SUMMARY OF DELIVERABLES

HYDROGEN

ABSTRACT

This program briefing summarizes all the Low-Carbon Resources Initiative (LCRI) deliverables completed in the initiative. Web links are included for each deliverable, which direct members to the download page for each publication on the LCRI website. The publications shown below each include the title, publication date, and an abstract. Publications marked with an * are available to the public free of charge. Webcasts organized and hosted by LCRI or TSCs are not included in this summary but can be accessed by members on the LCRI website.

For more information on LCRI, contact Neil Kern, nkern@epri.com. For more information on LCRI research, visit the LCRI website at www.lowcarbonlcri.com. To receive the LCRI's monthly newsletter with research updates, please subscribe here. To contact us please email LCRI@epri.com.

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LCRI PROGRAM

Feasibility Study for Green Hydrogen Generation and Cofiring Hydrogen in an Aeroderivative Gas Turbine: Solar, Battery Energy Storage System, Desalination, Electrolyzer, Hydrogen Storage, Natural Gas Blending, and LM2500 Gas Turbine Operation

EPRI Report 3002025998
Published June 2023

Abstract

A feasibility study was conducted to identify the initial design and cost considerations of a facility that could produce and use hydrogen for power generation. The design is based on hydrogen production using solar power and a battery energy storage system, desalination for an electrolyzer system, hydrogen storage, and hydrogen blending with natural gas for power generation in an aero-derivative gas turbine. A system-level model of the proposed system was developed and exercised to determine the initial inputs of the Class IV cost estimate. The system models are a capability that EPRI is using to gain insight into system designs, operation, and cost for these new hydrogen and hydrogen microgrid systems, which have few successful designs to rely on.

The report provides the details around the developed conceptual design for a mixed portfolio power generation facility that will produce green hydrogen using on-site solar power, compress and store the hydrogen, and blend it in with natural gas to supply fuel for a new gas turbine (maximum 20% hydrogen blend by volume) to produce up to 20 MW at a new grid connection. The report includes plant design information, including system and component designs, piping and instrumentation diagrams (P&IDs), single line diagrams, plant layout drawings, and control architectures. Total plant design and build Class IV cost estimates are included, as well as projected schedules.

GE Sharm El-Sheikh Hydrogen Test Report – GE LM6000

EPRI Report 3002027443
Published May 2023

Abstract

The hydrogen blending demonstration completed at the Sharm El-Sheikh power plant was conducted over a one-month time frame. Three days of testing (October 9, October 10, and November 5) were completed measuring the emissions of natural gas and blended fuels containing up to 5% hydrogen (H_2) by volume. The relatively small blend of hydrogen (5% by volume is equivalent to 0.65% by mass and 2% by fuel heating/energy content) makes it a challenge to use the data to make any conclusions about gas turbine operation with hydrogen blends.

The testing conducted was successful in demonstrating the capability of burning the prescribed hydrogen blend in the LM6000 turbine.

LCRI Hydrogen Powerplay (lcri-h2powerplay) v1.0.0

EPRI Software 3002026138
Published May 2023

Abstract

What is the potential role of clean hydrogen in a decarbonized power sector? With higher penetration of variable renewable energy (VRE) from solar and wind farms, dispatchable power sources will be needed for grid balancing. Clean hydrogen produced from electrolysis (inputs = VRE + water) could displace natural gas in some types of existing combustion turbines for dispatchable power at high or low-capacity factors. As a form of long-duration energy storage (LDES), hydrogen stored underground could represent a cost competitive approach for seasonal renewables load shifting and grid resilience events. The viability of electrolytic hydrogen in the power sector will depend on the regional economic and technical feasibility of the concept, along with continuing policy developments, relative to other low-carbon options such as natural gas with carbon capture and storage.

The purpose of this website is to provide an informational framework allowing exploration of the economic viability and system component considerations for VRE-based electrolytic hydrogen production, storage and use as a fuel for stationary gas turbine power plants.

To access the LCRI Hydrogen Power Play website, please visit https://apps.epri.com/lcri-h2powerplay

Platform Requirements

Modern web browsers for desktop or mobile operating systems, including recent versions of:

- Chrome
- Safari
- Firefox
- Edge

LCRI Resource Library v1.0.0

EPRI Software 3002026204
Published March 2023

Abstract

The LCRI Resource Library is a website that provides a searchable collection of technical resources for the Low-Carbon Resources Initiative. LCRI sponsors can use the Resource Library to discover and search for technical results, software, presentations and recordings from past events, recent project status updates, technical subcommittee (TSC) updates, and monthly LCRI newsletters. This website complements the existing LCRI main website as both sites provide compilations of the same resources.

To access the Resource Library, please sign in to www.epri.com and navigate to https://apps.epri.com/lcri-library/

Platform Requirements

Chrome
Safari
Firefox
Edge

Low-Carbon Resources Initiative (LCRI) Research Vision: An Outline for Research, Development, and Demonstration Activities to Enable Economy-Wide Decarbonization by Midcentury – Version 2.0.0

*(*Korean Translation*) (*Spanish Translation*)*
EPRI Report 3002020677
Executive Summary 3002022055
Published August 2022

Abstract

The Low-Carbon Resources Initiative (LCRI) Research Vision provides an outline for research, development, and demonstration activities to enable economy-wide decarbonization by midcentury.

The Electric Power Research Institute (EPRI) and GTI Energy are together addressing the need to accelerate development and demonstration of low-carbon energy carriers and fuels and the cross-cutting technologies needed to support their production, transport, storage, and utilization. The Research Vision presents the motivation for the LCRI, research questions that address the initiative's focus areas, and preliminary research plans aimed at advancing critical technologies in support of the LCRI's objectives.

The LCRI is organized by Technical Subcommittees that focus on the value chain of alternative energy carriers/fuels applied across the economy. This document outlines the potential roles of alternative energy carriers in supporting a low-carbon future and provides details on the preliminary research plans to be executed through the Technical Subcommittees.

The details (technologies, activities, and prioritization, among others) provided in this document are subject to change over the course of the initiative as new findings, perspectives, and knowledge are incorporated into the overall research vision.

This report represents version 2.0.0 of the LCRI Research Vision, after conducting an annual review in Spring 2022. A summary of changes from previous versions is provided here: https://lcri-vision.epri.com/versions.html

Research Vision Website

A web-based interactive version of the research vision is available. To read the executive summary and the main report online, please visit this public website: https://lcri-vision.epri.com

ENVIRONMENTAL ASPECTS & SAFETY/INTEGRATED ANALYSIS

Water Considerations and Needs for Electrolysis

EPRI Report 3002027351
Published June 2023

Abstract

This interactive infographic outlines the role of water in the electrolysis process for the production of hydrogen. Water electrolysis, the production of hydrogen from water and electricity, could play an important role in decarbonizing the economy. High-purity water is required for the electrolysis reaction, and cooling water is likely required for the electrolysis and hydrogen compression operations. Wastewater is produced from the high-purity water treatment system, hydrogen purification process, and cooling water blowdown. Understanding the water requirements associated with electrolysis is important for the planning, siting, and balance-of-plant design for this low-carbon generation technology.

Environmental Impacts of Alternative Energy Carriers in Power Generation: Water Use

EPRI Report 3002026600
Published May 2023

Abstract

The energy system is experiencing a transition that may have a variety of environmental impacts. One element of the transition is a shift to fuel sources called alternative energy carriers (AECs). Water requirements may vary for different types of AECs used in power generation, especially relative to traditional fossil generation. Water use may also vary based on factors such as land use, land cover, other water users, and water rights. Water stress could result in regions with insufficient water resources and/or competition for such resources. This product examines the potential water requirements for three selected AECs: hydrogen (H_2), ammonia (NH_3), and biofuels.

Environmental Impacts of Alternative Energy Carriers in Power Generation: Land, Groundwater, and Surface Water

EPRI Report 3002026601
Executive Summary 3002027160
Published May 2023

Abstract

Achieving net-zero emissions across the economy by 2050 will require accelerating a safe, affordable, reliable, and environmentally-responsible energy transition, as well as advancing a variety of clean energy technologies and options. The Low-Carbon Resources Initiative (LCRI) is evaluating pathways for alternative energy carrier (AEC) deployment in support of decarbonization across the energy economy by mid-century. Low-carbon fuels that can be produced, transported, and handled safely at a reasonable cost constitute attractive alternatives.

This report provides an in-depth, focused assessment of the potential impacts of four specific AECs—hydrogen, ammonia, petroleum drop-in biofuels, and renewable natural gas (RNG)—on land, groundwater, and surface water resources in the event of an accidental leak or spill to the environment.

Environmental Impacts of Alternative Energy Carriers In Power Generation: Air Emissions

EPRI Report 30020226500
Executive Summary 3002026602
Published April 2023

Abstract

Achieving net-zero emissions across the economy by 2050, will require accelerating a safe, affordable, reliable, and environmentally-responsible energy transition, as well as advancing a variety of clean energy technologies and options. Low-carbon fuels that can be produced, transported, and handled safely at a reasonable cost constitute attractive alternatives. Some existing low-carbon fuels, such as those derived from biomass, are already well characterized and commonly used in the energy sector, but others are more novel to power generation applications.

