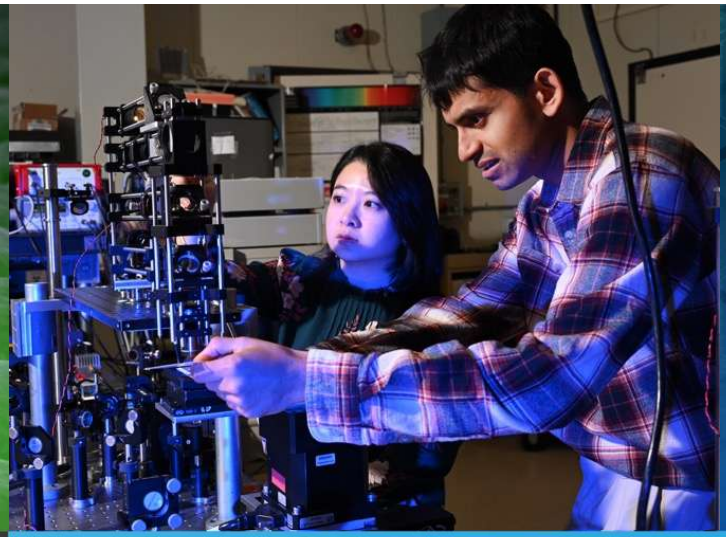






October 12-14, 2026

Daniel Mikkelson, PhD
Integrated Energy Modeling and Simulation Engineer
Daniel.Mikkelson@inl.gov

Nuclear System Modeling for Integrated Energy Systems Analyses

Idaho National Laboratory

INL/CON-26-96229

Accelerating advanced reactor demonstration and deployment

2026

IDAHO
- **Aalo-X Critical*** Aalo | *Experiment*
- **Kaleidos*** Radiant | *Test Reactor*
- **R1 Mark-0*** Antares | *Experiment*
- **Unity Nuclear Battery** Deployable Energy | *Experiment*
- **MARVEL** INL | *Test Reactor*

TEXAS
- **PWR-5*** Last Energy | *Test Reactor*
- **MSR-1*** Natura Resources | *Test Reactor*
- **Groves*** Atomic Alchemy | *Test Reactor*

KANSAS
- **Gravity*** Deep Fission | *Test Reactor*

UTAH
- **Ward 250*** Valar Atomics | *Test Reactor*

IDAHO
- **DOME** INL | *Test Bed*
- **NRAD** INL | *Test Bed*
- **RACE** INL | *Test Bed*
- **T-REXC** INL | *Test Bed*



2027

IDAHO
- **Aalo-X Full Power*** Aalo | *Micro*



- **R1 Mark-1*** Antares | *Test Reactor*



TEXAS
- **Tetra*** Terrestrial Energy | *Test Reactor*



TENN.
- **Hermes 1** Kairos | *Test Reactor*



2028

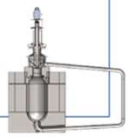
IDAHO
- **Project Pele** DoD & BWXT | *Micro*



- **Aurora*** Oklo | *SMR*



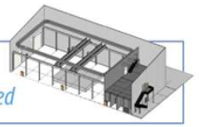
- **MCRE** Southern Company *Experiment*



TENN.
- **Hermes 2** Kairos | *SMR*



IDAHO
- **LOTUS** INL| *Test Bed*



2029

TEXAS
- **Xe-100** X-energy & Dow | *SMR*



2030

TEXAS
- **MSR-100** Natura Resources | *SMR*



MICHI.
- **SMR-300** Holtec | *SMR*



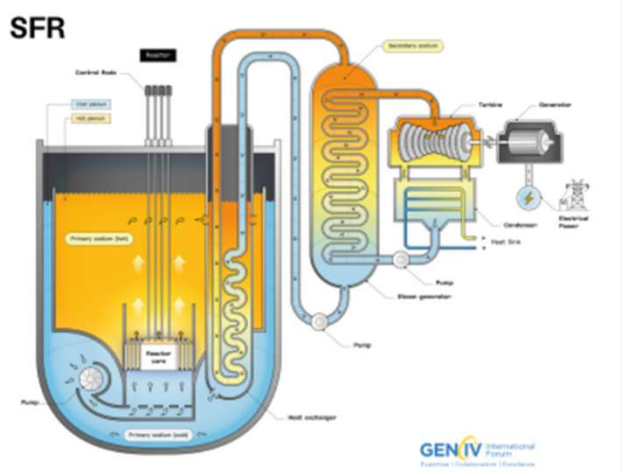
WYO.
- **Natrium** TerraPower | *SMR*

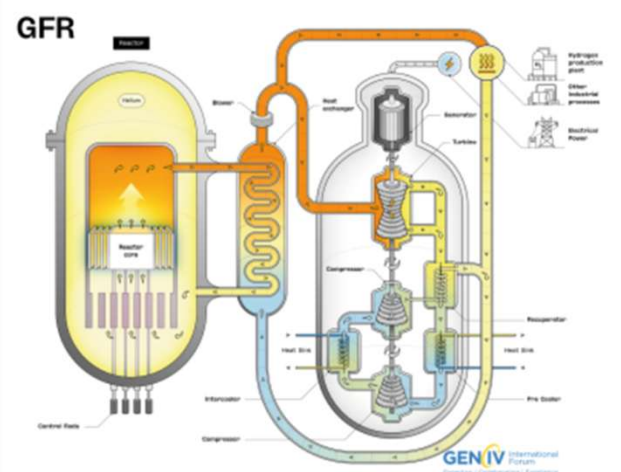


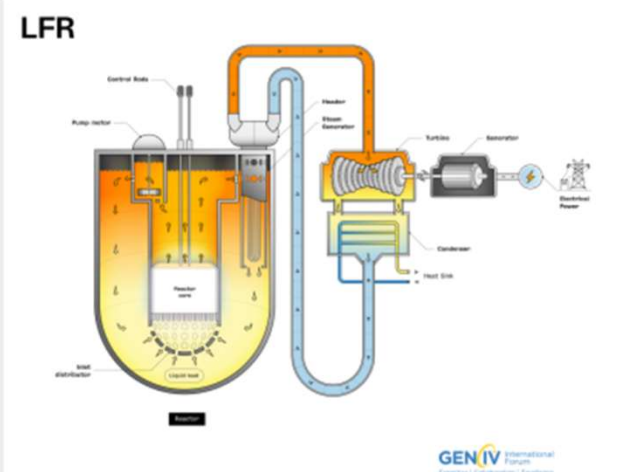
**Reactor Pilot Program*

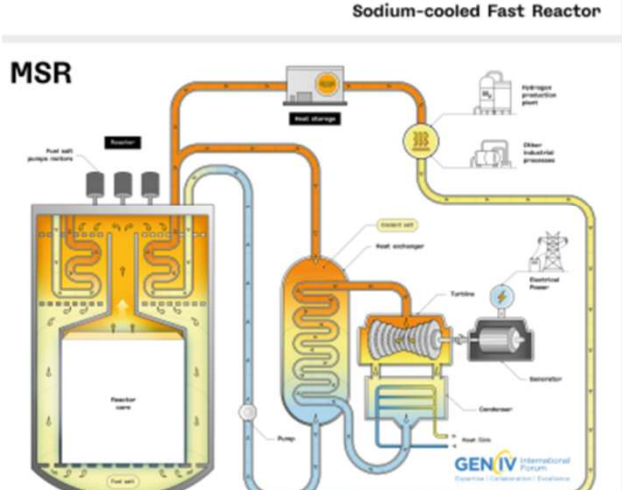
https://www.gen-4.org/generation-iv-criteria-and-technologies

