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Light Water Reactor Sustainability Program

Nuclear Energy Prospector for Identifying U.S. LWR Non-Grid Opportunities

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Nuclear Energy Prospector for Identifying U.S. LWR Non-Grid Opportunities

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EXECUTIVE SUMMARY

The objective of this report is to showcase a graphical user interface and database, the Nuclear Energy Prospector, developed to visualize and provide data regarding the distance and volume information for hydrogen demands, carbon dioxide sources and industrial heat demand in proximity to U.S. Light Water Reactors (LWRs). The Nuclear Energy Prospector offers insights into the strategic opportunities and challenges to using LWR heat and power to produce hydrogen, heat for industry, and utilizing carbon dioxide together with hydrogen to produce valuable non-grid products.

The primary purpose of the Nuclear Energy Prospector (NEP) is to show regional demand for hydrogen, heat and power from U.S. LWRs to produce hydrogen and to use CO_2 and hydrogen to potentially produce synfuels and chemicals, leveraging datasets specifically processed for these facilities. Additionally, the underlying infrastructure is built to extend its analytical capabilities to any location, making it potentially useful for future studies that may explore the siting of advanced nuclear reactors.

The Nuclear Energy Prospector supports a broad range of users, including researchers, and industry stakeholders, by providing a platform for selecting and comparing multiple existing U.S. LWR sites for hybrid integration to produce non-grid products. It offers detailed attributes such as potential hydrogen demand, CO_2 availability, biomass availability, and potential geological storage options. These attributes are presented through interactive charts, web GIS, and tables, allowing for a comprehensive analysis surrounding all existing LWR sites. Moreover, the ability to export data in formats like CSV and geographic shapefiles enhances its utility, enabling users to integrate extracted data into broader analytical or spatial frameworks.

NEPs dual capability of detailed data analysis and data export plays a significant role in advancing research and development in sustainable nuclear energy configurations. This design not only bridges the gap between current LWR capabilities and future potential revenue sources within the industry but also ensures that NEP remains adaptable for future expansions in both data scope and geographical coverage. The final beta version of NEP is attached in the following link: "https://ep.fptz.org".

The Nuclear Energy Prospector features five distinct modules—1) Plant Selection, 2) Potential Hydrogen Demand, 3) CO_2 Availability, 4) Geologic Storage Availability, and 5) Biomass Availability—that enhance its utility for assessing energy production possibilities and resource availability. Each module integrates seamlessly with the others, providing users with a robust platform for conducting detailed analyses of energy resources associated with nuclear plant operations. This integration of diverse datasets and functionalities into a user-friendly interface significantly strengthens NEP's analytical capabilities, supporting informed decision-making and comprehensive infrastructure planning in the realm of sustainable energy solutions.

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ACRONYMS

API	Application programming interface
CCU	Carbon capture and utilization
DOE	Department of Energy
DRF	Django Rest Framework
EPA	Environmental Protection Agency
HTSE	High temperature steam electrolysis
LWR	Light water reactor
NATCARB	National carbon sequestration database and geographical information system
NEP	Nuclear Energy Prospector
NPP	Nuclear power plant
GIS	Geographic information system
SMNR	Small modular nuclear reactor
STAND	Siting tool for advanced nuclear development
UI	User Interface
U.S.	United States
WFS	Web feature service
WMS	Web map service

NUCLEAR ENERGY PROSPECTOR FOR IDENTIFYING U.S. LWR NON-GRID OPPORTUNITIES

1. Introduction

Hydrogen is a proven chemical feedstock with wide-ranging applications, including transportation, energy storage, and industrial chemical synthesis. The growing recognition of hydrogen's crucial role in achieving a sustainable and low-carbon energy future has positioned nuclear power plants (NPPs) as potential hydrogen producers and key contributors to realizing the potential of clean, near-zero-carbon hydrogen production and industrial heat supply.

The U.S. fleet of light-water reactors (LWRs) is increasingly acknowledged by government, scientific, policy, and industrial sectors as having a critical role in supporting the nation's shift toward a clean energy future. The Department of Energy's (DOE) Light Water Reactor Sustainability (LWRS) Program, through its Flexible Plant Operations and Generation Pathway, is developing strategies to enable U.S. NPPs to contribute in these areas. This includes helping NPPs, traditionally designed for steady baseload operation, to adapt by integrating with intermittent wind and solar power. By flexibly dispatching heat and electricity to industrial users, these plants ensure a reliable supply of clean energy for the nation.

Light Water Reactors (LWRs), which dominate the global nuclear energy landscape, hold substantial promise for hydrogen production. By utilizing the thermal energy produced by LWRs, it is possible to support high-temperature steam electrolysis (HTSE) processes. HTSE technology based on solid oxide electrolysis cells (SOEC) has drastically improved in recent years and shows the potential to produce hydrogen at higher efficiency than with low temperature electrolysis. HTSE integrated with LWRs could provide a consistent and low-carbon source of hydrogen, which is crucial for various industrial applications, energy storage, and the transition to a cleaner energy system. LWRs can also play a vital role in carbon management strategies. Integrating carbon capture and utilization (CCU) technologies with LWRs can help reduce CO_2 emissions by using the captured carbon for various industrial processes, such as producing synthetic fuels or materials. Additionally, LWRs can be paired with biomass processing facilities to create a carbon-neutral or even carbon-negative energy cycle synthetic fuels and chemicals, combining the benefits of both nuclear and renewable energy sources.

As presented in Figure 1, nuclear energy can be a continuous source of thermal and electrical energy with near-zero emissions. Using the existing asset base of LWR power stations, there are potential opportunities for coupling nuclear plants a wide variety of processes including chemical or computational to increase the sustainability of nuclear technology, while producing more competitive products and fuels with reduced emissions.

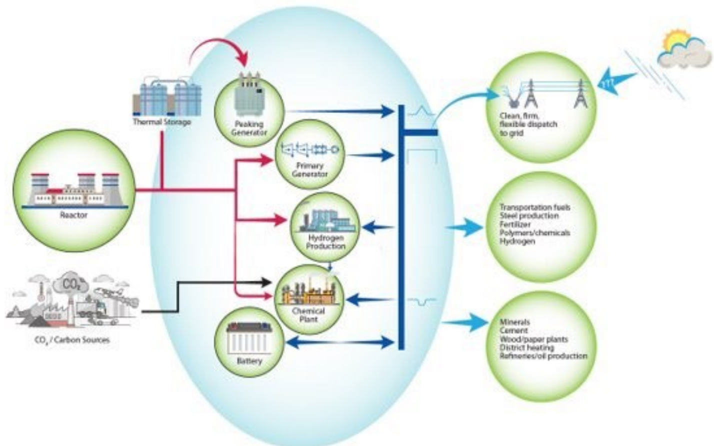

Figure 1. A new paradigm for nuclear power plants for decarbonizing industry and transportation.

Recent technical and economic assessments have shown that nuclear power plants can be profitably operated as hybrid plants that produce electricity and hydrogen. As hybrid plants, the electricity that is most often directed to the electrolysis plants can be dispatched to the grid when non-spinning reserves for peak power are needed. The ability to rapidly dispatch power between the grid and the electrolysis plants or other loads may allow the nuclear hybrid plants to support grid stability.

In the Nuclear Energy Prospector, hydrogen demands are categorized into three tiers. Tier 1 covers existing hydrogen demands, such as hydrogen used for oil refineries or ammonia plants, that can be easily supplied with nuclear hydrogen without significant changes in the infrastructure and any need of external impetus. Tier 2 hydrogen demands are areas where hydrogen is not currently used in existing process but could be substituted. Tier 2 includes use in direct reduced iron production and blending with natural gas for electricity generation or fired furnace heat applications. Lastly, futuristic industries are categorized under Tier 3. Tier 3 industries would require new plant construction for hydrogen demand to develop. Tier 3 opportunities are paired with carbon dioxide source locations for synfuel or E-fuel production.

The three main functions of the NEP are site discovery, exploration, and comparison. In site discovery, the user sets priorities by answering a series of questions and top matches are reported and ranked. In site exploration, the user can view a reference map and select locations to compare. Site comparison allows the user to rank a series of factors related to nuclear restrictions, energy price, net electricity imports, nuclear sentiment, nuclear inclusive policy, market regulation, and construction labor rate. The site comparison output shows the best and worst quantitative measures across each site for each attribute previously ranked by the user.

This highlights the use and utility of the Nuclear Energy Prospector to explore and evaluate the potential integration of LWRs with hydrogen production facilities, carbon sources, and industrial operations. The report provides a comprehensive analysis of how the NEP can be used to highlight opportunities for LWRs to be strategically paired with hydrogen production and CCU to reduce carbon emissions and contribute to a more sustainable energy future. The release of the NEP intended to provide energy planners, policymakers, and industry stakeholders with a powerful resource for evaluating the feasibility and benefits of integrating LWRs with hydrogen and carbon management technologies. NEP’s primary goals are to facilitate the identification of suitable sites for these integrations, enhance understanding of the spatial dynamics of energy systems, and support the development of sustainable, low-carbon energy infrastructure.

2. Application Design and Development

The Nuclear Energy Prospector was designed and developed to facilitate a comprehensive evaluation of existing Light Water Reactors (LWRs) with regard to their integration with hydrogen, carbon sources, and industrial facilities. The primary application of this tool is to analyze the current demand for heat and power from LWRs using datasets specifically processed for these facilities. Its underlying infrastructure, however, is designed with the capacity to extend its analytical capabilities to any location. This makes it potentially useful for future studies that might explore the siting of advanced nuclear reactors, pending the expansion of the current datasets to encompass a wider geographical coverage.

2.1.1 Objectives and Requirements

The initial goal of the application was to support users—including researchers, policymakers, and industry stakeholders—in selecting and comparing multiple existing LWR sites. It would provide detailed attributes such as potential hydrogen demand, CO2 availability, biomass availability, and storage options through interactive charts, web GIS, and tables surrounding all existing light water reactor sites (LWRs). The planned functionality also included the ability to export data in multiple formats, such as CSV and geographic shapefiles, significantly enhances its utility. This feature facilitates the integration of extracted data into broader analytical or spatial frameworks, thereby supporting comprehensive infrastructure planning and decision-making processes regarding sustainable energy solutions.

This dual capability of detailed data analysis and data export underscores the tool's role in advancing research and development in sustainable nuclear energy configurations, bridging the gap between current capabilities and the future potential within the industry. The architectural flexibility of the tool ensures that it not only meets current analytical needs but is also preparatory for future expansions in data and geographic scope.

2.1.2 Application Design

The user interface (UI) design for the Nuclear Energy Prospector is pivotal in ensuring that the tool remains accessible, intuitive, and efficient for its diverse user base, which includes researchers, policymakers, and industry professionals. The design process was comprehensive, emphasizing user-centered design principles at each step to guarantee that the final product would meet the specific needs and preferences of its users.

2.1.2.1 Style Guide

The design process began with the development of a comprehensive style guide. This guide outlined the color palette, typography, and UI components' styles to ensure consistency across the tool. The color scheme was chosen to enhance readability and usability, with distinct colors designated for different types of data visualizations to aid in quick interpretation. Originally named the Hydrogen Prospector, the application was renamed to the Nuclear Energy Prospector to accommodate a broader scope in data coverage and usage. This change aimed to enhance the tool's flexibility, a decision that is reflected in the early stages of its UI design process, including the style guide and initial prototypes. This can be seen in the style guide images shown in *Figure 2*.

Figure 2. Selected design components of the Nuclear Energy Prospector style guide.

2.1.2.2 Initial Prototype

An initial prototype was created to lay out the basic structure and flow of the user interface. These prototypes provided a skeletal framework for the tool's layout, emphasizing ease of navigation and minimalistic design to avoid overwhelming users. Key features were strategically placed to facilitate easy access to the tool's core functionalities, such as data selection, parameter inputs, and the visualization dashboard.

