Advanced Energy Systems

Nuclear-Fossil-Renewable Hybrid Systems

Nuclear Energy Agency

Committee for Technical and Economical Studies on Nuclear Energy Development and Fuel Cycle

April 4-5, 2013

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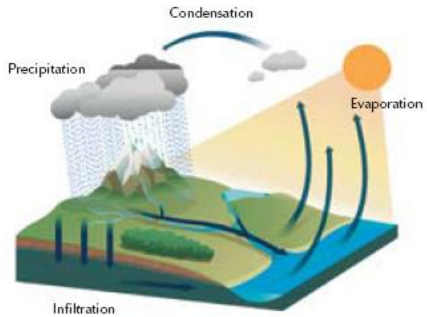
Idaho National Laboratory

Outline

- Clean, affordable, reliable, secure, resilient ***energy services***
- Energy currency ***infrastructure evolution***
- Generation, Storage, Delivery ***dynamic integration***
- Nuclear-Renewable-Fossil ***hybrid energy systems***
- Small-to-medium modular reactors ***opportunities and role***
- ***Market challenges and research needs***

Energy Security: A Balance of Priorities



Clean

Low greenhouse gas emissions
Reduce water withdrawals
Reduce land impacts

Secure

Domestic source
Physical & cyber protection

Energy Security

Affordable

Reasonable TOTAL costs
Predictable, stable price
Profitable in global economy

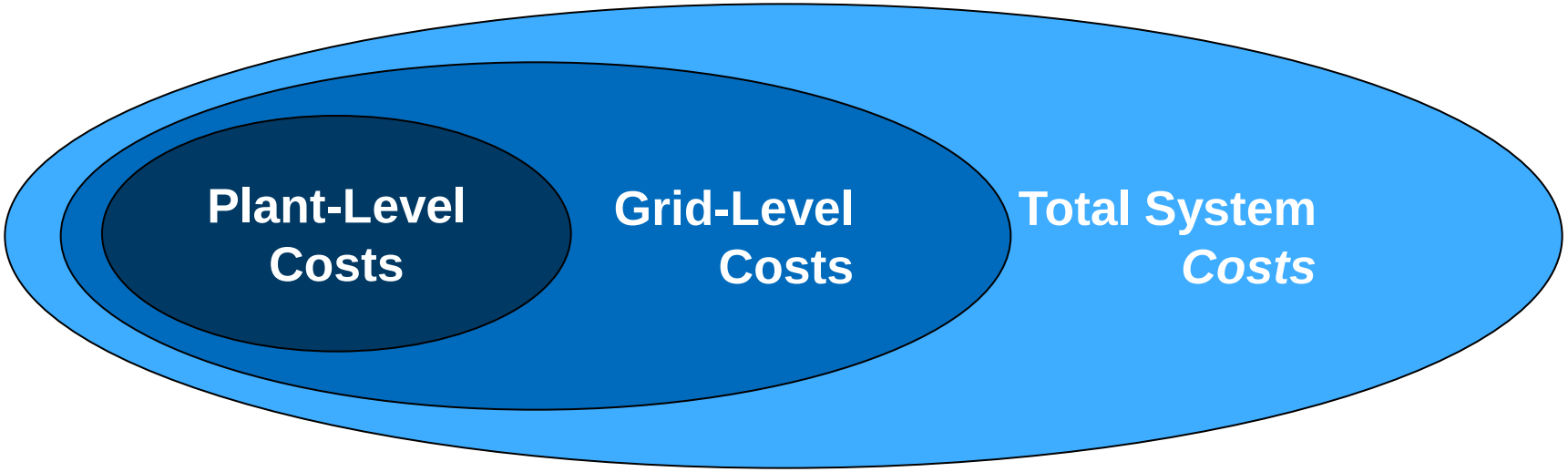
Reliable

Available on demand
Continuous quality
Easily maintainable

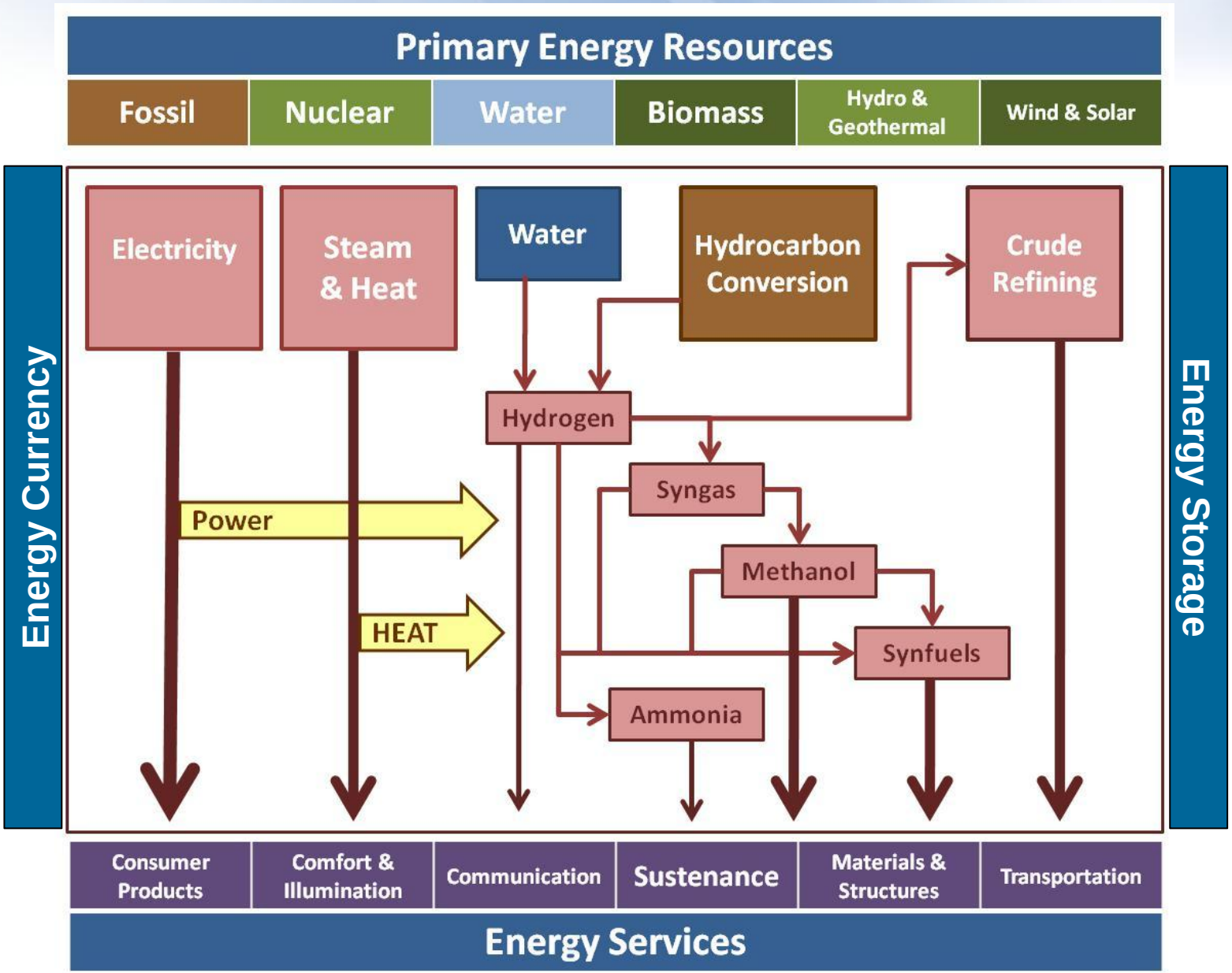
Resilient

Adapts to resource characteristics
Adjusts to market demands
Capable of meeting new regulations