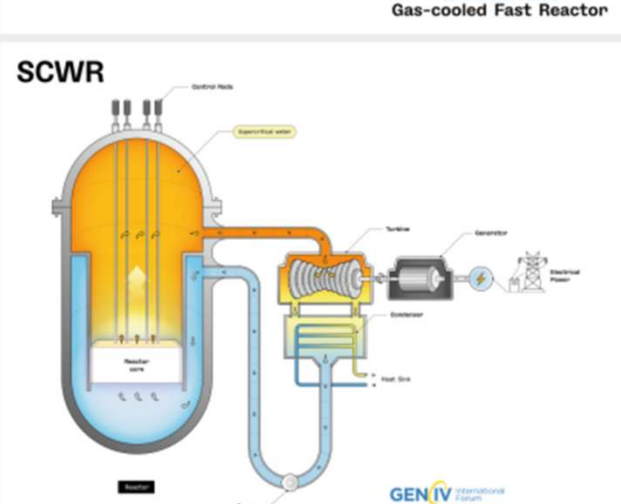
Gen-IV Types

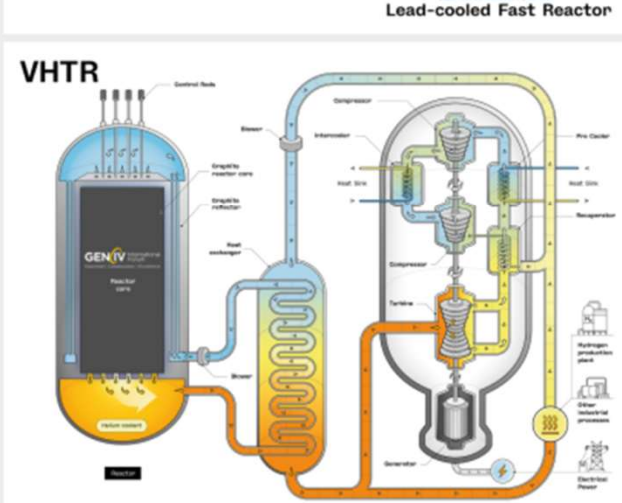












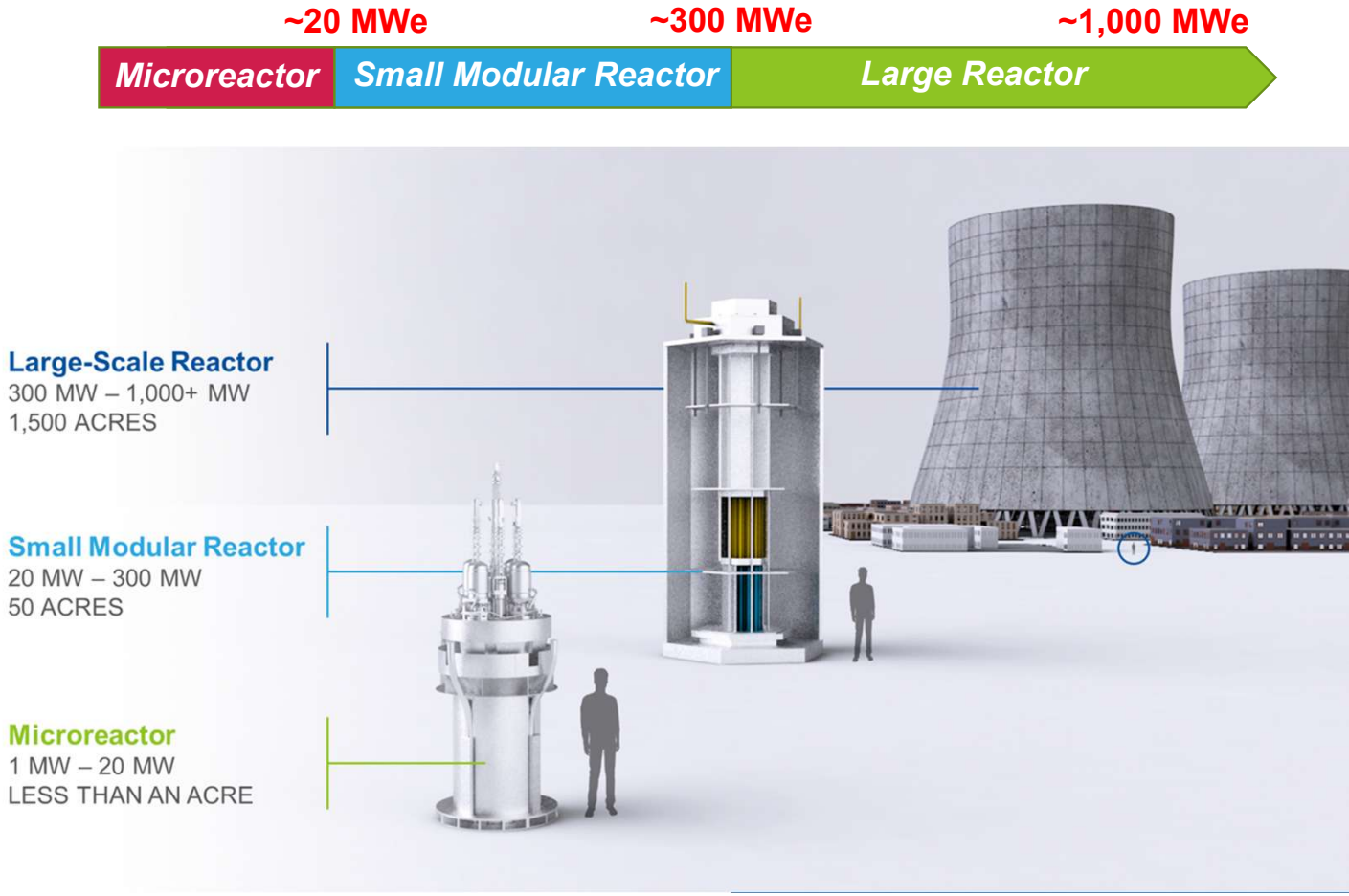
LWR vs. SMR vs. Microreactors

Small Modular Reactors (SMRs)

- Smaller power output and footprint
- Modular fabrication and assembly
- Passive safety

