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Developing and Demonstrating Nuclear-based Integrated Energy Systems

October 2022

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Changing the World's Energy Future

Idaho National Laboratory

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Developing and Demonstrating Nuclear-based Integrated Energy Systems

MARVEL Technology Review

20 October 2022

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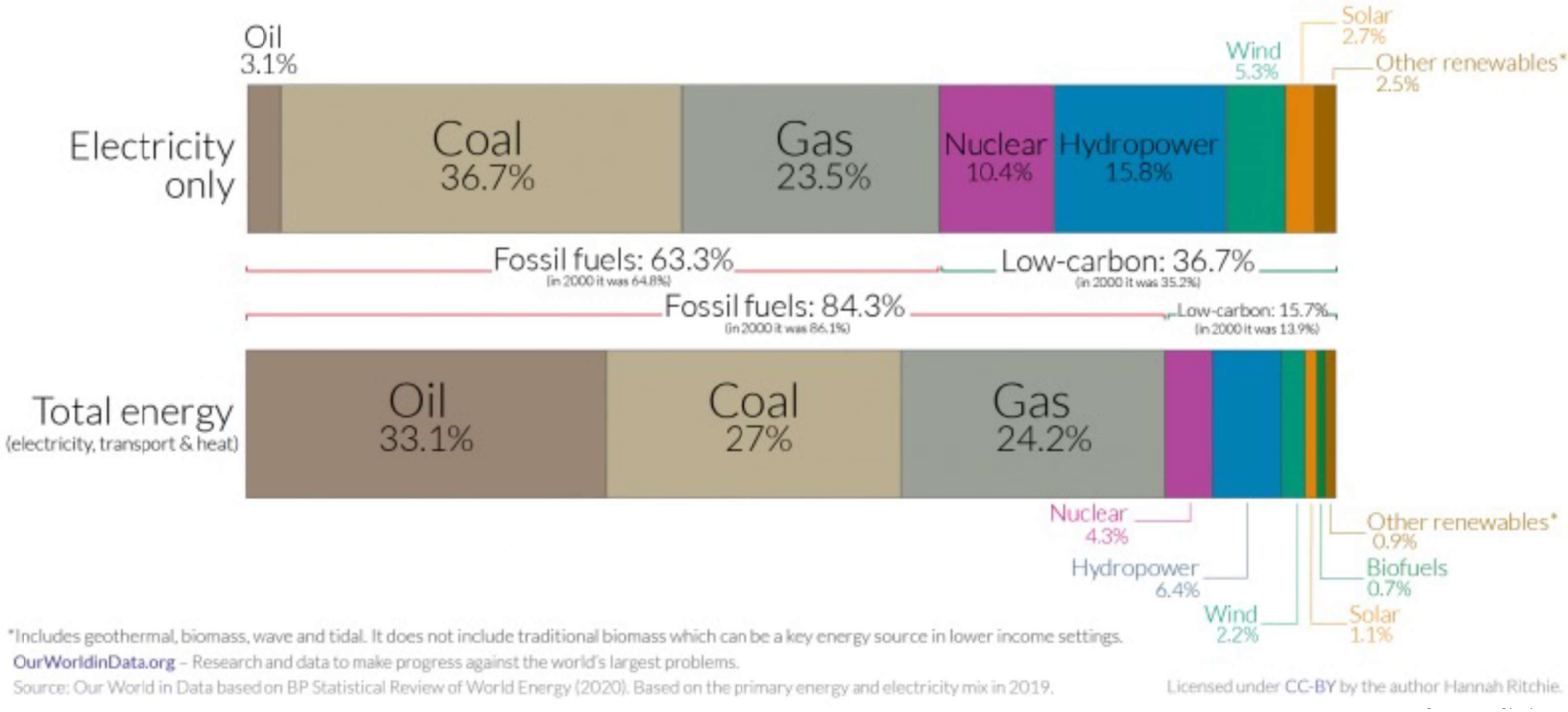
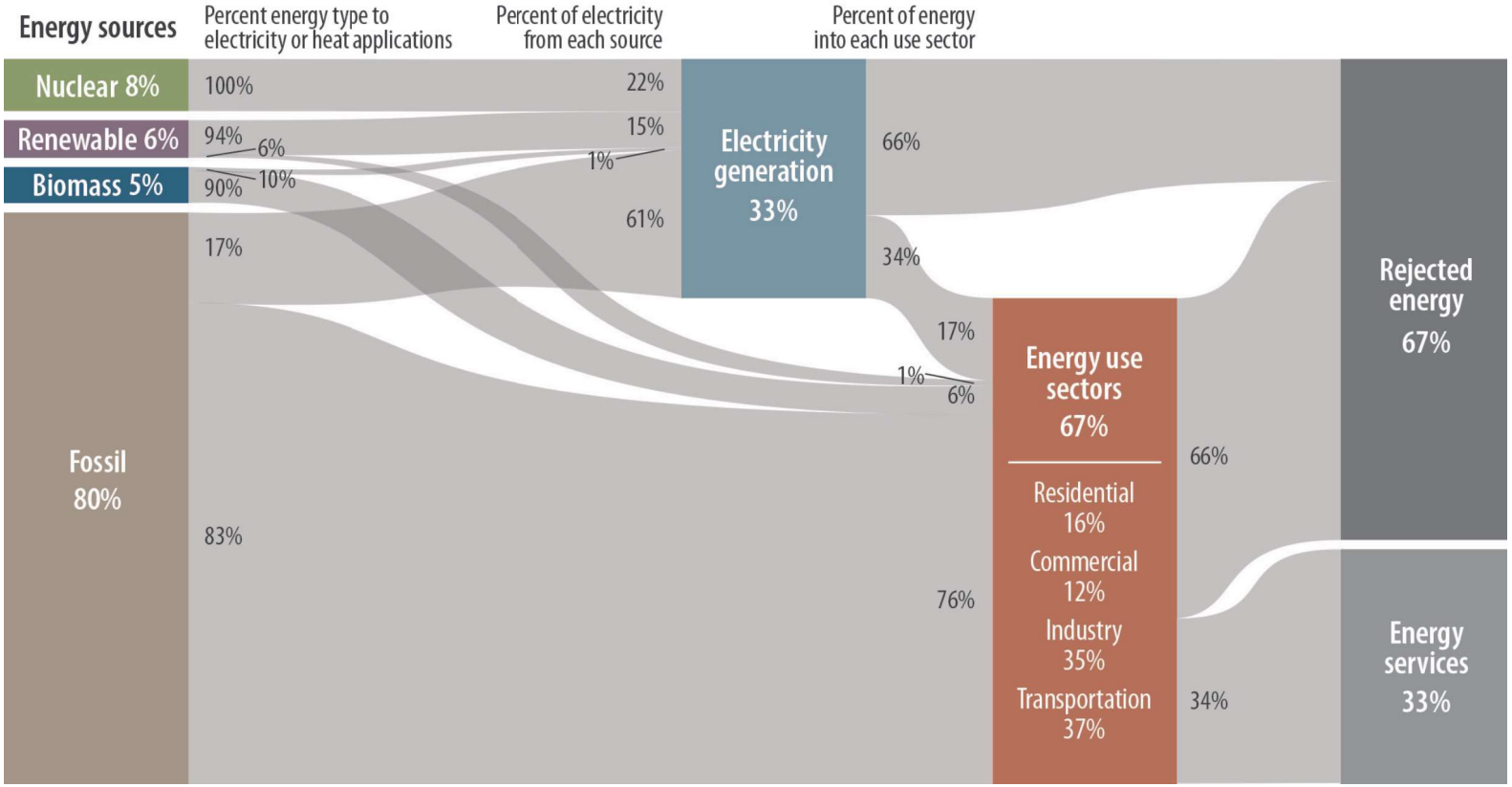
The global challenge:
Decarbonizing electricity and total energy sources (2019)



