INL/CON-23-75539-Revision-0

Integrated Energy Systems: Extending Nuclear Energy to Support a Decarbonized Industrial Sector

November 2023

Changing the World's Energy Future

Shannon M Bragg-Sitton

Idaho National Laboratory

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

14 November 2023

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2023 ANS Winter Meeting, Washington, D.C.
Nuclear Energy for Industrial Uses: Bridging the Gap

INL/CON-23-75539

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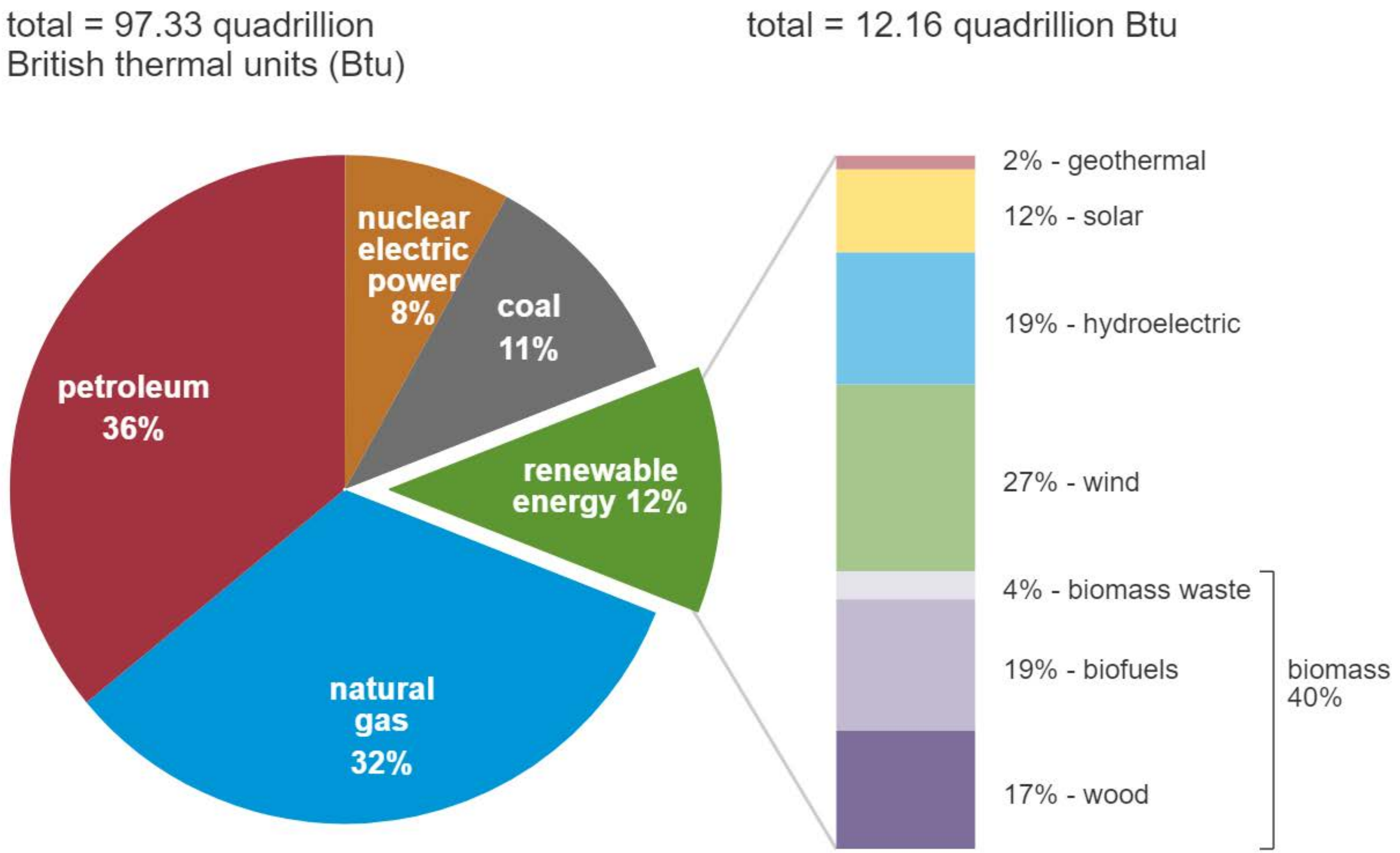
U.S. primary energy consumption by energy source, 2021



Data source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3 and 10.1, April 2022, preliminary data
Note: Sum of components may not equal 100% because of independent rounding.

Summary of total energy consumption, including electricity, heating, industry, and transportation.

80% fossil fuels
20% non-fossil sources

Summary data available at https://www.e-education.psu.edu/ebf301/node/457

Key challenges to deep decarbonization

- Providing clean, non-emitting electricity on a dispatchable basis
- Replacing the high-quality heat that is currently provided by fossil fuels to many industrial processes
- Developing a non-emitting source for a key energy carrier (i.e., hydrogen) that can support applications across all energy use sectors, including industry and transportation
- Maintaining reliability, resilience, and affordability

Nuclear energy, working alongside renewables, can meet these decarbonization challenges

The U.S. Department of Energy is doubling down on the commitment to clean energy

- *Energy Earthshots™ will accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade. They will drive the major innovation breakthroughs that we know we must achieve to solve the climate crisis, reach our 2050 net-zero carbon goals, and create the jobs of the new clean energy economy.* (*https://www.energy.gov/policy/energy-earthshots-initiative*)

Hydrogen Shot ← **Goal: <\$1/kg clean H_2 by 2031**
Clean H_2: <2 kg CO_2e/kg H_2 at the site of production

