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Revision 0

Light Water Reactor Sustainability Program

Plan for Scaling Up Hydrogen Production with Nuclear Power Plants

July 2022

U.S. Department of Energy

Office of Nuclear Energy

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Plan for Scaling Up Hydrogen Production with Nuclear Power Plants

Richard Boardman, Tyler Westover, and Jason Remer
Idaho National Laboratory

Jack Cadogan
Cadogan Technology Consulting

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EXECUTIVE SUMMARY

The United States (U.S.) Department of Energy's (DOE's) Light Water Reactor Sustainability (LWRS) Program Flexible Plant Operations and Generation (FPOG) Pathway is developing options to help U.S. nuclear power plants (NPPs) better integrate with intermittent wind and solar capacity and the recent surge of natural gas power generation. Research is focusing on improving NPP flexibility through hybrid production of electricity and other products, such as hydrogen (H_2) and energy storage for the purpose of shifting power production to a later time. In the case of H_2 production, the clean electrical and thermal power from an NPP can be used to split water using electrolysis.

This report outlines the opportunity for NPPs to participate in a first-of-a-kind (FOAK) commercial nuclear H_2 project intended to bring industry partners together to create regional clean H_2 hubs. The Bipartisan Infrastructure Law (BIL) will fund at least one hub up to $1.25 billion as federal cost share totally no less than 50% to execute a nuclear H_2 project. The report discusses the set of activities that are now underway or that are planned for completion by the FPOG Pathway to reduce the economic, technical, regulatory, and safety risks of these projects. DOE cross-program activities are being coordinated to ensure success in the timeframe allowed by the BIL. Figure ES-1 shows the approximate schedule of coordinated research and development (R&D) and pilot demonstration projects leading up to the first commercial nuclear H_2 production project. Execution of this plan requires DOE and industry collaboration. DOE research accomplishments are being provided to the electric utilities or industries looking to participate in the H_2 hub proposal and project execution process.

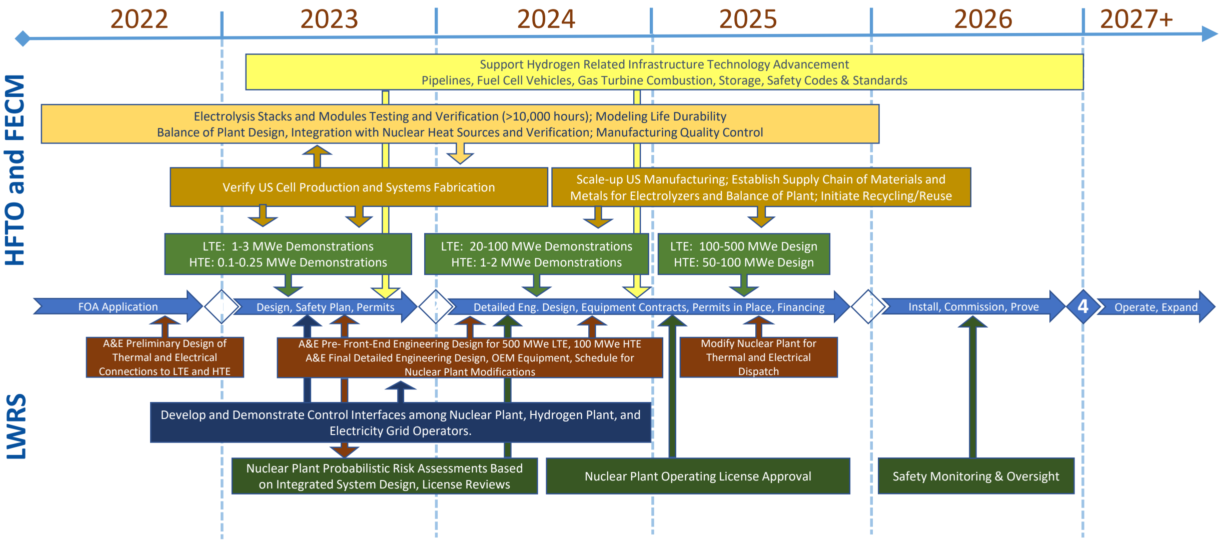

Figure ES-1. Approximate schedule for R&D and pilot demonstration projects leading up to the first commercial project.

ACKNOWLEDGMENTS

The LWRS Program and the Hydrogen and Fuel Cell Technology Office (HFTO) have exercised significant collaboration with results as outlined in this report. LWRS supports basic and applied research to help modernize and keep our nuclear fleet operating deep into the 22nd Century by evaluating non-electrical markets while continuing to help make NPPs more competitive in electricity markets.

Jason Marcinkoski, the Federal Program Technical Manager for the LWRS FPOG Pathway, generated Figure 2 of this report, which reflects his leadership and interest in the success of the electrolysis demonstration projects being carried out at NPPs, as well as the commercialization of nuclear H_2 and investment of this clean H_2 in the production of other energy products to help decarbonize the entire energy sector.

This Plan is not intended to specify detailed work plan priorities and execution of Funding Opportunity Announcements from either the LWRS Office or HFTO; rather, it is meant to guide the prioritization of the next-level work that will support DOE’s goals to achieve their program cost targets.

CONTENTS

FIGURES

ACRONYMS

BIL	Bipartisan Infrastructure Law
BWR	boiling water reactor
CDF	core damage frequency
CFR	Code of Federal Regulations
CO_2	carbon dioxide
CRADA	Cooperative Research and Development Agreement
DBNPS	Davis-Besse Nuclear Power Station
DOE	U.S. Department of Energy
DOE-EERE	U.S. Department of Energy–Office for Energy Efficiency and Renewable Energy
DOE-NE	U.S. Department of Energy–Office for Nuclear Energy
FMEA	Failure Modes and Effects Analysis
FOA	Funding Opportunity Announcement
FOAK	first-of-a-kind
FPOG	Flexible Plant Operation and Generation
H_2	hydrogen
H3RG	Hydrogen Regulatory Research Review Group
HFTO	Hydrogen and Fuel Cell Technology Office
HTE	high-temperature electrolysis
IIJA	Infrastructure Investment and Jobs Act
INL	Idaho National Laboratory
ION	Integrated Operations for Nuclear
LAR	License Amendment Request
LCOE	levelized cost of energy
LCOH	levelized cost of hydrogen
LERF	large early release frequency
LOOP	loss of off-site power
LTE	low-temperature electrolysis
LWR	light water reactor
LWRS	Light Water Reactor Sustainability Program
MMT	million metric tons
MW_e	mega-watt electric
MW_{th}	mega-watt thermal
NG	natural gas

NOAK	nth-of-a kind
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
PEM	proton exchange membrane
PRA	probabilistic risk assessment
PWR	pressurized water reactor
R&D	research and development
RD&D	research, development, and demonstration
rSOC	reversible solid-oxide cell
SOEC	solid-oxide electrolysis cell
SOFC	success of oxygen ion conducting fuel cells
SPP	Strategic Partnership Project
StMR	Steam Methane Reforming
TRL	technology readiness level
UFSAR	updated final safety analysis report
U.S.	United States

1. INTRODUCTION

This report lays out a plan to scale-up hydrogen (H_2) production at several nuclear power plants (NPPs) by 2030 based on recent technical and economic studies. Attainment of one or more nuclear source hydrogen hubs is critical to this mission. The technical and economic evaluations completed up to this point have motivated utilities to investigate this scaled-up H_2 production option for NPPs that have experienced diminishing revenues in electricity markets. In fact, some NPPs have already shut down, while several others continue to face an uncertain future as surplus natural gas (NG) supplies have until recently resulted in historically low prices. In addition, various policy and economic incentives encouraging the advancement of wind and solar energy have led to a steady buildup of these intermittent clean resources. As a nearly zero carbon-emissions-free energy source, nuclear energy can produce clean H_2, on a 24/7 basis which in turn can be invested to decarbonize industry, transportation, and the United States (U.S.) power grid.

The U.S. currently uses around 10 million metric tons (MMT) of H_2 annually, while projected uses for H_2 as an energy carrier could reach five times this amount by 2050. The U.S. Department of Energy (DOE) H_2@Scale Initiative[a] was launched in 2017 on the basis that this increase has the potential to reduce total U.S. greenhouse gas emissions by 50%, giving rise to the slogan '50 MMT H2 for 50% Carbon Reduction by 2050' or 50:50:50.

***A million metric tonnes is designated with the unit MMT, where a tonne is 1,000 kg.**

A program plan was developed by the U.S. Department of Energy (DOE's) Light Water Reactor Sustainability (LWRS) Program that charts the path to scale-up and the adoption of H_2 production at NPPs by 2030 [1]. Ten NPPs rated at 1,000 mega-watt electrical (MW_e) could produce between 1.5 MMT of H_2 annually based on new proton electrolyte membrane (PEM) low-temperature electrolysis to 2.3 MMT of H_2 based on solid-oxide electrolysis cells (SOEC) high-temperature [steam] electrolysis. A plan to scale-up pilot plant electrolysis demonstration projects to full-scale plants is shown in Figure 1. Vendor supplied modular electrolysis plants are generally now able to be designed and manufactured in 1 to 10 MW_e unit blocks. Low-temperature electrolysis requires electricity, while high-temperature electrolysis requires an electrical and a heat source (which is more efficient design, but currently lags in development and demonstration).

***Conventional water-splitting electrolysis is referred to by industry as low-temperature electrolysis (LTE). High-temperature electrolysis (HTE) refers to the electrolysis of steam, where the steam is superheated up to the operating temperature of electrolysis cells operating at 750–800°C.**

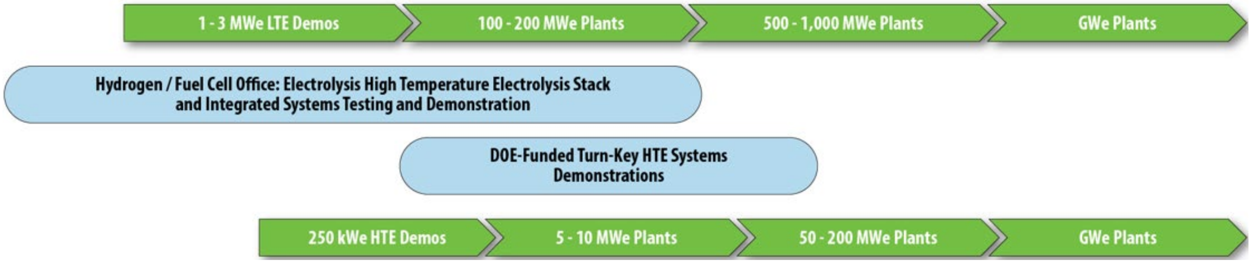

Figure 1. Scale-up of nuclear H_2 demonstration projects to multiple nuclear plants by 2030.