As regulations are established to reduce carbon and other emissions across the economy, stakeholders need access to current, consolidated, and actionable information to guide their decisions on technologies and approaches when implementing future projects. This report serves as an important step by presenting the state of research in this area and revealing current knowledge gaps that future research needs to address.

What is Hydrogen?

EPRI Report 3002026599
Published April 2023

Abstract

Atomic hydrogen (H) contains one proton and one neutron and is the most abundant element in the universe. However, by itself, it exists at a relatively low concentration in the atmosphere. In nature, it combines with other elements to form compounds such as water, ammonia, and methane. Molecular hydrogen (H_2) consists of two hydrogen atoms and is a gas at ambient conditions that is used as an energy carrier/fuel or a feedstock in chemical processes. This fact sheet provides an overview of hydrogen, including its potential applications in the energy industry, safety concerns, and areas in which more research is needed.

LCRI Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis

EPRI Web Version 3002024882
Published September 2022
EPRI PDF Report 3002024993

Abstract

This is the main report download for LCRI Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis. As part of the Low-Carbon Resources Initiative (LCRI), EPRI and GTI Energy led an integrated energy system scenario modeling exercise to evaluate alternative technology strategies for achieving economy-wide net-zero emissions of carbon dioxide (CO_2) in the U.S. by 2050. The analysis builds on extensive, collaborative research, including an inter-model comparison assessment and related EPRI studies. The study found that a broad portfolio of clean-energy technologies is integral to an affordable and reliable clean energy transition. This report highlights several key insights for the potential role and value of low-carbon technologies, informing both R&D strategy and decarbonization investments over the next decade.

Low-Carbon Energy Supply Technology Cost and Performance Study

EPRI Report 3002023656
Published August 2022

Abstract

This report establishes a baseline of cost and performance data sets that will be used to inform system modeling and other related techno-economic analysis as part of the Low-Carbon Resources Initiative (LCRI).

The focus of the activities is to develop and update the design performance, capital cost, and economics of various state-of-the-art hydrogen production technologies, including: electrolysis, natural gas reforming, and gasification of various feedstocks (coal, biomass, and waste); moreover, ammonia synthesis technology (with capture of carbon dioxide) and power generation technologies were also assessed, the latter including: solid oxide fuel cells, advanced combustion turbines, and reciprocating engines using hydrogen, ammonia, or a combination of both as fuel.

The study provides data to enable the development of scalable and customizable cost and performance estimates based on technology type, locational attributes, and project size.

Assessment of Environmental, Health, and Safety Issues Related to the Introduction of Alternative Energy Carriers

EPRI Report 3002019994
Executive Summary 3002024992
Published June 2022

Abstract

Alternative energy carriers (AECs) are fuels that are potential substitutes for fossil fuels and are produced via electrochemical, thermochemical, or biochemical pathways using low- or zero-carbon inputs to reduce greenhouse gas (GHG) emissions. An important aspect of the adoption of AECs is understanding and addressing not only GHG but other environmental, health, and safety (EHS) aspects of these fuels. This is important to ensure that adverse incidents or issues in the early stages of adoption do not derail market expansion for these fuels and that environmental benefits equitably inure to all communities. This study, performed by the University of California, Irvine, assesses EHS aspects of eight fuels that are being deployed or are under development as AECs, as follows:

- Hydrogen
- Methane
- Ammonia
- Petroleum drop-in fuels (diesel, gasoline, jet fuel)
- Ethanol
- Methanol
- Butanol
- Dimethyl ether (DME)

The findings presented in this report are based on review of more than 150 technical reports and research articles addressing EHS issues relevant to the AECs. A full, bottom-up assessment of EHS across the value chain for each AEC and potential use case is beyond the scope of the analysis. However, a comprehensive framework is useful for organizing information and identifying potential analogies across fuels and applications. Specific findings, along with recommendations for priority actions and future work, are provided in this report.

US-REGEN Model Documentation Website v1.0

EPRI Software 3002022891
Published November 2021

Abstract

The US-REGEN Documentation website provides current and historical interactive documentation for EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model—an energy-economy model of the United States. The documentation describes the model, the methodology and theory that underlie it, and the construction of associated datasets—inputs and assumptions—that inform the model. The model is updated and maintained by EPRI, and features are added regularly to address new research questions.

To access US-REGEN Model Documentation Website v1.0, click here. https://us-regen-docs.epri.com

Platform Requirements

Modern web browsers for desktop or mobile operating systems, including recent versions of: Chrome, Safari, Firefox, and Edge.

HYDROGEN PRODUCTION

Detailed Analysis of Balance of Plant Components Required for Electrolysis

EPRI Report 3002027878
Executive Summary 3002027879
Published July 2023

Abstract

This study provides an overview of balance of plant (BOP) components required for electrolysis systems for hydrogen production. The BOP components of an electrolysis system include all the supporting systems and equipment necessary to ensure efficient and safe operation of the electrolysis process. The BOP components may vary depending on the specific type of electrolysis system, but generally include the following: power electronics, water treatment process, hydrogen processing units, compression units, and other miscellaneous components. In addition to component requirements and their costs, manufacturing and scale up considerations are discussed. Two different sizes have been considered in this analysis, 20 MW and 200 MW. Costs of specific balance of plant components required for alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide (SOEC) electrolysis are also listed and compared in this report. A sensitivity analysis is also included to demonstrate how the costs on balance of plant sections affect the levelized cost of hydrogen. The goal of this study is to understand what components of electrolysis are required beyond the electrolysis stack, what components are included by electrolysis vendors and what additional components must be sourced by the purchaser or engineering, procurement, and construction (EPC) partner. An additional goal was to estimate how the cost of these components contributes to the cost of hydrogen and how we can reasonably expect cost reductions through mass production and scale up. This report will serve to inform the Low-Carbon Resources Initiative (LCRI) members on what may be included or excluded in an electrolysis system so that informed strategy and procurement decisions can be made for future large scale energy system deployments.

Development and Techno-Economic Assessment of Steam Methane Reforming and Autothermal Reforming with High-CO_2 Capture Rates

EPRI Report 3002026299
Published July 2023

Abstract

Hydrogen (H_2) production is a critical component in achieving net-zero emissions and transitioning to a low-carbon future. This report focuses on steam methane reforming (SMR) and autothermal reforming (ATR) as leading technologies for H_2 production. To mitigate carbon dioxide (CO_2) emissions, carbon capture and storage (CCS) methods are integrated into these processes.

To fully explore the potential of CCS-enabled SMR and ATR facilities in a low-carbon future, the project team conducted the following steps:

- Literature Review: Conducted a comprehensive review of the existing literature to identify key process design parameters and operating conditions.
- Process Design: Generated a literature-backed process design, accompanied by performance benchmarks and operational limits.
- Model Development of SMR and ATR: Developed preliminary SMR and ATR models, absent CCS, utilizing the data derived from the process design literature.
- Model Development of SMR and ATR with CCS: Combined SMR and ATR with CO_2 capture models.
- Cost Model Development: Conducted techno-economic analysis for the SMR/ ATR CCS base scenarios.

The proposed models and optimization approach offer valuable guidance for identifying optimal operating conditions in the development of cost-effective and environmentally friendly CCS systems. This research contributes to the advancement of low-carbon H_2 production and addresses the challenges posed in effectively mitigating CO_2 emissions from large scale hydrocarbon processes.

Aspen Plus was employed to construct SMR and ATR models based on the 2022 National Energy Technology Laboratory (NETL) report [1]. Methyldiethanolamine (MDEA) and monoethanolamine (MEA) were used as solvents for the carbon capture system. In the Aspen Plus model, a rigorous column model was utilized for the absorber and stripper. Extensive optimization processes were applied to determine the size of the CCS equipment, which included parameters such as lean loading, column diameter and height, and reboiler duty.

The project team identified three potential locations for carbon capture: the shifted gas following the water-gas shift (WGS) reaction, the tail gas from the pressure swing adsorption (PSA), and the flue or stack gas at the SMR or ATR outlet. Based on the model results, capturing CO_2 from the shifted gas and flue gas emerged as the better choice.

The report evaluates the performance of SMR CCS and ATR CCS systems, considering auxiliary power requirements, water usage, energy consumption, total plant cost (TPC), and levelized cost of hydrogen (LCOH).

Cost and Performance Summary—Electrolysis

EPRI Report [3002026206]
Published March 2023

Abstract

As hydrogen is incorporated into long-range energy resource plans, utility planners need reliable cost and performance data on electrolyzer technologies. This report provides a high-level overview of that information by summarizing the electrolysis sections of EPRI report *Low-Carbon Energy Supply Technology Cost and Performance Study* (3002023656) as well as other EPRI reports and external resources. It also suggests considerations for evaluating quotes and reviews the state of electrolyzer technology, the market, and ongoing research.