Long Duration Storage Shot

Carbon Negative Shot

Enhanced Geothermal Shot

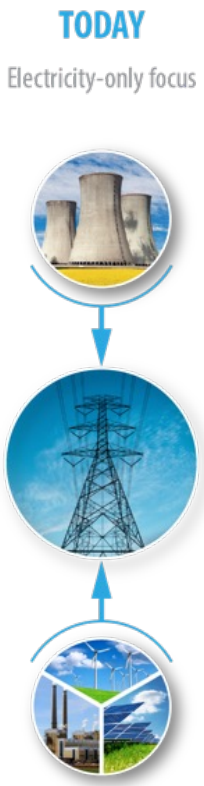
Floating Offshore Wind Shot

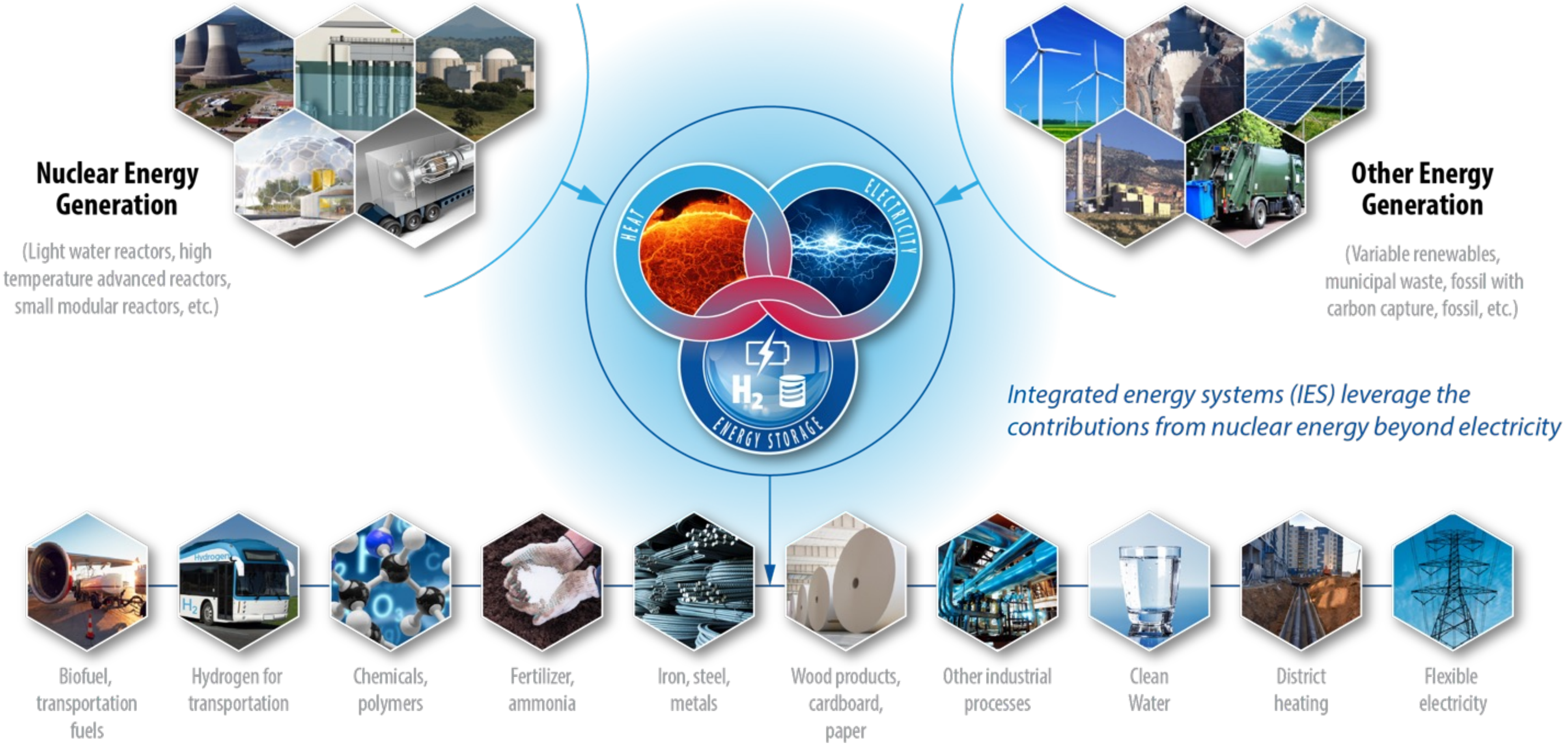
Industrial Heat Shot

Clean Fuels & Products Shot

(Industrial Heat Shot and Clean Fuels & Products Shot) **Goal: >85% reduction in GHG emissions by 2035**

Shifting the energy paradigm

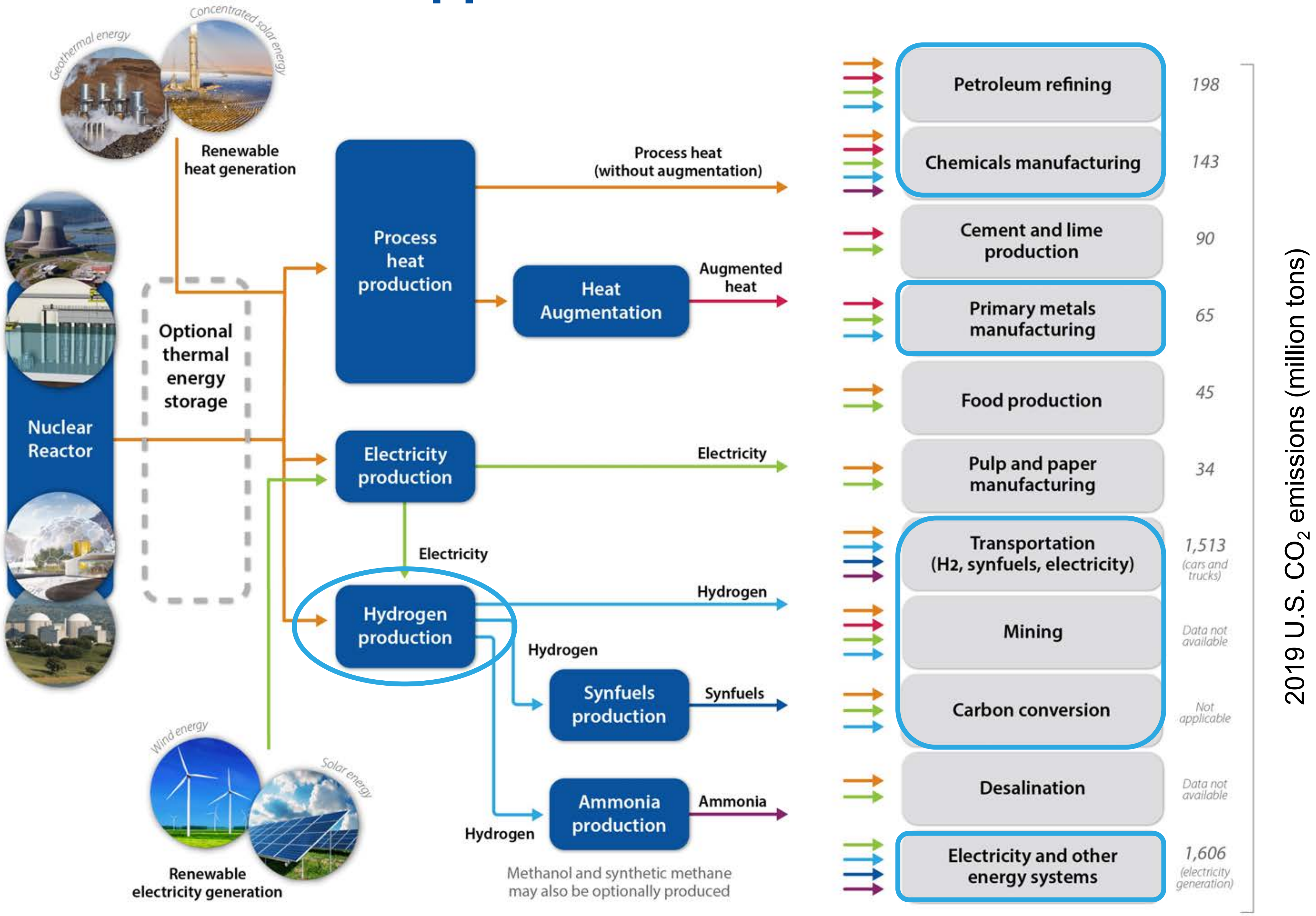




Potential nuclear-driven IES opportunities

Reactor sizes align with the needs of each application; heat augmentation can be applied if needed to match process temperature demands.