2018 energy sources and consumers, U.S.



Forsberg and Bragg-Sitton, Maximizing Clean Energy Use: Integrating Nuclear and Renewable Technologies to Support Variable Electricity, Heat and Hydrogen Demand, *The Bridge*, National Academy of Engineering, 50(3), p. 24-31, 2020. Available at https://www.nae.edu/239120/Fall-Issue-of-The-Bridge-on-Nuclear-Energy-Revisited.

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.

Adapted from LLNL (2020), https://flowcharts.llnl.gov/

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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: Achieve $1/kg-$H_2$ within a decade, emissions free**

Long Duration Storage Shot

Carbon Negative Shot

Enhanced Geothermal Shot

Floating Offshore Wind Shot

Industrial Heat Shot

ENERGY earthshots U.S. DEPARTMENT OF ENERGY

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Thinking outside the box: Clean nuclear energy for non-grid applications

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Future clean energy systems – transforming the energy paradigm

Nuclear Energy Generation

Light water reactors, high temperature advanced reactors, small modular reactors, or microreactors.

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

Other Energy Generation

Variable renewables, municipal waste, fossil with carbon capture, etc.

Biofuel

New chemical processes

Clean water

Industry

Electricity

Hydrogen for vehicles and industry

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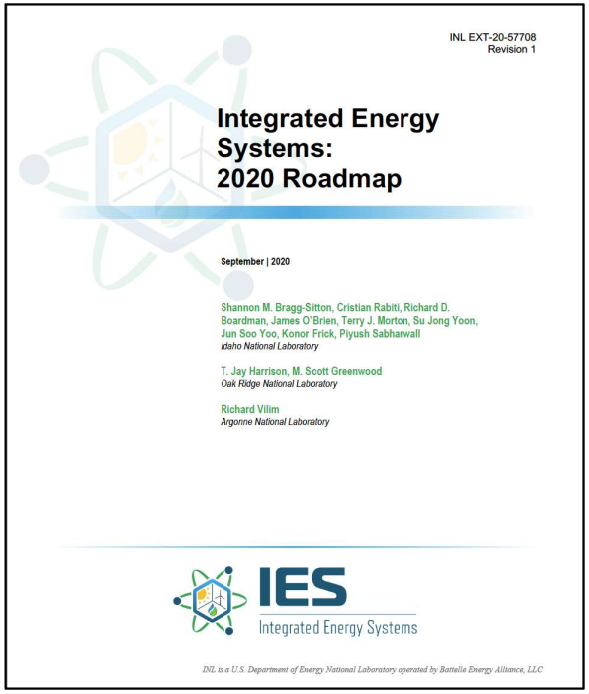
DOE-NE R&D Programs for Multi-Output Integrated Energy Systems