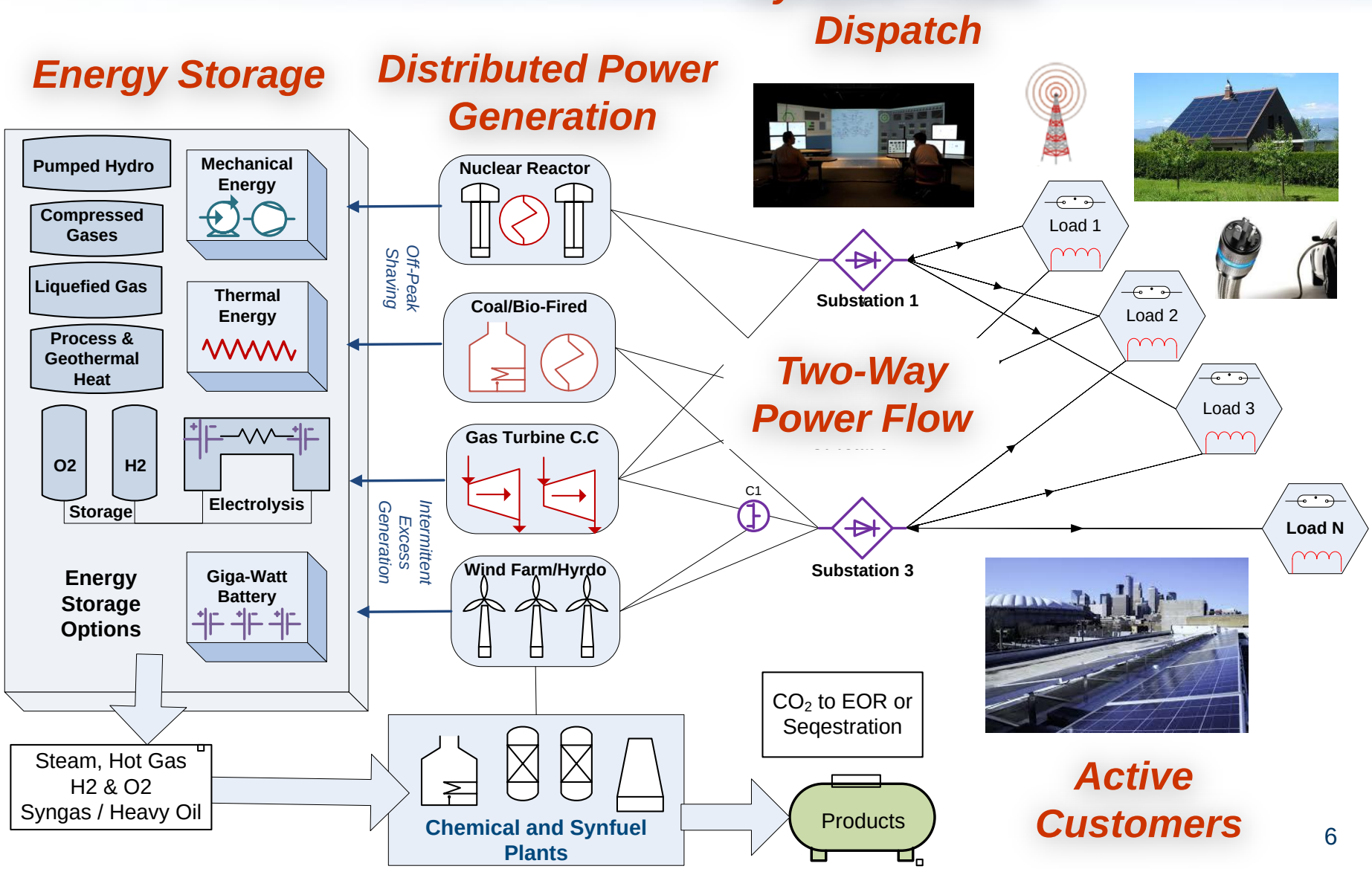
Systems Costs Analysis



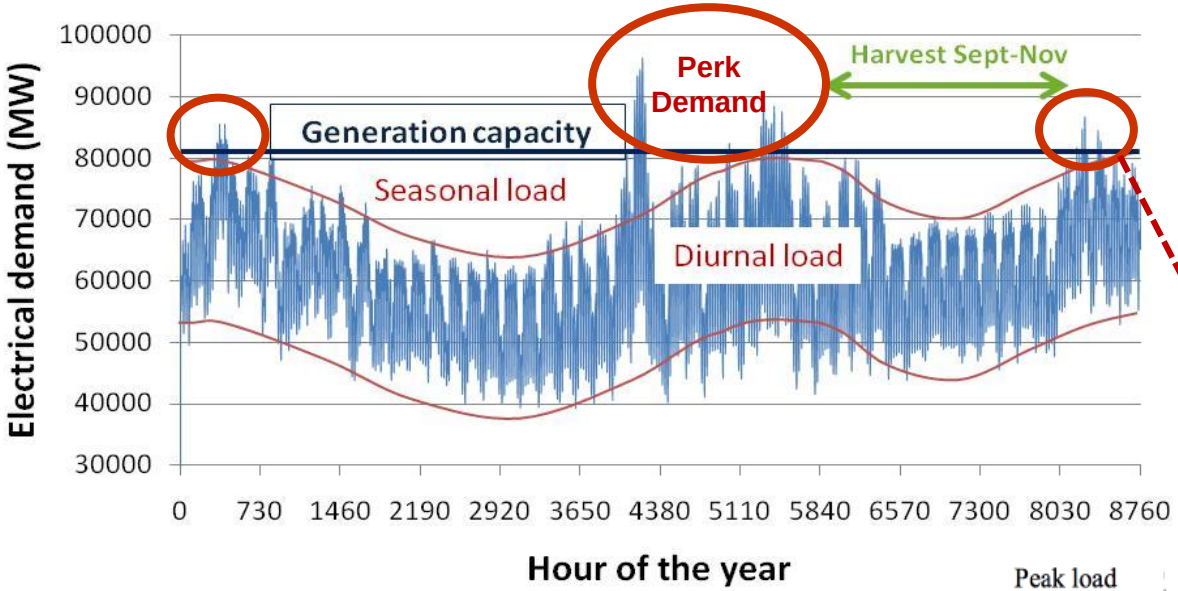
- Grid-level system costs already constitute real monetary costs, and are mediated by the electrical grid markets and regulations
- Total system costs include costs external to the electricity market, such as environmental costs or impacts on the security of supply