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[a] For more information about the DOE H2@Scale Initiative, visit https://www.energy.gov/eere/fuelcells/h2scale.

The 2022 Bipartisan Infrastructure Law (BIL), officially known as the Infrastructure Investment and Jobs Act (IIJA)[b], provides up to $8 billion to help establish Regional Clean Hydrogen Hubs over the next 5-6 years. This Bill is key to addressing several barriers that must be addressed for many nuclear reactors to implement hydrogen production.

To qualify as clean H_2, the life-cycle emissions of carbon dioxide (CO_2) of the H_2 produced must be less than 2 kg-CO_2e[c] per kg-H_2. At least one of these hubs must use nuclear energy for some fraction of the H_2 produced in a given region. The Federal cost share of up to 50% of the total project costs up to $1.25 billion should make it possible to realize a favorable return on investment for first-of-a-kind (FOAK) demonstration projects.

Technical and economic assessments of H_2 production by NPPs indicate that light water reactors (LWRs) will be able to feasibly produce clean H_2 through water-splitting electrolysis for an nth-of-a-kind (NOAK) nuclear H_2 plant. This is based on, a H_2 plant that is built and integrated into an existing NPP when the price of electrolysis units is consistent with an established supply chain of materials and fabrication year-over-year. The BIL also intentionally includes $1 billion to help raise the technology and commercial-scale manufacturing readiness of electrolysis. The assumption is that several large-scale demonstration projects and the required manufacturing industries will make it possible to expand the leading projects at NOAK economics.

Based on the preponderance of positive technology evaluations and preliminary safety assessments in an LWR, it should be possible by 2026 to support a commercial H_2 plant ranging from 100–500 MW_e for low-temperature electrolysis and approximately 100 MW_e for high-temperature electrolysis. In the case of high-temperature electrolysis, the NPP would also involve a heat transfer loop that would extract and deliver approximately 25 mega-watts thermal (MW_{th}) power via a secondary steam-to-steam heat exchange design or other exchange transfer media capable of producing dry steam for an HTE electrolysis plant.

1.1 The New Paradigm for Nuclear Energy

Our Goal: ***Provide NPP owners and utilities with tools, a thermal energy delivery design basis, and permitting guidance needed for a commercial-scale hydrogen demonstration project. To this end, the DOE LWRS Program and the Hydrogen and Fuel Cell Technology Office (HFTO) are engaging with U.S. stakeholders to conduct research and development (R&D) that reduces the economic, technical, and safety risks of commercial scale hydrogen demonstration projects.***

The emerging gap between the growth of non-dispatchable renewable energy generation[d] and lagging clean energy storage continues to contribute to the unproductive expansion of time-of-day excess clean generation. The overlapping impact of the dominant clean generating sources (e.g., intermittent renewables and baseload nuclear power) exacerbates this challenge during daily supply-and-demand cycles.

A contributing factor is that both intermittent renewables and baseload nuclear have inherent flexibility constraints in their operational models. Nuclear power has significant near-term potential to change its long-standing operational model by shifting generation output away from an electrical generation when there is no additional grid demand for clean energy. During these times, nuclear can

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[b] H.R.3684 - 117th Congress (2021-2022): Infrastructure Investment and Jobs Act | Congress.gov | Library of Congress.

[c] CO_2e refers to a unit of greenhouse gas reductions equivalent to the impact of CO_2. As a reference, the conventional process of producing hydrogen by steam methane reforming emits 7-10 kg CO_2 per kg H_2 produced depending on the process design and accounting for life-cycle emissions associated with NG production.

[d] Solar photovoltaics has on average capacity factor of 25%, which wind energy is approximately 35%. https://www/statista.com/statistics/report-content/statistic/183680.

flexibly produce real-time usable or storable clean energy to decarbonize functions across the power, industrial, and transportation sectors.

This is not a new paradigm for nuclear energy. Instead, it is a consideration for the way nuclear energy can be directly coupled to industry processes, while supporting the buildup of variable renewable energy sources, which will require a change in the manner that NPPs are currently operated. It creates new opportunities to firm the grid while helping to decarbonize the industry and the transportation sector, as observed in Figure 2.

With nuclear energy, a broad spectrum of carbon sources can be converted into consumer products and fuels that can be dropped into the existing infrastructure. This model sets a course to closing the carbon cycle with nuclear energy, especially maximizing the conversion of natural, agriculture, and municipal carbon sources into fuels that will be needed for transportation systems that are impossible to electrify.

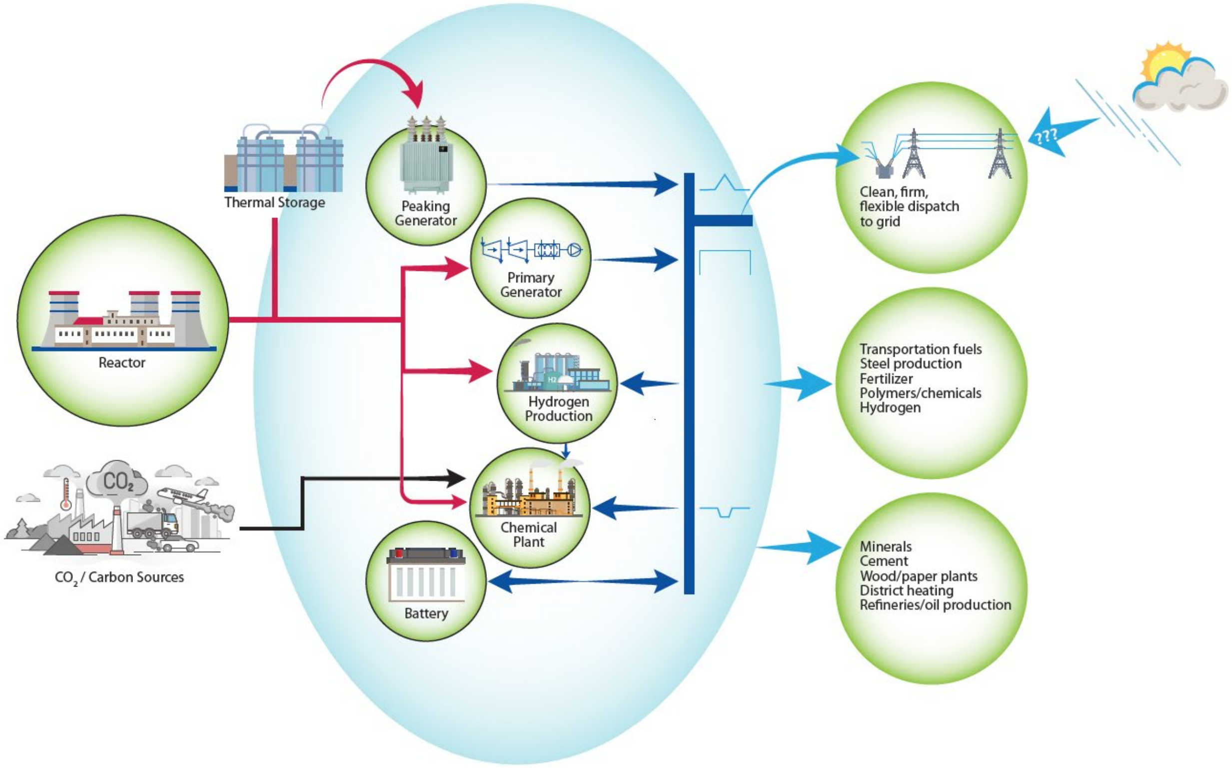

Figure 2. Expanded NPP markets.

The LWRS Program is accelerating key technology development to establish the strategic viability of NPPs as a complimentary clean energy contributor in electricity markets versus low-cost NG power plants and wind and solar energy. The emerging extremes of climate change (e.g., hurricanes and cold weather) are only expected to become more challenging. Nuclear power is often by design more resilient in riding through and recovering from such climate extreme events.

Given all these considerations, critical nuclear capabilities can and should be strategically preserved in cost-competitive market conditions as alternate energy providers where carbon-offsetting products like H_2 and synthetic fuels can be generated in place of electrical output when nuclear is not the lowest short-term marginal electricity cost.

1.2 Background: Why Nuclear Generated Hydrogen?

H_2 by electrolysis as a flexible energy stream from the existing NPP fleet specifically has the potential to favorably influence all sectors as a storage medium and energy carrier for an excess intermittent carbon-free generation. H_2 is a principal feedstock for ammonium and urea-based fertilizer. It is essential for the production of petroleum or biomass-based fuels. It can replace most of the fossil fuels used for iron and steel production. Finally, it can provide large-scale energy storage, as a fossil fuel replacement technology for industrial electric power generation and process heating.

On November 12, 2020, DOE released its Hydrogen Program Plan, which represents a strategic framework under which multiple DOE offices can operate under a cohesive and coordinated effort in support of the national advancement of H_2 technology research, development, and demonstration (RD&D) activities. It reaffirms DOE's vision that H_2 is a vital part of a comprehensive energy portfolio, discusses the myriad benefits of H_2 in the energy sector, and explains the challenges facing H_2 technologies being addressed through DOE RD&D leadership. The Plan also establishes DOE's framework for achieving H_2 at scale and identifies the Program's strategy for funding RD&D efforts. It also defines the technology focus areas and RD&D thrusts in areas such as H_2 production, delivery, storage, conversion, and other applications.

The Hydrogen Plan mission is:* *"to research, develop, and validate transformational H_2 and related technologies including fuel cells and turbines, and to address institutional and market barriers, to ultimately enable adoption across multiple applications and sectors." The Plan also hearkens to Congress' goal of Job Creation, a Sustainable and Equitable Energy Future, and Clean Energy Emissions Reduction Across Sectors.

The first DOE goal was to produce H_2 for under $2/kg by 2026. However, in June 2021, the Secretary for the DOE announced a bold Earthshot Target of producing H_2 for $1/kg by 2030.[e] Attaining either target requires four conditions to be true.

