Nuclear Hybrid Energy Systems

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Steven Aumeier
Director, Energy Systems & Technologies Division
Idaho National Laboratory

Contributors:
- Dr. Richard Boardman
- Dr. Robert Cherry

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DOE Strategic Plan

- **Catalyze the timely, material, and efficient transformation of the nation's energy system and secure U.S. leadership in clean energy technologies.**
  - **Reduce energy-related greenhouse gas emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline**
  - **By 2035, 80% of America's electricity will come from clean energy sources. [1]**
  - **Support deployment of 1 million electric vehicles (EVs) on the road by 2015.**
- **Demonstrate and Deploy Clean Energy Technologies**
  - **Double renewable energy generation (excluding conventional hydropower and biopower) by 2012 (High Priority Performance Goal).**
  - **Support battery manufacturing capacity for 500,000 plug-in hybrid electric vehicles a year by 2015 (High Priority Performance Goal).**
- **Modernize the Electric Grid**
  - **Reduce utility-scale energy storage costs 30% by 2015.**
- **SMR Deployment**
- **Establish Technology Test Beds and Demonstrations**
- **Leverage Partnerships to Expand Our Impact**

1) President Obama State of the Union Speech, February 2011 – "Doubling the share of electricity generated from clean energy sources by 2035: By proposing to make sure that 80 percent of electricity comes from clean energy sources, the President is proposing new standards that will help create a market to unleash innovation across a *range of energy sources, from renewable sources to nuclear power, clean coal, and natural gas*."

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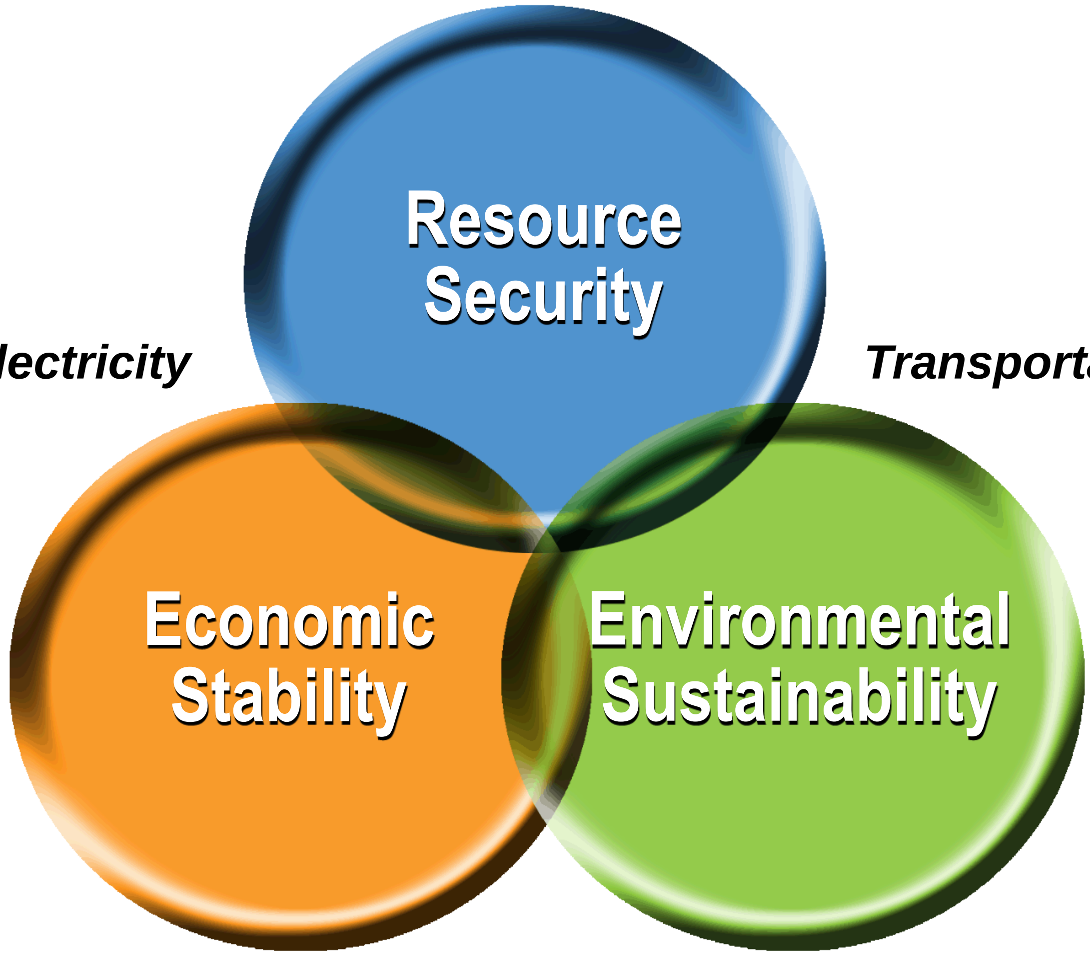
A New Era and the Need for Energy Security…

