GEN IV International Forum℠

MAXIMIZING CLEAN ENERGY INTEGRATION: THE ROLE OF NUCLEAR RENEWABLE TECHNOLOGIES IN INTEGRATED ENERGY SYSTEMS

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Meet the Presenter

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Dr Shannon Bragg-Sitton is the **Lead for Integrated Energy Systems (IES)** in the Nuclear Science & Technology Directorate at **Idaho National Laboratory (INL)**. Within this role, Shannon serves as the co-Director for the INL Laboratory Initiative on IES, which includes focus areas for thermal energy generation, power systems, data systems, and chemical processes/industrial applications.

Shannon is also the INL lead for the DOE Applied Energy Tri-Laboratory Consortium, which includes INL, the National Renewable Energy Lab, and the National Energy Technology Lab. Shannon has held multiple leadership roles in DOE Office of Nuclear Energy programs since joining INL in 2010, ranging from space nuclear power and propulsion systems, to advanced nuclear fuel development, to her current work in integrated system design and demonstration. She currently serves as the National Technical Director for the DOE-NE IES program within Crosscutting Technologies Development. IES designs seek to coordinate the use of multiple clean energy generation sources—e.g. nuclear and renewables—to meet both thermal and electrical energy needs.

Shannon holds a PhD and MS in Nuclear Engineering from the University of Michigan, an MS in Medical Physics from the University of Texas at Houston, and a BS in Nuclear Engineering from Texas A&M University.

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DESIGNING FUTURE ENERGY SYSTEMS

What goals are we trying to achieve?

How will energy be used?

What role(s) can each energy source fill?

Global Reality

28% by 2040

Projected increase in world energy use by U.S. Energy Information Administration.*

2.7 degrees by 2040

Projected increase in atmospheric temperatures if global greenhouse gas emission continue at current rate by Intergovernmental Panel on Climate Change

The Next Generation of Federal Clean Electricity Tax Credits
Federal policy makers should design a new generation of tax incentives… to decarbonize the US electricity sector almost entirely by midcentury—an integral step in decarbonizing the overall economy to combat climate change.
By Dr. Varun Sivaram and Dr. Noah Kaufman
https://energypolicy.columbia.edu/research/commentary/next-generation-federal-clean-electricity-tax-credits

A major US utility is moving toward 100% clean energy faster than expected
Xcel Energy…committed to going completely carbon-free by 2050…carbon-free includes not only renewables but also advanced nuclear power plants and fossil fuel power plants with carbon capture and sequestration…
By David Roberts, Vox
https://www.vox.com/energy-and-environment/2018/12/5/18126920/xcel-energy-100-percent-clean-carbon-free

Three More Nuclear Plant Owners will Demonstrate Hydrogen Production
The projects…aim to improve long-term competitiveness of the nuclear sector...
By Sonal Patel
https://www.powermag.com/three-more-nuclear-plant-owners-will-demonstrate-hydrogen-production/

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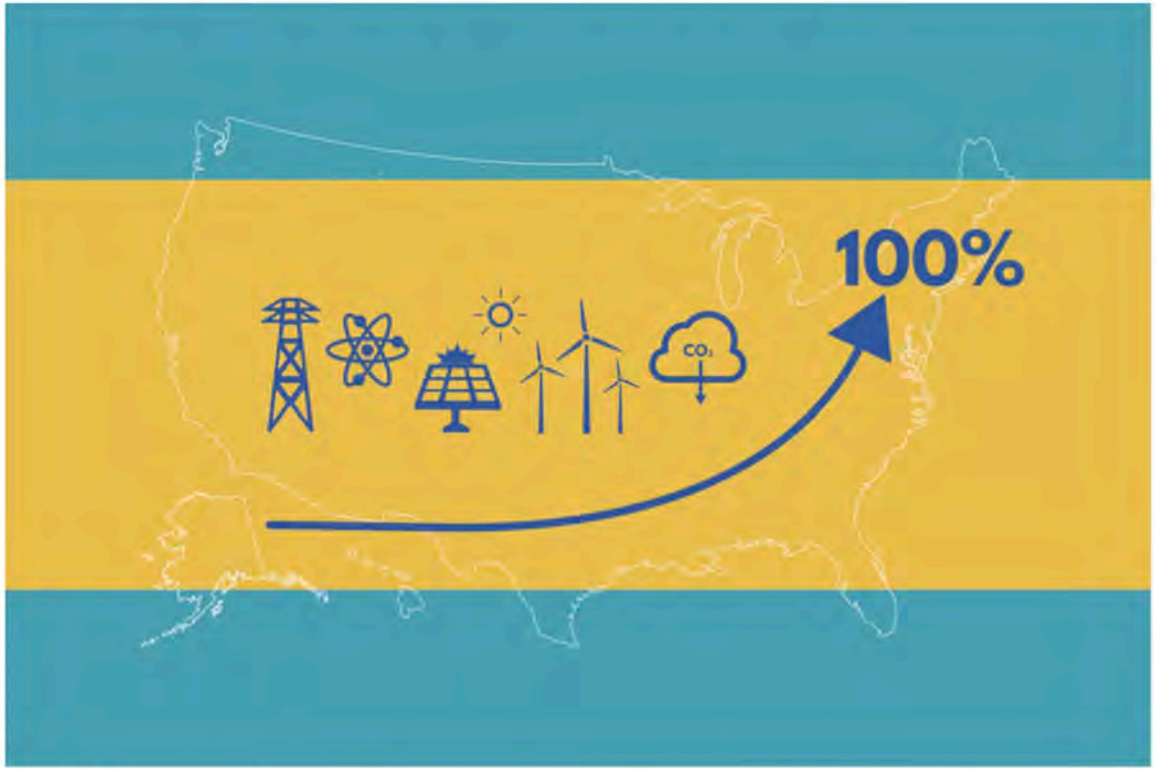
THIRD WAY

GRAPHIC *Published December 11, 2019 · 16 minute read*

Clean Energy Targets are Trending



Farah Benahmed
Former Policy Advisor, Climate and Energy Program
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Lindsey Walter
Senior Policy Advisor, Climate and Energy Program
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To meet its climate goals and bring emissions down to net-zero by 2050, the US needs to shift to carbon-free power as fast as possible. While federal efforts to clean up the grid have stalled, Third Way analysis shows that states, major cities, and utilities have literally doubled-down on policies and targets to get the job done. We took the data and created an interactive dashboard to help spot important trends that could be expanded across the country. Two essential themes stood out to us:

Two essential themes:

Clean energy commitments are rapidly gaining popularity. Our research identified a total of 121 portfolio standards and other commitments to clean energy since 1983. But a whopping 58% of them were adopted just since 2016.

Climate leaders want more technology options to choose from. Prior to 2016, 90% of commitments were exclusive to renewable energy. That trend has almost completely reversed since then, with 65% of states, utilities, and major cities now embracing “technology-inclusive” commitments like clean energy standards that take advantage of nuclear power, carbon capture, and other carbon-free options.

Go to the article

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U.S. Utilities with Commitments to Reduce Emissions

Utility	Clean Energy Goal	Target Date		Utility	Clean Energy Goal	Target Date
Alliant Energy	80% CO2 Reduction	2050		IDACORP	100% Carbon-Free	2045
Ameren Missouri	80% CO2 Reduction	2050		MGE Energy	Net-Zero Carbon	2050
APS	100% Carbon-Free	2050		MidAmerican Energy	100% Renewable Target	None
AVANGRID	Carbon Neutral	2035		National Grid	80% Carbon Reduction	2050
Avista	100% Carbon-Free	2045		NiSource	90% CO2 Reduction	2028
CMS Energy	90% CO2 Reduction	2040		OG&E	50% CO2 Reduction	2050
Dominion Energy	Net-Zero CO2	2050		PG&E	80% GHG Reduction	2050
DTE	100% Carbon-Neutral	2050		Portland General Electric	100% Carbon-Free	2050
Duke Energy	Net-Zero CO2	2050		PSEC	Net-Zero Carbon	2050
Entergy	50% Emissions Reduction	2030		Southern Company	Net-Zero Carbon	2050
Evergy	80% CO2 Reduction	2050		Tucson Electric Power	30% GHG Reduction & 30% Renewables	2030
First Energy	90% CO2 Reduction	2045		WEC Energy Corp	80% CO2 Reduction	2050
Great River Energy	50% Renewable	2030		Xcel Energy	100% Carbon-Free	2050
Hawaii Electric Light	100% Renewable	2045				

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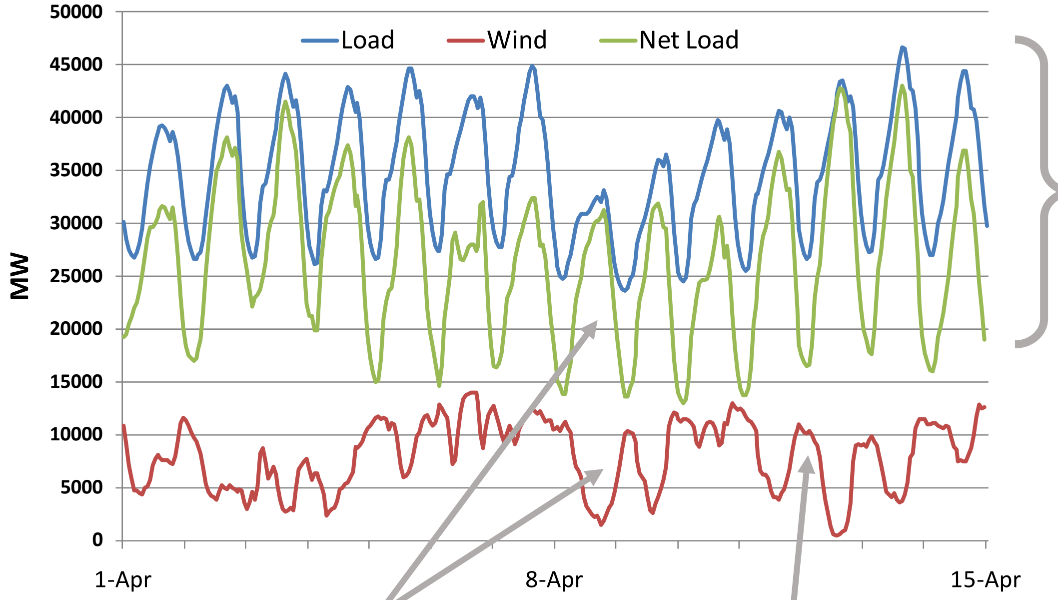
Consequences of Increasing Variable Renewable Power Generation



Ramp Range (Increases in this two-week period from 19.3 GW/day to 26.2 GW/day)

Variation in wind output increases net load ramp rate (Increases in this period from 4,052 MW/hour to 4,560 MW/hour)

Uncertainty in wind output increases uncertainty in net load to be met with conventional generators

Figure courtesy NREL

Energy storage is Needed for shift excess generation to evening

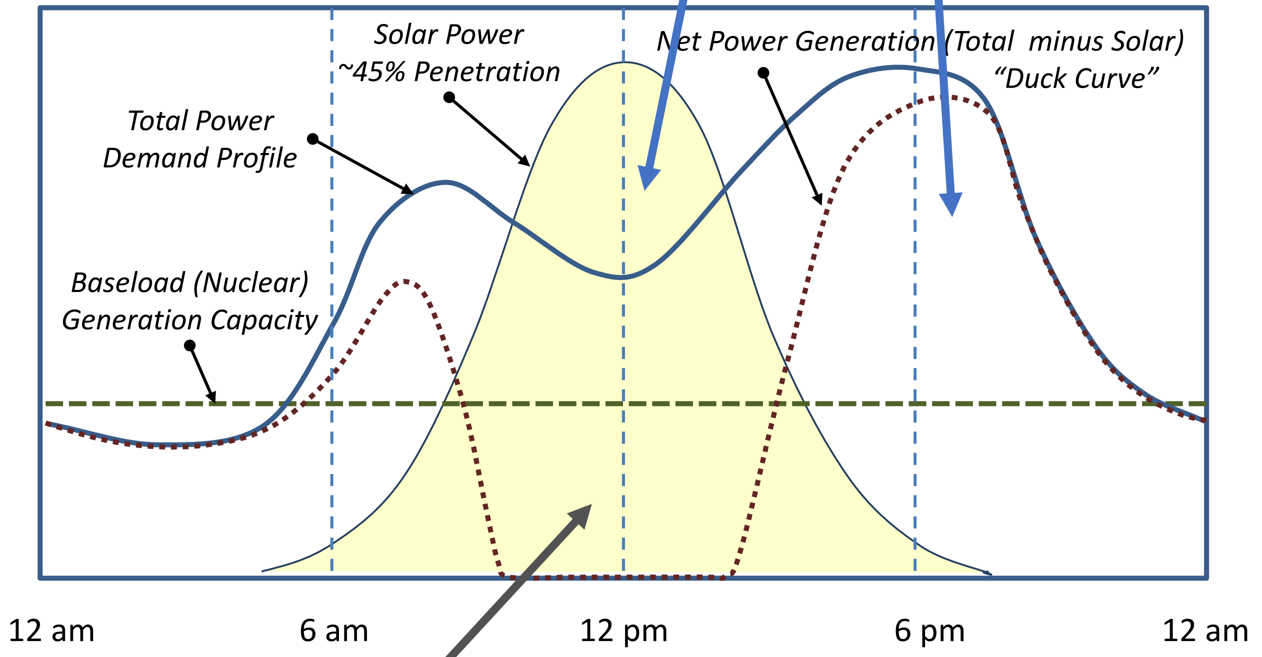


Figure developed by INL

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

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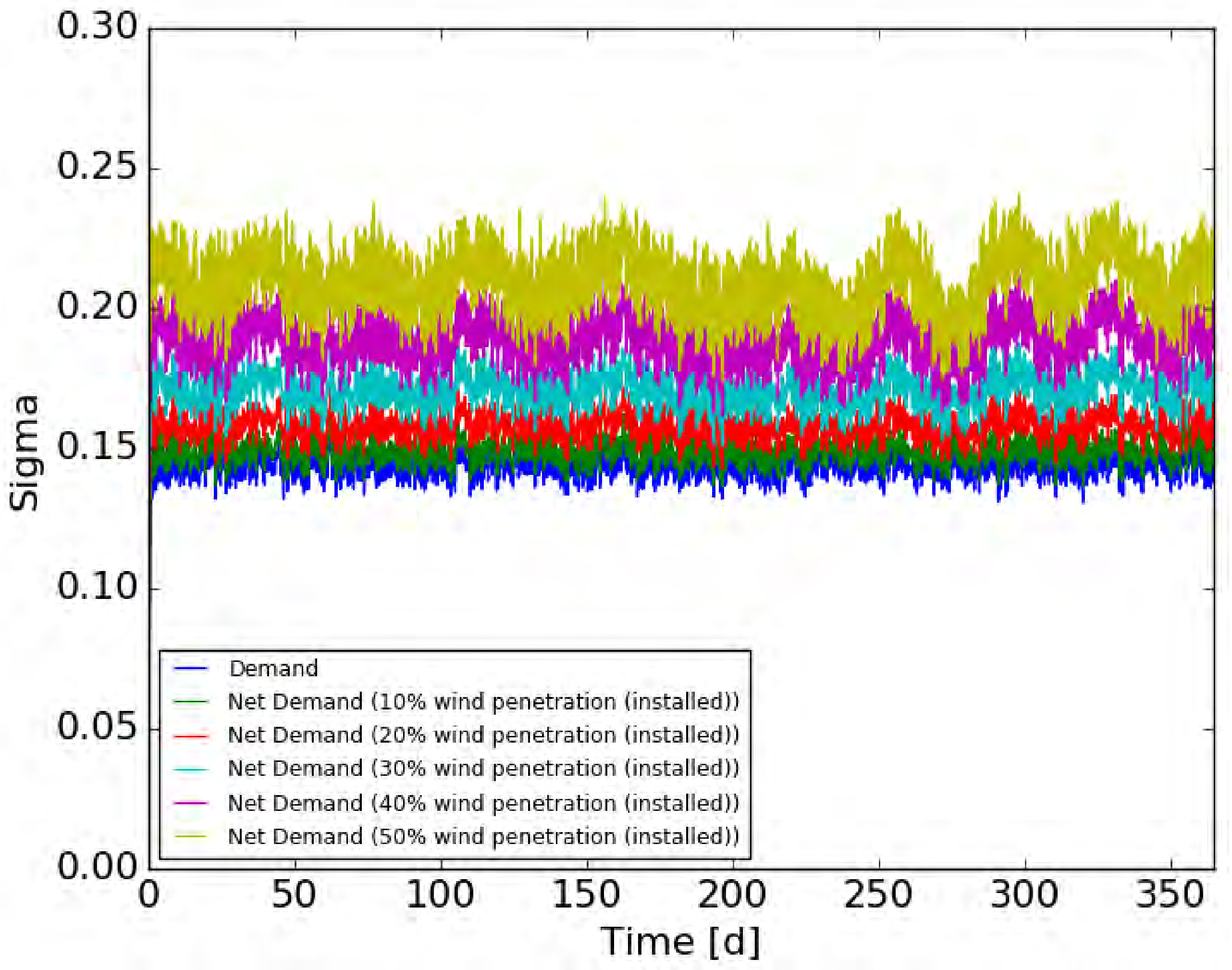
IES: Volatility Increase with Increasing VRE



Synthetic time histories for wind and demand have been used to compute the sigma (in %) of net demand

While only one wind source was used (thus not taking advantage of spatial decorrelation), the increase of volatility is remarkable

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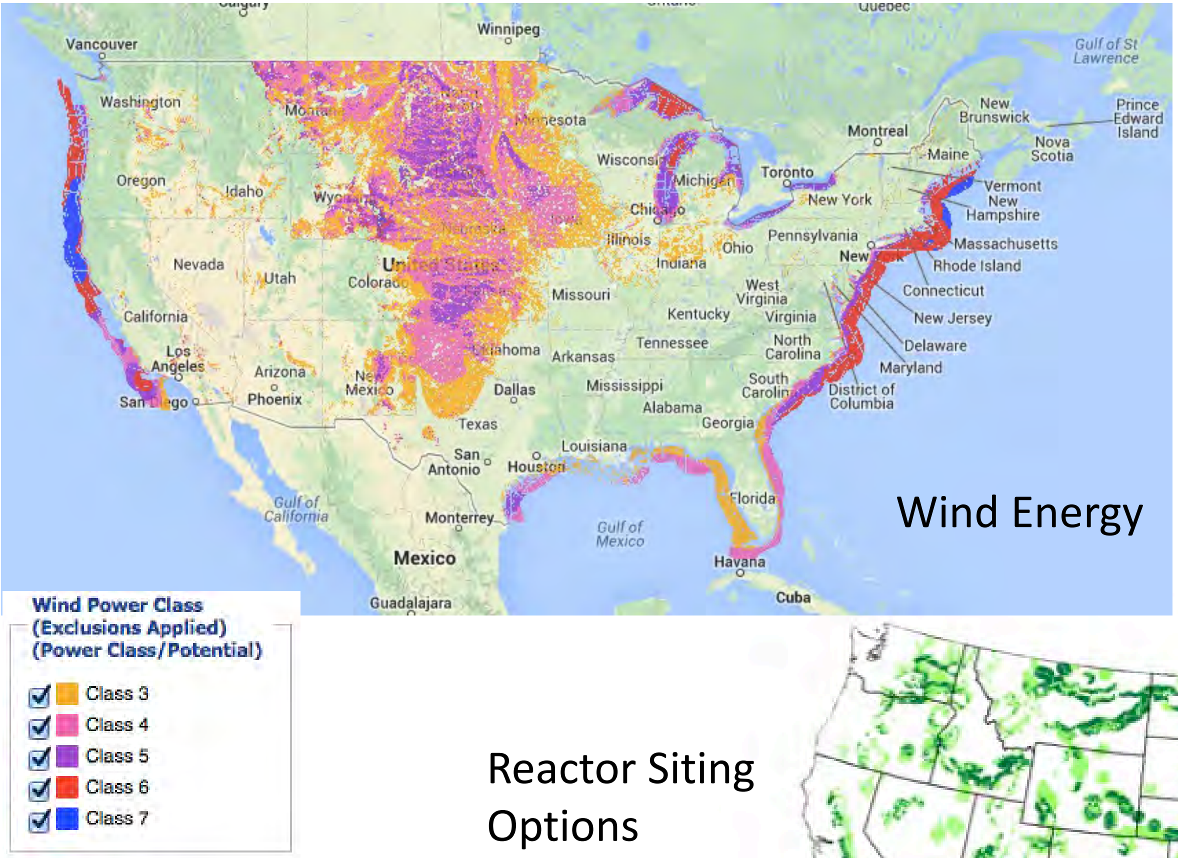
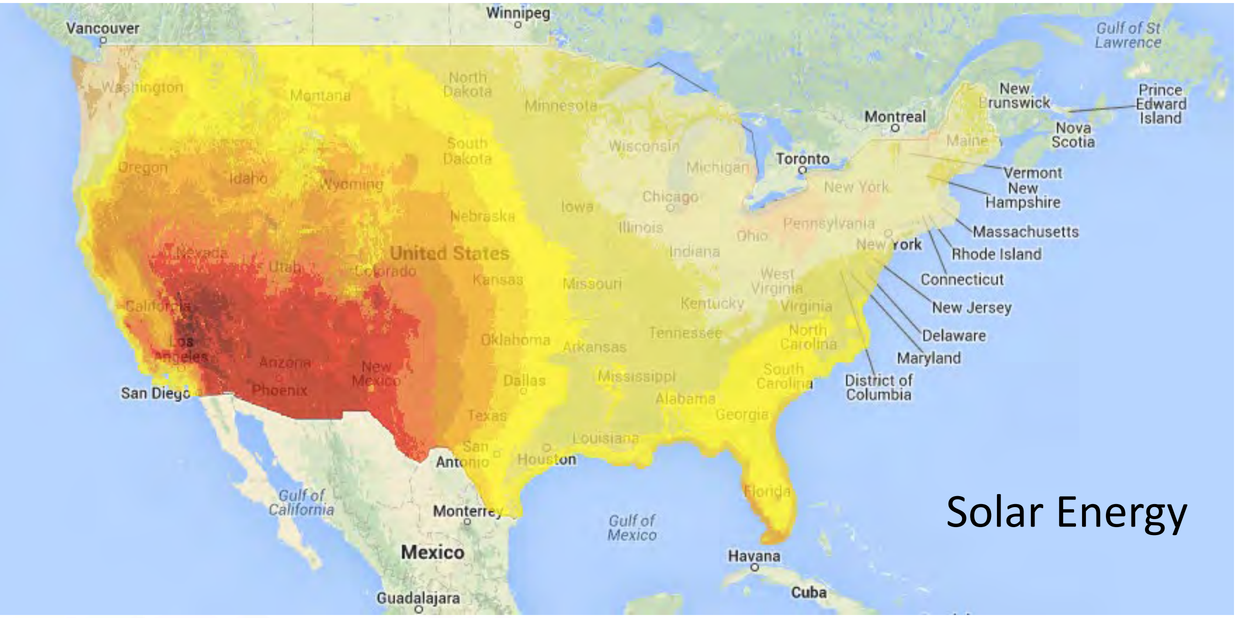
What is the resource potential in a selected region?