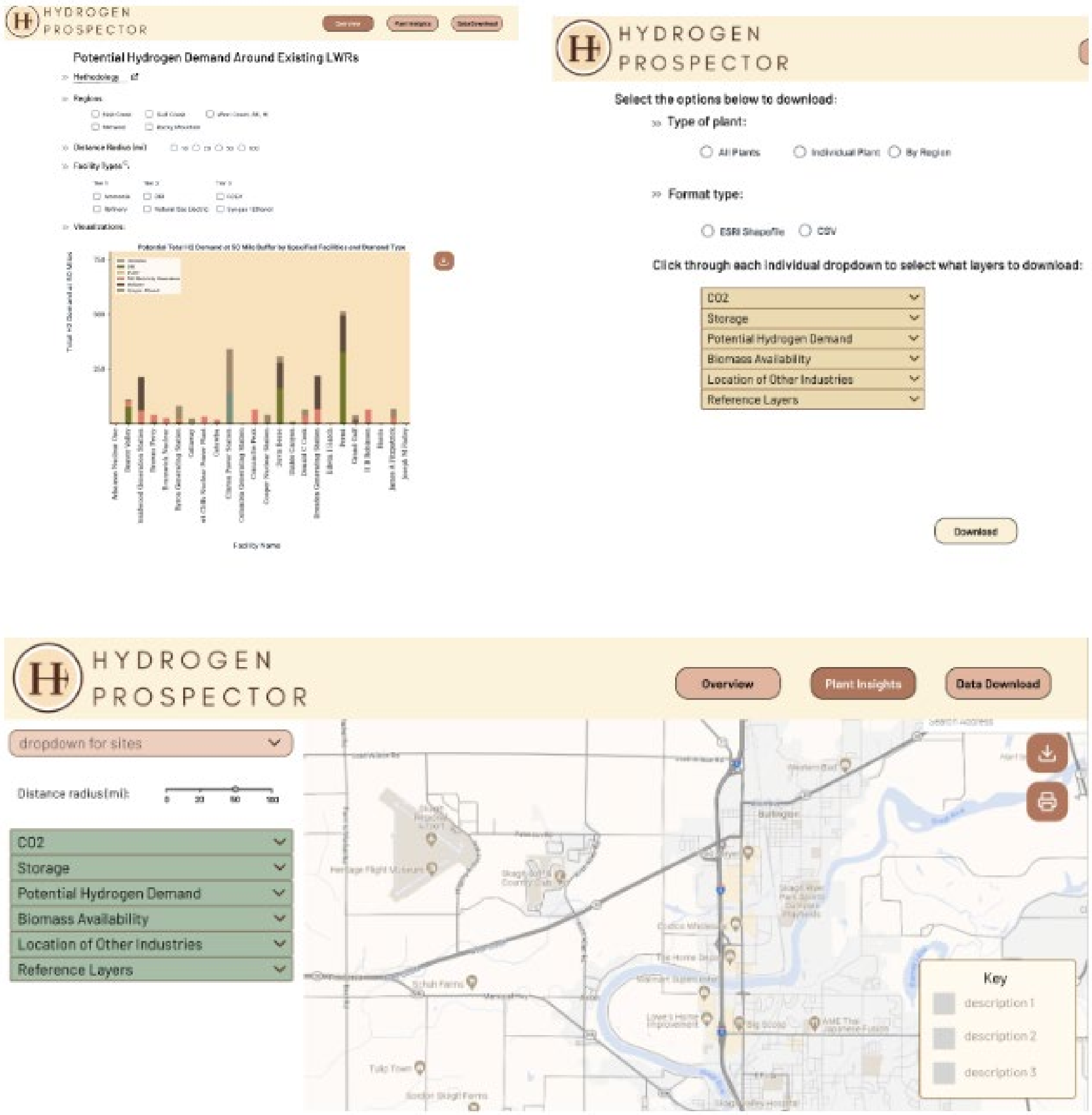

Figure 3 Selected components of the Nuclear Energy Prospector initial prototype

The final prototype was adapted to incorporated advanced interactive charts and graphs allowing for detailed comparison across different Light Water Reactor (LWR) sites. These visual tools were integrated alongside the web GIS components, providing a cohesive and interactive experience. Users can now manipulate data variables in real-time, see immediate updates on the GIS platform, and compare different data sets visually on graphs and charts displayed concurrently.

The final interface design combines functionality with aesthetics, adhering to the initial style guide while incorporating flexible data visualization tools that cater to the complex needs of its users. This UI facilitates an engaging and informative interaction, enabling users to make informed decisions based on comprehensive spatial and statistical data analysis.

This UI design approach ensures that the Energy Prospector Database Tool not only meets the functional requirements of its diverse user base but also adheres to standards of design consistency and user experience quality.

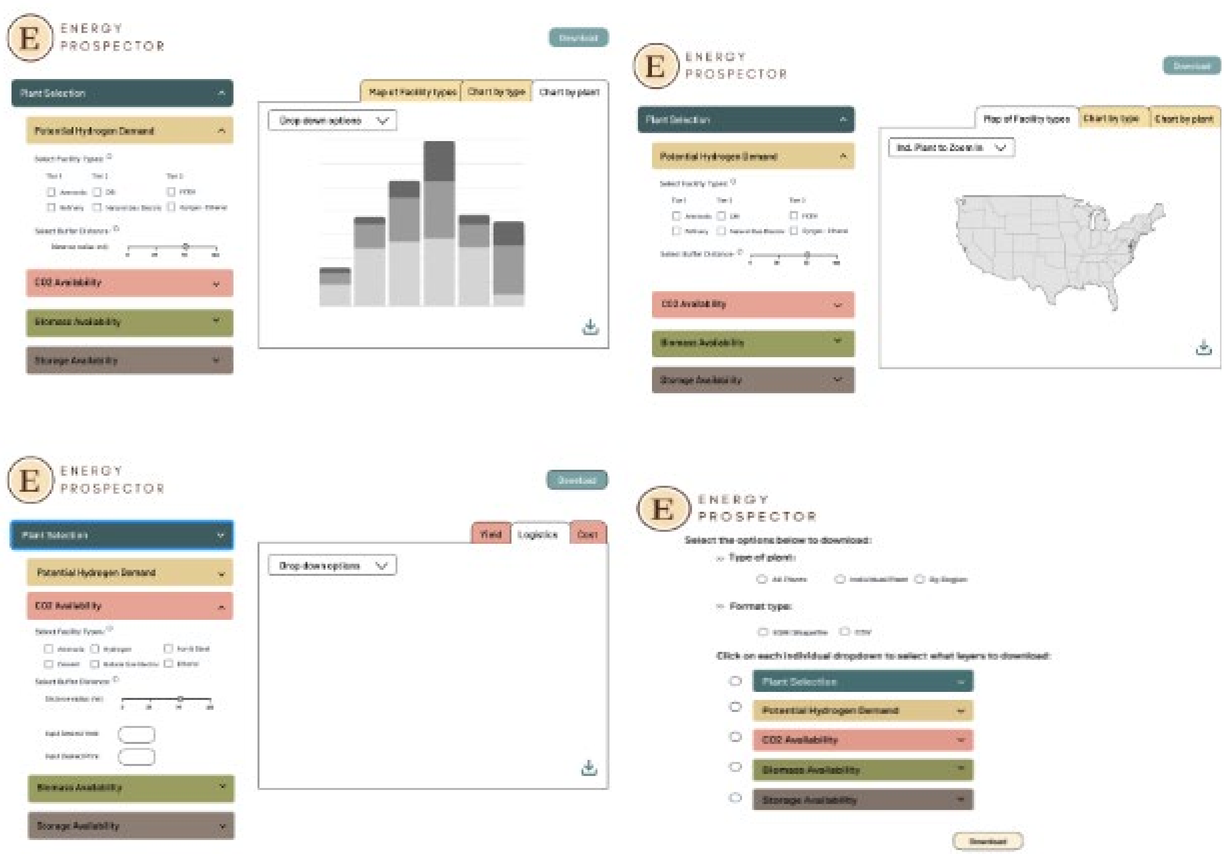

Figure 4. Selected components of the Nuclear Energy Prospector final prototype.

2.2 Application Development

Energy Prospector is hosted on Google Cloud Platform using a combination of Infrastructure as a Service and Platform as a Service resources (namely Compute Engine, Cloud SQL, and Cloud Run) to achieve a balance among time to release, site reliability, security, uptime, and maintenance cost. The application itself was built using software packages chosen according to their maturity, the experience of the development team, and specific solutions to the functional requirements of Energy Prospector. All software dependencies are either open source or licensed to the Fastest Path to Zero Initiative (FPTZ).

PostgreSQL with the PostGIS extension is the database platform. PostgreSQL is a powerful and SQL compliant relational database management system. PostGIS adds geospatial data types and functions that many queries made by Energy Prospector rely on.

Django and the Django Rest Framework (DRF) provide the web server and application programming interface (API), respectively. They both use the Python programming language which is used heavily by the FPTZ Data Science team and therefore simplifies translating a proof of concept into production code. Geoserver handles all web map service (WMS) and web feature service (WFS) requests. It uses Open Geospatial Consortium standards and integrates easily with relevant technologies elsewhere in the Energy Prospector stack.

The user interface (UI) of Energy Prospector is built on the Vue.js framework with additional packages for specific functional requirements. The Pinia store library is used for state management. Standard UI components and functionality come from the Vuetify framework. The OpenLayers library provides GIS functionality. The Highcharts library is used for all other charting. The Axios library handles API requests.

The development process generally adhered to the following steps in series but each was revisited after subsequent steps had begun for change requests and bug fixes:

1. Data Processing
2. API Development
3. User Interface Scaffolding
4. Business Logic
5. User Interface Styling

Data Processing is collecting all datasets required by the application and loading it into the database. The logical design of the database was dependent on the format of the required datasets and their intended use within Energy Prospector. Most datasets required some amount of cleaning such as data type transformations and normalization to remove redundant values. Database views (saved queries) were added as needed to simplify requests made by the application.

API Development is coding endpoints that deliver data for consumption by the user application. This includes endpoints managed by DRF and Geoserver. Most DRF endpoints are derived directly from a database table while others require custom parameterization and logic to leverage functionality in the database such as functions provided by PostGIS . The Geoserver endpoints are built on database tables and views that include a geospatial column. They are configured with map symbology and can be filtered using the Common Query Language.

User Interface Scaffolding is developing the most basic functionality of the UI. This ensures that the UI design is generally implementable before thorough development of any individual UI component is completed. At this point the application deployment pipeline is created, and internal review of the 'live' application begins.

Business Logic is how the application requests data and changes the UI state according to user interactions. Energy Prospector makes requests to its own internal API for chart and table data, and to an external Geoserver instance for web map data. Since Energy Prospector is a single page application, all these requests are made asynchronously and Vue.js is setup to update UI components in reaction to data updates. For example, in the Plant Selection module the initial list of nuclear power plants is loaded when the application initializes with only the plant names, regions, and IDs. When the user selects a plant, a request for geographic coordinates and reactor data specific to the plant ID is made and all UI components that use this new data are notified of the change and updated accordingly. Configuration of most data visualizations and development of module forms occurred during the Business Logis development step.

User Interface Styling is adding the colors, fonts, and other aesthetic details to the UI. Vuetify provides many convenience classes that were sufficient for most custom styling.

3. Tool Capabilities

The Energy Prospector tool features five distinct modules that enhance its utility for assessing energy production possibilities and resource availability. Below is a detailed overview of each module:

Plant Selection Module

- **Region Filtering**: Allows users to filter plants by region or select individual plants for focused analysis.
- **Map Visualization**: Displays selected plants on a map with detailed attributes for each location.
- **Comparison Tools**: Enables comparison of plant attributes such as capacity (net, thermal, design, gross) using charts or tables.

Potential Hydrogen Demand

- **Distance-Based Analysis**: Calculates potential hydrogen demand from selected plants by radial distances (10, 20, 50, 100 miles).
- **Map Visualization**: Hydrogen demand is displayed on a map, with clickable attributes for more detailed information.
- **Comparison Tools**: Facilitates the comparison of multiple plant attributes through interactive charts.