Source: Adapted from INL, National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs, April 2021



Past experience in *operational* nuclear cogeneration, as summarized by Gen-IV International Forum signatory countries

- UK Calder Hall Magnox (heat supported onsite nuclear fuel plant, shut down in 2003)
- Norway Halden BWR (steam for the Saugbrugs paper factory, shut down in 2018)
- Switzerland Gösgen PWR (transport of steam over 2 km to a cardboard factory)
- Canada Bruce A CANDU (district and industrial heating, cogeneration stopped in 1997)
- Germany Stade PWR (salt refinery, nuclear plant shut down in 2003)
- Switzerland Beznau (district heating)
- Various Eastern European countries (district heating)
- >200 reactor-years operating experience with seawater desalination (mostly Japan, India, Kazakhstan; MSF, MED, RO technologies)

See *Summary Report* from the *GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.

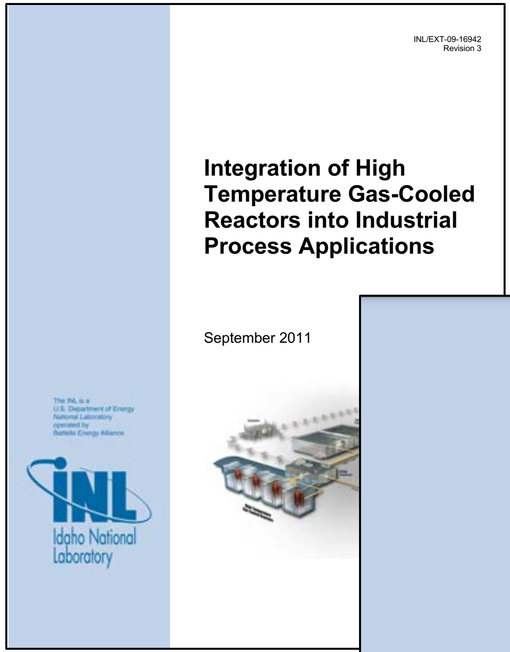
Past experience in *operational* nuclear cogeneration, reflections and lessons learned

- If possible, it is important to consider heat applications at the design phase of nuclear energy systems to avoid potentially costly retrofitting of a system exclusively designed for electricity production.
- Precedent has been established for safe, reliable operation of nuclear cogeneration systems.
- Nuclear standards and regulations have evolved since many of these systems operated and must be reviewed as a part of current efforts.

See *Summary Report* from the *GIF NEANH Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.

U.S. DOE Next Generation Nuclear Plant program—key takeaways

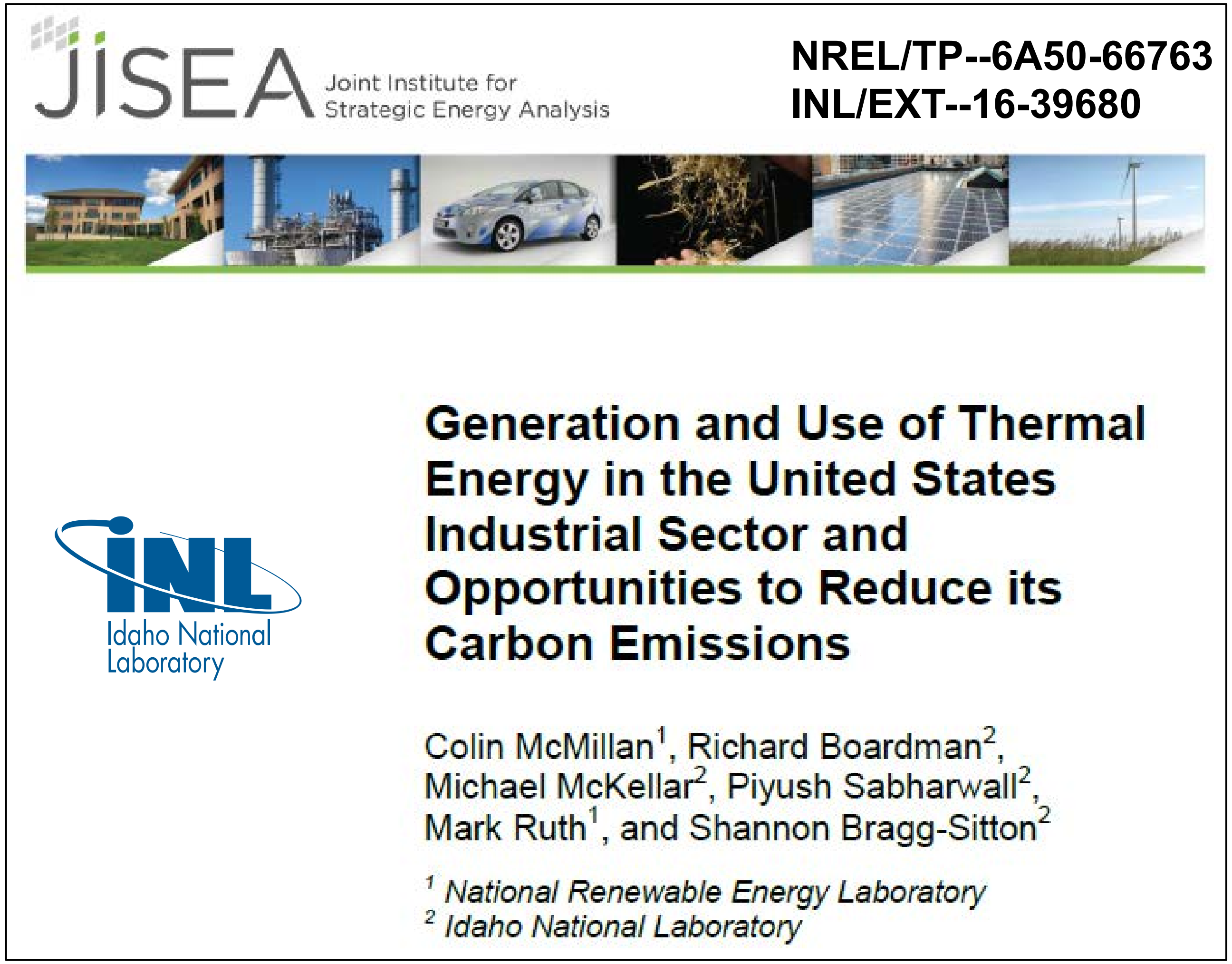
- Cases examined for high temperature gas-cooled reactor utilization (2011)
  - Power generation
  - Hydrogen generation using natural gas
  - Methanol to synthetic gasoline using natural gas
  - Synthetic diesel (liquid) production using natural gas or coal
  - Ammonia production using Natural Gas or Coal
  - SAGD for oil recovery
  - Coal to Natural Gas Production
- High temperature heat, electricity, and hydrogen provided by an HTGR with high temperature steam electrolysis (HTSE) offers many opportunities for integration of nuclear energy in industrial applications
- Results are highly sensitive to economic assumptions and cost inputs
- Cases should be re-evaluated in light of current technology costs, energy markets, and assumptions



Report available for download at OSTI.gov: https://doi.org/10.2172/1032079

Also see https://doi.org/10.2172/1481779

Evaluating the options: Heat market study (2016)



JISEA Joint Institute for Strategic Energy Analysis

NREL/TP--6A50-66763
INL/EXT--16-39680

INL Idaho National Laboratory

Generation and Use of Thermal Energy in the United States Industrial Sector and Opportunities to Reduce its Carbon Emissions

