The Essential Role of Nuclear Energy in Achieving Economy-wide Net-Zero Solutions

April 2022

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517
The Essential Role of Nuclear Energy in Achieving Economy-wide Net-Zero Solutions

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37th Korea Atomic Power Annual Conference:
Clean Energy for a Net Zero and Hydrogen Economy
April 28, 2022
Presentation overview

- Energy systems status quo
- New nuclear paradigm: A vision for the future
  - New market opportunities beyond electricity
- Integrated energy systems
  - Concept
  - Design/analysis
  - Opportunity for new markets
- Advancing nuclear and integrated energy systems through demonstration
Today’s energy systems

• Individual generators contribute to meeting grid demand, managed by an independent grid operator
• Individual thermal energy resources typically support industrial demand
• Transportation mostly relies on fossil fuels (with growing, yet limited, electrification)

**Achieving net-zero emissions will require us to consider the role(s) of all clean energy generation options—and we must look to non-emitting sources of heat in addition to electricity.**
The current role of nuclear energy in the U.S.

Nuclear power is one of America’s largest and most reliable domestic sources of clean energy.

2018 SOURCES OF EMISSION-FREE ELECTRICITY

NUCLEAR: 55%

HYDRO: 20%

WIND: 19%

SOLAR: 5%

GEOTHERMAL: 1%

2018 ENERGY CAPACITY FACTOR*

NUCLEAR: 92.6%

*Capacity factor = average power generated / rated peak power
Decarbonizing electricity is only part of the challenge.

Electricity accounts for only 17% of total energy use in the U.S. across all “Energy use sectors,” with the remaining 83% used in the form of heat.
Future clean energy systems – transforming the energy paradigm

Integrated energy systems (IES) leverage the contributions from nuclear fission beyond electricity

Nuclear Energy Generation
- Light water reactors, high temperature advanced reactors, small modular reactors, microreactors, etc.

Other Energy Generation
- Variable renewables, municipal waste, fossil with carbon capture, etc.

Integrated energy systems (IES) leverage the contributions from nuclear fission beyond electricity
Potential nuclear-driven IES opportunities

Examples not exhaustive

Source: INL, National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs, April 2021
Nuclear-hydrogen production and utilization

Motivation for H₂ production to support multiple processes/products beyond electricity

1) Provides energy storage, for electricity production or H₂ user (e.g., chemicals and fuels synthesis, steel manufacturing, ammonia-based fertilizers)

2) Provides second source of revenue to the generator; allows generator to operate at nominal power at all times

3) Provides opportunity for grid services, including reserves and grid regulation
Why hydrogen?

Hydrogen applications in industry

• Agriculture/chemical industry: ammonia, ammonia-based fertilizers
• Petroleum refining: hydrocracking to produce gasoline, diesel
• Methanol production
• Other:
  − Food (e.g., hydrogenated oils)
  − Metalworking
  − Welding
  − Flat glass production
  − Electronics manufacturing
  − Medical applications

Data source: Hydrogen Europe
hydrogeneurope.eu/hydrogen-applications
Integrated energy systems analysis and optimization

- Technoeconomic assessment
  - Portfolio Optimization
  - Dispatch Optimization
  - Process Model Simulation
  - Economic Analysis
  - Supervisory Control
  - Stochastic Analysis
  - Workflow Automation

For more information and to access open source tools, see https://ies.inl.gov/SitePages/System_Simulation.aspx.
Example: Disruptive potential of nuclear produced hydrogen

- Collaboration between INL, ANL, NREL, Constellation (Exelon), and Fuel Cell Energy
- Evaluated potential of using existing nuclear plants to make hydrogen via high temperature steam electrolysis (HTSE) in parallel to grid electricity
  - Low grid pricing $\rightarrow$ hydrogen is more profitable
  - High grid pricing $\rightarrow$ grid is more profitable
  - $\text{H}_2$ storage provides flexibility in plant operations, ensures that all demands are met
  - $\text{H}_2$ off-take satisfies demand across steel manufacturing, ammonia and fertilizer production, and fuel cells for transportation
- Analysis results suggest a possible revenue increase of $\$1.2\ billion\ ($2019$) over a 17-year span
Example: Disruptive potential of nuclear produced hydrogen

**Outcome:** Award from the DOE EERE Hydrogen & Fuel Cell Technologies Office with joint Nuclear Energy funding for follow-on work and demonstration at Constellation Nine-Mile Point plant.