Reactor Siting Options

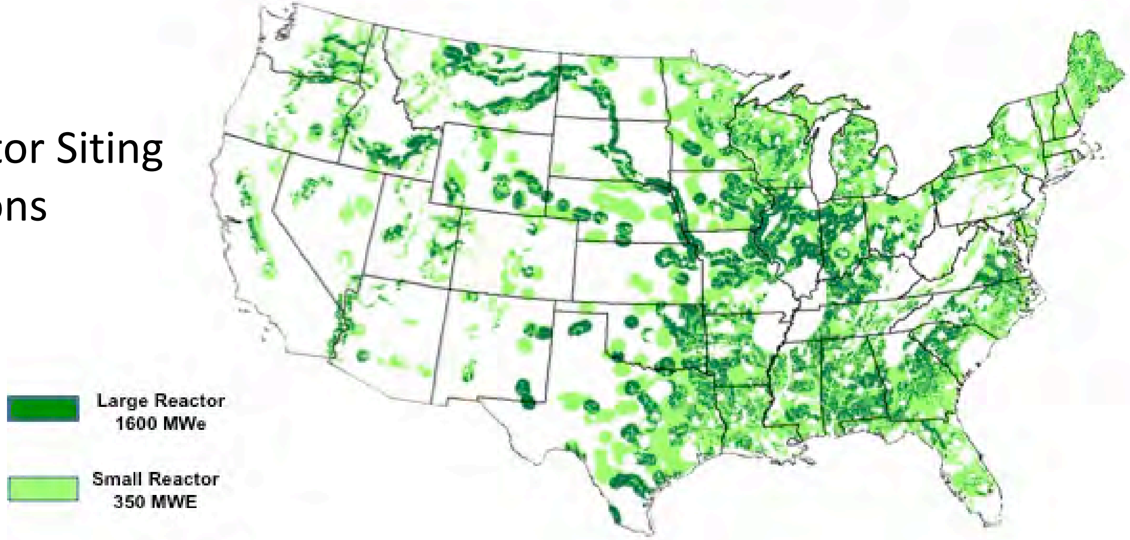


Figure excerpts from the 2014 *Handbook of Small Modular Nuclear Reactors*, Ch. 13, “Hybrid Energy Systems.”

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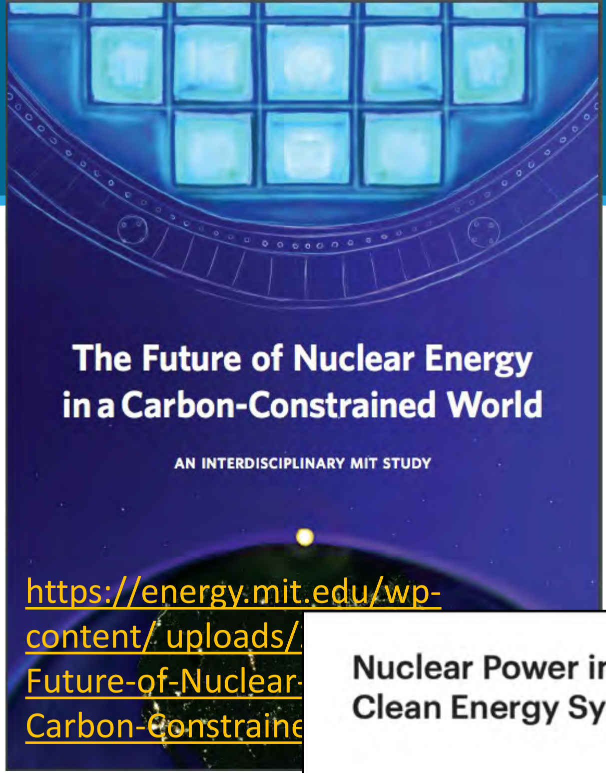
What is the Future of Nuclear Energy?

MIT Future of Nuclear Energy Study (2018): Key Findings

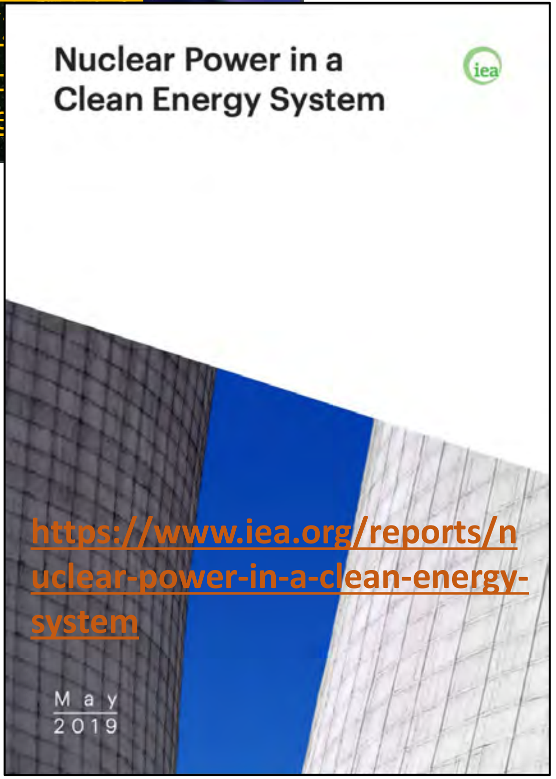
- The world faces the new challenge of drastically reducing emissions of greenhouse gases while simultaneously expanding energy access and economic opportunity to billions of people
- A variety of low- or zero-carbon technologies can be employed in various combinations to meet the growing energy demand, but…
  - Without contribution from nuclear, the cost of achieving deep decarbonization targets increases significantly
  - The least-cost portfolios include an important share for nuclear, the magnitude of which significantly grows as the cost of nuclear drops



https://energy.mit.edu/wp-
content/ uploads/
Future-of-Nuclear-
Carbon-Constraine

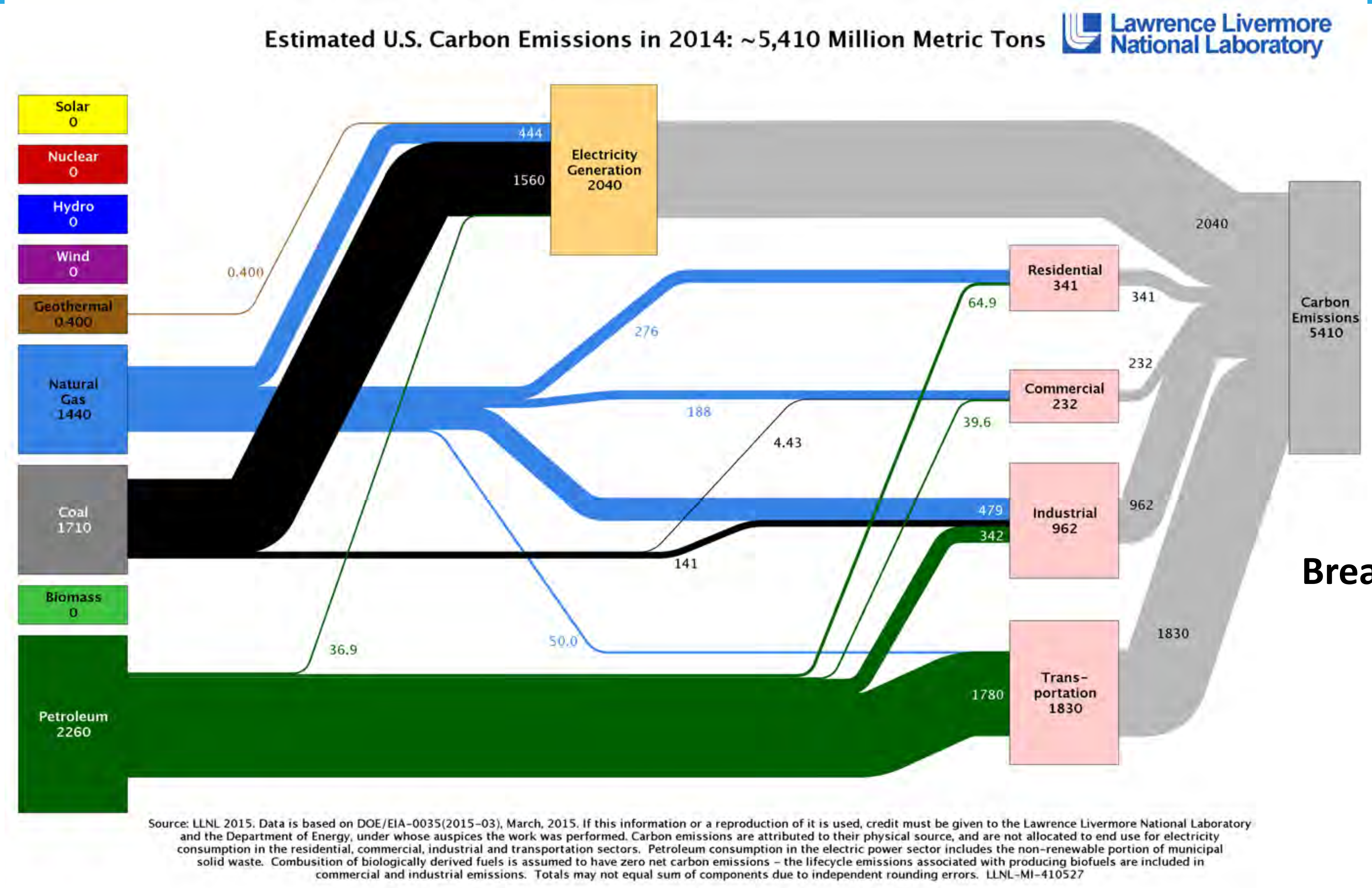
International Energy Agency, Nuclear Power in a Clean Energy System (May 2019)

- Despite significant renewable energy growth over the last 20 years, the overall contribution of clean energy supply to electric generation has not changed
- In the U.S. and many parts of the world, low cost natural gas is displacing nuclear generation
  - NG turbines are scalable, allow rapid ramping – complement to wind, solar



https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

Decarbonizing the Industrial Sector is Challenging



18% of the U.S.'s GHG emissions are direct emissions from the industrial sector.

Alternative energy sources are limited due to heat delivery requirements.

Breakdown on U.S. Emissions:

38% Electricity
34% Transportation
18% Industrial
6% Residential
4% Commercial

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Planning our Future Energy Resources: Energy Market Modeling

Introduction to energy market modeling and how it is used

- Capacity Expansion Models (CEMs) for long-term energy mix assessment
- Production Cost Models (PCMs) for market and revenue assessment

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CEMs and PCMs

- Capacity Expansion Models (CEMs)
  - Used to model evolution of system of electricity generation assets
  - Considers change in demand, retirements and completion of construction projects to determine if additional capacity is needed in future years
    - If so, determines lowest cost capacity additions to meet projected demand (including reserves), with consideration of construction lead time
  - Some models include other parts of the economy to determine demand

- Production Cost Models (PCMs)
  - Models the current year in much greater detail
  - Predicts which existing facilities will operate when to meet demand
    - Selection based primarily on lowest short-run operating costs
    - Constrained by physical limitations of grid, dispatchability, start-up time, ramp rates, etc.
  - Outputs include electricity costs, plant revenues, reserve margins, etc.

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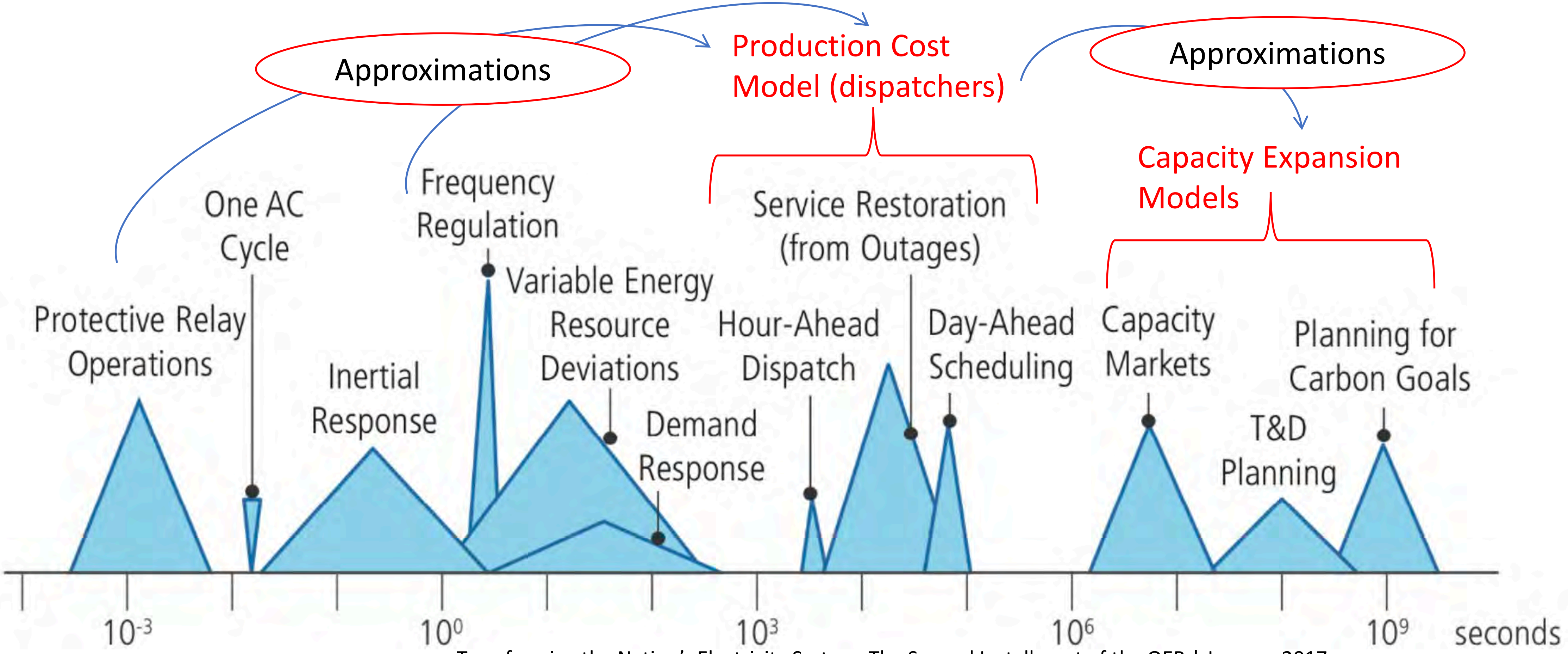
Grid Timescale

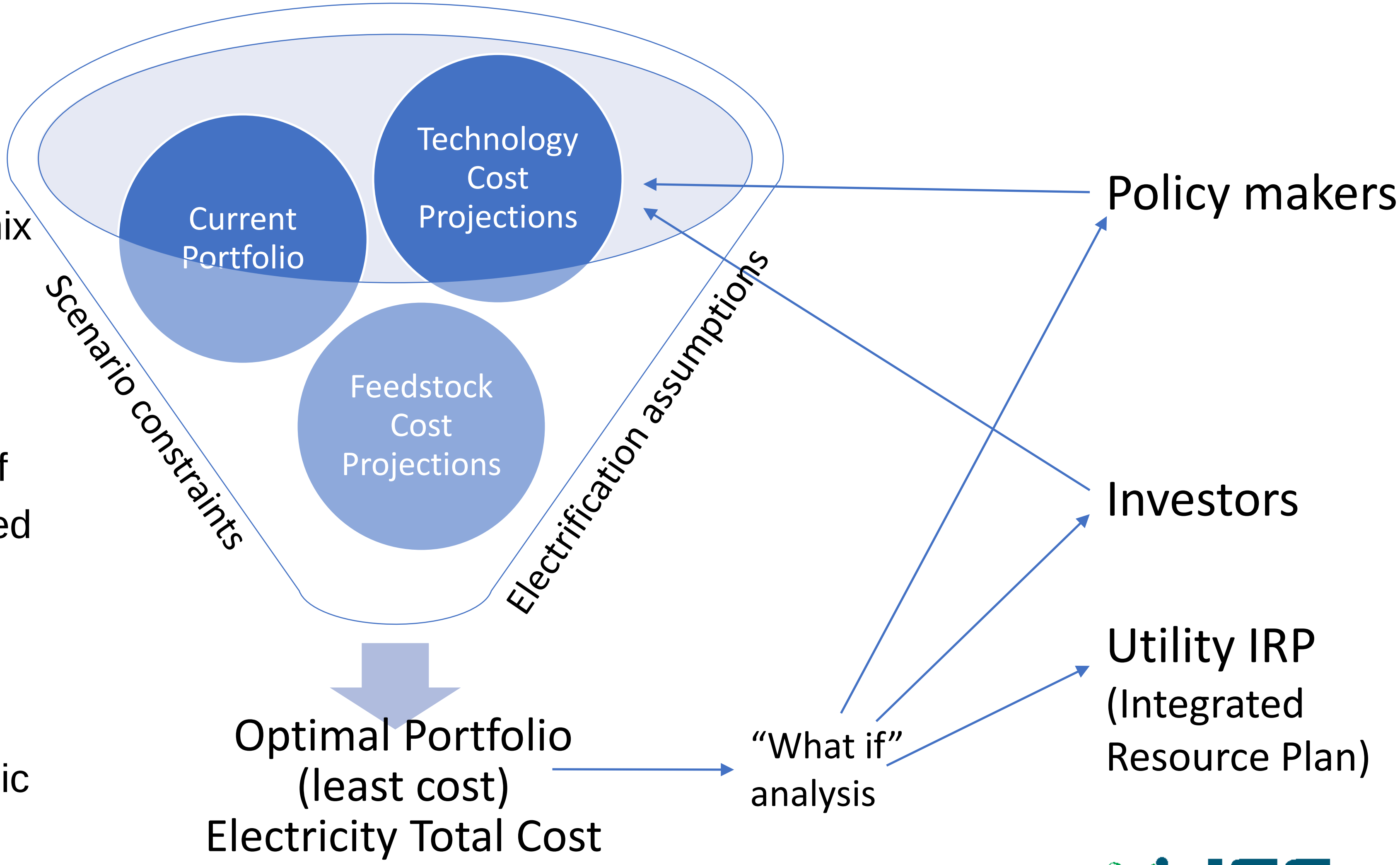


Transforming the Nation's Electricity System: The Second Installment of the QER | January 2017

Changes in the portfolio mix (VRE, batteries, decrease of large generators) and technological assumptions (IES, plant lifetime, etc.) are outdating current models

Scenario Modeling: Capacity Expansion Model (CEM)

- Covers the whole U.S. or large U.S. regions
- The prediction of the portfolio mix evolution is highly sensitive to initial conditions
- Creates a nonlinear feedback of externalities that are not modeled
- Time horizon: 30 or more years
- Designed for long-term economic equilibrium



CEMs: What type of information is generated?

- Outputs:
  - Projected portfolio composition
  - Increase/decrease in cost of electricity
  - CO_2 emissions

- “What if scenarios” are considered with respect to
  - Policy: Impact of current and potential new policies that constrain the portfolio composition
  - Technology maturation: Impact of changes in technology costs and capabilities
  - Resources: Changes in the feedstock (e.g. gas) supply availability and price

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How results from CEMs are used

- Used by federal organizations to inform policy makers concerning how achievable goals may be, and at what costs; possible goals include:
  - CO_2 emission limits
  - energy independence
  - portfolio diversification
  - grid reliability

Scenario studies have a strong feedback mechanism!!

- Research organizations (e.g., DOE offices) – to prioritize the research budgets to meet technology deployment goals
- Large private companies – to prioritize research and capital investments, and as input to energy planning
- International organizations (e.g., OECD, IAEA) and developing nations also rely on scenario analyses in development planning

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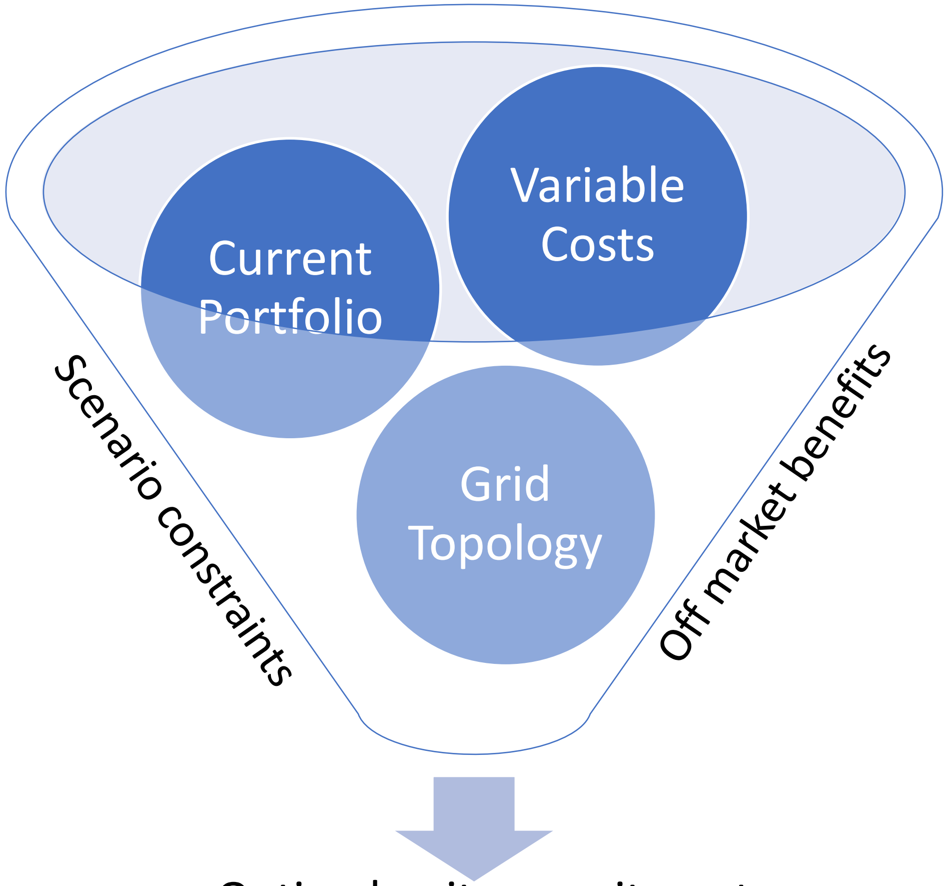
Production Cost Models (PCMs)

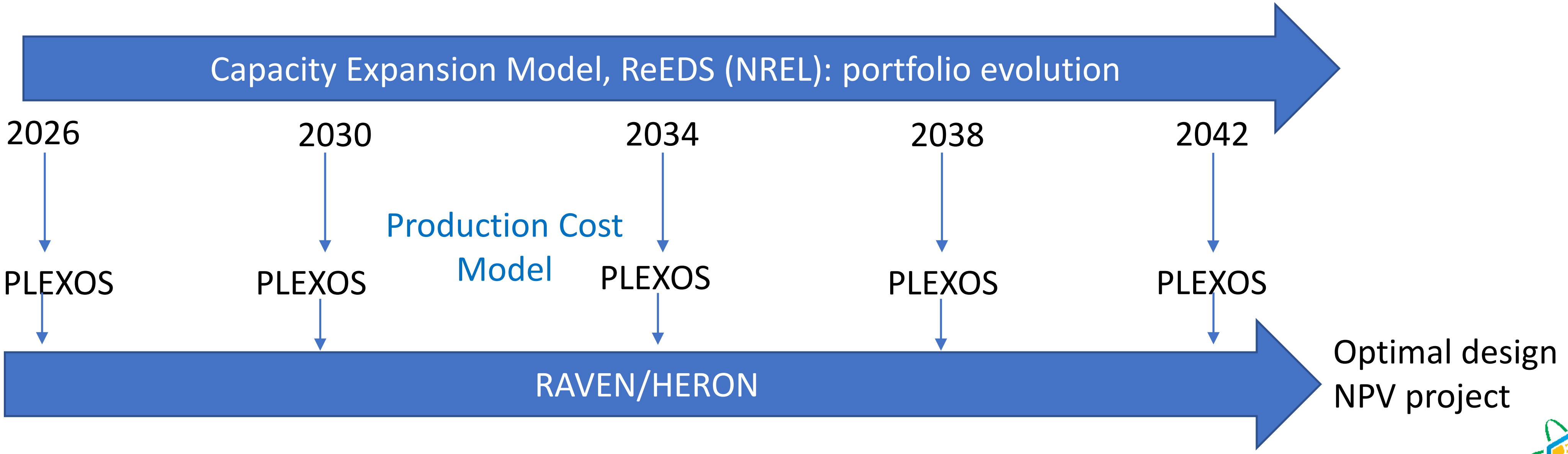
- Cover large regions with different levels of fidelity
- Time horizon: 1 year
- Independent from deregulated or regulated market assumption



Optimal unit commitment
Electricity cost (only marginal cost)
Information on ancillary services

How Production Cost Models are Used

- Testing dispatch strategies
- Evaluating grid congestion problems
- Predicting unit revenues
- Reserve adequacy estimation
- Example, Exelon Case:



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Areas for Possible CEM Improvements in the Approach to Nuclear Energy Technologies

Nuclear technology representation

- Nuclear power plant sizes
- License extension
- Economic dispatch (i.e., load following)
- Progressive capacity addition (multi-module SMRs, uprates, etc.)