CO_2 Availability

- **Distance-Based Analysis**: Calculates CO_2 availability from selected plants by radial distances (10, 20, 50, 100 miles).
- **Map-Based View**: Allows users to filter CO_2 availability by facility type and radial distance.
- **Economic Analysis**: Provides calculations for CO_2 yield based on varying prices and determines the average price for maximum yield by distance.
- **Visual Tools**: Includes charts that illustrate supply curves, yield, and price to aid in comparative analysis.

Storage Availability

- **Mapping Options**: Features maps of potential storage sites including sedimentary basins, saline aquifers, coal fields, salt deposits, oil and gas reservoirs, quaternary basalts, and hard rock formations.
- **Interactive Features**: Each geological formation on the map includes detailed information relevant to its storage capacity.

Biomass Availability

- **Regional Selection**: Users can select counties based on a defined radial distance from processing depots, categorized by feedstock type.
- **Map Visualization**: The map interface allows users to click on selected counties to access an attribute table displaying feedstock type and available dry tons.

Each module of the Energy Prospector integrates, providing users with a robust platform for conducting detailed analyses of energy resources associated with nuclear plant operations. This integration of diverse data sets and functionalities into a user-friendly interface strengthens the tools analysis capabilities.

3.1 Data Visualization and Mapping

This section will provide a series of screen captures from the application to display its data visualization and mapping capabilities.

3.1.1 Potential Hydrogen Demand

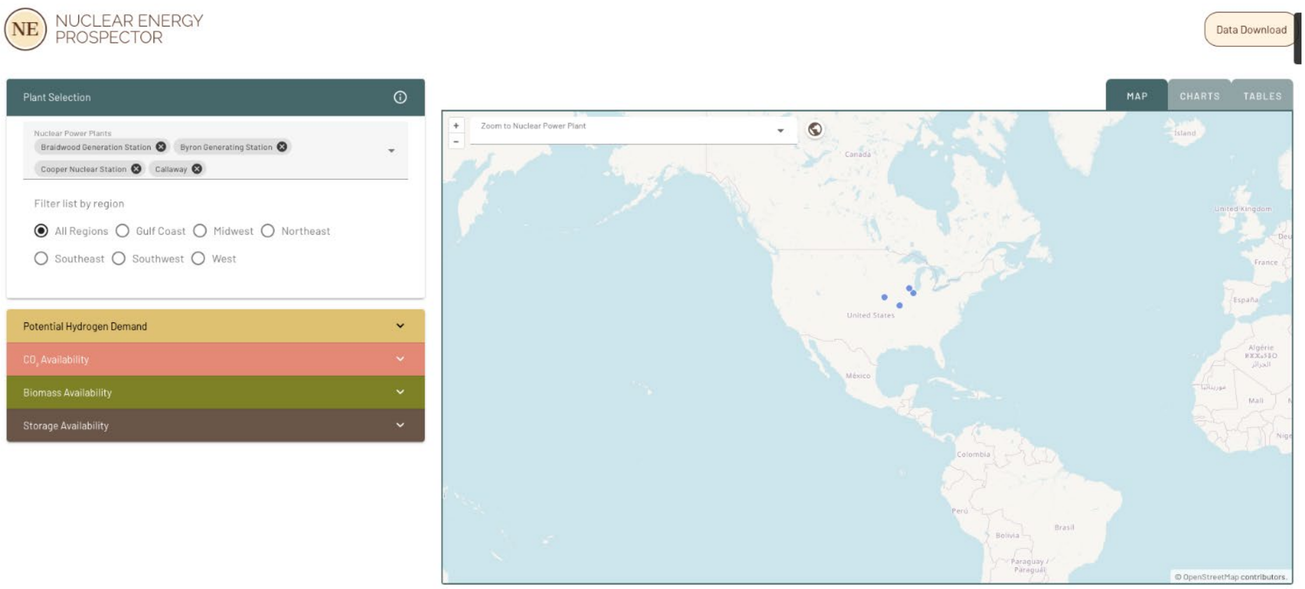

Figure 5. Nuclear Energy Prospector plant selection control panel and map display.

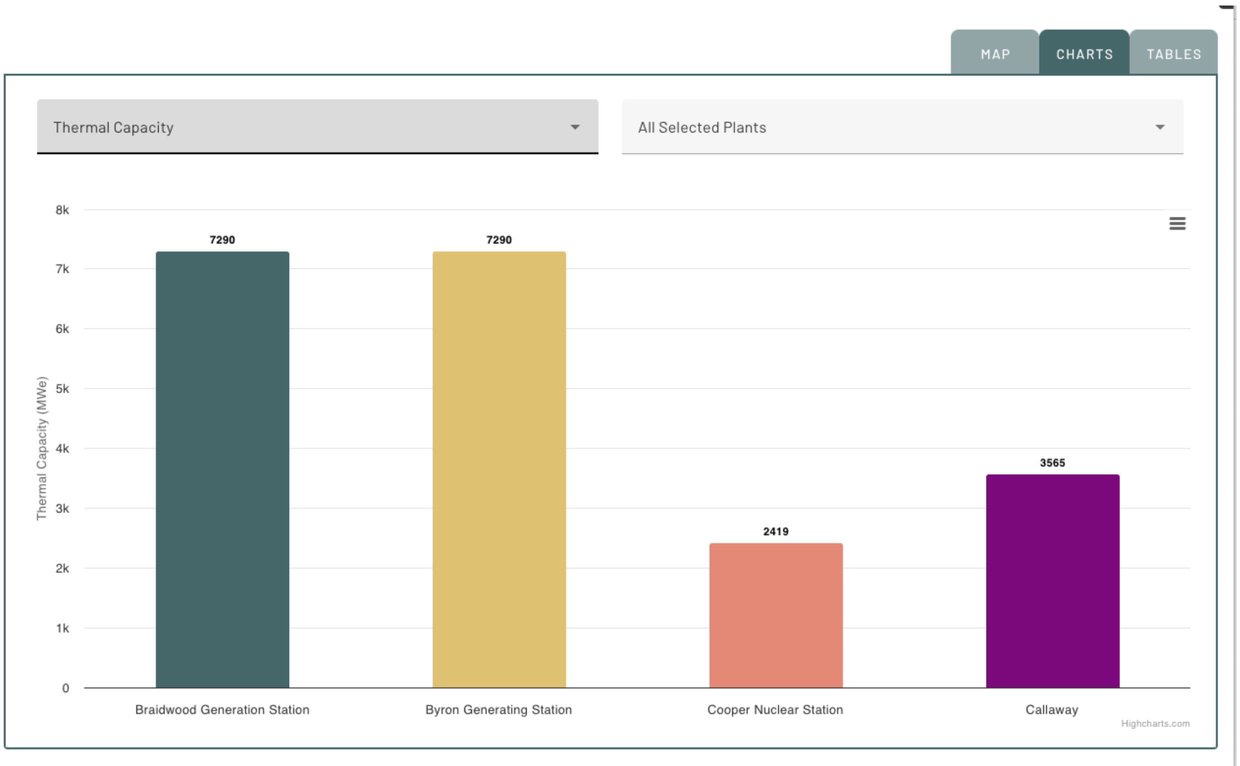

Figure 6. Nuclear Energy Prospector plant chart visualization.

MAP CHARTS TABLES

Reactors at Selected Plants

Facility	Reactor	Model	Process	Grid Connection
Braidwood Generation Station	Braidwood 1	W (4-loop)	PWR	1987-07-12
Braidwood Generation Station	Braidwood 2	W (4-loop) DRYAMB	PWR	1988-05-25
Byron Generating Station	Byron 1	W (4-loop) (DRYAMB)	PWR	1985-03-01
Byron Generating Station	Byron 2	W (4-Loop) (DRYAMB)	PWR	1987-02-06
Cooper Nuclear Station	Cooper	BWR-4 (Mark 1)	BWR	1974-05-10
Callaway	Callaway 1	W (4-loop) DRYAMB	PWR	1984-10-24

Reactor Capacities at Selected Plants

Facility	Reactor	Net Cap. (MWe)	Gross Cap. (MWe)	Thermal Cap. (MWt)	Design Net Cap. (MWe)
Braidwood Generation Station	Braidwood 1	1194	1270	3645	1120
Braidwood Generation Station	Braidwood 2	1160	1230	3645	1120
Byron Generating Station	Byron 1	1164	1242	3645	1120

Figure 7. Nuclear Energy Prospector plant table visualization.

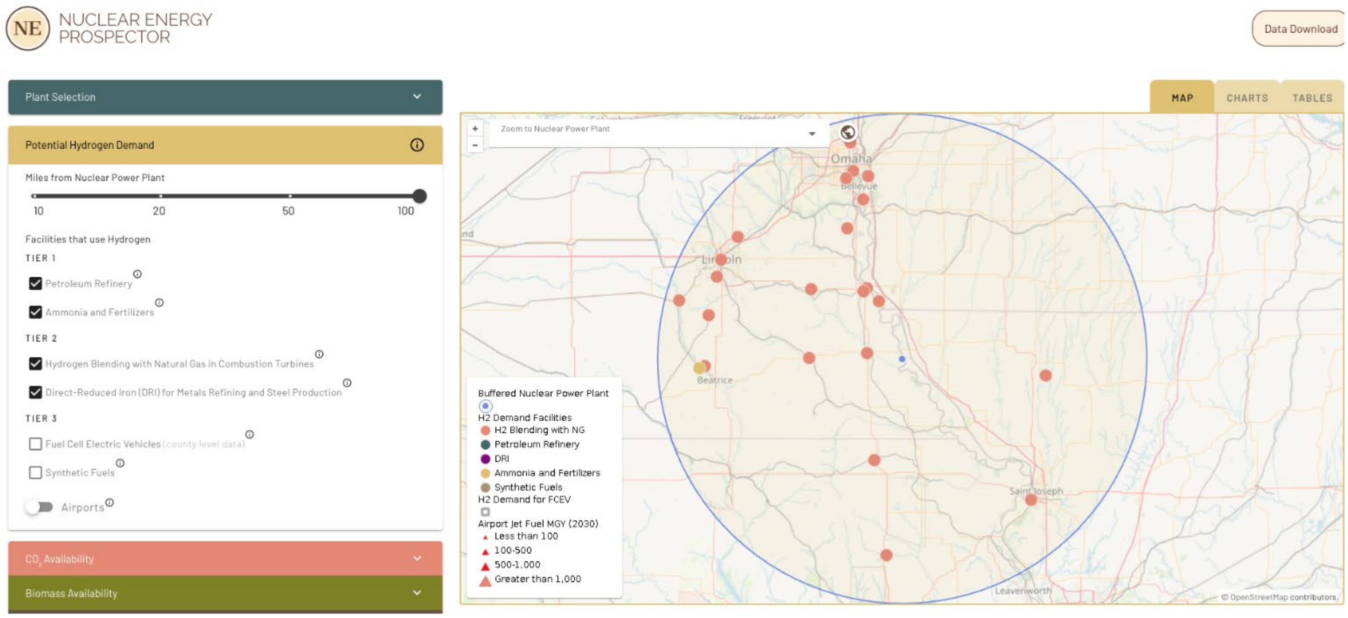

Figure 8. Nuclear Energy Prospector potential hydrogen demand control panel and map display.