Primary Energy Resources
Fossil
Nuclear
Water
Biomass
Hydro & Geothermal
Wind & Solar
Energy Currency
Electricity
Steam & Heat
Water
Hydrocarbon Conversion
Crude Refining
Hydrogen
Syngas
Methanol
Synfuels
Ammonia
Power
HEAT
Energy Storage
Consumer Products
Comfort & Illumination
Communication
Sustenance
Materials & Structures
Transportation
Energy Services

Future Electrical Grid

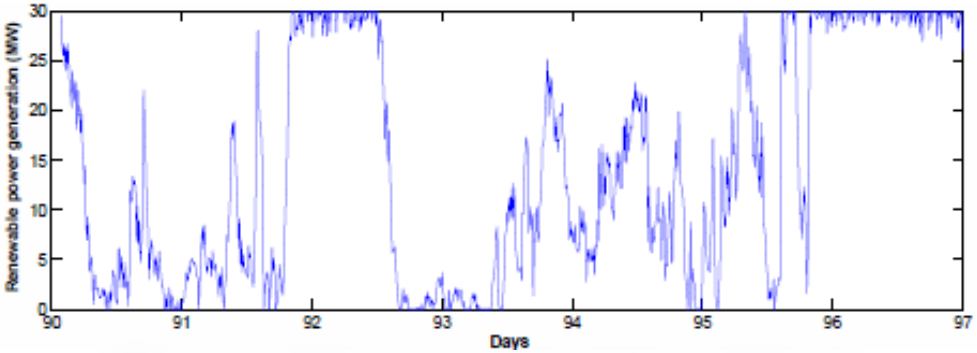


Power Dynamics Create Hybrid System Opportunities

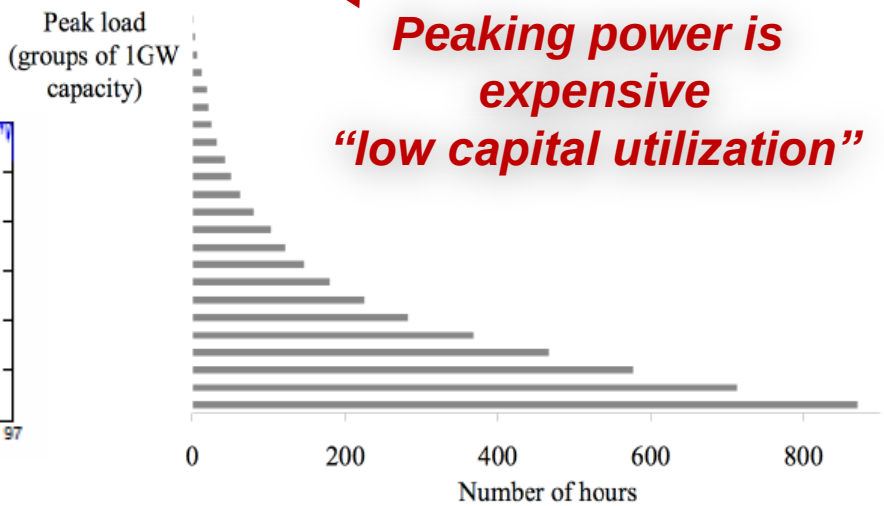


Excess seasonal variation Is available for other work

Excess diurnal capacity Is available year round



Renewable power is intermittent



Peaking power is expensive "low capital utilization"

Co-Gen? Hybrid? What's the Difference?

Thermodynamic Efficiencies

Reactor as "Heat Machine" For General Purposes

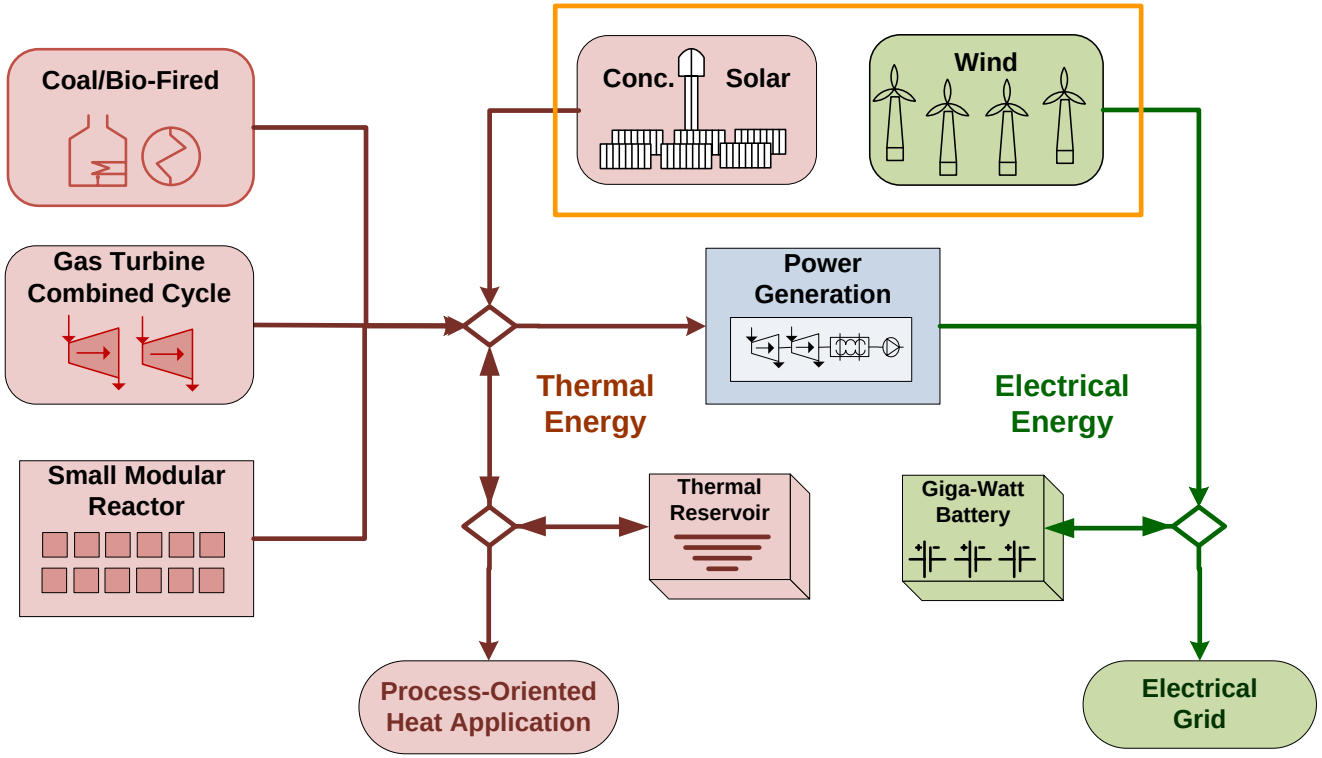
Economic Efficiencies: Capacity Factor and Time-of-Use Value