Market

- Least cost vs. market driven
- Outside market subsidy
- Market elasticity (only some tools)

Definition of global system costs

- Waste management and environmental impacts
  - Spent fuel management
  - Environmental impacts management (e.g. decommissioning, CO_2 emission)
- Life cycle costs

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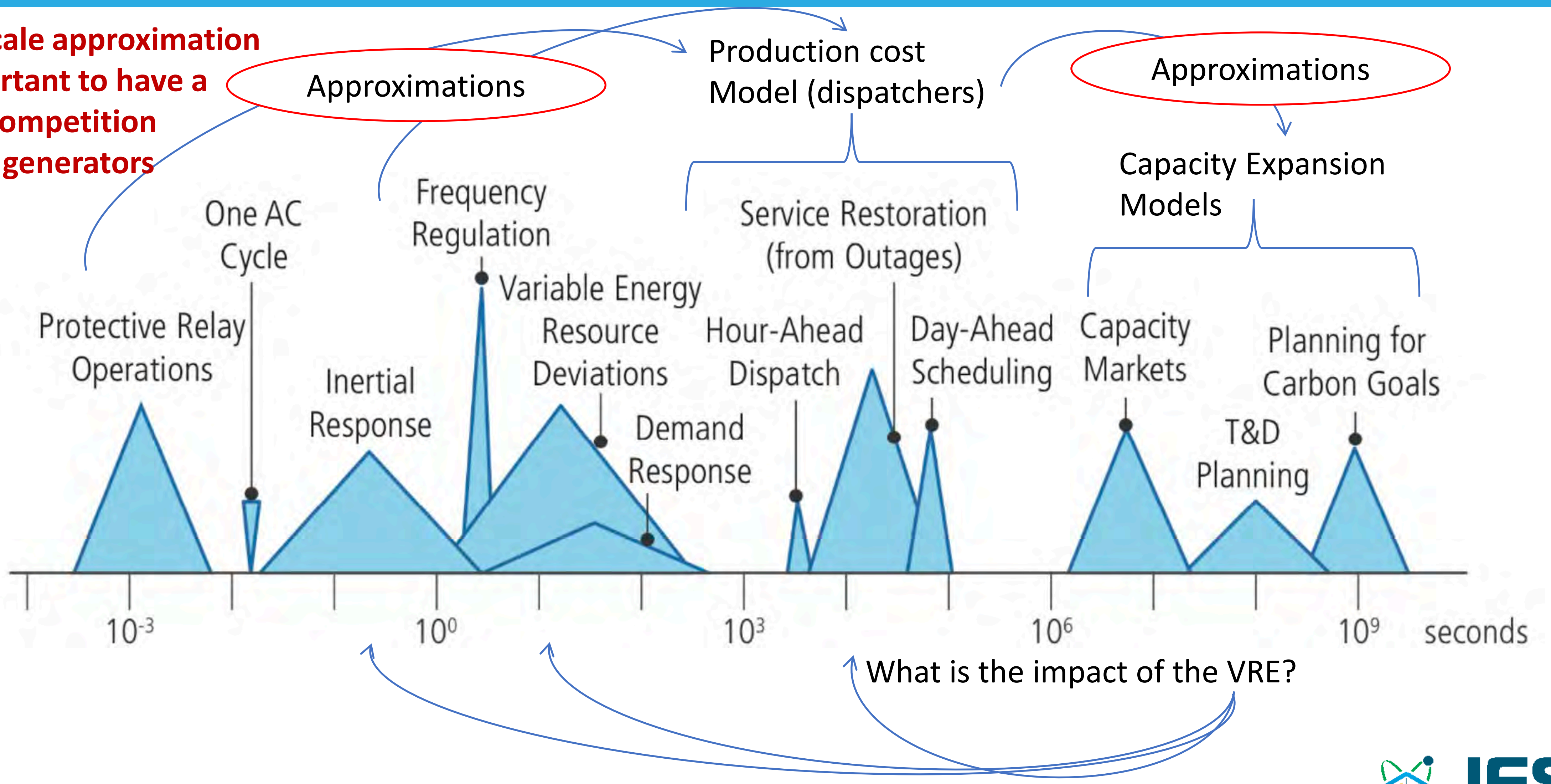
Areas of Possible Improvements (CEM): Multiscale Approximation

Multiscale approximation is important to have a "fair" competition among generators



To capture the cost/benefit of changes in the portfolio all scales need to be accounted for

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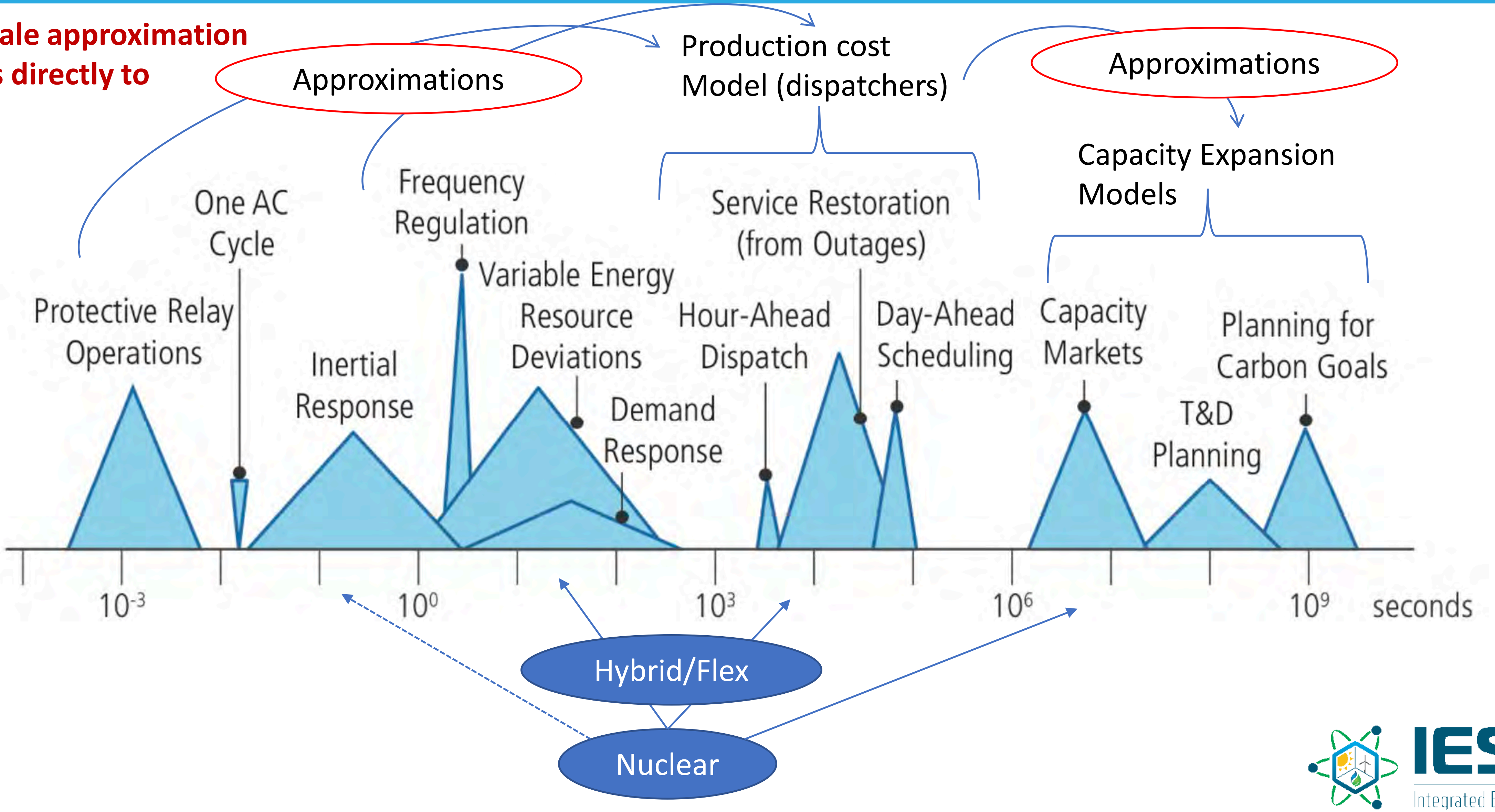
Areas of Possible Improvements (CEM): Multiscale Approximation

Multiscale approximation matters directly to nuclear



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Areas of Possible Model Improvements for PCM

- Similar to CEMs, PCMs contain multiple time scale approximations
- Not used to cover more than one year (computational limit), therefore neither grid expansion nor capacity portfolio changes can be assessed
- Ramp rates are linear (missing important memory effects)
- Uncertainties in demand and VRE production are seldom accounted

Energy Market Modeling Takeaways

- Modelling of the techno-economic aspects of nuclear technology can be improved; this appears feasible with the currently available CEMs
  - Current CEMs mostly model nuclear with one option – a GW-scale LWR operating as baseload with a 40-60 year life
  - Key additions would include modeling of more types and sizes of reactors, load following, etc., and assessment of modeling assumptions for any bias and estimate impacts
- Market representation can be improved; this appears feasible with the currently available CEMs
- Total life cycle cost, while more challenging, provides a more balanced approach for evaluating competing generation technologies
- Risk metrics (uncertainties) should be introduced
- Multiscale approximations are sensitive to portfolio mix, which might lead to bias in the predictive results

ANALYSIS OF INNOVATIVE NUCLEAR TECHNOLOGIES FOR CURRENT AND FUTURE ENERGY SYSTEMS

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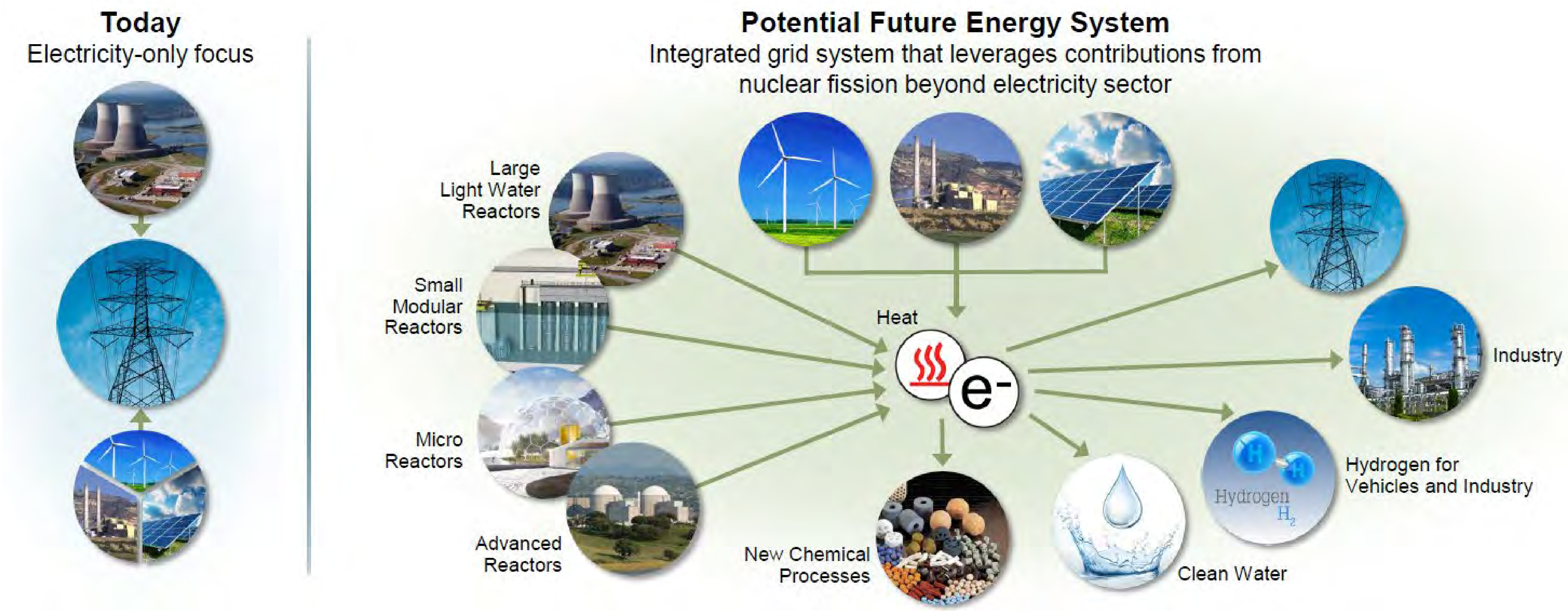
Maximizing energy utilization, generator profitability, and grid reliability and resilience through systems integration



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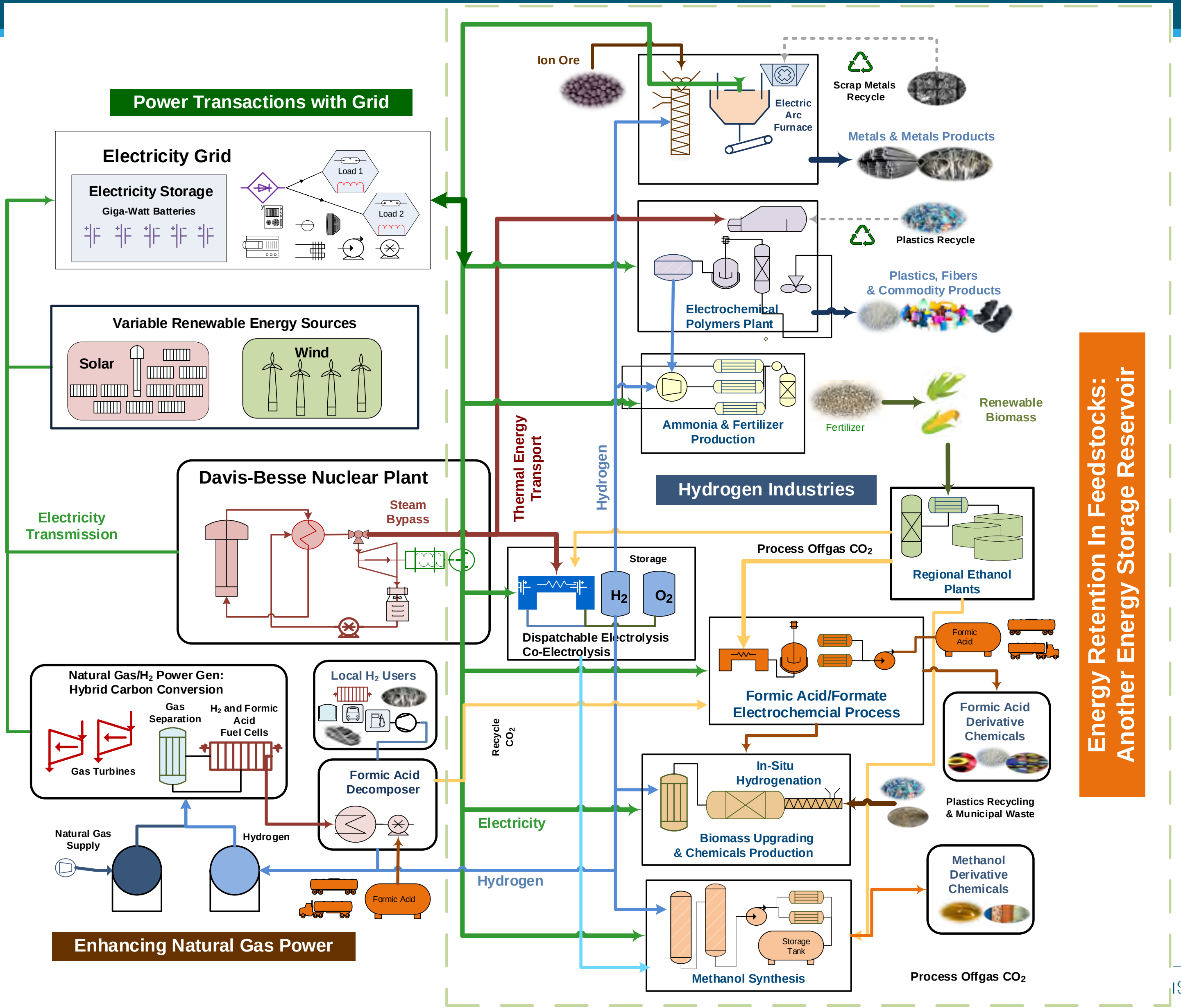
New Technology for Energy Transport, Conversion & Storage with IES

Integrated Energy Systems Involve:

- Thermal, electrical, and process intermediates integration
- More complex systems than co-generation, poly-generation, or combined heat and power
- May exploit the economics of coordinated energy systems
- May provide grid services through demand response (import or export)

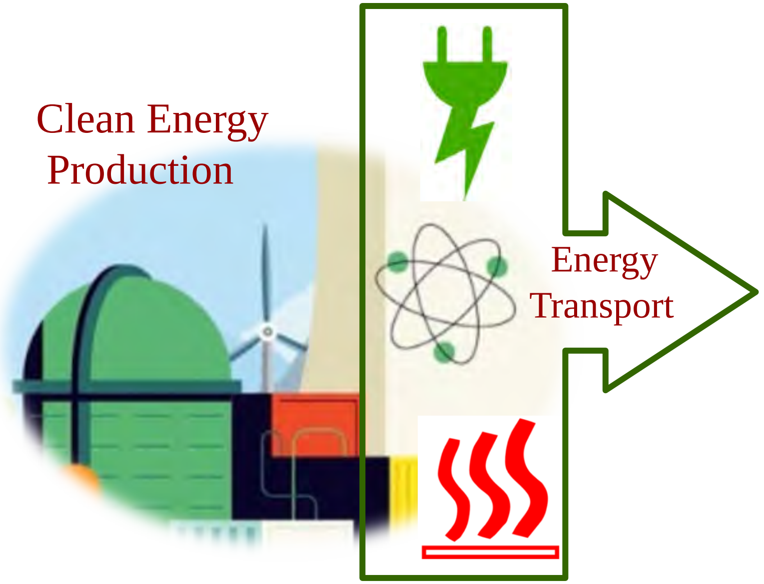
Technology Development Needs & Opportunities:

- New energy storage technologies (thermal, chemical, and electrical)
- Thermo-Electrical chemical conversion processes
- Modern advanced informatics and decision systems for massive data
- Embedded sensors for health monitoring and cyber security

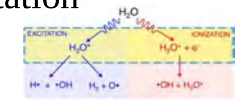


A new paradigm for nuclear energy

- Direct tie to plant substation for electricity dispatch
- Independent steam loop to support thermal duties (e.g. storage, industrial plants)
- Produce energy carriers such as hydrogen and other chemical feedstock

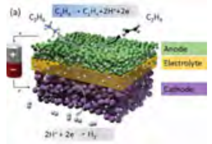


Process Electrification
- Water Electrolysis (AE and PEM)
- Desalination with RO
- Non-thermal plasmas excitation



Process Intensification
- Steam Electrolysis/Co-Electrolysis (HTSE)
- Advanced catalysis
- Electro/thermal conversion applications

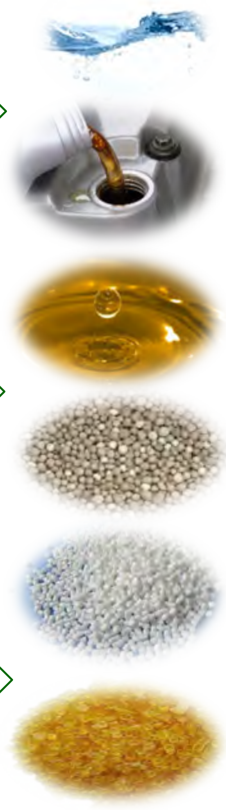
Evolutionary Direct Conversion
- Proton-conducting ceramics
- Multi-functional micro chemical reactors
- Proton initiating CO_2 reduction
- Nitrogen fixation



Fresh Water
Hydrogen Reformate

Syngas & Hydrogen
Chemical Feedstock

Polymers & Mixed Alcohols



Water
Lubricants
Fuels
Fertilizers
Polymers
Specialty Chemicals

DOE-NE Crosscutting Technology Development IES

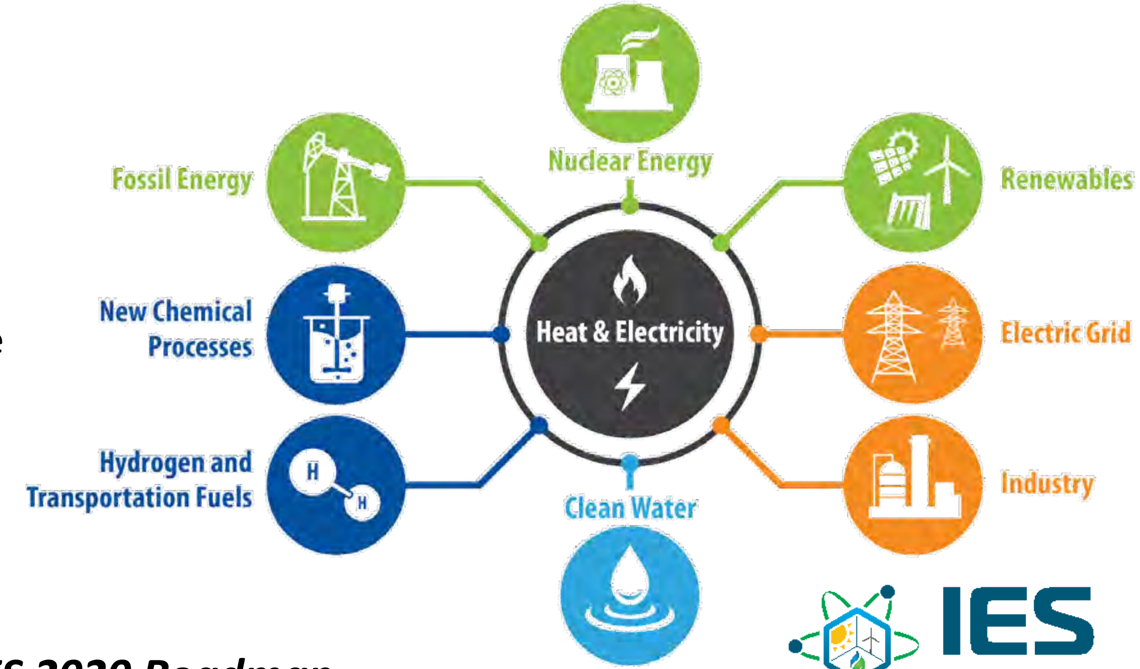
Mission: Maximize energy utilization, generator profitability, and grid reliability and resilience through novel systems integration and process design, using nuclear energy resources across all energy sectors in coordination with other generators on the grid.