Repowering Coal-Fired Power Plants for Hydrogen Production with Electrolysis

EPRI Report 3002025895
Published February 2023

Abstract

In response to mounting pressure to retire coal-fueled generating assets, U.S. utilities have announced thousands of megawatts of coal plant retirements to take effect over the next 15 years. Until recently, newly constructed natural gas-fired units typically replaced decommissioned coal plants.

Considering the potential future demand for hydrogen in the energy economy, placing a hydrogen production facility at a former coal plant site is one viable approach to leveraging the existing site assets. In the same time frame as the projected coal retirements, large-scale intermittent renewable resources are expected to expand greatly, creating a source of clean energy for electrolysis-based hydrogen production. Repurposing a coal site for an electrolysis facility offers several advantages, including the potential to reuse existing site infrastructure, operating and environmental permits, equipment, facilities, and water access and storage. The large site area, relative remoteness, and available water and wastewater systems typical of most coal plants provide opportunities to accommodate operational safety and fire management planning that could be challenging in more urban installations.

This paper summarizes key issues to consider and understand when evaluating whether a closing coal-fired plant can effectively be repurposed for hydrogen production using electrolysis. It is part of a series of EPRI papers addressing different options for coal sites after decommissioning.

Blue Hydrogen Production

EPRI Report 3002021307
Executive Summary 3002026029
Published February 2023

Abstract

Hydrogen is inherently a low-emission fuel at the point of use, but its life-cycle greenhouse gas emissions can be substantial without a means to reduce CO_2 emissions from its production. Thus, the efficacy of hydrogen as a fuel, chemical feedstock, energy carrier, or energy storage medium in a low-carbon economy is rooted in the ability to produce low-carbon hydrogen economically. The production of hydrogen from natural gas by a chemical reaction in conjunction with capture and sequestration of the CO_2 produced during the process (known as "blue" hydrogen) has become an important part of the global response to limiting greenhouse gas emissions and climate change impacts.

This report describes an array of commercial and developmental technologies for producing hydrogen from fossil fuels—chiefly natural gas, but, in some cases, other hydrocarbons—along with approaches to economically incorporate CO_2 capture into the production process. Approaches to CO_2 capture covered in the report span chemical absorption, adsorption, membrane, and cryogenic processes, along with developmental pyrolytic processes for the direct capture of solid carbon from methane.

Modeling the Flexible Operation of Electrolyzers for Hydrogen Production in a Low-Carbon Energy System: Important Considerations

EPRI Report 3002025738
Published January 2023

Abstract

In a future low-carbon energy system, flexible assets such as electrolyzers could be deployed to increase the uptake of variable renewable energy (VRE) on the grid and to utilize available renewable energy sources more efficiently. An understanding of the technical, and economic factors with VRE use and hydrogen production in electrolyzers need to align across electricity supply, hydrogen production, and hydrogen offtake/use. Hydrogen's role in the changing energy landscape is yet to be determined and could vary significantly across investors, utilities, vendors, and end users. Modeling electrolyzers, especially at a systems scale, is crucial to understanding how they can be optimized for overall hydrogen production. This technology brief describes the types of electrolyzers and their components, the five modeling domains needed for electrolyzer modeling, the types of electrolyzer models, electrolyzer model dimensionality and model state considerations, and case study results from an input-driven analytical modeling approach. Research is needed to investigate the effect of variations in temporal and spatial resolutions of variables (O&M costs and electrical current availability) on the total hydrogen production in electrolyzers. This would help stakeholders make best use of their available assets while minimizing the cost of hydrogen production from electrolyzers.

Summary Brief: Insight Report on Electrolyzer Technologies

EPRI Report 3002023084
Published October 2022

Abstract

Because most of today's hydrogen production requires fossil fuels, there is a significant need to transition to clean hydrogen production to achieve decarbonization goals. Water electrolyzers are established technologies that produce emission-free hydrogen when coupled with clean electricity such as solar, wind, or nuclear. Electrolysis technologies are in different stages of maturity, but each has advantages and disadvantages that may allow them to play a role in economy-wide decarbonization. This report provides an overview of several electrolysis technology options.

Water Electrolyzer Stack Degradation

EPRI Report 3002025148
Published September 2022

Abstract

Low-carbon hydrogen is critical for achieving deep economy-wide decarbonization. Electrolysis is a process that produces hydrogen by splitting water molecules without emitting greenhouse gases. However, less than 4% of hydrogen is produced by electrolysis globally. For electrolysis to be realized as a promising and reliable process for future large-scale hydrogen production, electrolysis systems need to produce hydrogen reliably, affordably, and durably. Many recent efforts have focused on reducing the cost of hydrogen production via electrolysis, but the durability of these systems remains uncertain. Electrolyzer stacks are the heart of any electrolysis plants, and stack degradation is the most important durability consideration for such plants. Although technology improvement has significantly decreased stack degradation in the past decade, two important research questions remain: the effect of dynamic operation on stack degradation, and the effect of future electrolyzer stack cost reduction on stack degradation. This white paper summarizes the importance of understanding stack degradation and highlights areas where more research is needed.

State of Technology - Methane Pyrolysis

EPRI Report 3002021275
Executive Summary 3002025116
Published July 2022

Abstract

Hydrogen (H_2) is a potential clean energy solution when addressing global energy requirements in a deeply decarbonized future. Most current H_2 production processes, such as steam methane reforming (SMR) or coal gasification, dissociate H_2 from hydrocarbons via chemical transformation and co-produce carbon dioxide (CO_2) that must be captured. Other clean H_2 production methods are beginning to be scaled up and commercialized as investment in the broader technology space increases. These methods include water electrolysis and methane pyrolysis (MP). Water electrolysis does not require fossil fuel input, when produced with clean electricity, and has been discussed in prior Low-Carbon Resources Initiative (LCRI) reports (see *Insight Report on Electrolyzer Technologies:* 3002021864). The current report will address production of clean H_2 via methane pyrolysis. This process is unique in clean H_2 production from fossil fuels because no CO_2 is formed as the products are gaseous H_2 and solid carbon. This is potentially advantageous as the transport and storage of solid carbon are likely to be easier and cost less than those of CO_2, with the solid carbon having the potential to be sold in a number of commercial products.

This report will provide a high-level technical overview of MP, a comparative analysis of existing and emerging technologies, including their technology readiness levels (TRL), anticipated techno-economic barriers, and knowledge gaps.

Insight Report on Electrolyzer Technologies

EPRI Report 3002021864
Executive Summary 3002023083
Published March 2022

Abstract

This study provides an overview of electrolysis and other water splitting technologies for hydrogen generation, describing both their corresponding features and challenges. The most mature, alkaline electrolyzers and proton exchange membrane electrolyzers, two widely known system types, are presented along with developing technologies such as solid oxide electrolyzers and anion exchange membrane electrolyzers. Furthermore, the advantages and disadvantages of each system relative to others and the specific research gaps for each technology are outlined. For both commercial and developing technologies, overcoming these gaps is critical to meeting performance requirements for system stability, durability, and efficiency over the product lifetime. In addition to technologies, this report also looks into current manufacturers, large scale hydrogen electrolysis project announcements, government policy and regulations, and the need for social acceptance for the future deployment of hydrogen production by electrolysis as an alternative low- to zero-carbon fuel source. Hydrogen production by

electrolysis also comes with uncertainties and risks such as the price of electricity over time, the flexibility of the electrolyzer response to power variation, and competition from other low-carbon hydrogen production methods. These risks, along with key performance considerations for water electrolyzers, are discussed in this report.

LCRI Hydrogen Electrolysis Techno Economic Analysis Tool (LCRI H_2 Electrolysis TEA Tool) v1.0.0

EPRI Software 3002023135
Published January 2022

Abstract

Hydrogen has the potential to be vital player in economy-wide decarbonization of our energy systems. Over the past decade, green hydrogen production using electrolyzers has advanced significantly, and as a result have become more cost effective and OEMs have laid out roadmaps for further cost reductions in the future. Proton exchange membrane water electrolysis and alkaline water electrolysis are the two main commercially available low-temperature electrolyzer technologies. Although, technology advancement has reduced the cost of these systems significantly, major cost reduction is expected to be achieved by production scale up. Understanding the cost breakdown of electrolyzers would aid in singling out the possible effect of scale up on the overall cost of hydrogen production. To better frame our cost understanding, the LCRI Hydrogen Electrolysis Techno-Economic Analysis Tool has been developed to provide an easy-to-use tool to support customized techno economic analysis. This tool will be updated periodically, and more features will be added throughout the Low-Carbon Resources Initiative (LCRI). Version 1.0 of the tool is intended to provide an initial high-level overview of the hydrogen cost and scale to the LCRI members. Future versions of this tool are planned for 2022 that include customizable assumptions to support various sensitivity analysis capabilities.