Integrated Energy System to Make Synthetic Fuels in Quantity

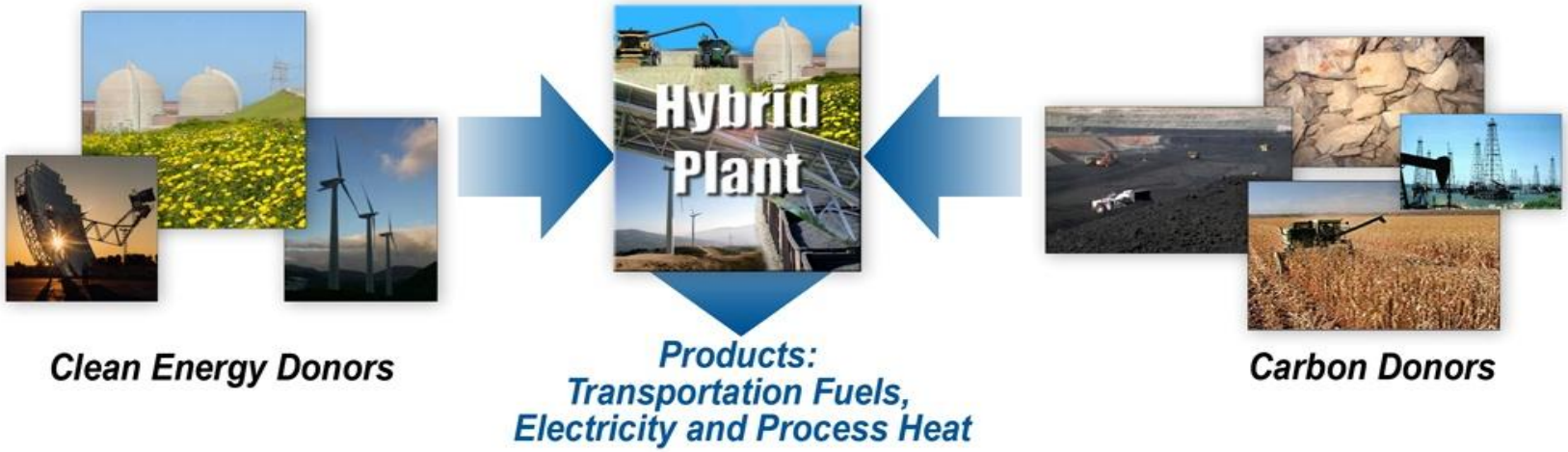
Co-Generation

Process Heat Applications

Hybrid Systems



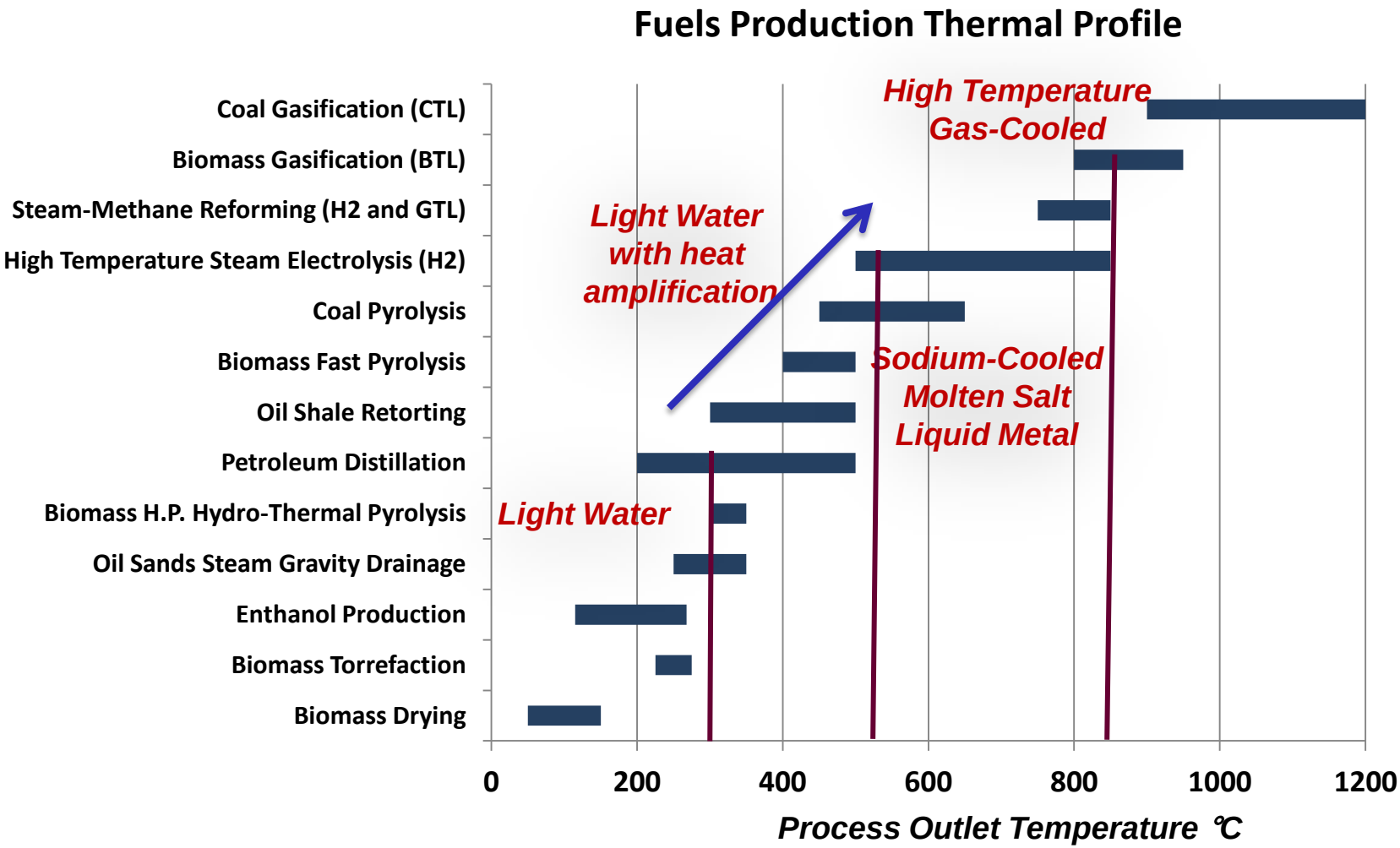
Extending the Opportunity for Nuclear Energy