Colin McMillan[1], Richard Boardman[2], Michael McKellar[2], Piyush Sabharwall[2], Mark Ruth[1], and Shannon Bragg-Sitton[2]

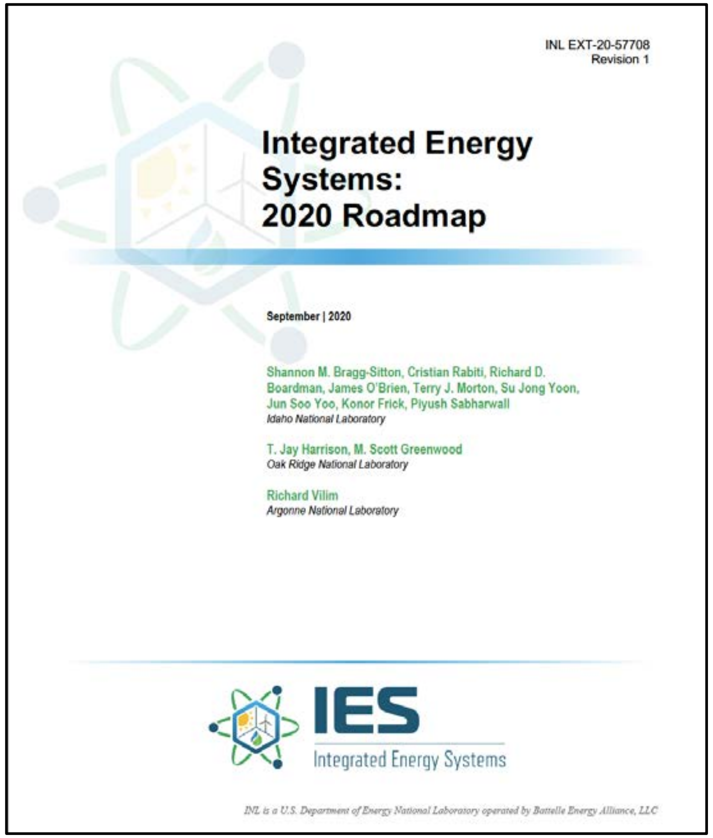
[1] *National Renewable Energy Laboratory*
[2] *Idaho National Laboratory*

http://www.osti.gov/scitech/biblio/1334495-generation-use-thermal-energy-industrial-sector-opportunities-reduce-its-carbon-emissions

Key conclusions:

- Less than 0.5% of all U.S. manufacturing facilities were responsible for nearly 25% of industrial GHG emissions
- SMR technologies are expected to be well-matched to the scale of demand of oil refineries, pulp/paper manufacturing, methanol, fertilizer plants, among others
- Heat recuperation and temperature boosting are important thermal energy management concepts that may benefit lower temperature energy sources
- Hybrid thermal/electricity generation may help balance hourly, daily, and/or seasonal electrical cycles

Current DOE-NE R&D programs for multi-output integrated energy systems



Crosscutting Technology Development
Integrated Energy Systems

IES
Integrated Energy Systems

https://ies.inl.gov

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.

Flexible simulation ecosystem for system design, analysis, technical and economic optimization

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Experimental demonstration for technology development and model validation

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Greenfield system design and advanced reactor applications

Reduce risk for commercial LWR-IES deployment

Energy dispatch design and implementation

Technical and economic analysis, near-term markets

Safety assessment and licensing considerations

Timeline for Nuclear IES Deployment

Current fleet **NOW**—Advanced Reactors **5-15 years**

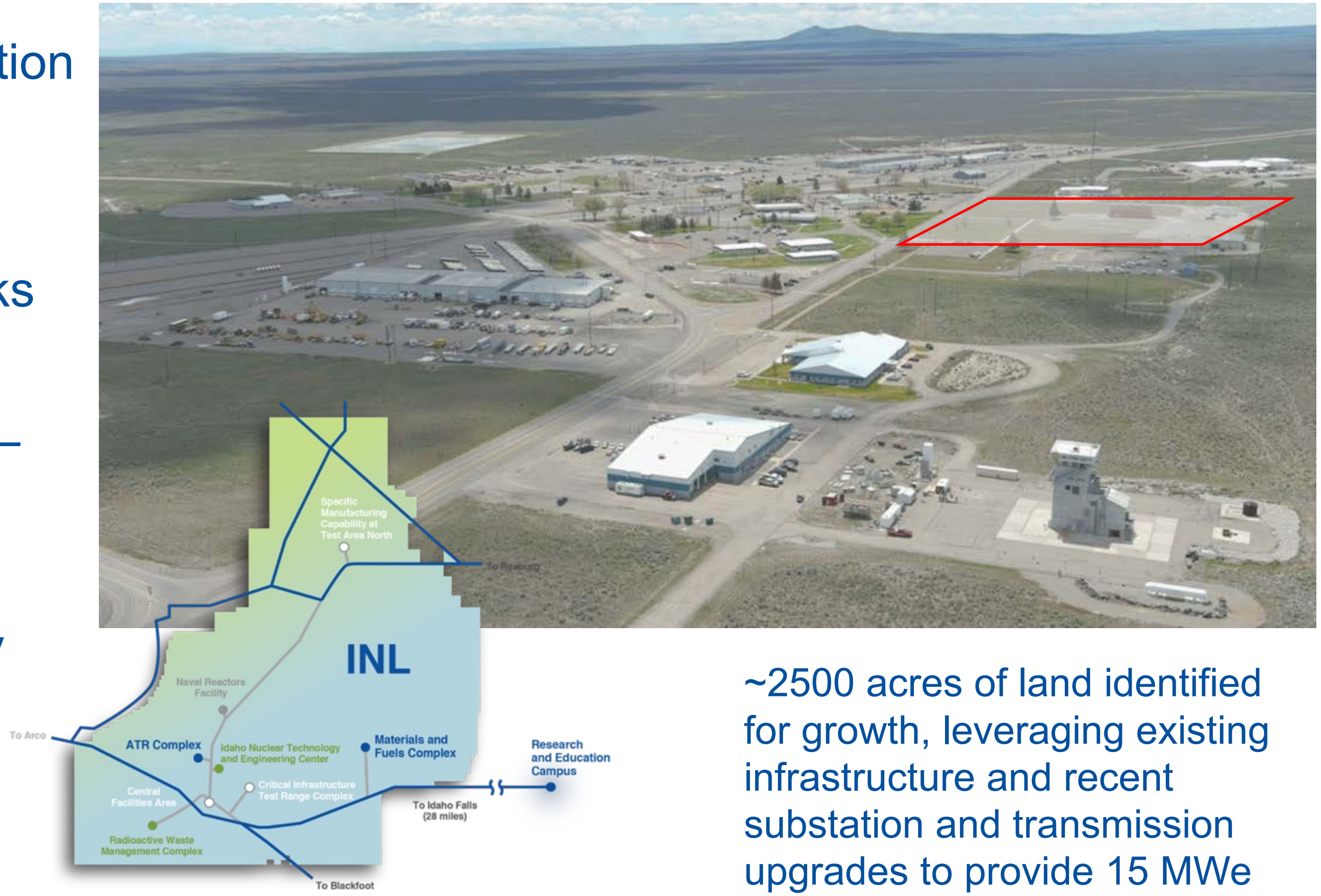
Flexible Plant Operations & Generation Pathway