Microreactors

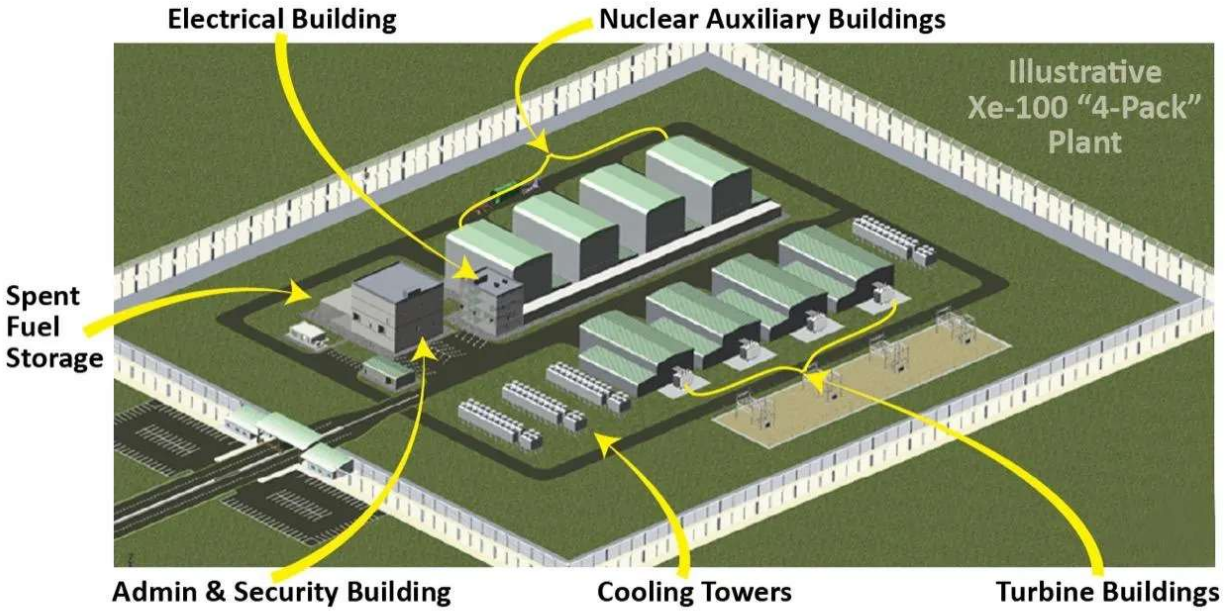
- Transportable and fast installation
- Cater to remote communities
- Simplified safety (low source term)



Small Modular Reactors (SMRs) vs Large Reactors



Vogtle PWR (USA): 2,430 MWe
- ***Plant footprint: ~1,000 acres***
- ***EPZ boundary: 10 miles***

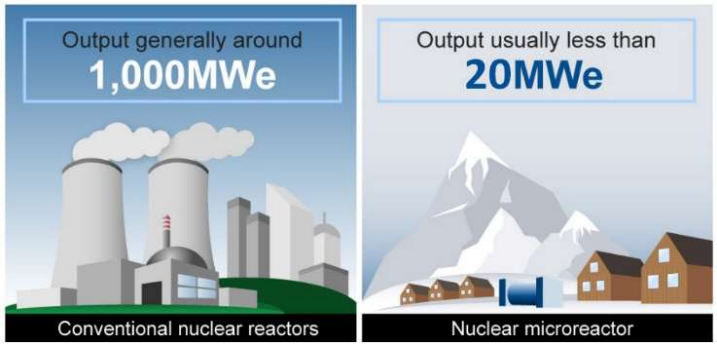


- **Secure:** underground reactor layout is possible
- **Scalable:** allows for build-out based on power demand
- **Small:** can be built on 10 acres of land and allows for grid independence
- **Safe:** smaller EPZ allows for building close to existing infrastructure

X-energy: 4x80 = 320 *MWe*
- ***Plant footprint: < 50 acres***
- ***EPZ boundary: < 0.6 miles***

https://www.southernnuclear.com/our-plants/plant-vogtle.html
https://x-energy.com/

What are Microreactors?



Source: GAO. | GAO-20-380SP



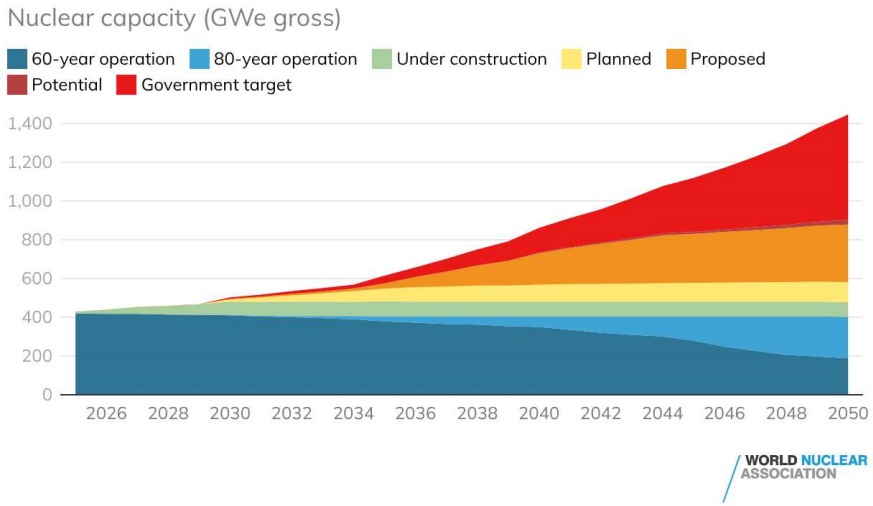
- Electrical output up to 50 MWe
- Much smaller and simpler than traditional nuclear power reactors.
- Technologies evolving from advances in materials, space reactor technologies, advanced nuclear fuels, and modeling & simulation.

- Minimum site preparation
- Flexible operation
- Enhanced safety
- Refueling (every 2-10 years)
- Operational lifetime: 5 – 20 years.

Energy market trends and nuclear commitments

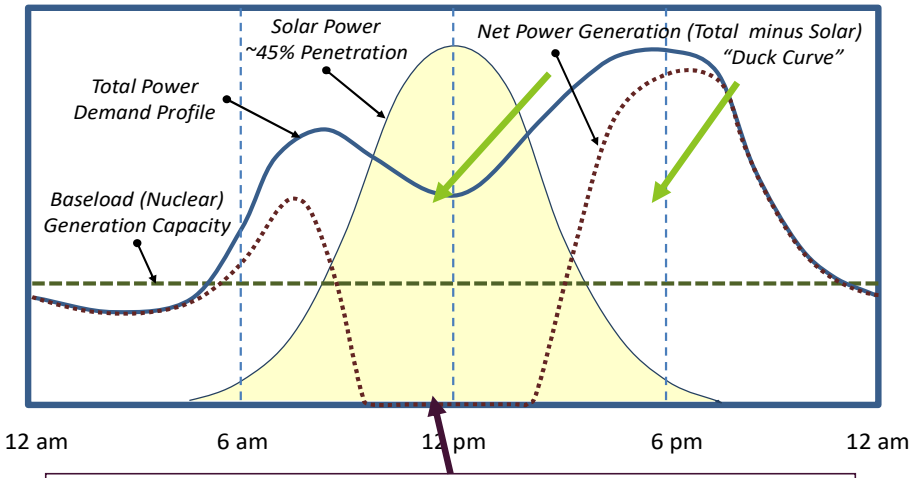
Nuclear Commitments

Figure 4.2 Global nuclear capacity projections 2025-2050



-At least 43 countries have endorsed the Declaration to Triple Nuclear Energy by 2050.
-United States goal is to reach 400 GW (from 93 GW) by 2050.