To access LCRI H_2 Electrolysis TEA Tool, click here: https://lcri-tools.epri.com

Platform Requirements

Modern web browsers for desktop or mobile operating systems, including recent versions of:

- Chrome
- Safari
- Firefox
- Edge

Low-Carbon Technology Assessment: Electrolysis – Sunfire

EPRI Report. 3002020367
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of Sunfire's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Low-Carbon Technology Assessment: Electrolysis – McPhy

EPRI Report. 3002020370
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of McPhy's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Low-Carbon Technology Assessment: Electrolysis – Haldor Topsoe

EPRI Report: 3002020365
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of Haldor Topsoe's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Low-Carbon Technology Assessment: Electrolysis – ThyssenKrupp

EPRI Report. 3002020366
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of ThyssenKrupp's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Low-Carbon Technology Assessment: Electrolysis – ITM Power

EPRI Report: 3002020371
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of ITM Power's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Technology Assessment: Electrolysis – Fuel Cell Energy

EPRI Report: 3002020372
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of Fuel Cell Energy's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Low-Carbon Technology Assessment: Electrolysis – Nel ASA

EPRI Report 3002020369
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of Nel ASA's electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

Low-Carbon Technology Assessment: Electrolysis – Siemens

EPRI Report: 3002020368
Published January 2021

Abstract

Hydrogen has the potential to reduce greenhouse gas emissions for difficult-to-decarbonize sectors if it is produced via low-carbon means. Electrolysis, an electrochemical process that splits water into hydrogen and oxygen using electricity, produces no direct carbon dioxide emissions. This document provides a review of Siemens' electrolysis offerings and development activities, as well as an introductory overview of electrolysis technologies, their research needs, and their potential applications.

DELIVERY & STORAGE

Overview of Large-Scale Hydrogen Storage and Delivery Technologies: Review of Global Projects

EPRI Report 3002025239
Executive Summary 3002027746
Published June 2023

Abstract

As global energy economies seek rapid decarbonization to meet climate goals, hydrogen is one alternative energy carrier being investigated to facilitate a clean energy transition. Current hydrogen delivery and storage methods are readily scalable to provide dispatchable power as grids continue to build out intermittent renewable resources. However, more research is needed to overcome some of the technical challenges that hydrogen poses. There are ongoing global efforts to close some knowledge gaps regarding hydrogen use in energy grids, including underground storage and pipeline delivery of hydrogen.

This report presents the current landscape for large-scale hydrogen delivery and storage methods and associated challenges and knowledge gaps. The report also provides a select list of ongoing and announced pilot and demonstration projects specific to hydrogen delivery and storage.

Database of Existing Geologic Underground Storage Facilities

EPRI Software 3002027164
Executive Summary 3002027165
Published June 2023

Abstract

Driven by deep decarbonization targets, the potential use of hydrogen as an alternative energy carrier has received increasing attention. Cost-effective and high-capacity hydrogen storage is an important component for successful deployment of hydrogen technologies Large-scale hydrogen storage will be needed to balance production from electrolysis in electricity markets with high shares of intermittent renewable generation. Underground storage in geologic structures has been identified as a key, large-scale option for centralized hydrogen storage.

Hydrogen presents unique challenges for underground storage due to its highly diffusive nature. However, in a general sense, its behavior underground is expected to be largely comparable to natural gas, which may allow for extrapolation of useful learnings, since NG has been successfully stored underground for decades. Moreover, hydrogen storage using above-ground tanks or similar technology is very expensive and only viable at relatively small scale (for example, to absorb daily fluctuations in an otherwise seasonally flat profile of supply or demand). The main geologic options for hydrogen storage are porous reservoirs containing brine (aquifer storage), depleted oil and gas reservoirs, natural or man-made salt caverns, and hard rock caverns. Geologic structures vary significantly across regions, which presents technical challenges for the

design of storage facilities and adds complexity in terms of representing the cost of hydrogen storage in economic and energy models. However, such a representation is crucial for an assessment of hydrogen deployment costs and trade-offs with other low-carbon fuel pathways.

This spreadsheet is a database of existing U.S. underground storage facilities (USF), including operating conditions and geologic parameters. This database can be a useful tool to identify the best possible natural gas storage facilities that could be converted to H_2 storage, or to analyze what geologic characteristics need to be present when expanding to new storage facilities.

Review of Hydrogen Geologic Storage Options in the U.S.: Existing Facilities and Potential for Future Storage Expansion

EPRI Report 3002026653
Published June 2023

Abstract

Driven by deep decarbonization targets, the potential use of hydrogen as an alternative energy carrier has received increasing attention. Cost-effective and high-capacity hydrogen storage is an important component for successful deployment of hydrogen technologies Large-scale hydrogen storage will be needed to balance production from electrolysis in electricity markets with high shares of intermittent renewable generation. Underground storage in geologic structures has been identified as a key, large-scale option for centralized hydrogen storage.

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The main geologic options for hydrogen storage are porous reservoirs containing brine (aquifer storage), depleted oil and gas reservoirs, natural or man-made salt caverns, and hard rock caverns. Geologic structures vary significantly across regions, which presents technical challenges for the design of storage facilities and adds complexity in terms of representing the cost of hydrogen storage in economic and energy models. However, such a representation is crucial for an assessment of hydrogen deployment costs and trade-offs with other low-carbon fuel pathways.

This report provides a review and summary of existing geologic storage facilities in the U.S., taking into consideration their geologic setting, capacity, recharge/discharge rates, etc. Furthermore, we provide a description of the salt deposits across the U.S. and their potential to add new hydrogen storage capacity.

The key findings include:

- A database with existing U.S. underground storage facilities (USF) was compiled, including operating conditions and geologic parameters (see EPRI product 3002027164, *Database of Existing Geologic Underground Storage Facilities*).
- This database, which has been summarized in the present report, can be a useful tool to identify the best possible natural gas storage facilities that could be converted to H_2 storage, or to analyze what geologic characteristics need to be present when expanding to new storage facilities.
- Since not all the existing facilities are located within ideal geologic conditions, a better understanding of the geology can give important insights into long term economic success.
- An overview of salt deposits in the U.S., which provides potential for expanding USF, was presented.

Summary of Underground Hydrogen Storage: Bibliography

EPRI Software 3002025985
Executive Summary 3002025984
Published January 2023

Abstract

There is great interest in developing geological hydrogen storage (GHS) for decarbonizing the electricity sector. Although there are analogous deep subsurface porous media fluid injection and withdrawal activities carried out

worldwide, the technical feasibility of GHS has not been tested or demonstrated. To make progress in evaluating GHS, EPRI carried out a literature review on it. The goal of the review was to identify and summarize research and experience relevant to evaluating the technical feasibility of large-scale GHS. EPRI researchers mainly used bibliographic mining to identify relevant papers and reports, focusing on literature that describes the current state of knowledge of GHS, identifies critical issues and challenges, and addresses the repurposing of existing storage systems for GHS. This spreadsheet compiles the results of the literature review into a bibliographic database.

Summary of Underground Hydrogen Storage: Literature Review

EPRI Report 3002025983
Executive Summary 3002025984
Published January 2023

Abstract

There is great interest in developing geological hydrogen storage (GHS) for decarbonizing the electricity sector. Although there are analogous deep subsurface porous media fluid injection and withdrawal activities carried out worldwide, the technical feasibility of GHS has not been tested or demonstrated. To make progress in evaluating GHS, EPRI carried out a literature review on it. The goal of the review was to identify and summarize research and experience relevant to evaluating the technical feasibility of large-scale GHS. EPRI researchers mainly used bibliographic mining to identify relevant papers and reports, focusing on literature that describes the current state of knowledge of GHS, identifies critical issues and challenges, and addresses the repurposing of existing storage systems for GHS. The researchers then read and briefly summarized these papers creating a spreadsheet that serves as a bibliographic database.

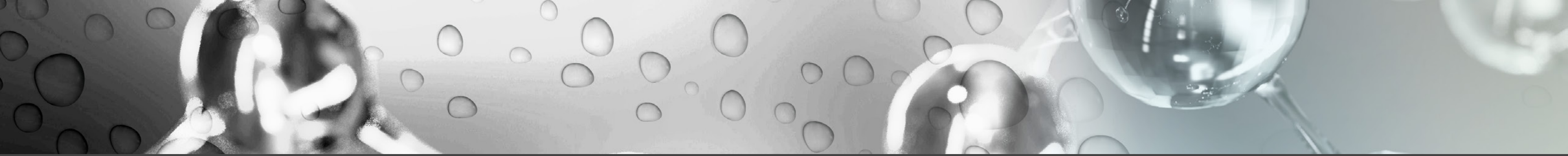
Transitioning Line Pipe to Hydrogen Service: Service Experience

EPRI Report 3002025327
Executive Summary 3002025329
Published December 2022

Abstract

As the world embarks on a global transition to significantly reduce greenhouse gas emissions to limit the rise in global temperatures below the 1.5°C above preindustrial thresholds, hydrogen is expected to play a key role in decarbonization. Whether hydrogen can ever replace natural gas as a primary energy carrier may come down to our ability to transport it safely, reliably and economically. While pipeline transmission of hydrogen provides the best option for moving large volumes over relatively long distance, the cost (and potential regulatory hurdles) associated with the build-out of a new, purpose-built interconnected hydrogen pipeline network that is designed in accordance with hydrogen specific codes may not be practical. Thus, there is significant interest in leveraging the existing natural gas infrastructure for hydrogen service; however, this brings about some key materials challenges that need to be addressed in order to minimize risk and maintain system integrity.