Crosscutting Technology Development
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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

———

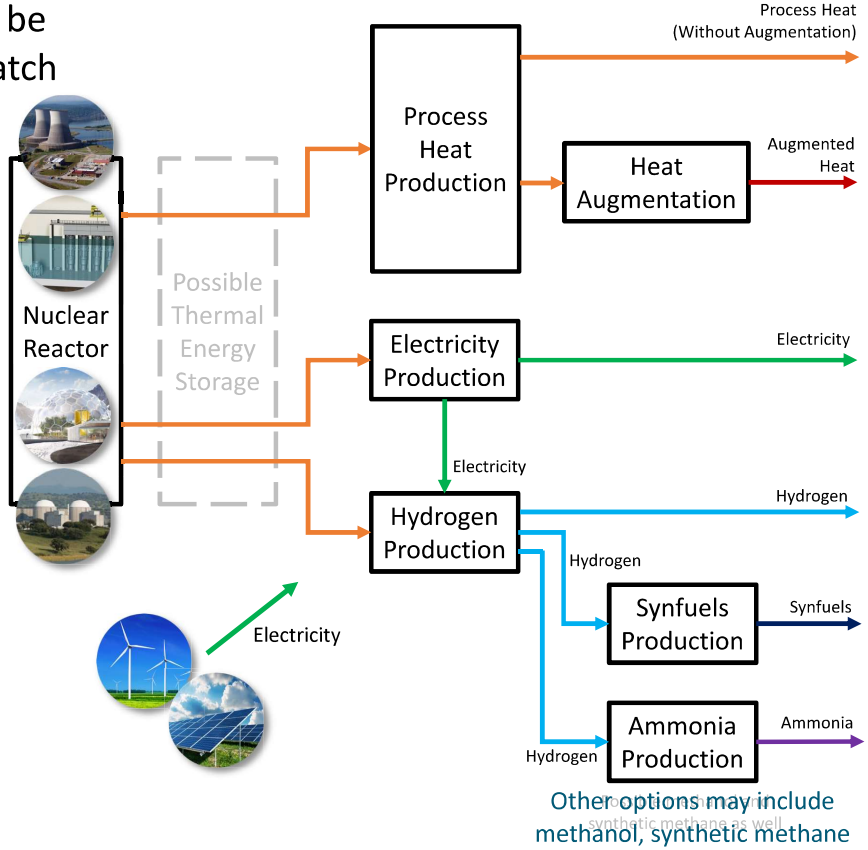
Current fleet **NOW**—Advanced Reactors **5-15 years**

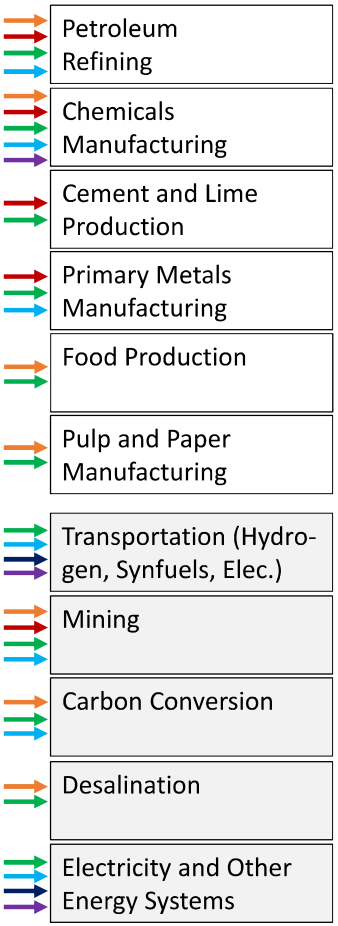
Flexible Plant Operations & Generation Pathway

LWRS LIGHT WATER REACTOR SUSTAINABILITY

Summary of 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: INL, *National Reactor Innovation Center (NRIC) Integrated Energy Systems Demonstration Pre-Conceptual Designs*, April 2021

Guiding questions in evaluating integrated energy systems

- What are **economically and technically viable** options for integrated energy system (IES) coupling to nuclear power plants in specific grid energy systems?
- What is the **statistically ideal** mix for Nuclear-IES within various markets?
- What are **driving economic factors** that existing and future nuclear technologies can leverage though IES production coupling?
- What are the **optimal coupling strategies** between IES technologies and nuclear plants?

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Why focus on hydrogen?

THE POTENTIAL

Hydrogen is an **economic commodity** and an element for moving energy into fuels and chemicals in the industrial, agricultural, and transportation sectors.

THE PROBLEM

About **95%** of the hydrogen produced in the U.S. comes from **natural gas**, resulting in emissions.