Impact of VREs on electric grid

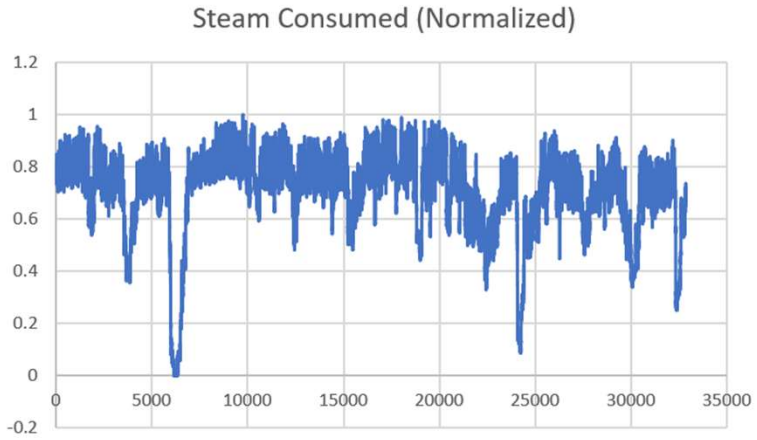


Thermal power plants will be curtailed unless the energy can be used for non-electricity production

- Peak generation ≠ peak demand
- Requires additional components and approaches to maintain stable, reliable grid

7

Motivation for Dynamic Analyses



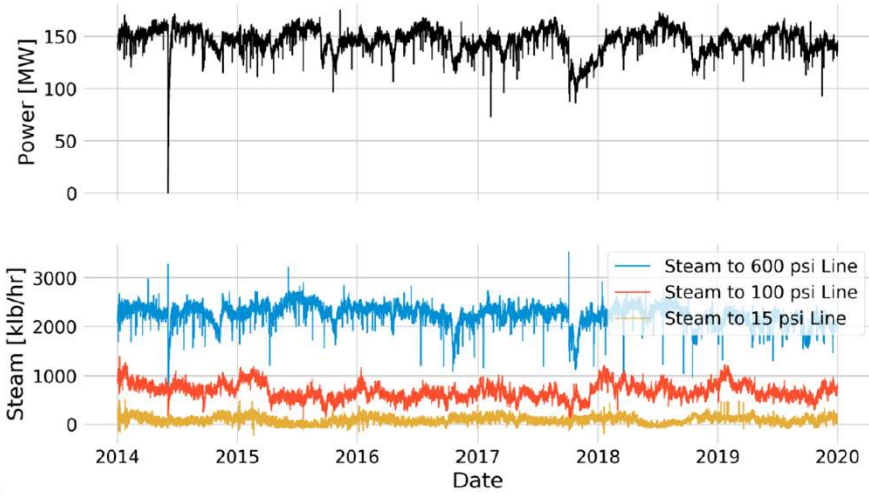
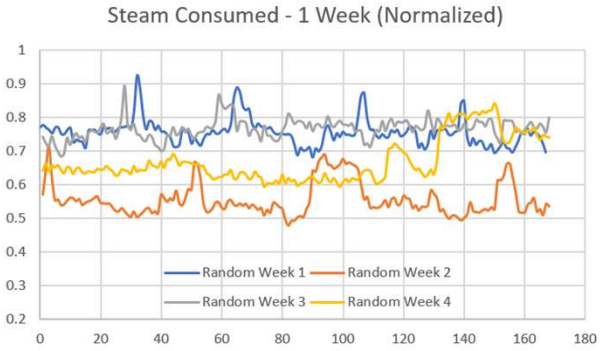
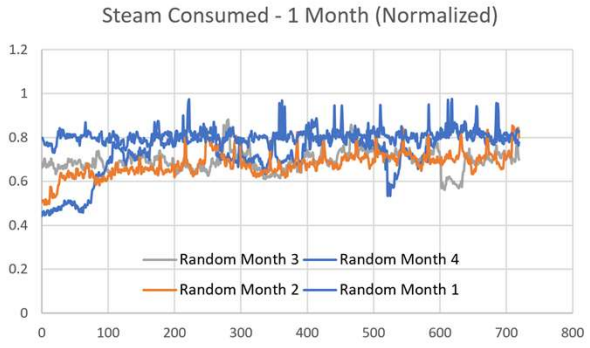


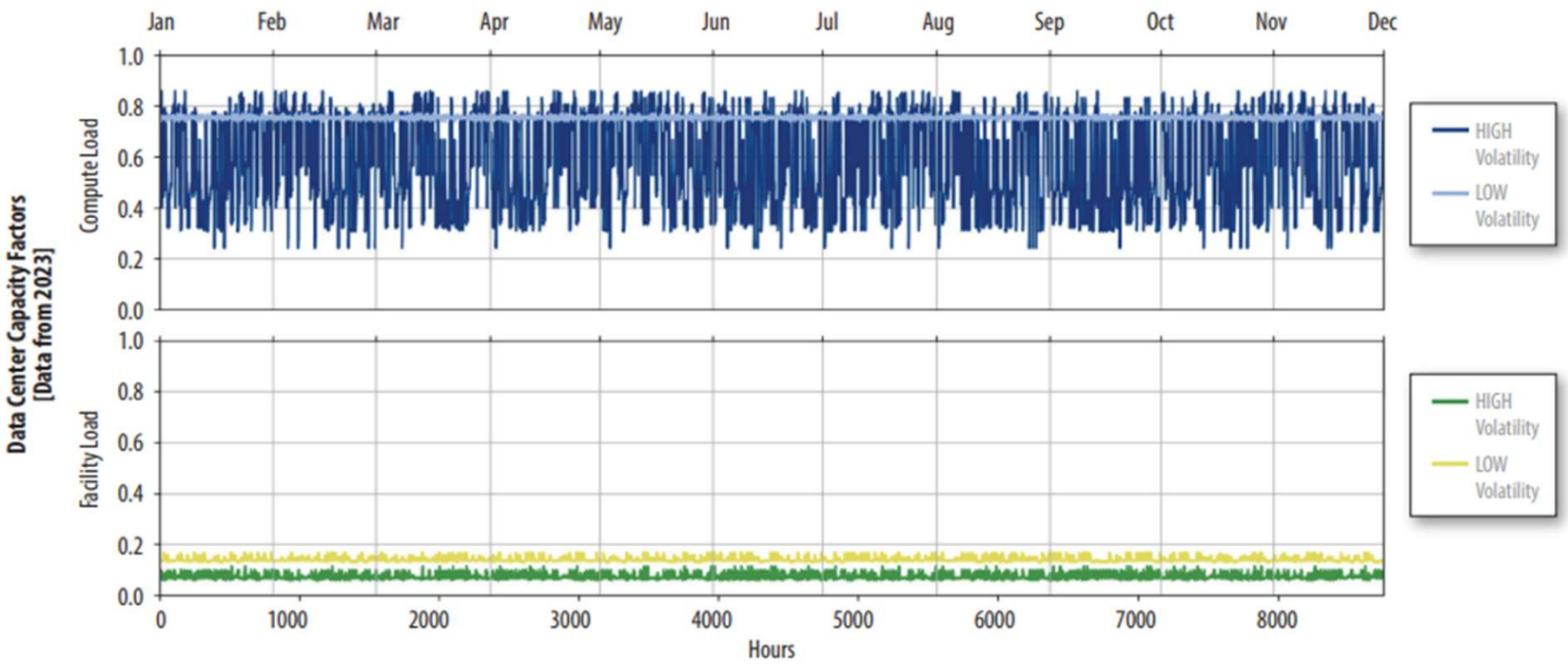
Figure 9. Eastman Kingsport electricity generation and steam lines for the period of 2014–2020 at minute intervals.