LWRS LIGHT WATER REACTOR SUSTAINABILITY

https://lwrs.inl.gov

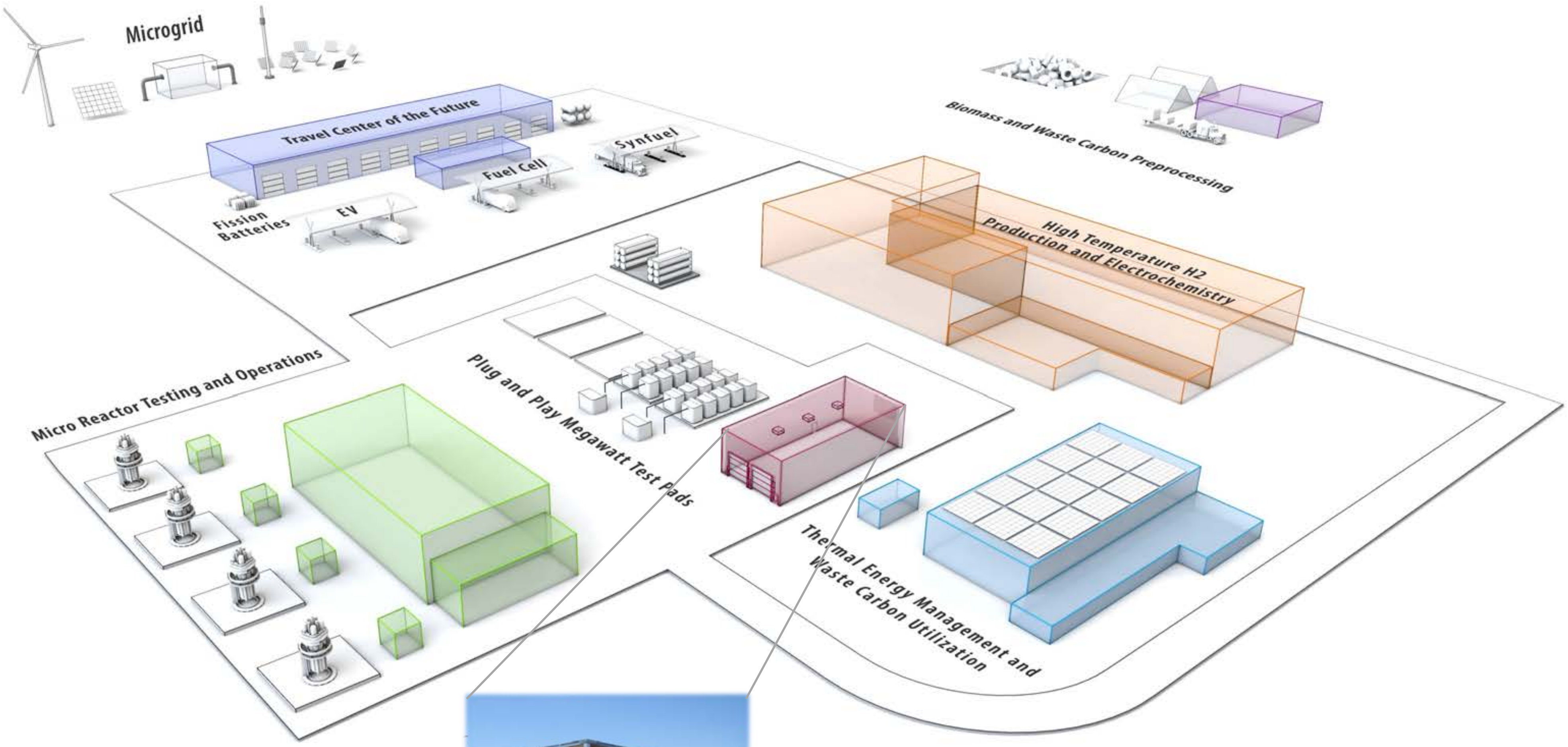
Proposed INL Energy Technology Proving Ground (ETPG)—Multi-scale research program areas

- High Temperature Hydrogen Production
- Thermal Energy Management
- High Temperature Electrochemistry
- Biomass & Waste Carbon Feedstocks
- Transportation & Electric Storage
- Distributed Clean Energy Systems — Microgrid
- Microreactor Testing & Operations
- Digital Engineering & Cyber Security
- Real-Time Power & Energy Analysis



~2500 acres of land identified for growth, leveraging existing infrastructure and recent substation and transmission upgrades to provide 15 MWe

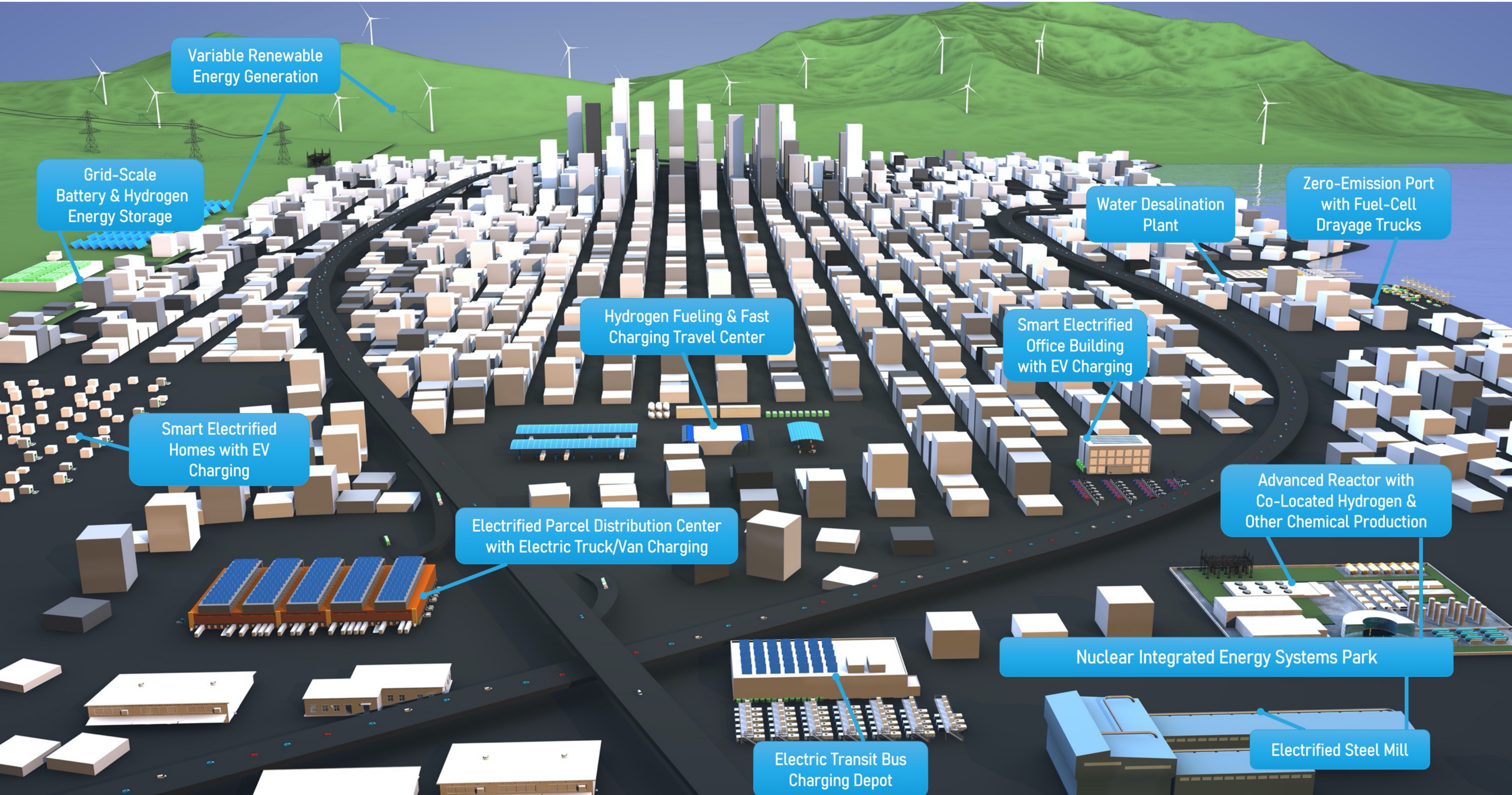
Proposed Energy Technology Proving Ground—planned facilities