This report provides a high-level summary of historical incidents based on data from three databases: European Gas Pipeline Incident Data Group (EGIG), Pipeline Hazardous Materials and Safety Administration (PHMSA), and DNV's root cause analysis database. Value is added through expert commentary on the potential influence that hydrogen has on the likelihood and severity of future incidents. Also provided is an overview of typical design conditions for existing hydrogen and natural pipelines (as a relative percentage of the specified minimum yield stress) to highlight operational changes that may be required when transitioning to hydrogen service. Finally, success stories, lessons learned and actions required for successful operation of purpose-built and repurposed hydrogen pipelines are presented.



Transitioning Line Pipe to Hydrogen Service: Integrity Management

EPRI Report 3002025331
Executive Summary 3002025333
Published December 2022

Abstract
In the United States, more than half of the nearly 300,000 (~483,000 km) miles of in-service natural gas (NG) pipelines were built prior to 1970 using codes, standards and materials specifications that have evolved over time. While the opportunity to use these NG pipelines for transmission of hydrogen gas has huge potential cost benefit, it is imperative that the technical challenges and risks associated with introducing hydrogen to the existing infrastructure are identified, and required engineering assessments are performed to maximize safety. Thus, as a pipeline is transitioned from NG to H_2 service, integrity management programs must be reviewed and updated to account for the additional threat that gaseous hydrogen poses on system integrity.

This report presents practical guidance and specific considerations that should be incorporated into an operator's integrity management program where relevant and details industry best practice recommendations and integrity management requirements for hydrogen pipeline service. The report also includes review and commentary on requirements and recommendations for converting existing pipelines to hydrogen service.

Transitioning Line Pipe to Hydrogen Service: Literature Review

EPRI Report 3002025050
Executive Summary 3002025051
Published October 2022

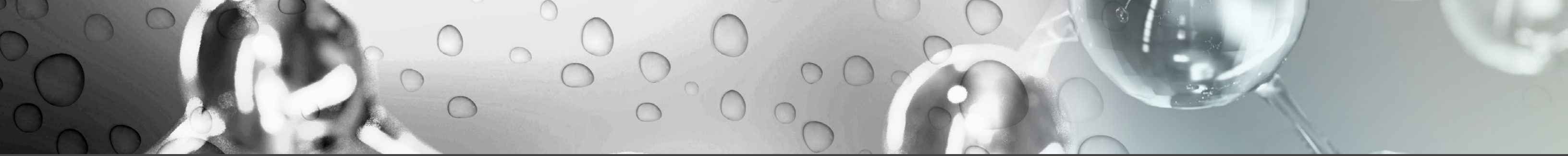
Abstract
It is well established that transmission pipelines provide the best option for moving large volumes of gas over relatively long distances. In the United States (U.S.) there are approximately 300,000 miles (483,000 km) of large, high-pressure transmission pipelines used for transporting a continuous and robust supply of natural gas across the country. Local supply to residential and commercial customers is achieved using an integrated, low(er) pressure distribution system. In contrast, there are currently only about 1,600 miles (~2,600 km) of hydrogen pipelines in the US, which are primarily owned and operated by merchant producers. Thus, it is apparent that while there is broad long-term knowledge available regarding the performance of systems used for natural gas, information on hydrogen systems is more limited.

EPRI and the Low Carbon Resources Initiative (LCRI) are involved in research that will integrate knowledge from materials science with evaluation of the long-term performance of components. Wherever possible, the knowledge will include the results of 'root cause" investigation of defects found in existing pipelines. This report provides a technical summary from a growing list of publications and covers a number of topics, including: materials considerations; pipeline design, manufacturing and construction practices; integrity management; equipment, components, and system considerations; and operator experience.

Applicable Codes and Standards for Delivery and Storage of Alternative Energy Carriers

EPRI Software 3002025324
Published September 2022

Abstract
This product provides a detailed listing and organizational structure for evaluating codes, standards, regulations (CSR), specifications, recommended practices, guidance documents, and test methods from various worldwide organizations that may be applicable when constructing new or repurposing existing infrastructure for delivery and storage of alternative energy carriers (AECs). While this product is complementary to and has been harmonized with 3002025256: *Hydrogen Codes and Standards Master List,* the listed documents are generally specific to delivery and storage and have broad relevance to AECs beyond just hydrogen. The searchable fields can be sorted according to topical areas, including document type, delivery and storage application, design and construction, asset integrity, materials degradation, safety, and risk. Note that the applicability of the documents to



each topical area is based on a review of abstracts and other publicly available information and thus, is intended as a quick reference guide to assist the user in identifying relevant CSR documents.

Hydrogen Codes and Standards Master List

EPRI Software 3002025256
Published August 2022

Abstract

This product is a master compendium of hydrogen codes and standards applicable to a wide range of segments of the hydrogen industry and intended for broad use by LCRI funders. Fields include organization; code number, title, and brief description; mapping to LCRI Technical Subcommittees; and reference link.

Underground Storage of Natural Gas and Hydrogen

EPRI Report 3002019966
Executive Summary 3002021873
Published June 2022

Abstract

Compared with natural gas and coal, hydrogen does not emit greenhouse gases when combusted. Unfortunately, hydrogen has a very low-volumetric energy density compared to hydrocarbons, requiring that it be liquified at very low-temperatures or compressed to very high-pressures to provide comparable energy. Liquefaction and compression consume large amounts of energy. Underground storage of large volumes of hydrogen in geologic formations is a feasible option that is being practiced to a limited extent today. Underground storage of natural gas and town gas are mature technologies that have been implemented since the early 1900s. This study summarizes a literature review of the state-of-the-industry on the underground storage of hydrogen, and its analog, the underground storage of natural gas.

END-USES/POWER GENERATION

Reversible Fuel Cell Review

EPRI Report 3002026192
Executive Summary 30020226193
Published June 2023

Abstract

Reversible fuel cells are systems that can act as low-carbon hydrogen producers and in reverse as power generators, potentially reducing cost and space requirements by combining the two functions in one device. They can also serve as mid- and long-duration energy storage systems with minimal standby losses. Multiple fuel cell and electrolyzer companies are working to advance the technology readiness level of reversible fuel cell technologies, typically with support from government research organizations. Reversible fuel cells have the potential to provide the benefits of fuel cell power generation (high efficiency, low emissions, and quiet operation) and electrolytic ("green") hydrogen production combined in one device. These benefits can currently be achieved using optimized electrochemical stacks in separate fuel cells and electrolyzers. Thus, a fundamental question for unitized reversible fuel cells is whether design trade-offs can be balanced in such a manner that their levelized cost is lower than the levelized cost of a paired system of similar capacity, but independent, electrolyzer and fuel cell. In the broader context of energy storage, hydrogen energy storage using an electrolyzer and fuel cell must develop to be competitive with other energy storage technologies capable of durations ranging from diurnal to seasonal with minimal standby losses. Further, technical questions remain about the potential readiness of reversible fuel cells, including their ability to be durable and flexible over long periods of operation with daily cycling; their ability to meet capital cost and efficiency targets, including for some technologies the ability to function effectively with low-cost alternatives to platinum-group metal catalysts; their ability to manage and store thermal energy between power generation and electrolysis cycles; and their timeline for becoming commercially competitive.

This report summarizes a literature review of reversible fuel cell technologies and current research funded by the U.S. Department of Energy and others. EPRI findings from previous fuel cell reports also served as a source of information.

Best Practice Guidance on Procedures for Characterizing Engineering Alloys Exposed to Alternative Energy Carrier Fuel Combustion Products

EPRI Report 3002027446
Executive Summary 3002027447
Published June 2023

Abstract

Burning of alternative energy carrier (AEC) fuels such as hydrogen and ammonia is actively being considered as a viable strategy to achieve significant reductions in greenhouse gas emissions for power generation applications. Combustion of AECs, either directly or as a blend, will produce distinct flame characteristics and combustion products and are likely to result in more aggressive service conditions (higher temperatures and moisture content) and thus accelerate or lead to different degradation mechanism(s). Understanding how changes in service conditions influence factors such as mechanical properties, formation of oxide scales, nucleation and growth of precipitate phases, and/or changes in size, shape and distribution of microstructural features can aid in the development of life management strategies.