THE IMPACT

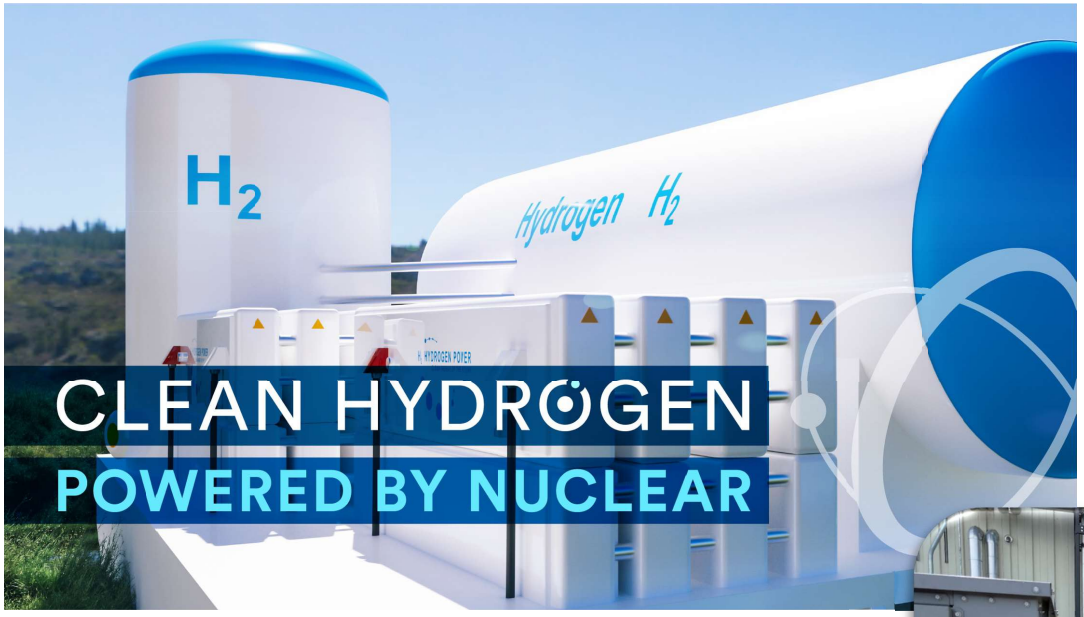
Creates **clean hydrogen** at a **competitive price** for many applications:

- Oil Refining
- Fertilizer Production
- Steel Production
- Synthetic Fuels
- Grid Storage
- Transport Fuels

integrated Energy Systems

https://ies.inl.gov

Research and development in nuclear-based IES will enable a clean hydrogen future



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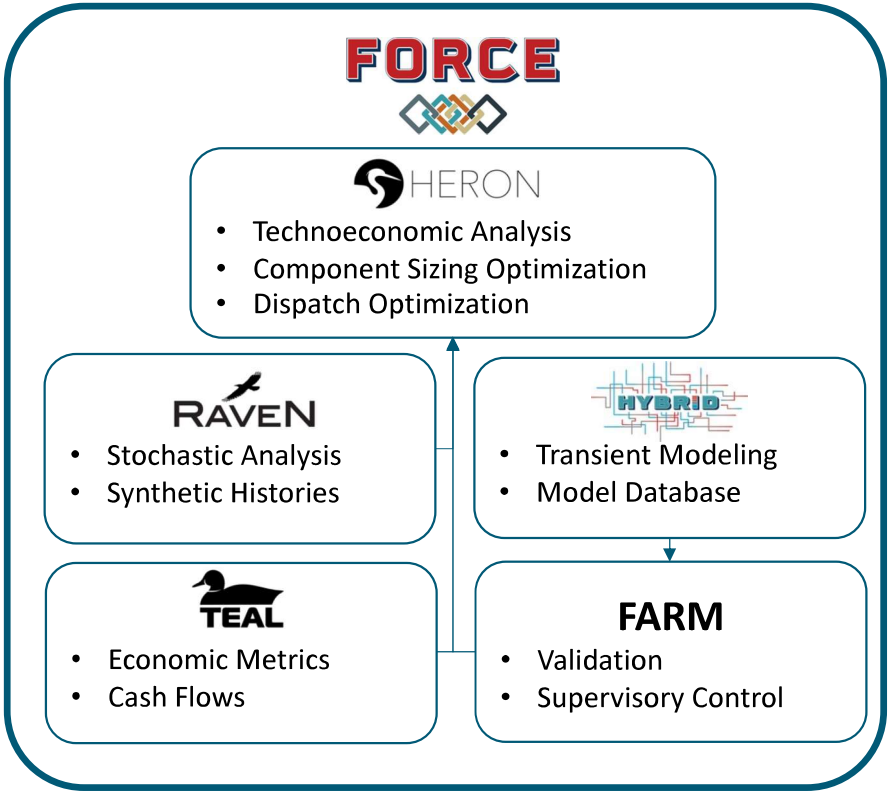
THE RESULT

- Reduces air emissions
- Deploys hydrogen at scale
- Expands the use of carbon-free nuclear energy into the transportation and industrial sectors
- Supports the Hydrogen Shot goal of reducing the cost of clean hydrogen by

80% *to $1 per kilogram within a decade*

IES analysis and optimization tool suite

- Technoeconomic Assessment for IES: Framework for Optimization of ResourCes and Economics (FORCE)
  - Optimization
    - Portfolio
    - Dispatch
  - Analysis
    - Economic
    - Stochastic
    - Physical
  - Supervisory Control
  - Workflow Automation



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.