1. Demand for clean H_2 increases significantly beyond current market needs. Industry interest has been piqued by the benefits of clean H_2 for the production of the goods and services, society needs, and demands. Several studies have shown the demand for clean H_2 could reach 5 MMT by 2030, 20 MMT by 2040, and 50 MMT by 2050 [2].
2. Availability of low-cost clean energy. Existing NPPs and regions with excess solar and wind generation will likely meet this condition. Some merchant NPP operating costs have been decreased to under $28/MWh where there is a single reactor. Reducing the cost of operating NPPs is a key long standing goal of the LWRS Program. One R&D supported area uses an "Integrated Operations for Nuclear" (ION) approach to outline various possible improvements to reduce operating costs [3]. The ION Generation I analysis identified near-term technology, process, human performance, and governance changes that are under investigation by NPPs as operating cost reduction strategies that target practical pathways to the levelized cost of energy (LCOE) in the $21/MWh$_e$ range.
3. High-volume electrolyzer manufacturing. Second, to the cost of energy, the cost of manufacturing electrolysis (e.g., inclusive of robust stacks and balance of plant components) is critical in reaching both the $2/kg H_2 cost. It is anticipated the cost of electrolyzers will drop rapidly as a supply chain of materials and automated manufacturing plants are stood-up to meet market demands. The challenge is establishing the leading commercial projects before the cost of electrolysis units comes down.

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[e] For more information, visit DOE Hydrogen and Fuel Cell Technology Office at https://www.energy.gov/eere/fuelcells/hydrogen-shot.

4. Policy incentives and private-public partnerships are set up that help establish the manufacturing and adoption of H_2 as an energy currency in the U.S. (and/or elsewhere). The 2022 BIL, which is officially known as the IIJA[f], makes it possible to realize an adequate return on investment for FOAK demonstration projects to draw companies that self-fund projects, venture capitalists, and financial institutions to support the initiative of Clean Regional Hydrogen Hubs.

2. DOE HYDROGEN HUB NOTICE OF INTENT

For H_2, the BIL aligns with the Hydrogen Shot priorities by directing work to reduce the cost of clean H_2 to \$2/kg by 2026. It requires developing a national strategy and roadmap and includes \$9.5 B in funding for clean H_2 in the following thrusts:

- \$1B over 5 years for electrolysis RD&D.[g]
- \$0.5B over 5 years for clean H_2 technology manufacturing and recycling R&D.[h]
- \$8B over 5 years for at least four regional clean H_2 hubs.[i]
- Includes working with the U.S. Environmental Protection Agency to develop an initial clean H_2 production standard that provides ≤ kg CO_2e per kg H_2.[j]

A Notice of Intent to finance H_2 hubs was formally issued on June 6, 2022, by the DOE–Office of Clean Energy Demonstrations in collaboration with the HFTO.[k] The general plan was presented at the HFTO Annual Merit Review and summarized in Figure 3. The official Funding Opportunity Announcement (FOA) is anticipated around October 2022. It likely will request applications within 60–90 days. The following assumptions provide a general understanding for creating this Plan for scaling up nuclear H_2 projects:

October 2022 – December 2022. Phase 1: Proposals development and submission.

January 2023 – December 2023. Phase 1: Detailed plans for H_2 hubs, including preliminary engineering and design and project plans.

January 2024 – December 2025. Phase 2. Detailed engineering design, permits, and financing.

January 2026 – December 2028. Phase 3. Construction and project start-up and commissioning.

January 2029 – December 2030. Phase 4. Project ramp-up and operations.

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[f] H.R.3684 - 117th Congress (2021-2022): Infrastructure Investment and Jobs Act | Congress.gov | Library of Congress.

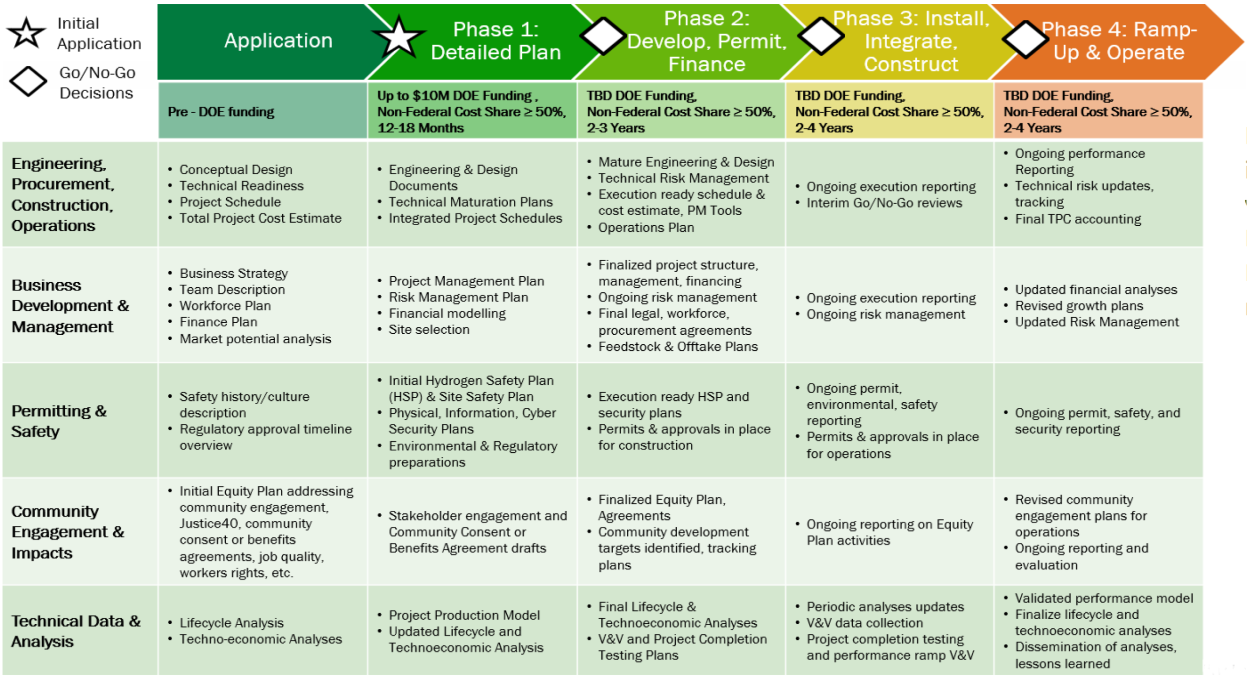
[g] Sec. 40314 (EPACT Sec 816).

[h] Sec. 40314 (EPACT Sec 815).

[i] Sec. 40314 (EPACT Sec 813).

[j] Sec. 40314 (EPACT Sec 814).

[k] NOI (DE-FOA-0002768), visit: https://oced-exchange.energy.gov/.



☆ Initial Application ◇ Go/No-Go Decisions	Application	☆ Phase 1: Detailed Plan	◇ Phase 2: Develop, Permit, Finance	◇ Phase 3: Install, Integrate, Construct	◇ Phase 4: Ramp-Up & Operate
	Pre - DOE funding	**Up to $10M DOE Funding , Non-Federal Cost Share ≥ 50%, 12-18 Months**	**TBD DOE Funding, Non-Federal Cost Share ≥ 50%, 2-3 Years**	**TBD DOE Funding, Non-Federal Cost Share ≥ 50%, 2-4 Years**	**TBD DOE Funding, Non-Federal Cost Share ≥ 50%, 2-4 Years**
Engineering, Procurement, Construction, Operations	• Conceptual Design • Technical Readiness • Project Schedule • Total Project Cost Estimate	• Engineering & Design Documents • Technical Maturation Plans • Integrated Project Schedules	• Mature Engineering & Design • Technical Risk Management • Execution ready schedule & cost estimate, PM Tools • Operations Plan	• Ongoing execution reporting • Interim Go/No-Go reviews	• Ongoing performance Reporting • Technical risk updates, tracking • Final TPC accounting
Business Development & Management	• Business Strategy • Team Description • Workforce Plan • Finance Plan • Market potential analysis	• Project Management Plan • Risk Management Plan • Financial modelling • Site selection	• Finalized project structure, management, financing • Ongoing risk management • Final legal, workforce, procurement agreements • Feedstock & Offtake Plans	• Ongoing execution reporting • Ongoing risk management	• Updated financial analyses • Revised growth plans • Updated Risk Management
Permitting & Safety	• Safety history/culture description • Regulatory approval timeline overview	• Initial Hydrogen Safety Plan (HSP) & Site Safety Plan • Physical, Information, Cyber Security Plans • Environmental & Regulatory preparations	• Execution ready HSP and security plans • Permits & approvals in place for construction	• Ongoing permit, environmental, safety reporting • Permits & approvals in place for operations	• Ongoing permit, safety, and security reporting
Community Engagement & Impacts	• Initial Equity Plan addressing community engagement, Justice40, community consent or benefits agreements, job quality, workers rights, etc.	• Stakeholder engagement and Community Consent or Benefits Agreement drafts	• Finalized Equity Plan, Agreements • Community development targets identified, tracking plans	• Ongoing reporting on Equity Plan activities	• Revised community engagement plans for operations • Ongoing reporting and evaluation
Technical Data & Analysis	• Lifecycle Analysis • Techno-economic Analyses	• Project Production Model • Updated Lifecycle and Technoeconomic Analysis	• Final Lifecycle & Technoeconomic Analyses • V&V and Project Completion Testing Plans	• Periodic analyses updates • V&V data collection • Project completion testing and performance ramp V&V	• Validated performance model • Finalize lifecycle and technoeconomic analyses • Dissemination of analyses, lessons learned

Figure 3. H_2 hub tentative project phases and deliverables [2].

The goal of this plant is to ensure support for potential projects throughout each of the respective phases where the goal is for an NPP to be in a position to start the construction and operation of commercial-scale H_2 plants directly connected to an NPP by 2026. This mandates that the technical designs, operating concepts, and license considerations be addressed before this date.

3. TECHNICAL AND ECONOMIC CASE FOR NUCLEAR HYDROGEN

A series of technical and economic assessments of H_2 production by NPPs have been completed with funding provided by the U.S. Department of Energy–Office of Energy Efficiency and Renewable Energy (DOE–EERE) and U.S. Department of Energy–Office for Nuclear Energy (DOE–NE). These studies provided an incentive to conduct pilot plant demonstrations of H_2 production at NPPs of the respective utilities.