Energy production, capture and utilization

- The CFA Energy Technology Proving Ground (ETPG) will be the first to demonstrate a clean energy “community”
- Provides the foundation for future carbon-free infrastructure such as
  - Microreactors for clean industrial thermal and electrical energy uses
  - Microgrid integration of multiple clean energy generators (nuclear, wind, solar, geothermal)
    - Heat for industrial applications and chemical synthesis
    - Electricity for traditional loads and transportation
    - Hydrogen and bio-carbon for transportation, synthetic fuels, and chemical synthesis
- Expect to demonstrate both government-developed and private sector technologies through multiple partnership options

A vision for a net-zero future



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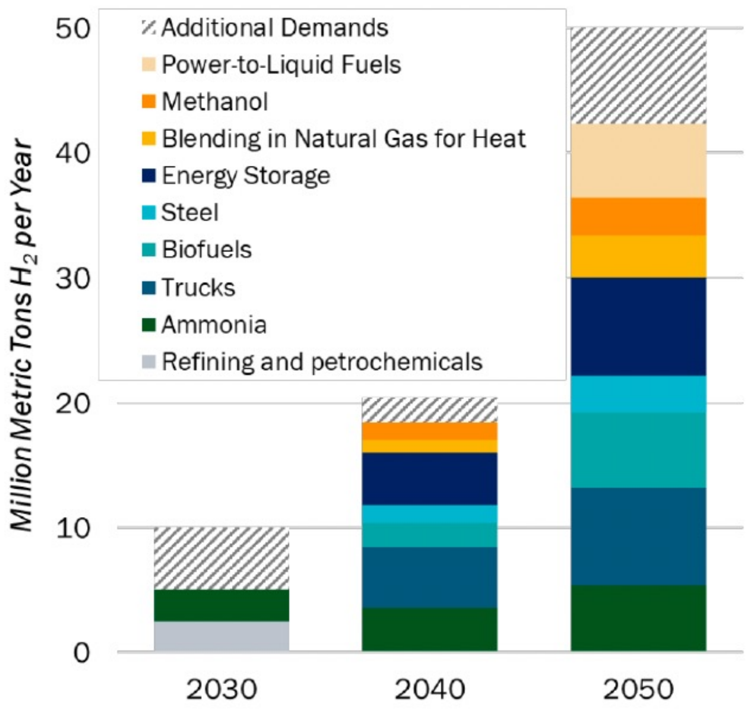
Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

Additional references

- *Summary Report* from the Generation-IV International Forum (GIF) Nonelectric Applications of Nuclear Heat (NEANH) *Virtual Workshop and Information Exchange on Development of Cogeneration Applications of Gen IV Nuclear Technologies*, July 2022.
- GIF NEANH, *Non-electric applications of nuclear workshop*, October 2022, https://www.gen-4.org/gif/jcms/c_206303/non-electric-applications-of-nuclear-workshop-in-collaboration-with-ifnec.
- Bragg-Sitton, S.M., and Boardman, R., "Introduction to Non-electric Applications of Nuclear Energy," *Encyclopedia of Nuclear Energy*, Section 12: Non-electric applications of terrestrial nuclear reactors, Vol. 3, p. 1-7, 2021.
- IAEA Nuclear Energy Series, *Nuclear Renewable Hybrid Energy Systems*, No. NR-T-1.24, Vienna, 2022, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB2041_web.pdf.
- DOE-NE IES program reports: https://ies.inl.gov/SitePages/Reports.aspx
- DOE-NE LWRS, Flexible Plant Operations & Generation reports: https://lwrs.inl.gov/SitePages/GroupedReports-sorted.aspx?ReportCategory=Flexible%20Plant%20Operation%20and%20Generation

National clean H_2 strategy—The opportunity for clean H_2

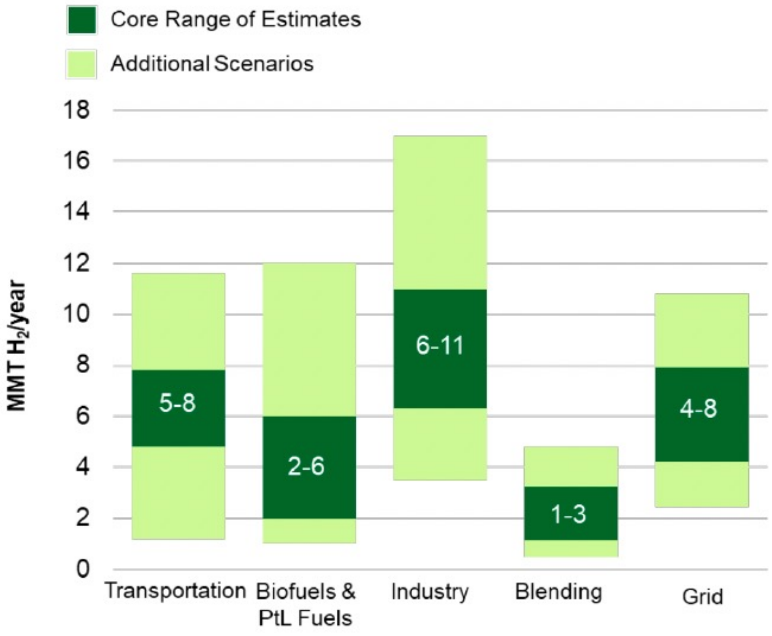
Opportunities for Clean Hydrogen Across Applications



Clean Hydrogen Use Scenarios

- Catalyze clean H_2 use in existing industries (ammonia, refineries), initiate new use (e.g., sustainable aviation fuels (SAFs), steel, potential exports)
- Scale up for heavy-duty transport, industry, and energy storage
- Market expansion across sectors for strategic, high-impact uses