Vision: A robust and economically viable fleet of light-water and advanced nuclear reactors available to support US clean baseload electricity needs, while also operating flexibly to support a broad range of non-electric products and grid services.

Goals: The IES program develops tools and technologies that will lead to demonstration of multiple integrated energy systems that have a clear path toward commercialization. Timelines follow the associated reactor concepts and designs (current fleet now, SMRs 1-5 yrs, non-LWR 5-15 years).

Strategic R&D Areas:

- ***System Simulation***. Develop and exercise an ecosystem for modeling, analysis, optimization of IES that can accommodate various reactor types, renewable technologies, and energy users.
  - ***Economic Analysis.*** Establish a reference capability to validate current practices in valuing nuclear energy in the energy market (electric and non-electric).
- ***Experimental Evaluation***. Establish and operate a fully-functional and diverse non-nuclear facility for model validation and initial technology demonstration.



Issued updated IES 2020 Roadmap

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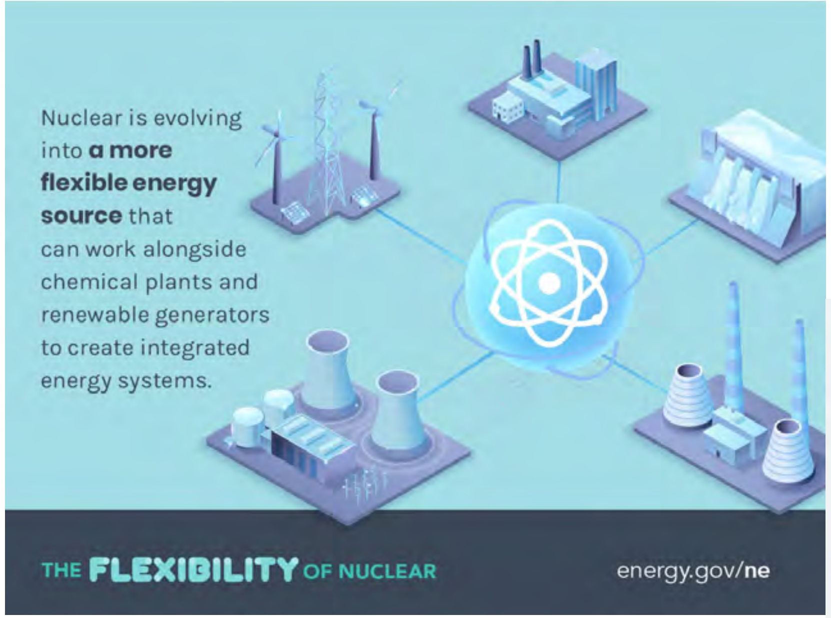
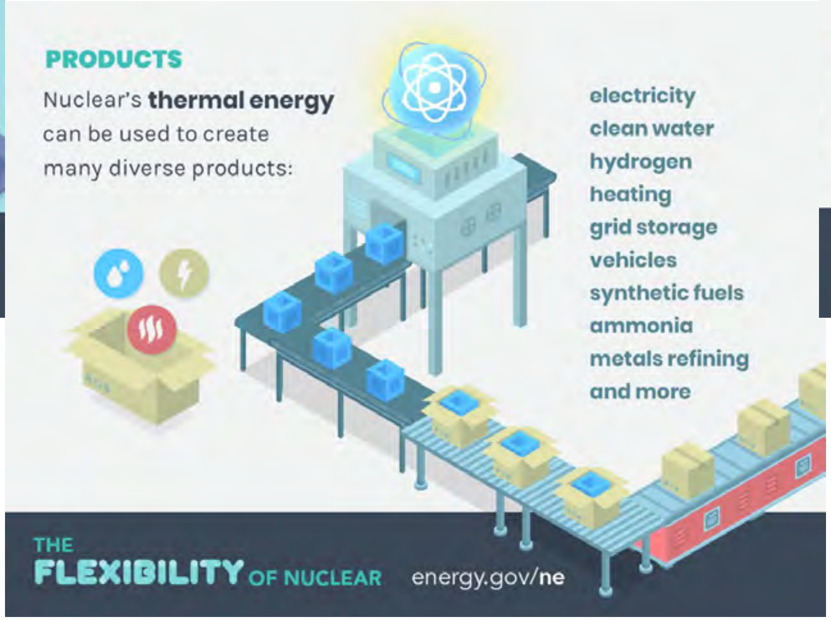
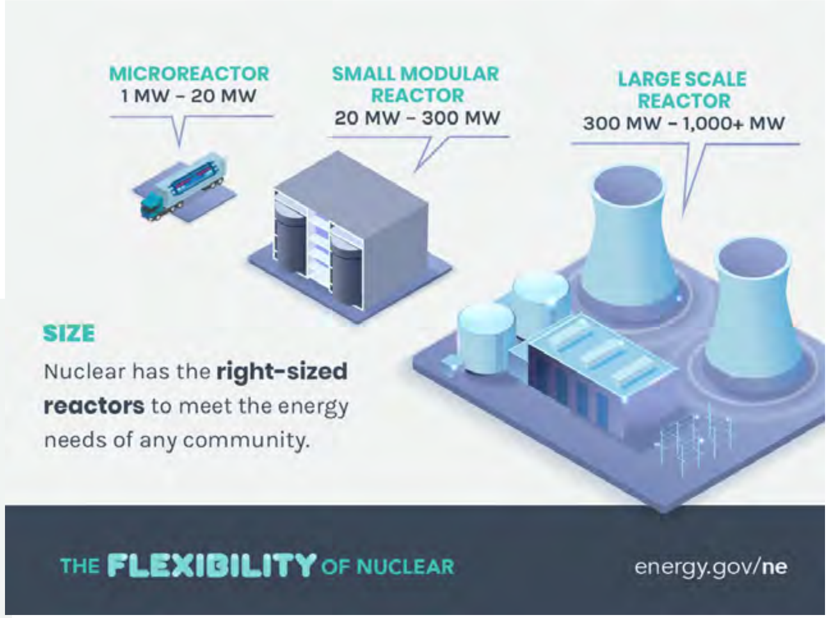
IES—A key opportunity for flexibility

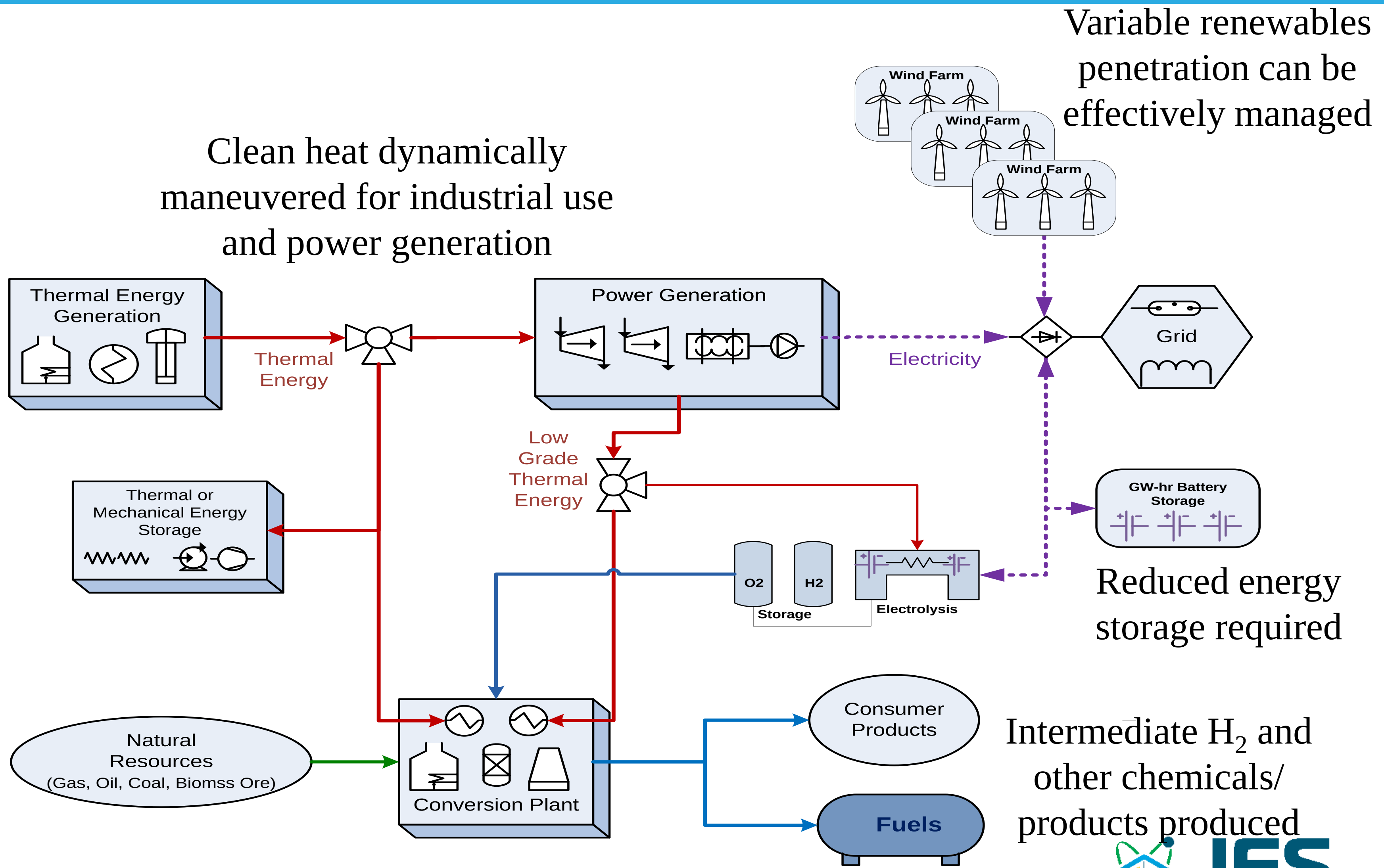






Evaluation of Candidate IES

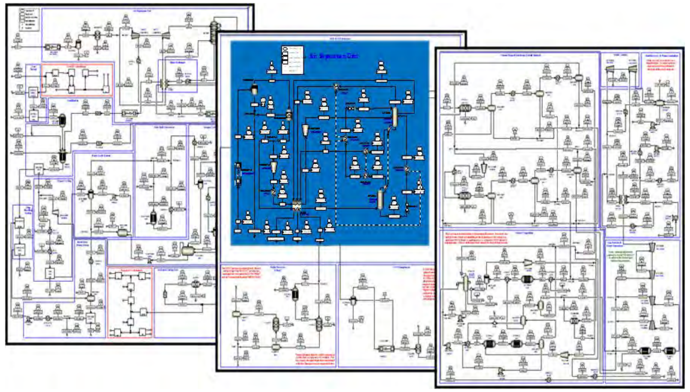
- **Technical Feasibility:** Tightly coupled systems involve dynamic exchange of energy streams, process conditions data, and diagnostics/ prognostics control commands.
- **Economic Feasibility Requires Efficient Capital Utilization:** The impact of improved capital utilization, increased reliability, and enhanced maintainability on overall plant revenue must be characterized and understood.



Energy System Modeling, Analysis, and Evaluation for Energy System Optimization

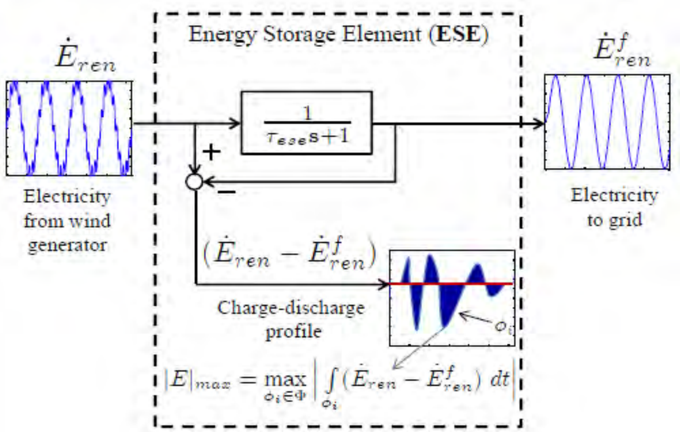
Graded approach to identify design, and evaluate hybrid system architectures

Aspen Plus® and HYSYS® Process Models



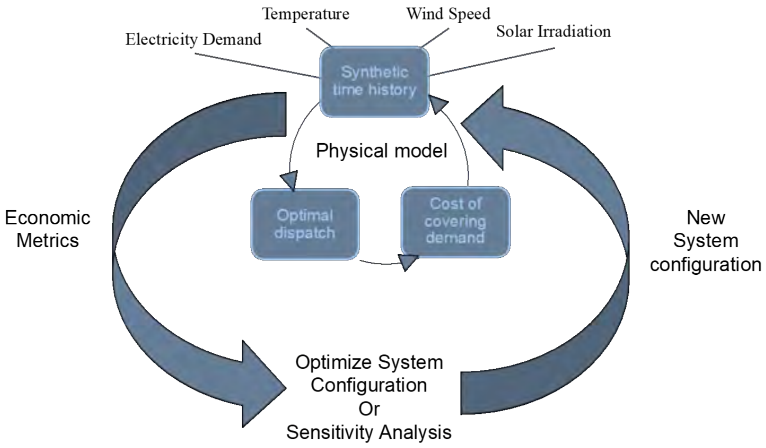
Process modeling addresses technical and economic value proposition

Modelica®, Aspen Dynamics®



Dynamic modeling addresses technical and control feasibility

RAVEN (INL System Optimization)



System modeling addresses whole-system coordination

Consideration of Resource—Technology—Economic—Market Potential

IES Integrated Energy Systems

Technical & Economic Assessments (TEA)

Resource Potential

- Market size
- Resource availability
- Resource attributes
- Infrastructure requirements

Technology Potential

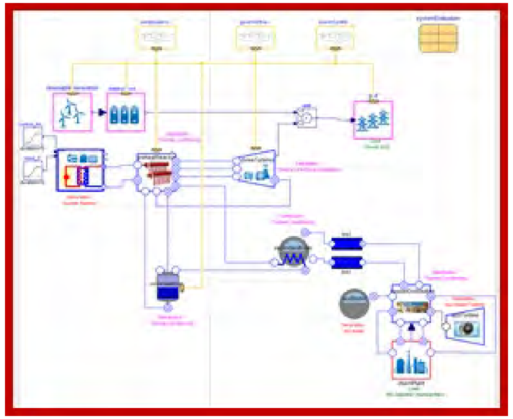
- Thermodynamics
- Performance
- Systems integration and control

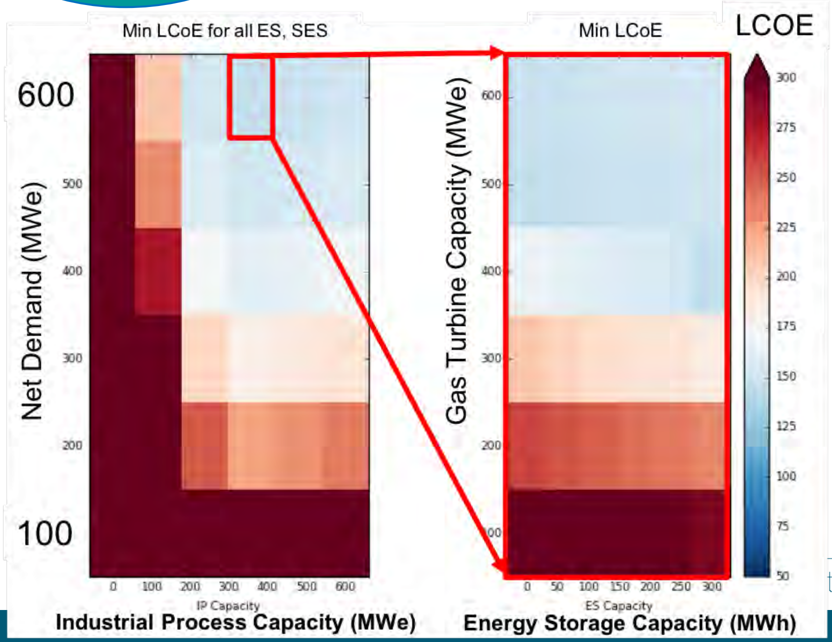
Economic Potential

- Pro forma
- ROI / IRR
- Cash Flow

Market Potential

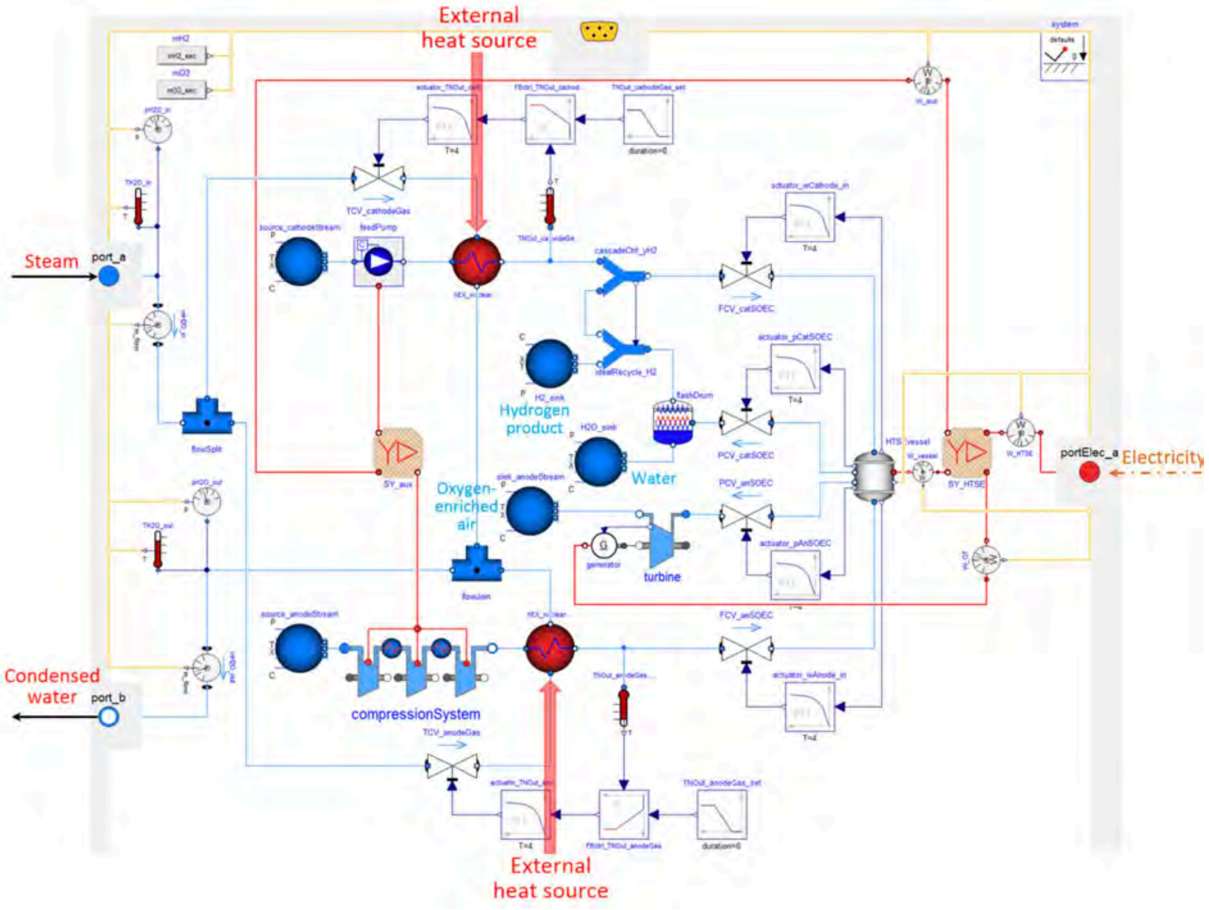
- Competition
- Policy, Regs





IES: Physical Asset Models

- **Provide high fidelity system model for short time scales**
- The IES program has developed several detailed dynamic models:
  - LWRs (PWRs, SMRs)
  - High Temperature Steam Electrolysis (H_2)
  - Reverse Osmosis
  - Gas Turbine
  - Batteries
- New models are currently being developed
  - Heat storage
  - Advanced reactors



HTSE Modelica Model

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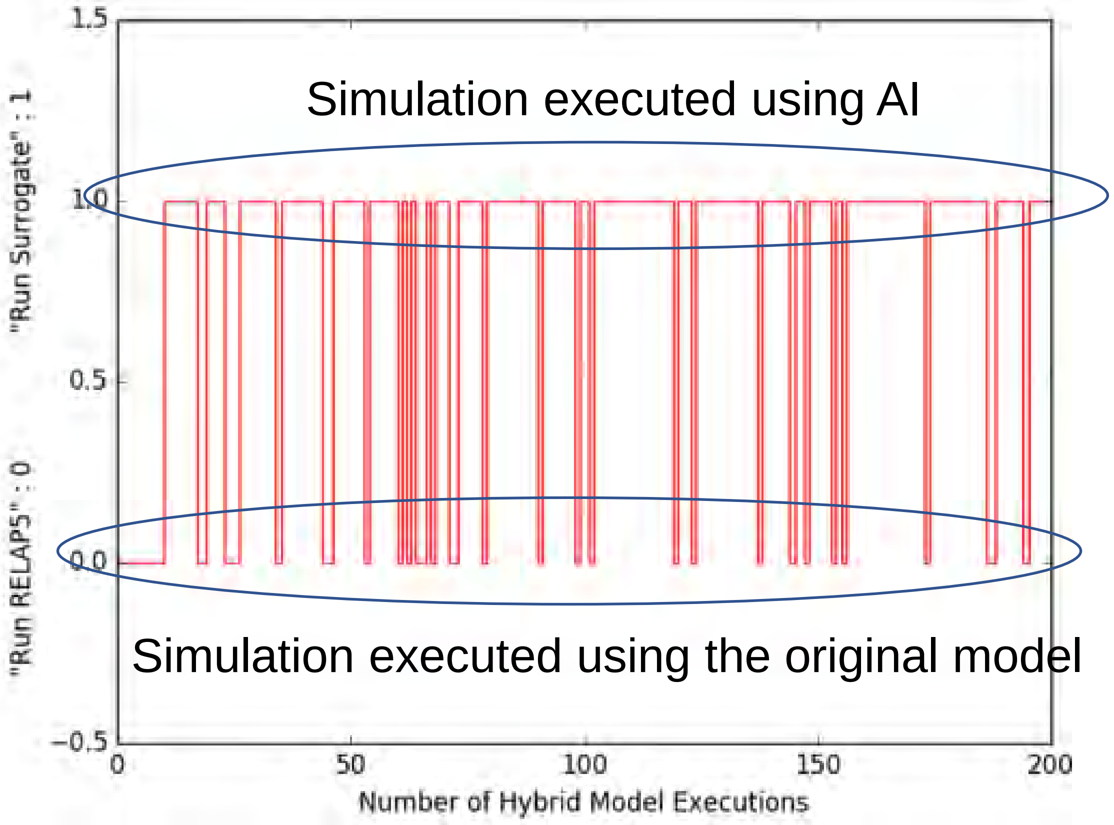
IES: Artificial Intelligence (AI, Supervised Learning) Generation and Validation