In recent years, the technology readiness levels (TRLs) of water-splitting electrolysis systems have dramatically increased as interest in clean H_2 production and global decarbonization of transportation, industry, and other sectors have increased. Electrolyzed H_2 produced by renewables and LTE is already emerging as a near-term clean stored-energy carrier. This clean storage capability will likely be an important and diversified national complement to limited renewable electricity storage via lithium-ion batteries. It is also notable that in addition to H_2 electrolysis displacing the carbon associated with H_2 by SMR, electrolysis produces highly purified H_2 and valuable end-product without the need for further refinement before being able to be used in specialized applications. HTE systems can achieve relatively higher overall system efficiencies as compared to LTE. Several commercial vendors in the U.S. and Europe have now developed commercial SOEC HTE stacks and have determined optimal operating current/voltage, temperatures, and pressures to maximize the stack thermodynamic efficiencies. Nuclear generators are unique in their capability to deliver both the needed clean electrical and heat energy output—the two components needed to produce clean, high-efficiency H_2 by HTE.

A recent Idaho National Laboratory (INL) study evaluated the feasibility of nuclear-integrated HTE from a performance and cost standpoint, assuming a NOAK project that is built when electrolysis manufacturing is stood up for high-volume sales [4]. A process design model was created that considered the performance of basic steady state constant H_2 production scenarios. The study evaluated the feasibility of HTE equipment utilizing the full energy output from a 1,000 MWe LWR to produce approximately 600 metric tons of H_2 per day. This would require approximately 5% of total steam flow to provide process-heat input to vaporize process water feedstock to the electrolysis equipment and XX% of electrical generation capacity. Most of the reactor-produced steam flow would continue to provide electrical generation both to meet HTE process power demands and to provide continued clean energy to the grid.

Within the parameters invoked, the study concluded that an LWR selling electricity to an HTE plant at \$30/MWh, the base case HTE plant can produce pure H_2 at a levelized cost of hydrogen (LCOH) of \$1.86/kg, excluding product storage or transportation costs. Figure 4 plots the recent cost projections for H_2 production by HTE using the combination of electrical and thermal power provided by a NPP as compared to the cost of H_2 produced by conventional NG reforming. The parameters that have the greatest impact on LCOH are energy price and direct capital cost. For example, a decrease in the electricity price from \$30/MWh_e to \$20/MWh_e results in an LCOH decrease of \$0.41/kg-H_2. Although historical LCOE values for NPPs have been around \$30/MWh several nuclear operators already have LCOEs approaching \$20/MWh_e. Lately, many studies have been done to outline roadmaps for further decreasing nuclear-operating costs.

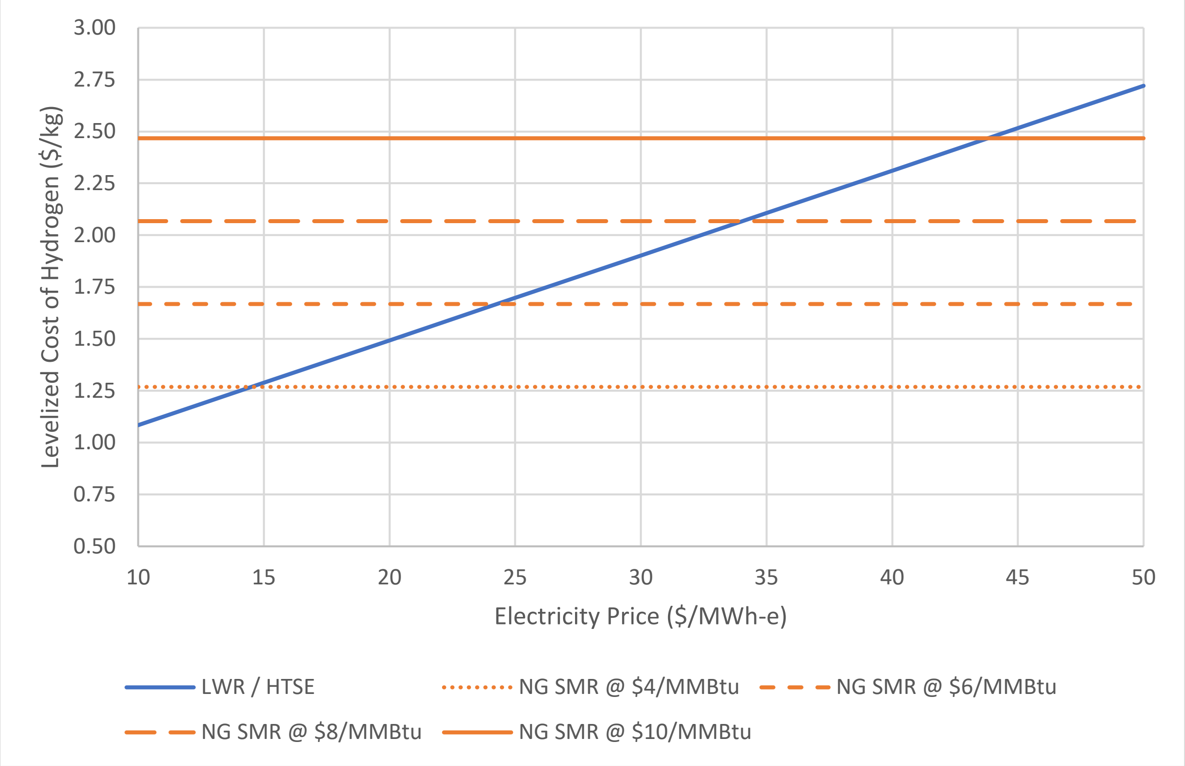


Figure 4. LWR integrated HTE plant LCOH as a function of electricity price for an NOAK. Also shown is the NG steam methane reforming (StMR) LCOH corresponding to selected NG pricing levels.

These techno-economic research findings conservatively did not assign special market or decarbonization value to H_2 produced by water electrolysis in two important ways:

- The low-or no-contaminant value proposition of clean H_2 produced by water electrolysis can serve very high-purity applications without additional processing.

- The purity of H_2 produced by electrolysis is valuable for ammonia production, H2 storage, use with fuel cells, and electronic-grade metals refining.
- The inherently low carbon footprint of < 0.5 kg of CO_2 per kilogram of produced H_2 is significantly less than the clean H_2 standard of 2 kg of CO_2 per kilogram of H2 produced.
- The sale of co-product oxygen increases plant revenues and hence the return on capital investments. Future large markets include the production of so-called “blue hydrogen,” which can use oxygen for the partial oxidation of a steam-methane reforming process, we well as industrial oxy-fired heaters that concentrated CO_2 in the exhaust for easy capture and management.

Comparatively, the dominant H_2 production method of steam-methane reforming without carbon capture and sequestration produces up to 9 tons of CO_2 for each ton of H_2 and, based on the production constituent of NG, inherently produces contaminants that must be further processed for high-purity H_2 applications.

The advent of commercial AE technology (with production ramping both nationally and internationally), and nascent PEM technology (with several factories announced and some under construction in Europe) will make it possible to supply large, centralized, FOAK commercial projects, including NPPs within 3-5 years. Steam electrolysis using solid-oxide cells is lagging behind but promises to reduce the energy costs of water-splitting if manufacturing costs and materials degradation can be reduced. Multiple companies have developed or are developing HTE systems that recuperate the heat from the high-temperature stacks. This means that any source of dry steam (steam above the saturation point) can be used to achieve higher efficiencies with HTE. Additionally, a thermodynamic analysis indicates that HTE most efficient when steam is supplied from a thermal energy source; however, HTE with electric steam generation is still more energy efficient than LTE

A sensitivity analysis was completed to evaluate the impact of several key processes and economic parameters on the HTE LCOH. The upper and lower bounds for each of the input parameters were selected to encompass the possible range of expected technology advancements and/or variations in market conditions. The results of the sensitivity analysis are shown in Figure 5. The LCOE is the biggest factor controlling the cost of nuclear-based H_2. A reduction in the cost of electricity provided by the H_2 plant to \$20/MWe will push the LCOH under \$1.50/kg.

The second priority is reducing the capital costs of the H_2 project, and this is mainly dependent on the cost of the stacks and the electrolyzers. The DOE HFTO program funds research that is helping electrolysis vendors improve the performance and durability of stacks and design, as well as build and test integrated modules that can be scaled to commercial plants. The BIL allocates \$1B to accelerate basic development and demonstration of electrolysis and to establish manufacturing plants to deliver hundreds of megawatts installed capacity each year. While the combined benefits of research and development are projected to reduce the cost of electrolysis for an NOAK plant by \$0.25-\$0.30/kg H_2, this work is also necessary to achieve the operating parameters that were considered feasible by the cost analysis breakdown of Wendt et al. [4].

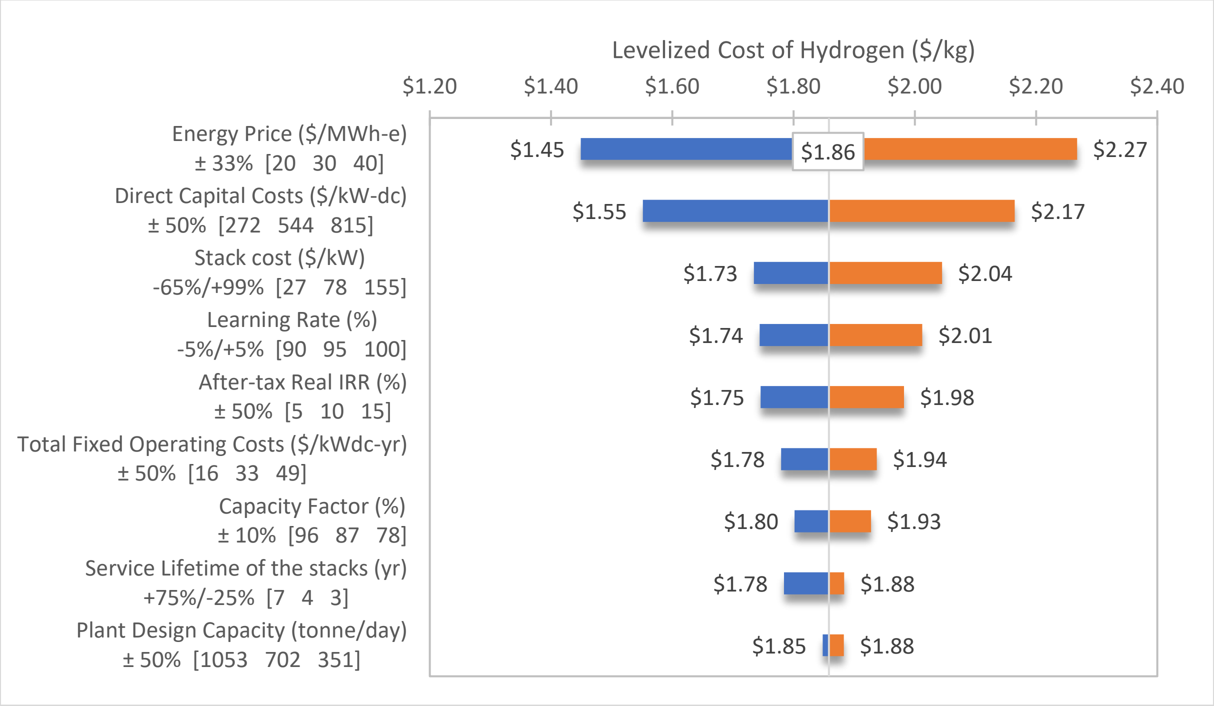


Figure 5. Sensitivity of LCOH to selected constant H_2 production case input parameters [4].