IES Integrated Energy Systems

Motivation for Dynamic Analyses



IES Integrated Energy Systems

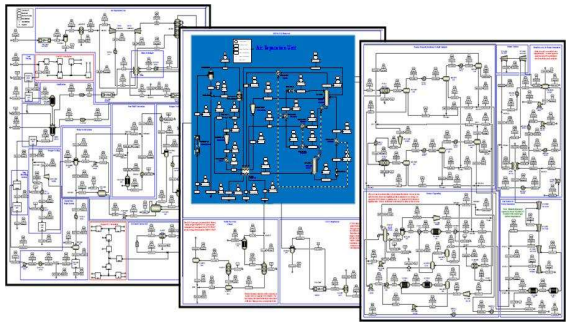
Open Source Modelica Libraries for Nuclear Modeling

- HYBRID
  - Built at INL with subsystem focus
  - Uses TRANSFORM as dependency
  - https://github.com/idaholab/hybrid
- TRANSFORM
  - TRANsient Simulation Framework of Reconfigurable Models
  - Developed at ORNL
  - First open source nuclear kinetics package
  - https://github.com/ORNL-Modelica/TRANSFORM-Library/
- TANDEM
  - Small Modular ReacTor for a European sAfe aNd Decarbonized Energy Mix
  - https://gitlab.pam-retd.fr/tandem/tandem

FORCE: Framework for Optimization of Resources, Controls, and Economics

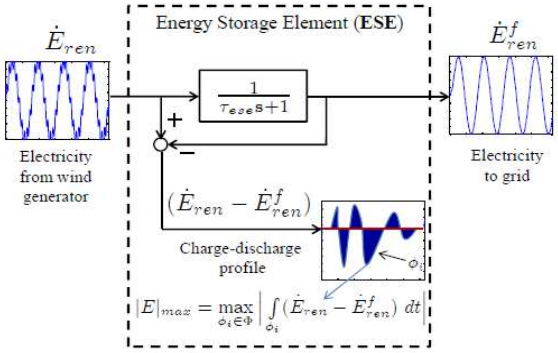
Graded approach to identify design, and evaluate hybrid system architectures

Aspen Plus® and HYSYS® Process Models



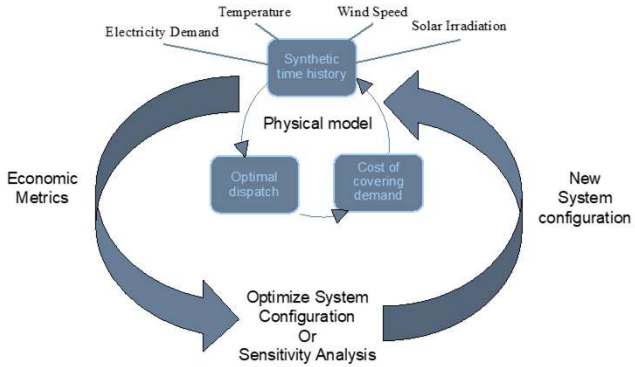
Process modeling addresses technical and economic value proposition

Modelica®, Aspen Dynamics®



Dynamic modeling addresses technical and control feasibility

HERON (INL System Optimization)



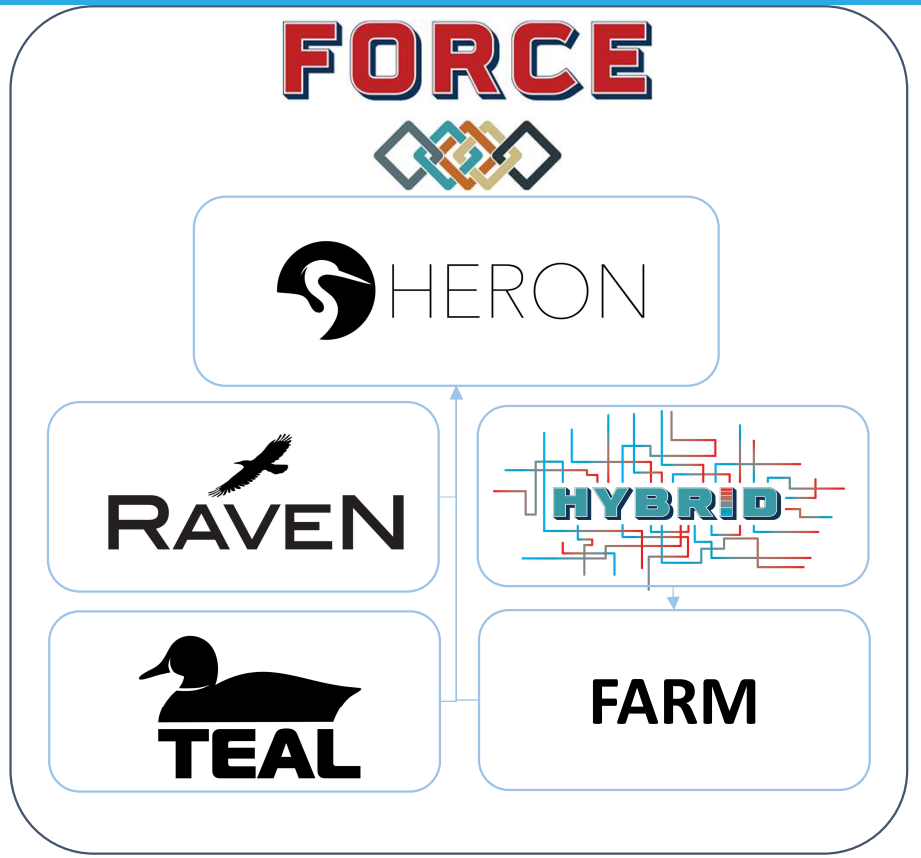
System modeling addresses whole-system coordination