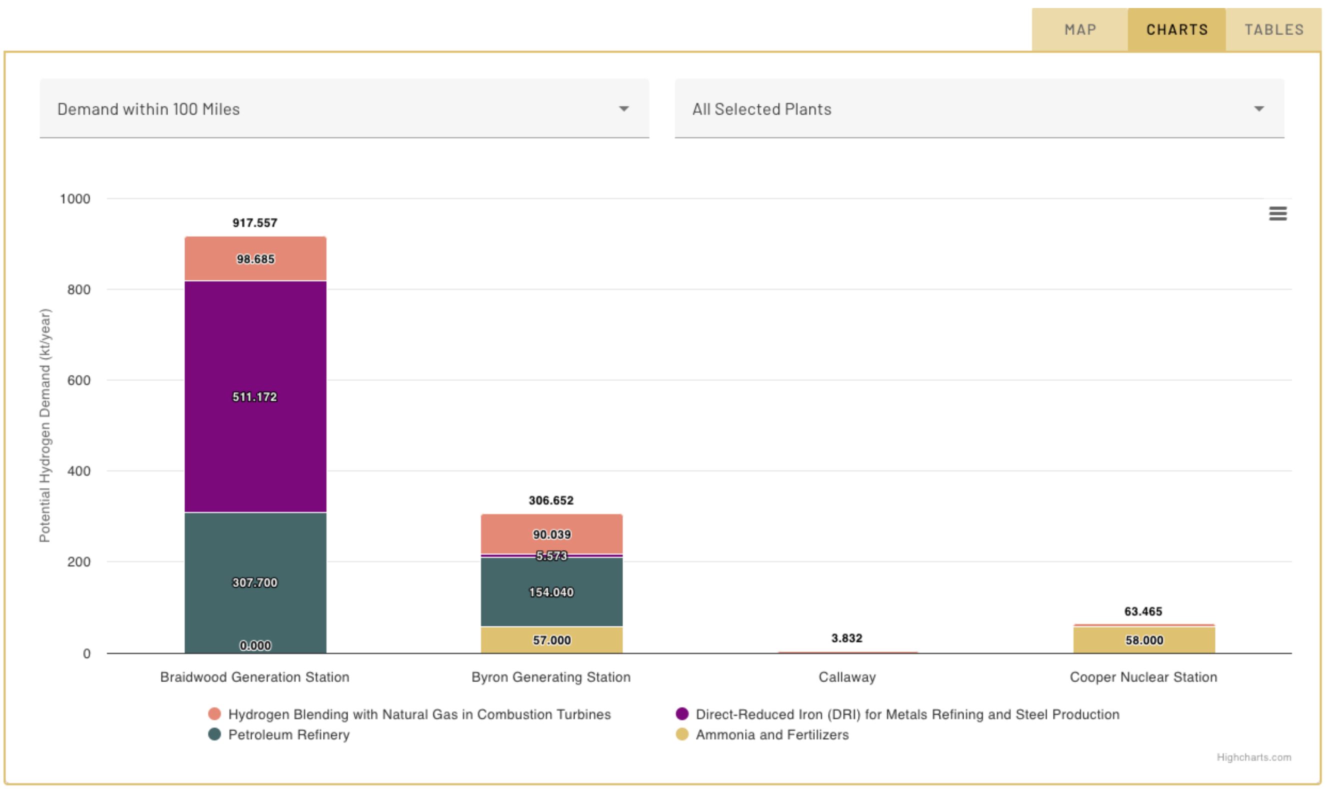

Figure 9. Nuclear Energy Prospector potential hydrogen demand chart visualization demand by distance plant comparison.

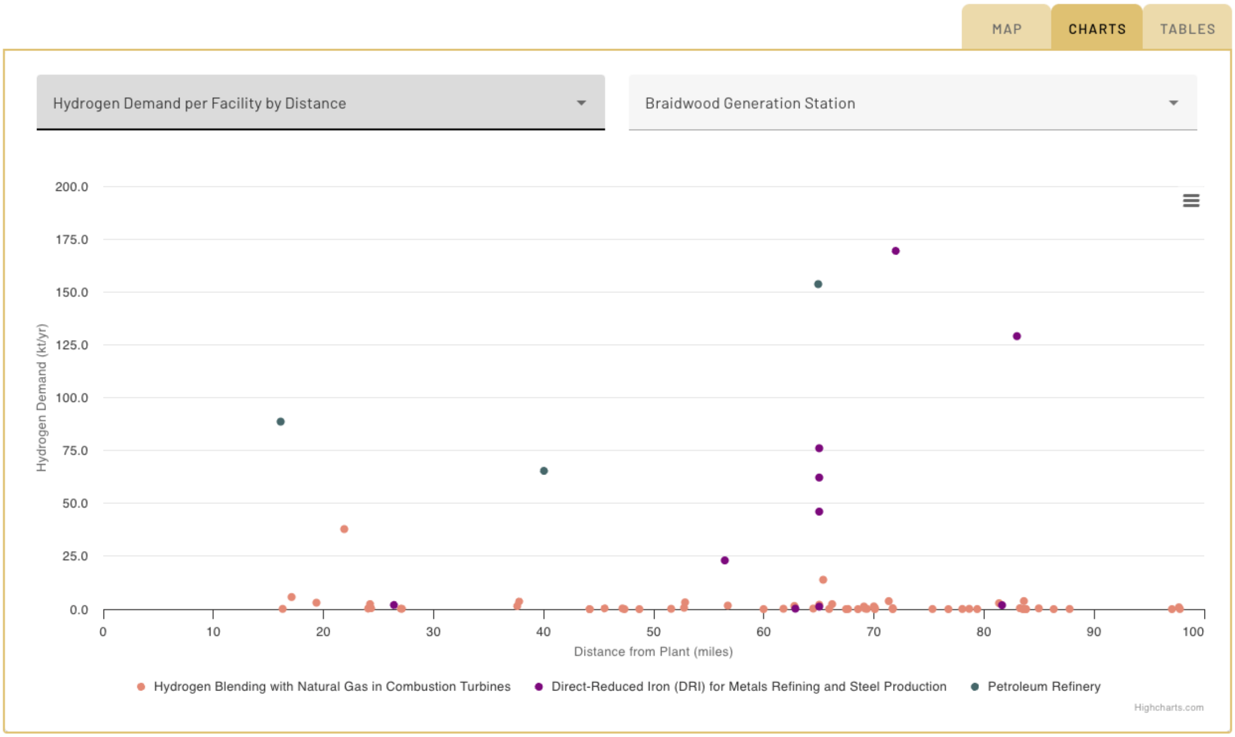

Figure 10. Nuclear Energy Prospector Potential hydrogen demand chart visualization demand by distance alternative view.

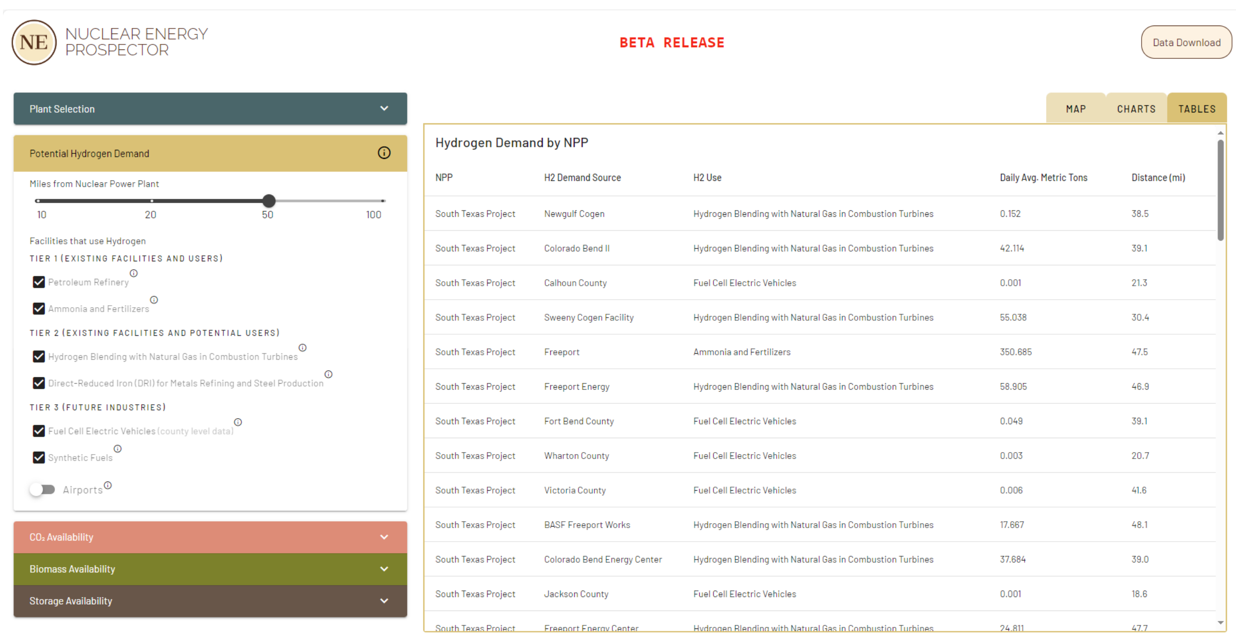

Figure 11. Nuclear Energy Prospector Hydrogen Demand and Distances.

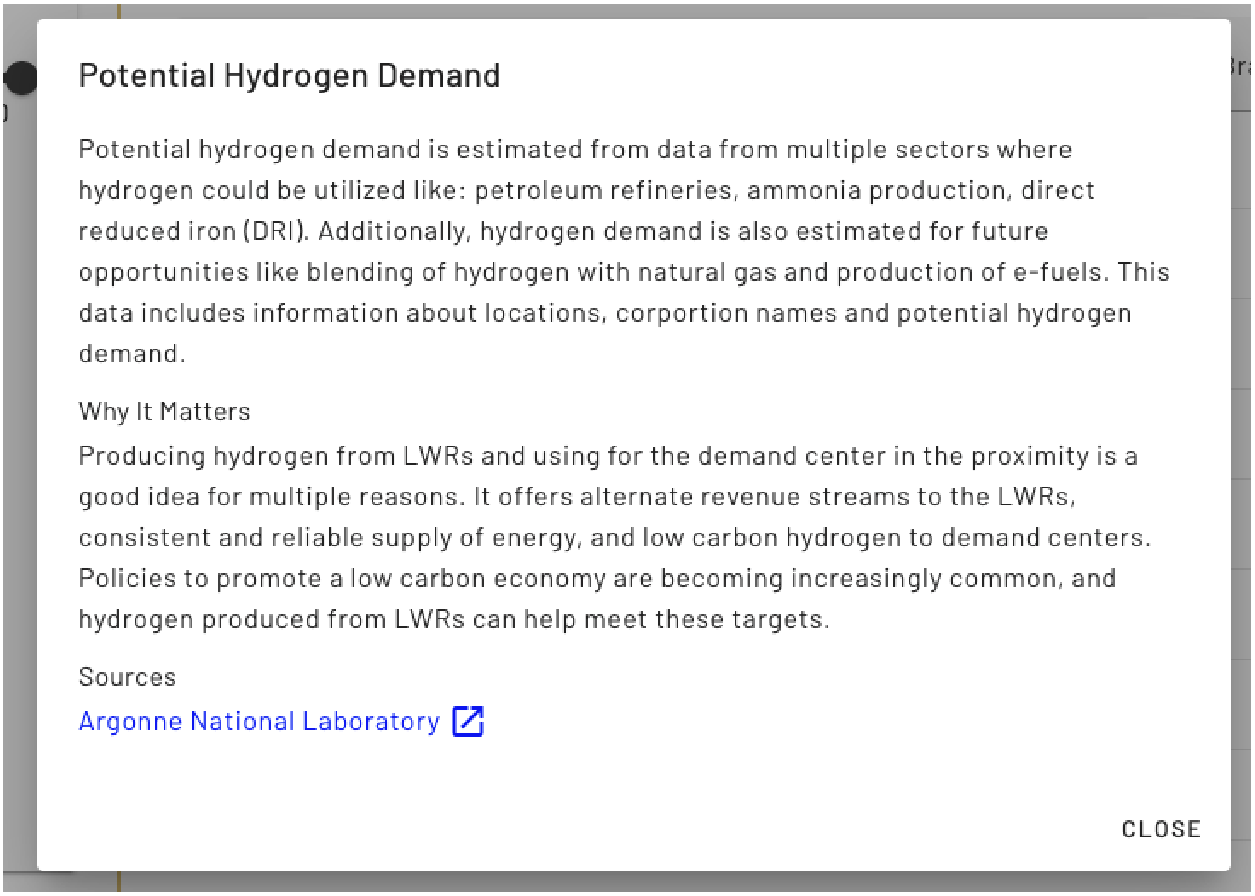

Figure 12. Module level information box example: Potential Hydrogen Demand.