The final steps to realizing the Earthshot goal through electrolysis, including NPPs being competitive with steam-methane reforming in the absence of any clean energy production incentives, is related to the expected revenue that is generated by selling the liberated oxygen that can be a second product of splitting water. It will also be possible to contract with the grid to provide reserve capacity and ancillary services if the NPP can rapidly switch the power transferred to the H_2 plant to the grid. Therefore, research on the means for producing and delivering oxygen from the H_2 plant, as well as the capability of ramping the H_2 plant from a low to high capacity need to be developed and proven.

A dynamic programming algorithm using historical pricing data from the New York ISO (8760 hours) during 2019 was employed to optimize the hydrogen production schedule for an example simulation [5]. The dynamic programming algorithm was developed and reported in previous work. The maximum rated electric power consumed by the SOEC stacks to produce hydrogen was an assumed power of 100 MW. Hydrogen production at this rate also requires an input of approximately 25 MW of thermal energy to produce the steam needed for high-temperature steam electrolysis. That thermal energy could have been converted to 8.5 MW of electric power and sold at market price, so the effective electric power consumption of the HTE plant is 108.5 MW (electric), when operating at full capacity. The effective electric power consumption of 108.5 MW is the value used to determine the monetary value of the energy needed to produce hydrogen. The electrolyzer conversion rate is assumed to be 21.74 kg/MWh (equal to 46 kWh/kg-H_2, based on data from Bloom Energy [6], which yields a hydrogen production of 2.36 tonnes-H_2/hr.

Available hydrogen storage was assumed to be 100,000 kg (100 tonnes), and the capacity factor of the HTE plant was assumed to be 80%. Figure 6 shows the optimized hydrogen production times as red dots superimposed over the 2019 New York ISO electricity prices. It is evident that the controller succeeds at operating the hydrogen production system during periods of relatively low electricity pricing. The data in Figure 10 indicates that the price point at which the hydrogen production systems turn on and off varies throughout the year. Electricity prices were relatively high from January 1 through the end of

March (0-2200 hours) and from mid-June to mid-August (4100-5500 hours), indicating that low-cost electricity was rarely available during those periods of time.

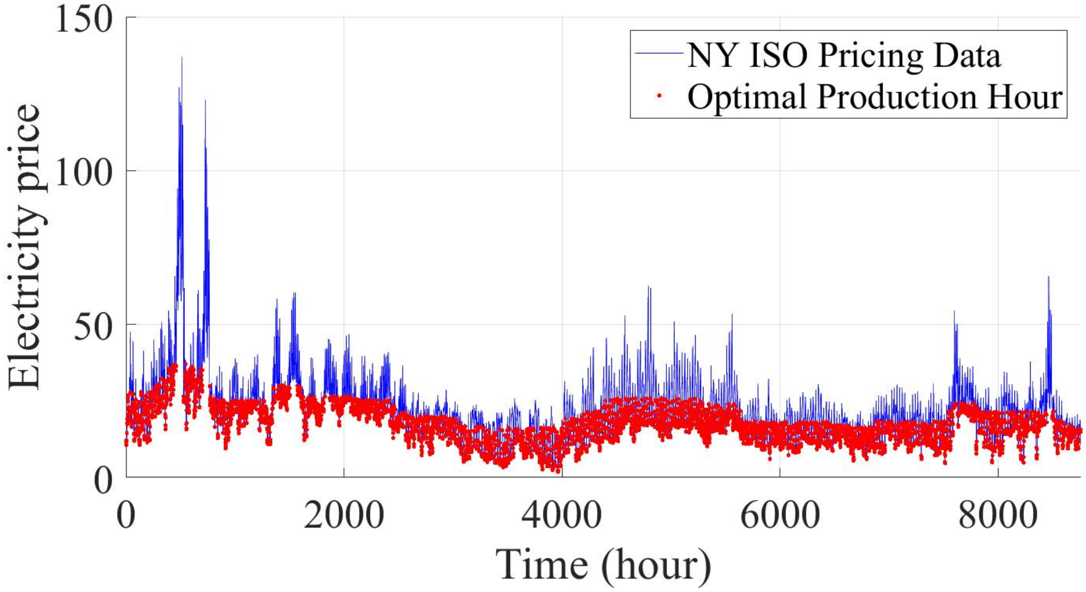


Figure 6. Optimal hydrogen production hours for 80% capacity factor with hydrogen storage of 100 tonnes [5]

Knowing the cost of electricity for every hour that the HTE plant operates makes it possible to calculate the total cost of electricity and thermal power used to produce hydrogen throughout the year as well as the contribution of that cost to the levelized cost of hydrogen production (LCOH). Figure 4-3 shows the average cost of the power used to produce hydrogen on a \$/kg-H_2 basis as a function of the hydrogen storage capacity and capacity factor. As expected, increasing the hydrogen storage capacity has the greatest impact when the capacity factor is low, so that hydrogen storage allows the HTE plant to stop hydrogen production when power prices are high. At a capacity factor of 100%, hydrogen storage does not offer opportunity to utilize low-cost power to produce and store hydrogen because the HTE plant must operate fulltime. It is important to note that the power costs associated with hydrogen production shown in Figure 7 do not include the cost of the HTE plant or hydrogen storage, and those costs must be included to develop an overall optimized system design. Hydrogen production costs increase with decreasing HTE plant capacity factor and with increasing hydrogen storage due to increased capital equipment costs per kilogram of hydrogen produced.

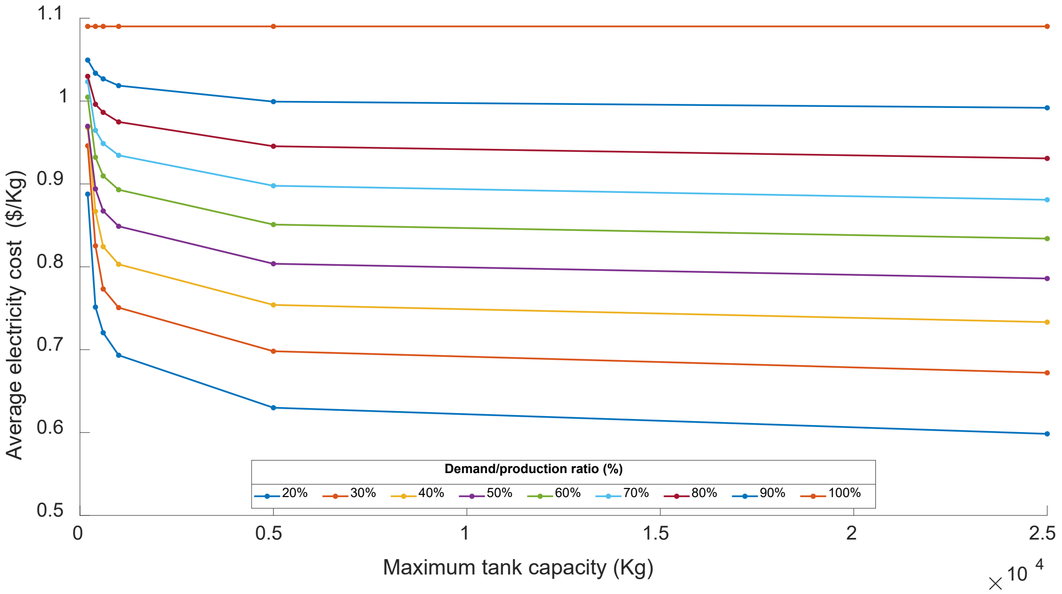


Figure 7. Average electricity cost for different hydrogen storage tank capacities [5].

4. RESEARCH, DEVELOPMENT, AND DEPLOYMENT NEEDS

Successful innovative R&D technology needs to follow a technology commercialization readiness path from invention to full-scale commercialization. The role of DOE is to apply fundamental science in the discovery of new technology and improvement of existing technology that achieves the nation's energy requirements and environmental protection. Technology developed by the National Laboratories is transferred to U.S. companies and industries for testing, demonstration, and deployment through partnerships referred to as Strategic Partnership Projects (SPPs) and Cooperative Research and Development Agreements (CRADAs). CRADAs are jointly funded by DOE and private companies, while SPPs are fully funded by the private entity for projects that align with DOE's missions. The goal is to ensure the success of U.S. competitiveness by reducing the technical and economic risk when scaling-up new processes.

4.1 Electrolysis Technology Commercialization

The HFTO supports industry with the development, testing, and demonstration of electrolysis. INL aims to work with commercial vendors to accelerate technology readiness for commercial-scale LTE and HTE by 2025. This entails R&D to improve electrolysis materials and stack performance and then moving up to the integrated stack assemble and system tested, as shown in Figure 8, before pilot plants are built and demonstrated.