Range of Potential Demand for Clean Hydrogen by 2050



- **Core range: ~ 18–36 MMT H_2**
- **Higher range: ~ 36–56 MMT H_2**

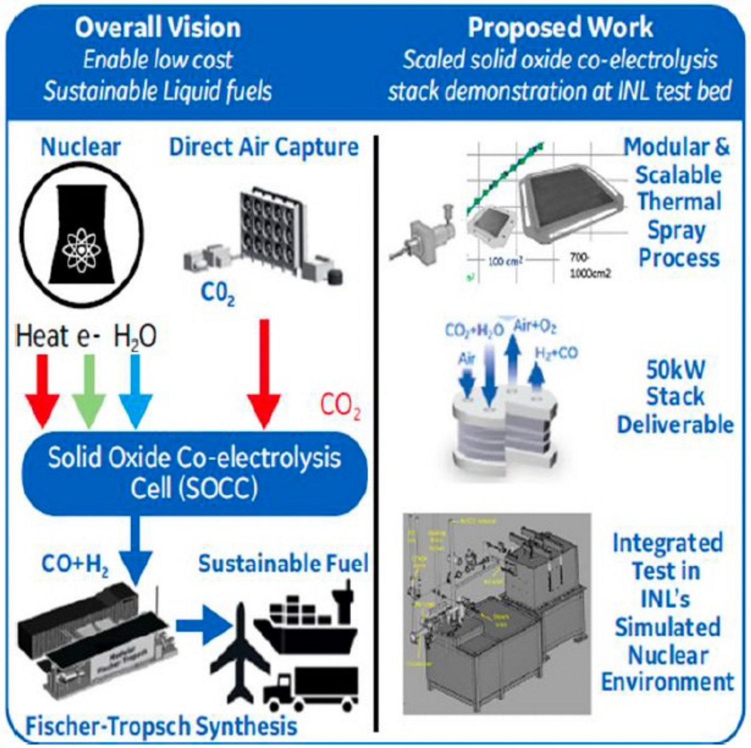
Refs: 1. NREL MDHD analysis using TEMPO model; 2. Analysis of biofuel pathways from NREL; 3. Synfuels analysis based off H2@Scale ; 4. Steel and ammonia demand estimates based off DOE Industrial Decarbonization Roadmap and H2@Scale. Methanol demands based off IRENA and IEA estimates; 5. Preliminary Analysis, NREL 100% Clean Grid Study; 6. DOE Solar Futures Study; 7. Princeton Net Zero America Study

U.S. Opportunity:
10MMT/yr by 2030, 20 MMT/yr by 2040, 50 MMT/yr by 2050

Information provided by DOE-EERE Hydrogen & Fuel Cell Technologies Office, July 2023
https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

New nuclear-H_2 integration projects (cross-DOE collaboration)

GE Research – Scaled Solid Oxide Co-Electrolysis for Low-Cost Syngas Synthesis from Nuclear Energy



Goals:

Complete engineering design/testing for **production of synthetic jet fuel using nuclear energy from existing light water reactors & Solid Oxide Co-Electrolysis**

- Complete TEA
- Manufacture of scaled solid oxide cells
- Integration & testing of 50kW stack at INL

Potential Impact: Nuclear to H_2 + CO to Synthetic Aviation Fuel

Westinghouse – FEEDs for Integrating Commercial Electrolysis H_2 Production with Selected LWRs

Goals:

Complete Front-End Engineering Designs (FEEDs) development for **nuclear-coupled SOEC H_2 production** at specific U.S. LWR plants

- Designs will be developed for **both pressurized water reactor (PWR) & boiling water reactor (BWR)**
- Licensing impact assessments will be completed
- TEA & LCA for markets under consideration

Westinghouse

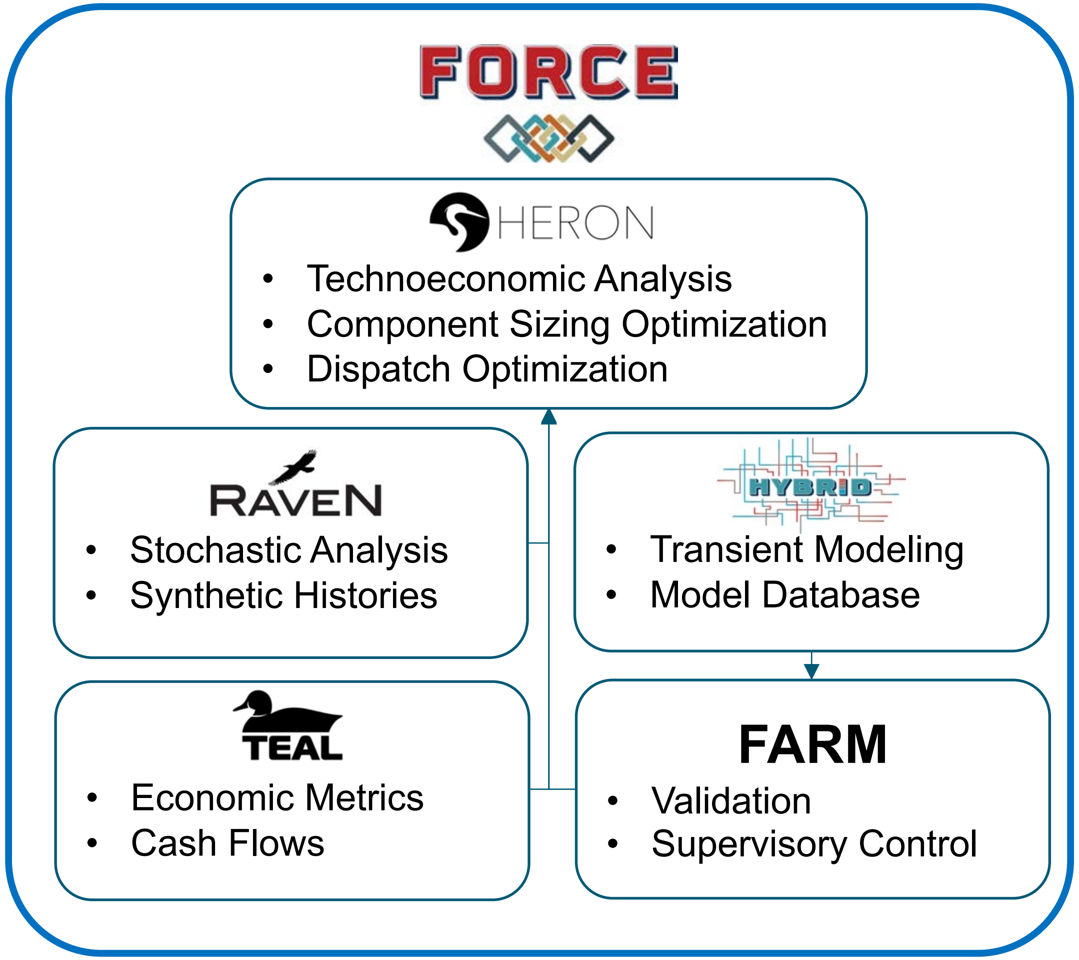
Sub-Recipient/FFRDC	INL Idaho National Laboratory
Utility Support	aps (1); energy harbor (1); Xcel Energy (1)
Industry Support	Bloomenergy (1); FAUSKE & Associates, LLC (2)
Academia Support	The University of Toledo (3)