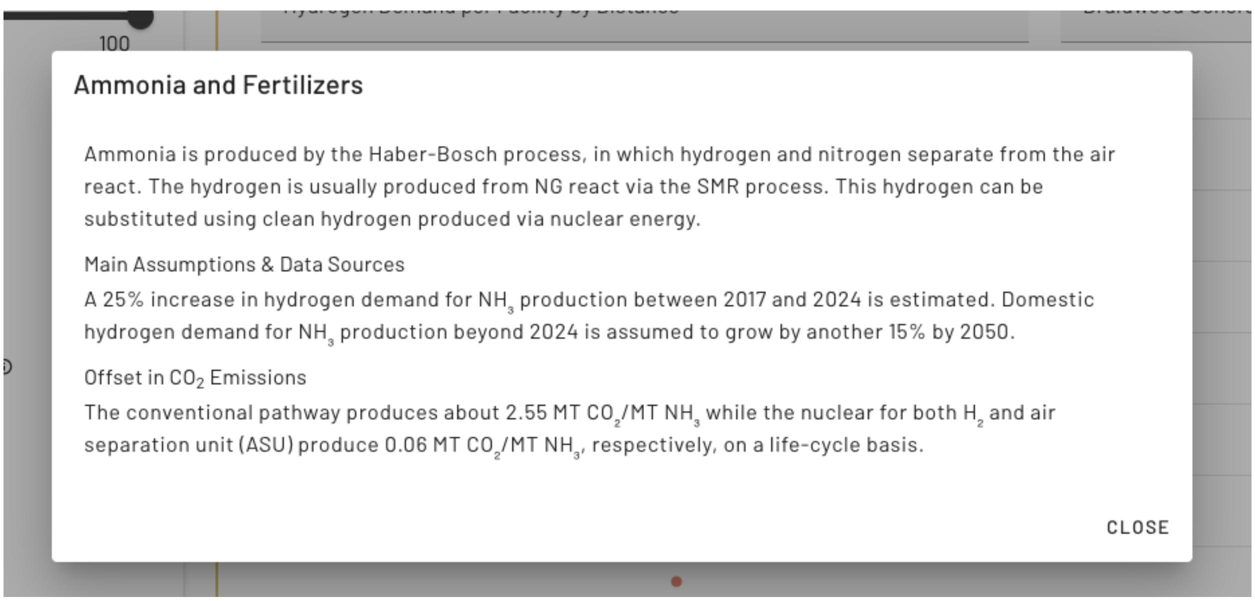

Figure 13. Sub-module level information box example: Potential Hydrogen Demand (Ammonia and Fertilizers).

3.1.2 CO_2 Availability

Figure 14. Nuclear Energy Prospector CO_2 emissions by sector.

CO_2 Availability

CO2 emissions from different industries sectors in the US. The cost of capturing CO_2 refers to the expenses associated with extracting carbon dioxide from industrial processes. This cost includes the capital investment in capture technology, operational costs, energy requirements, and maintenance. The specific cost can vary widely depending on the source of CO_2, the capture method used , and the scale of the operation. Typically, capturing CO_2 from concentrated sources like power plants is less expensive than capturing it from more dilute sources, such as ambient air. Reducing these costs is critical for making carbon capture, utilization, and storage (CCUS) economically viable and supporting efforts to mitigate climate change.

Why It Matters

Understanding the cost of capturing CO_2 is essential when integrating it with a Light Water Reactor (LWR) system, especially in the context of producing hydrogen or other value-added products. Knowing these costs helps in assessing the economic feasibility of coupling CO_2 capture with nuclear energy, as it directly impacts the overall cost of carbon management strategies, such as carbon capture, utilization, and storage (CCUS).

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Sydney Hughes et al (2022) COST OF CAPTURING CO2 FROM INDUSTRIAL SOURCES

D. Morgan, A. Guinan and A. Sheriff, FECM/NETL CO2 Transport Cost Model (2022): Description and User's Manual, National Energy Technology Laboratory, DOE/NETL-2022/3218, Pittsburgh, PA, March 14, 2022.

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Figure 15. Module level information box example: CO_2 availability.

3.1.3 Biomass Availability

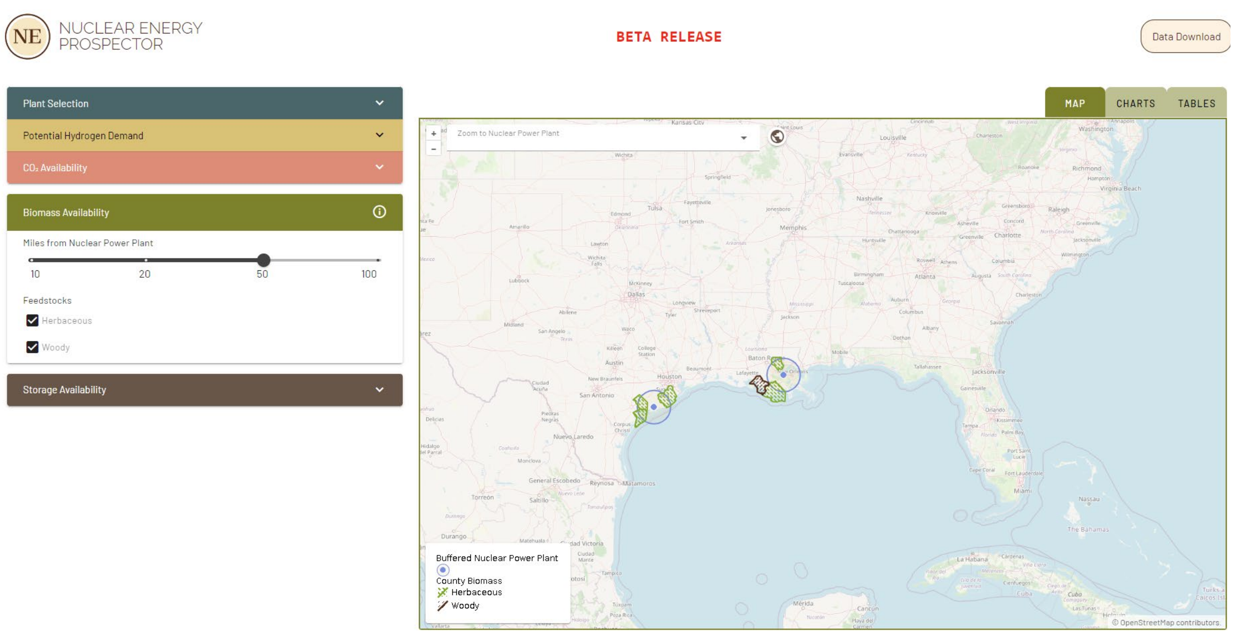

Figure 16. Nuclear Energy Prospector suggested Biomass Depot Location.

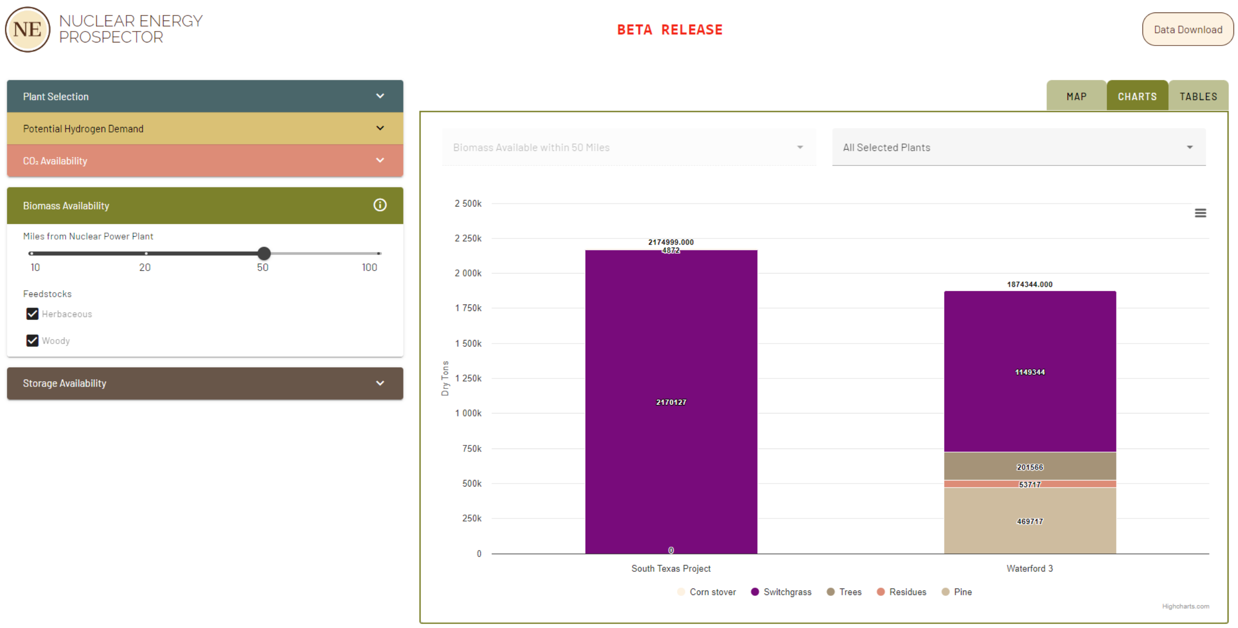

Figure 17. Nuclear Energy Prospector Biomass availability 50 miles.

Biomass Availability

Available supply of herbaceous and woody biomass at preprocessing facilities (Depots) within the required cost and quality constraints for delivering to the biorefinery gate for conversion to biofuel. Herbaceous biomass quality refers to ash content less than or equal to 5% (dry basis), moisture content greater than or equal to 20% and carbohydrate content greater than or equal to 59% (dry basis-including total anhydro-C6 and C5) with a target delivery cost of $79.07/dry ton (2016$) to the biorefinery. For woody resources, ash content is less than or equal to 1.75%, moisture content is less that of equal to 10% and carbon content is less than or equal to 50.51% with a target delivery cost of $85.51/dry ton (2016$) to the biorefinery.

Why It Matters

The integration of biomass logistics with Light Water Reactors (LWRs) is relevant as it enables the co-production of biofuels or biochemicals using nuclear heat and electricity, enhancing the overall efficiency and sustainability of the energy system. Effective biomass logistics, including the sourcing, transportation, and processing of biomass, is crucial for minimizing costs and ensuring a steady, reliable supply of feedstock to the LWR-integrated biorefinery. This integration supports the decarbonization of the industrial sector by providing a low-carbon, continuous energy source from LWRs, while the utilization of biomass can contribute to reducing greenhouse gas emissions and diversifying the energy mix. Additionally, using biomass for hydrogen (H2) production is a sustainable method, leveraging agricultural and forestry residues. This process can achieve carbon neutrality or even negative emissions when combined with carbon capture technologies. Hydrogen produced from biomass enhances energy security by diversifying the energy mix and reducing reliance on fossil fuels. Additionally, it helps manage waste by converting organic by-products into valuable energy resources. The integration of biomass into hydrogen production supports rural economic development and can seamlessly fit into existing hydrogen infrastructure.

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Figure 18. Module level information box example: Biomass Availability.

