MW)	125	122.0	-2.4%
Steam temperature (°C)	540	540	N/A
Steam pressure (MPa)	14.0	14.0	N/A
Steam mass flow rate (kg/s)	50	48.0	-4.0%
Feedwater temperature (°C)	208	208	N/A
Primary mass flow rate (kg/s)	47.5	48.4	-2.1%
Core exit temperature (°C)	750	750	N/A
Core inlet temperature (°C)	255	265	3.9%

IES
Integrated Energy Systems

Validation: Experimental data

- Dynamic Time Warping
  - Metric for comparison of two time series
  - Insensitive to different lengths and time delays (unlike Euclidean distance)
  - Output: wrapping path (map)
- Similarity: sum of distances between matched features
- FOM: Normalized distance, DTWscore (differences in time), sum of diagonal elements (amplitude between the two sequences), histograms of relative matching





Thermal Systems R&D: Thermal Systems Component

Dynamic System Modeling

Heat Extraction & Delivery

Heat source?
(e.g., nuclear reactors)

Heat application?
(e.g., industry users)

- Operating conditions (e.g., P, T, $\dot{m}$)
- Energy carrying fluids
- Supply capacity (heat source)
- Heat duty (heat exchanger)
- Components sizing
- System dynamics (e.g., thermal cycle)
- Customer demand / requirements

Component Technologies Evaluation & Selection

Thermal Systems Component

1. Evaluation framework
   - **Heat exchanger**
   - **Thermal transport comp (e.g., HT fluid, piping, valve)**
   - **Heat pump**

2. Knowledge base
   - Identify components/candidates
   - Literature & market survey
     (e.g., technical gap/readiness, technical performance factors, safety factors, cost factors, cost correlations)
   - Identify Figures-Of-Merit

3. Case study
   - Optimal components selection

Techno-Economic Modeling & Analysis

Techno-economic Analysis

· Which components contribute most significantly to the system cost and associated uncertainty?
· Trade-offs between performance and cost
=> Optimal combination of components?

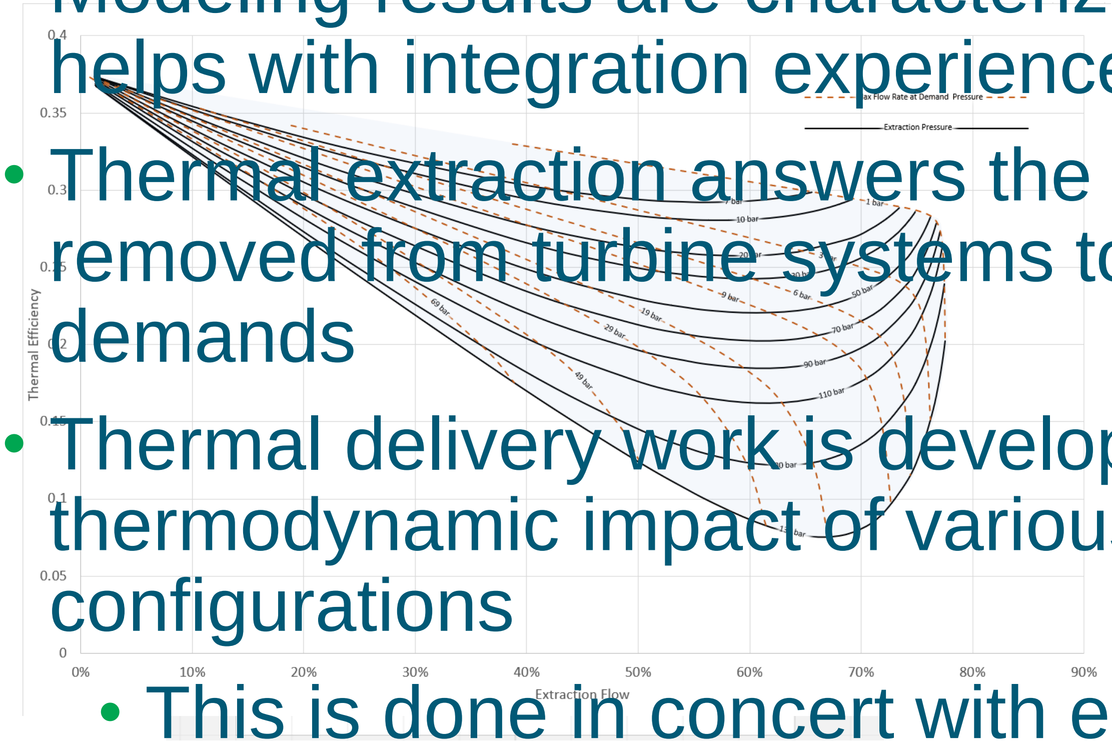
Experimental Demonstration

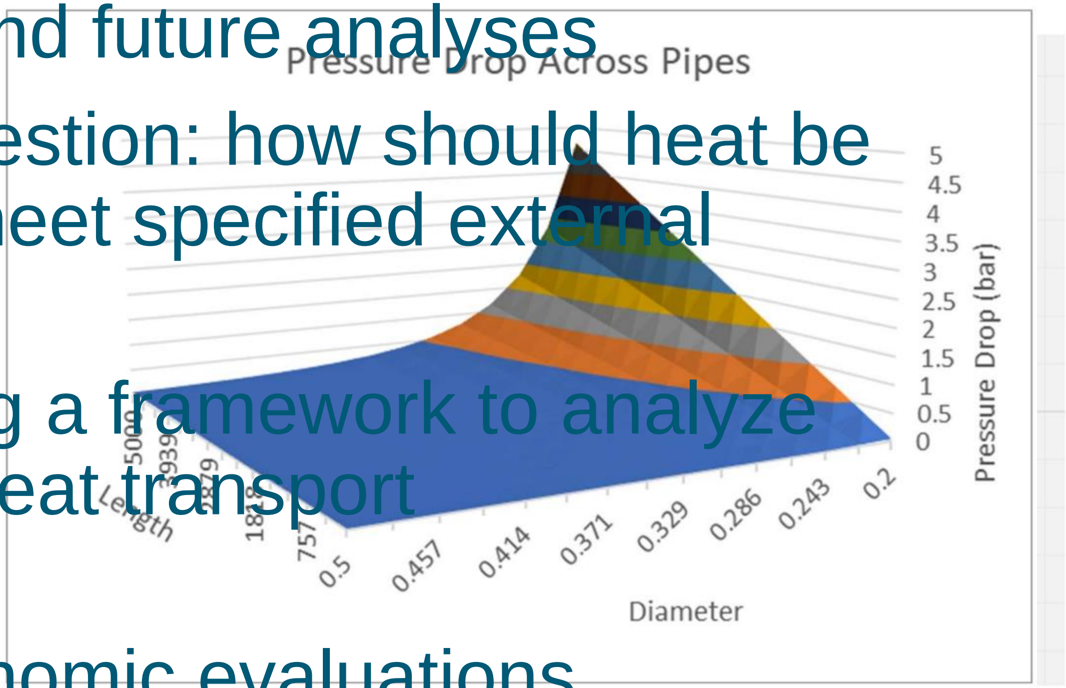
· Components selection for experimental demonstration (e.g., DETAIL)
· Validation of techno-economic model/analysis

IES Integrated Energy Systems

Thermal Extraction & Delivery Modeling

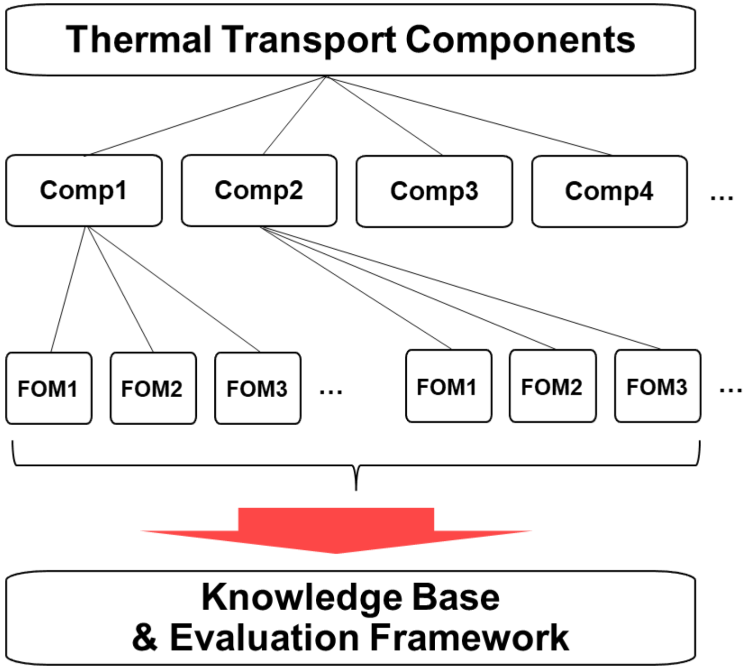
- Modeling results are characterized using dynamic modeling: helps with integration experience and future analyses
- Thermal extraction answers the question: how should heat be removed from turbine systems to meet specified external demands
- Thermal delivery work is developing a framework to analyze thermodynamic impact of various heat transport configurations
  - This is done in concert with economic evaluations





Thermal Systems R&D: Thermal Transport Components

- Identify and Evaluate Thermal Transport Components
  - ✓Establish a Knowledge Base and Evaluation Framework
    - To support the optimal selection of thermal transport components
    - FY23 goal: (i) identify major components & Figures-Of-Merits (FOMs),
      (ii) outline the evaluation strategy to support optimal selection



[Major Tasks to be Done]

Identify the list of major components
(e.g., working fluid, piping, insulation materials, etc.)

Identify Figures-Of-Merit (FOMs)

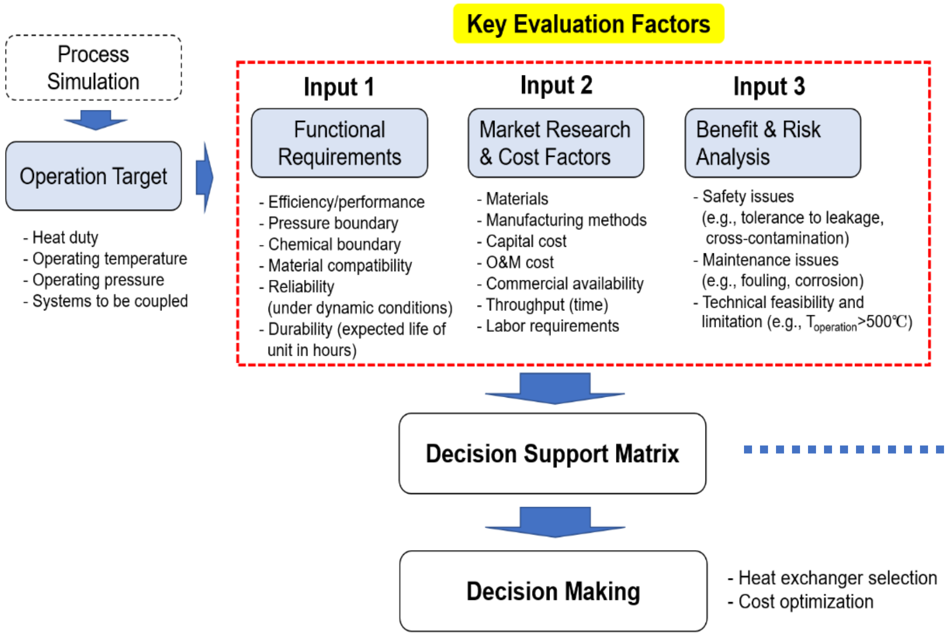
Evaluate FOMs & Database building

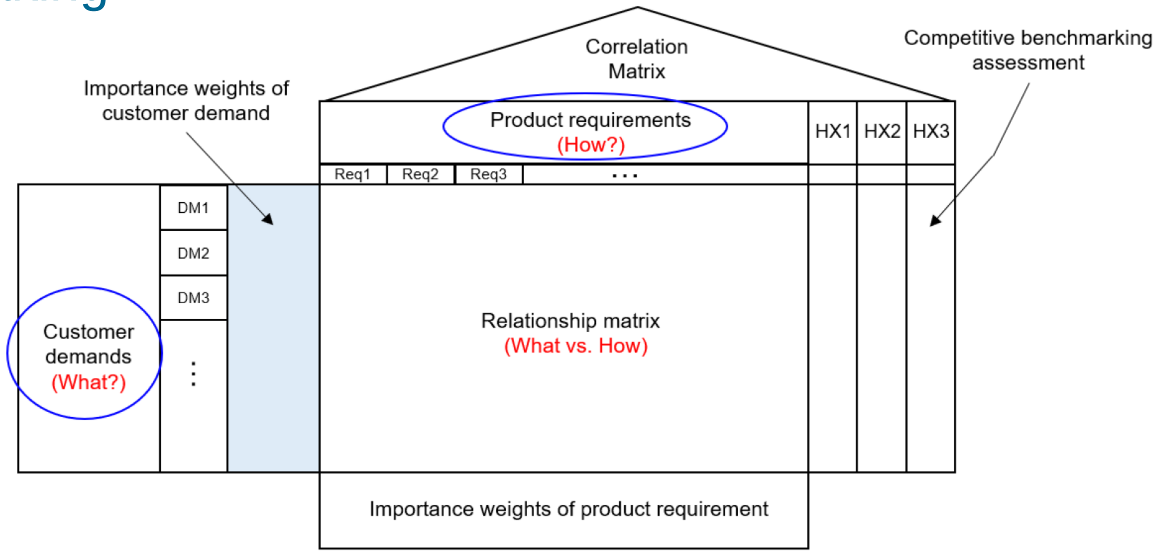
Build an evaluation framework to support optimal design of thermal transport