Electricity

Transportation Fuels



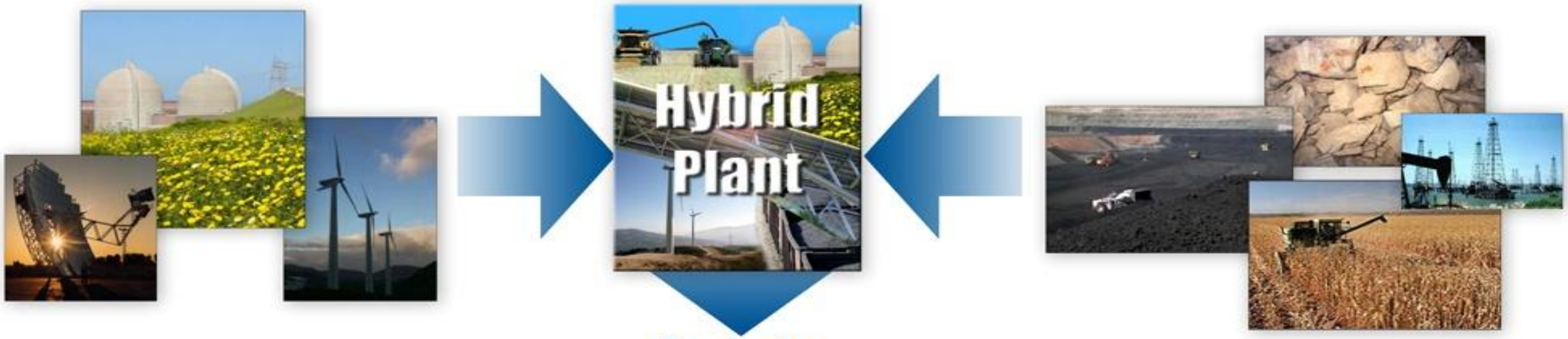
Process Heat

A global imperative for the 21st century

Implications for Nuclear Energy

- **Market potential for nuclear is too constrained, limiting its potential impact in driving energy security, stability, and sustainability solutions. Nuclear energy should be integrated into broader energy markets.**
  - Under the present paradigm, nuclear energy only has the *potential* to address a portion (baseload electricity) of the total U.S. energy demand (approximately 16%), and none in the most volatile area (transportation)
  - NOT simply a challenge of using process heat for industrial applications
- **Accelerated integration of renewable energy, particularly non-dispatchable electric generation, is a priority. This can be problematic (capacity factor optimization, grid dynamics). Nuclear energy can solve this problem.**
  - Electrical system architecture and load patterns drive low effective capacity factors, system vulnerability and instability, and create inefficiencies in capital investment. Nuclear-based hybrids, particularly SMR driven systems, may be key to improved capacity factors for renewables.
  - Nascent biofuels and biopower on-boarding and benefits can be augmented with SMR hybrids
- **The US possesses enormous fossil energy reserves that will be continue to be competitive. Unconventional methane in particular is a game-changer for nuclear.**
  - Development of approaches to convert domestic fossil resources into *infrastructure-compatible* fuels for transportation with low-lifecycle GHG attributes could markedly improve US energy security. Nuclear energy can be the key that unlocks this door.
  - SMR hybrids may provide a pivotal enabling approach.
- **New "energy networks" should be designed to accommodate a transition in the mix of fuels used, e.g. accommodate a transition in light transportation from liquids to electricity**

What is a Hybrid Energy System?



Clean Energy Donors

Products: Transportation Fuels, Electricity and Process Heat

Carbon Donors

- **Tightly coupled systems that exploit complementary characteristics of various energy processes and inputs to produce multiple energy products with life-cycle attributes that help achieve national energy security objectives**
  - Carbon and energy resource considered separately
  - Integration and multi-product approach creates efficiency and flexibility
- **Benefits include:**
  - Greenhouse gas emissions reduction
  - Optimal use of carbon / non-carbon energy resources
  - Energy production efficiency, adaptability and reliability
  - Greater system stability while integrating intermittent sources
  - Flexibility in accommodating technology change & product demand change
  - Domestic resource & production based

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A Substantial Technical Foundation-

- **Jones, J. E. et al.,** Assessment of Very High-Temperature Reactors in Process Applications, Oak Ridge National Laboratory Report, ORNL/TM-5410 (1977)
- **Vision 21: Fossil Fuel Options for the Future,** National Research Council Program Review, National Academies Press (2000)
- **Yamashita, K. and Barreto, L.,** Energyplexes for the 21st Century: Coal Gasification for Co-Producing Hydrogen, Electricity, and Liquid Fuels, Energy, **30**(13):2453-2473 (2005)
- **Ruixian, C et al.,** Development of Multifunctional Energy Systems (MESs), Energy, 2009, (1-8)
- **Hemmes, K. et al.,** Towards multi-source Multi-Product Energy Systems, International Journal of Hydrogen Energy, 2007, 32, (1332-1338)
- **Phadke, A. et al.,** Advanced Coal Wind Hybrid: Economic Analysis, E.O. Lawrence Berkeley National Laboratory Report - LBNL-1248E (2008)
- **Bartis, J.,** Research Priorities for Fossil Fuels, Testimony presented before the U.S. Senate Energy and Natural Resources Committee (March 2009)
- **Idaho National Laboratory Report,** "Integration of High-Temperature Gas Cooled Reactors into Industrial Process Applications", INL/EXT-09-16942 (2009)
- **Larson, E.D. et al.,** Co-production of Decarbonized Synfuels and Electricity from Coal+Biomass With CO2 Capture and Storage: An Illinois Case Study, Energy and Env. Science, 2010, 3,(28-42)
- **Bartis, J and Bibber, L**. "Alternative Fuels for Military Applications", RAND National Defense Institute report for the Office of the Secretary of Defense (2011)