This report provides an overview of the analytical tools and techniques that can be used for characterizing metallurgical samples, and offers best practice guidance on procedures and methods based on EPRI's experience and expertise. Due to the technical nature of the subject matter, case studies are presented throughout to demonstrate proper application of analytical techniques utilized on a range of power generation components, and the optimized system parameters for achieving the best possible outcome. While none of the case studies were performed on samples exposed to AEC combustion products due to the lack of long-term testing done to date, the procedures and methods will be directly applicable to components exposed to AEC fuel combustion products. Thus, as opportunities arise, LCRI and EPRI's materials characterization laboratory will be engaging with researchers to perform detailed characterization on samples subjected to AEC combustion products.

Guidance for Sample Preparation of High-Temperature Components Exposed to Alternative Energy Carrier Fuel Combustion Products

EPRI Report 3002025325
Executive Summary 3002025326
Published April 2023

Abstract

With the push to limit the rise in global temperatures due to greenhouse gas emissions to less than 2.0°C (3.6°F) above pre-industrial levels, many countries and organizations are establishing decarbonization strategies that rely on the use of carbon free or alternative energy carrier (AEC) fuels such as hydrogen or ammonia. For power generation applications, changes in physical properties of a given fuel can alter the combustion dynamics and lead to significant differences flue gas constituents, temperatures, and heat distribution, which can impact system the materials degradation behavior and system reliability.

This document provides general guidance and practices useful to equipment owners and operators that will have hot section parts replaced, repaired, modified. or evaluated as a result of burning AEC fuels in their power generation assets. Examples of equipment and components include gas turbines, heat recovery steam generators, boilers, reciprocating engines, fuel cells, and other related hardware such as piping, valves, and instrumentation.

Opportunities and Challenges for Reciprocating Internal Combustion Engines When Using Low-Carbon Fuels

EPRI Report 3002025733
Executive Summary 3002025734
Published May 2023

Abstract

Reciprocating internal combustion engines (RICE) have a long history of providing reliable service in the marine transportation and power generation sectors, traditionally using liquid fuels, such as heavy fuel oil and diesel, and more recently using natural gas for peaking and load-following power plants. Substituting low-carbon fuels in place of conventional hydrocarbon fuels offers a pathway for RICE to operate competitively in a low-carbon world. Although biofuels can usually be substituted directly for conventional fossil fuels with few (if any) engine modifications, their potential availability at scale may be limited and their point-of-use emissions are similar to conventional fuels. Thus, the focus of research and development for operation of RICE units on low-carbon fuels centers on ammonia, hydrogen, and methanol. The wide range of physical, chemical, and combustion characteristics between these fuels requires development of new engine models to fully unlock each fuel's potential. Key questions are the types of engines in development, the approaches manufacturers are taking to ensure safety and optimize output and performance, and the expected timing of new engines entering the market.

This report provides an assessment of work by RICE original equipment manufacturers (OEMs) to modify their medium-speed engines to run on low-carbon fuels. The findings are drawn from research and policy reports, technical papers, trade press news articles, and Internet sources, as well as nonproprietary information made directly available by RICE OEMs.

Fuel Cell Technology Assessment— Potential Future Costs and Low-Carbon Fuel Considerations

EPRI Report 3002026233
Executive Summary 3002026260
Published March 2023

Abstract

Fuel cells were first developed over a century ago but have not emerged as a dominant choice for stationary (for example, power generation) or transportation (for example, fuel cell electric vehicles) applications due to tough competition from other technologies with more favorable value propositions, such as internal combustion engines. There is a dearth of independently-developed cost and performance estimates for fuel cells due to a historical lack of transparency around products and projects; a relatively small number of real-world projects, often with highly site/project-specific requirements; and the ability of fuel cells to be used for numerous, sometimes niche, applications. Fuel cells continue to garner interest as a potential key component of a decarbonized economy. However, even less is understood about the techno-economics of larger fuel cell systems directly fueled (fed) by hydrogen (that is, as opposed to systems that feed a hydrocarbon fuel through a fuel processor to extract hydrogen to then feed into a fuel cell).

While sharing some of the limitations inherent to the current fuel cell literature, this research uses foundational insights on fuel cells obtained from *2022 Fuel Cell Technology Assessment: Current State and Look Ahead* (3002025147) to develop cost projections to provide a coherent narrative around the prospects and potential future costs of transportation and stationary fuel cells, as well as potential implications of direct hydrogen fueling of selected stationary fuel cells.

Assessment of Low-Carbon Fuel Pathways for Light-Duty Vehicles

EPRI Report 3002020045
Executive Summary 3002026038
Published January 2023

Abstract

Worldwide, passenger cars and light commercial vehicles are responsible for 46% of greenhouse gas emissions in the transportation sector. Deep decarbonization of this sector requires the development, deployment, and consumer adoption of affordable alternative fuels (including electricity), vehicles that can use the fuels, and infrastructure to deliver fuel whenever and wherever it is needed. Due to the long life and slow turnover of these vehicles, decarbonization solutions that require changes to vehicles will likely take a considerable amount of time to penetrate the market.

This report focuses on low-carbon alternative fuel candidates for light-duty vehicles and the associated fueling infrastructure. It describes criteria for a successful alternative fuel for light-duty vehicles, potential alternative fuels in this space (including drop-in fuels and low-carbon additives, hydrogen fuel cells, and electricity), alternative fuel policies and regulations, key trends and challenges, and recommended next steps.

Review of Advanced Gaseous Fuel Blend Monitoring Technologies and Developers

EPRI Report 3002025561
Executive Summary 3002025562
Published December 2022

Abstract

Gas turbines (GTs) represent a large fraction of power generation worldwide, producing affordable electricity, meeting regulations for criteria pollutants, and providing dispatchable load following capabilities. As a step toward decarbonizing the power sector, GT original equipment manufacturers (OEMs) are developing combustion systems for hydrogen (H_2) and natural gas (NG) fuel blends. In parallel, instruments using a range of technologies are being developed by multiple companies to monitor H_2/NG fuel blend composition at the inlet of GTs and other prime movers. An initial landscape study was developed and executed for the Low-Carbon Resources Initiative (LCRI) to review the current state of the industry in terms of fast response, H_2/NG fuel blend monitoring solutions. This report presents the results of the study, including descriptions of commercially available instruments and technologies under development.

Assessment of Low-Carbon Fuel Pathways for the Cement and Glass Industries

EPRI Report 3002021284
Executive Summary 3002025555
Published December 2022

Abstract

Cement and glass are both vital to the world economy. These manufacturing industries are also energy intensive and produce significant carbon emissions. Decarbonization challenges include the historical dominance and low costs of fossil fuels. While potential decarbonization pathways using alternative fuels have been identified, they face significant barriers to widespread adoption, including technical challenges, availability, and cost.

This report describes incumbent fuels, process flows, and source emissions in these industries. It concludes that measures to improve both electrical and thermal energy efficiency (for example, waste heat recovery systems) can lower carbon emissions in these industries. Among alternative fuel options for both industries, waste-derived fuels—created from tires, sawdust, waste oils, sludge, and other types of waste—are most promising because they are less expensive, offer a lower-carbon footprint, and are an effective method of waste management. Additional potential decarbonization approaches in these industries include raw material substitution, demand reduction, and in the long-term, use of low-carbon hydrogen and carbon capture and sequestration. The report concludes with adoption barriers and identifies research needs.

Conversion of Existing Natural-Gas-Fired Duct Burners to Hydrogen: State of Knowledge and Issues Assessment

EPRI Report 3002025334
Executive Summary 3002025560
Published December 2022

Abstract

Large-scale, combined-cycle gas turbines (CCGT) for industrial or power generation applications often use duct burners upstream of the heat recovery steam generator (HRSG) to increase peak load production or steam production. Also known as supplemental firing systems, these burners typically fire natural gas (NG) and thereby contribute to the overall greenhouse gas footprint generated by the greater CCGT unit. Accordingly, there is a need to investigate potential pathways for converting NG duct burners to low-carbon fuels such as hydrogen. This report addresses the state of knowledge, issues, and resource requirements for converting existing NG-fired duct burners to hydrogen in a safe, reliable, and economical manner.

Assessment of Low-Carbon Fuel Pathways for Building Water Heating

EPRI Report 3002021230
Executive Summary 3002025553
Published October 2022

Abstract

Delivered fossil fuels are the predominant energy source for water heating in buildings in the United States and many other nations. In aggregate, water heating represents a substantial source of greenhouse gases (GHGs). Notable advances have been made recently in the development and deployment of advanced technologies for energy conservation and efficiency in water heating, including innovative controllers and plumbing technologies to mitigate energy waste in hot water distribution, grid-interactive controls and communication protocols, and electric or fuel-fired heat pump water heaters.

Despite this progress, achieving deep decarbonization of water heating equipment will require additional measures. Low- or zero-carbon fuels—such as renewable and synthetic natural gas (R/SNG) and hydrogen—are likely to play a key role. This report addresses both efficiency and low-carbon fuel solutions, together with policy drivers, costs, recent demonstration projects, and practical concerns. A technical appendix provides a rigorous discussion of low-carbon fuel combustion.