- Addresses computational cost of probabilistic analysis
  - AI is used to develop surrogate models for complex, computationally expensive, physical models
  - Concepts such as the hybrid model in RAVEN are currently being extended to time dependent AI (supervised learning)
  - AI validation is being tuned for these applications



- Needed 1000 simulations to generate a good statistic
- AI learned to replace the original simulation
- Only about 200 simulations were executed using the real model

IES Integrated Energy Systems

Energy Market Modeling Study Areas, Opportunities for Enhancement

- Ability to accommodate a more complex set of nuclear generation options, timelines for capacity addition, and capital expenditures
- Capability of a nuclear power plant to be dispatched based on marginal cost, i.e., allowing for load following (shallow/deep)
- Assess which direct and indirect costs and benefits are considered and possible impacts of excluded costs and benefits on the optimal portfolio
- CEMs are based on a least system cost approach; assess how, in deregulated markets, this calculation approach may miss the actual basis used by decentralized decision makers to construct or retire plants
- Assessment of the time slice approximation to determine the impact on reserve requirements, ancillary systems, inertia, etc., and on market share projections of generation technologies and storage; explore options for improvement
- Inclusion of Integrated Energy System approach
    - Volatility absorption (resulting in decreased need for ancillary services, reserves, etc.)
    - Additional revenue streams (e.g., non-electricity products, heat applications)
- Model uncertainties need to be quantified, and the impact of these uncertainties needs to be characterized and communicated, including their impact on financial analyses

IES
Integrated Energy Systems

IES Plant Modeling and Simulation Scope

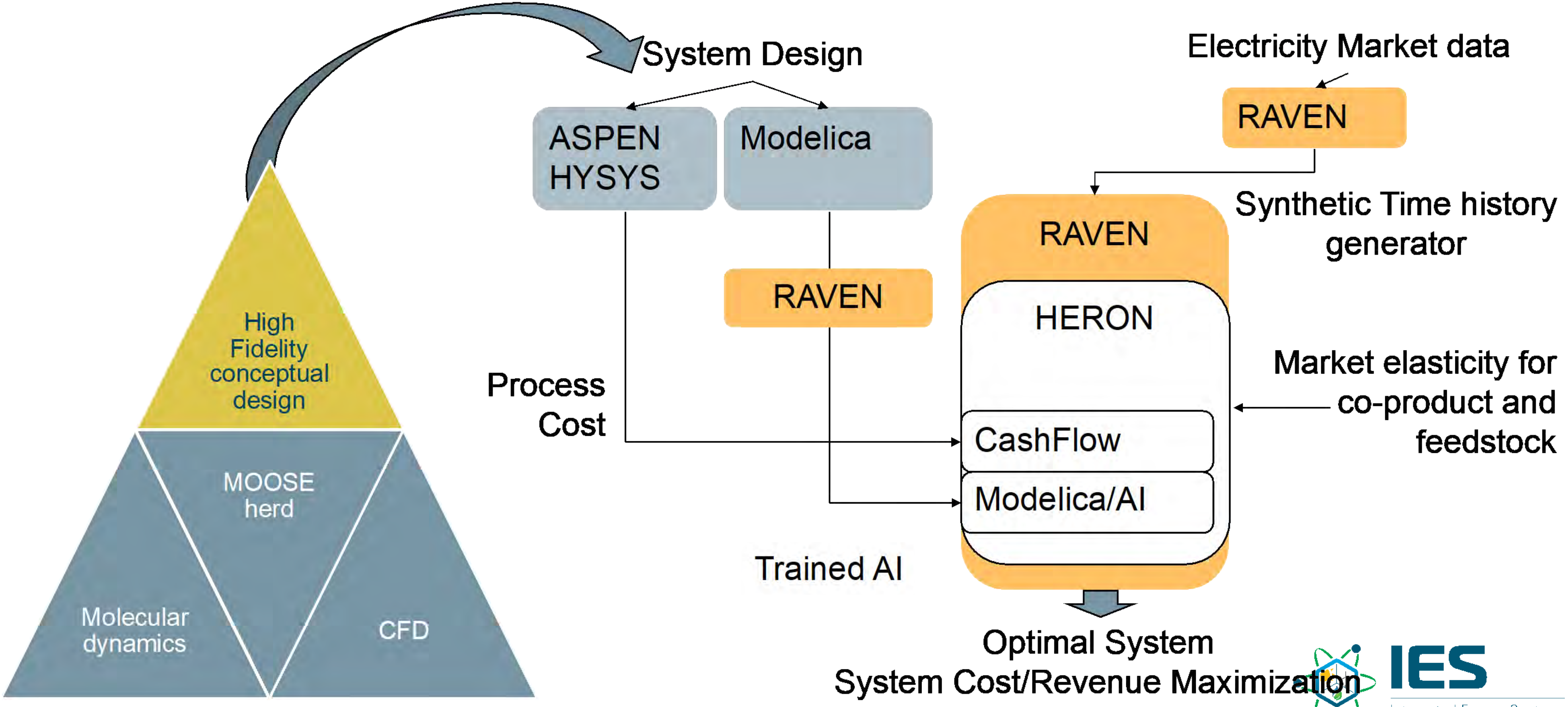
- Connect the technical aspects with the economic analysis
- Assess the cost of inserting volatility or, in other terms, the benefits of absorbing volatility is necessary to assess the system impact
- System costs driven by volatility arise at all time resolutions (hourly, five minutes, seasonally)
- The physical modeling of the system become more and more relevant (system inertia) as the time scale decreases

IES Integrated Energy Systems

Financial Framework

- System cost approach (profit analysis is also feasible)
- The system must cover (net) demand with high reliability
- The question to be answered is if the integrated energy system helps to decrease the costs of electricity
- We use the term LCOE (levelized cost of energy/electricity), but in reality it is an effective levelized cost of covering demand

Financial Analysis Workflow



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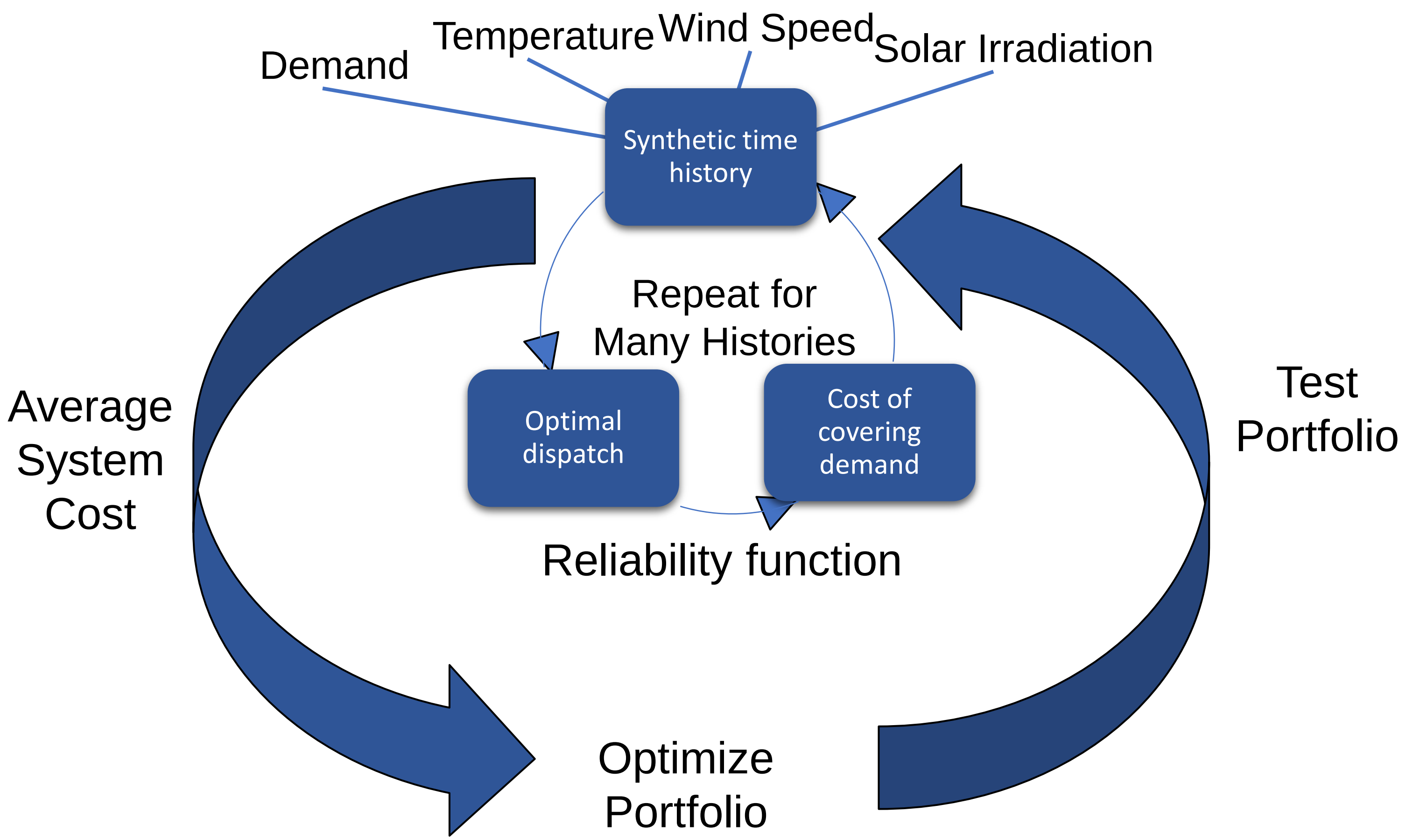
Overall RAVEN Optimization Scheme



INL-developed code for optimization: RAVEN

Reactor **A**nalysis and **V**irtual Control **EN**vironment (RAVEN)

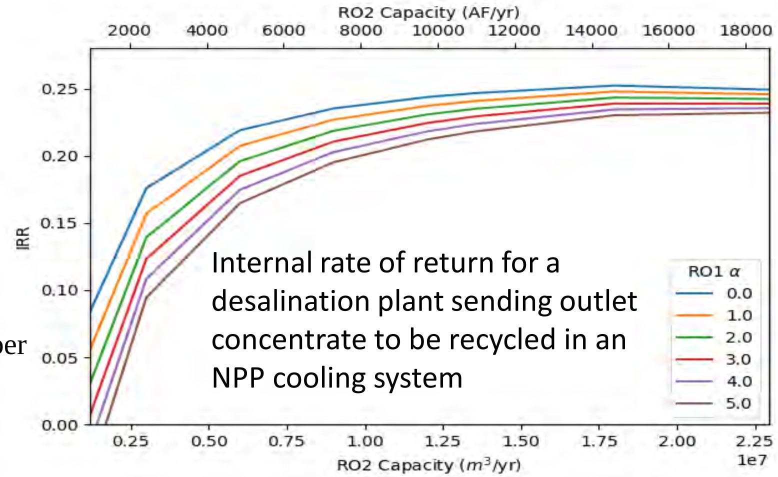
Allows researchers to understand and manage the probabilistic nature of complex systems and their numerical representation

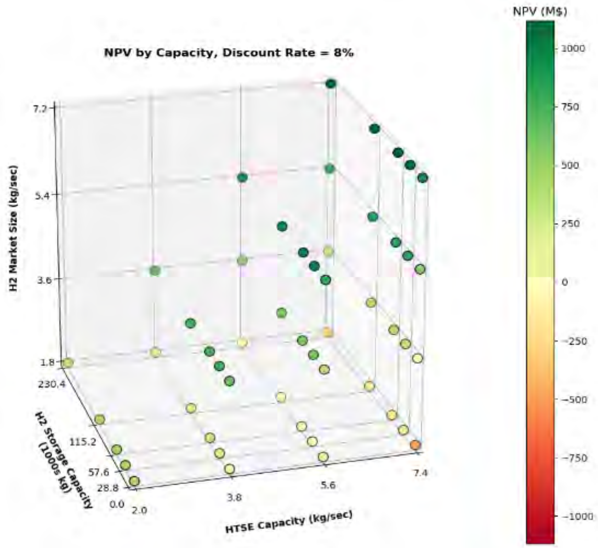
Goal: Optimize economic performance under technical performance constraints and assurance of grid resilience.

IES Open Source Software Tools

TEAL

A. Epiney, et al., Case Study: Integrated Nuclear-Driven Water Desalination—Providing Regional Potable Water in Arizona, September 2019, INL/EXT-19-55736





HERON

R. Boardman, et al., Net Present Value Parametric Study for Hydrogen Production Using HERON (INL/EXT-55395)

- INL released two new RAVEN plug-ins to support Flexible Power Operation and Generation and overall Integrated Energy System (IES) design and optimization
- TEAL (Tool for Economic AnaLysis) is a tool designed to support Net Present Value (NPV)/Cash Flow analysis for energy systems
  - TEAL can be downloaded at: https://github.com/idaholab/TEAL
- HERON (Holistic Energy Resource Optimization Network) enable optimization of IES design, including component sizing for multiple energy generators and energy users
  - HERON can be downloaded at: https://github.com/idaholab/HERON

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Andrea.Alfonsi@inl.gov

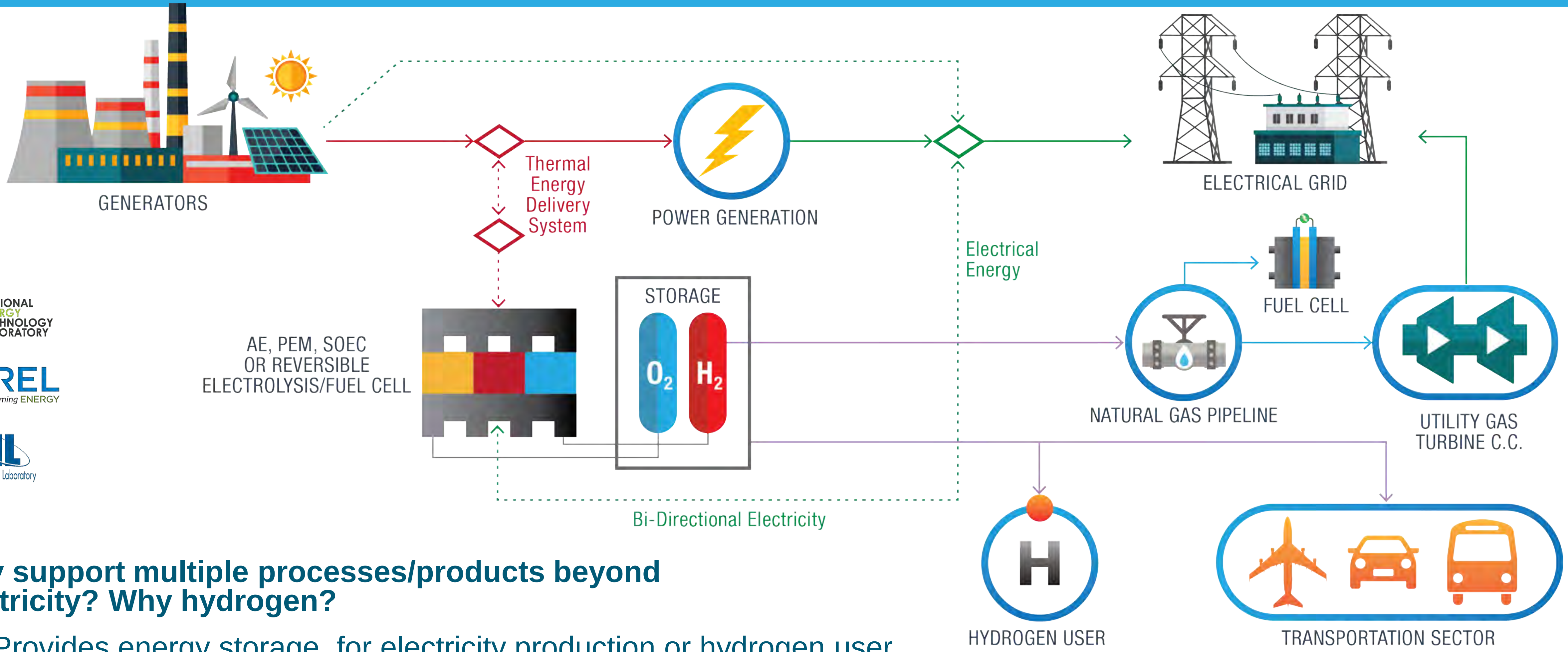
IES Integrated Energy Systems

We Are Breaking New Ground

- Other efforts exists to optimize energy systems
- What makes the IES approach different
  - Nuclear has different requirements that must be considered
    - NQA 1
    - Safety, licensing
    - Reactor operation
  - Full probabilistic approach is unique
  - Detailed system dynamics
- Leveraging existing and ongoing efforts and toolsets to further enhance analysis and system optimization capability

IES
Integrated Energy Systems

Example: Hydrogen Production via Electrolysis



Why support multiple processes/products beyond electricity? Why hydrogen?

1) Provides energy storage, for electricity production or hydrogen user (e.g., chemicals and fuels synthesis, steel manufacturing, ammonia-based fertilizers)
2) Provides second source of revenue to the generator
3) Provides opportunity for grid services, including reserves and grid regulation

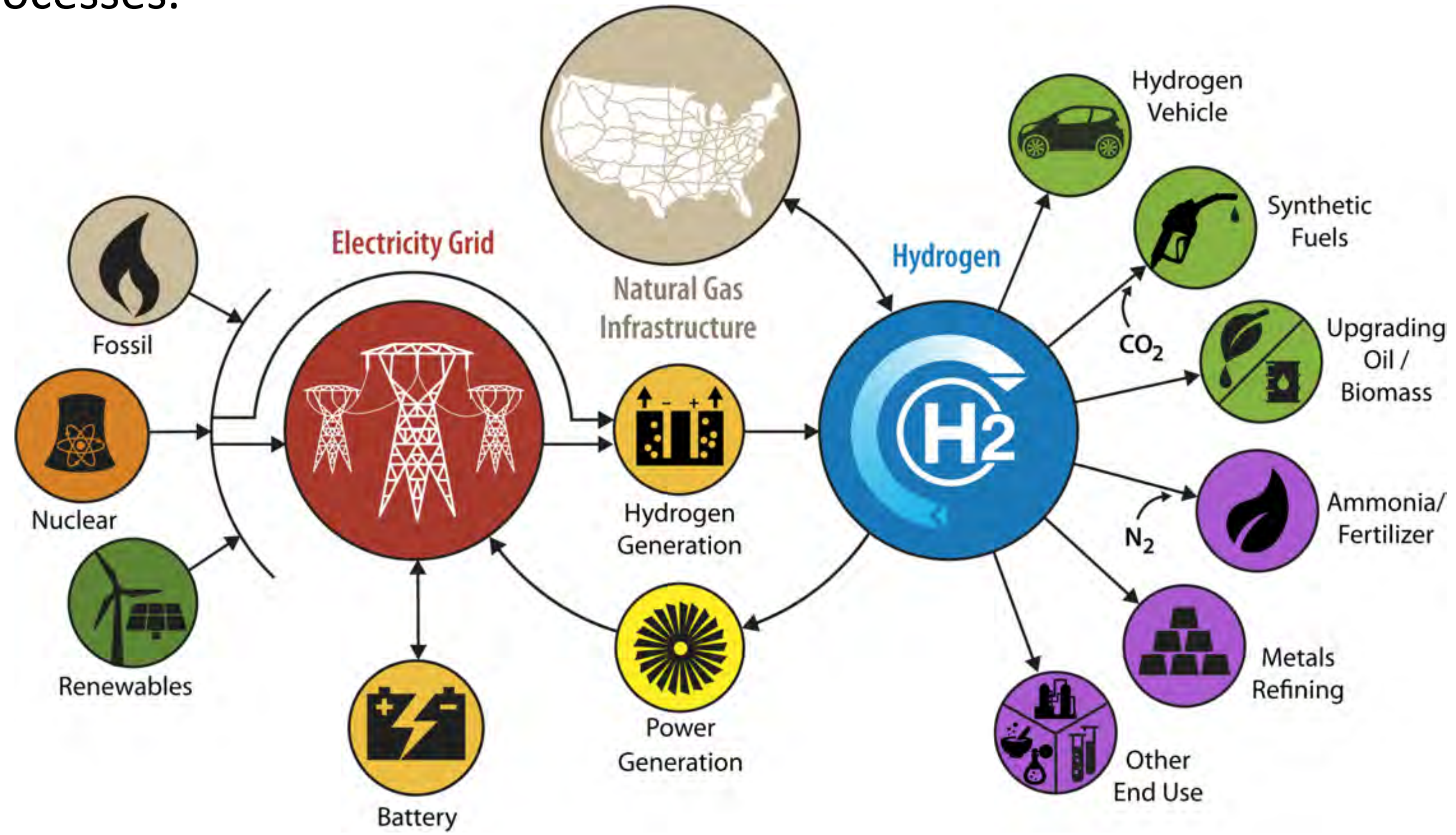
High Priority Application: Conceptual H_2@Scale Energy System*

Can hydrogen effectively be a new energy currency for LWRs?

Vision: Leverage hydrogen's unique ability to address cross-energy sector issues and to enable clean, efficient industrial and transportation processes.