Potential Impact: Higher system efficiencies / lower cost through thermal integration of SOEC with nuclear plant

Information provided by DOE-EERE Hydrogen & Fuel Cell Technologies Office, July 2023

IES analysis and optimization tool suite

- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Physical process, integration modeling and safety analysis
  - Long-term technoeconomic analysis
  - Capacity, dispatch optimization
  - Stochastic analysis, multiple commodities
  - Energy storage, various markets
  - Real-time optimization and control

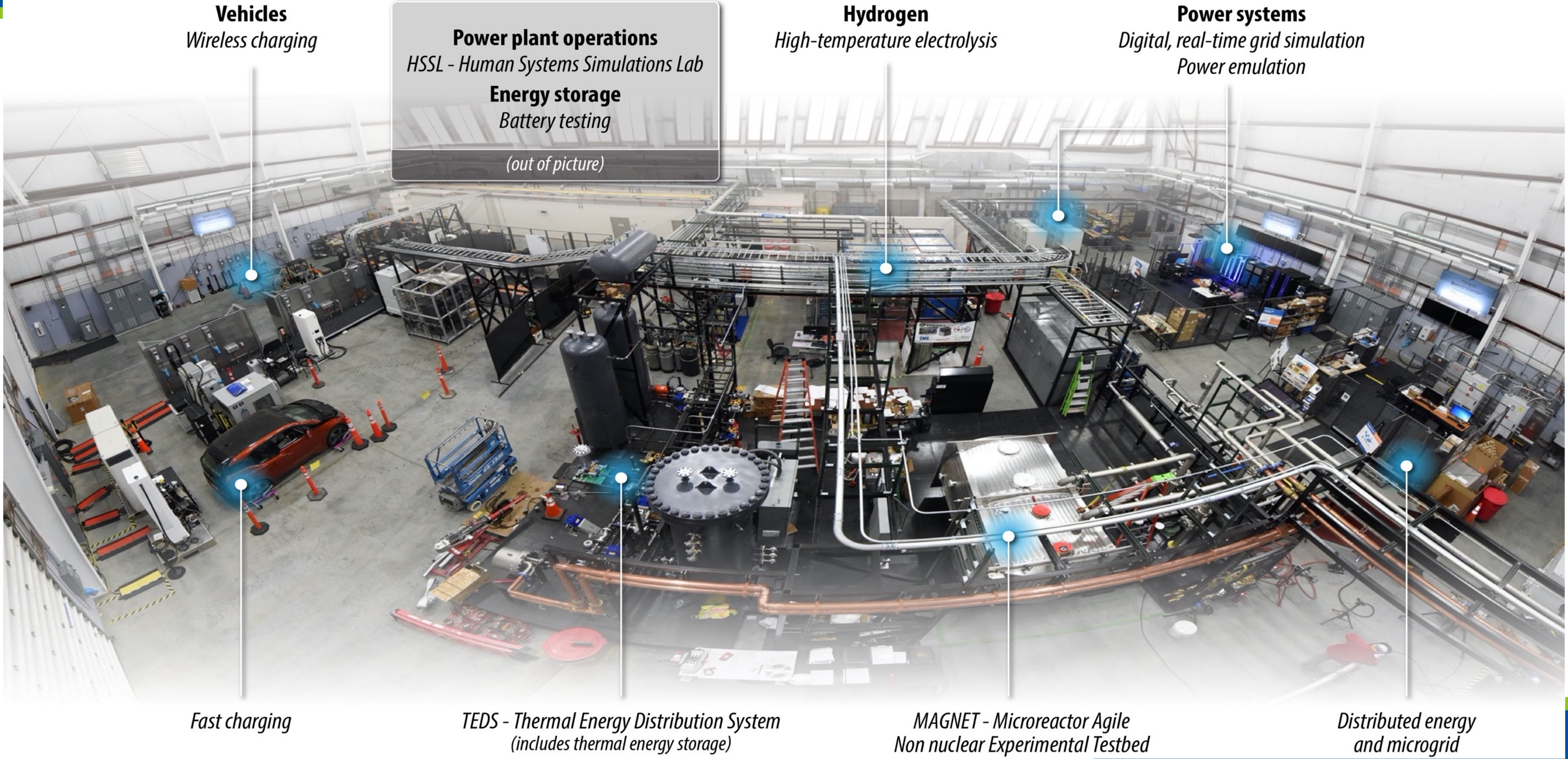


For more information and to access opensource tools, see ***https://ies.inl.gov/SitePages/System_Simulation.aspx****.*
Recorded training modules can be viewed at https://ies.inl.gov/SitePages/FORCE_2022.aspx.

A variety of detailed dynamic models are available for use

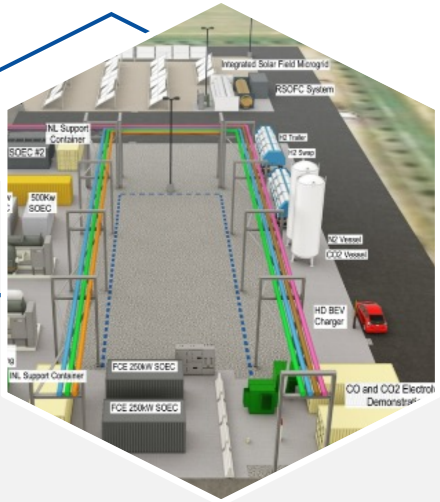
- Reactor technologies
  - 4-loop PWR
  - Small modular IPWR
  - Small modular natural circulation IPWR
  - High temperature gas-cooled reactor
  - Sodium fast reactor
  - Molten-salt cooled reactor (in development)
- Energy storage
  - Solid media thermal energy storage (TES)
  - 2-tank TES
  - Thermocline TES
  - Latent heat TES
  - Compressed air
  - Li-ion battery
- Energy use technologies
  - Reverse osmosis desalination
  - High T steam electrolysis (HTSE) for H_2 prod
  - HTSE “experimental”
  - Single-stage balance of plant
  - Two-stage balance of plant
  - Stage-by-stage balance of plant
  - Synthetic fuel production (F-T and methanol pathways in development)
  - Carbon conversion (in development)
- Other
  - Steam manifold
  - Switchyard
  - Electric grid
  - Natural gas turbine

Dynamic Energy Transport and Integration Laboratory (DETAIL)



At-scale demonstrations, > 1 MW systems, fill the gap

25 kWe High Temperature Electrolysis Stacks V&V



100-500kWe Modular High Temperature Electrolysis Pilot Plant Demonstration

"The GAP"

2-10 MWe Modular HTE Units

- Integrated proof of operation system
- Hydrogen supply for user technology demonstrations
- Accelerates high temp H2 production pathway to commercialization

Wide Commercial Deployment:

- Hydrogen production at nuclear power plants
- Industry-embedded hydrogen production and use

INL Central Facilities Area (CFA)

Home of the proposed Energy Technology Proving Ground (ETPG)

- INL has committed to becoming a net-zero campus by 2031
- Attributes of a small city or county
- 890 sq mi
- >5800 employees
- >50 MWe purchased in FY2020
- >300 DOE-owned buildings
- Existing microgrid
- 3 fire stations, 1 museum, medical facilities, …
- >40 miles primary roads