….. But missing: a) nuclear and/or b) full integration and resulting benefits and/or c) consideration of carbon and energy separately

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Market and National Interests Driving Toward Greater Energy Systems Integration

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Equity Fund Backing Renewable-Gas Hybrid Projects

Energy Investors Funds, a private equity fund with investments in numerous high-profile power-sector projects, and NTE Energy LLC jointly announced Monday the formation of a joint venture to develop and operate large-scale "hybrid energy" projects across the country combining different types of renewable and conventional energy technologies.

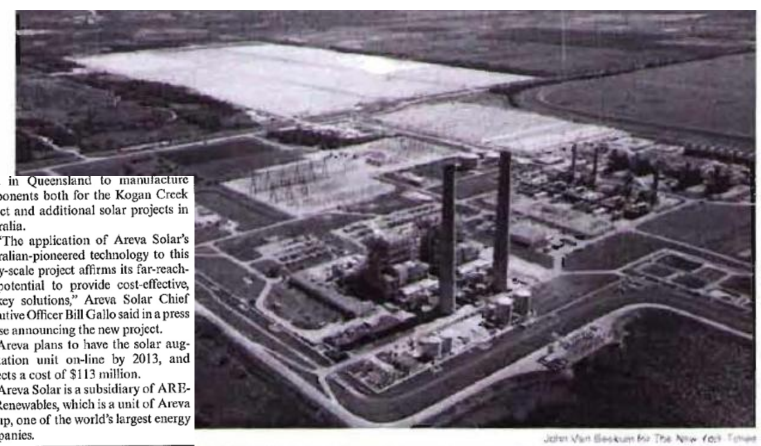
In a statement announcing the creation of EIF-NTE Hybrid Renewable Energy LLC, the companies said the purpose of the joint venture is to deploy new sources of electric power that cost less than traditional renewable energy resources such as wind and solar.

To produce hybrid energy, the joint venture will build power plants that combine solar, biomass and other renewable technologies with natural gas turbine technology. The companies said they plan to site hybrid energy facilities in South Carolina, Alabama and Florida, where NTE, a startup focused on hybrid energy technology, is headquartered.

Energy Investors Funds, which has offices in Boston, New York and San Francisco, has made more than 100 diversified investments totaling more than $15 billion in asset value. The private equity fund is backing, among other projects, the 30-mile, 550-megawatt undersea power line linking the grids of British Columbia and Washington state.

The Energy Daily
April 8, 2010

*The Newest Hybrid Model – FPL Experiments With Solar Thermal ……. **NY Times.com** March 3, 2010*



DARPA

2010 Request for Information / 2012 Proposed Program for Nuclear Energy Driven Mobile Energy Platform (Hybrid)

Areva Announces Solar Project To Boost Aussie Coal Plant

Areva's solar subsidiary announced a deal April 13 to build a 44 megawatt solar thermal unit designed to enhance output at a large coal plant in Queensland, Australia, a project that Areva calls the largest solar project south of the Equator and the largest such augmentation project of its type in the world.

Areva's project will use a proprietary "superheated" steam system to boost the steam generation system at the coal-fired Kogan Creek Power Station, owned by Australia's CS Energy. That will boost Kogan Creek's output by up to 44 megawatts in peak solar conditions above the plant's current capacity of 750 megawatts and will avoid the production of 35,600 tons of greenhouse gas emissions annually, according to Areva Solar.

Areva says it plans to use the Kogan Creek project as a "gateway" to support additional solar thermal project development in Queensland, an area rich with solar resources.

With that in mind, the French company says it will build a manufacturing plant in Queensland to manufacture components both for the Kogan Creek project and additional solar projects in Australia.

"The application of Areva Solar's Australian-pioneered technology to this utility-scale project affirms its far-reaching potential to provide cost-effective, turnkey solutions," Areva Solar Chief Executive Officer Bill Gallo said in a press release announcing the new project.

Areva plans to have the solar augmentation unit on-line by 2013, and projects a cost of $113 million.

Areva Solar is a subsidiary of AREVA Renewables, which is a unit of Areva Group, one of the world's largest energy companies.