As noted earlier, solid-oxide ion conducting membrane cells have reached a nascent commercial state—although improvements to performance and durability will greatly enhance the commercial success of oxygen ion conducting fuel cells (SOFCs) and electrolysis cells (SOECs), including cells that can be operated reversibly (r-SOFC/SOEC) and cells that can co-electrolyze steam and CO_2 to produce syngas. Electrolysis materials development and stack testing are funded by HFTO under the HydroGEN Energy Materials Network program and the H_2NEW consortium for LTE and HTE.

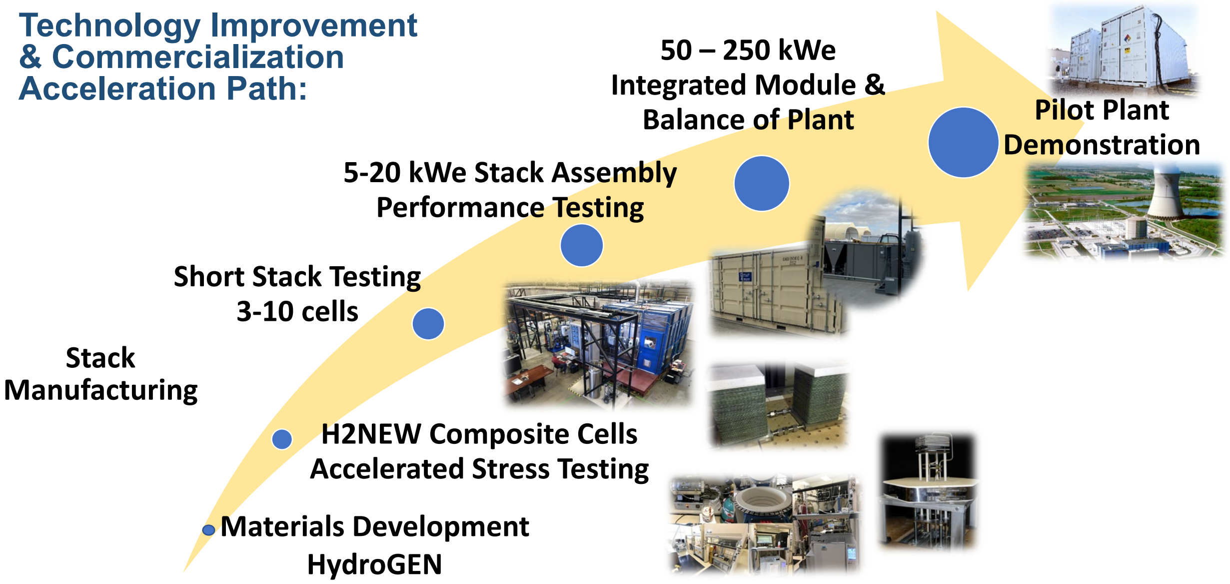


Figure 8. HTE path to commercial demonstrations.

Two U.S. companies are currently testing turn-key integrated modules at INL. These systems are being tied to the INL Thermal Energy Distribution Systems and the INL Real-Time Grid Simulation and Human Systems Simulation Laboratory for testing in a representative real-world environment.

DOE has awarded funding to four pilot-scale demonstration projects aimed at proving H_2 can be produced at an actual nuclear reactor site. Three are based on a simple electrical connection to LTE modules, and the other will demonstrate the integration of plant thermal and electrical energy with HTE. These projects are breaking ground for scale-up of commercial plants by providing relevant experience in setting up infrastructure to support H_2 production and understanding how nuclear H_2 plants can support grid demand responses and reserve capacity.

4.1.1 INL Test High-Temperature Electrolysis Module Testing

INL is setting up several HTE systems at the Energy Systems Laboratory. The 100 kW Bloom energy HTE system, as shown in Figure 9, is currently being operated to prove the performance of systems. A 250 kW FuelCell Energy system is being sent to INL in Fall 2022 for similar testing and verification. A 50 kW HTE system, and a 30 kW rSOC system that can operate in either electrolysis or fuel cell mode are being installed. The discussion below focuses on the 100 kW Bloom HTE system and the HTE Support Facility that provides DC power, steam, nitrogen, and other facilities to operate the Bloom system. The HTE Support Facility also cools the H_2/steam product stream from the Bloom system, separates the H_2 from the steam, and vents the product H_2 in a dilution fan.

Figure 9. Photograph of the Bloom prototype 100 kW HTE system under testing at INL.

4.1.2 Nuclear Power Plant Hydrogen Pilot Demonstrations

Four DOE awards have been made to U.S. nuclear utility applicants to demonstrate the production of H_2 at NPPs. These projects have been highlighted at many public meetings, as well as the HFTO workshops on H_2@Scale and the Program Annual Merit Review.

Energy Harbor

Energy Harbor will install an LTE H_2 generation pilot plant unit at Davis-Besse Nuclear Power Station (DBNPS). The expected result of this project is to have a fully functional and operating H_2 generation skid that has been integrated into the normal operating routine of an NPP.

Major interfaces required for LWR hybrid operations will be developed and installed. Those interfaces include demineralized water supply, H_2 conditioning, storage, and transport, as well as dynamic controls to apportion power output between the electrical grid and LTE unit. A detailed report will be provided after operating data has been accumulated that will highlight the technical feasibility and economic viability of this hybrid system. The use of hybrid systems can preserve the benefits of NPPs, including grid stability and carbon-free energy while creating a market-based solution in response to increasing low-cost power, as well as variable renewable energy supplies. Additionally, this project includes technical-economic assessments for the potential hybrid systems at plants operated by Arizona Public Service (APS) and Xcel Energy, Inc. These assessments will offer summaries of the economic data and will be used to develop proposals and support the technical and financial feasibility of hybrid operations (i.e., integration of H_2 generation facility). This information, along with pre-front-end engineering design input from the collaborating utilities will be used to produce an investor-grade report stating the business case for undertaking similar projects to implement H_2 generation hybrid operations at other LWR NPPs.

Xcel Energy

Xcel Energy will install a 100+ kW HTE system at an NPP in the Minneapolis/St. Paul region and operate that system for a few hundred hours. Xcel Energy is working with Sargent & Lundy to design and execute a thermal connection to supply steam for H_2 production. Xcel Energy will also be responsible for all necessary site preparations. The 100+ kWe HTE system will be supplied by a U.S. company. The schedule of this project is as follows. Approximately by the start date of the project, a subcontract will be negotiated with a U.S. company to provide 100+ kW HTE systems. During the first 18 months of the project, Xcel Energy will work with Sargent & Lundy to prepare the site at an NPP for a demonstration, including preparing connections to extract thermal and electrical energy from the NPP. During the same time period, the HTE system will be built and delivered to Xcel Energy, and INL will perform simulations of a 200 MW HTE system integrated with an NPP. The 100+ kWe HTE system will be set up and operated at an NPP for a minimum of three weeks over a 6-month time period, and the results of those tests will be used to validate simulation predictions from INL. The outcomes of the project will include: (1) the demonstration of thermal energy extraction at greater than 100 kWe from an NPP; (2) the demonstration of efficient production of clean H_2 production using nuclear energy; (3) the verification of reference U.S.-based HTE system design; (4) support for U.S. manufacturing and technology in H_2 production using nuclear energy; (5) simulations of HTE system performance at 200 MWe scale; and (6) engineering design for thermal energy extraction from the Palo Verde nuclear station, indicating the general applicability of project results.

Constellation

This project will explore the potential benefits of on-site H_2 production at Nine Mile Point Nuclear Station in Oswego, NY. Exelon Generation will partner with Nel Hydrogen, Argonne National Laboratory, INL, and the National Renewable Energy Laboratory (NREL) to demonstrate integrated production, storage, and normal usage at the station. A PEM electrolyzer will be installed and use the station's existing H_2 storage system and supporting infrastructure. The electrolyzer will be installed and operations are expected to begin in 2022. The project will generate an economical supply of H_2, a natural byproduct of nuclear energy, to be safely captured, stored, and potentially taken to market as a 100 percent carbon-free source of power for other purposes, including industrial applications like transportation.

Arizona Public Service

APS is evaluating the integration of a reversible high-temperature electrolysis system at its Palo Verde Nuclear Generating Station located approximately 50 miles west of the Phoenix metropolitan area. The effort will begin in mid-2022 and will determine the feasibility of installing a 10 MW electric HTE and supplying approximately 2.5 MW of thermal energy from one of the three Palo Verde 1400 MWe units. A plant design change package will be subsequently developed as part of the effort provided the feasibility assessment demonstrates that the infrastructure will support the demonstration installation. The reversible system design will include H_2 storage of sufficient capacity to provide up to 100 MWh of electric power storage. APS and INL will work with HTE vendors to improve total cycle efficiencies in both electrolysis and fuel cell modes and to eventually advance the technology as an option to traditional electric power storage. Future installation of the demonstration will be evaluated based on the final conclusions of the two-year integration feasibility assessment and design change package project.

In a collaborative effort with Pacific Northwest Hydrogen LLC, INL, NREL, the National Energy Laboratory, and other participants from academia and industry, APS will demonstrate specific end-uses of H_2 produced from carbon-free nuclear power. The project will demonstrate the optimization and economic value of H_2 production as a vector for electric power storage, and as a feedstock for the synthesis of liquid hydrocarbons. Approximately 8 tons of H_2 will be produced daily using a 20 MWe PEM electrolyzer located at the APS Saguaro Power Plant north of Tucson with electricity that is dedicated from the Palo Verde plant and distributed on APS transmission lines. H_2 generated during periods of low grid demand will be stored and later co-fired in a NG turbine at the Saguaro Power Plant during periods of high demand. The demonstration advances H_2 combustion limits up to 50% and de-risks the safe use of H_2 in existing turbines. In addition to providing a responsive load to obviate the need for daily nuclear curtailment, blending H_2 with NG provides a cost-effective bridging strategy for existing turbines, with longer-term replacement by large turbine units fully capable of 100% H_2 operation as the U.S. transitions to a fully decarbonized future. The project will also demonstrate the synthesis of hydrocarbons from produced H_2 and the reduction of an on-site source of CO_2 to CO. Conversion of the H_2 and CO_2 to liquid hydrocarbons will be completed at small-scale to inform the designs for large-scale production and to assess the economics for the commercial-scale production of high-value products like jet fuel and diesel. Fuels derived from carbon-free nuclear power can make large strides toward the difficult task of fully decarbonizing transportation.