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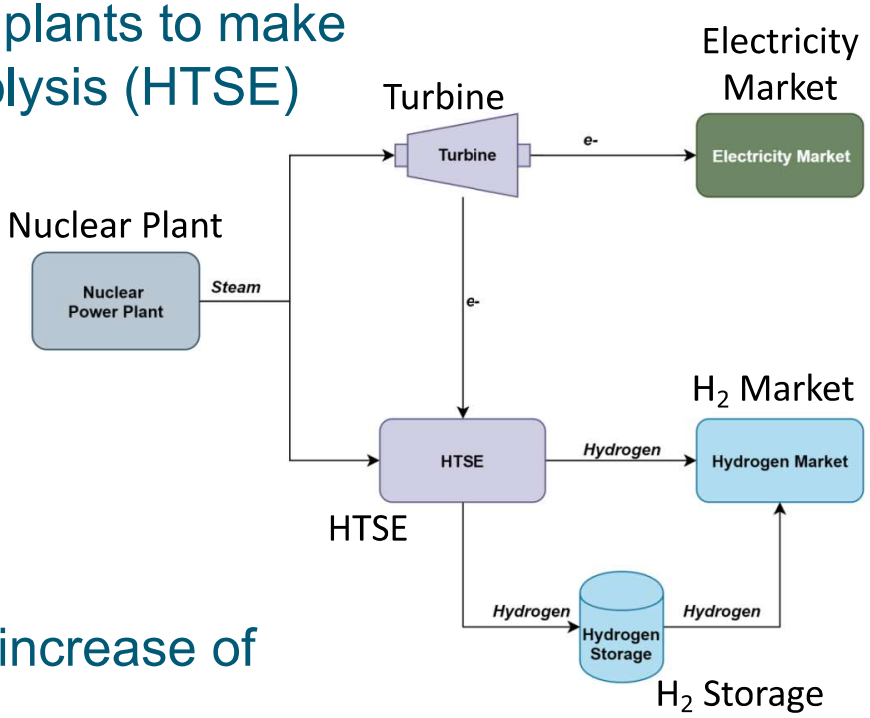
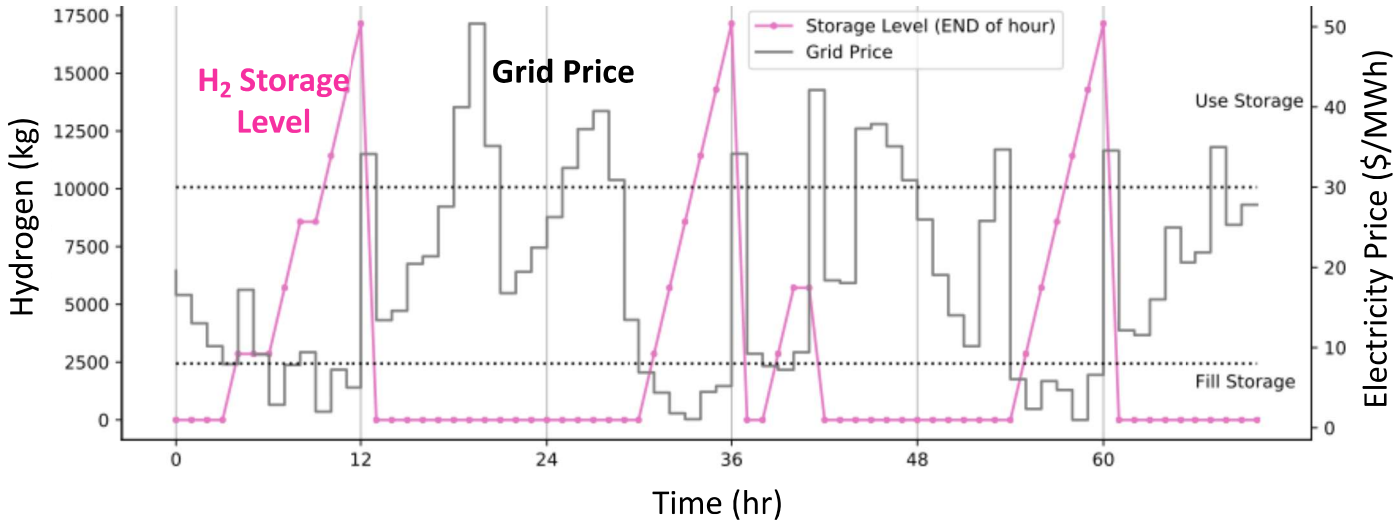
Example: Disruptive potential of nuclear produced hydrogen

- 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 → hydrogen is more profitable
  - High grid pricing → grid is more profitable
  - H_2 storage provides flexibility in plant operations, ensures that all demands are met
  - 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



Flexible Hydrogen production

- 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-H_2 demonstration projects

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

- H_2 production using direct electrical power offtake
- Develop monitoring and controls procedures for scaleup to large commercial-scale H_2 plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce H_2 for captive use by NPPs and clean hydrogen markets