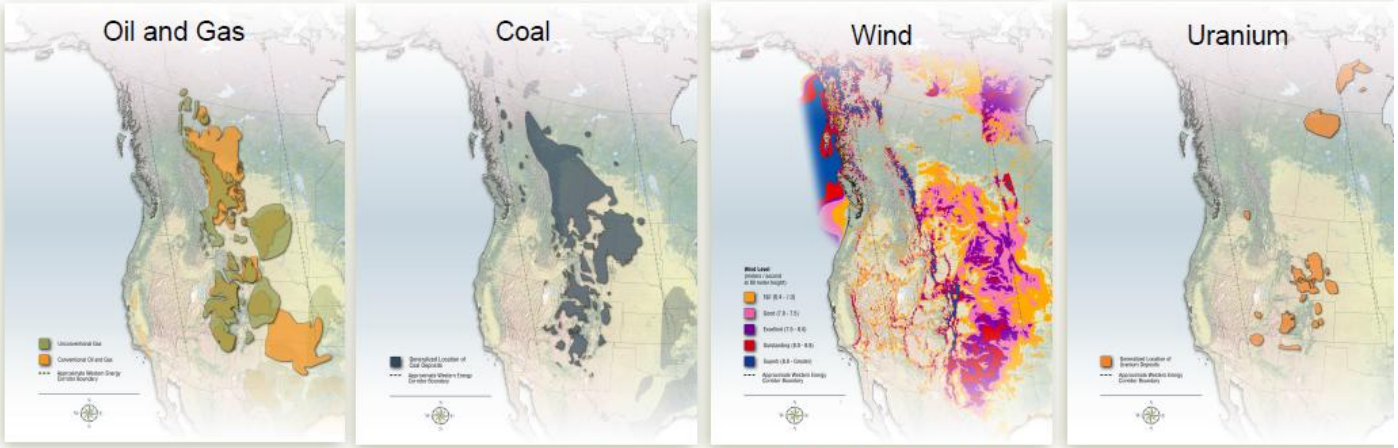
Hybrid Energy Systems integrate energy conversion processes to optimize energy management, reliability, security, and sustainability

- ✓ Facilitate effective integration of renewable energy, overcoming the challenges of intermittency and transmission constraints
- ✓ Open markets for nuclear energy beyond only a percentage of base load power
- ✓ Promote better usage of carbon sources, including natural gas and biomass, for the production of transportation fuels while reducing GHG environmental impact
- ✓ Support smooth integration and enhanced efficiency of conversion of available energy resources into infrastructure compatible products

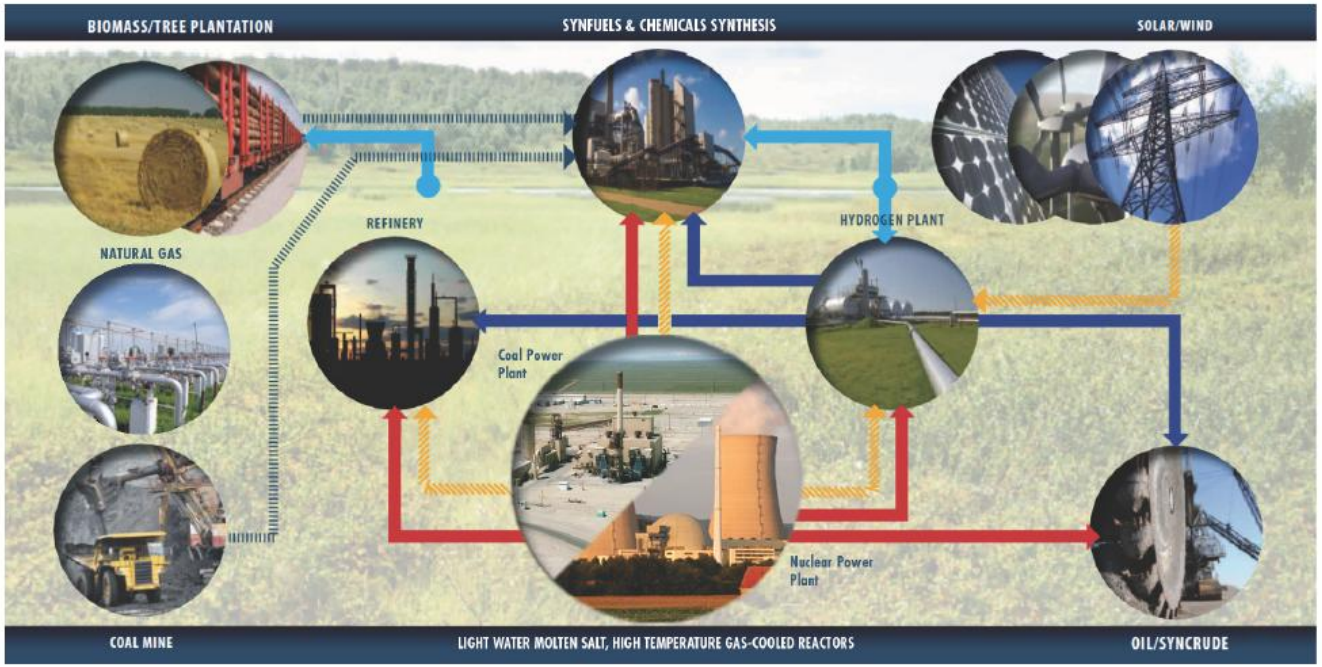
HES Alternatives for Fuels Manufacturing