3.1.4 Hydrogen Storage Availability

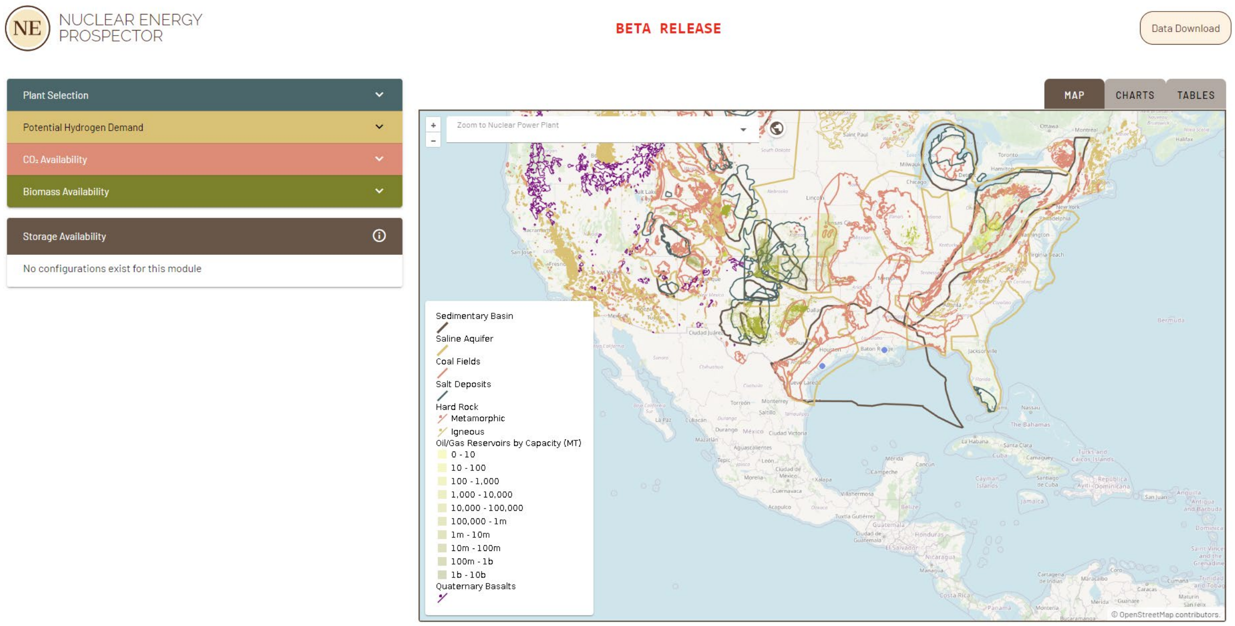
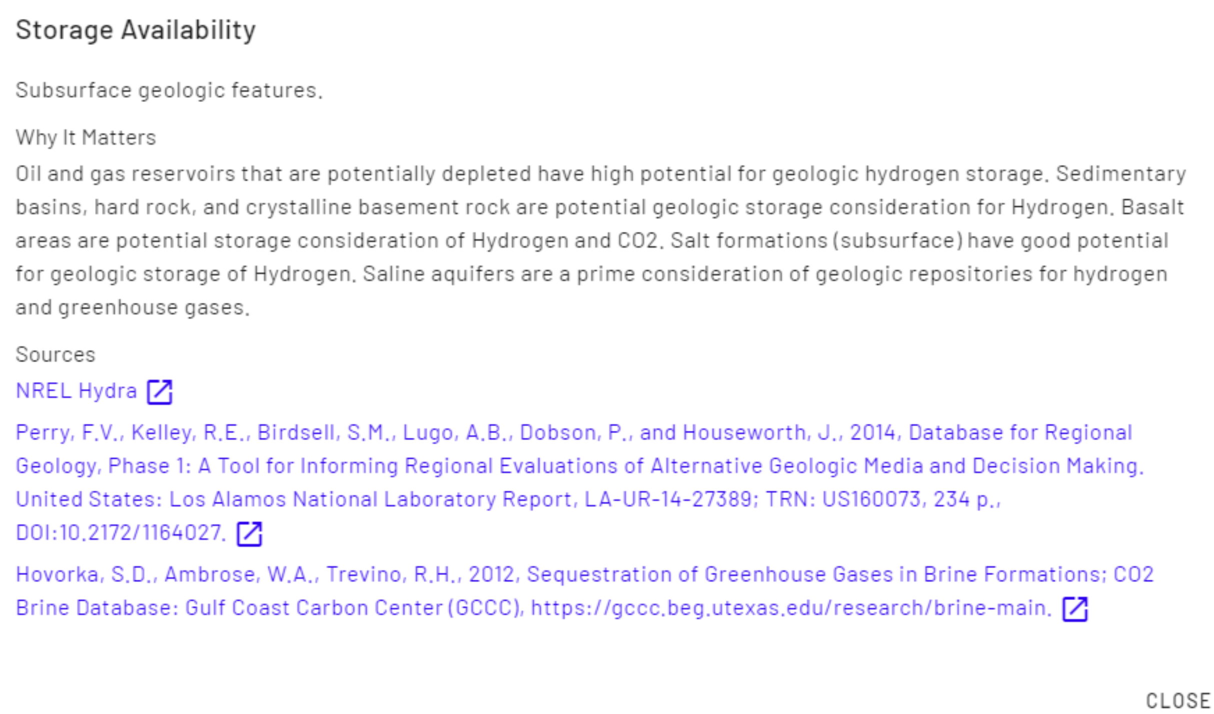


Figure 19. Nuclear Energy Prospector Potential Hydrogen Storage.


Storage Availability

Subsurface geologic features.

Why It Matters

Oil and gas reservoirs that are potentially depleted have high potential for geologic hydrogen storage. Sedimentary basins, hard rock, and crystalline basement rock are potential geologic storage consideration for Hydrogen. Basalt areas are potential storage consideration of Hydrogen and CO2. Salt formations (subsurface) have good potential for geologic storage of Hydrogen. Saline aquifers are a prime consideration of geologic repositories for hydrogen and greenhouse gases.

Sources

NREL Hydra

Perry, F.V., Kelley, R.E., Birdsell, S.M., Lugo, A.B., Dobson, P., and Houseworth, J., 2014, Database for Regional Geology, Phase 1: A Tool for Informing Regional Evaluations of Alternative Geologic Media and Decision Making. United States: Los Alamos National Laboratory Report, LA-UR-14-27389; TRN: US160073, 234 p., DOI:10.2172/1164027.

Hovorka, S.D., Ambrose, W.A., Trevino, R.H., 2012, Sequestration of Greenhouse Gases in Brine Formations; CO2 Brine Database: Gulf Coast Carbon Center (GCCC), https://gccc.beg.utexas.edu/research/brine-main.

CLOSE

Figure 20 Module level information box example: Potential Hydrogen Storage

4. Future Work and Recommendations

4.1 Future Research Directions

In FY25 it is proposed to continue this work into a deeper realm to develop the data, the database, and online tool beyond the initial output.

- Expand the data sets to have coverage across the CONUS to allow not just the analysis and suitability of co-locating with existing plants but also where a new reactor facility could be sited.
- Expand opportunities analysis beyond Hydrogen to cover heat and power demands to leverage additional economic cases for nuclear energy:
    - Industrial heat and power
    - Carbon capture and utilization
    - Oxygen demand from electrolysis powered by nuclear to supply future oxy-firing of industrial furnaces
    - Cement
    - Desalination
    - Data centers
- Investigate more deeply water usage requirements and availability for hydrogen production
- Expand the biomass dataset which can be used for biogenic CO2 sources for carbon utilization
- Deepen data connections and representations to enable broader conclusions about siting feasibility.

Evaluation of synfuels production sighting based on LWR location, hydrogen production, CO2 availability, transportation, and storage and proposed advanced reactor siting.
Tie data together into a model that would be able to provide broader conclusions about siting feasibility.

5. Conclusions

This report underscores the strategic importance of integrating Light Water Reactor (LWR) plants with emerging energy technologies, including hydrogen production, carbon sources, and industrial facilities. Leveraging the capabilities of the Nuclear Energy Prospector tool, the report provides valuable insights into the opportunities and challenges inherent in optimizing LWR operations within the broader context of sustainable energy and carbon management.

Key Takeaways:

- **Comprehensive Evaluation:** The Nuclear Energy Prospector tool is instrumental in evaluating the potential integration of existing LWR plants with hydrogen production, carbon sources, and industrial facilities, offering a strategic framework for enhancing nuclear energy's role in a sustainable energy future.
- **Data-Driven Insights:** The tool's ability to process and analyze extensive datasets related to heat and power demand, hydrogen production potential, CO_2 availability, and biomass resources at LWR sites equips stakeholders with critical data to support informed decision-making.
- **Modular Design for Versatility:** The five distinct modules—Plant Selection, Potential Hydrogen Demand, CO2 Availability, Storage Availability, and Biomass Availability—provide a robust platform for detailed analysis, ensuring that all aspects of LWR integration with emerging energy technologies are comprehensively assessed.

- **Adaptability and Future Expansion:** The Nuclear Energy Prospector is designed not only to meet current analytical needs but also to remain adaptable for future expansions in both data scope and geographical coverage, making it a valuable tool for ongoing research and development in sustainable nuclear energy configurations.
- **Enhanced Utility through Data Export:** The tool's data export capabilities allow users to seamlessly integrate extracted data into broader analytical or spatial frameworks, further enhancing its utility for a wide range of users, including researchers and industry stakeholders.

In conclusion, the Nuclear Energy Prospector tool offers a comprehensive, adaptable, and data-driven platform that bridges the gap between existing LWR capabilities and future energy integration possibilities, supporting the transition to a more sustainable and efficient energy landscape

6. References

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7. Appendix

7.1 Hydrogen Demand

Table 1 Main assumptions for estimating hydrogen demand

End-Use	Main Assumptions & Data Sources (Ref)	Background Information, If Any	Offset in CO_2 Emissions
Hydrogen Blending with NG in Combustion Turbines	Potential demand is estimated for hydrogen by assuming it can be used by NG CTs with a volume ratio of 30% hydrogen blended with 70% NG. Electricity generators were identified using the data sets from the EIA-860 and EIA-923 forms describing electricity generator facility locations and fuel use.	The clean hydrogen produced from the nuclear energy can be injected into NG pipelines for use as a low-carbon green component of a natural gas/hydrogen fuel mix for general heating or for exclusive use in combustion turbines (CTs) for power generation.	The life-cycle greenhouse gas (GHG) emissions are estimated at 493-g CO_2e/kWh when using only NG as the feed, and 442-g CO_2e/kWh for the mixture of 30% hydrogen and 70% NG by volume for different NG turbines technology shares.
Petroleum Refineries	The crude inputs are estimated to increase from 16 to 18 Mbbl/d (with a steeper increase of 9% from 2015 to 2021 and then a more gradual increase to 2050), gasoline output decreases from 8 to 6 Mbbl/d, diesel output increases slightly, and average jet-fuel output increases roughly 0.5 Mbbl/d from about 1.7 to 2.2 Mbbl/d. Based on these assumptions, in addition to the internal hydrogen production via catalytic reforming of naphtha, the total U.S. hydrogen demand for petroleum refining is estimated as 5.9 MMT/year in 2017 and 7.5 MMT/year in 2050.	Hydrocracking is used to produce diesel from heavy crude, and hydrotreating is used to remove sulfur from feed, intermediate, and product streams. Hydrogen is used in these two processes. This hydrogen can be produced internally in a refinery via catalytic reforming of naphtha. Hydrogen produced from the NPPs can be substitute/complement the internally produced hydrogen.	The well-to-gate CO_2e emissions for H_2 produced from NG steam methane reforming (SMR) and HTSE (nuclear) are estimated to be 9.28-kg CO_2e/kg H_2 and 0.15-kg CO_2e/kg H_2, respectively.