IES Integrated Energy Systems

Thermal Systems R&D: Heat Exchanger

- Heat Exchanger Evaluation & Optimal Selection
  - ✓Develop an evaluation methodology & framework to support evaluation, strategic selection, and optimization of heat exchangers for IES
    - Identify and/or develop evaluation metrics for IES application
    - Collect state-of-the-art market data (e.g., technical feasibility, cost)
    - Support "application-specific" decision-making





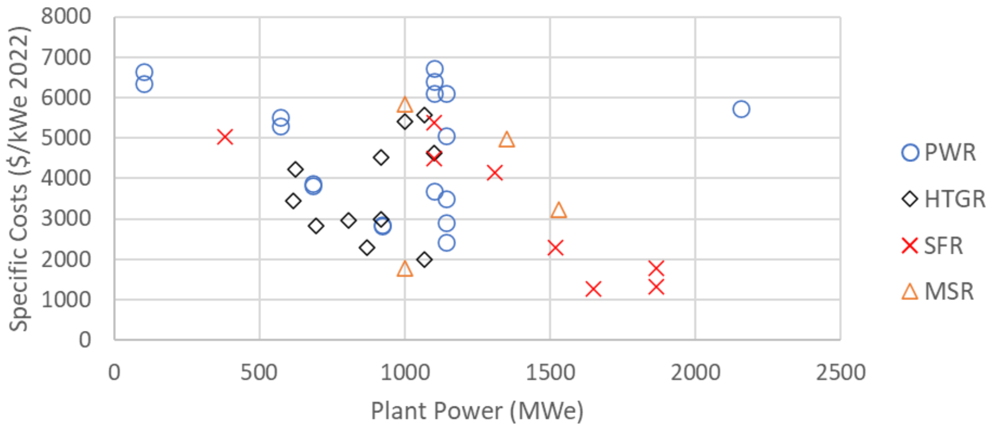
House-of-Quality (HOQ), a decision support matrix to compare the quality of different heat exchangers

Thermal Systems R&D: Heat Pumps

- Identify and Evaluate Heat Pump Technologies for IES
  - ✓ Build a knowledge base to evaluate heat pump technologies
    - Mechanical and chemical heat pumps
      - The current focus is on "high-temperature" application
      - Collaborating with University of Idaho for chemical heat pump systems
    - Literature survey (e.g., state-of-the-art, commercial technology status, operating requirements, thermal performance, technology gap (research needs), etc.)
    - Develop a methodology for fair comparison among different heat pump technologies
  - ✓ Heat Pump Models Development and Performance Study
    - Develop reference models (using ASPEN) for various heat pump cycles
      - For detailed assessment and comparison of technical performance (e.g., temperature lift, cycle efficiency)
    - Modeling studies on optimal design of heat pump cycles

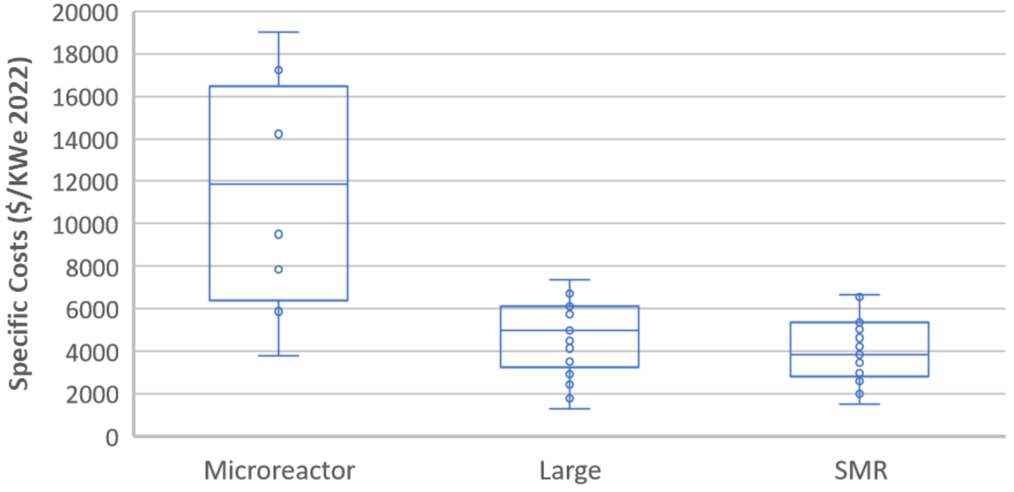
Integrated Energy Systems

- Conducted literature review of advanced reactor cost estimates (> 25 references)
- Meta-study provided recommendations for overnight and annualized costs provided in tables below
- Note that these estimates for reactor Between first and n^{th} of a kind (BOAK)
- **Key findings:**
  - Significant overlap in literature among different reactor types
  - Significant overlap between projected costs for large vs. SMR
- **Ongoing work**: Subcontract setup for detailed bottom-up estimate for a sodium fast reactor



Recommended Values:

	Low	Med	High	Sd
Overnight Costs	$3,000 /kWe	$4,500 /kWe	$6,000 /kWe	$1,500 /kWe
O&M Costs	$15 /MWh	$25 /MWh	$35 /MWh	$17 /MWh
LCOE (estimated)	$45 /MWh	$70 /MWh	$95 /MWh	$57 /MWh



IES
Integrated Energy Systems

21

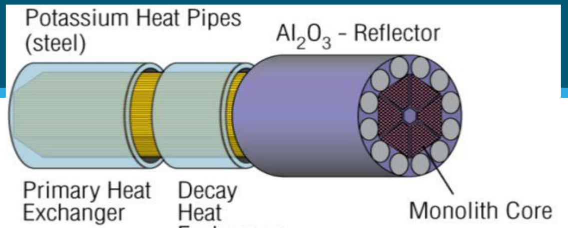
Note: Work funded by SA&I program

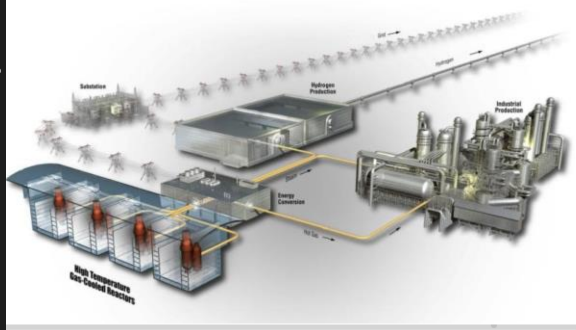
System Analysis & Integration

Example use cases:

- INL-ANL collaboration on development of the *Algorithm for Comprehensive Cost Estimation of Reactor Technologies* (ACCERT):
  - Goal is to obtain high-level initial cost estimates that are transparent and parametrizable
  - Models for: PWR12-BE, ABR-1000 (sodium) NGNP (gas), and Design A (micro)
- Leverage capability for bottom-up estimate for and proposed modifications to meet market targets (e.g., for microreactor below)

Microreactor Design A





NGNP HTGR Concept

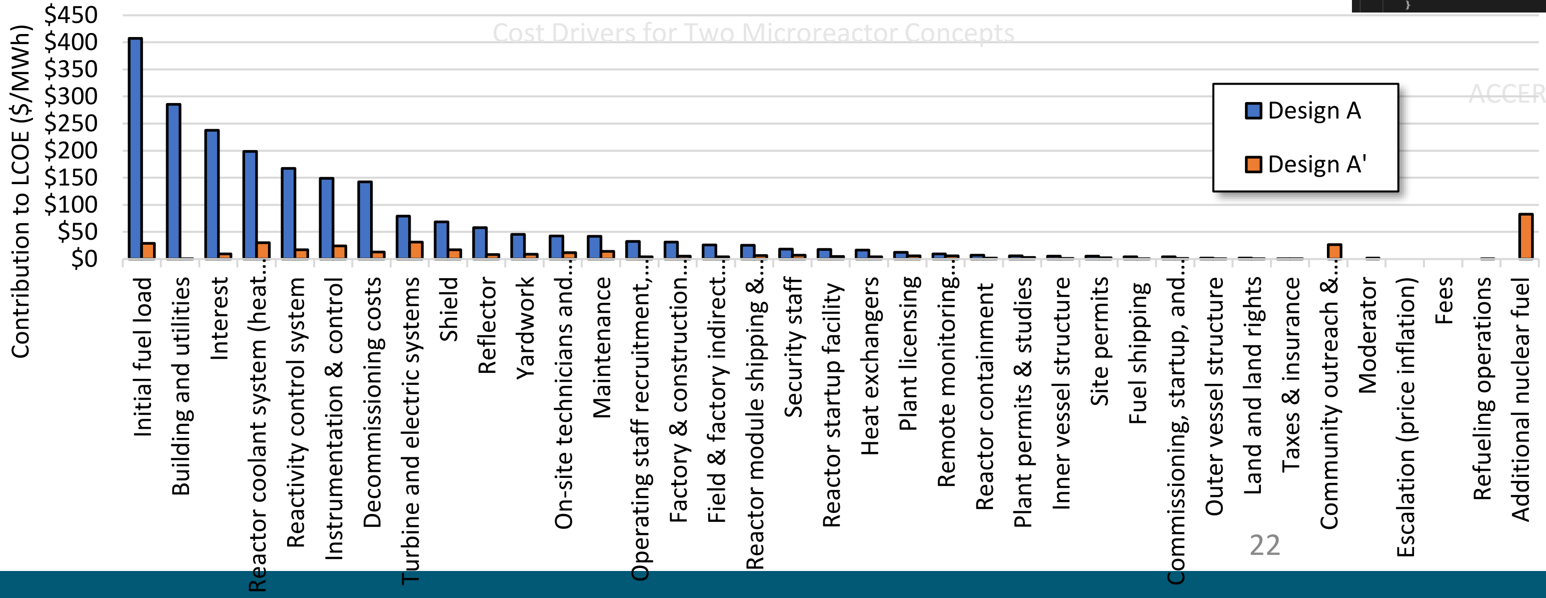
```
accert{
    ref_model = "PWR12-BE"
    % Define the required parameters
    % The required parameters are thermal power and electrical power.
    power(Thermal){ value = 3000   unit = MW }  % Reference value for PWR-12BE is 3431 MW
    power(Electric){ value = 1000   unit = MW } % Reference value for PWR-12BE is 1143 MW
    l0COA(2){
        l1COA(21){
            l2COA(211){
            % Inside COA 211, there several cost elements
                % The first cost element is the factory cost
                ce("211_fac"){
                    alg("esc_1987"){
                        var(ref_211_fac){ value = 0.27   unit = million }
                        var(ref_211_mat){ value = 10.3   unit = million }
                    }
                }
            }
            l2COA(213){
                ce("213_fac"){
                    alg("MWth_scale"){
                        % This cost element is calculated by an algorithm called 'MWth_scale'
                        % The variable c_213_fac is 1.79 million USD
                        var(c_213_fac){ value = 1.79   unit = million }
                    }
                }
            }
            l2COA(217){
                % Instead of using the cost element '213_fac',
                % we can use the total cost as well.
                total_cost{value = 28149700 unit = dollar}
            }
        }
        l1COA(22){
            l2COA("220A"){
                l3COA("221.12"){
                    ce("221.12_fac"){
                        alg("unit_weights"){
                            var("c_221.12_cs_weight"){value = 538 unit = ton}
                            var("c_221.12_ss_weight"){value = 40340 unit = lbs}
                        }
                    }
                }
            }
        }
```

ACCERT Input

Search | Edit: | Export/Import:

		…iption	total_cost	unit	level	main_subaccou…	supaccount	cost_elements
1	211	Yardwork	71213900	dollar	2	NULL	21	211_fac,211_lab,211_mat
2	212	Reactor containment building	182702257.3	dollar	2	NULL	21	212_fac,212_lab,212_mat
3	213	Turbine room and heater bay	65970400	dollar	2	NULL	21	213_fac,213_lab,213_mat
4	214	Security building	3880760	dollar	2	NULL	21	214_fac,214_lab,214_mat
5	215	Primary auxiliary building and tunnels	52634700	dollar	2	NULL	21	215_fac,215_lab,215_mat
6	216	Waste processing building	40938300	dollar	2	NULL	21	216_fac,216_lab,216_mat
7	217	Fuel storage building	28149600	dollar	2	NULL	21	217_fac,217_lab,217_mat
8	218A	Control Room/Diesel Generator Building	51570400	dollar	3	NULL	218	218A_fac,218A_lab,218A_mat
9	218B	Administration + Services Building	18938200	dollar	3	NULL	218	218B_fac,218B_lab,218B_mat
10	218D	Fire Pump House, Including Foundations	1216200	dollar	3	NULL	218	218D_fac,218D_lab,218D_mat
11	218E	Emergency Feed Pump Building	7119140	dollar	3	NULL	218	218E_fac,218E_lab,218E_mat
12	218F	Manway Tnls. (Radiological Ctrl Access…	2170960	dollar	3	NULL	218	218F_fac,218F_lab,218F_mat
13	218G	Elec. Tunnels	193104	dollar	3	NULL	218	218G_fac,218G_lab,218G_mat
14	218H	Non- Essen. Switchgear Bldg.	1526990	dollar	3	NULL	218	218H_fac,218H_lab,218H_mat
15	218J	Main Steam + Feedwater Pipe Enc.	22416800	dollar	3	NULL	218	218J_fac,218J_lab,218J_mat
16	218K	Pipe Tunnels	904119	dollar	3	NULL	218	218K_fac,218K_lab,218K_mat
17	218L	Technical Support Center	2249450	dollar	3	NULL	218	218L_fac,218L_lab,218L_mat
18	218P	Containment Equipment Hatch Missile…	626665	dollar	3	NULL	218	218P_fac,218P_lab,218P_mat
19	218S	Waste Water Treatment	2186330	dollar	3	NULL	218	218S_fac,218S_lab,218S_mat
20	218T	Ultimate Heat Sink Structures	13097500	dollar	3	NULL	218	218T_fac,218T_lab,218T_mat
21	218V	Control Rm Emergency Air Intake Buildi…	253976	dollar	3	NULL	218	218V_fac,218V_lab,218V_mat
22	218	Other structures	124470000	dollar	2	218A, 218B, 218…	21	218_fac,218_lab,218_mat
23	21	Structures and improvements subtotal	569959917.3	dollar	1	211, 212, 213, 21…	2	21_fac,21_lab,21_mat
24	220A.211	Vessel Structure (NSSS)	70000000	dollar	3	NULL	220A	220A.211_fac,220A.211_lab,…
25	220A.2121	Lower Internals (NSSS)	31780000	dollar	3	NULL	220A	220A.2121_fac,220A.2121_la…
26	220A.2122	Upper Internals (NSSS)	31780000	dollar	3	NULL	220A	220A.2122_fac,220A.2122_la…
27	220A.2131	Control Rods (NSSS)	3100000	dollar	3	NULL	220A	220A.2131_fac,220A.2131_la…
28	220A.2132	Control Rod Drives (NSSS)	34900000	dollar	3	NULL	220A	220A.2132_fac,220A.2132_la…

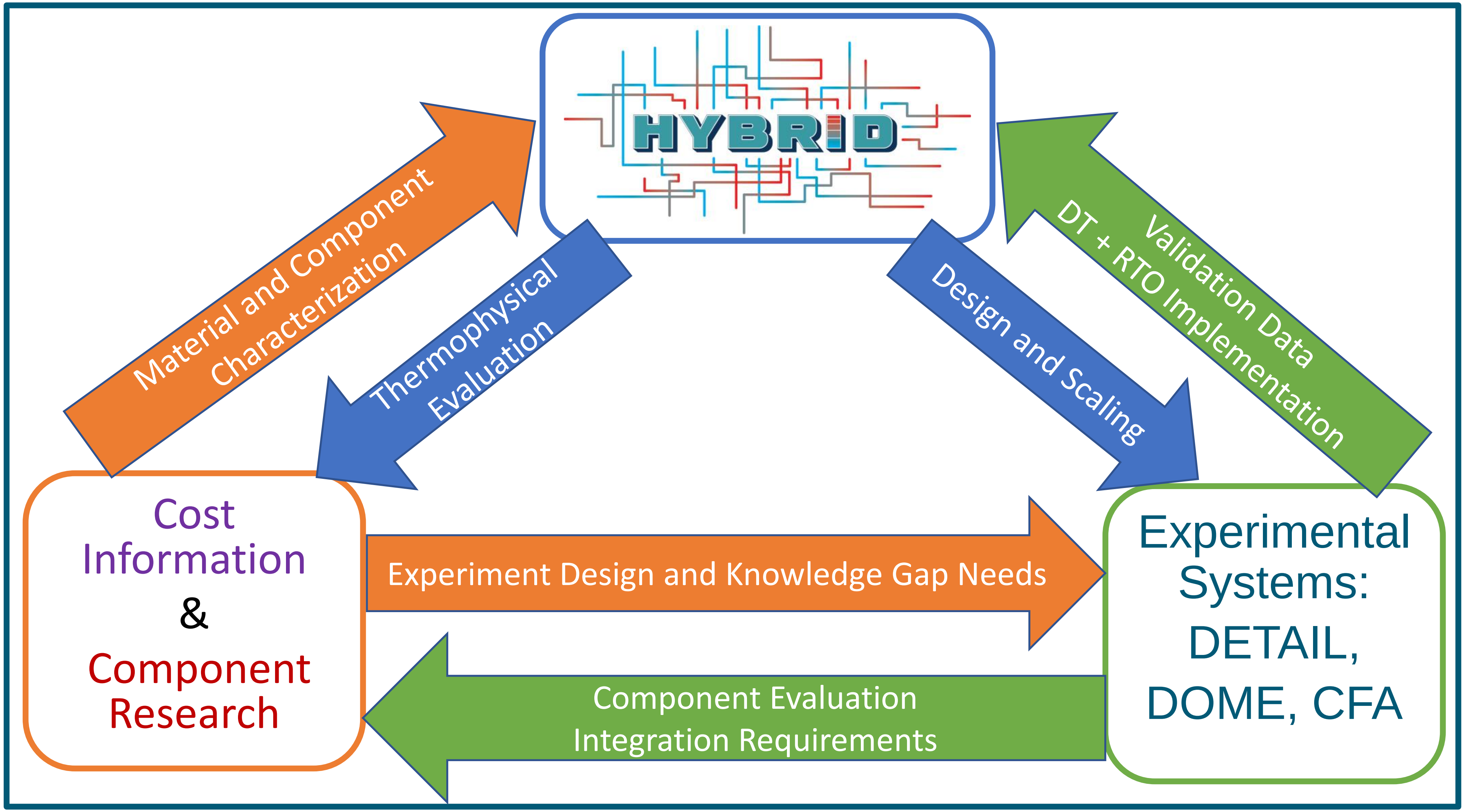
ACCERT Database



IES Integrated Energy Systems

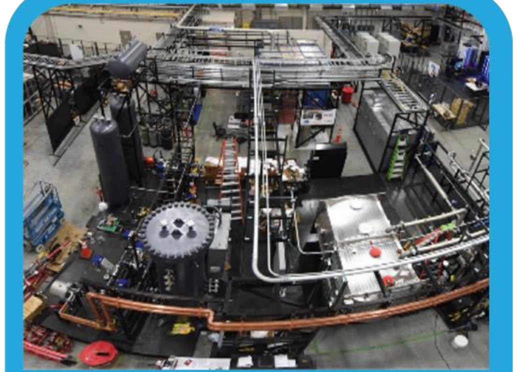
22

Lab-Scale IES Analysis Capability

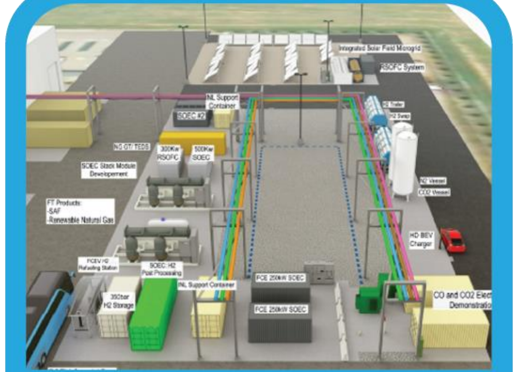


IES
Integrated Energy Systems

Scale-up and implementation of nuclear-integrated clean energy systems, initial focus on high temperature electrolysis (HTE)



25 kW High
Temp Electrolysis Stacks V&V



100-500kWe
Modular High
Temp Electrolysis Pilot Plant
Demonstration

Coupled with TEDS to make the DETAIL facility

"THE GAP"

Filled by-
INL Energy Technology Proving Center (ETPC)
(Technology Readiness Level 6-7)

Decrease risk for H2 HUB projects (50-100 MW);
Accelerate hitting the H2 EARTH SHOT Goal;
Accelerate Hybrid, Nuclear/ Renewable – HTE Systems Deployment
Implement the INL "Net Zero in 10 Years Plan"

2-10 MWe Modular HTE Units

- Integrated proof of operation system
- Hydrogen supply for user technology demonstrations
- Accelerates high temperature H_2 production pathway to commercialization

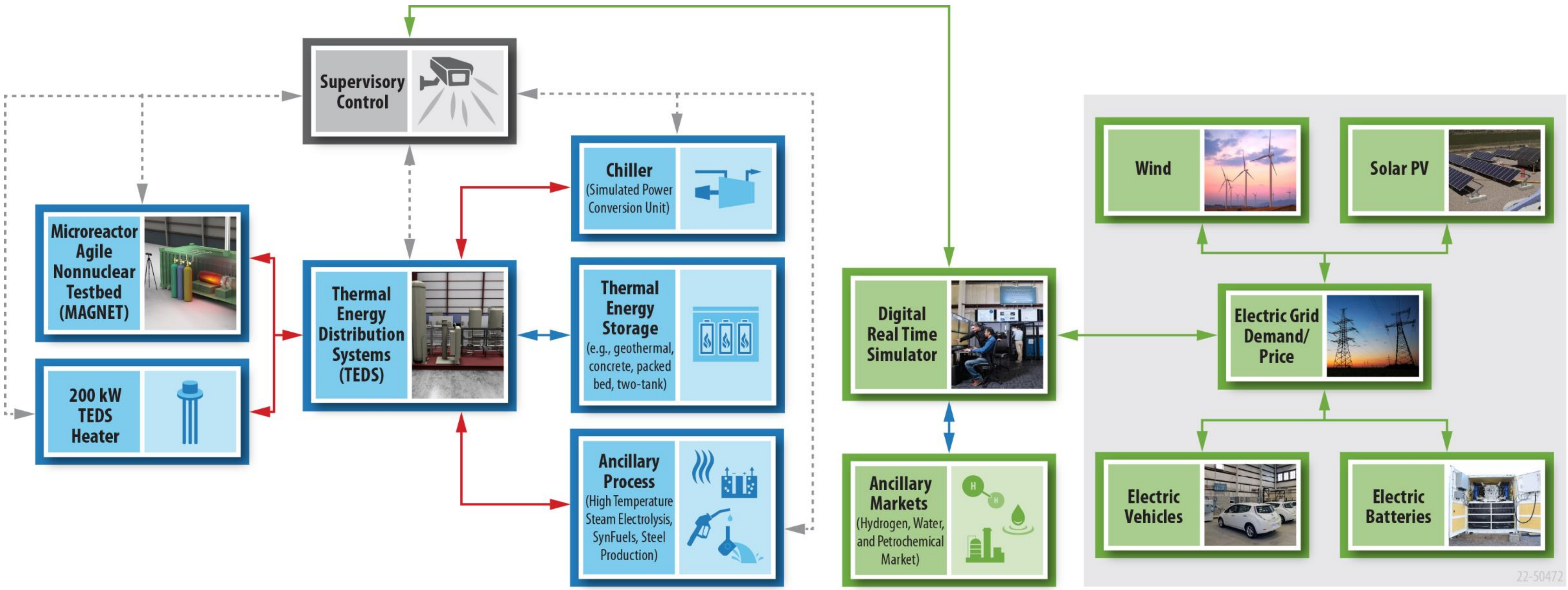
Wide Commercial Deployment

- Hydrogen production at nuclear power plants
- Industry-embedded hydrogen production and use