Hydrogen Attributes:
- Clean and convenient energy carrier
- Scalable energy storage
- Vital to fuels and chemicals production
- Used to upgrade coal to higher value products

Other key H2@Scale Benefits:
- Provides grid resiliency
- Deeply reduces air pollutant emissions



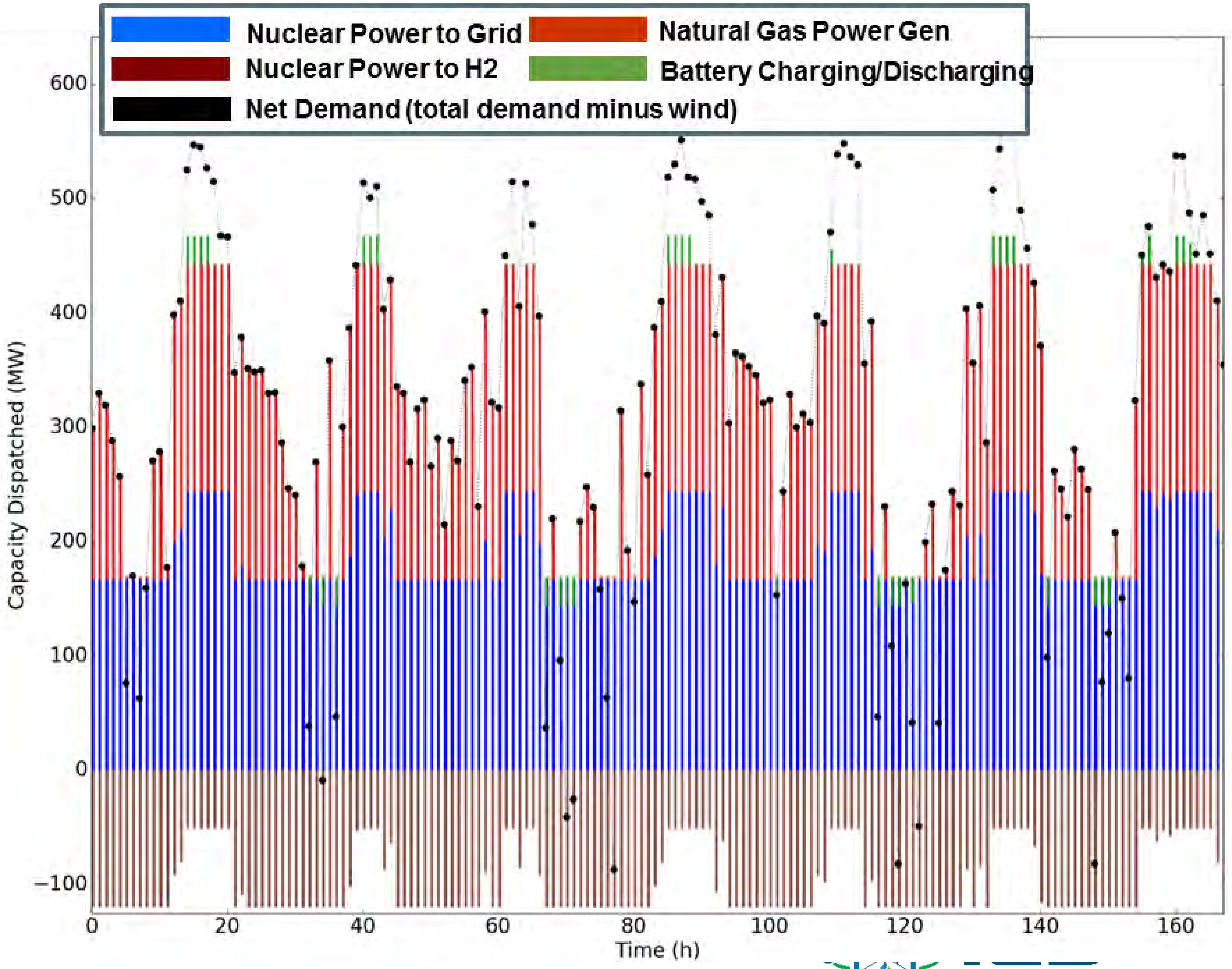
*H2@Scale is a complementary, collaborating program supported by the DOE Energy Efficiency & Renewable Energy Fuel Cell Technologies Office.

*Illustrative example, not comprehensive

IES Integrated Energy Systems

Example Optimized Hybrid System Performance Results
INL-Developed Toolset

- **System design optimization using time histories for one year**
- **Results shown for a selected time history, one week period (hourly resolution)**
- **Optimized component capacities**
  - Nuclear Reactor 300 MW_e
  - Hydrogen Plant Capacity 120 MW_e
    (shown as negative – electricity input; 70% turndown limit; H_2 market price - \$1.75/kg-H_2)
  - Gas turbine 200 MW_e
  - Electric battery 100 MWh
  - Wind penetration 400 MW_e
    (100% of mean demand, installed capacity, 27% capacity factor)
  - Penalty function applied for over or under production of electricity.



Rabiti and Epiney, INL, 2018

Integrated Energy Systems

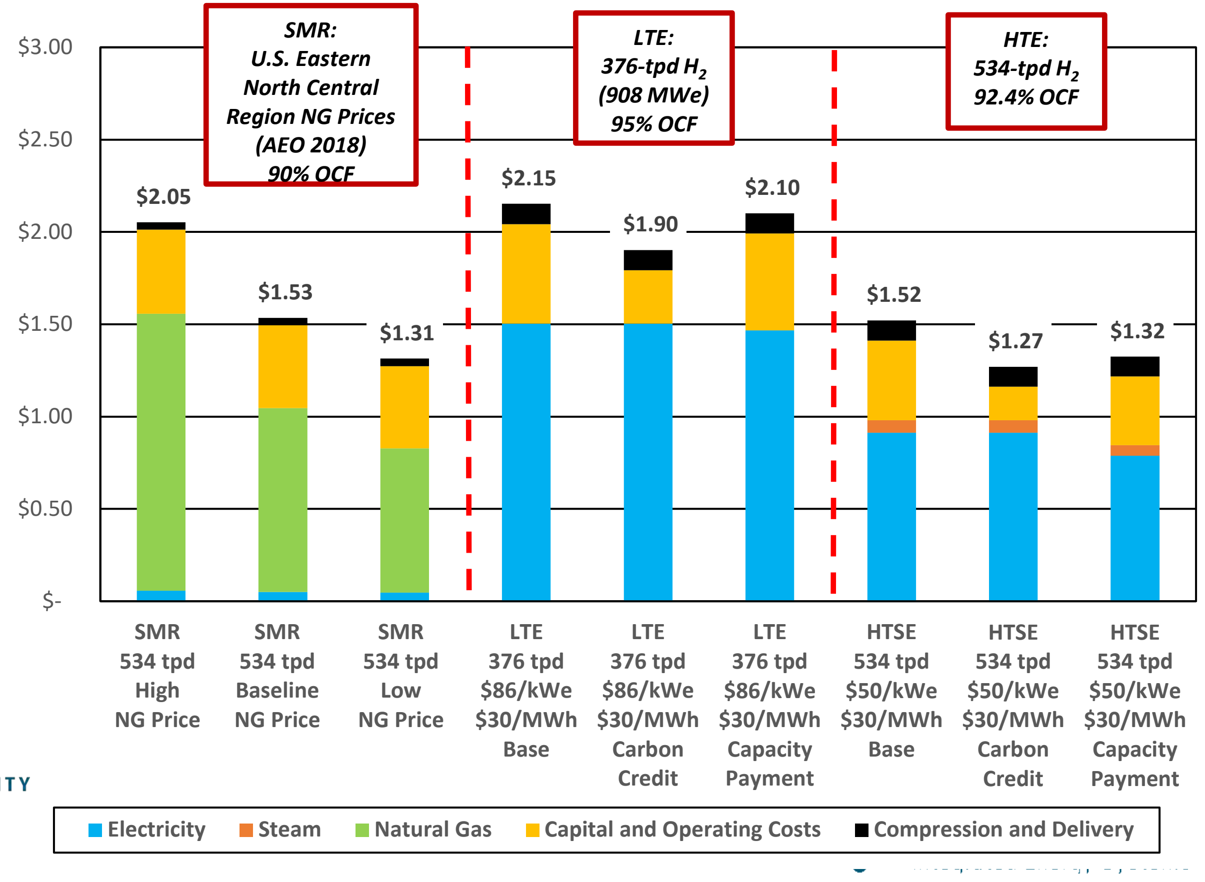
Recent Hydrogen Production Analyses for Current Fleet LWRs

INL issued public-facing reports on in FY19 that provide the foundation for demonstration of using LWRs to produce non-electric products:

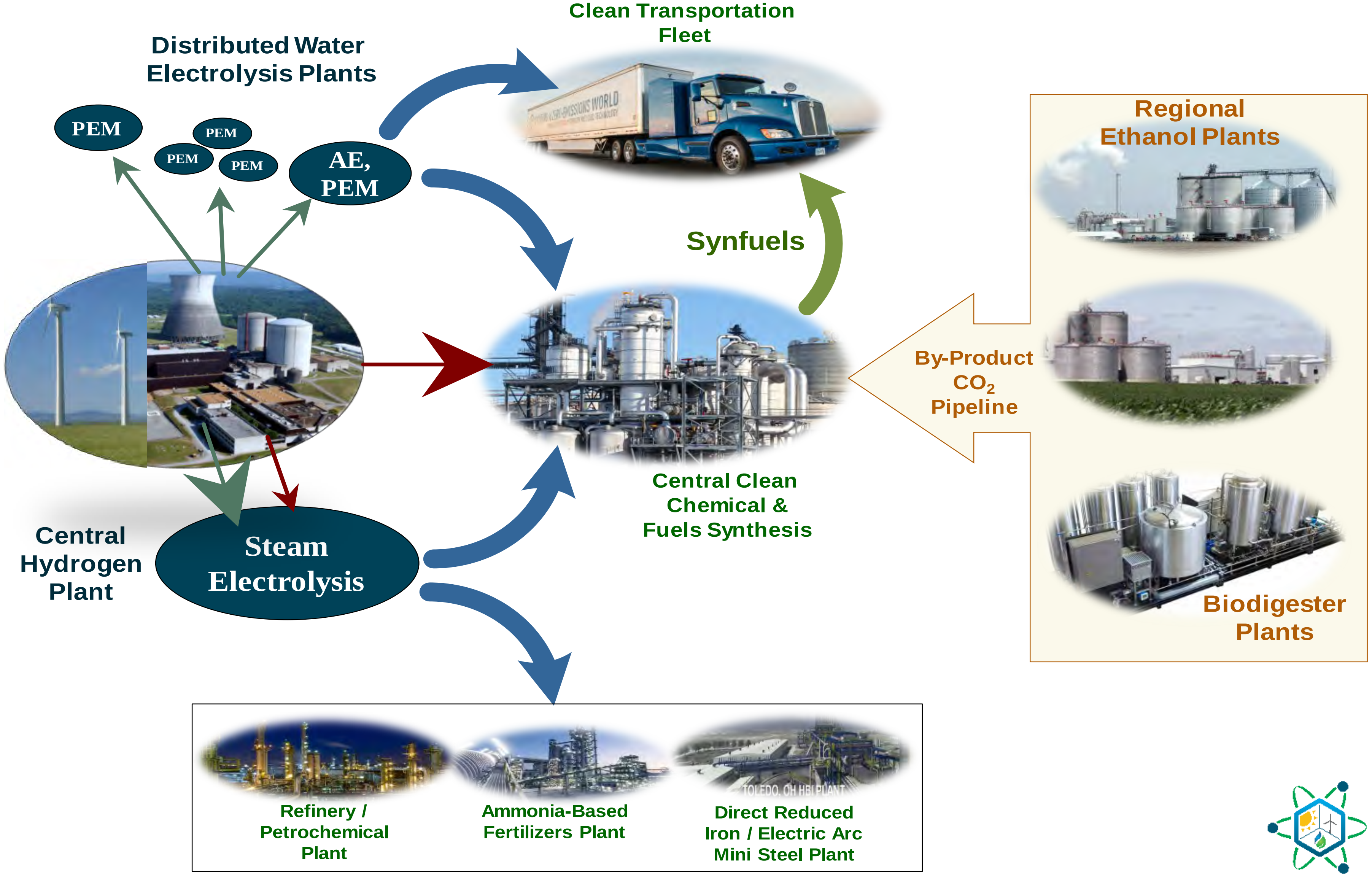
- ***Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest***
  Repurposing existing Exelon plant for H2 production via high temperature electrolysis; use of produced hydrogen for multiple off-take industries (ammonia and fertilizer production, steel manufacturing, and fuel cells) (INL/EXT-19-55395)

- ***Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest***
  LWR market opportunities for LWRs with a focus on H2 production using low-temperature and high-temperature electrolysis; initial look at polymers, chemicals, and synfuels (INL/EXT-19-55090)

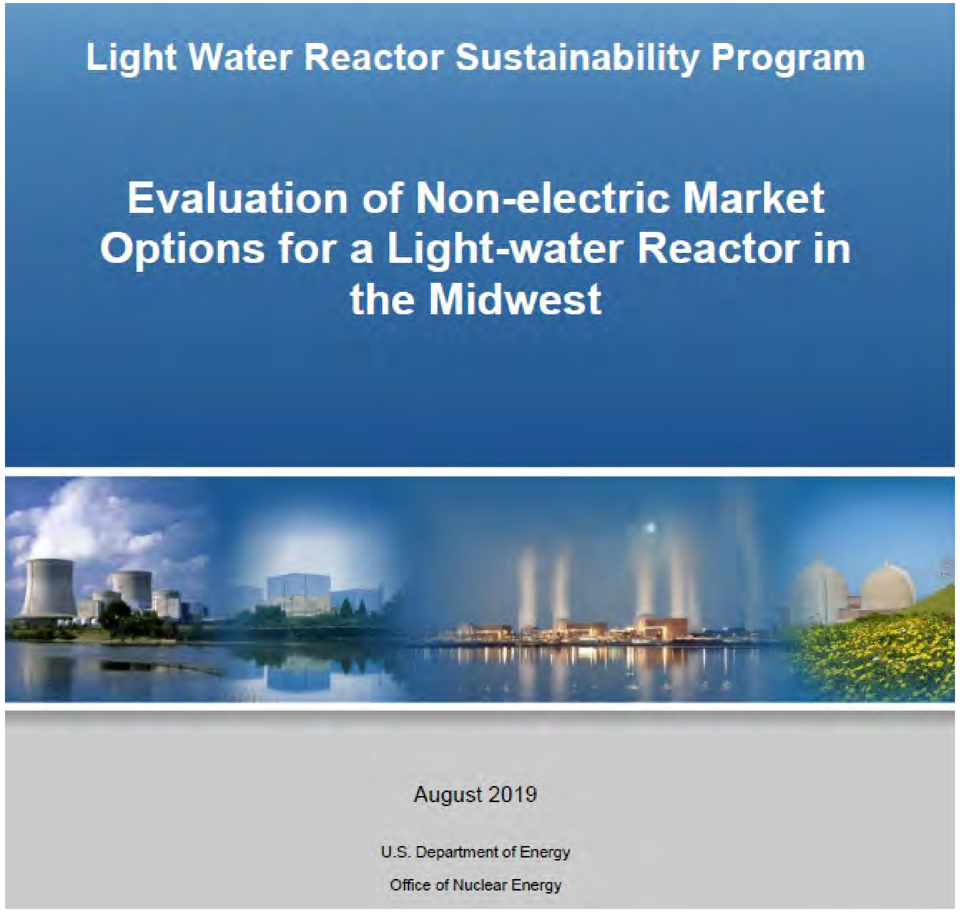
Example: Analysis results for H2 production, compression and delivery prices to meet ammonia plant demand.



Analysis of a Nuclear-Driven Energy Complex in the Upper Midwest



Hydrogen Production Cost Comparisons

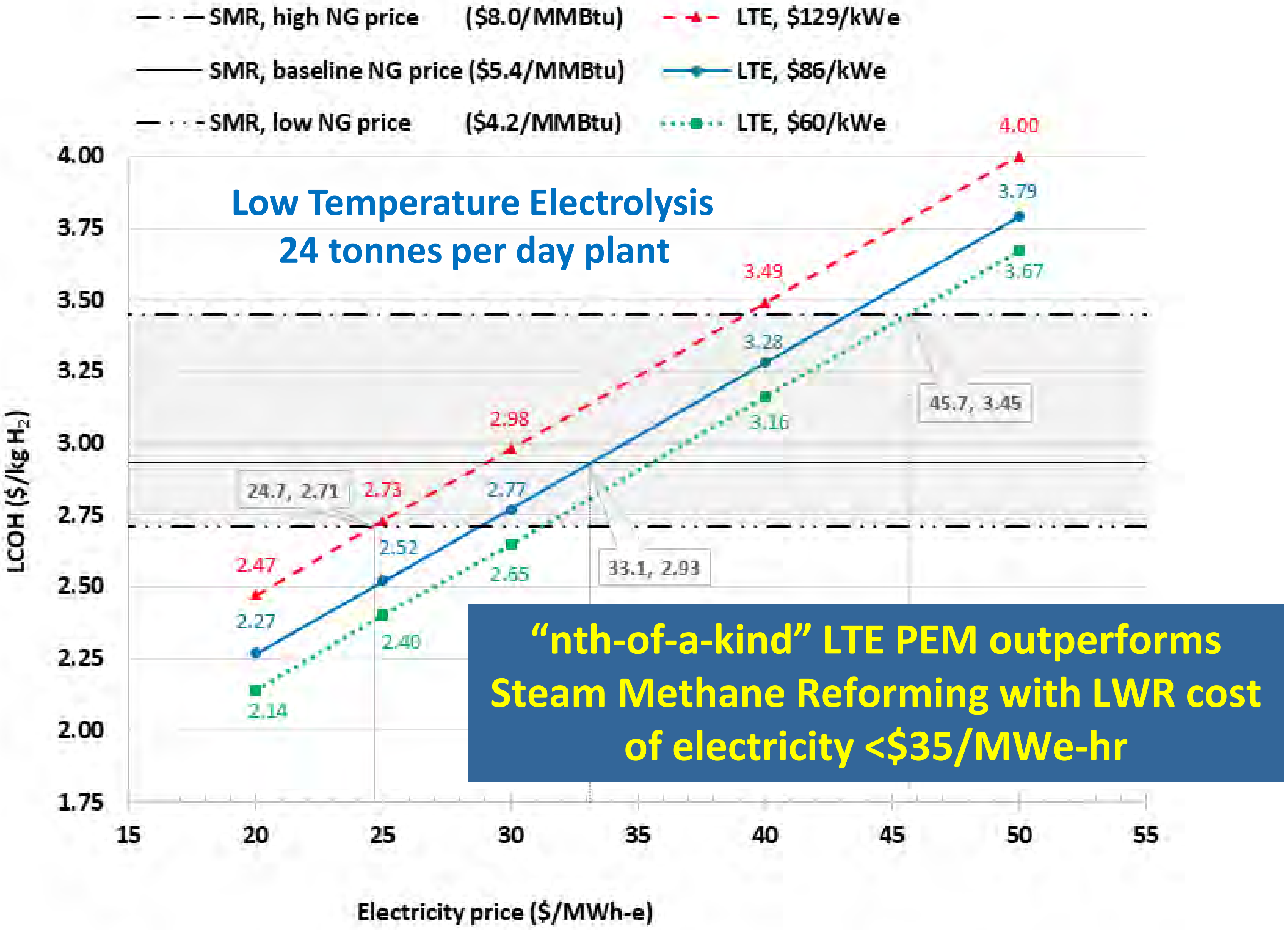

Light Water Reactor Sustainability Program

Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest

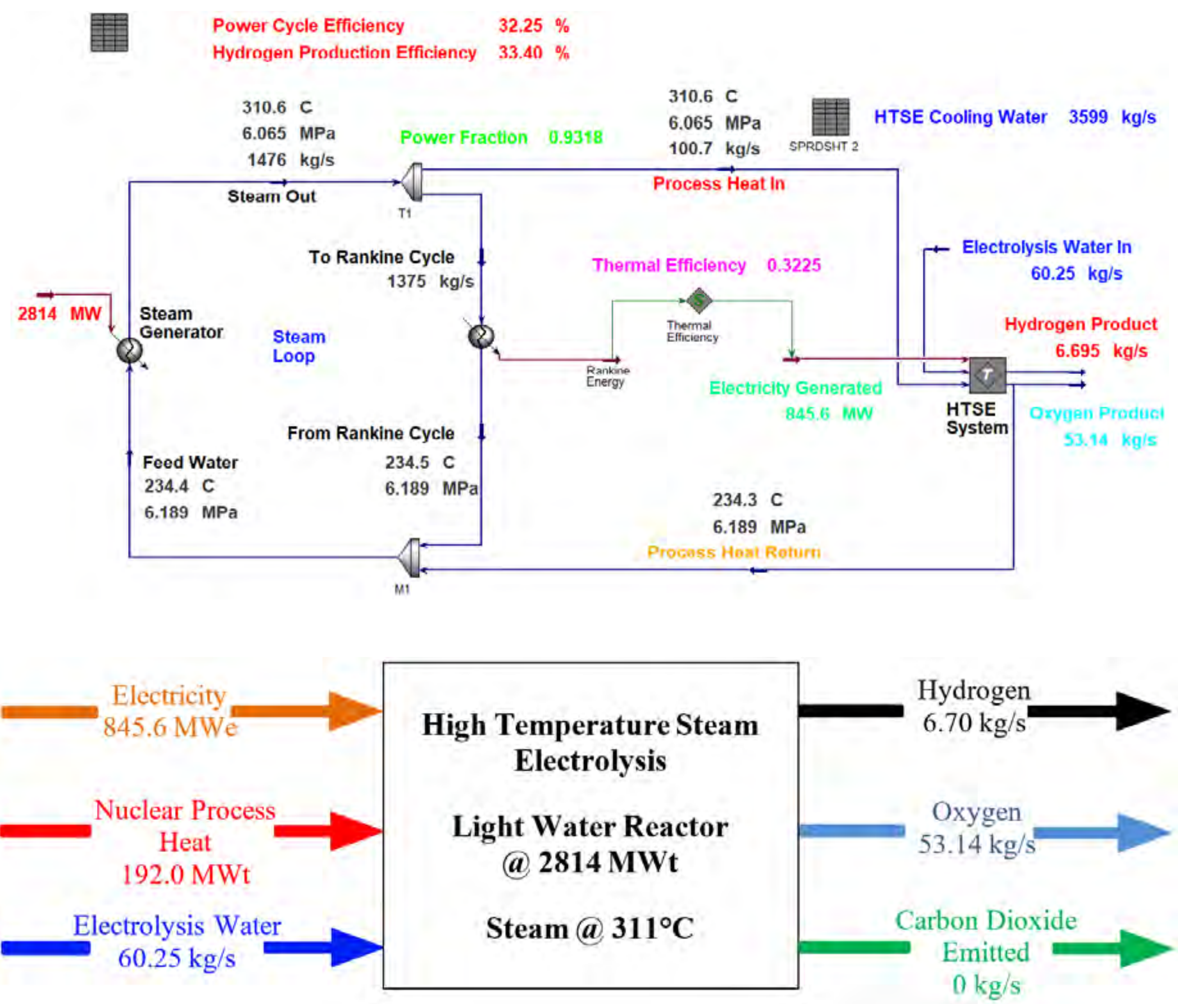
August 2019

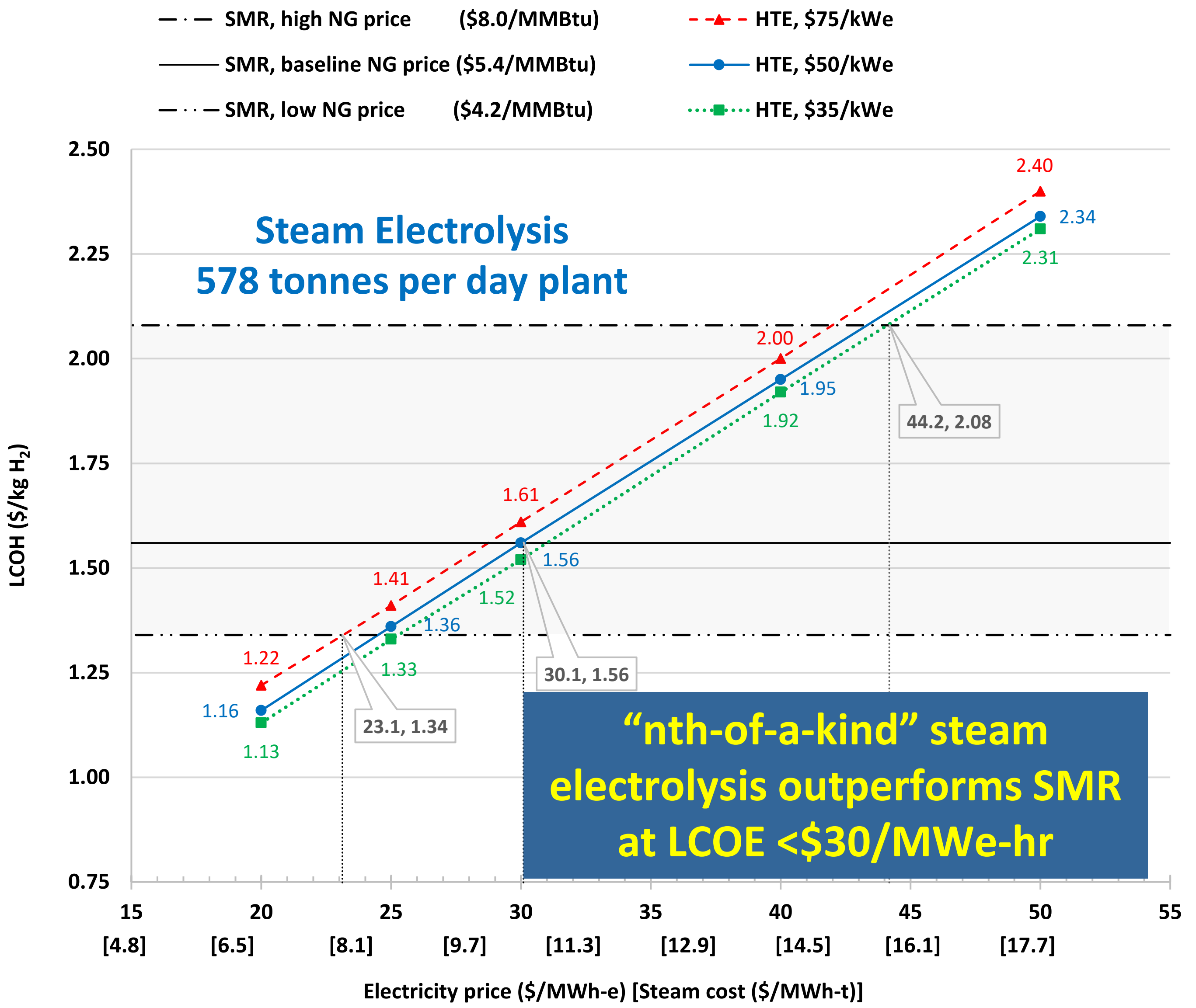
U.S. Department of Energy
Office of Nuclear Energy