5. SAFETY AND HAZARDS ANALYSIS AND LICENSING BASIS

A key research area required to validate the feasibility of NPP-integrated H_2 production is related to how supporting design changes would conform to the licensing regulatory framework required by the U.S. Nuclear Regulatory Commission (NRC). Design changes are routinely made at operating U.S. NPPs through a process where the licensee confirms that the proposed design change remains within the intent of the approved operating license. This process is contained under 10 CFR 50.59. Where a change is found not to be within the limits described by the approved operating license or licensing bases, a formal license amendment process is required with specific NRC approval.

5.1 Probabilistic Risk Assessments

Scale-up from pilot plant works to full-scale commercial projects requires an analysis of the safety risks and regulatory approval. With the support of Sandia National Laboratory, INL completed a preliminary probabilistic risk assessment (PRA) for a 500 tonnes per day H_2 plant located within 1 km of an NPP [7, 8].

Two generic preliminary PRAs were completed for a Mark 1 boiling water reactor (BWR) and a two-loop pressurized water reactor (PWR) tied to a full-scale HTE plant (ca. 1,000 MW_e, 200 MW_{th}). Several new internal and external safety initiating events were identified and evaluated using a rigorous, SAPHIRE-based, Failure Modes and Effects Analysis (FMEA) approach that identifies the impact on existing and new safety initiating events, such as a sudden leak in the new steam extraction system, loss of off-site power (LOOP), H_2 flames, or explosions at the nearby H_2 plant. All of the key PRA parameters, such as core frequency damage (CFD) and large early release frequency (LERF), and maximum credible accident (MCA) for a H_2 production plant located no further than 1 km from NPPs. The preliminary PRA was encouraging and suggested that all risks could likely be covered under the CFR 50.50 and RG 1.174.

Although the outcomes of this effort indicate the safety risks are inconsequential on the operating basis of the plant, a more rigorous PRA needs to be completed with site-specific and detailed engineering designs to carry out a large H_2 production demonstration.

5.2 Hydrogen Regulatory Research Review Group

A Hydrogen Regulator Research Review Group (H3RG) was formed to begin to identify the technical and safety risks that may need to be added to follow the 10 CFR 50.59 requirement [9]. The H3RGconsists of a broad group of experienced nuclear utility design and licensing lead personnel, DOE-Laboratory research leads, contracted architect engineering companies, nuclear plant operators, and licensing experts. The H3RG is divided into committees that address key sections of NPP operations, PRA leads, and plant design and operating license experts. The early finding of the H3RG is that the Flexible Plant Operation and Generation (FPOG) efforts should continue with realistic and even more rigorous PRA efforts and real-case thermal-hydraulic systems and electrical switch-gear modification designs and design reviews. The NRC is following the H3RG activities, but otherwise is not currently advising the group.

The formation of the H3RG is a natural result of feedback and discussions from ongoing LWRS FPOG Key Stakeholder meetings. This FPOG venue identified logical next steps for a generic end-user licensing research deliverable in support of H_2 production by HTE at nuclear facilities. DOE LWRS FPOG Pathway personnel at INL are providing coordination and overall project oversight, as shown previously.

The H3RG-informed design and regulatory research findings will be documented in a subsequent INL report, which will include pre-conceptual thermal-hydraulic, electrical, and control design areas; sections on 10 CFR 50.59 considerations; and documentation of current industry understanding of H_2 project designs that lend themselves to regulatory approval under the 10 CRF 50.59 process. Where likely License Amendment Requests (LARs) may be required, future research deliverables will be explored. These H3RG and laboratory R&D areas will support more informed decision-making for nuclear industry strategic leaders considering the adoption of integrated nuclear H_2 as an alternate energy product stream.

5.2.1 Approach

The H3RG will identify and inform research-related licensing approaches based on traditional NRC licensee requirements that support the introduction of H_2 production by HTE as an alternate energy stream at nuclear facilities.

The supporting architect engineering primary project path has the assigned development activity of proposing an integrated nuclear H_2 pre-conceptual design and draft 10 CFR50.59 evaluation. A generic four-loop pressurized water reactor (PWR) plant design is being used as the research model to characterize how a generic nuclear-integrated H_2 design concept may be implemented as a nuclear facility change under 10 CFR 50.59. Inputs being considered in the assumed design include:

- Steam line connections and mass steam flow for operational and faulted conditions
- Consideration of steam leak assumptions on existing plant analyses
- Secondary plant dynamics and operator control issues
- Analog and digital control schemes and limits of manual control including human system dynamics
- Operational considerations related to thermal energy extraction including any reactor core effects
- Dispatch limitations and transitions between electrical and H_2 production
- Electrical system design interactions and power off-take dynamics
- H_2 equipment physical plant stand-off requirements and on-site storage limits based on detonation analysis design requirements
- Plant PRA considerations – CFD and LERF
- Licensing basis events compatibility
- Initially, an assumed 100 MW nominal nuclear integrated hydrogen design will be assumed. Subsequent architect-engineer (AE) modeling will also be performed to identify any limits for percent-of-plant steam extraction thermal power that may define what regulatory approval processes would be required.

A starting premise for the H3RG is that a design change to implement nuclear-integrated H_2 by HTE must be screened for effects on the existing facility and procedures as described in the Updated Final Safety Analysis Report (UFSAR), as well as the integrated licensing bases, and that a formal

10 CFR 50.59 evaluation will likely be required. In support of informing regulatory approval approaches under the 10 CFR 50.59 process [10], the expert review also will be leveraged for:

- Comparative reviews of historical industry examples where approval of changes to the facility was appropriately completed under 10 CFR 50.59—especially for FOAK and fundamental operating approach changes
- Detailed reviews of historical NRC 10 CFR 50.59 industry feedback and lessons learned on the limits of use of the 10 CFR 50.59 process for approving changes to the facility
- Review of ongoing industry 10 CFR 50.59 evaluations that are being issued in support of LTE modifications or small-scale (kW-level) HTE demonstrations
- Consideration of historical regulatory challenges related to combustible gas concerns at nuclear facilities.

The approval feasibility of the envisioned pre-conceptual mechanical-thermal, electrical, and control changes under a 10 CFR 50.59 evaluation process will ultimately be determined from an integrated design perspective. However, the H3RG leverages a subcommittee structure that evaluates these piece-part design and operational review areas as stand-alone topics. This allows for targeted use of expert review resources for early identification of discrete subcommittee-assigned areas that indicate likely success paths or a need for additional research consideration. The subcommittees do not work in isolation. A web-based work platform (Taktix®) allows information-sharing and questions between the subcommittees, as well as INL and contracted AEs that are responsible for developing pre-conceptual design aspects of the pilot project.

Although the goal of the H3RG is to explore success paths for using the 10 CFR 50.59 process, it may also identify potential 'dividing lines' between the use of 10 CFR 50.59 evaluation and LAR processes or other licensing basis changes. If research points to a specific design or operational issues that fall outside successful evaluation under 10 CFR 50.59, those areas will be identified and considered for additional research that could toggle the change back to implementation under 10 CFR 50.59. Any design or licensing consideration area that has been selectively screened out of this initial research project scope will be documented for future R&D and end-user detailed development.

5.2.2 Structure

The structure of the H3RG is primarily designed around two goals:

1. Gather experience-based insights from LWR plant owners and operators applicable to regulatory approval of planned flexible H_2 operations at nuclear facilities.
2. Provide expert regulatory, design, and operational input to inform the work of laboratory scientists and contracted architect engineers tasked with pre-conceptual nuclear-integrated HTE designs and 10 CFR 50.59 deliverables.

The common intent in both areas is to integrate real-world industry regulatory operating experience into National Laboratory research in support of the timely rollout of flexible H_2 projects at U.S. NPPs. Foremost in these considerations are how such proposed design changes and operating methods may impact the plant's safety analyses. These safety analyses are contained in the updated UFSAR and form the cornerstone of each plant's licensing basis.

As shown in Figure 10, the H3RG is organized under several industry subcommittee research areas with leads selected from the pool of expert participants supporting the H3RG. These leads oversee reviews of individual regulatory subcommittee areas that will later be aggregated to support a generic 10 CFR 50.59 template deliverable. These include the following subcommittee areas:

1. Internal/external events and PRA considerations.

2. Integrated operations and reactor impacts.
3. Electrical and switchyard considerations.
4. Control system interactions and modifications.
5. Regulatory strategies.

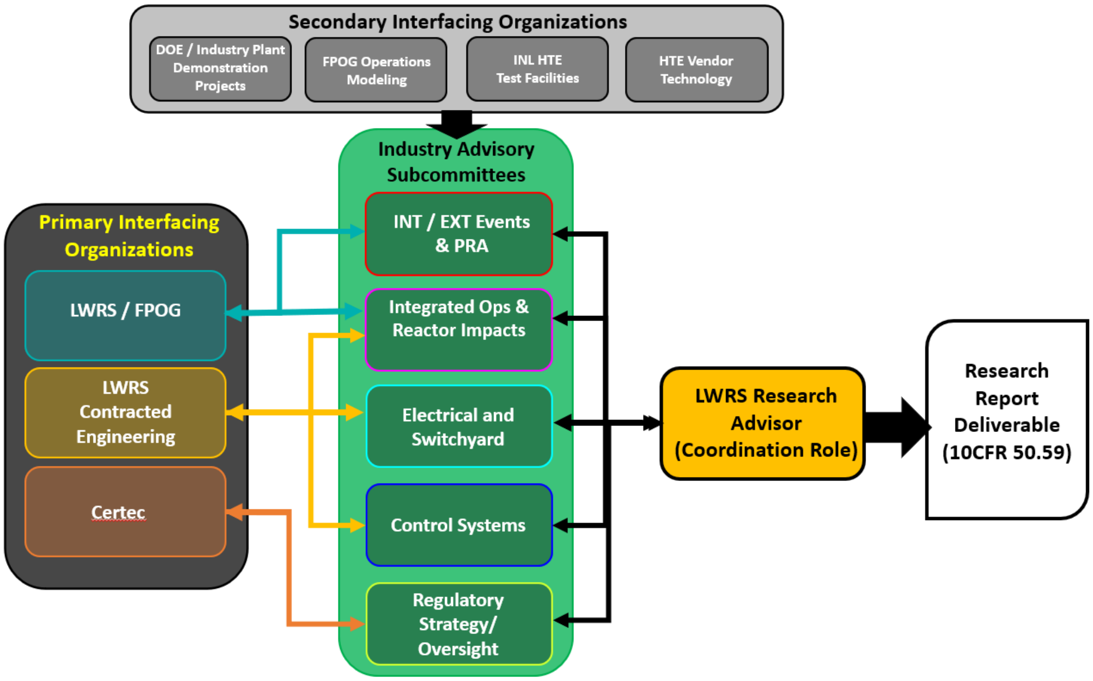


Figure 10. H3RG organizational structure.