IES
Integrated Energy Systems

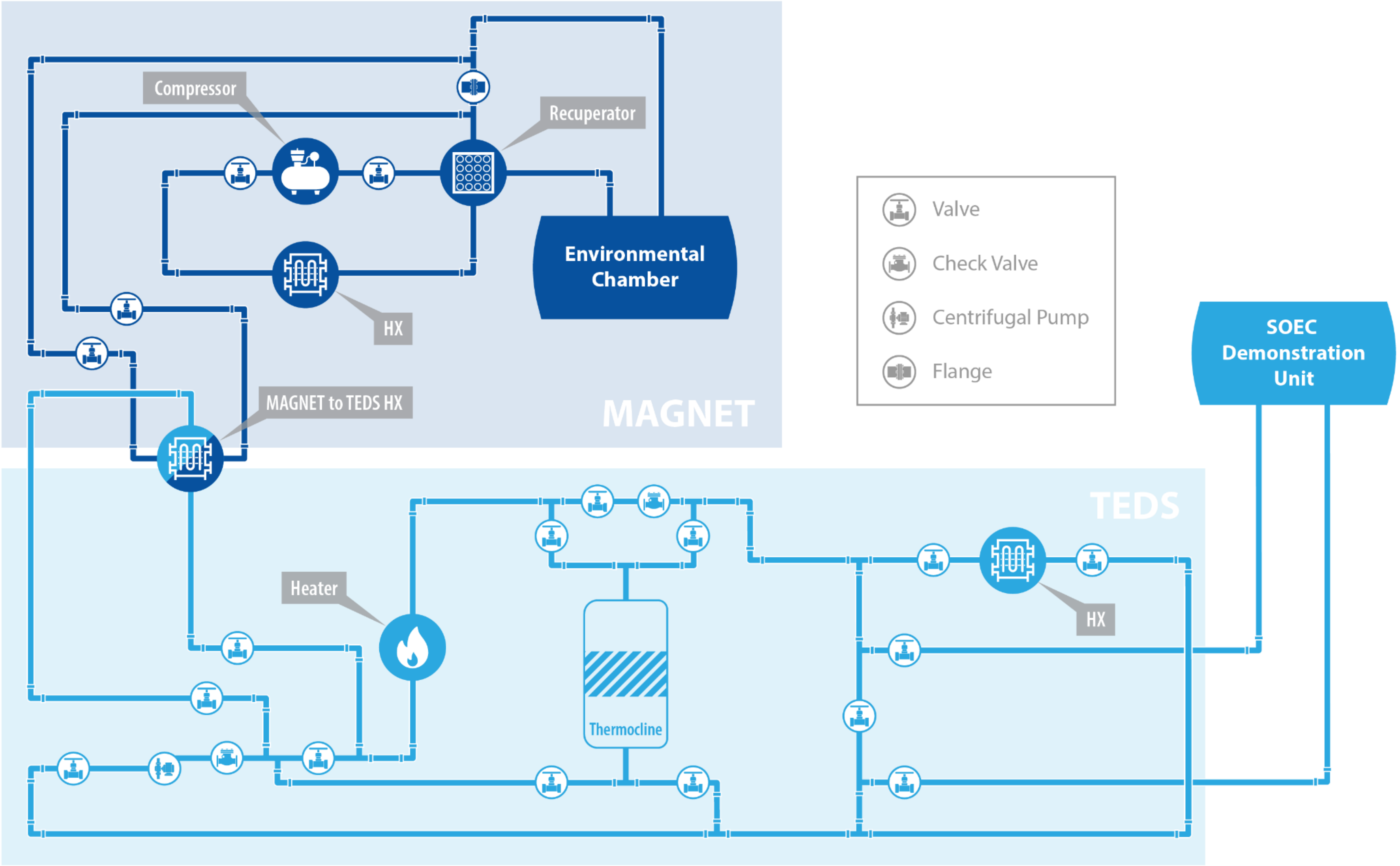
24

Dynamic Energy Transport and Integration Laboratory



IES Integrated Energy Systems

DETAIL Flow Diagram



IES Integrated Energy Systems

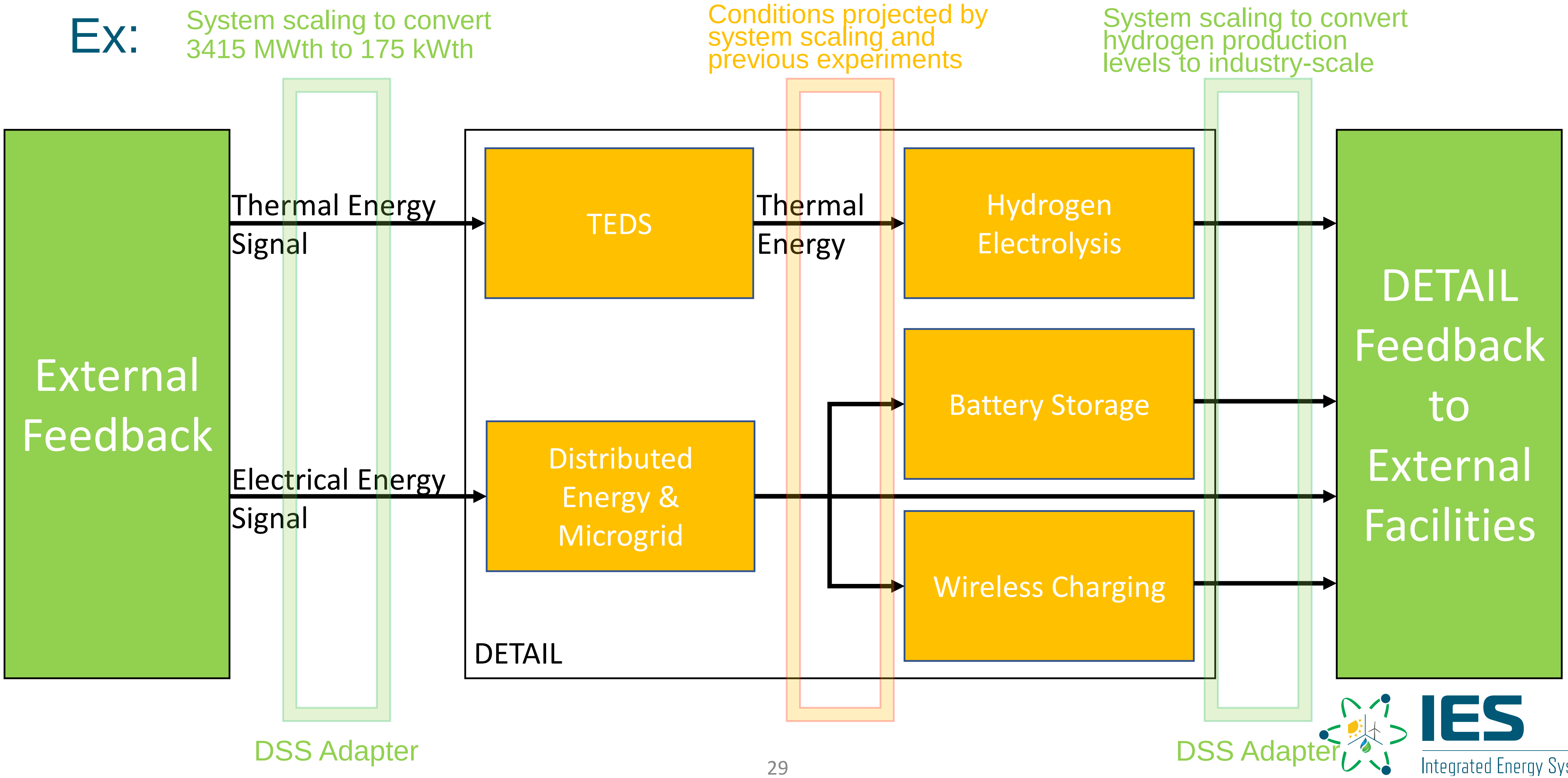
Thermal Energy Distribution System (TEDS)

- Demonstrate thermal energy distribution components: valves, flanges, gaskets, etc.
- Examine performance and operation of thermal energy storage in an integrated system
- Develop and test instrumentation and control strategies/systems for thermal energy distribution and storage
- Verification and validation data for computational models supporting scale up of integrated energy systems (e.g., Modelica, RELAP)
- Study packed bed thermal energy transport/transmission characteristics and performance
- Support cyber-informed engineering of controls and hardware

Therminol® Applicability to Industry

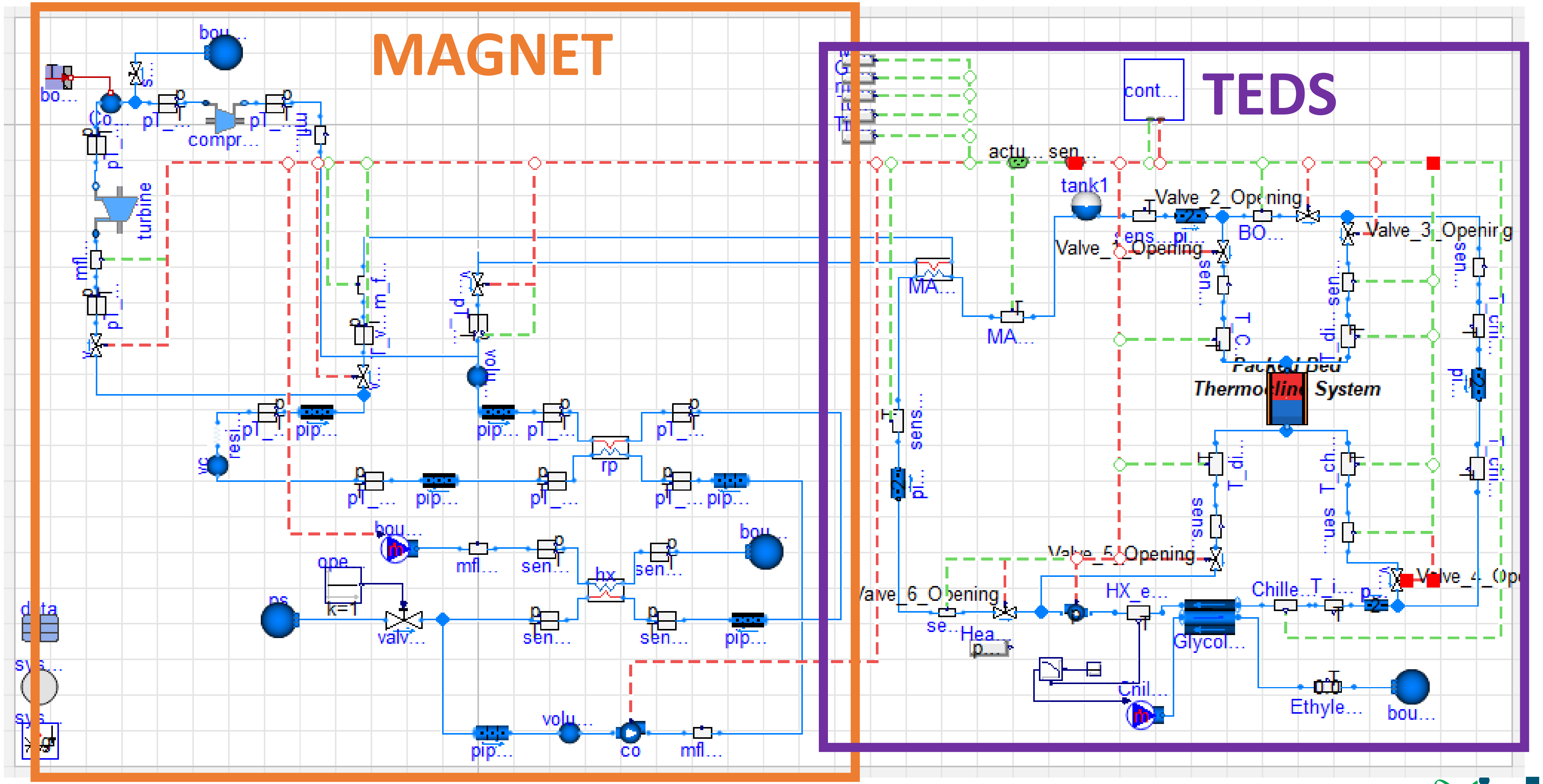
- Therminol®66 proposed as HTF for TES facility coupled with an APR1400
- Heat transfer oil used in ~62 of the 65 parabolic trough concentrated solar plants worldwide for both the working fluid and for TES
- Therminol®66 has an operating temperature range in line with PWRs with a boiling point higher than target temperatures
- Westinghouse has contracts/MOU in place for multiple TES systems of > 1GWh using Duratherm HF (a heat transfer oil with properties comparable to those of Therminol®66)

System-to-System Signal Feedback Conversion



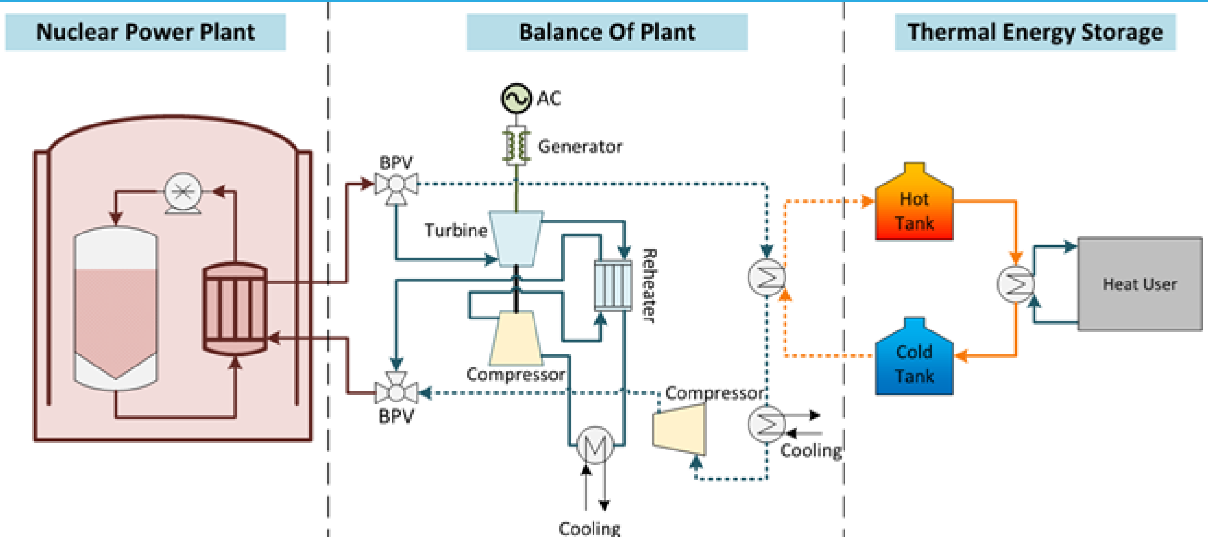
IES Integrated Energy Systems

DETAIL Model for V&V



IES
Integrated Energy Systems

Advanced Reactor Integrated Energy System (AR-IES)



