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

Reliable
- Available on demand
- Continuous quality
- Easily maintainable

Affordable
- Reasonable TOTAL costs
- Predictable, stable price
- Profitable in global economy

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

Energy Storage

- Power
- HEAT
- Hydrogen
- Syngas
- Methanol
- Ammonia
- Synfuels

Energy Services

- Consumer Products
- Comfort & Illumination
- Communication
- Sustenance
- Materials & Structures
- Transportation
Power Dynamics Create Hybrid System Opportunities

Excess diurnal capacity is available year round.

Excess seasonal variation is available for other work.

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

Coal/Bio-Fired
Gas Turbine
Combined Cycle
Small Modular
Reactor

Conc. Solar
Wind

Power Generation
Thermal Reservoir
Giga-Watt Battery

Thermal Energy
Process-Oriented
Heat Application

Electrical Energy

Electrical Grid
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

Fuels Production Thermal Profile

- Coal Gasification (CTL)
- Biomass Gasification (BTL)
- Steam-Methane Reforming (H2 and GTL)
- High Temperature Steam Electrolysis (H2)
- Coal Pyrolysis
- Biomass Fast Pyrolysis
- Oil Shale Retorting
- Petroleum Distillation
- Biomass H.P. Hydro-Thermal Pyrolysis
- Oil Sands Steam Gravity Drainage
- Enthanol Production
- Biomass Torrefaction
- Biomass Drying

Temperature Ranges:
- Light Water
- Light Water with heat amplification
- Sodium-Cooled Molten Salt Liquid Metal
- High Temperature Gas-Cooled

Process Outlet Temperature °C
U.S. Western Energy Corridor: An Opportunity for NHES

[Diagram showing energy resources and production processes]
HTGR Co-Generation of Electricity & Heat for Transportation Fuels

Source: INL-Wyoming CRADA with NGNP Alliance

Production Price of Gasoline for Coal & Natural Gas to Gasoline Processes

EIA Data -- Gasoline Price Components
Jan 2000 through March 2012

- WTI Cushing Price March 2012: $106.27/bbl
- Average Price in 2010: $79.40/bbl
- Average Price in 2011: $94.90/bbl

MTG Coal to Gasoline
- ($80/bbl)

MTG Coal to Gasoline w/HTGR/HTSE
- ($145/bbl)

Natural Gas to Gasoline w/HTGR
- ($61/bbl)

Natural Gas to Gasoline
- ($58/bbl)

Crude Oil Price, $/Barrel (WTI, Cushing, OK)

EIA Projections 2023 - 2035
AEO 2012 Early Release

Excel: "Diesel Fuel Components History 5-05-12"
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.
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)
Relative profitability of advanced hybrid (MIMO) increases with increase in renewable penetration

\[ \text{NAR} = \left( \frac{V_a - V_t}{\hat{O}_a} \right) \times 100 \]

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 (CO₂ emission)
- **\( \hat{O} \)**: Adjusted overnight capital cost

**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.

- **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

Dynamic Physical Systems Simulations
- Acausal dynamic simulations
- Causal dynamic simulations
- Multi-domain hybrid models

HES Dynamic Co-Simulation Test Bed

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

Data Analysis & Optimization
- Dynamic Performance Analysis
- Dynamic Cost/Economic Analysis
- Multidimensional 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)

Other Simulations & Legacy Models
- Fortran, C/C++, Java, Python programs
- MATLAB/Simulink, LabView, Scilab
- RELAP, ASPEN, HYSYS, FAST/AeroDyn

Collaborator links w/ Real-time data
- Energy Sciences Network (ESnet)
- INL RTDS & communication links
- Collaborators’ assets