The H3RG subcommittees each meet regularly for the following purposes:

- To gain an understanding of ongoing laboratory research and contracted architect engineering activities regarding nuclear-integrated HTE
- To identify key considerations associated with their subcommittee area that should be included in the 10 CFR 50.59 research report deliverable
- To report findings, questions, and help as needed in regularly scheduled combined H3RG meetings.

6. COMMERCIAL-SCALE HYDROGEN DEMONSTRATION PLAN

The three main options for H_2 production at NPPs are:

- **Option 1.** LTE is coupled to the NPP through the power transmission substation behind the electrical grid bus bar.
- **Option 2.** HTE is coupled electrically and thermally to the NPP.
- **Option 3.** HTE that is coupled electrically to the NPP, with steam generation by either an auxiliary electric boiler or an external heat source.

The first small-scale demonstrations intend to show electrical-only connected LTE projects, LTE and synthetic fuel synergies, and steam and electrically connected kW-level nuclear-integrated HTE. By comparison, nuclear HTE at the 100 MWe/25 MWth scale is effectively an order of magnitude larger, which introduces aggregate plant interaction considerations for evaluation. This medium-scale pilot project undertaking will require thermo-hydraulic, electrical, and controls integration engineering, and design basis analysis that includes evaluation of assumed detonation effects of nearby H_2 storage.

The focus of this plan will be on Option 2, which is bounding for Options 1 and 3.

6.1 Design for Hydrogen Plant Coupling

Pre-conceptual design details are based on a 100 MWe commercial-scale nuclear-integrated HTE pilot project that is in preparation and will be provided by September 30, 2022. The pre-conceptual scope deliverable will include the completion of the following tasks:

1. The initial thermal and electrical analysis to support a pre-conceptual design for coupling an NPP to the H_2 production facility.
2. A pre-conceptual design for the NPP focusing on the major plant interfaces to the H_2 production facility.
3. A cost range estimate for the pre-conceptual design at the NPP.
4. A draft 10 CFR 50.59 Evaluation supporting the pre-conceptual design at the NPP.

The initial deliverable from the pre-conceptual design effort will be a draft of the Design Report including the following areas:

- Critical Plant Modification Characteristics
- Thermal Analysis
- Electrical Analysis.

6.2 Operating Concepts for Energy Dispatch

A recent INL study evaluated the feasibility of thermal dispatch operations integrated with existing plant operations in a human-in-the-loop full-scope simulator experiment [11]. Modifying existing LWRs with thermal dispatch equipment and control systems will impact the existing concept of operations. The impacts can be broadly categorized as coordination impacts, additional operations specific to the thermal dispatch concept of operations, and impacts on operator responses to detecting, diagnosing, and mitigating adverse conditions.

Providing thermal power to a nearby industrial user requires additional coordination. Operators currently coordinate with electrical grid dispatch, but now operators must also coordinate with thermal power consumers and electrical dispatch in tandem. The type of coordination is therefore different. The frequency of coordination will also increase since the typical use case to take advantage of electrical wholesale prices dictates frequent transitions between purely electric and electric and thermal modes of operation occurring once each day.

The new capability ushers in new operations required to transition the equipment states between the two modes of operation. Operationally, transition to the thermal and electric mode entails closing the governor vales while opening the control valves for the thermal dispatch system. Operators must perform this transition to minimally affect reactor power as pressure deviations resulting from diverting the steam away from the turbine can adversely impact reactor power and induce undesired control rod movement. Therefore, this new operation to maintain flow balance while diverting the steam from the turbine to the thermal dispatch system requires a careful orchestration of the two systems. With the addition of the new system, maintenance must also be considered since there is now a new and significant steam flow path that must be considered when performing maintenance to both the existing main steam system, but also for the new thermal dispatch system.

The final primary operational impact resulting from the thermal dispatch augmentation is safety related and of critical importance. The thermal dispatch system renders the plant thermally coupled to the nearby industry thermal energy consumer. In some envisioned deployment configurations, the plant is also electrically coupled to the thermal energy consumer. To maintain licensing requirements, the licensed operators in the control room must have sole authority over the state of the plant and most importantly, reactivity control. The thermal and electrical coupling has the potential to provide feedback that could impact plant reactivity and therefore careful consideration was made to the concept of operations to ensure appropriate barriers prevent any external industrial consumer event from inadvertently controlling reactivity. The concept of operations testing performed under the INL study placed a large emphasis on ensuring operators could maintain control over reactivity when faced with external events related to the thermal dispatch system. As a result, operators must be able to contend with a sudden electrical load loss from the thermal dispatch consumer since the electrical consumption from this can proportionally account for the bulk of the electricity if not the entirety of the electricity produced as envisioned in some use cases. Thermal rejection must also be considered, but a contractual agreement may serve as a potential solution. In this agreement, the consumer would be required to ensure they can receive or dump the thermal energy into the atmosphere in the event they have an operational disruption. Alternatively, a potentially more costly approach could include the plant maintaining its capability to dump the thermal energy with existing or new equipment.

6.3 Summary Preliminary Findings

To date, the H3RG has reviewed the viability of the 100 MW nominal H2 plant design and found no technical or regulatory constraints associated with this magnitude of design. Ongoing review of technical and regulatory considerations will address the next phase of the planned pre-conceptual engineering and R&D associated with a 500 MW nominal hydrogen plant order of magnitude.

7. RESEARCH AND DEVELOPMENT ACTIVITIES AND SCHEDULE

An approximate timeline of general activities is shown in Figure 11. The goal is to raise the TRL of the integrated hardware and operational schema. The Pathway Technical Plan is shown for 5 years through the end of 2026. This timeline is not an official DOE Plan or Roadmap; rather, it is shown to help develop the LWR associated research activities to help utilities prepare for and execute H_2 projects in preparation for application to the FOA, and to pass the go/no-go decisions points by leveraging the DOE program activities.

The FPOG Technical Program Plan describes the supporting activities funding by LWRS. The HFTO owns the DOE-supported R&D relevant to electrolysis development and manufacturing and H_2 infrastructure development. The Office of Fossil Energy and Carbon Management (OCEM) oversees H_2 turbine and utility-scale fuel cell development and demonstration.

The LWRS will continue to engage with nuclear power utilities and industrial stakeholder with the Hydrogen Regulator Research Group and other stakeholder meetings.

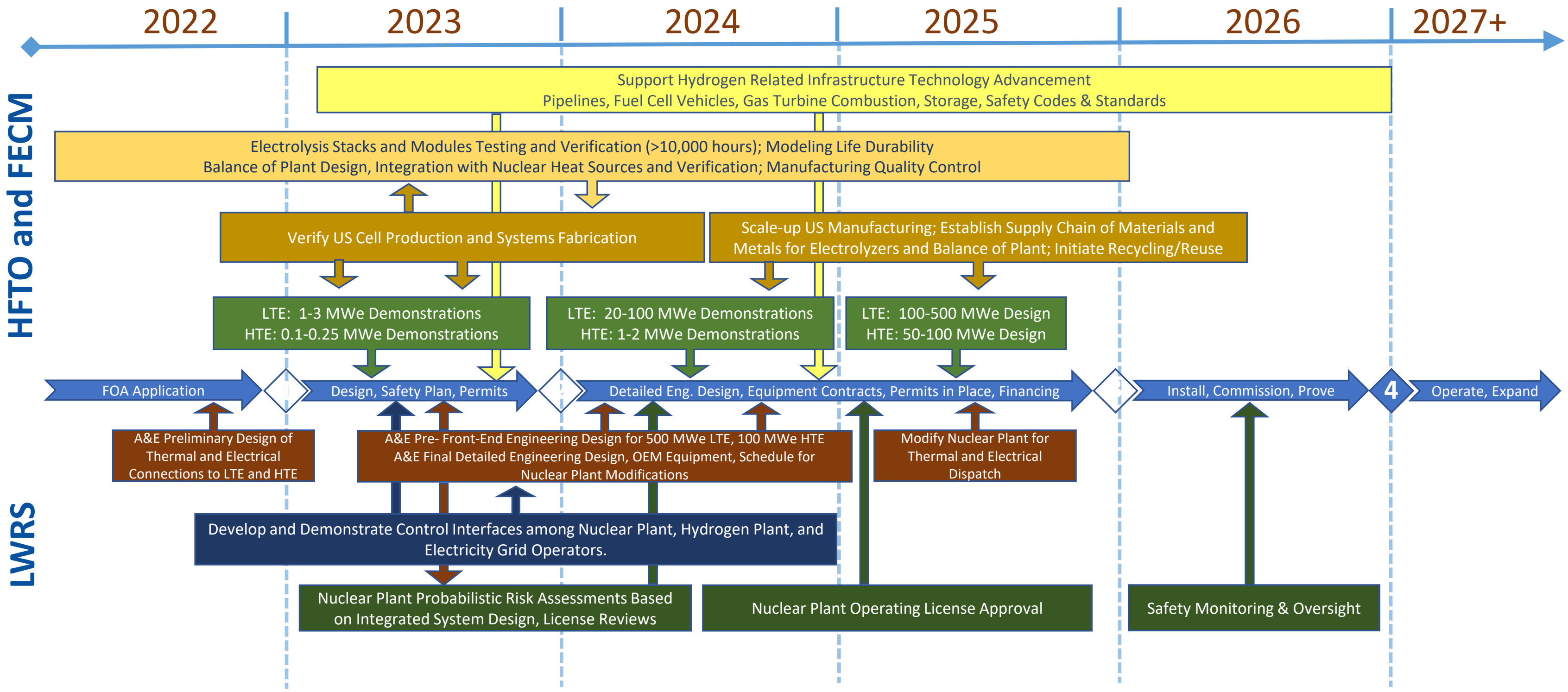


Figure 11. Joint program work activities supporting the creation of Regional Clean Hydrogen Hubs with Nuclear.

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