Assessment of Low-Carbon Fuel Pathways for Medium and Heavy-Duty Vehicles

EPRI Report 3002020533
Executive Summary 3002025554
Published October 2022

Abstract

Medium-duty and heavy-duty (MDHD) vehicles, including heavy pickups, delivery vehicles, transit and school buses, refuse trucks, and semi-tractors, are vital to transportation of freight and passengers. In 2019, MDHD vehicles produced 24% of U.S. transportation-related greenhouse gas (GHG) and 7% of overall GHG emissions. MDHD vehicles also produce over 40% of on-road nitrogen oxides and 50% of on-road particulate emissions. While MDHD vehicles account for a small share of the overall vehicle population, they represent a large share of vehicle miles traveled and energy used (20% of total transportation energy) due to higher driving intensity and fuel consumption per mile.

No single low-carbon fuel has emerged as a solution that best meets the needs of all MDHD vehicles and fleets. Each fuel presents unique advantages and challenges, offering a variety of pathways towards MDHD sector decarbonization. This report summarizes the landscape of available decarbonization solutions for MDHD vehicles, with a particular focus on low-carbon fuels. Current and potential uses of these fuels are discussed, as well as policy drivers, technology opportunities, economic and technical barriers, and key R&D needs associated with application in this sector.

Taking Gas Turbine Hydrogen Blending to the Next Level

EPRI Report 3002025438
Published September 2022

Abstract

Climate change, energy independence, renewable power, and the hydrogen economy are among the terms used in recent years and decades to describe society's most pressing challenges. Although the best way to face these challenges is a topic of controversy, it is important to estimate the potential of candidate technologies for reaching the goals before society commits to them completely. It is common to look for a quick fix, but solutions almost always require numerous technologies implemented throughout the entire energy value chain, involving millions of people and costing hundreds of billions (if not trillions) of dollars. These solutions are also likely to involve technologies that require incremental steps to prove that parts of the process are feasible. This typical case around technology innovation encapsulates the successful testing expounded on in this white paper. Moreover, for gas turbines, Noble et al. give a basis for the current capabilities on hydrogen inclusion for large-scale units.

Combustion or gas turbines are a highly valuable power generation and heating commodity. In many gas turbines, natural gas (NG) is the fuel used. NG is generally a low-cost and relatively high-energy- density fuel with a lower carbon content than coal or liquid fuels. This leads to reduced carbon emissions relative to those of fossil fuels. However, while burning NG, carbon dioxide (CO_2) remains a primary constituent of the exhaust emissions. Therefore, shutting down gas turbines or re-envisioning them for a low-carbon future is a popular focus of research, discussion, and development. One such proposed reconfiguration is blending hydrogen (H_2) with the NG fuel stream to further reduce CO_2 emissions.

Assessment of Low-Carbon Fuel Pathways for Construction, Agricultural, Mining, and Warehousing Equipment

EPRI Report 3002021272
Executive Summary 3002025557
Published September 2022

Abstract

Within the transportation sector, a significant fraction of mobile emissions is produced by equipment used in construction, mining, agriculture, and certain industrial subsectors such as warehousing. These vehicles present a diverse array of challenges for decarbonization, in part because their power requirements, functional constraints, design factors, and applications—including the environments in which they must operate—vary so widely even within narrowly-defined subsectors. However, with about 8% of the transportation industry's emissions traceable to these sources, addressing emissions in these industries is important to the overall drive to economy-wide decarbonization.

In the near term, technical and operational measures to improve fuel efficiency are expected to reduce emissions in the sector. However, transitioning to lower-carbon fuels and energy sources presents the greatest potential for emissions reductions in non-road transportation. This report summarizes current energy use and emissions of these mobile equipment types, as well as describes key decarbonization pathways available for them. These pathways include renewable and synthetic natural gas, hydrogen, ammonia, biofuels, and electricity.

Low-Carbon Fuel Pathways for Large-Scale Combined Heat and Power Applications

EPRI Report 3002021305
Executive Summary 3002025452
Published September 2022

Abstract

Combined heat and power (CHP) systems utilize a single engine (prime mover) to convert fuel to both thermal energy and electric power. Transitioning these systems to low-carbon fuels such as hydrogen and ammonia could play a key role in decarbonization of CHP. This report summarizes information from multiple Low-Carbon

Resources Initiative (LCRI) reports and projects covering specific industrial-scale CHP prime mover technologies. It provides an update on the current population, fuel types, and capacities of industrial and commercial CHP systems in the United States. The report summarizes the key combustion and emissions challenges introduced by firing low-carbon fuels, specifically hydrogen and ammonia, in larger industrial CHP prime movers, including combustion turbines, boilers, and reciprocating internal combustion engines. The report concludes with recommended future work for original equipment manufacturers and researchers to accelerate hydrogen and ammonia fuel pathways for relevant large-scale industrial and commercial CHP prime movers.

Hydrogen Cofiring Demonstration at New York Power Authority's Brentwood Site: GE LM6000 Gas Turbine

EPRI Report 3002025167
Executive Summary 3002025166
Published September 2022

Abstract

As part of the Low-Carbon Resources Initiative (LCRI), New York Power Authority (NYPA), EPRI, and General Electric (GE) jointly conducted a hydrogen blending project at NYPA's Brentwood Power Station. This collaborative effort demonstrated the burning of a hydrogen-natural gas blend on an LM6000 gas turbine (GT) to identify the resulting impact on combustion emissions (CO_2, NO_x, CO) and GT operation. This report contains the lessons learned during the design and execution of the project, along with recommendations for future LM6000 hydrogen cofiring investigations.

Conversion of Existing Natural Gas-Fired Industrial Boilers to Hydrogen: State of Knowledge and Issues Assessment

EPRI Report 3002025165
Executive Summary 3002025164
Published August 2022

Abstract

Industrial boilers can boast high efficiencies for process heat and steam needs and have generally proven to be reliable workhorses with long lifetimes. However, the existing natural gas-fired industrial boiler fleet in the United States represents a significant greenhouse gas footprint. Thus, investigation is needed into the difficulty of converting existing industrial boilers designed for natural gas fuel to low-carbon fuels, such as hydrogen. This report addresses the state of knowledge, issues, and resource requirements for retrofitting natural gas-fired industrial boilers to cofire and ultimately burn 100% hydrogen safely, reliably, and economically.

Assessment of Low-Carbon Fuel Pathways for Rail Transport

EPRI Report 3002020532
Executive Summary 3002025337
Published August 2022

Abstract

Rail transport plays an essential role in the modern global economy. Despite rail's inherent efficiencies, the scale of the industry and its emissions warrants decarbonization action. This report reviews decarbonization solutions for rail transportation, with a focus on line-haul locomotives because long-distance freight trains bear the greatest proportion of greenhouse gas emissions in this industry.

The discussion addresses direct electric pathways as well as the key alternative energy carriers under exploration: ammonia, hydrogen, natural gas (and related fuels), and biodiesel. Research gaps, development status, and noteworthy demonstration projects are discussed.

2022 Fuel Cell Technology Assessment: Current State and Look Ahead

EPRI Report 3002025147
Executive Summary 3002026260
Published June 2022

Abstract

Fuel cells are a well-understood technology but have not emerged as a dominant choice for stationary or transportation energy applications due to tough competition from other technologies with more favorable value propositions, such as internal combustion engines. A historical lack of transparency around fuel cell products—in large measure caused by intellectual property (IP) concerns—have led to a dearth of independently validated cost and performance information. Further, due to a relatively small number of real-world projects, fuel cell product cost and performance are often only able to be discussed speculatively (for example, how suitable a fuel cell would theoretically be for a given technology application, or how much cells might cost assuming a certain number were produced each year). While fuel cells continue to garner interest as a potentially key component of a decarbonized economy, even less is understood about the cost and performance of fuel cell systems directly fueled (fed) by hydrogen (that is, as opposed to systems that feed a hydrocarbon fuel through a fuel processor to extract hydrogen to then feed into a fuel cell) or utilizing other low-carbon fuels for applications beyond on-road vehicles. Foundational knowledge on base fuel cell systems is needed before the true implications of more advanced systems can be understood, researched, and modeled.

The purpose of the first phase of this study was to better understand fuel cell technology—its core components, functions, advantages, and challenges; potential applications; market status and outlook; baseline cost and performance; potential to achieve cost decreases via "learning" and major manufacturers. The insights from this study—including those presented in this interim report—could allow LCRI to develop more robust technology cost and performance projections and inform other related techno-economic analyses part of EPRI and GTI Energy's Low Carbon Resource Initiative (https://www.epri.com/lcri).