INL/EXT-19-55090

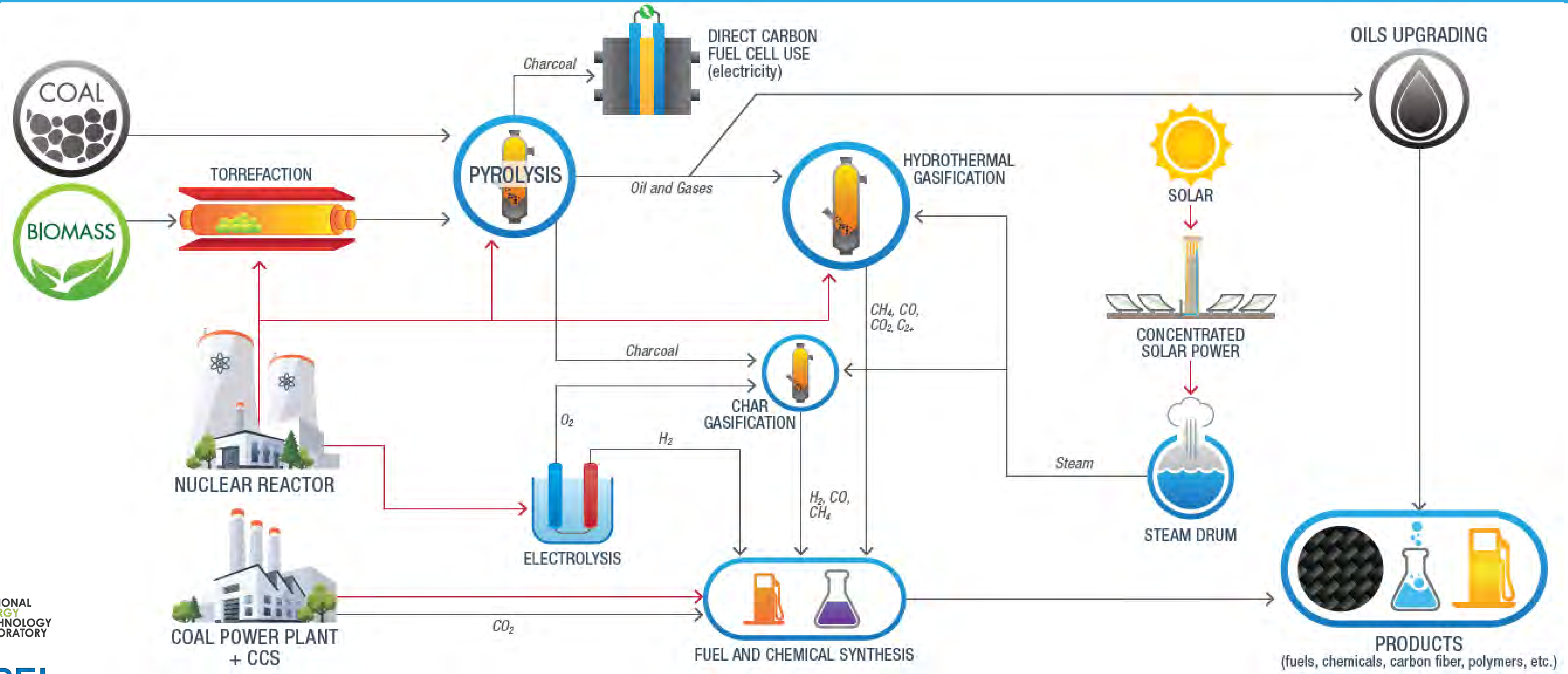


Hydrogen Production Cost Comparisons





Example: Carbon Feedstock Refinery



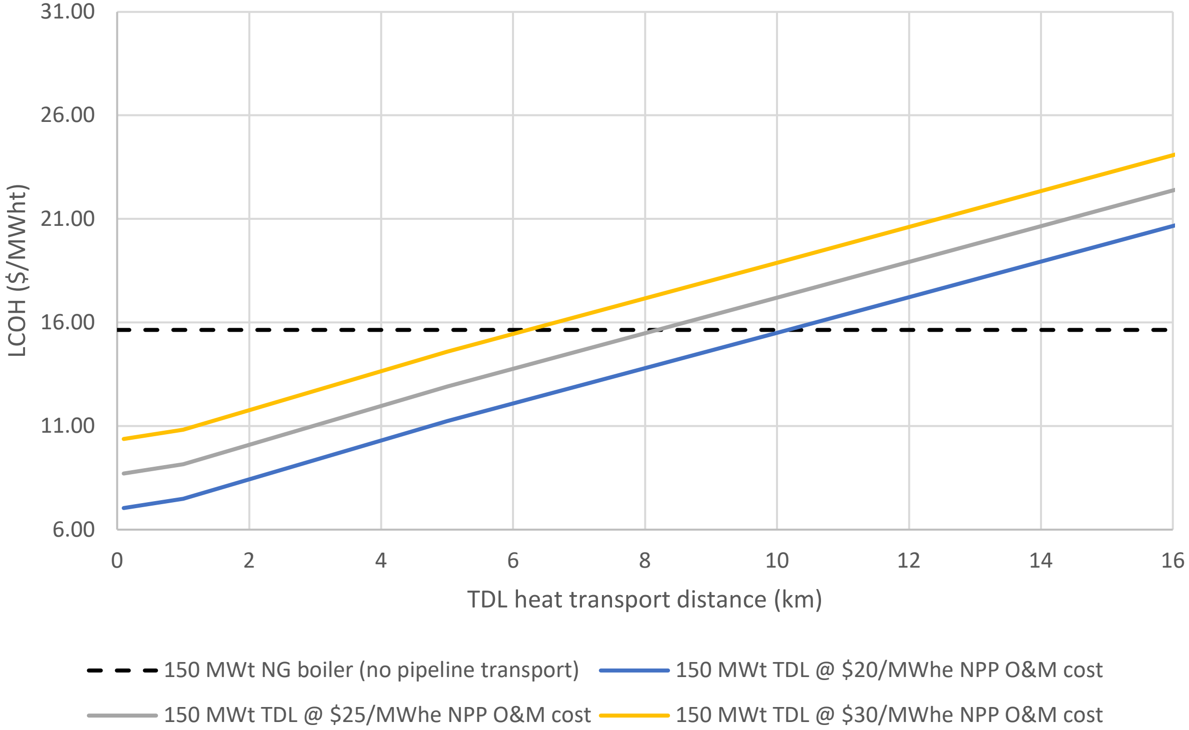
NATIONAL ENERGY TECHNOLOGY LABORATORY

NREL Transforming ENERGY

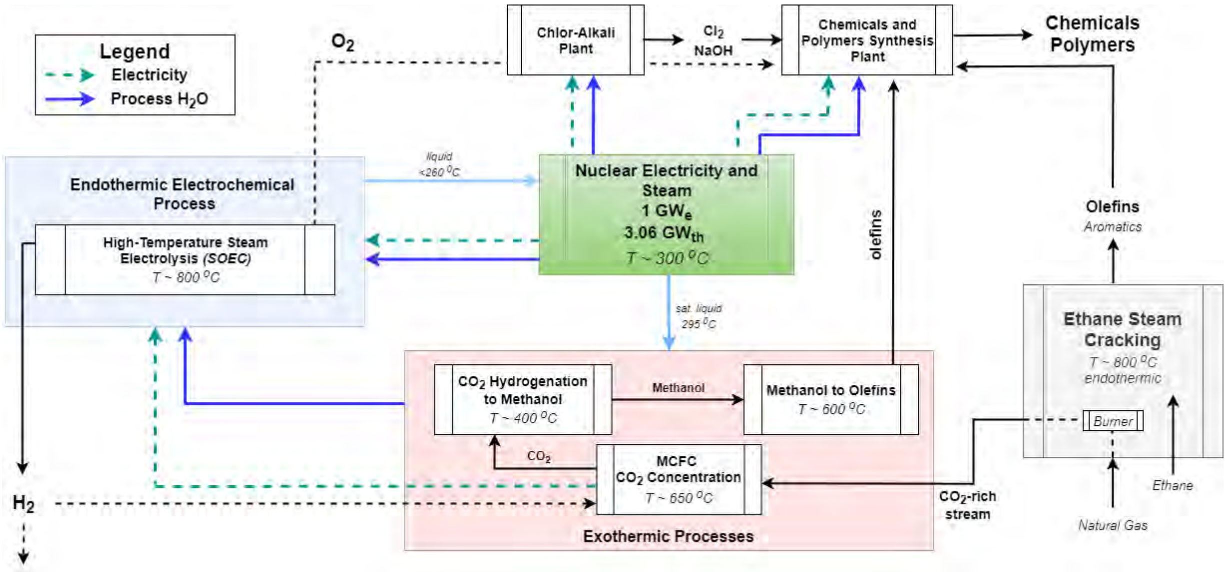
INL Idaho National Laboratory

IES Integrated Energy Systems

Finding cost-competitive markets for nuclear



Cost of High-Pressure Steam Delivery from a Nuclear Power Plant to Industrial Users versus Natural Gas Boiler (in 2019$)



Specific Industrial Park Concept using nuclear heat and electricity to produce chemicals and polymers with minimal CO_2 emissions

INL/EXT-20-58884: Markets and Economics for Thermal Power Extraction from Nuclear Power Plants for Industrial Processes, June 2020

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Dynamic Energy Transport and Integration Laboratory (DETAIL)

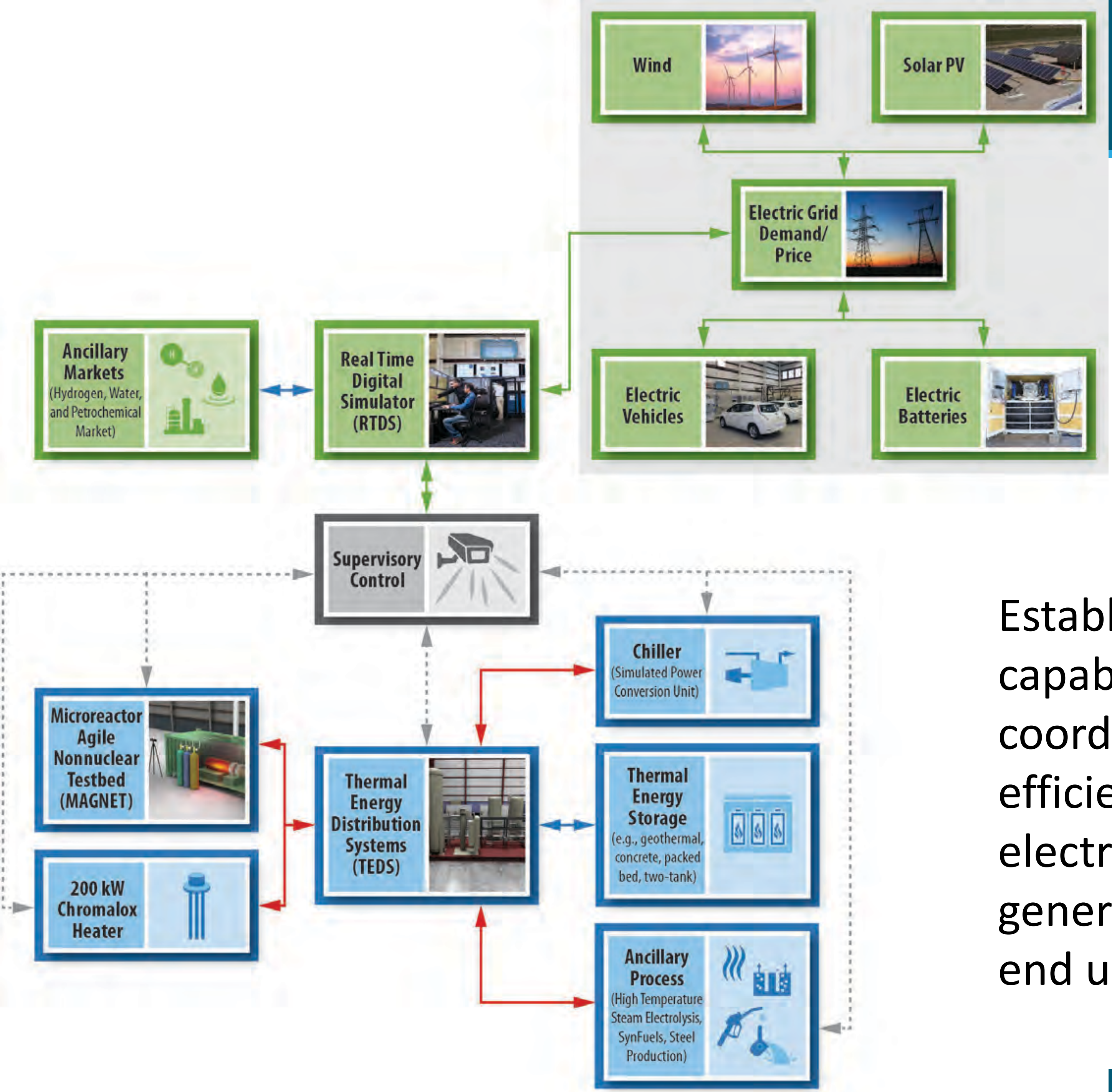
Human-in-the-Loop

Grid-in-the-Loop

Flexible Industrial Process

Thermal Energy Generation and Transport

IES
Integrated Energy Systems



Dynamic Energy Transport & Integration Lab (DETAIL)

Establishing the experimental capability to demonstrate coordinated, controlled, and efficient transient distribution of electricity and heat for power generation, storage, and industrial end uses.

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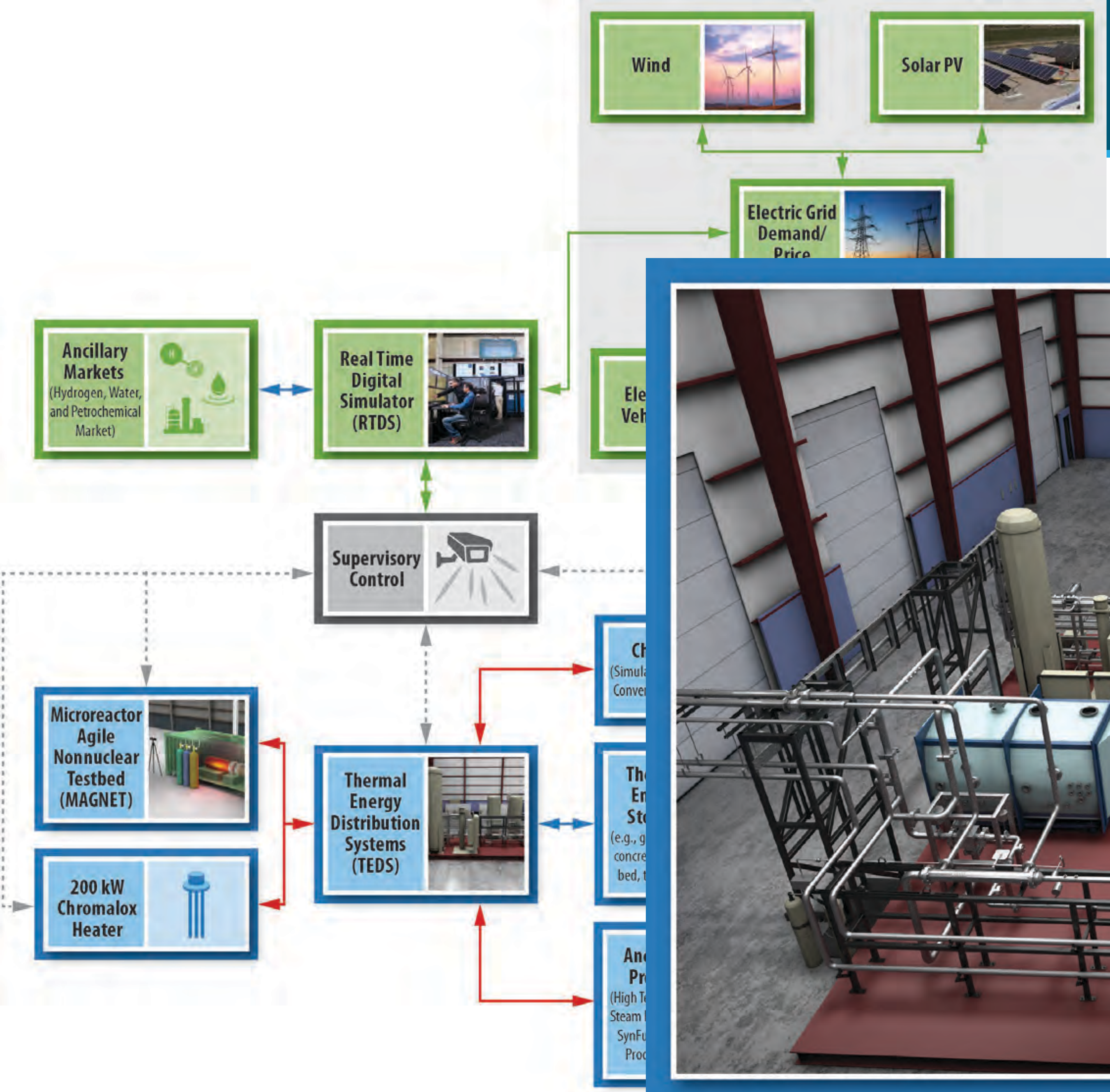
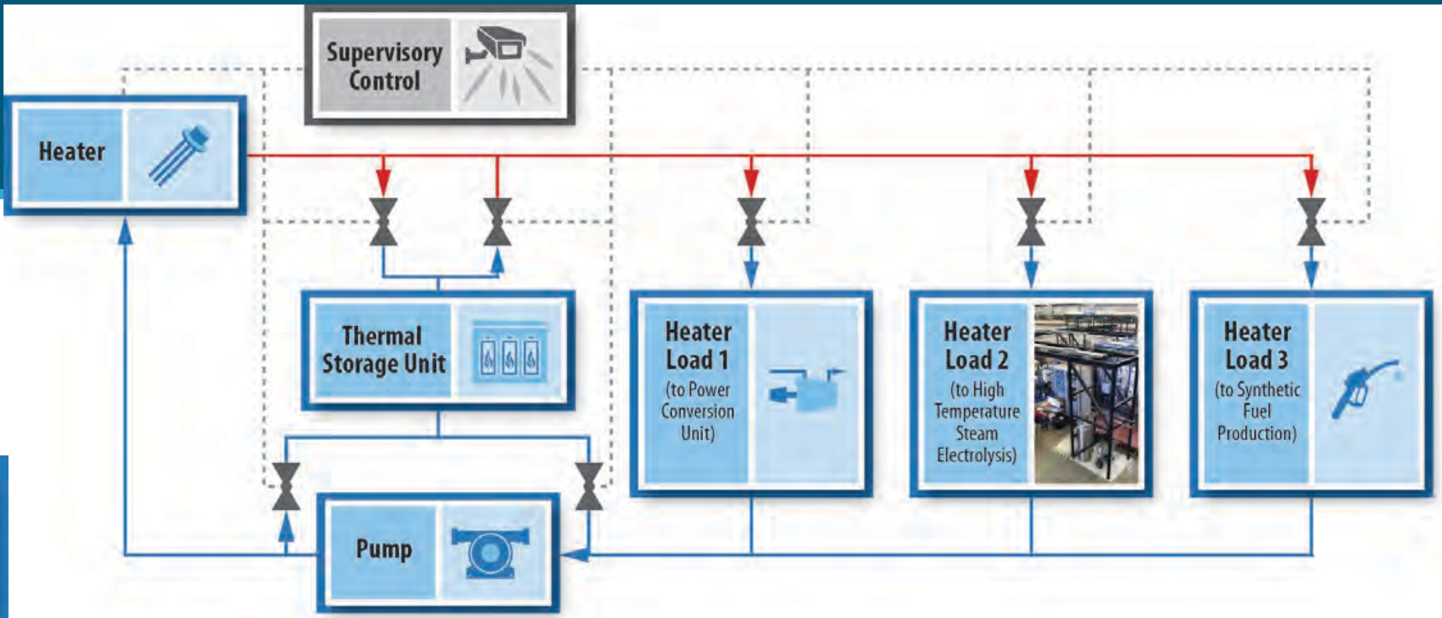

Wind
Solar PV
Electric Grid Demand/
Ancillary Markets
(Hydrogen, Water, and Petrochemical Market)
Real Time Digital Simulator (RTDS)
Supervisory Control
Microreactor Agile Nonnuclear Testbed (MAGNET)
200 kW Chromalox Heater
Thermal Energy Distribution Systems (TEDS)


TEDS
MAGNET
HTSE

Thermal Energy Distribution System



To begin initial operation in December 2020

IES Integrated Energy Systems

Deployed 25 kW High Temperature Electrolysis System

25 kW HTE Test Facility Overview in DETAIL within the INL Energy Systems Laboratory

25 kW HTE Test Facility Control Station

Enclosure Interior View

Gas alarm and Interlock System

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Nuclear Power Plant Hydrogen Production Demonstration Projects

- ***Purpose & Scope:***

1. Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant for a commercial, 1-3 MWe, low-temperature (PEM) electrolysis module

2. Acquaint NPP operators with monitoring and controls procedures and methods for scaleup to large commercial-scale hydrogen plants

3. Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations

4. Evaluate power inverter control response to provide grid contingency (inertia and frequency stability), ramping reserves, and volt/reactive control reserve

5. Produce hydrogen for captive use by NPPs

6. Produce hydrogen for first movers of clean hydrogen; fuel-cell buses, heavy-duty trucks, forklifts, and industrial users

- ***Laboratory role:*** *Support utilities with project test planning, controls and monitoring environment implementation and testing, data collection, systems performance evaluation, and project reporting.*

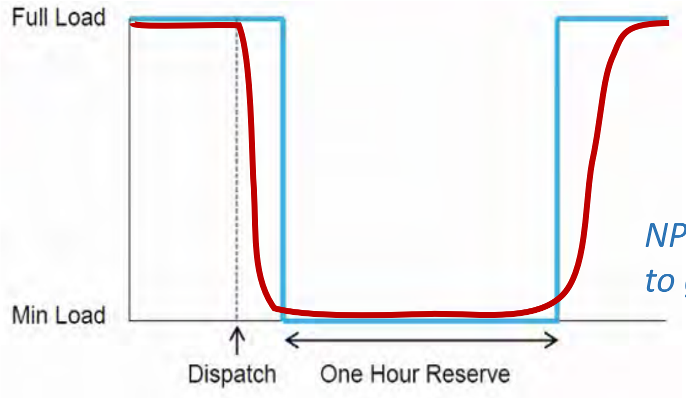
Two projects via Public/Private Partnerships:

(1) Exelon

(2) Energy Harbor Partnership with Xcel Energy and APS

Example Test for Non-Spinning Reserve:

Electrolyzer ramps down in 10 mins while NPP dispatches electricity to the grid; then returns to full load after one hour.