U.S. Western Energy Corridor: An Opportunity for NHES



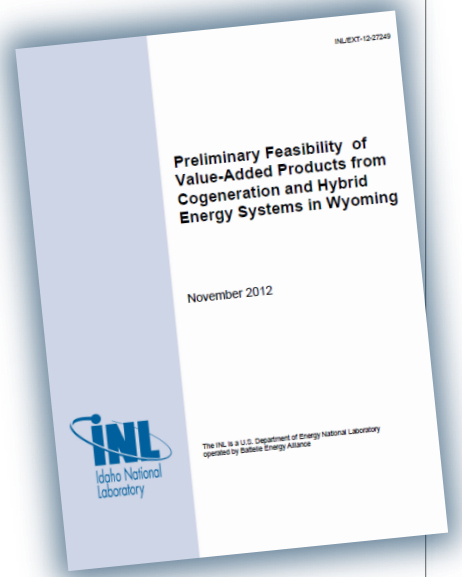
NREL Wind Resource Data

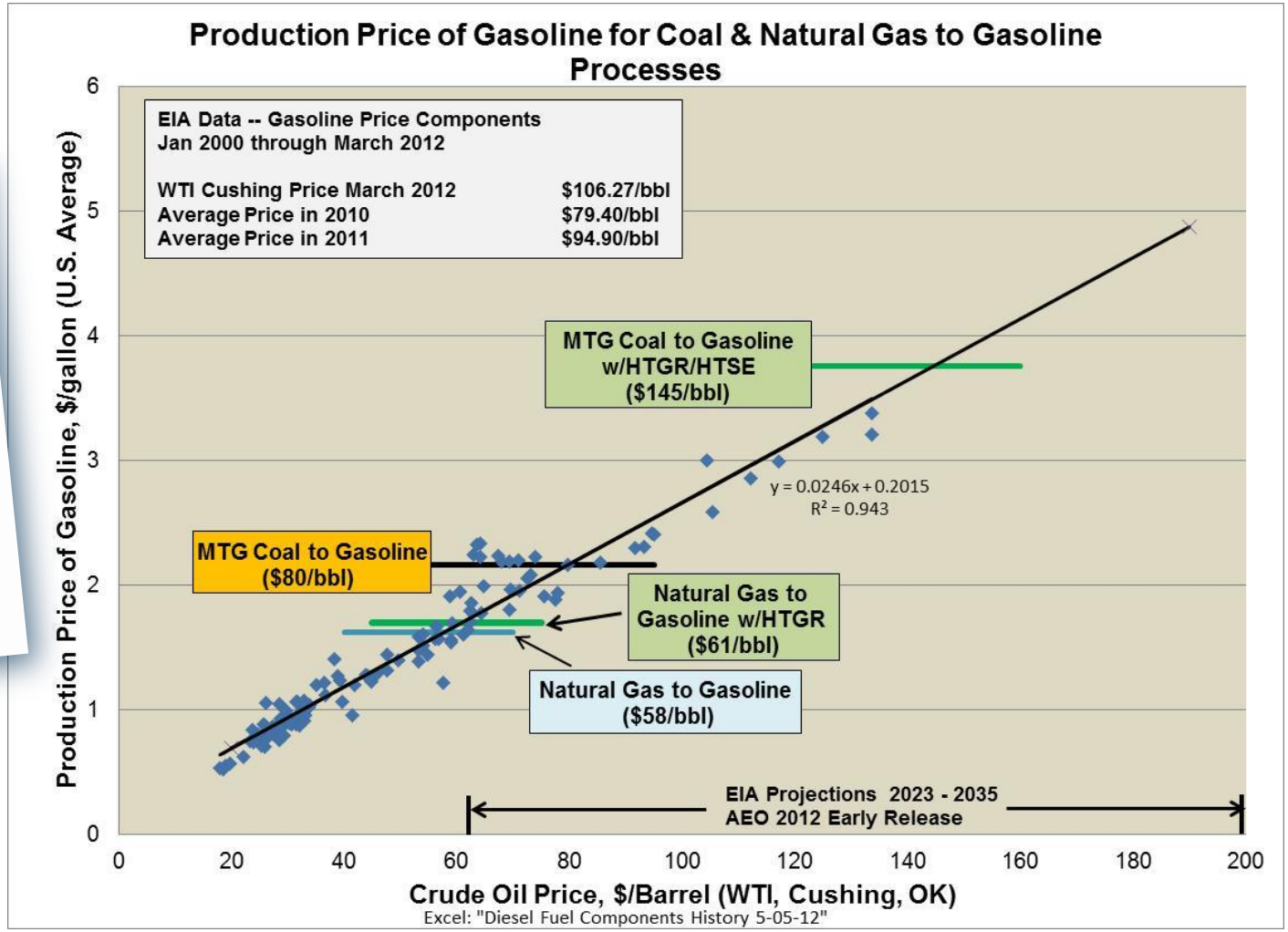


HTGR Co-Generation of Electricity & Heat for Transportation Fuels

Source:

INL-Wyoming CRADA with NGNP Alliance

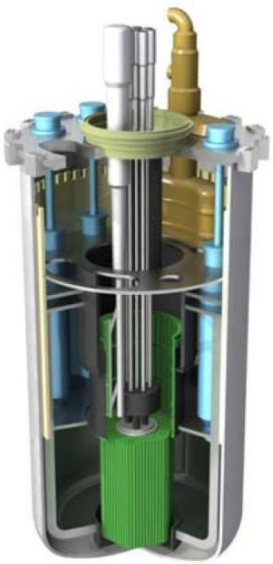




The Small-Medium, Modular Reactor (SMR)

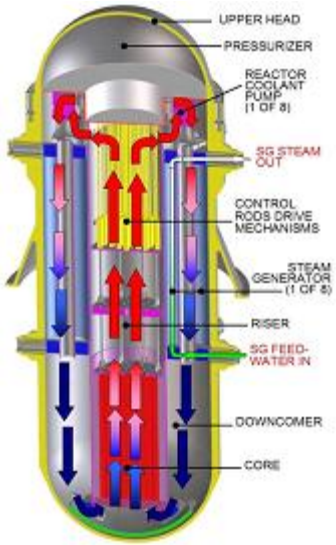
- **IAEA: Less than 300 MWe**
- **Motivated by:**
  - "Forgiving" safety characteristics
  - Eliminate major accident types (integral components)
  - "Factory fabrication"
  - Smaller capital outlay / favorable timing
- **Applications**
  - Smaller load communities (international and domestic)
  - Augment renewable energy (grid stability)
  - Non-electric applications
- **Challenges**
  - Licensing time line
  - Advanced fuel management
  - Diagnostics / control
  - Etc.