A key finding from this research is that all fuel cells can be directly fueled by hydrogen but purity matters. The proton exchange membrane fuel cell (PEMFC)—the most versatile and deployed fuel cell—requires purer hydrogen to operate than any other fuel cell type. PEMFC is already directly fueled by hydrogen for most transportation applications but there may be opportunities to more directly utilize hydrogen in stationary PEMFCs. Assuming hydrogen fuel of the requisite purity is available, the direct use of hydrogen may enable greater cost savings for low-temperature fuel cell systems (like PEMFC) by obviating the need for fuel processing equipment, which may not be required for high-temperature fuel cells (like solid-oxide fuel cells). However, more direct utilization of hydrogen in fuel cells may not fundamentally shift fuel cell economics because hydrogen storage is not cheap. Phase two of this study will utilize these foundational insights and others around cost and performance obtained from the literature to further evaluate the implications of directly utilizing hydrogen in fuel cells, including via outreach to technology developers and external experts.

Assessment of Distributed Fuel Cell Applications in a Low-Carbon Economy

EPRI Report 3002021291
Executive Summary 3002025102
Published June 2022

Abstract

Applications such as backup power generation, non-road mobile transportation, and combined heat and power (CHP) have historically relied on fossil fuels like diesel and natural gas to meet necessary energy demands. With the need for low-carbon energy growing as deep decarbonization becomes increasingly realized, distributed fuel cells using low-carbon fuels offer unique advantages for the aforementioned applications as well as others. Given the modularity and compact nature of fuel cells, in addition to the potential flexibility to operate using low-carbon fuels like hydrogen, renewable natural gas (RNG), and ammonia, fuel cells serve as an emerging low-carbon alternative to these traditionally fossil fuel-supplied applications.

Low-Carbon Fuel Pathways for the Primary Metals Industries

EPRI Report 3002021273
Executive Summary 3002025159
Published June 2022

Abstract

Primary metals manufacturing encompasses industries that take raw materials from mined ores or scrap metals and use heat, electricity, or other processes to produce refined metals, including alloys. These products are used across the economy for purposes such as manufacturing vehicles, machinery, construction steel, and consumer products. Recognizing the significant opportunity for emissions reductions in these key industries, this report provides an overview of the landscape of available decarbonization pathways for primary metals processing, with a particular focus on potential applications of low-carbon fuels. Relative competitiveness, applicability, development status, and research gaps are discussed.

Impacts of Cofiring Hydrogen in a Coalfired Steam Boiler: Numerical Modeling Assessment

EPRI Report 3002023986
Executive Summary 3002023987
Published May 2022

Abstract

Utility-scale, coal-fired steam boilers for power generation are significant sources of man-made CO_2. Accordingly, a timely opportunity exists to determine the technical challenges of cofiring low-carbon fuels, such as hydrogen, in these boilers. Doing so would leverage existing power plant infrastructure and help initiate the transition of the power industry to a low-carbon future. Impeding this opportunity are the risks that utility plant owners and operators would face in such an undertaking. Advanced tools, such as numerical modeling, can be used to gain technical insights and inform strategies for alleviating these risks.

Over the last several years, the Electric Power Research Institute's (EPRI's) combustion program used in-house numerical modeling tools to study and optimize natural gas cofiring approaches on many coal-fired boiler applications. With the focus now on decarbonization, the current project used these same modeling tools to study hydrogen cofiring with coal. The objective of the project was to identify potential combustion-related operability issues when cofiring 10% hydrogen (by heat input) on a tangential, coal-fired utility furnace design. Several parameters were investigated, including flue gas temperature and distribution, radiative heat transfer, velocity distribution, key gas species, and carbon in ash.

Assessment of Low-Carbon Fuel Pathways for Aviation

EPRI Report 3002021283
Executive Summary 3002023246
Published December 2021

Abstract

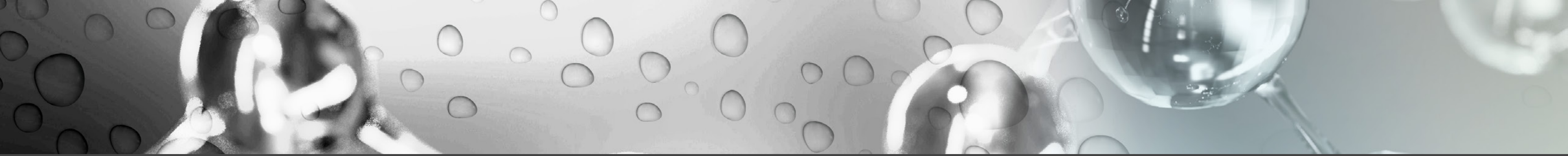
While technical and operational measures to increase fuel efficiency are expected to drive near term emissions reductions, achieving deep decarbonization of the aviation sector will require a large-scale transition to low-carbon fuels and energy sources. This report provides an overview of available emissions reductions pathways for the aviation transport sector and characterizes the landscape of key low-carbon fuel candidates, including their relative competitiveness, applicability, development statuses, and research gaps.

Low-Carbon Fuel Pathways for Combustion-Based Boiler and Heat Recovery Steam Generator Applications

EPRI Report 3002020531
Executive Summary 3002023231
Published December 2021

Abstract

Boilers and combined-cycle gas turbines (CCGTs) with heat recovery steam generators (HRSGs) for power generation and industrial applications comprise the largest stationary source consumers of fossil fuels. Accordingly, the potential conversion of the existing fleet of fossil-fired boilers and



CCGTs to low-carbon alternative fuels, either fully or even partially, represents a tremendous decarbonization opportunity. In addition to power generation, key industries where conversion to low-carbon fuels would yield the greatest impact include chemicals, petroleum, paper, food/beverage, and iron/steel production.

This report focuses on low-carbon fuel conversion pathways for existing boilers and HRSGs with duct burners. The report covers the major categories of larger fossil-fired boilers and HRSGs, including electric power generators, large industrial units, water tube and fire tube package boilers. As most of these units currently fire coal, oil, and/or natural gas, the report considers the technical hurdles that must be overcome for low-carbon fuel conversion. The report includes a general description of existing boiler and HRSG types within the power generation and industrial sectors. A summary of combustion, heat transfer, and emissions-related system components is also included. However, the level of detail has been limited to not go beyond the primary objectives.

Design Considerations for Cofiring Hydrogen in an Aeroderivative Gas Turbine: LM6000PC SPRINT Gas Turbine Feasibility Study

EPRI Report 3002020487
Executive Summary 3002022754
Published September 2021

Abstract

Worldwide goals for the power industry, as well as numerous other industries, include achieving carbon free power plant and industrial emissions by 2050. To realize these carbon reductions with the power generation industry, hydrogen cofiring with natural gas may be a viable energy production method in real-world applications. To date, hydrogen cofiring has been proven in laboratory and field experiments for selected gas turbine models, and at varying percentages of cofiring. This report details a feasibility study to support further testing for retrofitting hydrogen cofiring on an existing gas turbine. The study focused on design and cost considerations for cofiring hydrogen in an aeroderivative gas turbine.

Assessment of Low-Carbon Fuel Pathways for Maritime Transport

EPRI Report 3002021280
Executive Summary 3002022751
Published September 2021

Abstract

While technical and operational measures to increase fuel efficiency are expected to drive near term emissions reductions, achieving deeper decarbonization of the shipping sector will require a large-scale transition to low-carbon fuels and energy sources. This report provides an overview of available emissions reductions pathways for the maritime transport sector and characterizes the landscape of key low-carbon fuel candidates, including their relative competitiveness, applicability, development statuses, and research gaps.

Technology Update: Reciprocating Internal Combustion Engines for Low-Carbon Power Generation

EPRI Report 3002020044
Executive Summary 3002021871
Published July 2021

Abstract

As efforts intensify to decarbonize the power sector and generating assets capable of flexible operation take on a greater role in grid balancing, it is increasingly important to understand what options are available to contribute to low-carbon electricity in the future. Reciprocating internal combustion engines (RICE) are a candidate for low-carbon fuel use and have a potential role as part of the low-carbon power market because of their significant fuel and operational flexibility, relatively high efficiency, and low cost. This report provides a summary of the current status of engines, an overview of low-carbon fuels, challenges for RICE when using these fuels, research ongoing in this space, and potential next steps that could be undertaken as part of the Low-Carbon Resources Initiative to advance RICE using low-carbon fuels. The report summarizes a literature review and interviews with engineers at RICE manufacturers, national laboratory and university researchers, and consulting firms that provided insights into RICE operations and efforts to adapt the technology to low-carbon fuels, as well as recent findings from the Electric Power Research Institute's RICE Interest Group and Technical Assessment Guide activities.

Naturally Occurring Hydrogen Technology Update

EPRI Report 3002020181
Executive Summary 3002021141
Published April 2021

Abstract

Recent accidental discoveries have focused considerable attention on naturally occurring—or "native"—hydrogen as a potential new source of energy. This newfound possibility of extracting significant quantities of hydrogen from the subsurface has triggered R&D efforts to better understand the geological conditions that may enable long-term hydrogen production as well as subsurface hydrogen exploration. This report presents a review of known hydrogen seepages worldwide as well as the main hypotheses for the origin of native hydrogen, a summary of the economic development in Mali and the incipient exploration efforts for naturally occurring hydrogen, and a discussion of outstanding questions requiring further research efforts.

About EPRI

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