End-Use	Main Assumptions & Data Sources (Ref)	Background Information, If Any	Offset in CO_2 Emissions
Direct-Reduced Iron (DRI) for Metals Refining and Steel Production	DRI process, using 100% hydrogen as the reducing agent, requires up to 100 kg hydrogen per MT of steel (i.e., a mass ratio of approximately 10%). However, using hydrogen in a blend with NG up to 30/70 ratio by energy to produce DRI would not require modifications to the original technology which was developed to work solely with NG. The potential hydrogen demand for DRI was based on using 30% hydrogen and 70% NG on an energy basis.	The DRI is a process developed by Midrex Technologies, Inc., for producing high-purity iron from ore at temperatures below the melting point of iron by reducing the iron oxide ore and driving off oxygen in a reactor using a reducing agent. The reducing agent can be carbon coke, hydrogen, or syngas. DRI is converted to steel in an electric arc furnace (EAF).	The GHG emissions from each respectively is: 1.97-MT eq.CO_2 /MT steel from a blast furnace (BF), 1.47-ton eq.CO_2 /MT steel from an EAF using 100% NG, 1.28-MT eq.CO_2 /MT steel from EAF using 70% NG and 30% Nuclear H_2, and 0.99-MT eq.CO_2 /MT steel from EAF using only nuclear-H_2.
Ammonia and Fertilizers	A 25% increase in hydrogen demand for NH_3 production between 2017 and 2024 is estimated. Domestic hydrogen demand for NH_3 production beyond 2024 is assumed to grow by another 15% by 2050.	Ammonia is produced by the Haber-Bosch process, in which hydrogen and nitrogen separate from the air react. The hydrogen is usually produced from NG react via the SMR process. This hydrogen can be substituted using clean hydrogen produced via nuclear energy.	The conventional pathway produces about 2.55 MT CO_2/MT NH_3 while the nuclear for both H_2 and air separation unit (ASU) produce 0.06 MT CO_2/MT NH_3, respectively, on a life-cycle basis.
Synthetic Fuels	Synthetic fuels can be used for carbon-intensive energy sector end uses like transportation. Hence, the production and use of synthetic fuels can significantly support the efforts toward decarbonization. The hydrogen demand for synfuel production can be estimated based on the stoichiometric 1:3 mole	Synthesis gas (syngas) is a mixture of carbon monoxide and hydrogen. It is called syngas because these two molecules can be used to synthesize synthetic fuels (synfuels) and chemicals (synchemicals). Significant quantities of high-purity CO_2 are generated in industry processes such as ethanol production, SMR used for hydrogen production from	The GHG emissions per megajoule for various fuels like gasoline, jet-fuel, diesel fuel, and FT fuel (using nuclear H_2) are 93, 86, 91, and 9 g CO_2 eq./MJ, respectively.

End-Use	Main Assumptions & Data Sources (Ref)	Background Information, If Any	Offset in CO_2 Emissions
	ratio of CO_2 to H_2 that is required for the synthesis of Fischer-Tropsch diesel or dimethyl ether.	NG for refining, and ammonia production. These high-concentration CO_2 sources present opportunities to produce synfuels and synchemicals using a wide variety of pathways while minimizing the cost and energy penalty to capture CO_2 relative to other dilute CO_2 sources (e.g., from flue gases of coal and NG power plants).	
Fuel Cell Electric Vehicles (FCEV)	Hydrogen use was estimated for FCEVs at any given time using three key parameters for each vehicle class: (1) number of vehicles on the road, (2) annual vehicle miles travelled VMT, and (3) fuel economy or fuel consumption per mile. It was assumed the market penetration of FCEV's to be ~22% penetration 2050. Annual sales were calculated for FCEV's using the VISION model, computed annual vehicle stocks, VMT, and energy use. The Autonomie model provided the energy efficiency/fuel economy inputs needed for VISION to calculate energy use. The standard method for calculating fuel consumption for FCEV's established by the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) (EPA and NHTSA 2016) was utilized.	Fuel Cell Electric Vehicles, which are a type of zero-emission vehicle that uses hydrogen fuel cell technology to power an electric motor of a vehicle. In an FCEV, a fuel cell converts the chemical energy of hydrogen and oxygen into electricity, generating power for an electric motor that drives the vehicle's wheels. The battery pack in an FCEV is smaller than that of a typical battery-electric vehicle, and it is charged by the fuel cell rather than a standard plug from the electric grid.	The WTW emissions for a gasoline vehicle is about 0.25 kg CO_{2e}/ km, for a FCEV using clean hydrogen the emissions can be as low as 0.02 kg CO_{2e}/ km. (Ref.) Using clean hydrogen produced from nuclear powered electrolysis for FCEV's can avoid significant emissions.

Table 2 Hydrogen Demand for each NPP within 50 and 100 miles

Name	H2 Demand within 50 miles	H2 Demand within 100 miles
Arkansas Nuclear One	1.05	30.40
Beaver Valley	108.84	195.27
Braidwood Generation Station	212.08	1147.76
Browns Ferry	40.32	75.15
Brunswick Nuclear	25.77	25.79
Byron Generating Station	79.74	756.86
Callaway	22.39	33.88
Calvert Cliffs Nuclear Power Plant	35.80	139.97
Catawba	15.47	142.49
Clinton Power Station	342.62	644.57
Columbia Generating Station	2.31	66.53
Comanche Peak	61.82	213.26
Cooper Nuclear Station	40.18	223.49
Davis Besse	306.38	701.26
Diablo Canyon	10.49	97.58
Donald C Cook	63.39	790.01
Dresden Generating Station	217.80	1161.39
Edwin I Hatch	1.44	100.98
Fermi	513.72	568.90
Grand Gulf	37.29	187.03
Harris	1.32	179.14
H B Robinson	63.18	101.65
James A Fitzpatrick	67.92	77.64
Joseph M Farley	1.26	109.96
LaSalle Generating Station	268.34	1263.11
Limerick	300.74	590.81
McGuire	56.95	124.00
Millstone	41.09	257.73
Monticello Nuclear Facility	0.28	233.18
Nine Mile Point Nuclear Station	67.92	77.64
North Anna	88.99	353.66
Oconee	38.93	53.52
Palo Verde	110.60	168.99
Peach Bottom	96.53	447.00
Perry	100.68	147.55
Point Beach Nuclear Plant	20.70	86.44
Prairie Island	162.22	279.62
PSEG Hope Creek Generating Station	297.80	458.61
PSEG Salem Generating Station	297.52	455.88

Quad Cities Generating Station	161.01	814.31
R E Ginna Nuclear Power Plant	6.86	104.75
River Bend	620.97	2164.62
Seabrook	36.20	165.14
Sequoyah	36.08	78.57
South Texas Project	332.06	1302.23
St Lucie	108.94	309.10
Surry	128.56	227.77
TalenEnergy Susquehanna	47.63	224.53
Turkey Point	49.64	193.02
V C Summer	15.26	180.91
Vogtle	142.97	258.19
Waterford 3	2048.82	2402.82
Watts Bar Nuclear Plant	41.18	77.60
Wolf Creek Generating Station	22.50	79.15

7.2 CO_2 Logistics

CO_2 Availability and Supply Cost Data

Table 3 CO_2 transportation costs for Byron

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Ethanol	IL	55.3	0.5	0.5	26.1	0.47	26.1
Natural Gas	IL	68.1	0.3	0.3	39.1	0.74	30.8
Natural Gas	IL	51.7	0.1	0.1	40.9	0.82	31.8
Natural Gas	IL	42.3	0.1	0.1	52.4	0.88	33.2
Natural Gas	IL	56.2	0.0	0.0	55.3	0.91	34.0
Ethanol	IL	33.1	0.1	0.1	59.0	1.00	36.1
Natural Gas	IL	53.9	0.1	0.1	63.6	1.09	38.4
Iron and Steel	IL	29.8	0.1	0.1	64.0	1.16	40.1
Natural Gas	IL	19.0	0.0	0.0	75.8	1.20	41.1
Natural Gas	IL	43.0	0.0	0.0	96.3	1.23	42.5
Natural Gas	IL	24.0	0.0	0.0	97.5	1.27	44.3
Natural Gas	IL	43.7	0.0	0.0	107.4	1.30	45.5
Natural Gas	IL	54.8	0.0	0.0	120.9	1.34	47.8

Cement	IL	49.2	0.0	0.0	172.6	1.38	51.4
Natural Gas	IL	65.1	0.0	0.0	232.0	1.40	54.5
Natural Gas	IL	60.7	0.1	0.1	240.6	1.45	61.0
Ethanol	IL	67.4	0.4	0.4	320.9	1.84	115.6
Ethanol	IL	64.1	0.0	0.0	336.2	1.86	118.5
Natural Gas	IL	67.1	0.0	0.0	379.8	1.90	123.9
Cement	IL	52.7	0.8	0.7	433.9	2.58	205.9
Natural Gas	IL	58.0	0.0	0.0	435.4	2.61	207.95
Natural Gas	IL	53.4	0.1	0.1	561.0	2.69	218.35
Iron and Steel	IL	51.3	0.0	0.0	583.1	2.71	221.18
Natural Gas	IL	67.2	0.3	0.3	586.2	2.99	255.83

Table 4 CO_2 transportation costs for Calloway

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Cement	MO	87.9	1.8	1.6	92.8	1.65	92.8
Cement	MO	68.3	0.6	0.6	138.7	2.21	104.5
Ethanol	MO	34.7	0.1	0.1	92.9	2.27	104.2
Natural Gas	MO	34.6	0.1	0.1	97.5	2.33	104.0
Natural Gas	MO	85.1	0.1	0.1	113.5	2.42	104.4
Natural Gas	MO	28.7	0.0	0.0	148.6	2.45	104.9
Natural Gas	MO	81.3	0.1	0.1	138.3	2.52	105.8
Ethanol	MO	85.5	0.1	0.1	140.6	2.59	106.8
Natural Gas	MO	22.9	0.0	0.0	160.4	2.61	107.3
Natural Gas	MO	32.3	0.0	0.0	170.1	2.64	107.9
Natural Gas	MO	86.8	0.1	0.1	174.1	2.70	109.2
Natural Gas	MO	83.2	0.1	0.1	184.5	2.75	110.6
Ethanol	MO	75.5	0.0	0.0	198.3	2.79	112.0
Natural Gas	MO	45.8	0.0	0.0	211.1	2.82	112.9
Natural Gas	MO	32.8	0.0	0.0	220.7	2.84	113.6
Natural Gas	MO	79.8	0.0	0.0	281.5	2.87	115.4
Iron and Steel	MO	76.8	0.0	0.0	315.8	2.89	117.2
Ammonia	MO	61.2	0.0	0.0	948.1	2.90	119.0
Natural Gas	MO	85.5	0.0	0.0	3259.8	2.90	121.6

Table 5 CO_2 transportation costs for Clinton

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Natural Gas	IL	53.6	0.6	0.5	30.9	0.50	30.9
Ethanol	IL	60.2	0.1	0.1	34.2	0.62	31.5
Ethanol	IL	80.4	0.5	0.5	40.0	1.09	35.2
Natural Gas	IL	27.4	0.2	0.2	41.2	1.28	36.1
Ethanol	IL	30.9	0.2	0.2	48.0	1.45	37.5
Natural Gas	IL	23.4	0.0	0.0	105.2	1.49	39.2
Cement	IL	81.0	0.8	0.7	130.1	2.17	67.8
Natural Gas	IL	52.9	0.1	0.1	131.7	2.22	69.3
Ethanol	IL	59.3	0.1	0.1	133.5	2.28	70.9
Natural Gas	IL	66.2	0.1	0.1	134.9	2.34	72.6
Natural Gas	IL	36.1	0.0	0.0	202.4	2.36	73.8
Natural Gas	IL	80.9	0.0	0.0	222.3	2.40	76.3
Natural Gas	IL	29.4	0.0	0.0	251.0	2.42	77.4
Natural Gas	IL	80.5	0.0	0.0	267.1	2.45	79.8
Natural Gas	IL	59.9	0.0	0.0	270.6	2.47	81.7
Hydrogen	IL	54.2	0.1	0.1	274.2	2.54	86.8
Natural Gas	IL	71.1	0.0	0.0	282.2	2.57	88.9
Natural Gas	IL	71.6	0.0	0.0	319.4	2.59	91.0
Iron and Steel	IL	53.7	0.1	0.1	333.7	2.70	100.7
Ethanol	IL	79.4	0.0	0.0	343.1	2.72	102.8
Natural Gas	IL	80.4	0.0	0.0	349.7	2.75	104.98
Natural Gas	IL	48.8	0.0	0.0	372.2	2.76	106.36
Natural Gas	IL	36.4	0.0	0.0	444.5	2.77	107.47
Natural Gas	IL	74.0	0.0	0.0	501.9	2.78	109.56
Natural Gas	IL	56.4	0.0	0.0	626.4	2.79	111.25