Overall objectives:

- In collaboration with National Reactor Innovation Center (NRIC), design and construct an advanced reactor integrated energy system (AR-IES) demonstration
- Incorporate a TES study/facility to enable understanding and coupling with various thermal loads/users

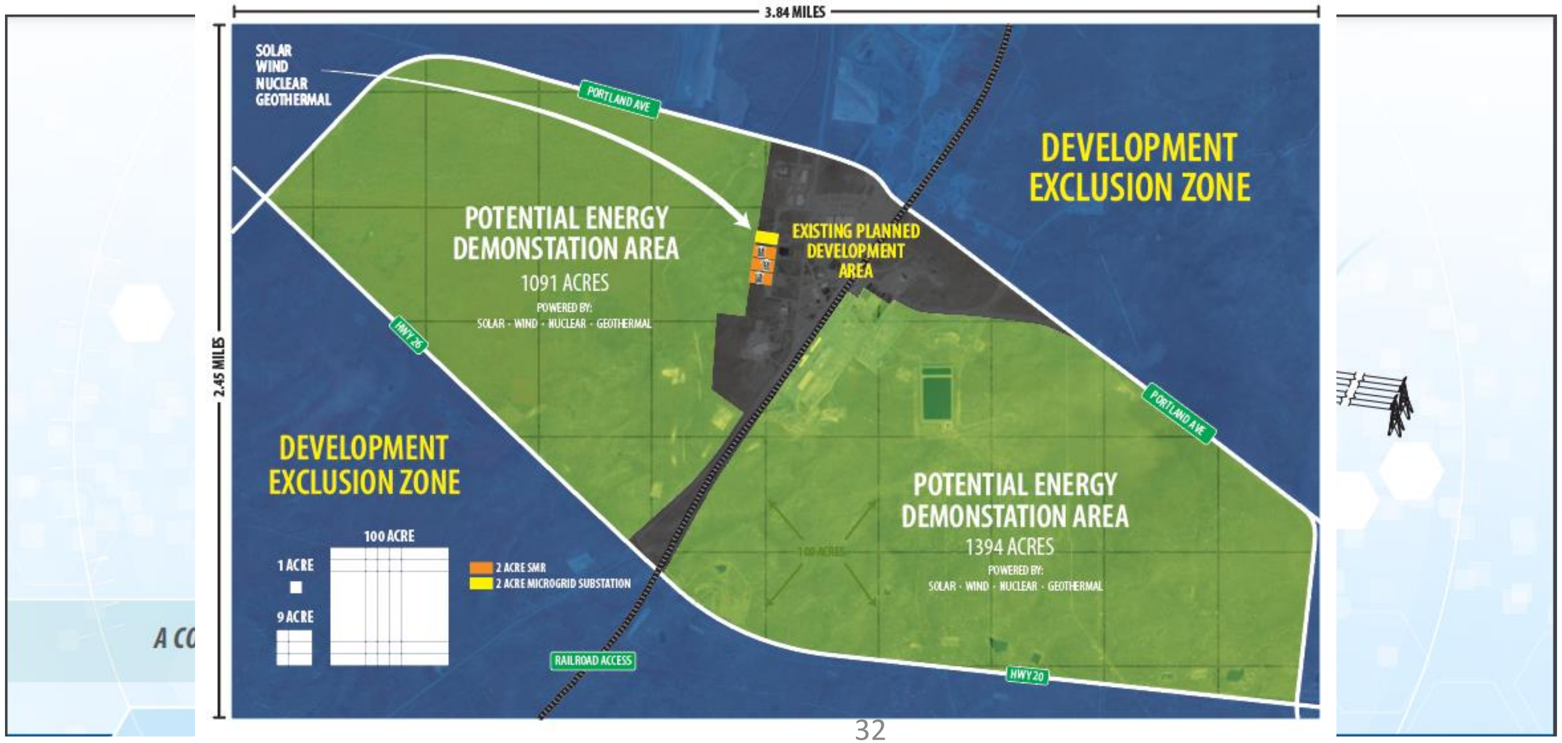
Background:

- Location: EBR-II Dome Testbed
- Demonstration platform to couple the thermal output from an advanced reactor to a controllable load and TES system.

IES Integrated Energy Systems

Net-Zero IES at CFA

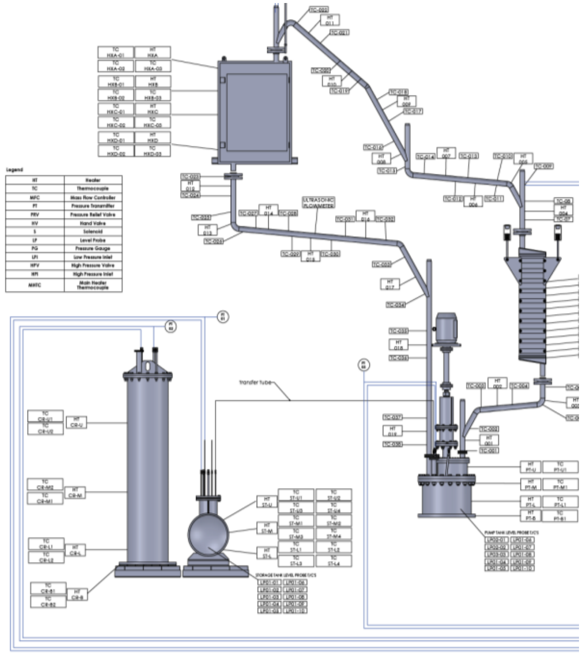
- IES program involved with Net-Zero planning
- System size plan 15MWe
- Installation by 2031
- Supports thermal islands for integration and distribution of heat to multiple users, with TES and conditioning



IES Integrated Energy Systems

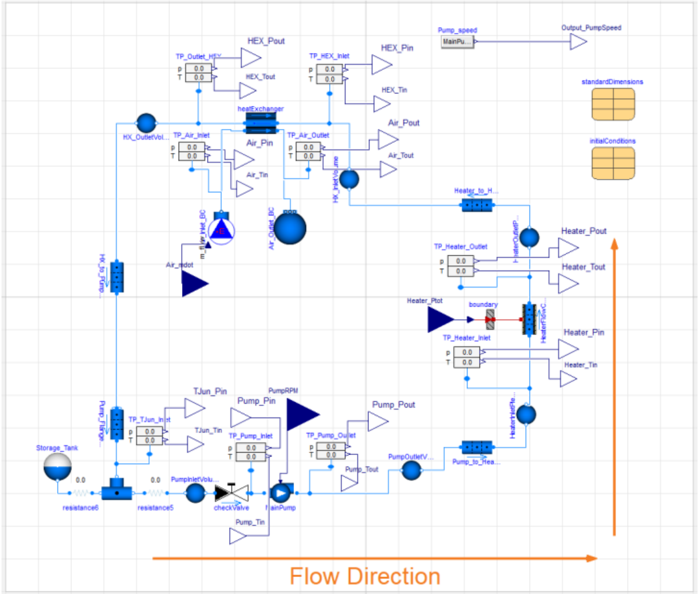
Overall Goal: Modeling Workflow

Physical Loop generating experimental data



System-level Representation

- Dymola IDE
- 1-D representation of components
- Avg. compute time on the order of seconds.
- Validation of the model currently underway with initial set of experimental data.

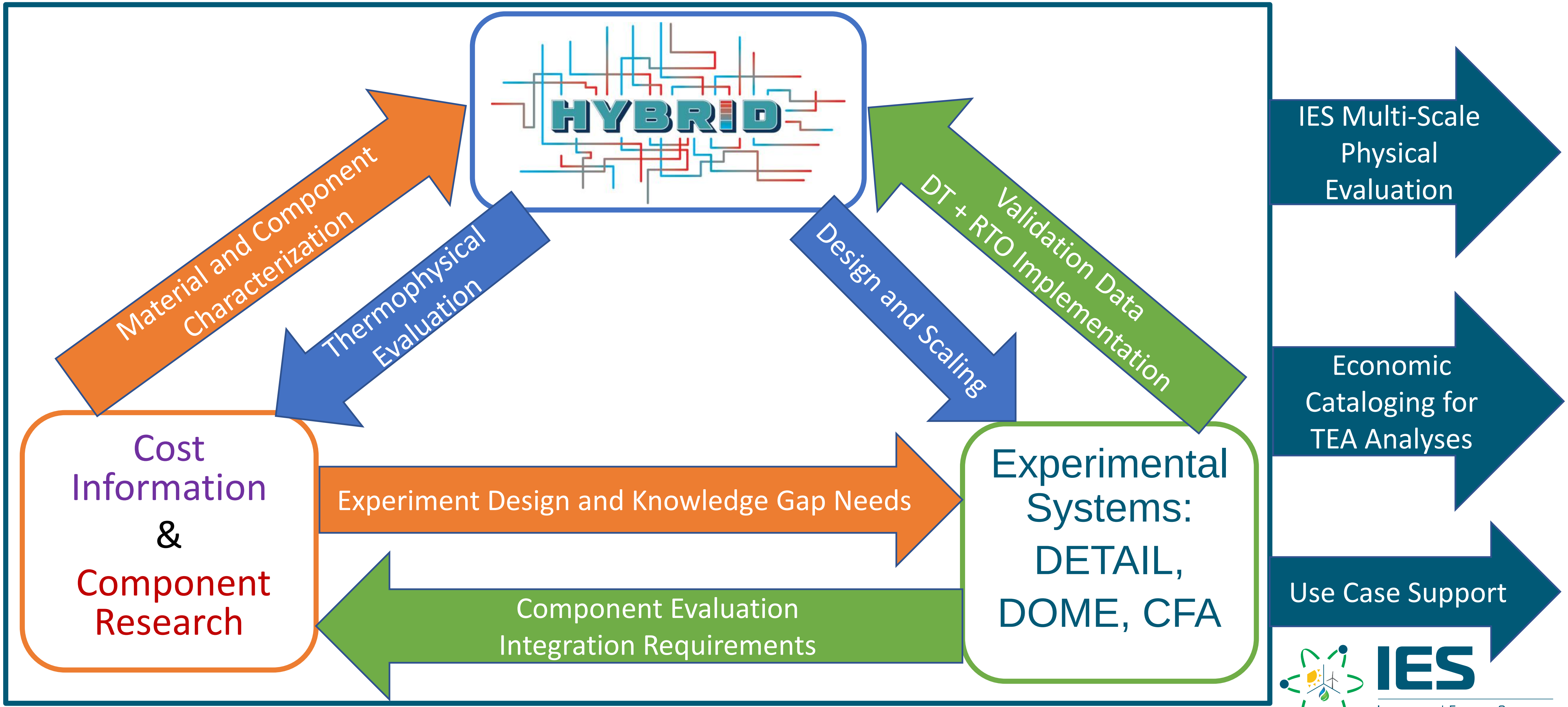


Digital Twin (DT) for semi-autonomous control

- DT of the Modelica model/ROM (using pyDMD) for faster runtime and calibrated to experimental data – currently underway.
- Currently setup to only read the tags from the LogixDriver and run an FMU/ROM of the Dymola Model.
- A future work scope would include informing the operator on potential deviation from normal operation – **lower maintenance and operational costs.**

Studio 5000 Logix designer via Pycomm3

Lab-Scale IES Analysis Capability



IES Integrated Energy Systems

TES Use Case: Motivating Problem

Lead: Rami Saeed

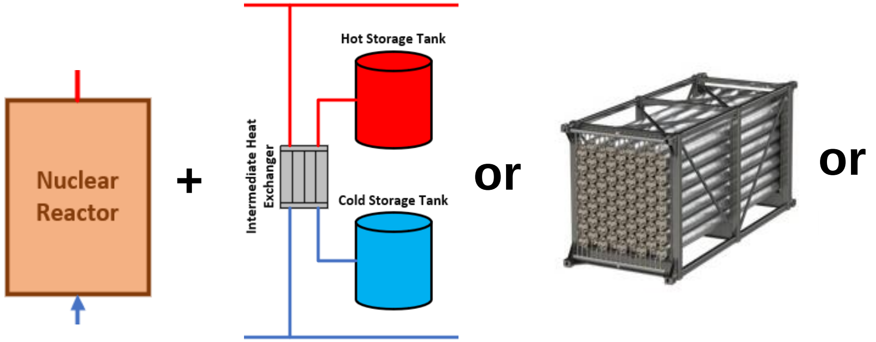
Advanced Reactor Company X: I want to add thermal energy storage. Which one makes the most sense? How do we choose? How does it work?