The Energy Daily
April 25, 2011

Numerous Variations of Nuclear Hybrids Possible

- **Nuclear-Coal**
  - This approach could offer a low-carbon path to utilizing abundant coal for liquid transportation fuels at attractive costs
- **Nuclear-Methane**
  - Enormous domestic reserves of natural gas (shale gas, coal-bed methane) are now recoverable, more than doubling US “booked” reserves in less than 5 years. Hybrids may offer a practical, infrastructure compatible path to utilizing this resource to produce hydrogen, chemicals, and transportation fuel
- **Nuclear-Biomass-Coal/Methane**
  - Potential for very low-carbon transportation fuel and other chemical products, using regenerable biomass
  - Approximately 1 billion (dry) tons of purpose-grown wood and other energy crops can be grown in the U.S. without impact on food production (or about 16 Quads)
- **Nuclear-Fossil-Intermittent Renewable**
  - Hybridizing fossil, nuclear and intermittent renewable energy (wind, solar) may offer significant advantages to increasing the effective capacity factor of renewable systems and offer a path to more quickly integrate more renewable energy into energy products while maintaining system stability and reliability
- **Variations and combinations of above**

Evolution of Hybrid Energy Systems

Gen I
Co-Gen
Loosely coupled system

Attributes:
- Thermodynamic efficiency
- Byproduct management

Gen II
Solar-Coal
Solar-Gas
Single product, i.e. electricity

Attributes:
- GHG mitigation
- Conversion efficiency
- Improved financial performance

Gen III
Biomass-Coal
Single product, i.e. electricity

Attributes:
- Significant GHG mitigation
- Capital lifetime extension
- Resource extension

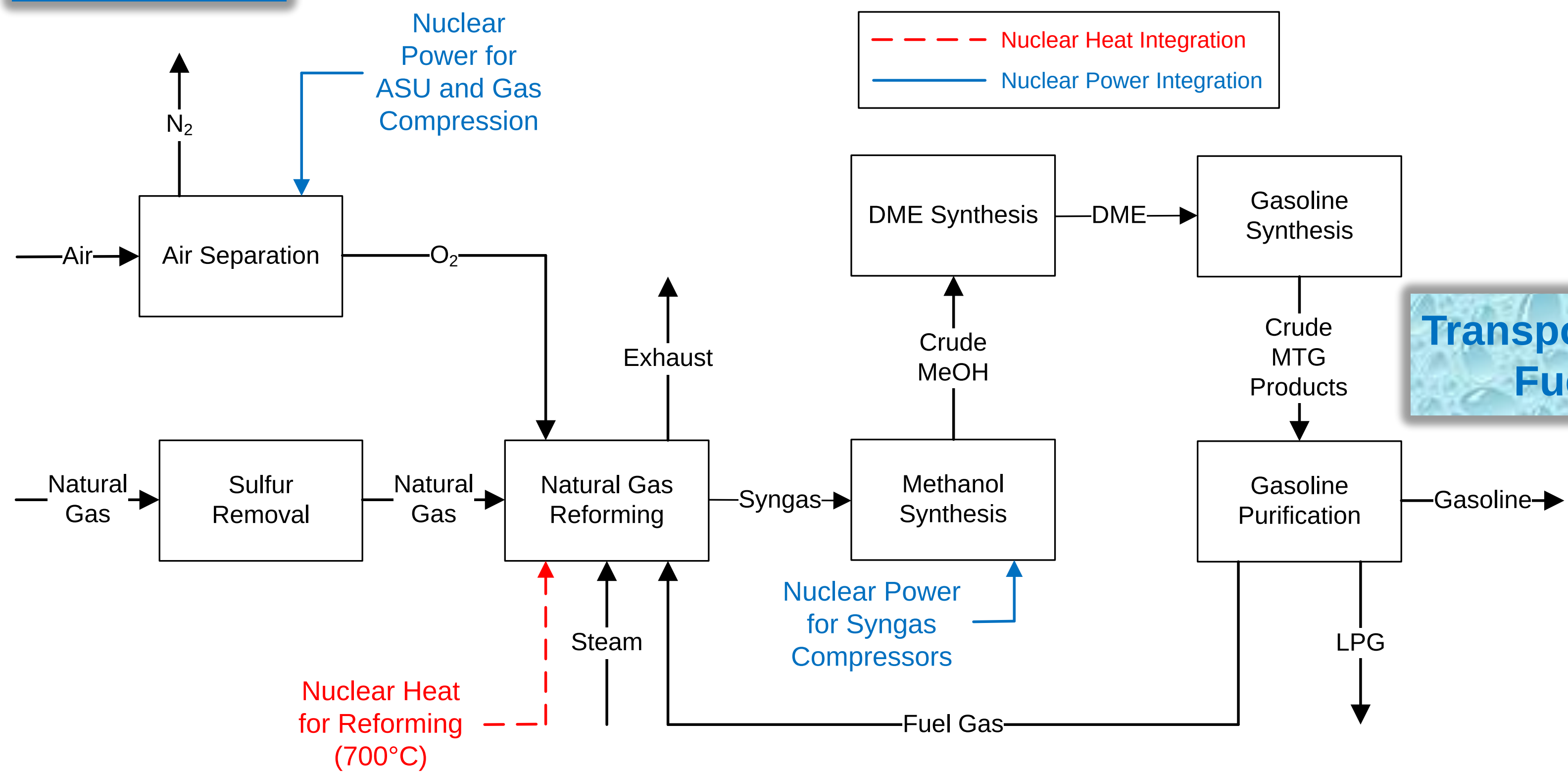
Gen IV
Nuclear-Gas / Coal
Multiple Products

Attributes:
- Grid stability
- Efficient Integration of renewables
- GHG mitigation
- Resource optimization
- Energy conversion optimization
- Foreign source mitigation/price stability