Table 2. CO_2 transportation cost data of Davis Besse

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Natural Gas	OH	20.9	1.6	1.4	16.8	1.40	16.8
Natural Gas	OH	16.9	1.2	1.1	17.7	2.52	17.2
Natural Gas	OH	19.4	0.7	0.7	21.8	3.19	18.2
Natural Gas	OH	14.5	0.2	0.1	39.5	3.34	19.1
Natural Gas	OH	18.9	0.1	0.1	71.8	3.40	20.0
Natural Gas	OH	19.9	0.1	0.1	78.8	3.45	20.9
Natural Gas	OH	13.5	0.0	0.0	80.8	3.49	21.6
Natural Gas	OH	19.7	0.0	0.0	124.3	3.51	22.3

Table 6 CO_2 transportation cost for Cooper

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Ammonia	NE	63.3	0.6	0.6	31.0	0.6	31.0
Ethanol	IA	30.0	0.1	0.1	68.8	0.6	36.3
Natural Gas	NE	62.0	0.2	0.1	70.1	0.8	42.2
Ethanol	NE	18.7	0.1	0.1	70.6	0.8	44.4
Ethanol	MO	18.7	0.1	0.1	70.6	0.9	46.2
Ethanol	IA	56.5	0.1	0.1	71.0	1.0	49.4
Natural Gas	IA	79.6	0.2	0.2	74.1	1.2	52.6
Natural Gas	IA	56.2	0.1	0.1	81.9	1.3	54.9
Natural Gas	NE	103.2	0.2	0.2	88.2	1.5	58.4
Natural Gas	MO	103.2	0.2	0.2	88.2	1.6	61.2
Ethanol	NE	104.5	0.2	0.2	88.7	1.8	63.7
Ethanol	IA	60.9	0.1	0.1	89.7	1.9	65.1
Ethanol	IA	103.7	0.2	0.1	94.1	2.0	67.2
Ethanol	NE	60.1	0.1	0.1	117.1	2.1	68.8
Ethanol	MO	60.1	0.1	0.1	117.1	2.1	70.3
Ethanol	NE	63.7	0.1	0.1	153.2	2.2	72.2
Natural Gas	NE	46.4	0.0	0.0	156.3	2.2	73.6

Natural Gas	IA	49.2	0.0	0.0	161.6	2.3	75.1
Natural Gas	NE	30.3	0.0	0.0	165.5	2.3	76.1
Natural Gas	MO	30.3	0.0	0.0	165.5	2.3	77.1
Ammonia	IA	83.2	0.1	0.1	181.6	2.4	79.3
Natural Gas	NE	33.6	0.0	0.0	208.5	2.4	80.4
Natural Gas	MO	33.6	0.0	0.0	208.5	2.4	81.5
Ammonia	NE	102.7	0.1	0.1	220.9	2.5	84.6
Natural Gas	NE	105.8	0.0	0.0	253.0	2.5	87.6
Natural Gas	MO	105.8	0.0	0.0	253.0	2.6	90.4
Natural Gas	NE	58.3	0.0	0.0	265.6	2.6	92.0
Natural Gas	NE	75.9	0.0	0.0	322.1	2.6	94.2
Natural Gas	NE	103.1	0.0	0.0	361.8	2.6	97.2
Natural Gas	MO	103.1	0.0	0.0	361.8	2.7	100.0
Natural Gas	NE	59.1	0.0	0.0	373.1	2.7	101.7
Natural Gas	NE	80.8	0.0	0.0	423.6	2.7	104.0
Natural Gas	NE	102.6	0.0	0.0	436.8	2.7	106.9
Natural Gas	MO	102.6	0.0	0.0	436.8	2.7	109.7
Natural Gas	IA	68.4	0.0	0.0	627.5	2.8	111.7

Table 7 CO_2 transportation cost for Donald Cook

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Natural Gas	MI	165.4	3.6	3.3	19.4	3.25	19.4
Natural Gas	MI	56.5	0.2	0.2	49.2	3.47	21.3
Natural Gas	MI	159.4	0.5	0.4	56.6	3.91	25.2
Natural Gas	MI	5.7	0.0	0.0	66.0	3.94	25.6
Natural Gas	MI	58.2	0.1	0.1	85.8	4.04	27.0
Natural Gas	MI	54.8	0.1	0.1	94.6	4.13	28.4
Natural Gas	MI	91.4	0.1	0.1	101.9	4.24	30.4
Natural Gas	MI	158.4	0.2	0.2	118.4	4.39	33.4
Ethanol	MI	95.2	0.1	0.1	161.6	4.46	35.4

Natural Gas	MI	74.2	0.1	0.1	168.2	4.51	36.9
Natural Gas	MI	160.7	0.1	0.1	197.8	4.60	39.9
Natural Gas	MI	160.7	0.1	0.1	198.4	4.68	42.7
Natural Gas	MI	85.8	0.0	0.0	226.5	4.72	44.3
Natural Gas	MI	85.7	0.0	0.0	226.7	4.76	45.9
Natural Gas	MI	60.8	0.0	0.0	227.6	4.79	47.1
Natural Gas	MI	75.9	0.0	0.0	249.5	4.83	48.4
Natural Gas	MI	161.5	0.1	0.1	265.6	4.89	51.2
Natural Gas	MI	160.8	0.1	0.1	270.4	4.95	53.8
Natural Gas	MI	81.4	0.0	0.0	272.0	4.98	55.2
Natural Gas	MI	77.8	0.0	0.0	299.5	5.01	56.5
Natural Gas	MI	90.9	0.0	0.0	306.8	5.04	58.06
Natural Gas	MI	138.5	0.0	0.0	320.0	5.08	60.28
Natural Gas	MI	46.3	0.0	0.0	326.7	5.10	61.11
Natural Gas	MI	141.2	0.0	0.0	328.5	5.14	63.33
Natural Gas	MI	68.9	0.0	0.0	330.2	5.16	64.47
Natural Gas	MI	74.9	0.0	0.0	338.5	5.18	65.69
Natural Gas	MI	77.7	0.0	0.0	357.7	5.21	66.95
Natural Gas	MI	95.8	0.0	0.0	380.1	5.23	68.47
Ethanol	MI	147.0	0.0	0.0	389.8	5.27	70.73
Natural Gas	MI	162.4	0.0	0.0	393.3	5.31	73.16
Natural Gas	MI	128.3	0.0	0.0	406.6	5.34	75.10
Natural Gas	MI	146.6	0.0	0.0	406.9	5.38	77.26

Natural Gas	MI	127.5	0.0	0.0	458.0	5.40	79.16
Natural Gas	MI	76.7	0.0	0.0	464.8	5.42	80.35
Natural Gas	MI	134.0	0.0	0.0	535.9	5.44	82.35
Natural Gas	MI	145.4	0.0	0.0	572.2	5.47	84.51
Natural Gas	MI	132.9	0.0	0.0	576.3	5.49	86.48
Natural Gas	MI	113.4	0.0	0.0	775.7	5.50	88.21
Hydrogen	MI	160.7	0.0	0.0	854.9	5.53	91.62
Natural Gas	MI	162.4	0.0	0.0	874.6	5.55	94.03
Natural Gas	MI	143.0	0.0	0.0	921.3	5.56	96.17

Table 8 CO_2 transportation costs for Dresden

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Natural Gas	IL	4.853914	2.661182	2.395064	13.17259	2.40	13.2
Natural Gas	IL	3.562936	0.31537	0.283833	26.14355	2.68	14.5
Ethanol	IL	3.423071	0.428188	0.385369	26.17237	3.06	16.0
Natural Gas	IL	2.53253	0.295407	0.265866	26.42851	3.33	16.8
Natural Gas	IL	3.731609	0.043783	0.039405	59.5799	3.37	17.3
Ethanol	IL	3.36513	0.047605	0.042844	59.87082	3.41	17.9
Hydrogen	IL	3.362201	0.100731	0.090658	188.0622	3.50	22.3

Table 9 CO_2 transportation cost data for Enrico Fermin

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Natural Gas	MI	22.8	0.9	0.8	20.9	0.79	20.9
Natural Gas	MI	22.7	0.4	0.4	29.2	1.14	23.5
Natural Gas	MI	10.3	0.2	0.1	37.5	1.28	25.1
Natural Gas	MI	28.1	0.2	0.1	48.6	1.42	27.4
Natural Gas	MI	21.3	0.1	0.1	49.2	1.54	29.1
Natural Gas	MI	23.1	0.1	0.1	49.3	1.66	30.5
Natural Gas	MI	43.1	0.1	0.1	102.5	1.72	33.1
Natural Gas	MI	18.5	0.0	0.0	107.0	1.75	34.4
Hydrogen	MI	23.0	0.4	0.4	116.9	2.12	48.6
Natural Gas	MI	48.2	0.0	0.0	152.8	2.16	50.5
Natural Gas	MI	57.4	0.0	0.0	181.8	2.19	52.7
Ethanol	MI	28.6	0.0	0.0	190.8	2.21	54.0
Natural Gas	MI	57.4	0.0	0.0	195.0	2.25	56.2
Iron and Steel	MI	23.4	0.3	0.3	237.3	2.54	77.0
Iron and Steel	MI	7.0	0.1	0.1	336.8	2.65	87.3
Natural Gas	MI	61.9	0.0	0.0	363.6	2.66	89.2
Natural Gas	MI	59.1	0.0	0.0	444.3	2.68	91.0
Iron and Steel	MI	4.9	0.0	0.0	614.3	2.70	94.5

Table 10 CO_2 transportation cost data for LaSalle

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Natural Gas	IL	27.8	2.7	2.4	14.4	2.40	14.4
Ethanol	IL	20.9	0.4	0.4	30.4	2.78	16.6
Natural Gas	IL	22.1	0.3	0.3	32.6	3.05	18.0

Table 11. CO_2 transportation cost data of Monticello

Source	Plant Location	Distance (mi)	Initial CO2 (MT/year)	Amount Of CO2 transported (MT/year)	Cost of CO2 logistics ($/MT)	Cumulative amount of CO2 transported (MMT/year)	Cumulative average supply cost of CO2 ($/MT)
Hydrogen	MN	55.6	4.2	3.8	49.9	3.8	49.9
Natural Gas	MN	41.0	0.1	0.1	68.9	3.9	50.4
Natural Gas	MN	37.6	0.1	0.1	75.3	4.0	50.9
Natural Gas	MN	49.5	0.1	0.1	79.3	4.1	51.6
Ethanol	MN	48.6	0.1	0.1	81.1	4.2	52.3
Natural Gas	MN	41.3	0.1	0.1	89.3	4.2	52.9
Natural Gas	MN	49.1	0.1	0.1	91.5	4.3	53.6
Hydrogen	MN	53.0	0.8	0.7	94.3	5.0	59.4
Natural Gas	MN	45.4	0.0	0.0	150.7	5.1	60.1
Natural Gas	MN	40.1	0.0	0.0	155.9	5.1	60.8
Natural Gas	MN	38.0	0.0	0.0	168.7	5.1	61.4
Natural Gas	MN	45.5	0.0	0.0	242.4	5.1	62.1
Natural Gas	MN	51.6	0.0	0.0	269.4	5.2	63.0
Natural Gas	MN	54.7	0.0	0.0	354.8	5.2	63.9
Natural Gas	MN	43.3	0.0	0.0	928.4	5.2	64.7
Iron and Steel	MN	50.9	0.0	0.0	1315.2	5.2	65.2