**Full report:** Evaluation of Hydrogen Production Feasibility for a Light Water Reactor in the Midwest (INL/EXT-19-55395)
Nuclear-H₂ demonstration projects

Four projects have been selected for demonstration of hydrogen production at U.S. nuclear power plants (NPP)

- H₂ production using direct electrical power offtake
- Develop monitoring and controls procedures for scaleup to large commercial-scale H₂ plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce H₂ for captive use by NPPs and clean hydrogen markets

Projects

- Constellation: Nine-Mile Point NPP (~1 MWe LTE/PEM)
- Energy Harbor: Davis-Besse NPP (~1-2 MWe LTE/PEM)
- Xcel Energy: Prairie Island NPP (~150 kWe HTSE)
- APS/Pinnacle West Hydrogen: Palo Verde Generating Station (~15-20 MWe LTE/PEM)
- FuelCell Energy: Demonstration at INL (250 kWe)
Thermal integration of steam electrolysis

Safety analysis summary conclusions

• The LWRS generic probabilistic risk assessment (PRA) investigation into licensing considerations concluded that following the assumptions made:
  − The licensing criteria is met for a large-scale HTE facility sited 1 km from a generic PWR and BWR
  − The safety case for less than 1 km distance is achievable

Operations with flexible thermal and electrical power dispatch

• The INL Human Systems Simulation Laboratory was used to test concepts for dispatching thermal and electrical power from nuclear reactors to a H₂ electrolysis plant
  – Two formerly licensed operators tested 15 scenarios
  – A modified full-scope generic Pressurized-Water Reactor was used to emulate the nuclear power plant
  – A prototype human-system interface was developed and displayed in tandem with the virtual analog panels
  – An interdisciplinary team of operations experts, nuclear engineers, and human factors experts observed the operators performing the scenarios

• This exercise emphasized the need to support the adoption of thermal power dispatch by
  – Leveraging automation to augment any additional operator tasking
  – Monitoring energy dispatch to a second user
Microreactors and small modular reactors can be deployed to provide reliable energy where it is needed with a small footprint that allows for siting very near to the intended use.

Artist renditions courtesy of GAIN and Third Way, inspired by the Nuclear Energy Reimagined concept led by INL. Learn more about these and other energy park concepts at thirdway.org/blog/nuclear-reimagined.
Advanced Reactor Design Concepts

Key Benefits
• Inherent/passive safety
• Deployment flexibility
• Versatile applications
• Long fuel cycles
• Reduced waste
• Advanced manufacturing to reduce cost

60+ private sector projects under development
Accelerating advanced reactor demonstration & deployment
Dynamic Energy Transport and Integration Laboratory (DETAIL)

- **Battery Testing** (out of picture)
- **Wireless Charging**
- **Fast Charging**
- **Human Systems Simulation Lab** (out of picture)
- **Energy Storage**
- **Thermal Energy Distribution System** Includes Thermal Energy Storage
- **High Temperature Electrolysis**
- **Hydrogen**
- **Power Emulation**
- **Digital, Real-Time Grid Simulation**
- **Power Plant Operations**
- **Vehicles**
- **Power Systems**
- **MAGNET Microreactor Agile Nonnuclear Experimental Testbed**
- **Distributed Energy & Microgrid**
- **Power Emulation**
- **Power Plant Operations**
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- **Energy Storage**
- **Fast Charging**
- **Thermal Energy Distribution System** Includes Thermal Energy Storage
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- **MAGNET Microreactor Agile Nonnuclear Experimental Testbed**
- **Distributed Energy & Microgrid**
Microreactor integration with a microgrid

**Microreactor Applications Research Validation and Evaluation (MARVEL) Objective:**
Operational reactor that produces **combined heat and power (CHP)** to a functional microgrid

Demonstrate nuclear microgrid operations and provide opportunity to demonstrate operation with coupled energy users, such as hydrogen production and desalination.