Gen V
Nuclear-Gas-Wind
Multiple Products
Intermittent Renewable Integration

Gen IV Hybrid – Nuclear/Natural Gas Synfuels

Carbon-Free Power

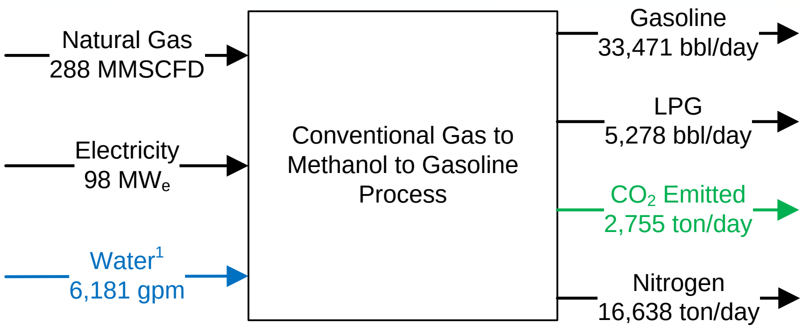


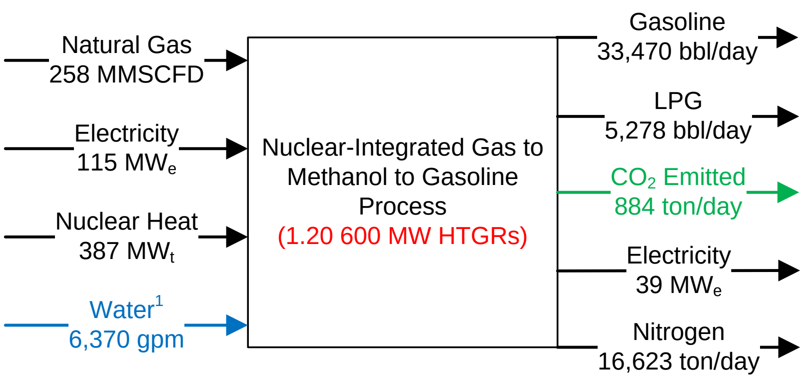
Transportation Fuels

Carbon-Free Energy

Results from Validated Engineered Simulation with Efficient Energy Integration

Process Modeling Results





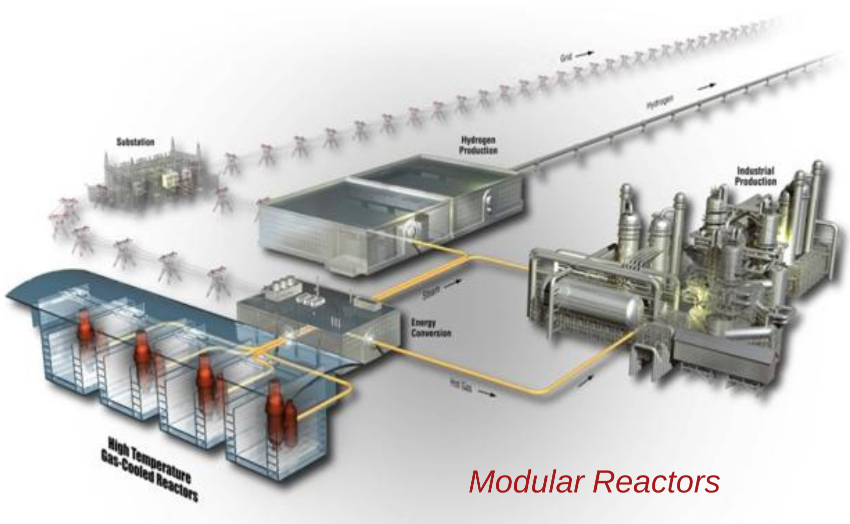
[1]Does not include heat rejection requirement for the nuclear plant.

Economic Model Assumptions

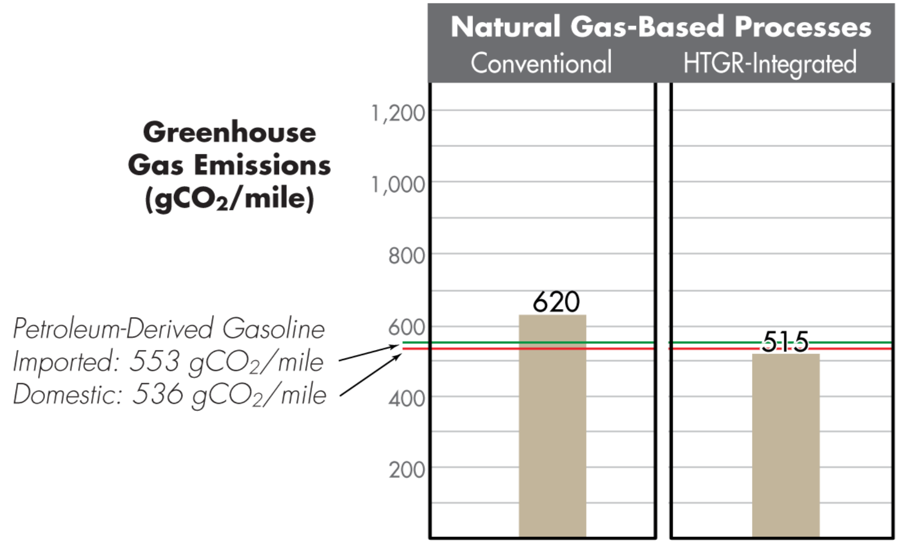
- **Plant economic life: 30 years (excludes construction time)**
- **Construction period**
  - Fossil plant: Three years
  - HTGR plant: Five years
- **Startup assumptions**
  - Operating costs: 80% of operating costs
  - Revenues: 60% of revenue
- **Capacity factor: 95%**
- **Internal rate of return (IRR): 12%**
- **Inflation rate: 3%**