Consideration of Resource—Technology—Economic—Market Potential

12

How HYBRID Fits in IES Toolset

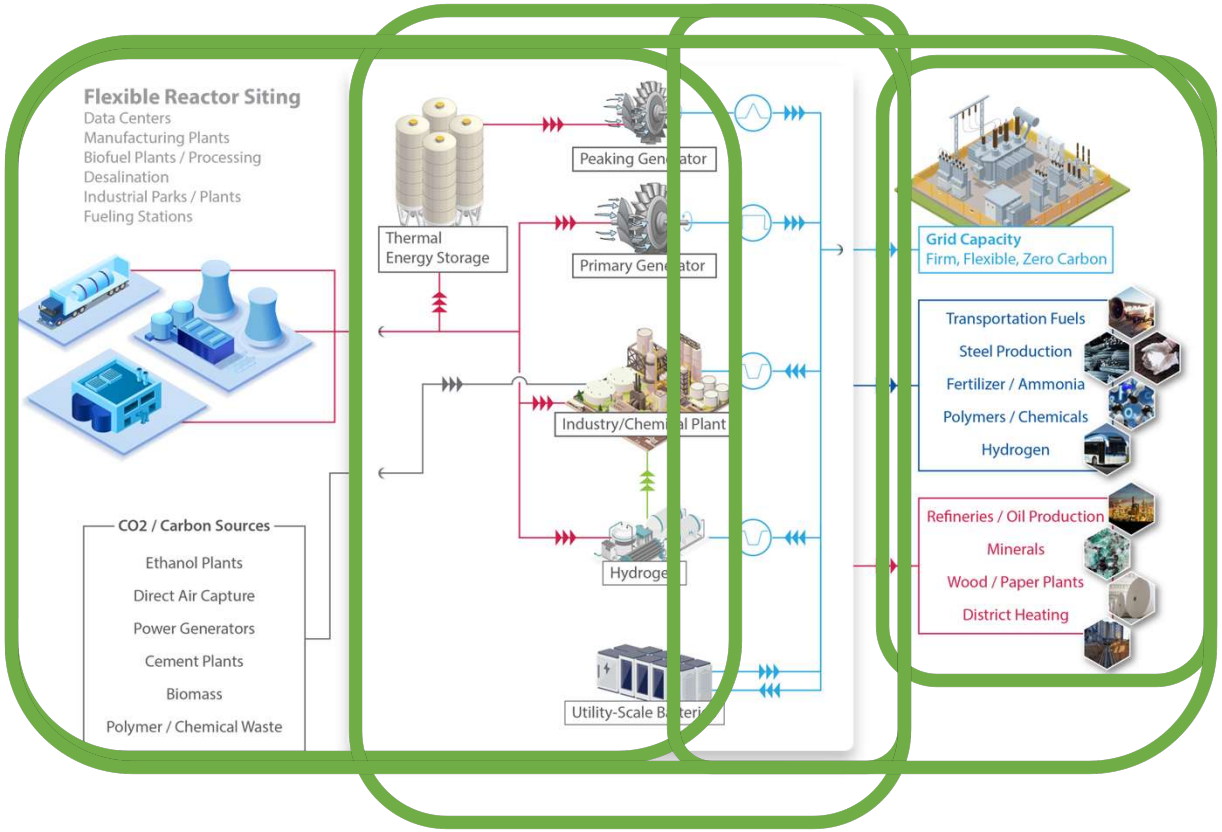
- INL tools enable IES modeling analysis
  - *Physical process, integration modeling*
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - *Stochastic analysis, multiple commodities*
  - *Energy storage, varied markets*
  - *Real-time optimization*



https://github.com/idaholab/FORCE

IES Integrated Energy Systems

Thermal Systems Modeling in IES

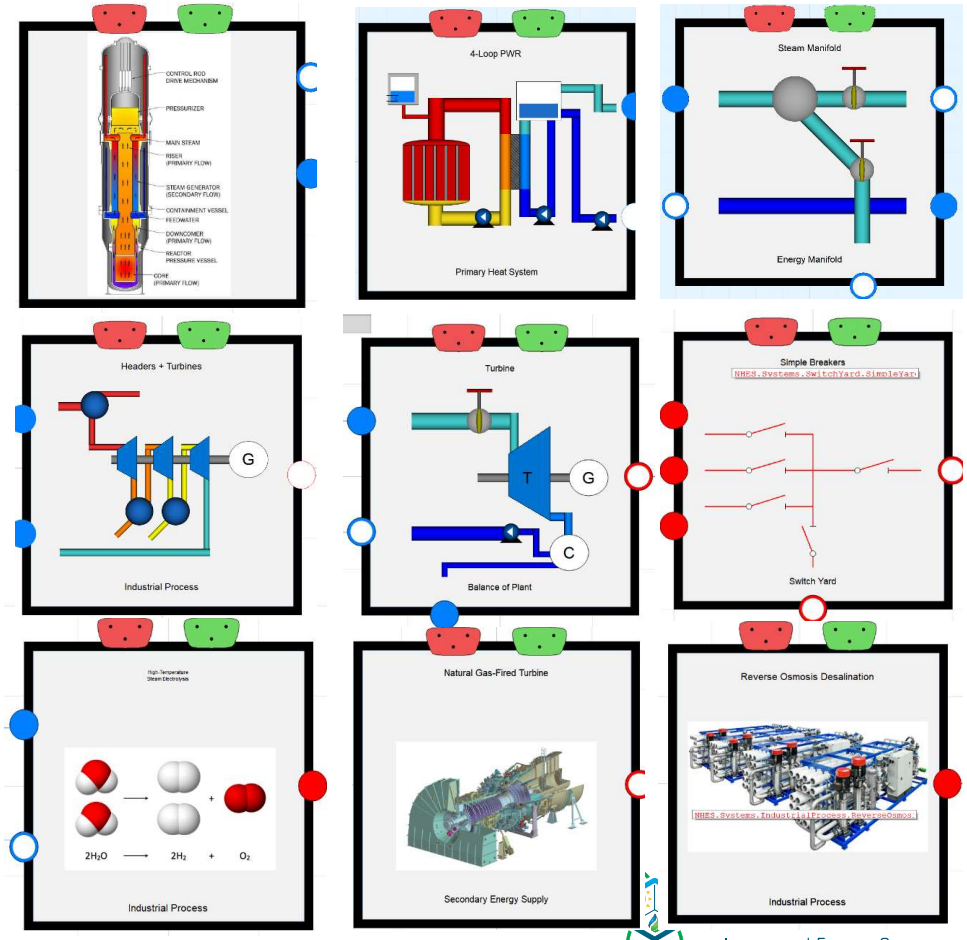


- How do subsystems operate?
  - Ramp rates
  - Internal energy flows
  - Control response
- How do systems respond to dispatch?
  - What is governing system control?
- What are external energy requirements?
  - Thermal and electrical energy use
- What are heat and chemical balances for IES?
  - How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