Projects

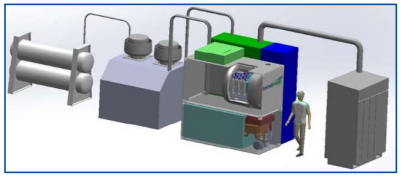
- Constellation: Nine-Mile Point NPP (~1 MWe LTE/PEM)
- Energy Harbor: Davis-Besse NPP (~1-2 MWe LTE/PEM)
- Xcel Energy: Prairie Island NPP (~150 kWe HTSE)
- FuelCell Energy: Demonstration at INL (250 kWe)

Nine Mile Point NPP LTE/PEM

Davis-Besse NPP LTE-PEM

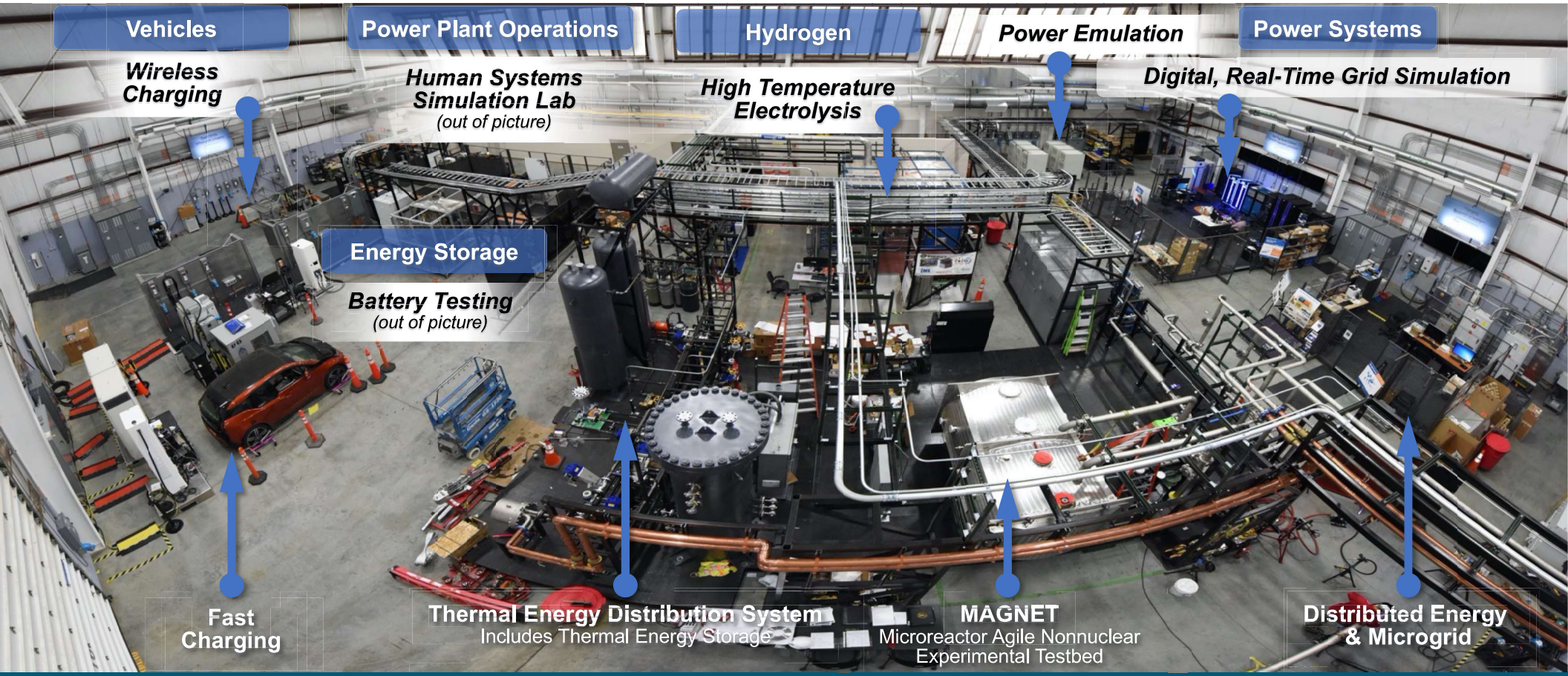
Thermal & Electrical Integration at Prairie Island NPP HTSE/SOEC

FuelCell Energy at INL, SOEC at increasing scale



~2024

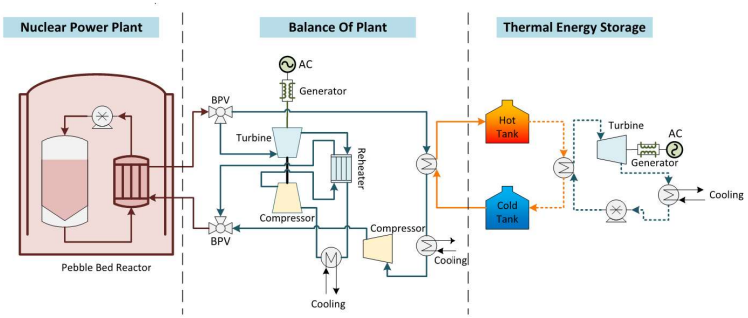
Dynamic Energy Transport and Integration Laboratory (DETAIL) for electrically heated testing of integrated systems