**MARVEL Construction:** Dec 2022
**MARVEL Criticality:** Dec 2023
**National Reactor Innovation Center (NRIC) advanced reactor testing infrastructure**

- **Goal:** Demonstrate two advanced reactors by 2025

- **Strategy:**
  - Repurpose two facilities at INL and establish two test beds to provide confinement for reactors to go critical for the first time
  - Build/establish testing infrastructure for fuels and components

- **Capabilities:**
  - NRIC DOME (Demonstration of Microreactor Experiments)
    - Advanced Microreactors up to 20 MWth
    - High-Assay Low-Enriched Uranium (HALEU) fuels < 20%
  - NRIC LOTUS (Laboratory for Operations and Testing in the US)
    - Up to 500 kWth experimental reactors
    - Safeguards category one fuels
  - Experimental Infrastructure
    - Molten Salt Thermophysical Examination Capability
    - Helium Component Test Facility

Anticipate initial reactor testing in ~2024. Flexible testbed to support testing of multiple reactor concepts using the same infrastructure ~annually.

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For more information on NRIC and to download resources, see https://nric.inl.gov/.
**Goal:** Use an advanced reactor to generate steam, heat, and electricity for a coal conversion plant.

**Representative Coal Conversion Process**

- **Coal**
  - Drying
  - Fracturing
  - Pyrolysis
  - Mercury Disposal
  - Mineral Processing
  - Advanced Reactor
  - High Temperature Reactor

- **Heat**
  - Heat Steam

- **Steam**
  - Steam

- **Electricity**
  - Electricity
  - Profit $ (Electric Market)

- **Syngas**
  - Syngas (H₂, CO)
  - CO₂ (+H₂O) (or recycle back into gasifier)

- **Conversion Market**
  - Profit $ (Electric Market)
  - Carbon Markets
    - To Carbon Production
    - To Asphalt/Tar Production

- **Products**
  - Char Ash
  - Asphaltenes
  - Hydrothermal Gasification
  - Oil + Gas
  - Solids
Nuclear Synthetic Fuels Production

**Goal:** Demonstrate the economic potential of using light water or advanced nuclear reactors for synthetic fuels production.

**Representative Nuclear-Coupled Synthetic Fuels Process**

- **Nuclear Plant**
- **CO₂ Feedstock Plant**
- **Reversible Water Gas Shift**
- **Fischer Tropsch Process**
- **Refining Process**
- **Hydrogen Production Plant**
- **Electricity**
- **Heat**

- **Products:**
  - Diesel
  - Naphtha
  - Jet Fuel
A vision for a net-zero future

- Variable Renewable Energy Generation
- Grid-Scale Battery & Hydrogen Energy Storage
- Smart Electrified Homes with EV Charging
- Electrified Parcel Distribution Center with Electric Truck/Van Charging
- Hydrogen Fueling & Fast Charging Travel Center
- Smart Electrified Office Building with EV Charging
- Electric Transit Bus Charging Depot
- Water Desalination Plant
- Zero-Emission Port with Fuel-Cell Drayage Trucks
- Nuclear Integrated Energy Systems Park
- Advanced Reactor with Co-Located Hydrogen & Other Chemical Production
- Electrified Steel Mill
- Variable Renewable Energy Generation
- Grid-Scale Battery & Hydrogen Energy Storage
- Smart Electrified Homes with EV Charging
- Electrified Parcel Distribution Center with Electric Truck/Van Charging
- Hydrogen Fueling & Fast Charging Travel Center
- Smart Electrified Office Building with EV Charging
- Electric Transit Bus Charging Depot
- Water Desalination Plant
- Zero-Emission Port with Fuel-Cell Drayage Trucks
- Nuclear Integrated Energy Systems Park
- Advanced Reactor with Co-Located Hydrogen & Other Chemical Production
- Electrified Steel Mill
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