Why Thermal Energy Storage (TES) Coupling?

- TES enables NPPs to respond nimbly to market variability and to participate in restructured markets.
- TES systems store nuclear energy in its original form (heat), enabling a more flexible use on the back end, which provides electricity or heat.

Key Research Areas:

1. ***TES ranking*** tool that allows advanced reactor companies to down-select TES systems based on their system design.
2. ***Steady-state physical models development*** and design considerations of thermal storage coupling for three advanced nuclear reactor (A-LWR, HTGR, and LMFR), each coupled to TES in three different scenarios and different thermal extraction ratios.
3. ***System design cost analysis and stochastic optimization*** of NPP-TES based on market price signals in a selected market.
4. ***Transient modeling and grid-wide economics*** of each design.



Two Tank Sensible Heat

Concrete

TES Systems

1. Liquid-based sensible heat storage:
   - Two-tank molten salt
   - Two-tank thermal oil
   - Thermocline molten salt
   - Thermocline thermal oil
   - Hot/Cold water
2. Underground (bore-holes and aquifers)
3. Thermochemical
4. Latent heat storage
5. Solid media
   - Firebrick
   - Concrete
   - Ceramics, graphite, and alloys
6. Steam accumulators.

IES Integrated Energy Systems

- * A-LWR: Advanced light water reactor; HTGR: High temperature gas cooled reactor; LMFR: Liquid metal fast cooled reactor

TES Use Case: Motivating Problem

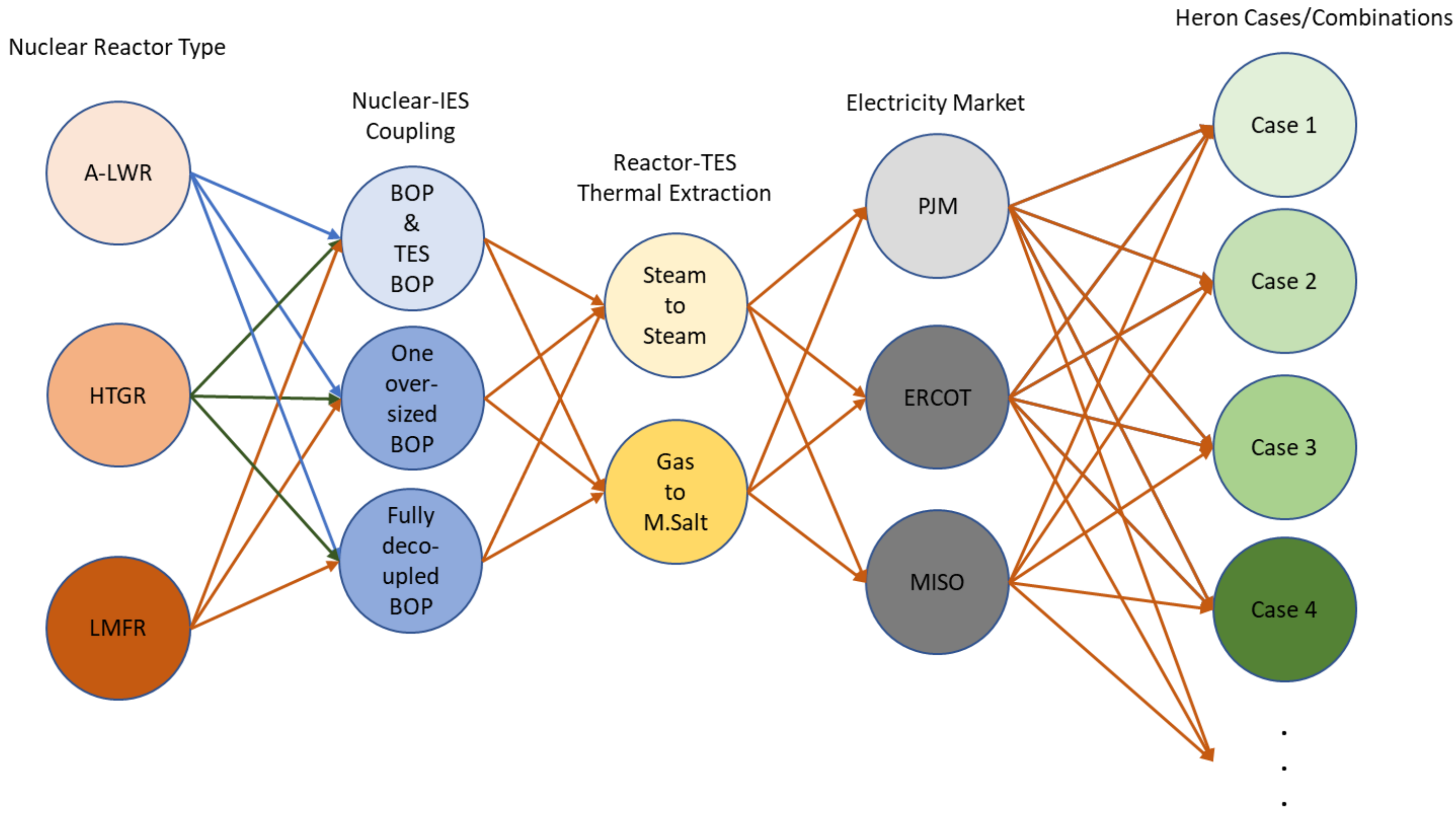
Advanced Reactor Company X: I want to add thermal energy storage. Which one makes the most sense? How do we choose? How does it work?

Why Thermal Energy Storage (TES) Coupling?

- TES enables NPPs to respond nimbly to market variability and to participate in restructured markets.
- TES systems store nuclear energy in its original form (heat), enabling a more flexible use on the back end, which provides electricity or heat.

Key Research Areas:

1. ***TES ranking*** tool that allows advanced reactor companies to down-select TES systems based on their system design.
2. ***Steady-state physical models development*** and design considerations of thermal storage coupling for three advanced nuclear reactor (A-LWR, HTGR, and LMFR), each coupled to TES in three different scenarios and different thermal extraction ratios.
3. ***System design cost analysis and stochastic optimization*** of NPP-TES based on market price signals in a selected market.
4. ***Transient modeling and grid-wide economics*** of each design.



- * A-LWR: Advanced light water reactor; HTGR: High temperature gas cooled reactor; LMFR: Liquid metal fast cooled reactor

** PJM: PJM Interconnection LLC (mid-Atlantic); ERCOT: Electric Reliability Council of Texas; Miso: Midwest Independent Transmission System Operator

IES Integrated Energy Systems

TES Use Case Methods and FORCE Tools

1. Steady-State and Physical Models Development

- Thermodynamic analysis of proposed systems
- What is the optimum Coupling approach?
- Develop fully-coupled TES-nuclear steady-state models
- Component-level analysis (heat exchange (HX) technology, geometries, sizes, etc.)
- Cost analysis and cost functions for discrete system sizes.

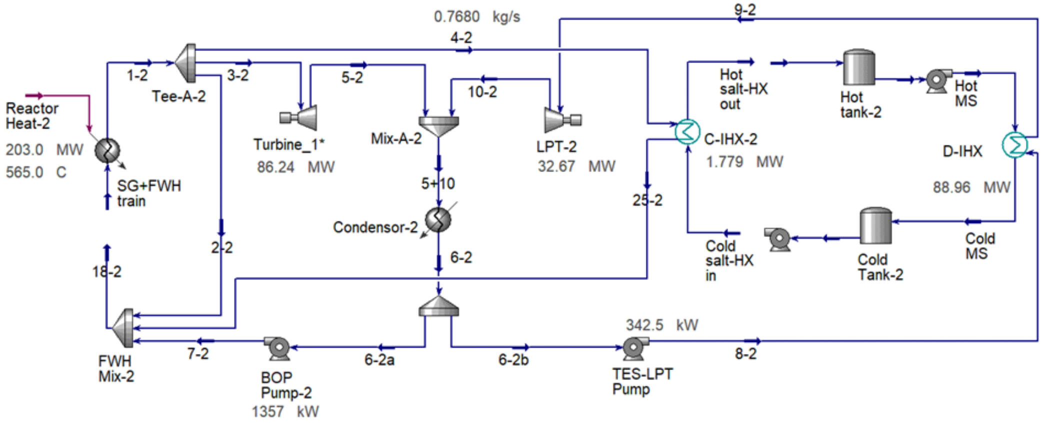
2. Stochastic Optimization Based on Market Price Signals

- Analyze and reproduce price signals from various markets
- What is the optimum system size for the highest net present value (NPV)?
- TES dispatch profiles of the IES system.

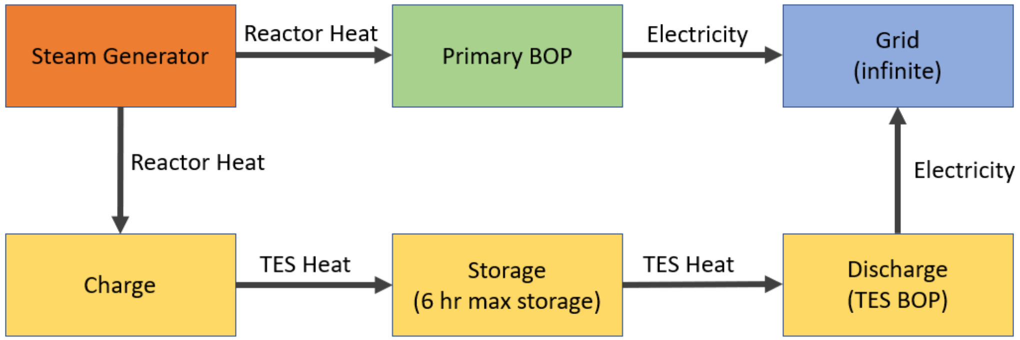
3. Transient Modeling and Dynamic Operation

- How do the dynamic behavior and system controls should look like?
- Is the dispatch profile with highest NPV feasible/reasonable dynamically?

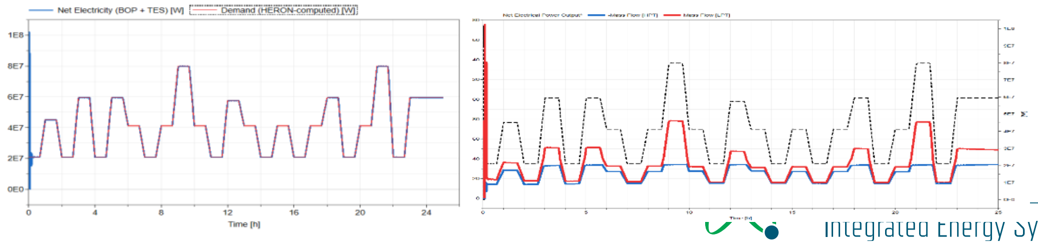
TES-Coupling in Aspen HYSYS (Steady-State Models)



HERON Optimization Workflow



Examples of Nuclear-TES Dynamic Modeling Results from Dymola

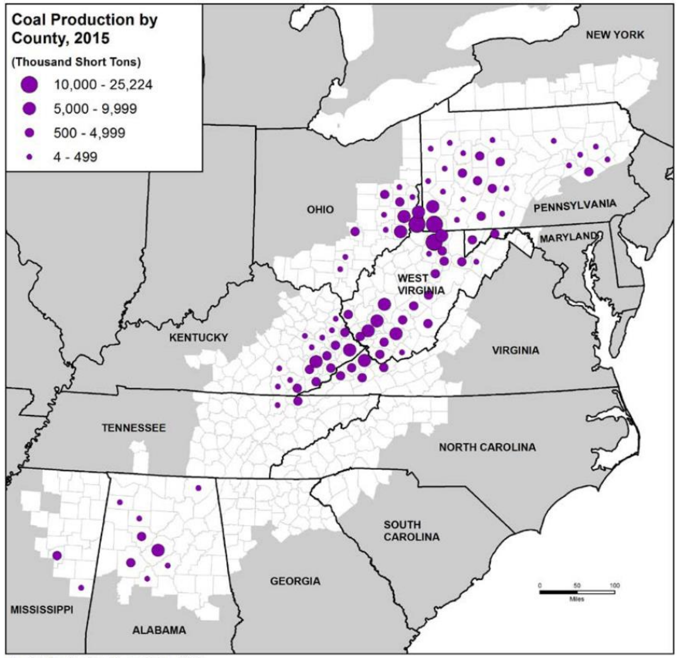


Integrated Energy Systems

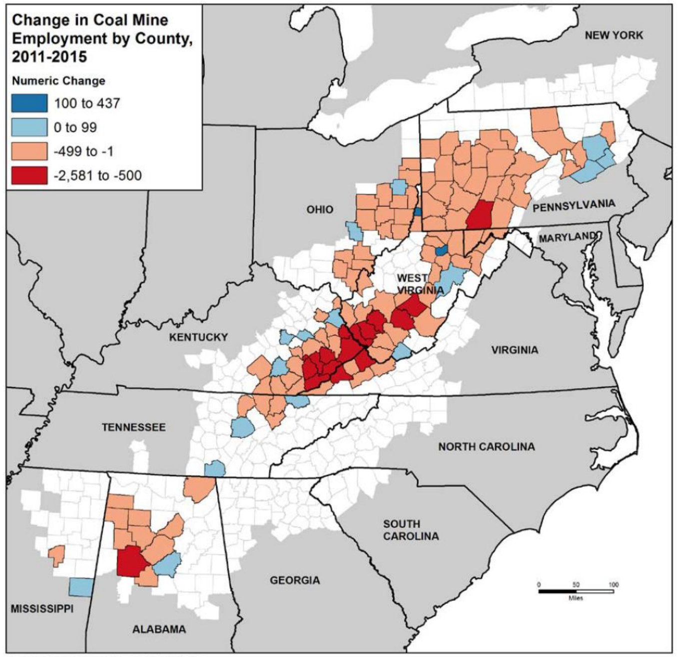
Carbon Conversion: Project Motivation

Lead: Elizabeth Worsham

- Limit the negative impact of decarbonization goals on local economies
- Focus on the coal industry in the Appalachian region of the United States
- From 2004 to 2014, coal production in Appalachia decreased by 45%, compared to 21% nationally