IES Integrated Energy Systems

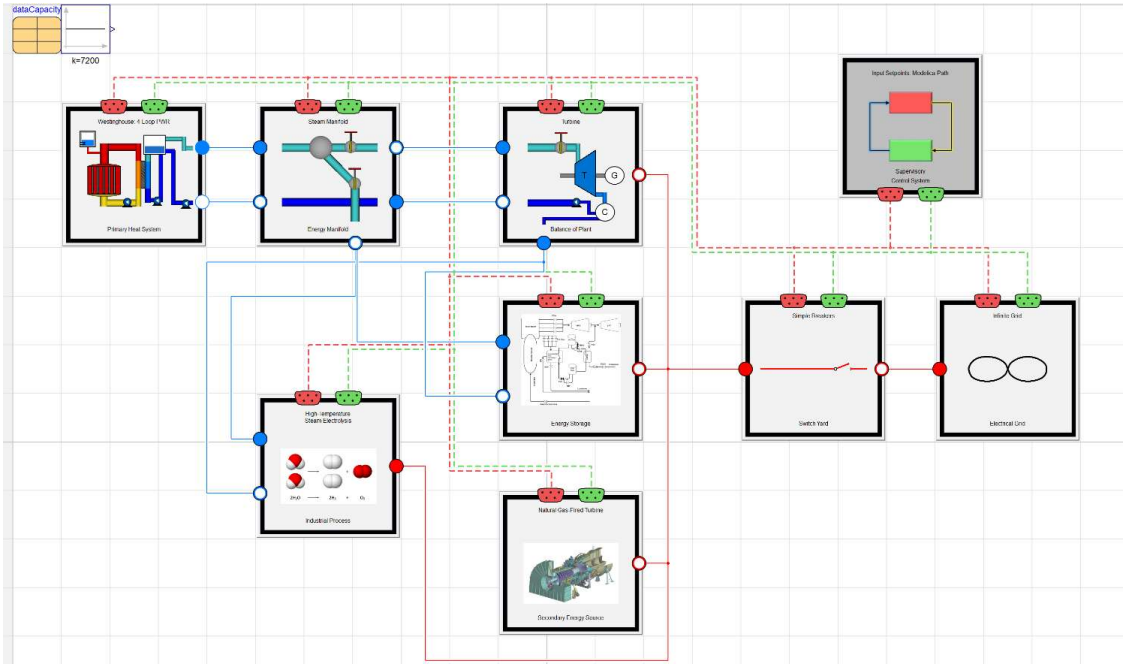
HYBRID Dynamic Modeling

- 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

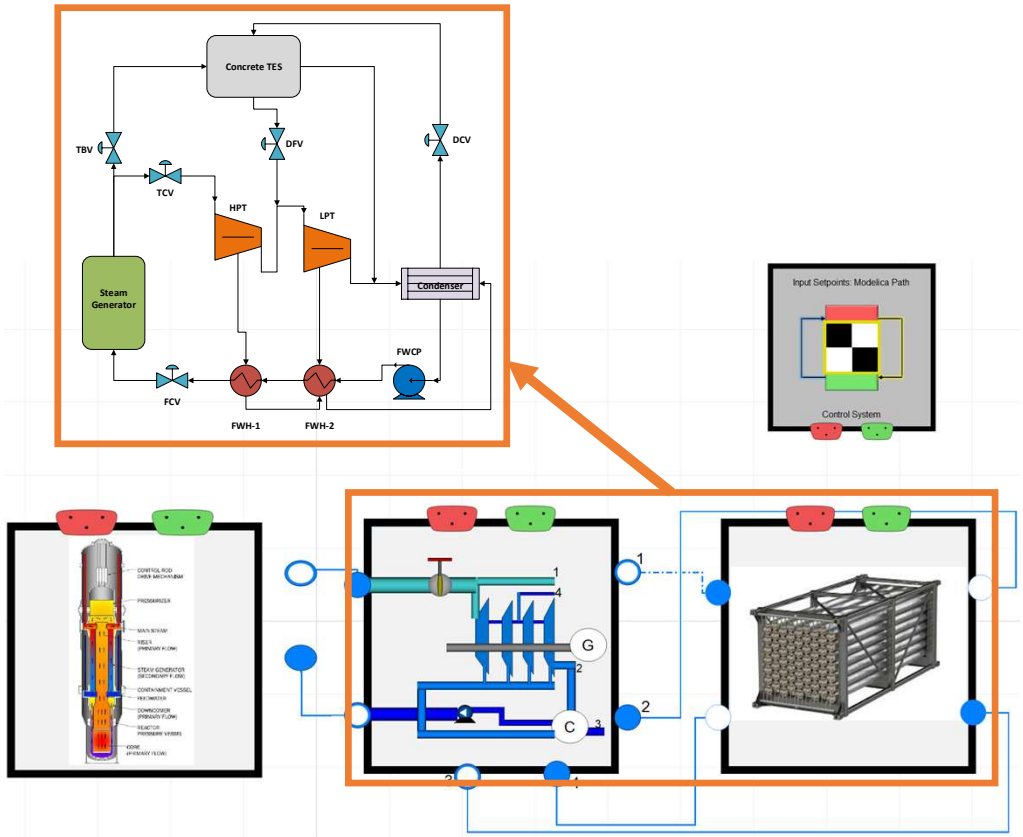
- Physical models are focused on process system bases
- Subsystem models are fully defined based on interconnects
- Dynamic balance across full system is calculated



IES Integrated Energy Systems

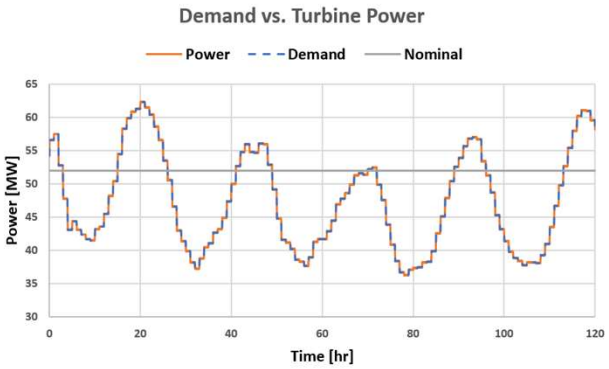
Energy Arbitrage IES

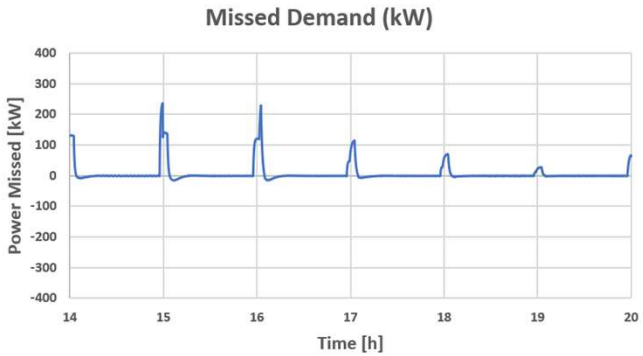
- NuScale-style SMR
- High-fidelity balance of plant
- Integrated-concrete thermal-energy storage system (dual network model)
- Week-long-scaled dispatchable demand profile calculated and input