Some commercially developing examples



PRISM - General Electric

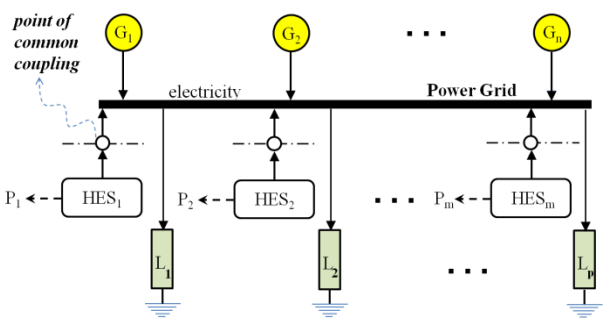
NuScale



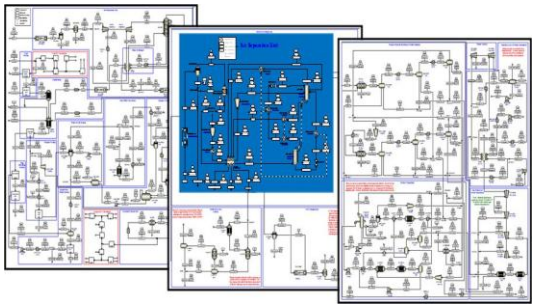
IRIS – Westinghouse

Energy System Modeling, Analysis, and Evaluation

SMR Architecture Identification Based on Local/Global Requirements & Constraints

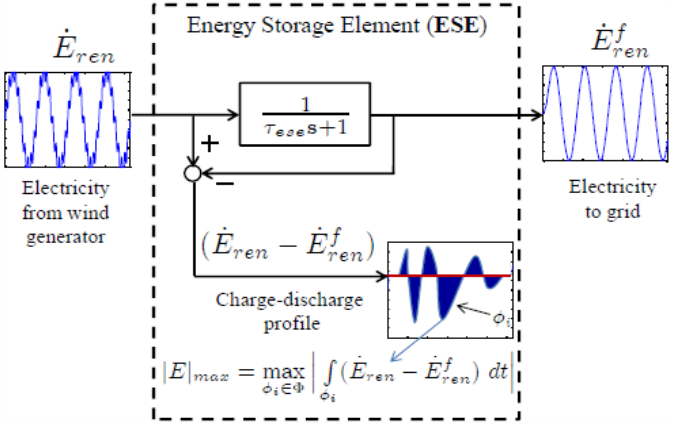


Feasibility, Life-Cycle & Economic Assessment of Identified Energy Solutions



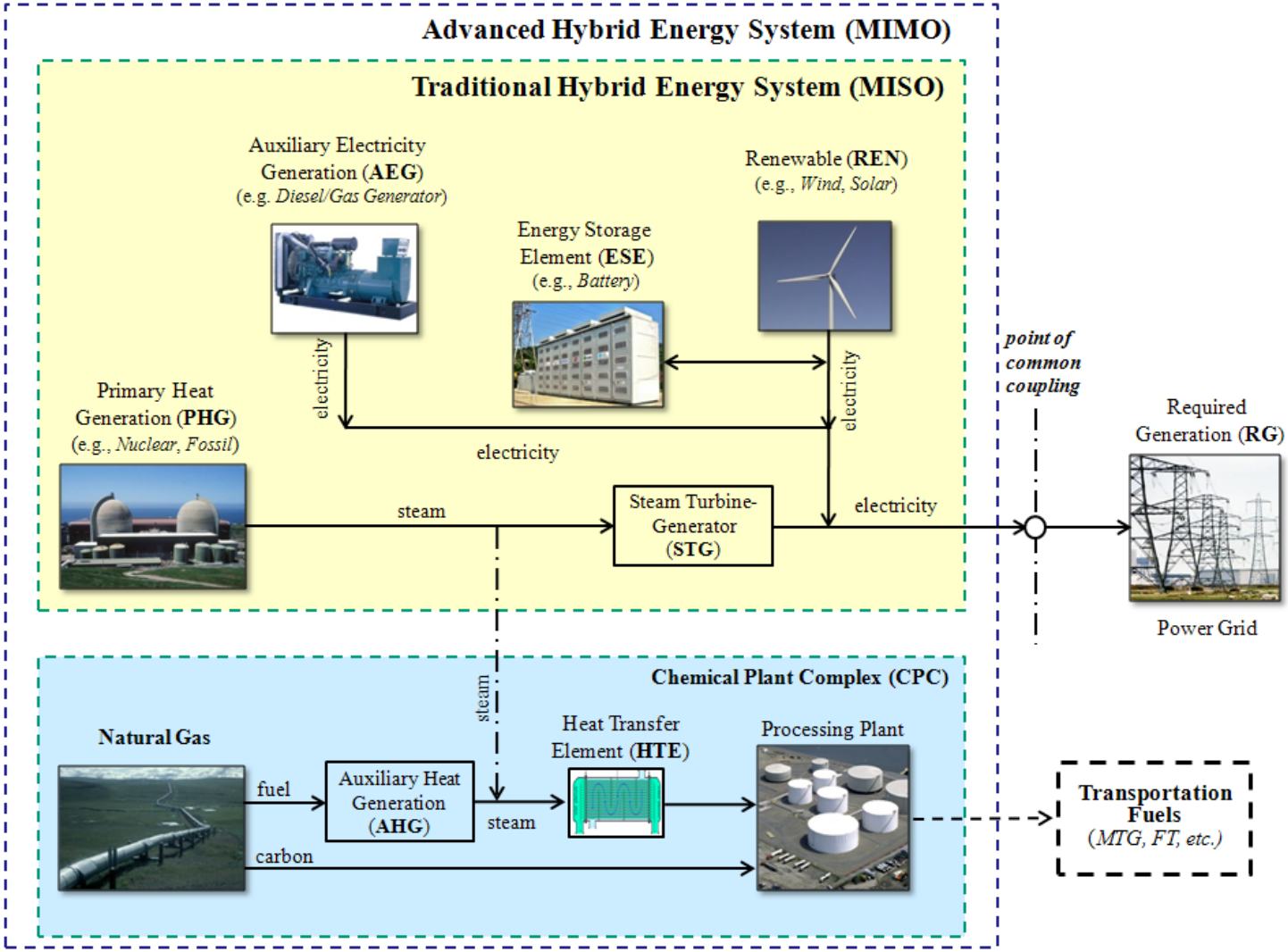
Graded approach to identify design, and evaluate SMR architectures

Dynamic Analysis, Optimization & Testing of Selected Energy Solutions



Development of dynamic modeling tools to address and develop M&C methods

Comparison between a traditional electricity-only generation **(MISO)** vs. an advanced electricity and chemical production hybrid **(MIMO)**



Hybrid Nuclear Hybrid Energy System

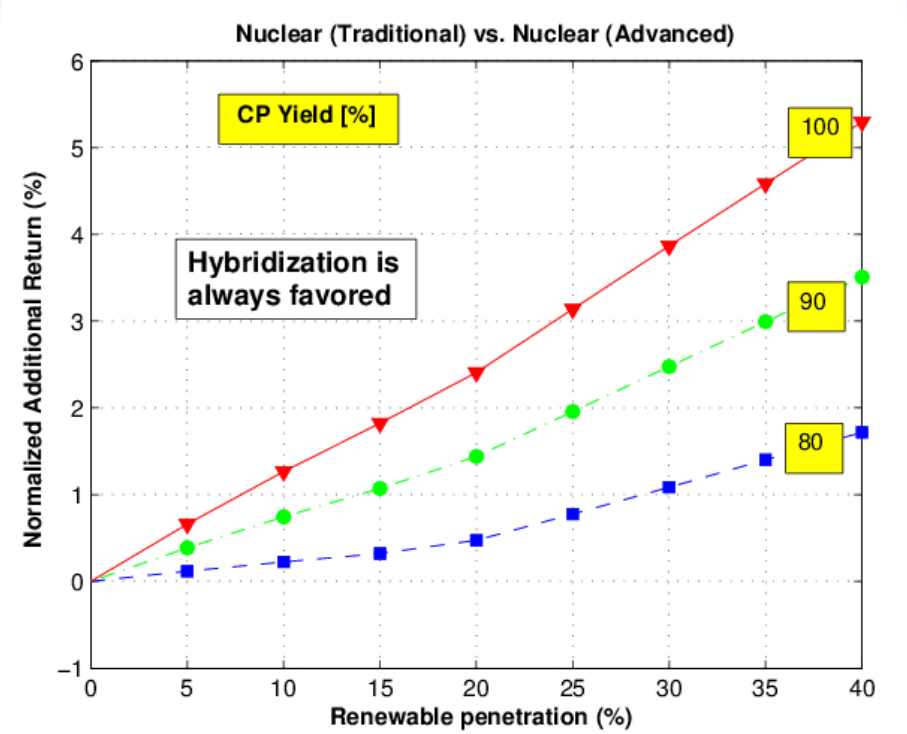
Relative profitability of advanced hybrid (MIMO) increases with increase in renewable penetration

$$NAR = \frac{(V_a - V_t)}{\widehat{O}_a} \times 100$$

Subscript

t: traditional (*phg*, *ren*, *sto*)

a: advanced (*traditional* + *cpc*)



An advanced nuclear hybrid becomes increasingly more economical than a traditional [electricity-generation-only] nuclear-based solution with increase in renewable penetration

$$V = (R_e + R_{cp}) - (C_{cap} + C_{O\&M} + C_{var} + C_{env})$$

NAR:	Normalized Additional Return
V:	Value generated
R_e:	Revenues from electricity
R_{cp}:	Revenues from chemical products
C_{cap}:	Cost of capital
$C_{O\&M}$:	Cost of operations & maintenance
C_{var}:	Cost of variability
C_{env}:	Cost of environmental impact (CO_2 emission)
$\widehat{O}$:	Adjusted overnight capital cost

Source: INL- Humberto Garcia, et. al. Renewable & Sustainable Energy Reviews, 2012

Key Technical and Market Challenges –

NHES systems approach requires RD&D in five broad areas that are related to and supported by, though not classically components of, nuclear technology RD&D.