National Reactor Innovation Center (NRIC) advanced reactor testing infrastructure

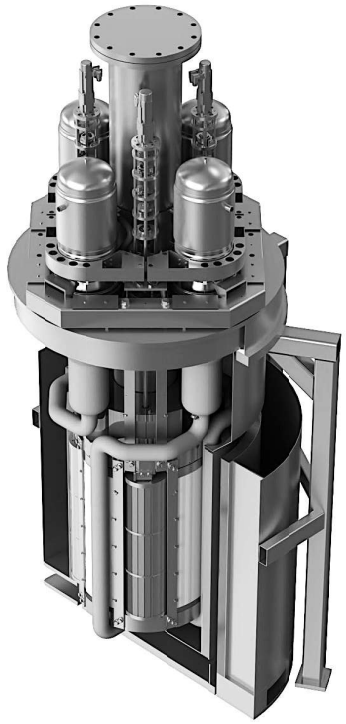
- NRIC Goal: Demonstrate two advanced reactors by 2025
- NRIC Strategy
  - Repurpose two facilities at INL and establish two test beds to provide confinement for reactors to go critical for the first time
  - Build/establish testing infrastructure for fuels and components
- NRIC DOME (Demonstration of Microreactor Experiments)
  - Advanced Microreactors up to 20 MWth
  - High-Assay Low-Enriched Uranium (HALEU) fuels < 20%
- NRIC-IES demonstration platform
  - Design and construct a highly flexible advanced reactor integrated energy system (AR-IES) demonstration platform
  - **Goal:** Demonstrate how advanced reactors can be coupled to various thermal energy users, and how thermal energy storage can enable coupled operation of various thermal loads/users.

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



For more information on NRIC and to download resources, see https://nric.inl.gov/.

Demonstrating IES with the MARVEL microreactor



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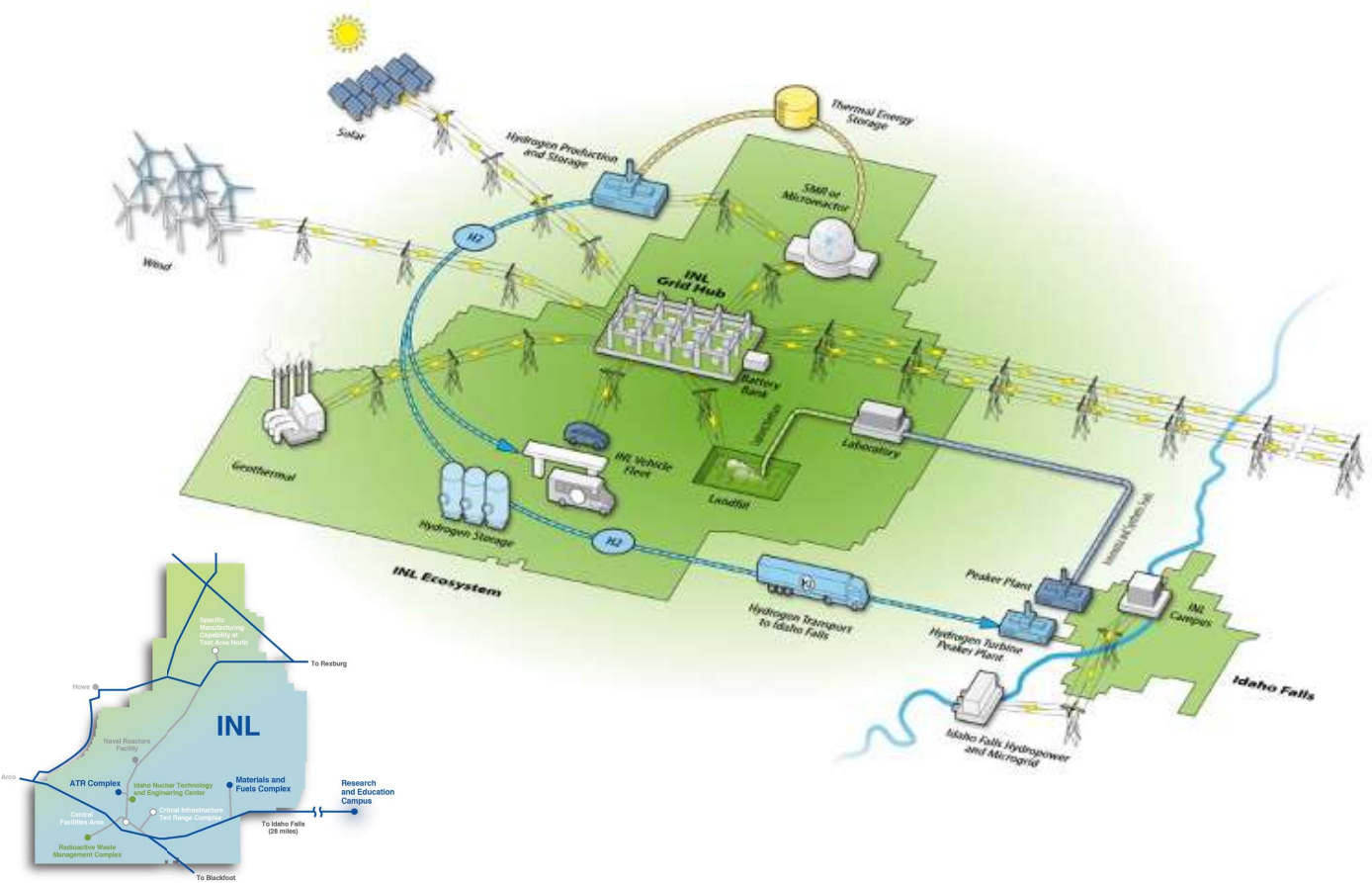
Demonstrating net-zero IES at INL