- Interest on debt: 8%
- Repayment on debt: 20 years
- Effective U.S. income tax rate: 38.9%
  - U.S. federal tax: 35%
  - U.S. state tax: 6%
- MACRS depreciation: 15-yr plant life
- Natural gas price: $9 per 1,000 scf
- CO_2 tax: $100/ton
- Debt-to-equity ratio: 80/20

Gas-to-Gasoline Hybrid System Benefits



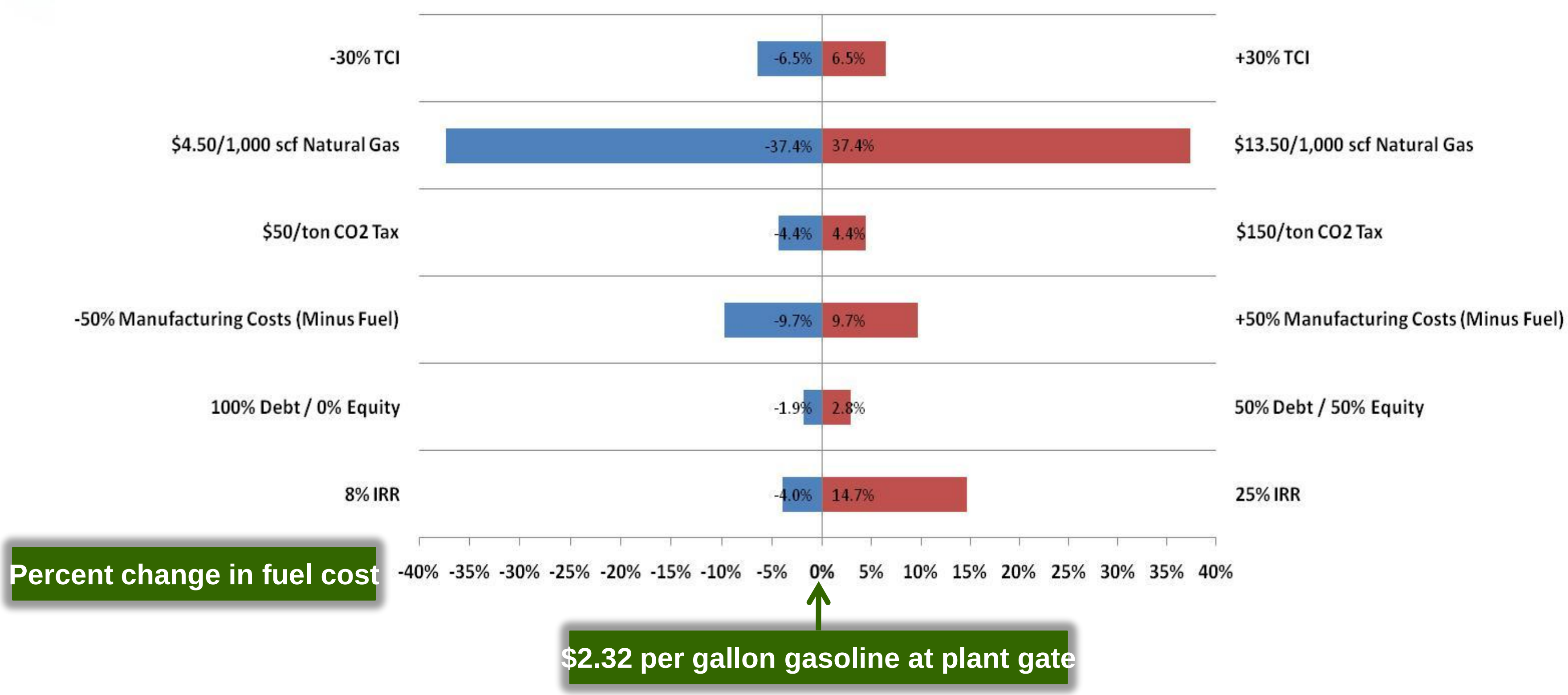
Modular Reactors



Note: The average U.S. domestic and imported life-cycle emissions for petroleum-derived gasoline were obtained from a 2009 NETL refinery report (DOE/NETL-2009/1362).