Appalachian Regional Commission, 2016
Data source: U.S. Mine Safety and Health Administration

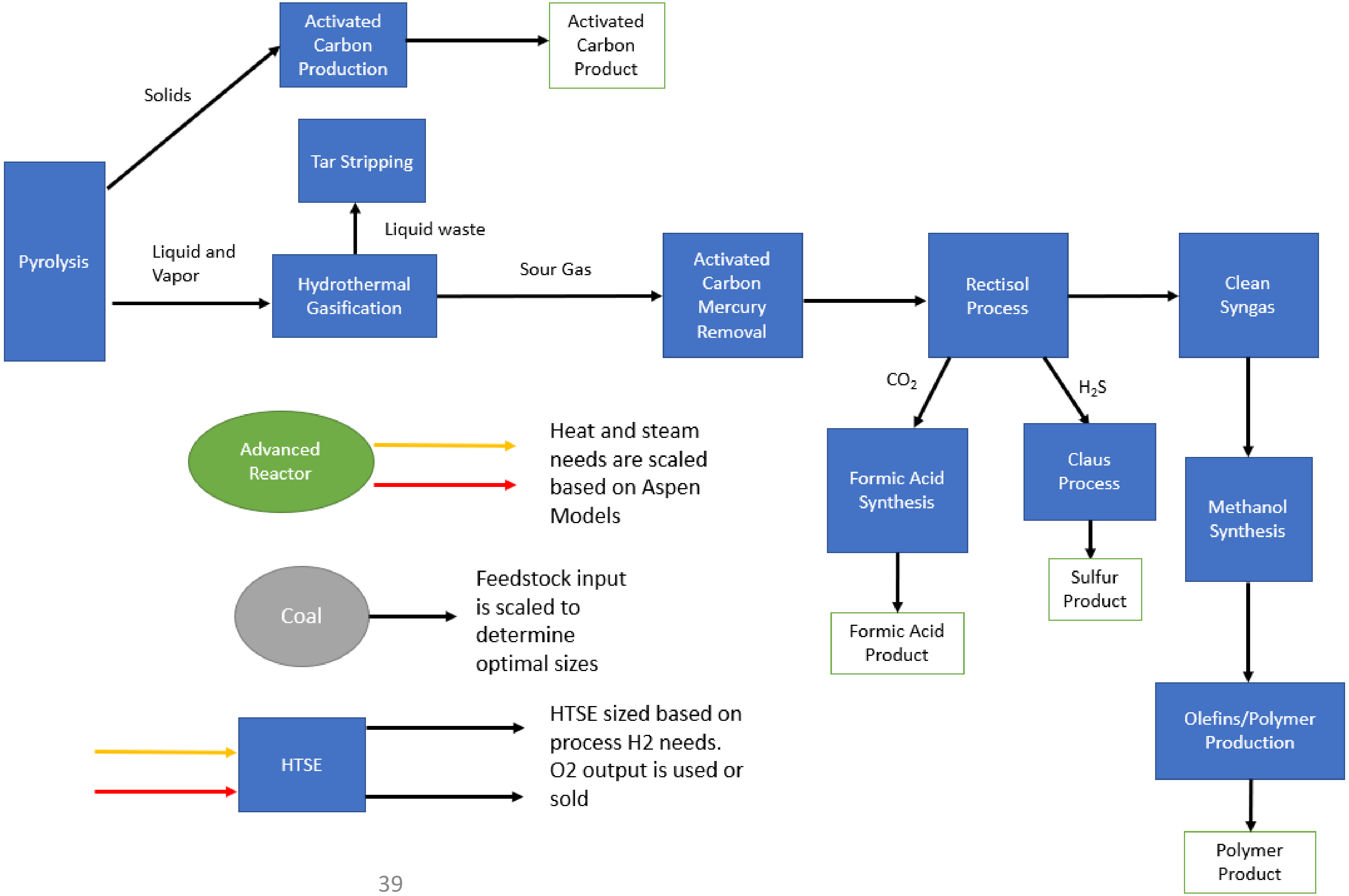


Appalachian Regional Commission, 2016
Data source: U.S. Mine Safety and Health Administration

IES Integrated Energy Systems

Carbon Conversion Refinery

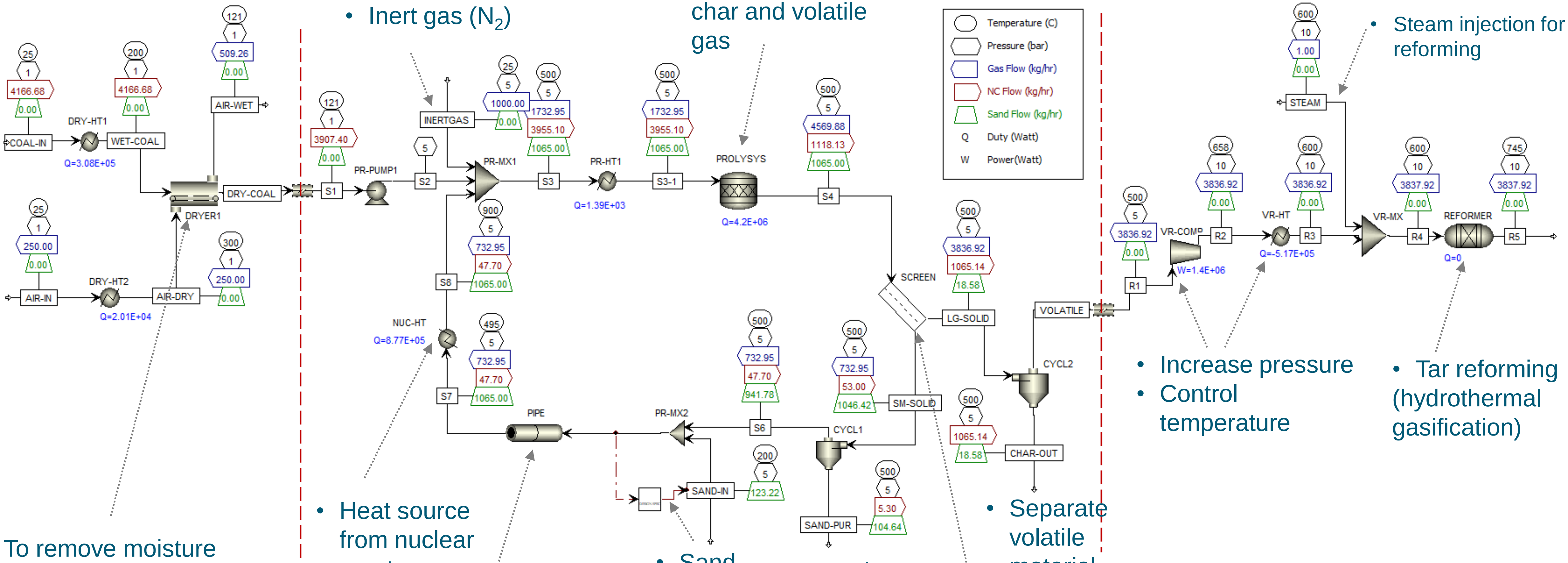
- Convert coal to valuable products via pyrolysis and gasification
- Reduce waste by utilizing products in other parts of the refinery
- Capture CO_2 and convert it to products as opposed to carbon sequestration
- Maximize revenue from various product streams
- Include High-Temperature Steam Electrolysis (HTSE) for hydrogen generation



Coal dryer

Pyrolysis and coal/sand circulation

Gas reforming



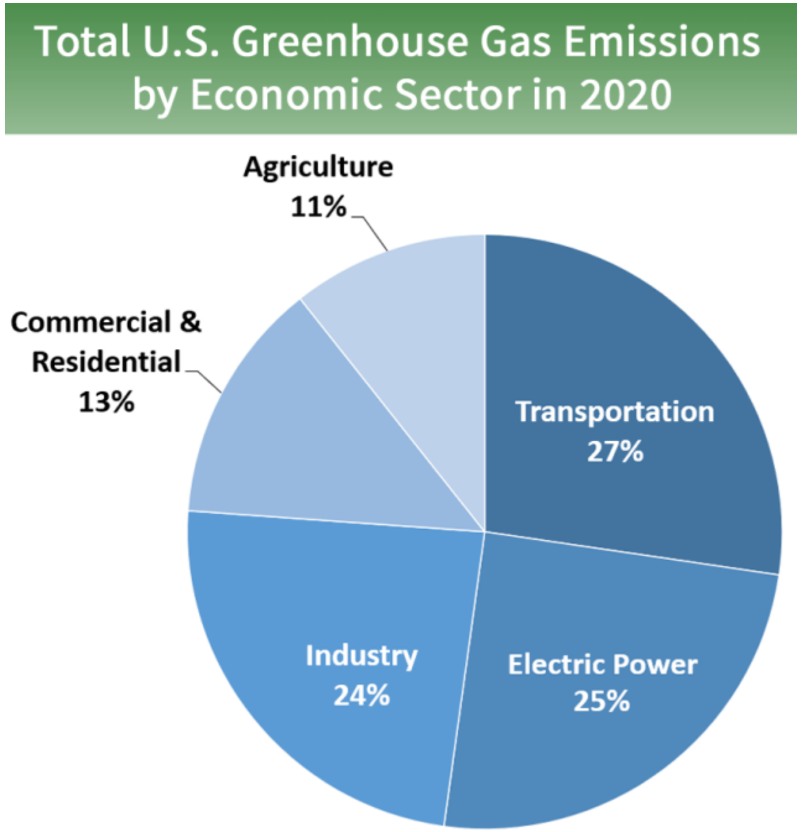
- Inert gas (N_2)
- Pyrolysis reactor converting coal to char and volatile gas
- Steam injection for reforming
- Increase pressure
- Control temperature
- Tar reforming (hydrothermal gasification)
- To remove moisture inside coal using hot air
- Heat source from nuclear reactor
- Sand makeup
- Sand purge
- Separate volatile material from char
- Calculate gas velocity required for particles (sand) to flow over
- Separate large solid particle (char) from small particles (sand)

Integrated Energy Systems

Synfuels: Motivation

Lead: Dan Wendt

- Transportation sector responsible for 27% of total U.S. greenhouse gas emissions
- Nuclear energy can be used to produce H_2 that could be combined with CO_2 to produce synthetic transportation fuels.
- Use of biogenic CO_2 sources could result in fuels with low life-cycle CO_2 emissions.
- Use of CO_2 derived from fossil-based sources could offset emissions associated with petroleum derived transportation fuels.

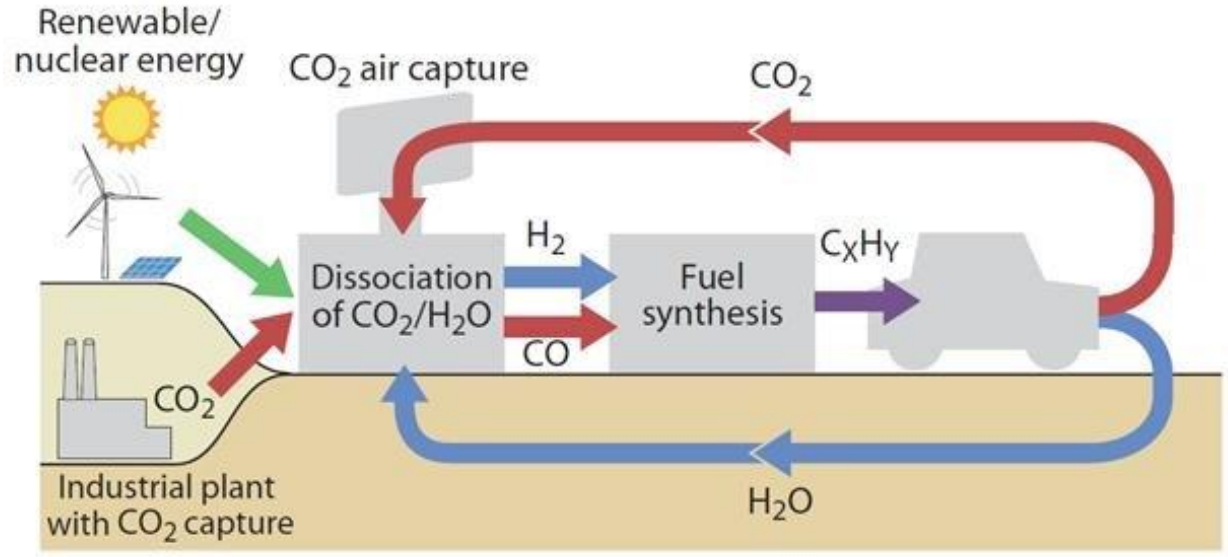


5,981 million tonnes total U.S. CO2 emissions in 2020
(EPA, 2022, Sources of Greenhouse Gas Emissions | US EPA)

Integrated Energy Systems

What are Nuclear Synfuels?