NPP dispatches to gird

LWRS LIGHT WATER REACTOR SUSTAINABILITY

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LWR-H_2 Demonstration Projects: Exelon, USA

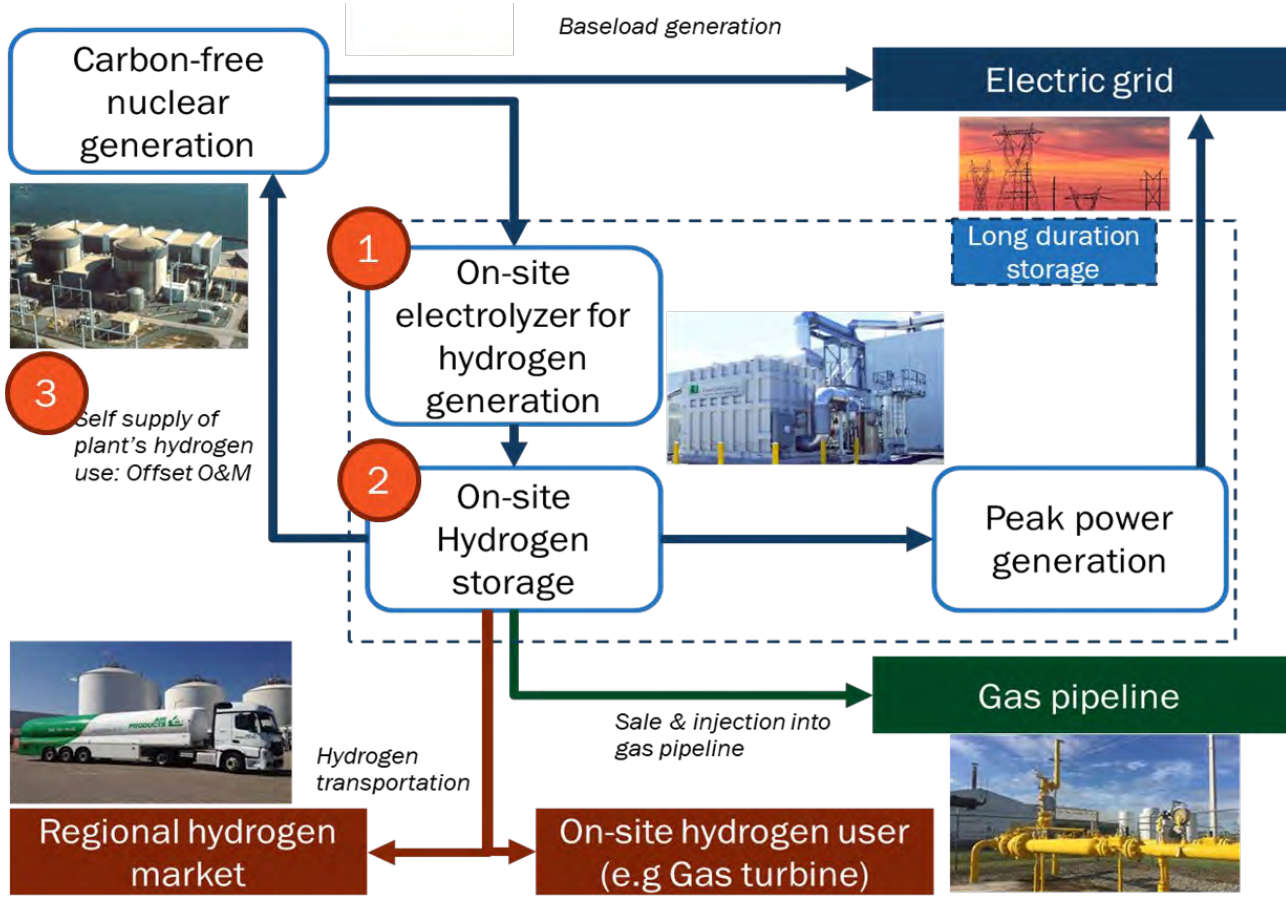
Exelon®

Partners: Nel Hydrogen, ANL, INL, NREL (via DOE)

Analysis Report: [Evaluation of Hydrogen Production for a Light Water Reactor in the Midwest]

Purpose:

- Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant and acquaint plant operators with methods and controls for scaling up to large commercial plants.
- Evaluate power offtake dynamics and inverter control response to provide grid contingency, ramping reserves, and volt/reactive control reserve.
- Produce hydrogen for captive use by NPPs
- Produce hydrogen for first movers of clean hydrogen; fuel-cell buses, heavy-duty trucks, forklifts, and industrial users



**Exelon will commence testing within 18-24 months at a to-be-announced LWR plant.

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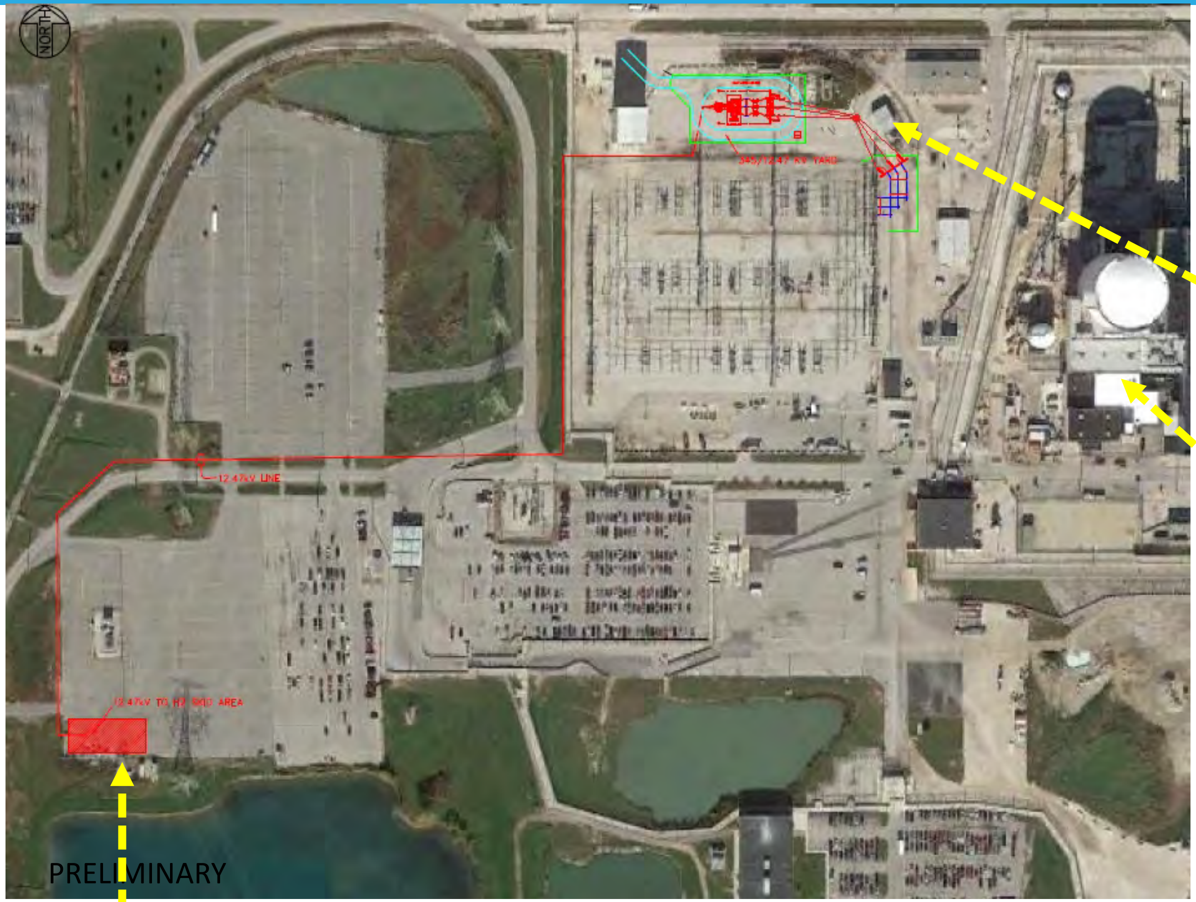
LWR-H_2 Demonstration Projects: Davis Besse, Ohio, USA



Electrical Tie-In

Power Block

Hydrogen Production Area

Industry Consortium of Energy Harbor, Xcel Energy, Arizona Public Service, DOE Labs

—

The engineering design team will design and locate the hydrogen production equipment such that the effect on the design and licensing basis is mitigated (to the extent practical).

**Commence testing in 24-36 months.

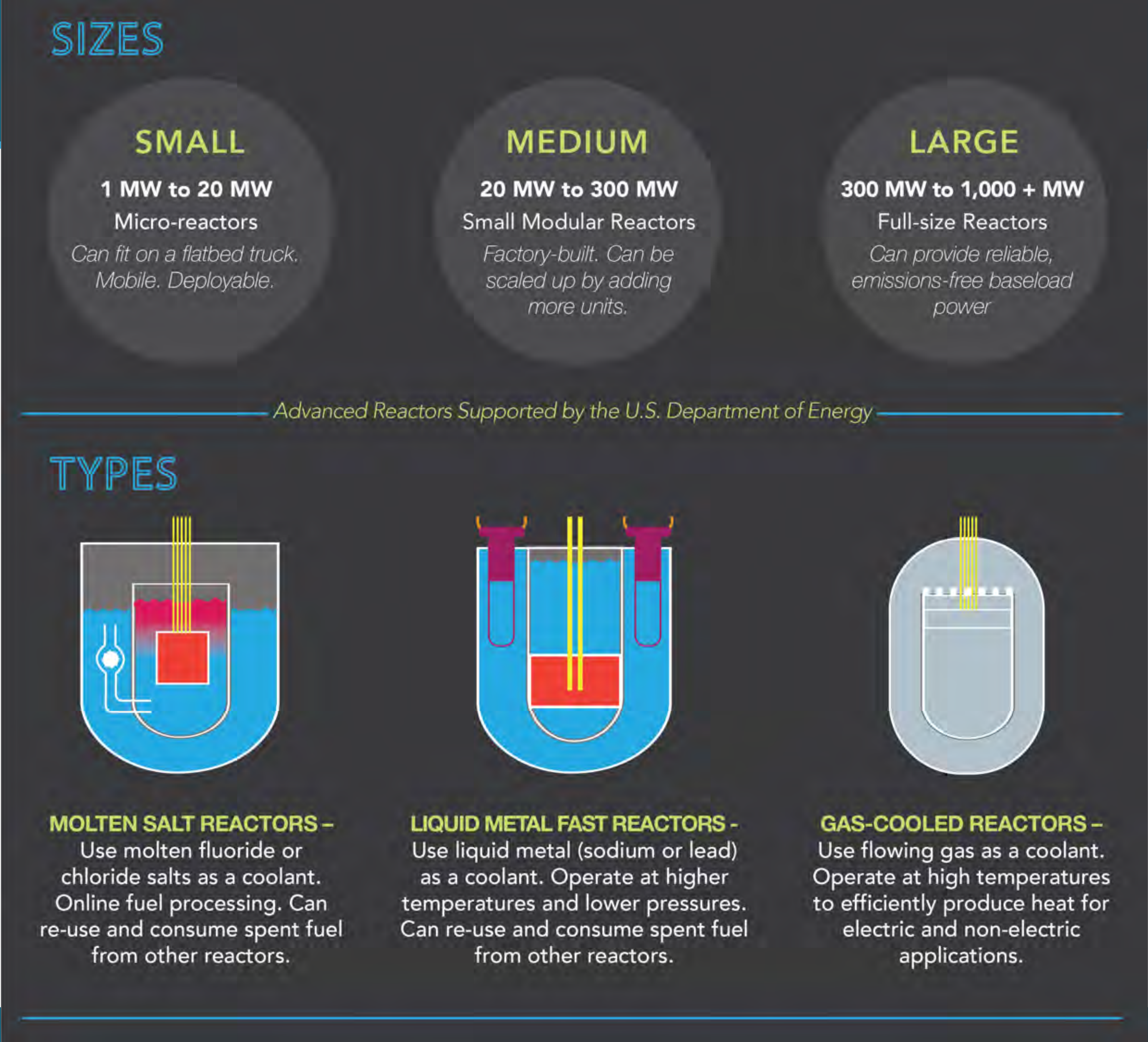
Purpose: *Produce hydrogen for first movers of clean hydrogen; fuel-cell buses, heavy-duty trucks, forklifts, and industrial users*

Analysis Report:
Evaluation of Non-electric Market Options for a Light-water Reactor in the Midwest

Advanced Reactors

Benefits:

- Enhanced safety
- Versatile applications
- Reduced waste
- Apply advanced manufacturing to reduce costs



Electrolysis Efficiencies vs Nuclear Reactor Type

Reactor Type	T-Out (Celsius)	Power Cycle	Power Cycle Eff.	Carnot Eff.	Electrolysis Electricity (kWh/kg-H_2)	Overall Nuclear Fuel Efficiency
LWR	N/A	Rankine	32%	50%	55 (PEM)	22%
LWR	300	Rankine	32%	50%	34 (HTSE)	35%
SFR	500	Supercritical Rankine	44%	63%	30 (HTSE)	54%
AHTR (MSR)	700	Sup-crit. CO_2	50%	70%	29.5 (HTSE)	62%
VHTR	900	Air Brayton	56%	75%	29 (HTSE)	70%

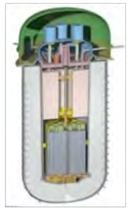
Gas Reactors

~750 – 1000 C

X-Energy Xe-100

Framatome SC-HTGR

Molten Salt Reactors



Terrestrial Energy USA IMSR

TerraPower MCFR

Elysium USA MCSFR

Kairos Power UCB PB-FHR

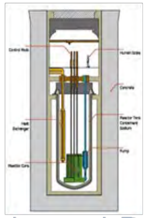
~700-800 C

Fast Reactors

~480 – 625 C

GE Hitachi PRISM

TerraPower TWR



Advanced Reactor Concepts LLC ARC-100

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National Reactor Innovation Center (NRIC) and the Gateway for Accelerated Innovation in Nuclear (GAIN)

Complementary and Coordinated Efforts to Support the Nuclear Energy Industry

GAIN

- Established in 2015 as a resource for accelerated development of nuclear innovations with lab partners
  - Comprehensive resource to entire nuclear innovation ecosystem at all development stages
  - Provides streamlined access to testing, MASL, experimental facilities, lab expertise, and legacy data
  - Regulatory expertise (e.g. NRC advanced reactor licensing strategy support)
  - Financial support

NRIC

- Provides a capability for building and demonstrating reactor concepts
  - Focused program to enable innovators nearing demonstration stage
  - Provides access to sites, required upgrades, site services, fuel material/fabrication facilities, and demonstration process support
  - Provides regulatory assistance related to demonstration
  - Facilitates NRC observation/ learning

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NRIC Supporting Technologies and Capabilities

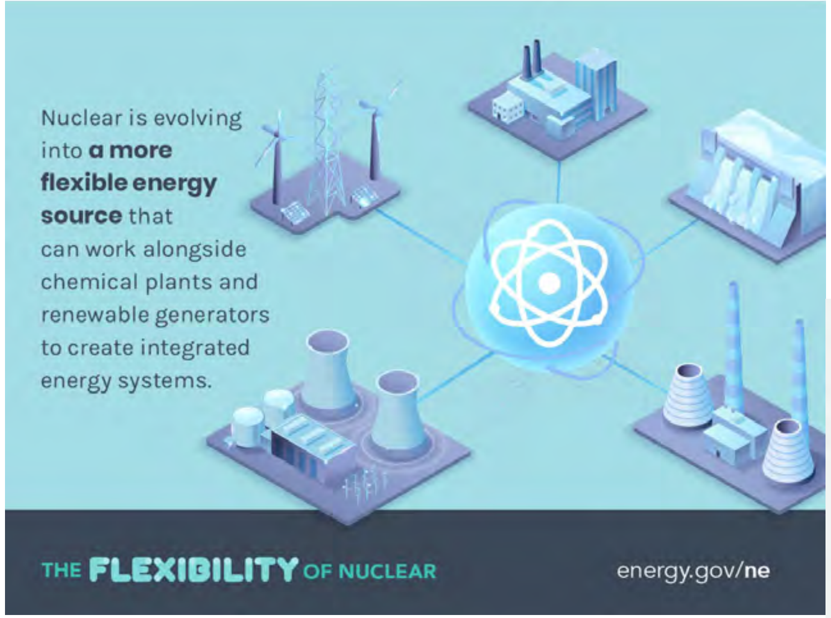
- **By 2025, NRIC will develop at least two advanced reactors**, extending the legacy of American nuclear innovation and establishing a foothold for advanced nuclear in this century.
  - Advanced Reactor Demonstration Program (ARDP) – proposals under review
- NRIC is equipped to facilitate the construction and demonstration of advanced reactor systems through a suite of services and capabilities. This includes a core, multidisciplinary team that can leverage government resources to meet private sector needs.
  - Digital Engineering
  - Advanced Construction Technologies Initiative
  - **Integrated Energy Systems**
  - NRC Coordination
  - Experimental infrastructure
  - Safety and environmental analysis
  - Project Planning & Coordination
  - Outreach and communications

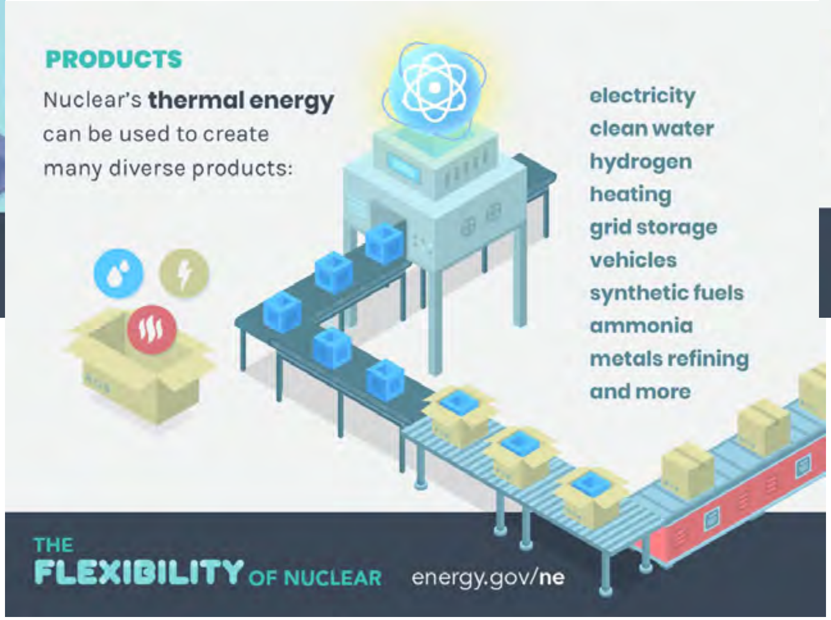
NRIC National Reactor Innovation Center

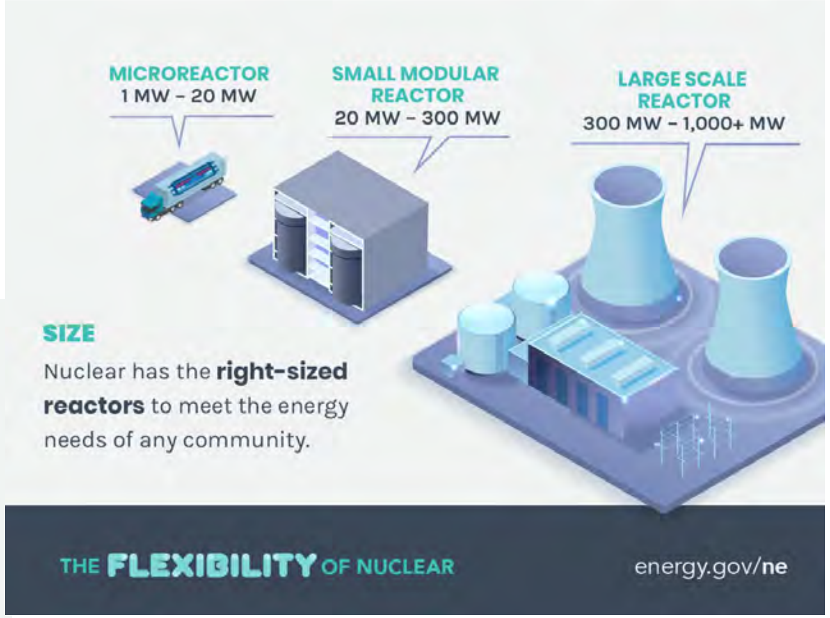
https://inl.gov/nric

IES Integrated Energy Systems

IES—A key opportunity for flexibility







U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

IES Integrated Energy Systems

Thank you!

Questions?

GEN IV International Forum[SM]

Upcoming Webinars

28 October 2020	Global Potential for Small and Micro Reactor Systems to Provide Electricity Access	Dr. Amy Schweikert, Colorado School of Mines, USA
19 November 2020	Neutrino and Gen IV Reactor Systems	Prof. Jonathan Link, Virginia Tech, USA
17 December 2020	Development of Multiple-Particle Positron Emission Particle Tracking for Flow Measurement	Dr. Cody Wiggins, University of Tennessee, USA