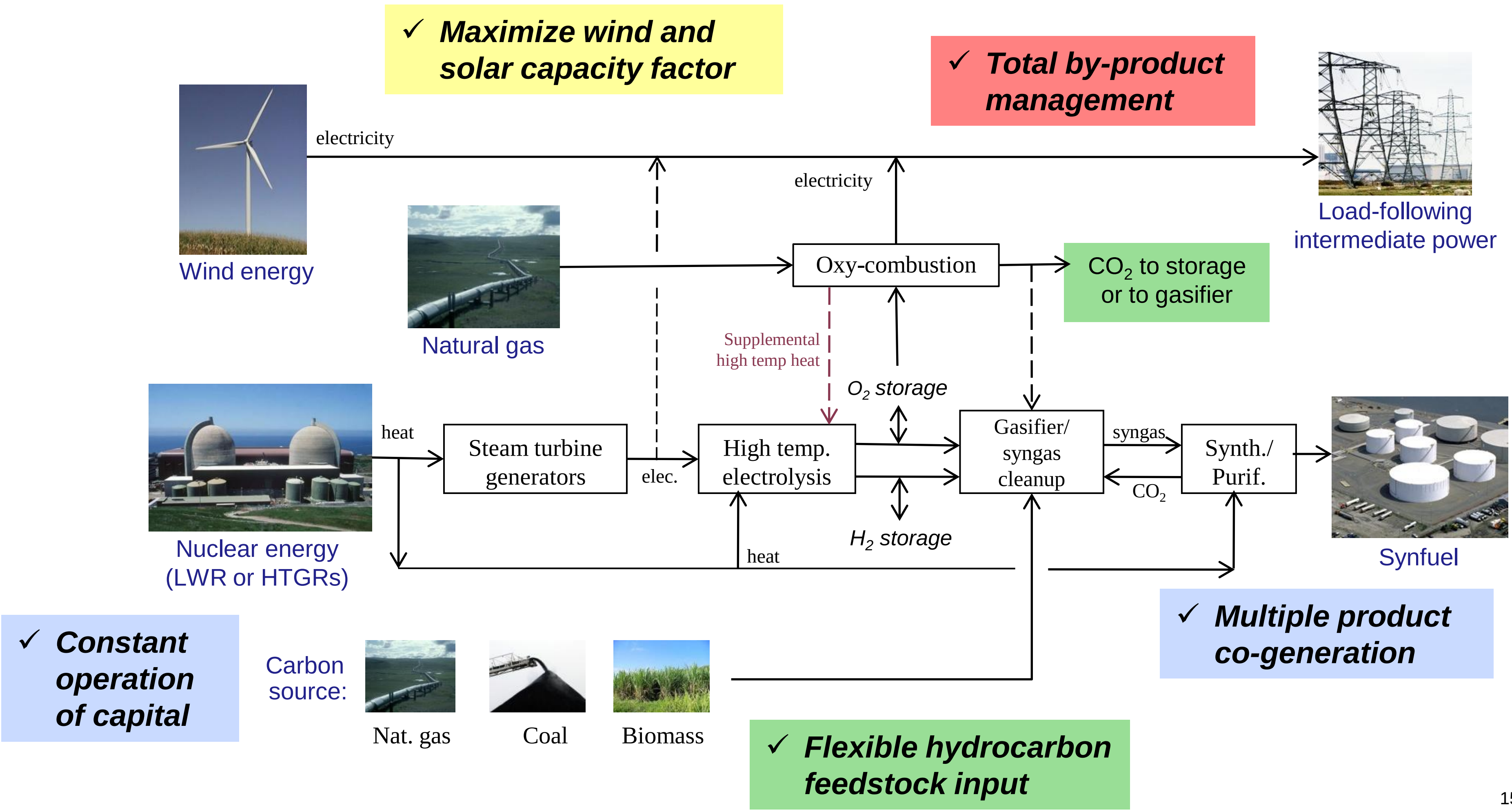
- **The conventional gas-to-gasoline process produces more greenhouse gas (GHG) emissions than either imported or domestic petroleum-derived gasoline**
- **Integrating nuclear technology with the conventional process can significantly reduce GHG emissions**
  - 17% lower than the conventional gas-to-gasoline process
  - 7% lower than imported petroleum-derived gasoline
  - 4% lower than domestic petroleum-derived gasoline

Sensitivity of HES Synfuels Economics



- **When a high natural gas price ($9.00 per 1,000 scf) and carbon tax ($100/ton) are assumed, the hybrid case can produce gasoline cheaper than the conventional case.**
  - $2.32/gal for hybrid vs. $2.55/gal for conventional gas-to-gasoline (not including gasoline taxes, fuel transportation costs, or seller markup)
  - Costs are competitive with current petroleum-derived gasoline
- **The most important variables impacting cost are natural gas purchase price and the IRR required on the capital investment**