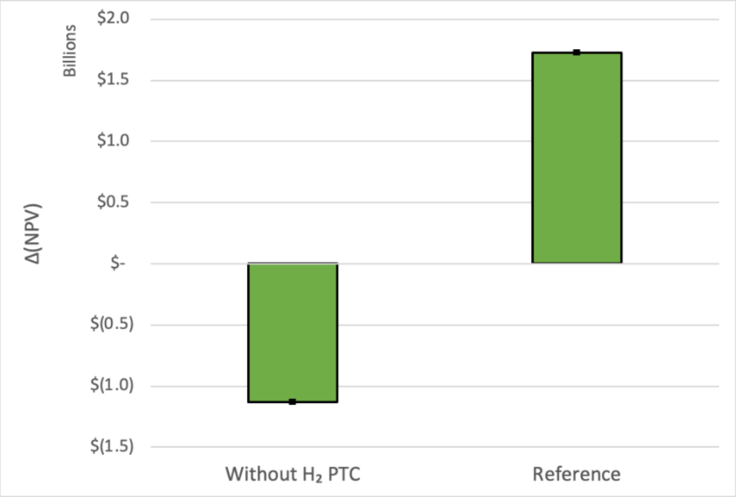
- Synthetic liquid hydrocarbon fuels, e.g., diesel fuel, jet fuel, gasoline
- Produced from carbon dioxide and hydrogen with energy input
- Nuclear energy used for hydrogen production (via electrolysis) and to power the synthetic fuel production plant

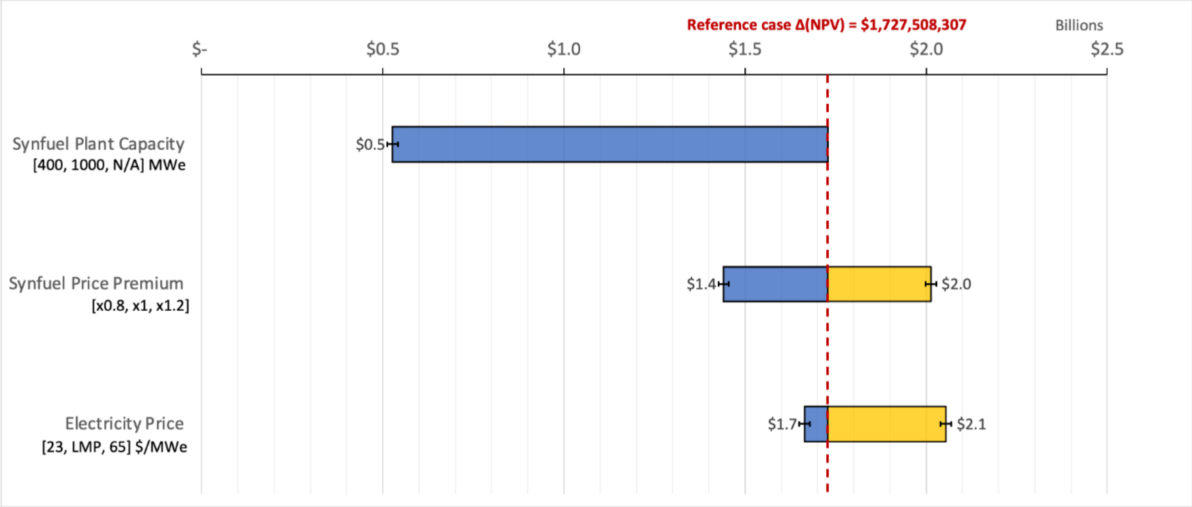


Source: Escobar (2015)
http://dx.doi.org/10.13140/RG.2.1.4250.7360

TEA of Nuclear Based Synfuel Production

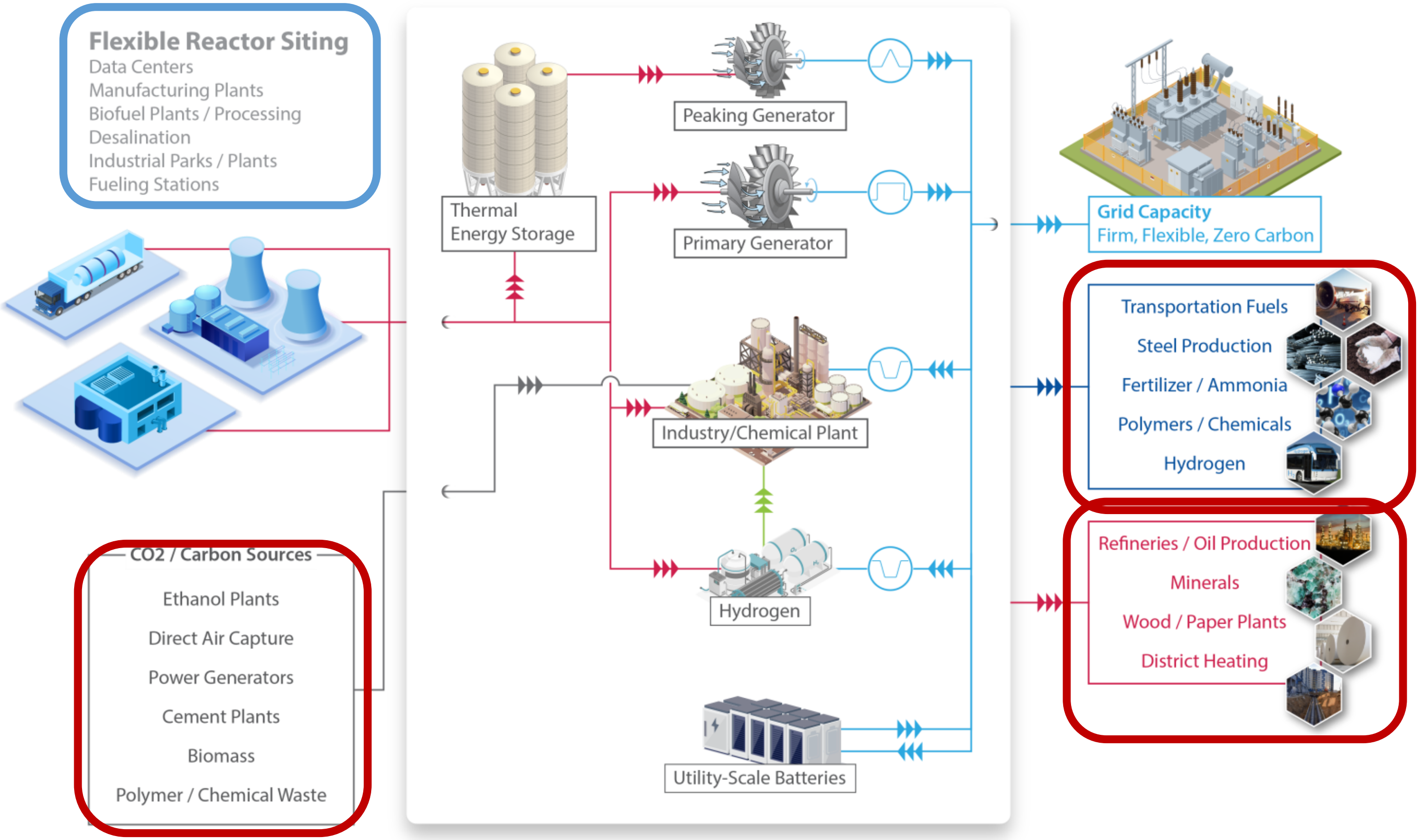
- The analysis predicts that a 1000 MW nuclear-powered synfuel plant could result in a NPV increase of approximately $1.7 billion when accounting for the additional revenues from the 2022 IRA clean hydrogen PTCs of $3/kg.
- Exclusion of the 2022 IRA clean hydrogen PTCs results in a negative NPV relative to the Business-As-Usual Case
- Sensitivity analysis indicates that:
  - Decreasing the synfuel production capacity decreases the NPV of the nuclear synfuel IES
  - A synfuel price premium increases the NPV
  - The Nuclear-Synfuel IES would have a greater NPV than the business-as-usual case when electricity market prices are low, suggesting that synfuel production could provide a strategy for decreasing the economic risks to NPPs posed by a loss of revenues attributed to falling electricity market prices.





Preliminary Results – Subject to Change

Industrial Requirements and Siting



- How will advanced reactors be sited?
  - ARs have smaller size, enhanced designs
  - Two-way impact considerations

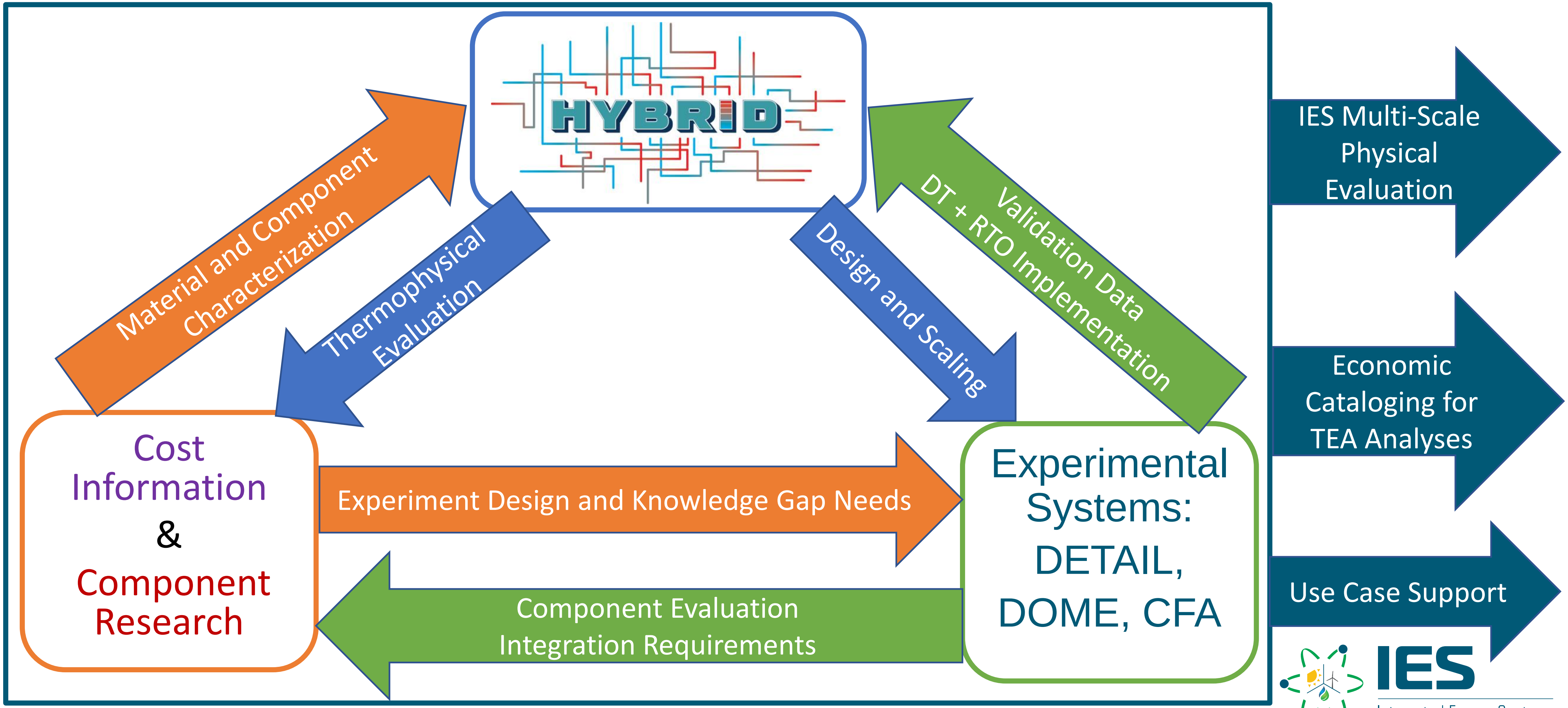
- Industrial facility characterization:
  - Reactants & Products
  - Reaction conditions
  - Energy flow configurations
    - HYBRID compatible
  - How can carbon emissions be offset?

- FY23:
  - Identifying five priority industries
  - Developing complete process documents

- FY24+ Use Cases

IES Integrated Energy Systems

Thermal Systems Capability



IES
Integrated Energy Systems