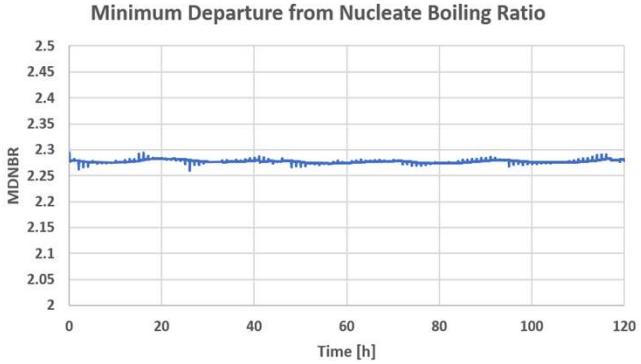


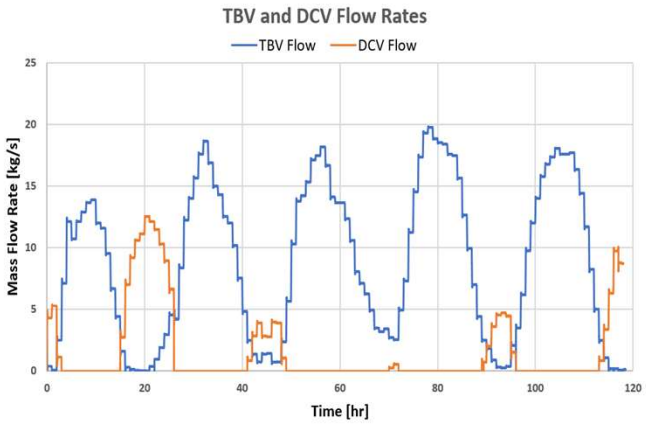
IES
Integrated Energy Systems

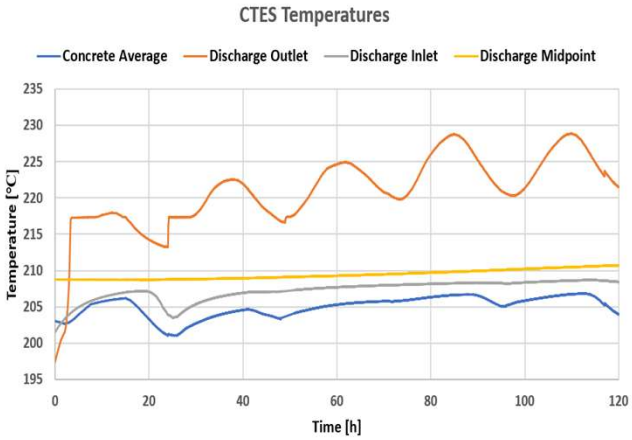
Energy Arbitrage IES

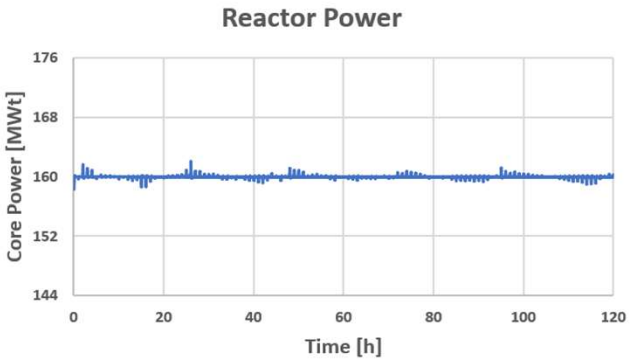








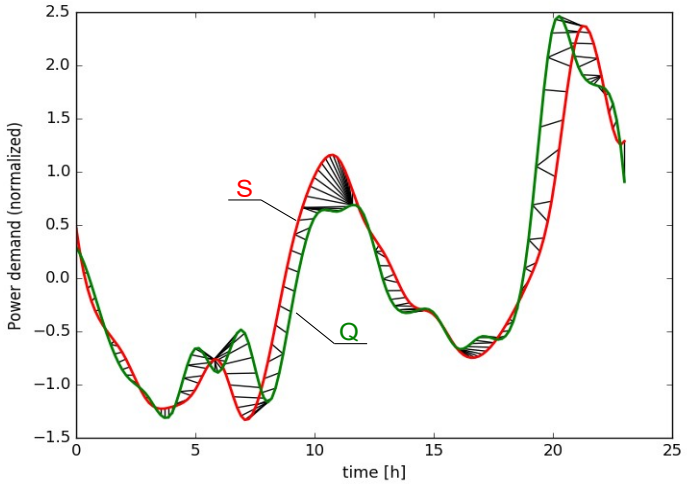


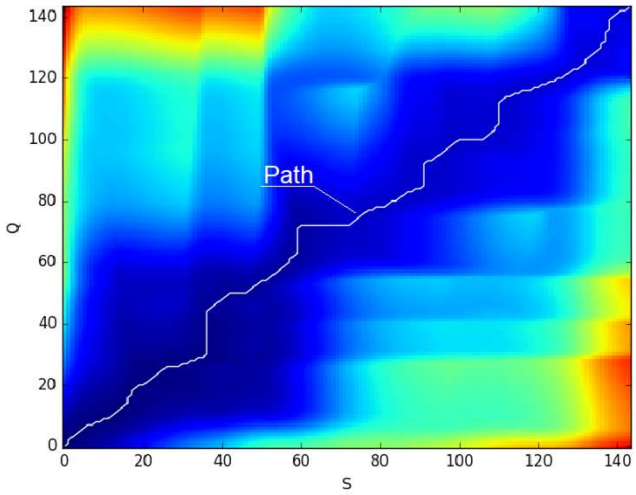


IES
Integrated Energy Systems

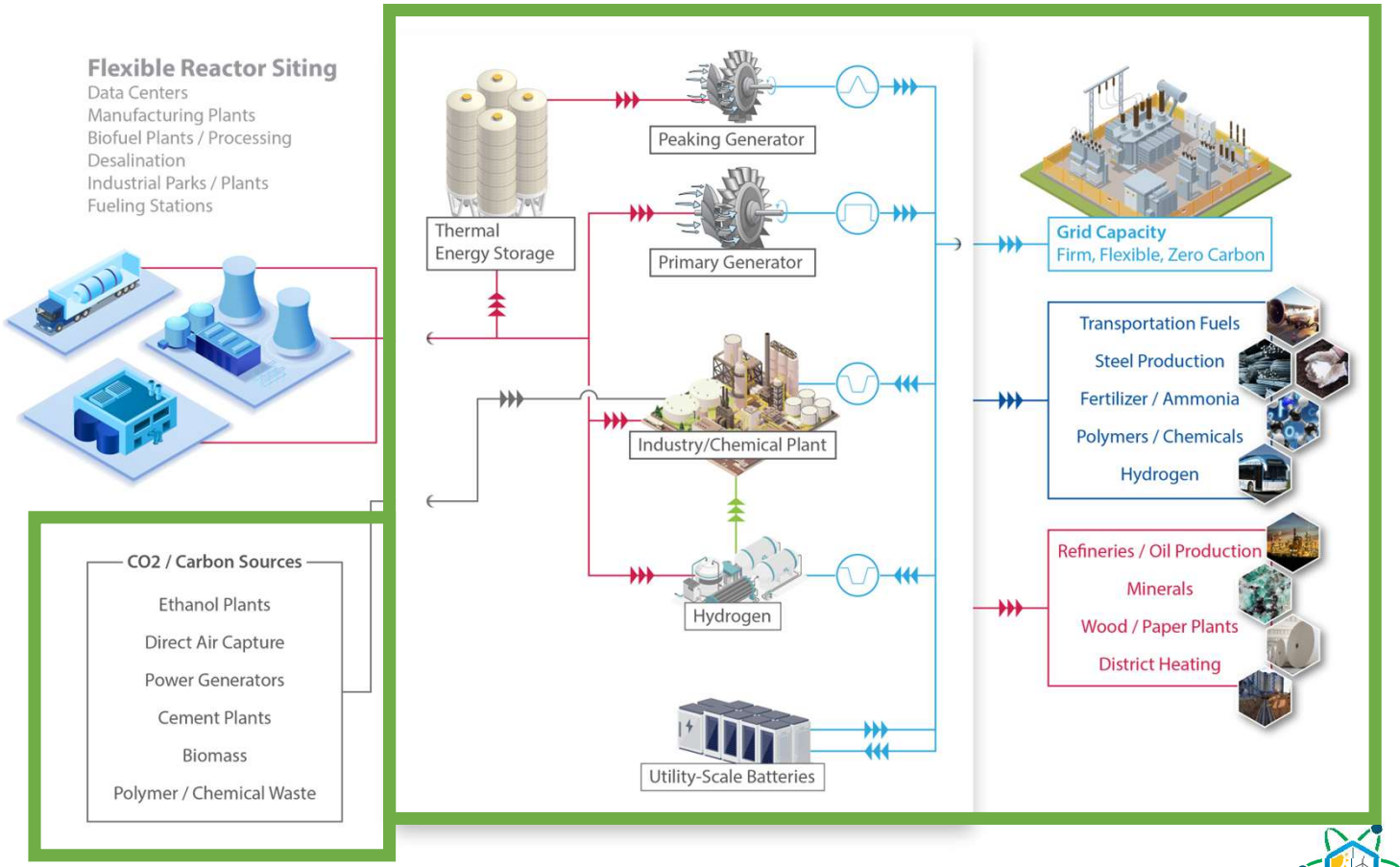
Validation: Experimental data

- 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





Modeling to Work With Nuclear: Areas to Focus



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INL

Idaho National Laboratory





WWW.INL.GOV