- INL has committed to becoming a net-zero campus by 2031
- Attributes of a small city or county
- 890 sq mi
- >5400 employees
- >50 MWe purchased in FY2020
- >300 DOE-owned buildings
- Existing microgrid
- 3 fire stations, 1 museum, medical facilities, …
- >40 miles primary roads

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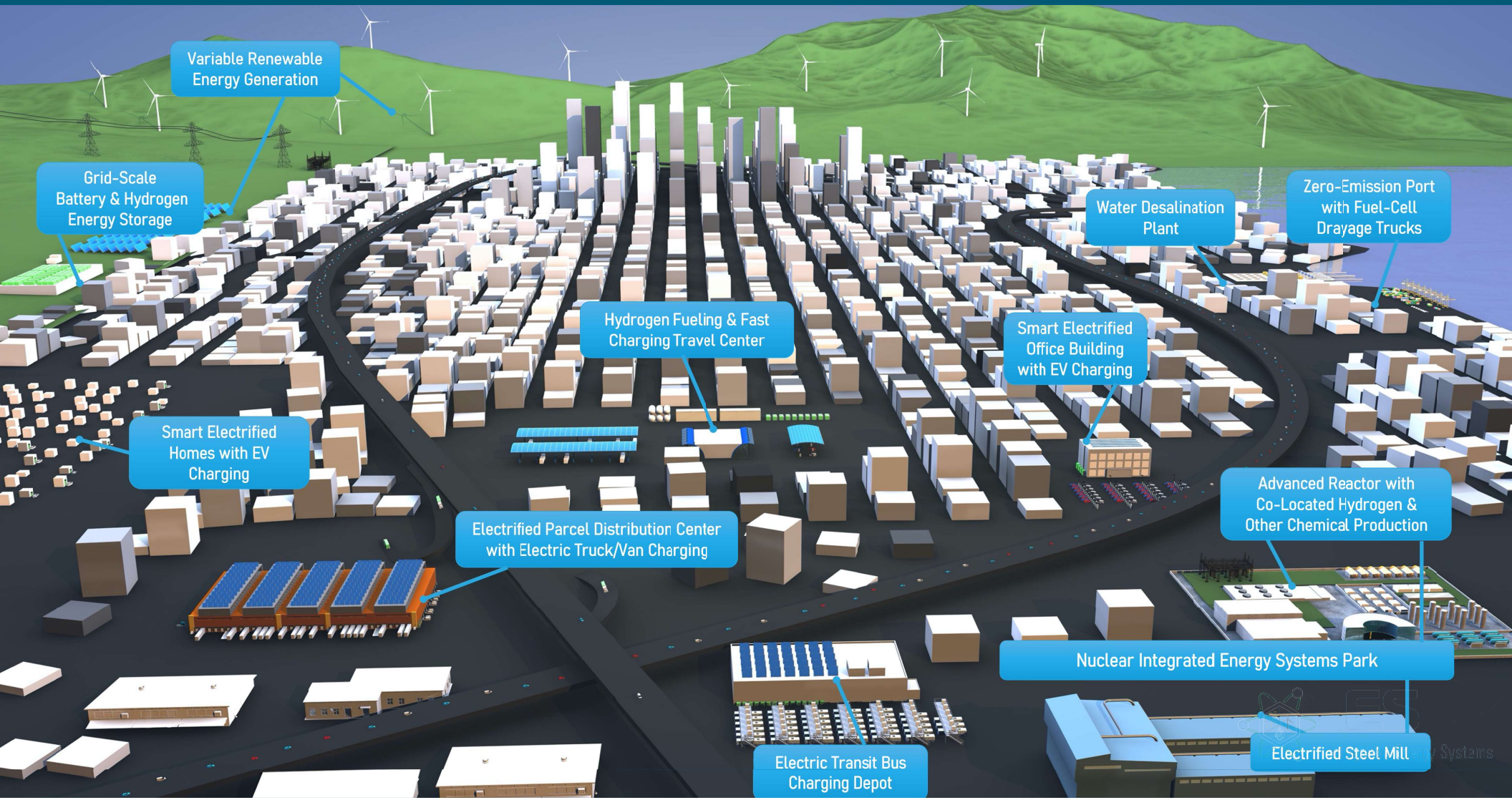
A vision for a net-zero future



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