Expand Nuclear HES for Optimal Use of Renewable Energy



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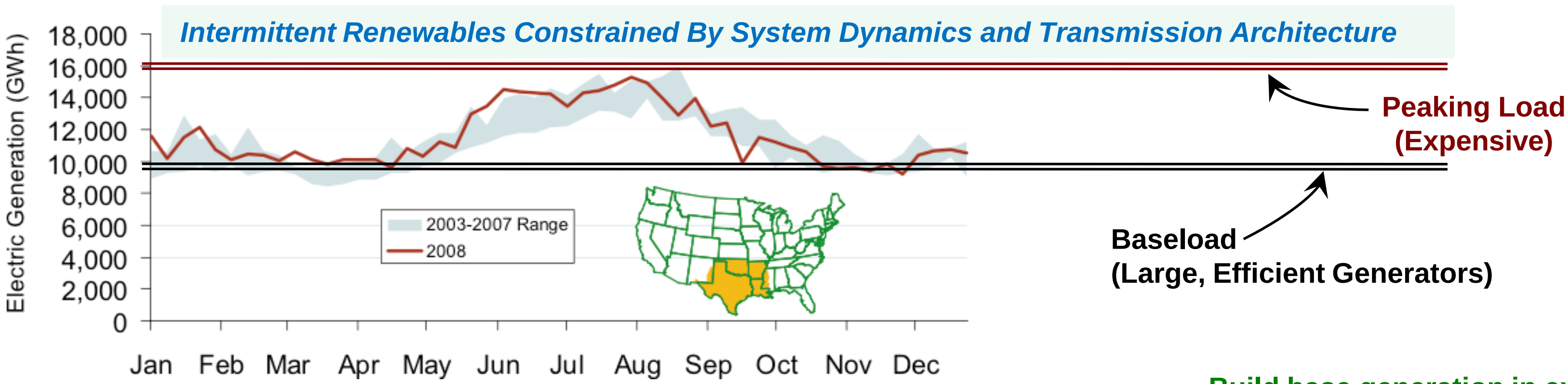
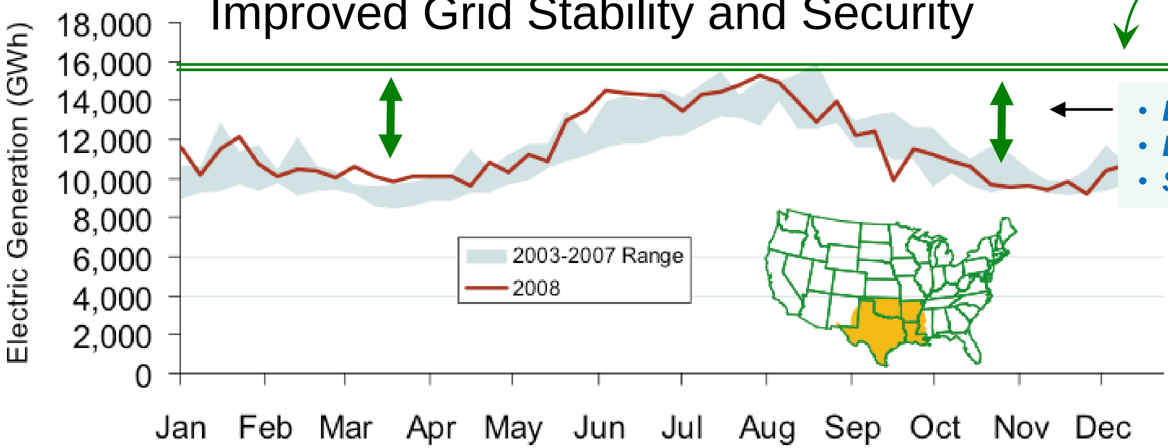
Hybridizing Nuclear Energy with Renewable Energy Enhances Integration To Grid & Increases Effective Capacity Factors

Electrical Generation – Present Approach



Build base generation in excess of peak. Energy not needed for electricity used to make transportation fuels

Improved Grid Stability and Security



- *Energy Storage via Fuel Production*
- *Efficiency Gains*
- *Stable and Resilient Grid*

Source: Electric Power Demand Data from Market Oversight @FERC.gov

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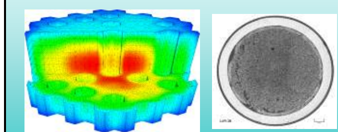
Increase Impact – Efficiency – Effectiveness Requires Dual Focus

Nuclear Energy Technologies

Advanced Reactor Design
Gen-IV Systems
LWR Sustainability

Reactor Systems

Fuel Performance Advanced
Fuel Design & Testing
Materials Performance

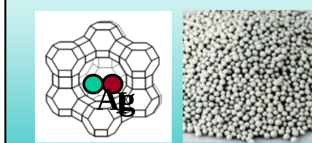


Advanced Fuels and Materials

Spent Fuel Separations

Fuel Cycle Technology

Waste Form Development & Testing



Radioactive Waste

Licensing Support
Design and Safety Methods

Nuclear Safety

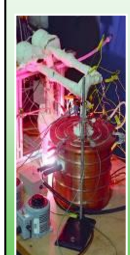
Nuclear Energy Integration

Resource extraction
Feedstock assembly
Thermal treatment

Feedstock Extraction & Processing

Heat exchanger/ heat circulation Heat deposition Gas & liquids T/H Thermal Design

Energy Transfer



Hydrogen Generation
Catalysis/Synthetic Fuels
Electrical Generation & Storage

Energy Storage

CO2 Separation,
Recycle or Sequestration
Alternative CO2 Uses

Byproduct Management

Lifecycle Analyses, Hybrid System Design, Signal Processing & Visualization
Advanced Controls

Systems Analyses, Integration, Monitoring & Control

… plus Commercialization Partnerships and Manufacturing