Hybrid process and systems design; Economic & lifecycle analysis; Advanced monitoring & controls

Systems Architecture, Integration, and Control

Thermal hydraulic component development/demonstration; Heat and electromagnetic process energy deposition

Energy Transfer

Dynamic electricity generation & storage; Hydrogen, fuels , & chemicals synthesis

Energy Conversion & Storage

Resource extraction and processing; Feedstock thermal treatment & conversion

Resource Production & Conversion

CO_2 separation & conversion; Solid waste conversion; Low grate heat recovery; Water treatment

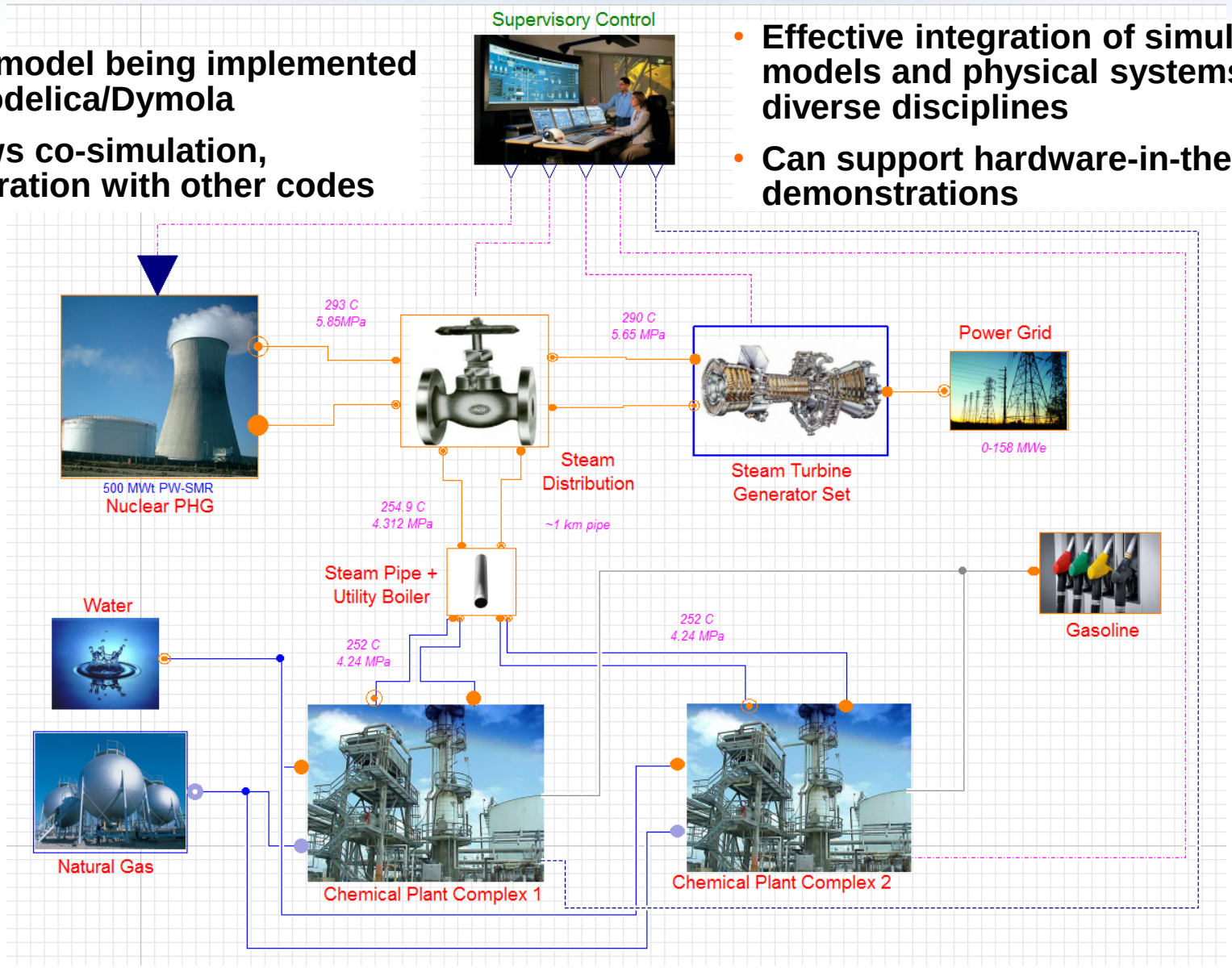
Byproduct Management

- Expanded use of nuclear energy for industrial applications raises economic as well as technical challenges, including safety and licensing considerations
- Renewable energy build-out creates system stability challenges and massive energy storage and recovery needs
- Complex integrated systems will require careful monitoring and control of feedback loops, optimization of high-fidelity processes, dynamic management and interface with the electrical grid, and many other non-traditional control strategies to be considered for nuclear reactor operation (particularly for multi-module SMRs)

INL Emphasis: Dynamic Analyses

- HES model being implemented in Modelica/Dymola
- Allows co-simulation, integration with other codes

- Effective integration of simulated models and physical systems from diverse disciplines
- Can support hardware-in-the-loop demonstrations

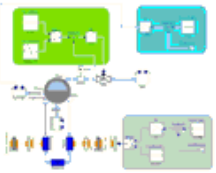


INL HES Co-Simulation: Modeling & Hardware

Analysis, Testing & Optimization of Dynamic Energy Systems

- Innovation
- Collaboration
- HiL demonstration

"Runtime integration and cooperation of simulation tools & hardware assets"



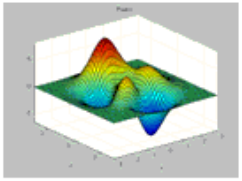
Dynamic Physical Systems Simulations

- Acausal dynamic simulations
- Causal dynamic simulations
- Multi-domain hybrid models

Monitoring, Controls & Intelligent Systems

- Resilient Control Systems
- Diagnostics & Prognostics
- Predictive Monitoring & Controls

HES Dynamic Co-Simulation Test Bed

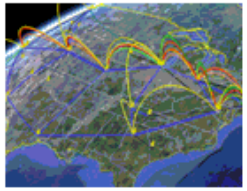


Data Analysis & Optimization

- Dynamic Performance Analysis
- Dynamic Cost/Economic Analysis
- Multidimentional Optimization

Hardware-in-the-Loop (HiL)

- INL Powergrid Test bed
- INL Telecommunication Test Bed
- Power / Thermal Converters
- Realistic Electrical / Thermal Components (e.g., SCADA, transformers, heat exchangers)



Collaborator links w/ Real-time data

- Energy Sciences Network (ESnet)
- INL RTDS & communication links
- Collaborators' assets

Other Simulations & Legacy Models

RELAP5 3D

- Fortran, C/C++, Java, Python programs
- MATLAB/Simulink, LabView, Scilab
- RELAP, ASPEN, HYSYS, FAST/AeroDyn